Effect of Nonlinear Dynamic Process on Formation and Breakdown of Blocking

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ABSTRACT

With the L—P approximate method(variation of parameter method), a barotropic channel model in β—plane is used to study the effect of nonlinear interaction between two waves with different scales on the formation of blocking. The approximate analytical solution, which can describe the process of the blocking formation, maintenance and breakdown, has been obtained by using the method of aproximate expansion. The importance of nonlinear interaction between two waves with different scales is stressed in the solution. The result suggests that the nonlinear interaction is the main dynamic process of the blocking formation. Some required conditions of blocking formation are also discussed.

I. INTRODUCTION

The situation of blocking is the special stage in the development and evolution of atmospheric general circulation, and a relatively stable synoptical phenomenon which may be maintained for a long time(over one week). The formation, the maintenance and the breakdown of blocking can cause very significant effect on atmospheric general circulation, synoptic processes and meteorological phenomena of large scale in controlling area, the downstream area and even the whole hemisphere. Therefore, many meteorological scientists have shown great concern for the study of blocking formation mechanism in recent years. The multiple equilibrium state of forcing and dissipating model has firstly been studied by Charney and Devore using highly truncated spectral expansion method by Charney and Devore (1979). It was suggested that blocking is a kind of quasi stable lower index equilibrium states.

With the same method, two kinds of equilibrium states have been studied by Zhu Zhenxin and Zhu Baozhen (1984) using a baroclinic model with zonal asymmetric heat forcing and considering the blocking as an ultra—long wave system. The study indicated that one of the equilibrium states is the stable one which is close to resonance state. Therefore, the deductions of dynamic mechanism of the blocking such as the resonance between waves and frocing and the controlling influence of heat forcing on the blocking have been posed.

It was indicated in the numerical simulation studied by Tibaldi and Ji (1983) and Ji and Tibaldi (1983) that the synoptical scale action is very important for the blocking maintenance while the effect of the earth surface is the basic condition in blocking formation and maintenance. The effect of topography on the phase of blocking, the vorticity transport and the steady wave is very significant. The effect of topographic forcing on moving component of waves can cause a series of eastward moving Rossby waves or stationary waves. It has been pointed out by Egger (1978) that as a large scale circulation system, blocking is supported by relative small scale vorticity.

In this paper, we try to study nonlinear interaction between two different scale waves in the process of blocking formation and maintenance without any extra source forcing and dissipation, which is helpful for understanding the real roles of heat and topographic forcings in the blocking formation. The model used in the study and the method to solve the model are described in Sections 2 and 3. Section 4 is for discussion and analysis. The final section is the conclusion.

II. DESCRIPTION OF MODEL

The quasi-geostrophic vorticity equation can be written as

$$\frac{\partial}{\partial t}\nabla^2\psi + J(\psi,\nabla^2\psi) + \beta\frac{\partial\psi}{\partial x} = 0 \tag{1}$$

Let L denote the horizontal scale; U, the west wind velocity; L / U, the time scale. The nondimensional equation of (1) can be written as

$$\frac{\partial}{\partial t}\nabla^2\psi^* + J(\psi^*,\nabla^2\psi^*) + \beta^*\frac{\partial\psi^*}{\partial x} = 0 \tag{2}$$

Here all symbols are generally used in meteorology. All variables are nondimensional, and

$$\beta^* = \beta L^2 / U$$

Eq.(2) is a nonlinear equation and impossible to obtain exact solution in some determining conditions. But it is possible to get approximate solution in certain conditions. Thus, we solve Eq.(2) with asymptotic method. In the channel model of β-plane with north and south borders being solid walls we firstly assume that the stream function can be decomposed into

$$\psi^* = -y + \varepsilon\psi \tag{3}$$

Here, ε is a small parameter, ψ is the nondimensional perturbation stream function. According to (3), Eq.(2) may be written as

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

Now, we assume the existence of two eastward moving waves with different scales initially. For the purpose of convenience, let one wave number be 2, the other be 4 and wave numbers in y direction be 1. Thus determining conditions of Eq. (4) can be written as

$$\begin{cases} \psi|_{t=0} = A_1^0[\sin(4x+y)+\sin(4x-y)] + A_2^0[\sin(2x+y)+\sin(2x-y)] \\ -\left.\dfrac{\partial\psi}{\partial x}\right|_{y=\pm\frac{\pi}{2}} = 0 \end{cases} \tag{5}$$

Eqs. (4) and (5) will be solved by using the method of asymptotic expansion of variation of parameters. The basic idea of variation of parameters is that in order to get an approximately identified solution, one should not only expand the function with small parameter but also asymptotically expand the arguments. Lindsted (1882) and Pioncare (1886) changed the parameters, such as the frequency and the period, of the equation in order to eliminate "long-range" terms, and got significant results when they solved the nonlinear ordinary differential equations. Therefore, we asymptotically expand the stream function ψ in orders of ε as

$$\psi=\psi_0+\varepsilon\psi_1+\varepsilon^2\psi_2+\varepsilon^3\psi_3+0(\varepsilon^4) \tag{6}$$

When expansion was truncated at order 2, two terms causing "long-range" appeared in the equation. Their frequencies are ω_1 and ω_2 respectively. To eliminate these terms, other parameters should be expanded as

$$\omega_1=\omega_1^0+\varepsilon\omega_1^1+\varepsilon^2\omega_1^2+0(\varepsilon^3) \tag{7}$$

$$\omega_2=\omega_2^0+\varepsilon\omega_2^1+\varepsilon^2\omega_2^2+0(\varepsilon^3) \tag{8}$$

Substitute (6), (7), (8) into Eqs. (4) and (5), we can get the following recurrence equations. Equations with order zero are as follows:

$$\begin{cases} \dfrac{\omega_i^0}{\omega_i}\dfrac{\partial}{\partial t}\nabla^2\psi_0+\dfrac{\partial}{\partial x}\nabla^2\psi_0+\beta^*\dfrac{\partial\psi_0}{\partial x}=0 \\ \psi_0\big|_{t=0}=A_1^0[\sin(4x+y)+\sin(4x-y)]+A_2^0[\sin(2x+y)+\sin(2x-y)] \\ -\dfrac{\partial\psi_0}{\partial x}\Big|_{y=\pm\frac{\pi}{2}}=0 \end{cases} \tag{9}$$

where i = 1,2.

Equations with order one are as follows:

$$\begin{cases} \dfrac{\partial}{\partial t}\nabla^2\psi_1+\dfrac{\partial}{\partial x}\nabla^2\psi_1+\beta^*\dfrac{\partial\psi_1}{\partial x}=-J(\psi_0,\nabla^2\psi_0)-\sum\limits_{i=1}^{2}\dfrac{\omega_i^1}{\omega_i}\dfrac{\partial}{\partial t}\nabla^2\psi_0 \\ \psi_1\big|_{t=0}=0 \\ -\dfrac{\partial\psi_1}{\partial x}\Big|_{y=\pm\frac{\pi}{2}}=0 \end{cases} \tag{10}$$

Equations with order two are as follows:

$$\begin{cases} \dfrac{\partial}{\partial t}\nabla^2\psi_2+\dfrac{\partial}{\partial x}\nabla^2\psi_2+\beta^*\dfrac{\partial\psi_2}{\partial x}=-J(\psi_0,\nabla^2\psi_1)-J(\psi_1,\nabla^2\psi_0) \\ \qquad -\sum\limits_{i=1}^{2}\dfrac{\omega_i^1}{\omega_i}\dfrac{\partial}{\partial t}\nabla^2\psi_1^i-\sum\limits_{i=1}^{2}\dfrac{\omega_i^2}{\omega_i}\dfrac{\partial}{\partial t}\nabla^2\psi_0^i \\ \psi_2\big|_{t=0}=0 \\ -\dfrac{\partial\psi_2}{\partial x}\Big|_{y=\pm\frac{\pi}{2}}=0 \end{cases} \tag{11}$$

We solved above equations, and got approximate solution with order two. ψ_j^i on right side of equations denotes the term with frequency ω_i and the approximate solution with order j, ψ_2 is

$$\psi_j=\sum_i\psi_j^i \tag{12}$$

III. ASYMPTOTIC SOLUTION OF INTERACTION BETWEEN TWO WAVES

For Eq. (9) with order zero, the solution is obviously as follows:

$$\begin{aligned}\psi_0 &= A_1^0[\sin(4x+y-\omega_1 t)+\sin(4x-y-\omega_1 t)] \\ &+ A_2^0[\sin(2x+y-\omega_2 t)+\sin(2x-y-\omega_2 t)]\end{aligned} \tag{13}$$

where $\omega_1^0 = 4 - \frac{4\beta^*}{17}$ and $\omega_2^0 = 2 - \frac{2\beta^*}{5}$ are the dispersion formulae with order zero.

For convenience, the dispersion formula may be written as

$$Ps(m,n) = m - \frac{m\beta^*}{m^2+n^2}$$

thus

$$\omega_1^0 = Ps(4,1),\ \omega_2^0 = Ps(2,1) \tag{14}$$

The Jacobi terms in Eq. (10) with order one was substituted by (13), then

$$\begin{aligned}-J(\psi_0,\nabla^2\psi_0) &= -12A_1^0A_2^0[\cos(6x+2y-\omega_1 t-\omega_2 t)-\cos(6x-2y-\omega_1 t-\omega_2 t)] \\ &+ 36A_1^0A_2^0[\cos(2x+2y-\omega_1 t+\omega_2 t)-\cos(2x-2y-\omega_1 t+\omega_2 t)]\end{aligned}$$

Therefore, the approximate solution with order one can be written as

$$\begin{aligned}\psi_1 &= A_1^1[\sin(6x+2y+\omega_1 t-\omega_2 t)-\sin(6x-2y-\omega_1 t-\omega_2 t)] \\ &+ A_2^1[\sin(2x+2y-\omega_1 t+\omega_2 t)-\sin(2x-2y-\omega_1 t+\omega_2 t)] \\ &+ A_3^1[\sin(6x+2y-\omega_3 t)-\sin(6x-2y-\omega_3 t)] \\ &+ A_4^1[\sin(2x+2y-\omega_4 t)-\sin(2x-2y-\omega_4 t)]\end{aligned} \tag{15}$$

where

$$A_1^1 = -12A_1^0A_2^0P(6,2,\omega_1+\omega_2),\ A_2^1 = 36A_1^0A_2^0P(2,2,\omega_1-\omega_2)$$

Let

$$P(m,n,\omega) = \frac{1}{\omega(m^2+n^2)-m(m^2+n^2)+m\beta^*},$$

$$A_3^1 = -A_1^1,\quad A_4^1 = -A_2^1,\quad \omega_3 = Ps(6,2),\quad \omega_4 = Ps(2,2)\ .$$

According to approximate solutions with orders zero and one, we can solve Eq. (11) with order two, the solving process is very complicated, for convenience of writing we introduced the symbols

$$\begin{aligned}[m,n,\omega] &= \cos(mx+ny-\omega t)+\cos(mx-ny-\omega t) \\ <m,n,\omega> &= \sin(mx+ny-\omega t)+\sin(mx-ny-\omega t).\end{aligned}$$

Eqs. (13) and (15) are substituted into Eq. (11) and the Jacobi term on right side of Eq. (11) can be expressed as

$$\begin{aligned}&-J(\psi_0,\nabla^2\psi_1)-J(\psi_1,\nabla^2\psi_0)-\sum_{i=1}^{2}\frac{\omega_i^2}{\omega_i}\frac{\partial}{\partial t}\nabla^2\psi_0^i \\ &= C_1\{[10,3,2\omega_1+\omega_2]+[2,1,\omega_2]+7[10,1,2\omega_1+\omega_2]+7[2,3,\omega_2]\} \\ &+ C_2\{[10,3,\omega_1+\omega_3]+[2,1,\omega_3-\omega_1]+7[10,1,\omega_3+\omega_1]+7[2,3,\omega_3-\omega_1]\} \\ &+ C_3\{3[6,3,2\omega_1-\omega_2]+3[2,1,\omega_2]+5[6,1,2\omega_1-\omega_2]+5[2,3,\omega_2]\}\end{aligned}$$

$$
\begin{aligned}
&+C_4\{3[6,3,\omega_1+\omega_4]+3[2,1,\omega_1-\omega_4]+5[6,1,\omega_1+\omega_4]+5[2,3,\omega_1-\omega_4]\}\\
&+C_5\{-[8,3,\omega_1+2\omega_2]-[4,1,\omega_1]+5[8,1,\omega_1+2\omega_2]+5[4,3,\omega_1]\}\\
&+C_6\{-[8,3,\omega_3+\omega_2]-[4,1,\omega_3-\omega_2]+5[8,1,\omega_3+\omega_2]+5[4,3,\omega_3-\omega_2]\}\\
&+C_7\{[4,3,\omega_1]+[0,1,\omega_1-2\omega_2]+3[4,1,\omega_1]+3[0,3,\omega_1-2\omega_2]\}\\
&+C_8\{[4,3,\omega_4+\omega_2]+[0,1,\omega_4-\omega_2]+3[4,1,\omega_4+\omega_2]+3[0,3,\omega_4-\omega_2]\}\\
&-\sum_{i=1}^{2}\frac{\omega_i^2}{\omega_i}\frac{\partial}{\partial t}\nabla^2\psi_0^i \quad .
\end{aligned}
\tag{16}
$$

where

$$
\begin{aligned}
&C_1=23A_1^0A_1^1\ ,\quad C_2=-C_1\ ,\quad C_3=-9A_1^0A_2^1\ ,\quad C_4=-C_3\ ,\\
&C_5=35A_2^0A_1^1\ ,\quad C_6=-C_5\ ,\quad C_7=3A_2^0A_2^1\ ,\quad C_8=-C_7\ .
\end{aligned}
$$

The forcing terms in Eq. (11) are those in Eq. (16), in which the frequencies of terms $[2,1,\omega_2]$ and $[4,1,\omega_1]$ are the same as the intrinsic frequencies of equation. Without eliminating them, the "long–range" terms (resonant terms) will be caused in the solution which enables strength of the wave becoming unlimited with time. It is obviously unreasonable in this case. The appearing of the "long–range" terms was caused by regular expanding. It is necessary to eliminate such "long–range" terms for getting the identified available solutions.

ψ_0 can be decomposited into

$$
\begin{aligned}
\psi_0^{1'}&=A_1^0[\sin(4x+y-\omega_1 t)+\sin(4x-y-\omega_1 t)]\\
\psi_0^2&=A_2^0[\sin(2x+y-\omega_2 t)+\sin(2x-y-\omega_2 t)]
\end{aligned}
$$

Therefore, we assume

$$
\begin{cases}
\dfrac{-\omega_1^2}{\omega_1}\dfrac{\partial}{\partial t}\nabla^2\{A_1^0[4,1,\omega_1]\}+(3C_7-C_5)[4,1,\omega_1]=0\\[2ex]
\dfrac{-\omega_2^2}{\omega_2}\dfrac{\partial}{\partial t}\nabla^2\{A_2^0[2,1,\omega_2]\}+(3C_3+C_1)[2,1,\omega_2]=0
\end{cases}
\tag{17}
$$

The "long–range" terms (resonant terms) can be eliminated from (17). We got

$$
\omega_1^2=\frac{3C_7-C_5}{17A_1^0}\qquad\qquad \omega_2^2=\frac{3C_3+C_1}{5A_2^0}
$$

thus

$$
\omega_1=\omega_1^0+\varepsilon^2\frac{3C_7-C_5}{17A_1^0}\ ,\quad \omega_2=\omega_2^0+\varepsilon^2\frac{3C_3+C_1}{5A_2^0}
\tag{18}
$$

Therefore, we obtain

$$
\begin{aligned}
\psi_2=\;&A_1^2<10,3,2\omega_1+\omega_2>+A_2^2<10,3,\omega_3+\omega_1>+A_{29}^2<10,3,\omega_5>\\
&+A_3^2<10,1,2\omega_1+\omega_2>+A_4^2<10,1,\omega_3+\omega_1>+A_{30}^2<10,1,\omega_6>\\
&+A_5^2<8,3,\omega_1+2\omega_2>+A_6^2<8,3,\omega_3+\omega_2>+A_{31}^2<8,3,\omega_7>\\
&+A_7^2<8,1,\omega_1+2\omega_2>+A_8^2<8,1,\omega_3+\omega_2>+A_{32}^2<8,1,\omega_8>\\
&+A_9^2<6,3,2\omega_1-\omega_2>+A_{10}^2<6,3,\omega_1+\omega_4>+A_{33}^2<6,3,\omega_9>\\
&+A_{11}^2<6,1,2\omega_1-\omega_2>+A_{12}^2<6,1,\omega_1+\omega_4>+A_{34}^2<6,1,\omega_{10}>
\end{aligned}
$$

$$+A_{14}^2<4,1,\omega_3-\omega_2>+A_{15}^2<4,1,\omega_2+\omega_4>+A_{35}^2<4,1,\omega_1>$$
$$+A_{16}^2<4,3,\omega_1>+A_{17}^2<4,3,\omega_3+\omega_2>+A_{18}^2<4,3,\omega_2+\omega_4>$$
$$+A_{36}^2<4,3,\omega_{11}>$$
$$+A_{19}^2<2,3,\omega_2>+A_{20}^2<2,3,\omega_3-\omega_1>+A_{21}^2<2,3,\omega_1-\omega_4>$$
$$+A_{37}^2<2,3,\omega_{12}>$$
$$+A_{23}^2<2,1,\omega_3-\omega_1>+A_{24}^2<2,1,\omega_1-\omega_4>+A_{38}^2<2,1,\omega_2>$$
$$+A_{25}^2<0,3,\omega_1-2\omega_2>+A_{26}^2<0,3,\omega_4-\omega_2>$$
$$+A_{27}^2<0,1,\omega_1-2\omega_2>+A_{28}^2<0,1,\omega_4-\omega_2> \tag{19}$$

where

$$A_1^2=C_1P(10,3,2\omega_1^0+\omega_2^0),\ A_2^2=C_2P(10,3,\omega_3^0+\omega_1^0)$$
$$A_2^2=7C_1P(10,1,2\omega_1^0+\omega_2^0),\ A_4^2=7C_2P(10,1,\omega_3^0+\omega_1^0)$$
$$A_5^2=-C_5P(8,3,\omega_1^0+2\omega_2^0),\ A_6^2=-C_6P(8,3,\omega_2^0+\omega_3^0)$$
$$A_7^2=5C_5P(8,1,\omega_1^0+2\omega_2^0)\ \ldots\ldots$$
$$A_{29}^2=-(A_1^2+A_2^2),\ A_{30}^2=-(A_3^2+A_4^2),\ A_{31}^2=-(A_5^2+A_6^2),$$
$$A_{32}^2=-(A_7^2+A_8^2),\ A_{33}^2=-(A_9^2+A_{10}^2),\ A_{34}^2=-(A_{11}^2+A_{12}^2),$$
$$A_{35}^2=-(A_{14}^2+A_{15}^2),\ A_{36}^2=-(A_{16}^2+A_{17}^2+A_{18}^2),$$
$$A_{37}^2=-(A_{19}^2+A_{20}^2+A_{21}^2),\ A_{38}^2=-(A_{23}^2+A_{24}^2),$$
$$\omega_5=Ps(10,3),\ \omega_6=Ps(10,1),\ \omega_7=Ps(8,3),\ \omega_8=Ps(8,1)$$
$$\omega_9=Ps(6,3),\ \omega_{10}=Ps(6,1),\ \omega_{11}=Ps(4,3),\ \omega_{12}=Ps(2,3)$$

Eqs. (18) and (19) represent the asymptotic solution with order two. The asymptotic solution with order three can be obtained with the same method, here we do not give the solving process.

The solution with order three is to be the solution of the equation (4) with conditions (5) in this paper.

IV. EFFECT OF NONLINEAR INTERACTION ON FORMATION OF BLOCKING

Substituting the approximate solution with different order into Eqs.(6) and (7) and selecting suitable parameters, we can get the stream function describing the whole process of blocking. Here, we select $L=2000$ km, which is corresponding to the wave with wave number 2 and wave length 6000 km and to the wave with wave number 4 and wave length 3000 km respectively. Let $F=1\times10^{-4}$ s, $\beta=1.5\times10^{-11}$ s^{-1} m^{-1} (at 45°N), the steady uniform westerly wind $U=13$ m/s, and small parameter $\varepsilon=0.1$; $A_1^0=1.2$ is the nondimensional amplitude of the longwave, which denotes the strength of the wave. $A_2^0=-3$ is the nondimensional amplitude of the ultra–long wave. If the amplitudes are changed into dimensional quantities, then

$$A_1^0=3.1\times10^7\,\mathrm{m^2s^{-1}},\quad A_2^0=7.8\times10^7\,\mathrm{m^2s^{-1}}\ .$$

By calculating stream function at different time, the variation of stream function field with time can be obtained.

In this paper, Fig.1—Fig.8 are obtained by calculating the approximate stream function

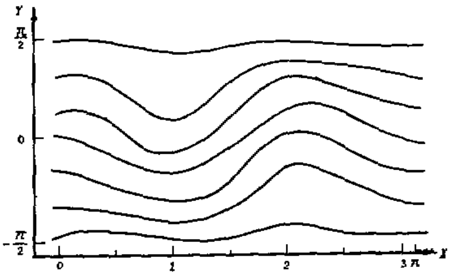

Fig.1. Steam function distribution at T= day 0.

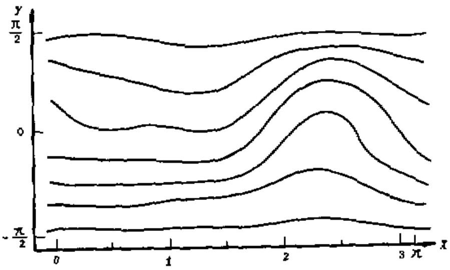

Fig.2. Stream function distribution at T= Day 1.

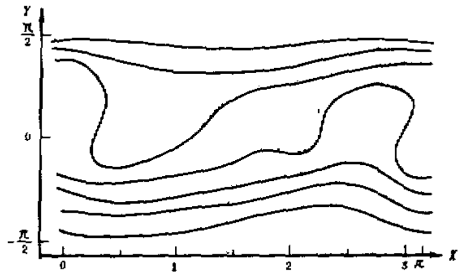

Fig.3. Steam function distribution at T= Day 2.

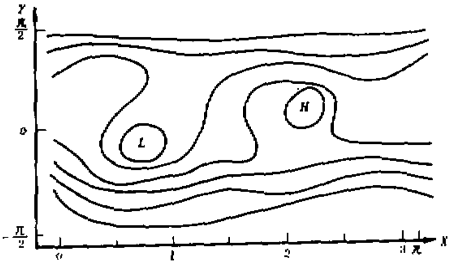

Fig.4. Stream function distribution at T= Day 3.

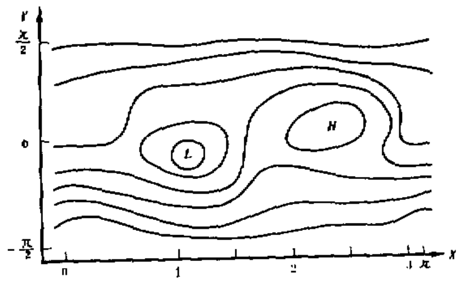

Fig.5. Steam function distribution at T= Day 4.

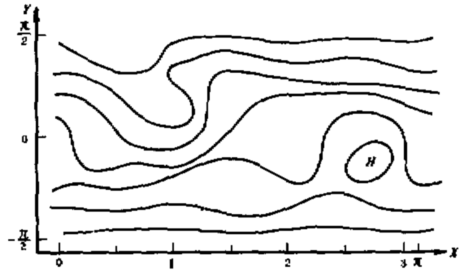

Fig.6. Stream function distribution at T= Day 6.

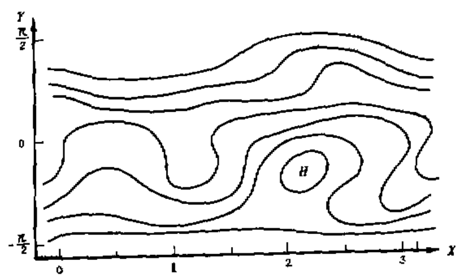

Fig.7. Steam function distribution at T= Day 8.

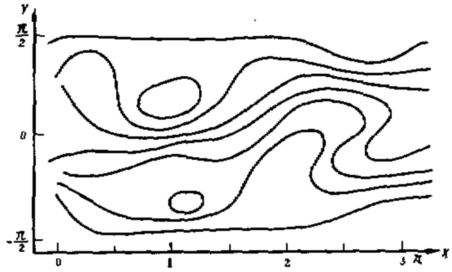

Fig.8. Stream function distribution at T= Day 11.

at different time t. The whole process of blocking formation, maintenance and breakdown was shown in these figures. The interval between two lines is 0.5 in these figures, in which x is the eastward direction and y, the northward direction. These figures illustrate stream function distributions at different time, in which L denotes the low value center and H, the high center.

1. *Nonlinear Interaction—the Main Dynamic Process of Blocking Formation and Breakdown*

Fig.1 shows the stream function distribution at initial time $t = day\ 0$. The linear overlapping of waves with wave numbers 2 and 4 is illustrated. From Fig.1 the relative strong ridge at $x = 2.1$ and relative strong trough at $x = 1$ can be found; and it can be seen from the vorticity distribution that a strong positive vorticity center is in the range of $x = 1.2 - 1.5$ and a negative vorticity center is in the range of $x = 1.7 - 2.0$.

Fig.2 illustrates the stream function distribution at $t =$ day 2. It is shown in the figure that the ridge is strengthened and moved northward obviously; but in two days later (see Fig.3), the trough has been strengthened strongly. So the ridge with "Ω" pattern has been formed primarily. But there is no closed center in high ridge and the system was developed and the typical situation of blocking has been formed on third day (see Fig.4). The high ridge of blocking was moved westward from $x = 2.5$ to $x = 2$ (about 1000 km), and closed high center has been formed at the same time. The trough in the west of the ridge has also been deepened and formed a cut low, while the center of the trough has been moved eastward. In other words, the east–west oriented gradient of pressure has been strengthened, the meridional flow is enhanced, and the zonal flow is weakened in the region of the blocking. The westerly flows at northern and southern flanks of the blocking have also been enhanced. These results are in agreement with the real weather fact in the atmosphere.

The stream function calculated day by day indicates that the blocking has been maintained for 9 days, and it is normally stable in the range of $x = 2.0 - 2.8$, but with little swing in the x and y directions. It is noticed (the figure is omitted) that a eastward moving cyclone is produced at $t =$ day 10 in the northwest of the calculated region. The strong positive vorticity advection invades into the region of the blocking obviously, so the blocking is weakened rapidly, the meridional flow is weakened and the high ridge is smoothed gradually (see Fig.8). The process of blocking breakdown is then shown clearly.

Above results indicate that under the condition with appropriate strength of the wave numbers 2 and 4, the solution of nonlinear interaction can simulate the real process of the blocking. Therefore, nonlinear interaction is the main dynamic process in blocking formation and breakdown.

2. *Some Necessary Conditions of Blocking Formation*

From large number of calculating the approximate stream function, we found that only suitable parameters being selected, the blocking can be formed and maintained.

Firstly, a strong and slowly moving ultra–long wave (about 6000 km in wave length) and a relatively weak long wave, such as pattern A or B or C or D, exist and the strength of ultra–long wave is 2 to 3 times of that of long waves, then the blocking formation and maintenance can be achieved. If the ultra–long wave is relatively strong, like pattern E, the nonlinear interaction of two waves can not cause significant changes of the ridge and the trough, so the blocking can not be formed and the circulation is still characterized by the ridge and the trough; if the long wave is relatively strong, and the effect of short waves is enhanced and resulting in significant change of flow field (see types D and F), the blocking can not be formed, even if the flow field with "Ω" type formed, the type flow field could move and vanish quickly; if both the waves are weak, the nonlinear interaction is not strong enough to form blocking (like type F), and if these two waves are strong, like pattern G , the stable blocking will not appear in the calculated flow field. In general, it is believed that the wave with wave number 2 is caused by the difference between land and sea heatings in the Northern Hemisphere. Thus, the existence of the wave with wave number 2 results in the effect of land–sea heating on blocking formation. This fact can explain why the blocking is mainly formed in the northern Pacific and the northern Atlantic Oceans. Results also suggested that relative large scale of wave and relative weak uniform westerly flow are the necessary conditions for blocking formation and maintenance, and relative high latitude is favourable for blocking formation and maintenance.

Table 1. Effect of Parameters on Stream Type

Parameters / Type	Amplitude of long wave	Amplitude of ultra–long wave	System moving	Stream type
A	1.2	3	very slowly	"Ω" type stream, weakly blocking property
B	1.2	3.2	very slowly	typical "Ω" type blocking situation
C	1.2	2.9	very slowly	"Ω" type stream, weakly blocking property
D	1.4	3	westward	"Ω" type stream
E	0.8	3.5	eastward	wave type stream mainly
F	0.8	2	eastward	wave type stream
G	1.4	3.5		irregular stream function is not convergence

3. *Effect of Interaction between Two Waves on Movement*

In the proper condition, interaction between two waves results in blocking formation. In the process of blocking formation, nonlinear interaction enables reducing the phase velocity. From (17) we can get

$$\omega_2 = \omega_2^0 + \varepsilon^2 \frac{3C_3 + C_1}{5A_2^0} + O(\varepsilon^3)$$

where

$$C_1 = 23A_1^0 A_1^1 , \qquad C_3 = -9A_1^0 A_2^1 ,$$

$$A_1^1 = -12A_1^0 A_2^0 P(6,2,\omega_1^0 + \omega_2^0), \quad A_2^1 = 36A_1^0 A_2^0 P(2,2,\omega_1^0 - \omega_2^0)$$

thus

$$\omega_2 - \omega_2^0 = \varepsilon^2 \frac{-3 \times 9A_1^0 A_2^1 + 23A_1^0 A_1^1}{5A_2^0}$$

$$= \varepsilon^2 \frac{-27 \times 36p(2,2,\omega_1^0 - \omega_2^0) - 12 \times 23p(6,2,\omega_1^0 + \omega_2^0)}{5} A_1^0 A_1^0$$

Substitute $\omega_1^0 = 4 - 4\beta^* / 17$ and $\omega_2^0 = 2 - 2\beta^* / 5$ into above formulae, thus

$$\omega_2 - \omega_2^0 \approx -\varepsilon^2 \frac{60}{\beta^*} A_1^0 A_1^0$$

where $\beta^* = \beta L^2 / U$. Therefore

$$\omega_2 - \omega_2^0 \approx -\varepsilon^2 \frac{60}{\beta L^2} U A_1^0 A_1^0$$

Above formula shows that the interaction between two waves with different wavelengths can cause the reduction of the phase velocity of ultra–long wave. The reduction level is proportional to the square of strength of long wave, and inversely proportional to β. This fact indicates that the strong eddy transport of long wave and high latitude are favorable for the blocking formation and maintenance.

V. CONCLUSIONS

The approximate solution of barotropic vorticity equation in β–plane and channel model has been obtained with the asymptotic method of variation of parameters. From above analysis, we can obtain the following conclusions:

(1) In the initial conditions of existing two waves with wave numbers 2 and 4 and without diabatic heating, topographic forcing and dissipation, the approximate solution which includes nonlinear effect can describe the main property of the blocking process. It is indicated clearly that the nonlinear interaction is the main dynamic process of blocking formation, maintenance and breakdown.

(2) Only the interaction between relative strong ultra–long wave and relative weak long wave can form the blocking. That the strength of ultra–long wave is 2 or 3 times of that of long wave is suitable for blocking formation.

(3) In the process of blocking formation and maintenance, the phase velocity of ultra–long wave is reduced by interaction between two waves. The reduced level is proportional to the square of strength of long wave, and is inversely proportional to β.

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