The Effect of Topographic Forcing on the Formation and Maintenance of Blocking

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ABSTRACT

A barotropic channel model in β–plane is used to study the effect of topographic forcing on the formation and maintenance of blocking. The approximate analytical solution of potential vorticity equation can show the main property of the whole process of blocking. It is indicated that the topographic forcing is one of the main factors causing the blocking process. The results suggest that the nonlinear interaction plays a very important role in the stable "Ω" situation of blocking. The atmospheric circulation with periodic and low–frequency oscillation, perhaps, is partly caused by topographic forcing.

I. INTRODUCTION

There have been many studies in blocking formation recently, and it is suggested that blocking is mainly caused by topography and heating factors. Charney and Elissen (1979) and Zhu Zhengxin and Zhu Baozhen (1983) studied nonlinear interactions of topography, heating and dissipation, using the method of high truncated spectra. They had obtained many favourable results in blocking dynamics.

It is suggested by Li Maicun (1984) that topographic forcing could produce steady standing and transient waves. The blocking mechanism was also studied by Eugenia and Merking (1983). Their results have shown that blocking occurs as a resonant enhancement of Rossby waves forced by two stationary sources of potential vorticity. It was also suggested by Zhu Zhengxin (1983) with numerical simulation that the strength of basic flow is very important to the blocking formation and its intensity. In other words, the effect of basic flow on blocking formation and maintenance is very significant. It has been demonstrated by Egger (1987) with numerical method that slowly moving free blocking is formed by the resonance caused by the interaction between slowly moving free wave and waves with different wave numbers. While Zhu Zhengxin (1984) suggested that blocking is formed by direct interaction between slowly moving wave and forcing source.

Authors have studied nonlinear interaction of two waves with different wave numbers in the primary conditions of existing slowly moving Rossby wave and fastly moving short Rossby wave. The result indicates that nonlinear interaction is the main process in blocking formation and maintenance.

With the study of many weather facts, scientists have discovered that blocking often formed and maintained in certain regions, like Wularer, Rockeis. So we can guess how topography affects blocking. The question of dynamic mechanism is worthy to be studied. Aiming at this question, in this paper, we only consider topographic forcing in primary condition of steady uniform westerly flow to study the effect of interaction between topography and circulation on blocking formation and to enhance our knowledge of nonlinear mechanism of topographic forcing.

II. DESCRIPTION OF THE MODEL

In certain conditions, the quasi–geostrophic barotropic potential vorticity equation can be written as

$$\frac{\partial}{\partial t}(\nabla^2 - \lambda_*^2)\psi + J(\psi,\nabla^2\psi) + \frac{f_0}{H}J(\psi,h) + \beta\frac{\partial\psi}{\partial x} = 0 \ , \tag{1}$$

where h is the function of topography, H is the height of homogeneous atmosphere, $\lambda_*^2 = f_0^2 / gH$; Other symbols are general used in meteorology. For convenience, we nondimensioned Eq.(1). Let L denote the horizontal scale; V, the west wind velocity; and L / V, the time scale.

$$\psi = LV\psi', \quad (x,y) = L(x',y'), \quad h = \alpha Hh', \quad t = \frac{L}{V}t' \tag{2}$$

α is the nondimensioned height of topography. According to Eq.(2), Eq.(1) can be nondimensioned as

$$\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi + J(\psi,\nabla^2\psi) + \frac{\alpha f_0 L}{V}J(\psi,h) + \beta^*\frac{\partial\psi}{\partial x} = 0 \ . \tag{3}$$

Eq.(3) is a dimensionless equation, and the symbol "'" is omitted, where

$$\lambda^2 = \frac{f_0^2 L^2}{gH}, \quad \beta^* = \frac{\beta L^2}{V} \ .$$

Eq.(3) is a nonlinear differential equation containing topography forcing, and it is impossible to get the exact solution in some given conditions. But it is possible to obtain approximate solution in certain conditions. We assume that both south and north borders of the β–plane channel model are solid walls, then the stream function can be decomposed into

$$\psi = -y + \varepsilon\psi^* \ ,$$

where ψ^* is a nondimensional perturbing stream function, ε is a small parameter. Thus, Eq.(3) becomes

$$\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi^* + \frac{\partial}{\partial x}\nabla^2\psi + \beta^*\frac{\partial\psi}{\partial x} = -\varepsilon J(\psi^*,\nabla^2\psi^*) - \varepsilon\alpha^* J(\psi^*,h) - \alpha^*\frac{\partial h}{\partial x} \ , \tag{4}$$

where

$$\alpha^* = \frac{\alpha L f_0}{V\varepsilon} \ .$$

Let perturbing stream function be zero at initial time, i.e.,

$$\psi^*\big|_{t=0} = 0 \tag{5}$$

and the boundary condition

$$-\frac{\partial\psi}{\partial x}\bigg|_{y=\pm\frac{\pi}{2}} = 0 \ . \tag{6}$$

To solve Eq.(4) under conditions (5) and (6), we use the method of variation of parameters. The basic idea of the method is that in order to get an approximately identified solution, one should not only expand the arguments with the small parameter, but also asymptotically expand the function to get the solution without "long–terms".

For the purpose of convenience, we simply select the function of topography as

$$h(x,y) = \sin 2x\cos y \ , \tag{7}$$

asymptotically expand the stream function ψ in powers of ε as

$$\psi^* = \psi_0 + \varepsilon\psi_1 + \varepsilon^2\psi_2 + \varepsilon^3\psi_3 + 0(\varepsilon^4) , \quad (8)$$

when the expansion is truncated at power 2. One term causing "long–range" appears in the equation. To eliminate this term, σ_i, the angular frequency of the term, is expanded as

$$\sigma_1 = \sigma_1^0 + \varepsilon\sigma_1^1 + \varepsilon^2\sigma_1^2 + \varepsilon^3\sigma_1^3 + 0(\varepsilon^4) , \quad (9)$$

substituting Eqs.(7), (8) and (9) into Eq.(4) and conditions (5) and (6), we get the following recurrence equation.

Equation with order zero is written as

$$\begin{cases} \frac{\sigma_1^0}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi_0 + \frac{\partial}{\partial x}\nabla^2\psi_0 + \beta^*\frac{\partial\psi_0}{\partial x} = -2\alpha^*\cos 2x\cos y \\ \psi_0\big|_{t=0} = 0 \\ -\frac{\partial\psi_0}{\partial x}\Big|_{y=\pm\frac{\pi}{2}} = 0 \end{cases} \quad (10)$$

Equation with order one is written as

$$\begin{cases} \frac{\sigma_1^0}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi_1 + \frac{\partial}{\partial x}\nabla^2\psi_1 + \beta^*\frac{\partial\psi_1}{\partial x} = -J(\psi_0, \nabla^2\psi_0) \\ -\alpha^* J(\psi_0,\ \sin 2x\cos y) - \frac{\sigma_0^1}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi_0 \\ \psi_1\big|_{t=0} = 0 \\ -\frac{\partial\psi_1}{\partial x}\Big|_{y=\pm\frac{\pi}{2}} = 0 \end{cases} \quad (11)$$

Equation with order two is written as

$$\begin{cases} \frac{\sigma_1^0}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi_2 + \frac{\partial}{\partial x}\nabla^2\psi_2 + \beta^*\frac{\partial\psi_2}{\partial x} = -J(\psi_0, \nabla^2\psi_1) - J(\psi_1,\ \nabla^2\psi_0) \\ -\alpha^* J(\psi_1,\ \sin 2x\cos y) - \frac{\sigma_1^2}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi_0 - \frac{\sigma_1^1}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2 - \lambda^2)\psi_1 \\ \psi_2\big|_{t=0} = 0 \\ -\frac{\partial\psi_2}{\partial x}\Big|_{y=\pm\frac{\pi}{2}} = 0 \end{cases} \quad (12)$$

III. THE APPROXIMATE SOLUTION OF TOPOGRAPHIC FORCING

According to Eq.(10) the solution with order zero is conveniently obtained as

$$\psi_0 = A_0\sin 2x\cos y - A_0\sin(2x - \sigma_1 t)\cos y$$

$$\sigma_1^0 = \frac{2(5-\beta^*)}{5+\lambda^2} , \qquad A_0 = \frac{\alpha^*}{5-\beta^*} . \quad (13)$$

Solution (13) is the same as that of linearized potential vorticity equation eliminating nonlinear effect. It shows that steady uniform flow produces wave–type flow under the topographic forcing.

Substituting Eq.(13) into Eq.(11), Jacobi terms in Eq.(11) with order one become

$$-J(\psi_0,\nabla^2\psi_0)=0$$
$$-a^* J(\psi_0,\sin 2x\cos y)=-a^* A_0\ \sin\sigma_1 t\sin 2y\ . \tag{14}$$

Therefore, Eq.(11) can be written as

$$\begin{cases}\dfrac{\sigma_1^0}{\sigma_1}\dfrac{\partial}{\partial t}(\nabla^2-\lambda^2)\psi_1+\dfrac{\partial}{\partial x}\nabla^2\psi_1+\beta^*\dfrac{\partial\psi_1}{\partial x}=-a^* A_0\sin\sigma_1 t\sin 2y \\ -\sigma_1^1 A_0(5+\lambda^2)\cos(2x-\sigma_1 t)\cos y \\ \psi_1\big|_{t=0}=0 \\ -\dfrac{\partial\psi_1}{\partial x}\bigg|_{y=\pm\frac{\pi}{2}}=0\end{cases} \tag{15}$$

No "long–range" term needs to be eliminated in Eq.(15), let the quantity be zero, i.e.,

$$\sigma_1^1=0\ , \tag{16}$$

thus, the solution of Eq.(15) can be obtained as

$$\psi_1=A_1\cos\sigma_1 t\sin 2y-A_1\sin 2y\ , \tag{17}$$

where

$$A_1=\frac{5+\lambda^2}{4+\lambda^2}\frac{A_0A_0}{2}\ .$$

According to the approximate solutions with orders zero and one, we can solve Eq.(12). Jacobi terms in Eq.(12) become

$$\begin{aligned}&-J(\psi_0,\nabla^2\psi_1)-J(\psi_1,\nabla^2\psi_0)\\ &=-A_0A_1[3\cos(2x-\sigma_1 t)-3\cos 2x+\cos(2x+\sigma_1 t)\\ &\quad-\cos(2x-2\sigma_1 t)](\cos 3y+\cos y)-a^* J[\psi_1,h(x,y)]\\ &=a^* A_1[\cos(2x+\sigma_1 t)+\cos(2x-\sigma_1 t)-2\cos(2x)](\cos 3y+\cos y)\ .\end{aligned}$$

Thus, Eq.(12) with order 2 can be written as

$$\begin{cases}\dfrac{\sigma_1^0}{\sigma_1}\dfrac{\partial}{\partial t}(\nabla^2-\lambda^2)\psi_2+\dfrac{\partial}{\partial x}\nabla^2\psi_2+\beta^*\dfrac{\partial\psi_2}{\partial x}=[(3A_0A_1-2\alpha^* A_1)\cos 2x \\ +(-3A_0A_1+\alpha^* A_1)\cos(2x-\sigma_1 t)+(-A_0A_1+\alpha^* A_1)\cos(2x+\sigma_1 t) \\ +A_0A_1\cos(2x-2\sigma_1 t)][\cos y+\cos 3y]-\dfrac{\sigma_1^2}{\sigma_1}\dfrac{\partial}{\partial t}(\nabla^2-\lambda^2)\psi_0 \\ -\dfrac{\sigma_1^1}{\sigma_1}\dfrac{\partial}{\partial t}(\nabla^2-\lambda^2)\psi_1 \\ \psi_2\big|_{t=0}=0 \\ -\dfrac{\partial\psi_2}{\partial x}\bigg|_{y=\pm\frac{\pi}{2}}=0\end{cases} \tag{18}$$

In the right hand side of Eq.(18), the term $\cos(2x-\sigma_1 t)\cos y$ is a "long–term" (resonant term). Without eliminating it, the solution would be the strength of the wave with time. It is obviously unreasonable in this case. To eliminate the "long–term", let

$$(-3A_0A_1+\alpha^* A_1)\cos(2x-\sigma_1 t)\cos y$$
$$-\frac{\sigma_1^2}{\sigma_1}\frac{\partial}{\partial t}(\nabla^2-\lambda^2)[A_0\sin 2x\cos y - A_0 sin(2x-\sigma_1 t)\cos y]=0 \ . \tag{19}$$

Thus, we obtain

$$\sigma_1^2=\frac{-3A_0A_1+A_1\alpha^*}{-(5+\lambda^2)A_0} \ . \tag{20}$$

Therefore, the identical approximate solution with order 2 can be obtained as

$$\psi_2 = A_1^2\sin 2x\cos y + A_3^2\sin(2x+\sigma_1 t)\cos y$$
$$+A_4^2\sin(2x-2\sigma_1 t)\cos y + A_5^2\sin(2x-\sigma_1 t)\cos y$$
$$+A_6^2\sin 2x\cos 3y + A_7^2\sin(2x-\sigma_1 t)\cos 3y + A_8^2\sin(2x+\sigma_1 t)\cos 3y$$
$$+A_9^2\sin(2x-2\sigma_1 t)\cos 3y + A_{10}^2\sin(2x-\sigma_2 t)\cos 3y \ , \tag{21}$$

where

$$\sigma_2=\frac{2(13-\beta^*)}{13+\lambda^2}, \quad A_1^2=(3A_0A_1-2\alpha^* A_1)\times P(2,1,0),$$
$$A_3^2=(-A_0A_1+\alpha^* A_0)\times P(2,1,-\sigma_1)$$
$$A_4^2=A_0A_1\times P(2,1,2\sigma_1), \quad A_5^2=-A_1^2-A_3^2-A_4^2$$
$$A_6^2=(3A_0A_1-2\alpha^* A_1)\times P(2,3,0), \quad A_7^2=(-A_0A_1+\alpha^* A_1)\times P(2,3,-\sigma_1),$$
$$A_9^2=A_0A_1\times P(2,3,2\sigma_1), \quad A_{10}^2=-A_6^2-A_7^2-A_8^2-A_9^2.$$

In practical calculating, we truncate asymptotic solution at power 3. The method to get approximate solution with order 3 is the same as above. Here we do not give the details for the solving process because of its complication.

According to the results mentioned above, we obtain the approximate solutions of potential vorticity equation which can describe topographic forcing.

$$\psi=-y+\varepsilon\psi^*$$
$$\psi^*=A_0[\sin 2x-\sin(2x-\sigma_1 t)]\cos y+\varepsilon A_1[\cos\sigma_1 t-1]\sin 2y+\varepsilon^2[A_1^2\sin 2x\cos y$$
$$+A_3^2\sin(2x+\sigma_1 t)\cos y + A_4^2\sin(2x-2\sigma_1 t)\cos y + A_5^2\sin(2x-\sigma_1 t)\cos y$$
$$+A_6^2\sin 2x\cos 3y + A_7^2\sin(2x-\sigma_1 t)\cos 3y + A_8^2\sin(2x+\sigma_1 t)\cos 3y$$
$$+A_9^2\sin(2x-2\sigma_1 t)\cos 3y + A_{10}^2\sin(2x-\sigma_1 t)\cos 3y]+0(\varepsilon^3) \ , \tag{22}$$

$$\sigma_1^0=\frac{2(5-\beta^*)}{5+\lambda^2}+\varepsilon^2\frac{-3A_0A_1+\alpha^* A_1}{-(5+\lambda^2)A_0}+0(\varepsilon^3) \ . \tag{23}$$

Ⅳ. PROCESS OF BLOCKING FORMATION AND MAINTENANCE

With the method of variation of parameters, we obtain the approximate solution of quasi–potential vorticity equations in the conditions of topographic forcing and primary steady uniform westerly flow. By selecting suitable parameters, the solution can demonstrate the main characteristics of topographic forcing circulation's evolution in three to four days, and the circulation changes from steady uniform westerly flow into typical blocking situation. Here, we select horizontal scale $L=1800$ km, Coriolis parameter $f_0=1\times10^{-4}$ s^{-1}, $\beta=1.6\times10^{-11}$ $s^{-1}m^{-1}$ (equivalent to 45°N), nondimensional height of topography $\alpha=0.1$ (equivalent to dimensioned height 1000 m), small parameter $\varepsilon=0.1$, intensity of westerly flow v = 15 m / s. Calculating the distribution at different time, we can get the variation trend of topographic circulation.

Fig.1 demonstrates the primary circulation at $t=$ day 0. The stream lines denote uniform westerly flow. The nondimensional interval between two lines is 0.5. x indicates the latitudinal direction and y, the longitudinal direction.

Two days later (see Fig.2), the circulation changes from uniform westerly flow into strong wave with trough–ridge. In the lee of topography at $x=\pi/2$ there is a deep trough. A strong high ridge is at $x=\pi$. The trough and the ridge have been enhanced greatly.

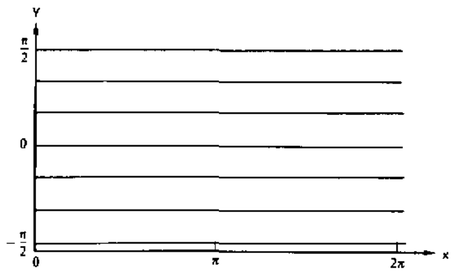

Fig.1. Circulation distribution at t = day 0.

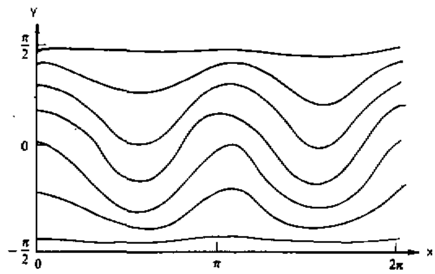

Fig.2. Circulation distribution at t = day 2.

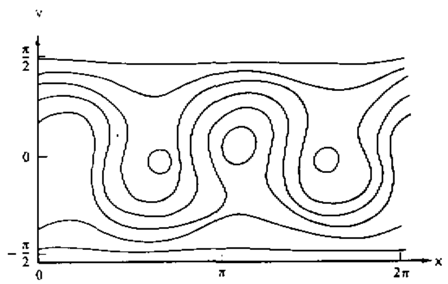

Fig.3. Circulation distribution at t = day 4.

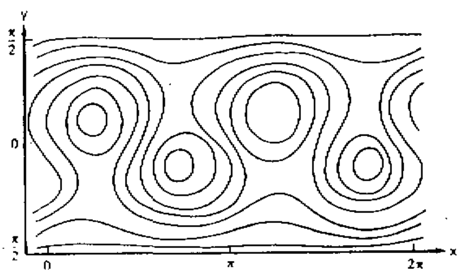

Fig.4. Circulation distribution at t = day 10.

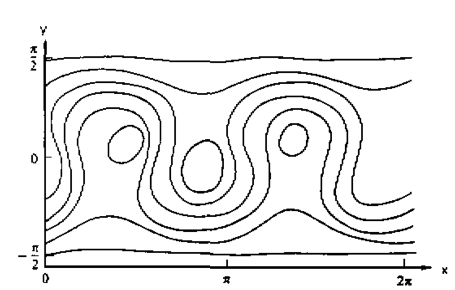

Fig.5. Circulation distribution at t = day 14.

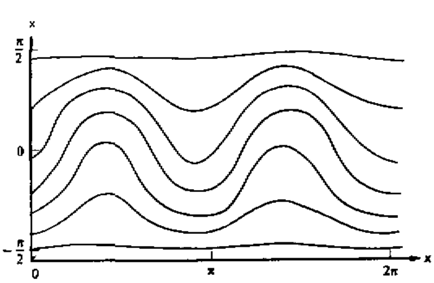

Fig.6. Circulation distribution at t = day 16.

As illustrated in Fig.3, the wave is gradually strengthened by topographic forcing at 4th day, the high ridge around $x = \pi / 4$ is strengthened and northward extended. But the south part of the ridge is sharply decreased in the vicinity of $y = \pi / 4$, and the high pressure is blocked. In the south part of the trough around $x = \pi / 2$, the trough is deepened, while north part of the trough is weakened, and the low is cut–off. The circulation becomes a typical "Ω" shape. As the meridional flow is strengthened and the zonal flow is weakened, the typical blocking situation is formed.

After the blocking formed, the system became very strong and stable. The strength of the system is gradually strengthened, and reached its peak in 10 days later (Fig.4); then the blocking is weakened, at t = day 14 the circulation is still a typical blocking (see Fig.5).

From Fig.6. we can see that the strong blocking is changed into wave type at t = day 16. From the point of view of stream type, the stream line distribution is reversed comparing Fig.2, the wave is trending to be vanished, and is very weak at t = day 18.

In the whole 18 days' life of the system, the "Ω" type blocking situation has maintained for 12 days. Its suitable parameters being adjusted, the blocking can be maintained longer. In the whole process, the blocking moved slowly. It moved less than $\pi / 4$ in 12 days (equivalent to dimensioned distance 1000 km).

It is discovered by calculating approximate solution (22) that the circulation presents a quasi–period obviously. The period is about 18 days according to the parameters selected above. The flow is rather weak at 18th day. The circulation at 20th day is similar to that of Fig.2, but opposite to that of t = day 16. Then the circulation will repeat the blocking situation. Here, we only illustrate the topographic forcing circulation evolution in a quasi–period. The solution with order zero is the largest one in asymptotical solutions. The change of solution with order zero will cause very significant effect on whole solution. With (13) we can know that the closer to 5 the β^* is, the longer the period of solution becomes. And the amplitude of the solution will be larger. The period is affected by horizontal and vertical scales of topography and latitude and intensity of westerly flow. It is indicated by calculating that with selecting suitable parameters the blocking system could have a two–week period. Relative large scales of topography (horizontal and vertical) and higher latitude and weaker strength of westerly flow will be favourable for forming long period of blocking and long time blocking maintenance.

It is a well–known fact that there are certain periods in atmospheric circulation. However, the basic reasons causing these periods and their mechanisms are not clear. In the atmosphere, strictly speaking, in the westerlies of the Northern Hemisphere, the large scale topography is fixed and not changed, but the intensity of westerly wind is changed greatly, that whether or not the blocking is formed by topographic forcing is determined by the intensity of westerly flow. If the westerly flow is relatively strong, blocking will not form easily, and the velocity of the system is relatively large. Here we have pointed out why blockings often present in certain lees of mountains. It has been a known fact that blocking is a system affecting the whole Northern Hemisphere, especially in winter, and the blocking formation and vanishment will cause very significant effect on large scale circulation in the middle and high latitudes, even low latitudes.

As indicated above, the interaction between topography and westerly flow will form periodical blocking; thus, we can deduct that quasi–period in the Northern Hemispheric circulation relates to the action of large scale topography. The variation of the period relates to the intensity and the scope of mean westerly flow.

V. TOPOGRAPHIC FORCING IN BLOCKING FORMATOIN

By selecting suitable parameters the approximate solution can describe the whole process of blocking formation, maintenance and vanishment, it demonstrates the importance of topographic forcing on westerly flow. However, topographic forcing can not always produce blocking in any conditions. In other words, only in suitable conditions, could the blocking form. The approximate solution (22) is analysed, so we can discuss the effect of physical factors on blocking formation with controlling parameters in approximate solution.

(1) Topographic Forcing in Westerly Flow

Through the topographic forcing, steady uniform westerly flow can be changed into trough–ridge wave in any conditions. From (22), we can see that the waves can be divided into two parts. One of them is steady topographic standing waves

$$A_0 \sin 2x \cos y \quad \text{and} \quad A_1^2 \sin 2x \cos y$$

and the other is moving waves being of topographic transient waves. Two parts of waves overlap, which causes the system presenting moving property. The velocity of the system and its intensity are related to topographic scale and westerly flow intensity.

Calculating approximate solution (22) with different parameters, we find that only the interaction between topography and westerly flow can form relatively strong and relatively long period system; therefore, the stable blocking can form (the closer to 5 the β is, the closer to resonance the interaction becomes). In the point of view of moving, stable blocking can form only in the condition that the absolute value of phase velocity is very small. From Eq.(13)

$$\sigma_1^0 = \frac{2(5-\beta^*)}{5+\lambda^2} \ , \tag{24}$$

we can see that when the interaction is near to resonance, β^* is closer to 5, which is controlled by latitude horizontal scales and magnitude of westerly flow. In this case, the absolute value of σ_0^1 is very small, the velocity of the system is also very small. From the point of view of the intensity of the system, because

$$A_0 = \frac{\alpha^*}{5-\beta^*} \ , \tag{25}$$

the amplitudes of other wave components can be expressed with A_9, so the absolute value of A_0 denotes the strength of the system. When the interaction is near to resonance, the denominator of Eq.(25) is very small, and the intensity of the wave is very strong. When the meridional flow is enhanced to a certain intensity, the circulation is relatively stable, and the blocking formed.

(2) The Effect of Nonlinear Interaction on the Process of Blocking

It has been demonstrated in a previous paper (Zhang et al., 1991) that it can be seen that under the initial conditions of only existing two waves with wave numbers 2 and 4, the approximate solution including nonlinear effect can describe the whole process of the blocking. It is clearly indicated in the paper that nonlinear interaction is the main process of blocking formation, maintenance and vanishment. The results of the coming paper will further confirm the conclusions (Zhang et al., 1991).

Without nonlinear interaction, the formula of stream function (22) will express the solution with order zero

$$\psi^* = A_0 \sin 2x \cos y - A_0 \sin(2x - \sigma_1 t)\cos y \tag{26}$$

The flow expressed in Eq.(26) will not form "Ω" type blocking and not vanish in any conditions. Thus, we can conclude that without nonlinear effect, the blocking with "Ω" type could not form. Eq.(26) can also be written as

$$\psi^* = \left\{ A_0 [2\sin\frac{\sigma_1 t}{2}] \right\} \cos(2x - \frac{\sigma_1 t}{2})\cos y \ . \tag{27}$$

It is expressed in Eq.(27) that the amplitude of the solution with order zero varies with time t. If the interaction between topography and westerly flow is nearly to resonance, the period of stream function in Eq.(27) is very long (of course, it is not suitable to discuss the interaction near to resonance, because the nonlinear action is very large), even can be several ten days. In other words, low–frequency oscillation and long–range maintaining of weather may be related to the action of topography.

To form "Ω" type flow, nonlinear interaction is required mainly. Without considering nonlinear interaction the flow only presents wave type, with considering nonlinear interaction, the approximate solution with order one of Eq.(22) is

$$\psi_1 = A_1 \cos\sigma_1 t \sin 2y - A_1 \sin 2y \ . \tag{28}$$

This term can form the flow with "Ω" type, where

$$A_1 = -\frac{\alpha^* A_0}{\alpha_1^0(\lambda^2+4)} = -\frac{\lambda^2+5}{\lambda^2+4}\,\frac{A_0 A_0}{2} \ . \tag{29}$$

It shows $A_1 < 0$ in any conditions. This term would cause the ridge of flow being strengthened and the trough of flow being weakened in the region of $y \in [0, \ \pi/2]$, and the greatest variation is in the vicinity of $y = -\pi/4$; the term also causes the trough of flow being deepened and southward extended and the ridge of flow being weakened in the region of $y \in [-\pi/2, \ 0]$, and the greatest variation is in the vicinity of $y = -\pi/4$. Overlapping of ψ_1 and ψ_2 will cause ridge being strengthened and northward extended in north part. While high ridge in south part is weakened; therefore, the high ridge is blocked. At the same time, the overlapping would cause low trough in south part being deepened and southward extended, the trough in northern part is weakened, and the low is cut–off. The circulation presents "Ω" type; the meridional flow has been enhanced and zonal gradient of pressure has been strengthened.

The velocity of eastward moving Rossby wave is reduced by nonlinear interaction. From Eq.(23),

$$\sigma_1 = \sigma_1^0 + \varepsilon^2 \sigma_1^2 + 0(\varepsilon^3) \ , \tag{30}$$

where

$$\sigma_1^0 = \frac{2(5-\beta^*)}{5+\lambda^2}, \quad \sigma_1^2 = \frac{5(2-\beta^*)}{2(4+\lambda^2)}\left(\frac{\alpha^*}{5-\beta^*}\right)^2 \ . \tag{31}$$

In middle latitudes of the Northern Hemisphere, topographic scale causing blocking is very small, so $\beta^* > 2$ and $\sigma_1^2 < 0$ in any conditions.

VI. CONCLUSIONS

(1) The effect of topographic forcing on westerly flow can cause standing and transient waves. In suitable conditions, resonance between topography and westerly flow enables the

meridional flow to enlarge and strengthen to form blocking situation.

(2) The blocking "Ω" situation is mainly caused by nonlinear action. At the same time, the nonlinear action makes slowly moving intensive wave slow down.

(3) The strength of westerly flow is as important as topography and heating factor in blocking formation, maintenance and vanishment.

(4) The topographic forcing on westerly flow makes circulation wave present periodicity. The period is affected by the intensity of westerly flow and its scale. The resonant interaction between topography and westerly flow not only can produce blocking, but also affect low–frequency oscillation and long–range weather process.

REFERENCES

Charney, J. G. and J. G. Deyore (1979), Multiple equilibria in the atmosphere and blocking *J. A. S.*, **36**: 1205–1216.

Egger, J. (1978), Dynamics of blocking highs, *J. A. S.*, **35**: 1788–1801.

Eugenia, K. R. and L. O. Merking (1983), On the effect of model resolution on numerical simulation of blocking, *Tellus*, **35**: 28–38.

Li Maicun and Luo Zhexian (1984), Topographic standing and transient waves, *Scientia Atmospherica Sinica*, **8**: 7–15 (in Chinese).

Zhang Pei and Ni Yunqi (1991), The efffect of nonlinear dynamic process on the formation and vanishment of blocking (to be published).

Zhu Zhengxin and Xiao Jie (1983), Numerical experiment of blocking dynamics, *Acta Meteorologica Sinica* **42**: 129–137 (in Chinese).

Zhu Zhengxin and Zhu Baozhen (1984), The effect of zonal asymmetric heating on nonlinear equilibrium state of ultra–long wave and blocking, *Scientia Atmospherica Sinica*, **8**: 361–371 (in Chinese).