Topographically Forced Rossby Wave Instability and the Development of Blocking in the Atmosphere①

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ABSTRACT

In this paper, the linear stability of disturbance superimposed on basic state Rossby wave forced by topography is investigated, and pointed out that when a certain criterion is satisfied by the basic flow and the height of topography for the subresonance, the small disturbance may be unstable. Furthermore, we also compare the evolution of the instability disturbance with the development of blocking in the Pacific, and we suggested that the topographically forced Rossby wave instability may provide a possible mechanism for the development of blocking in the Pacific.

I. INTRODUCTION

Atmospheric blocking is an important weather phenomenon in mid–high latitude westerlies, its initiation, development and maintenance play a great role in the changes of weathers in the mid–latitude region. Recently, there has been a great deal of interest in understanding blocking in the atmosphere, although the phenomenon had been known for many years(see the work of Rex, 1950a), the physical mechanism underlying blocking remained obscure. Egger(1978) showed that blocking can be caused by the nonlinear interaction of topographically forced Rossby wave with slowly moving free Rossby wave. Tung and Lindzen(1979) pointed out that atmospheric blocking may be explained by ways of linear resonance of planetary waves with respect to topography and diabatic heating. Charney and Devore(1979) proposed a multiple equilibria theory of blocking formation, and they suggested that one stable equilibrium state which is very similar to atmospheric blocking may be formed by topography and external forcing, but the above theories can not explain the formation of dipole blocking in the atmosphere. Mcwilliams (1980) proposed the equivalent modon theory of vortex pair blocking. Magluzzi et al. (1984) used the nonlinear stationary Rossby wave theory to explain the dipole blocking in the atmosphere. And Luo and Ji (1988, 1989) proposed the algebraic solitary Rossby wave and envelope solitary Rossby wave theories of dipole blocking. However, these above theories can not explain the geographical variation of dipole blocking, Luo and Ji (1989) studied the nonlinear interaction of the stationary waves forced by topography and diabatic heating, and pointed out that the nonlinear interaction of the stationary waves forced by topography is an important mechanism of local dipole blocking. Austin (1980) studied the role of planetary scale waves in blocking and pointed out that the interference between the stationary planetary scale waves could initiate a blocking, and she also demon–

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strated that a westward propagating wave–1 played an important role in a Pacific blocking event in january 1968. Lejanas and Doos (1987) investigated the behaviourof the stationary and travelling planetary scale waves during blocking respectively, and obtained the development process of omega type block. But the mechanism of the developing omega type blocking is not known. White and Clark (1975) analysed a blocking process occurred in the Pacific, and pointedout that the baroclinic instability is an important cause of the developmentof Pacific blocking. In this paper, the instability problem of Rossby wave forced by topography is discussed, and it is found that the barotropic instability of Rossby wave forced by topography is another mechanism for thedevelopment of Pacific blocking.

II. THE MOTION EQUATIONS

The vorticity equation governing the barotropic motion of a quasigeostrophic, inviscid, homogeneous fluid confined to mid–latitude channeled on a β plane with topography is

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

Where ψ is the stream function, β is the northward gradient of the Coriolis parameter f, $\bar{H}$ is the depth of fluid, h represents the height distribution of topography, $\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$ denotes the Laplace operator, $J(f,g)=\frac{\partial f}{\partial x}\frac{\partial g}{\partial y}-\frac{\partial f}{\partial y}\frac{\partial g}{\partial x}$ is the Jacobian operator, and f_0 is a constant. Here, the topography distribution is assumed to be

$$h=h_0\cos\theta\sin my \tag{2}$$

Where

$$\theta=Nx \text{ and } m=\frac{\pi}{L}\ .$$

III. THE LINEAR STABILITY ANALYSIS

The exact solution of Rossby wave forced by the topography distribution (2) is given by

$$\psi=\psi_0=-\bar{u}y+A\cos\theta\sin my \tag{3}$$

Where $A=-\frac{f_0h_0}{\bar{H}(K^2-F^2)}$, $K^2=m^2+N^2$, $F^2=\frac{\beta}{\bar{u}}$, $K^2-F^2\neq 0$ and $\bar{u}$ denotes the zonal wind.

Let ψ' represent the disturbance stream function, the solution of Eq.(1) may be assumed to be

$$\psi=\psi_0+\psi'=-\bar{u}y+A\cos\theta\sin my+\psi' \tag{4}$$

Substition of (4) into (1) yields the following linear equation for ψ'

$$(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x})\nabla^2\psi'+\beta\frac{\partial\psi'}{\partial x}-A[m\cos my\cos\theta\frac{\partial}{\partial x}+N\sin my\sin\theta\frac{\partial}{\partial y}](\nabla^2+F^2)\psi'=0 \tag{5}$$

The truncation solution of (5) may be taken to be

$$\psi' = e^{-i\lambda t}(p_0 \sin my + p_1 \sin 2my e^{i\theta}) + cc \tag{6}$$

Where cc represents the complex conjugate of its preceeding term, and p_0, p_1 denote the wave amplitudes of Rossby wave disturbance respectively. Introducing (6) into (5), we obtain

$$\begin{cases} \lambda m^2 p_0 + \frac{1}{4} ANm[-(4m^2+N^2)+F^2]p_1 = 0 \\ \frac{ANm}{4}[-m^2+F^2]p_0 + [(4m^2+N^2)(\lambda - \bar{u}N)+\beta N]p_1 = 0 \end{cases} \tag{7}$$

Obviously, for a nontrivial solution of p_0 and p_1, the following relation must be satisfied in the form

$$\lambda^2 - QN\lambda - \frac{A^2N^2}{16(4m^2+N^2)}(-m^2+F^2)[-(4m^2+N^2)+F^2] = 0 \tag{8}$$

Where

$$Q = \bar{u} - \frac{\beta}{4m^2+N^2} .$$

Thus, the two roots of Eq.(8) are

$$\lambda = \frac{NQ \pm N\sqrt{Q^2 + A^2(-m^2+F^2)[-(4m^2+N^2)+F^2]/4(4m^2+N^2)}}{2} \tag{9}$$

Clearly, from (9), when $m^2 < F^2 < 4m^2 + N^2$, and the amplitude of the stationary wave forced by topography satisfies

$$A^2 > A_c^2 \tag{10}$$

Where

$$A_c = 2|Q|\sqrt{\frac{4m^2+N^2}{(F^2-m^2)[4m^2+N^2-F^2]}} .$$

When λ is complex, the travelling Rossby wave is unstable, and (10) may be rewritten as

$$h_0^2 > h_c^2 \tag{11}$$

Where

$$h_c^2 = \frac{2\bar{H}}{f_0}|(K^2-F^2)Q|\sqrt{\frac{4m^2+N^2}{(F^2-m^2)(4m^2+N^2-F^2)}} .$$

And h_c is the critical height of topography.

It can be seen from (11) that when the height of topography exceeds the critical value h_c, the travelling planetary Rossby wave may produce instability, and when $F^2 < k^2$ (i.e. superresonance), the topographically forced stationary wave is in phase with topography, on the other hand, when $F^2 > K^2$ (i.e. subresonance), the stationary wave is exactly 180° out of phase with topography. We can also find from (11) that whether the topographic wave is super resonance or subresonance, when the height of topography satisfies (11), in this case, the planetary travelling Rossby wave is unstable. In the following discussion, we only consider the case $F^2 > K^2$, then, the instability conditions of the travelling planetary wave obtained are $m^2 + N^2 < F^2 < 4m^2 + N^2$ and $h_0 > h_c$, and $m^2 + N^2 = F^2$, $4m^2 + N^2 = F^2$ are shown in Fig.1. Only when m, N and the basic flow $\bar{u}$ are in the shaded region of Fig.1. and the height of topography exceeds the critical height, the travelling planetary Rossby wave is unstable.

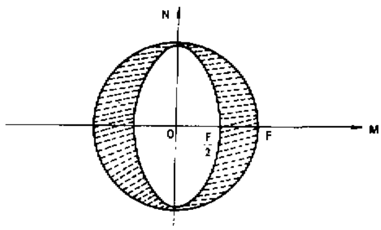

Fig.1. The curves of $m^2 + N^2 = F^2$ and $4m^2 + N^2 = F^2$.

IV. THE COMPUTATIONAL RESULTS

In the following calculation, we may let $\varphi_0 = 50°$N, $m = \frac{\pi}{L}$, $N = \frac{2\pi}{L_x}$, and $L = L_x = 6000$km, $h_0 = h_c + 100(m)$, $\bar{u} = \frac{\beta}{2m^2 + N^2}$, and the topography distribution is pictured in Fig.2.

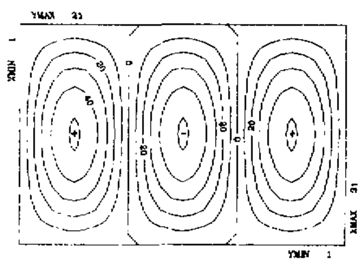

Fig.2. The topography distribution of $h = h_0\cos\theta\sin my$ for $\theta = Nx$ and $m = \frac{\pi}{L}$, interval:10, unit:10.

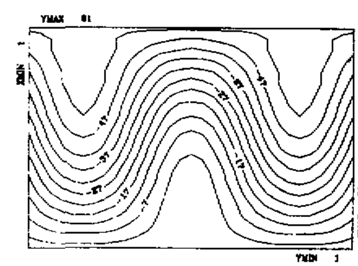

Fig.3. The streamline field for the basic state, interval:5 unit:1×10^6 m^2/s.

The negative value region of Fig.2. denotes oceans, and the positive ones represent two lands (the Asia land and the North America land), Fig.3. is the stream function of the basic state, that is, the stationary Rossby wave stream function. Obviously, a high ridge appears over the Pacific. White and Clark(1975) utilized a blocking process occurred in the Pacific, they found that the basic stream function is similar to Fig.3. during the initial time of blocking.

In order to discuss the development process of blocking, here, we considered a superimposed disturbance, which is not very large as the initial condition, and let $P_0 = 7 \times 10^6\ m^2/s$, *in this case, the streamline field is shown in* Fig.4a., clearly, a blocking which is not very strong appears in the Pacific, then, we computed the evolution of the blocking, and the results are shown in Figs.4a–i.

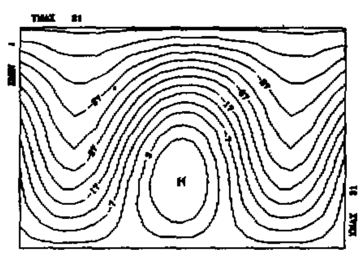

Fig.4a. The atmospheric streamline field at the initial time, interval: 5, unit: $1 \times 10^6\ m^2/s$.

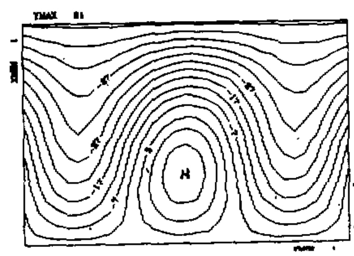

Fig.4b. The atmospheric streamline field for day 2, the others same as Fig.4a.

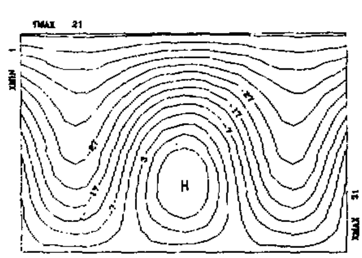

Fig.4c. The atmospheric streamline field for day 4, the others same as Fig.4a.

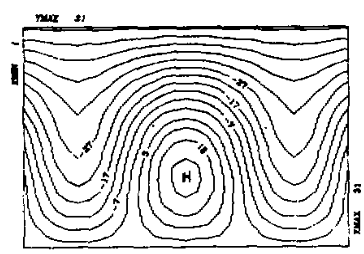

Fig.4d. The atmospheric streamline field for day 6, the others same as Fig.4a.

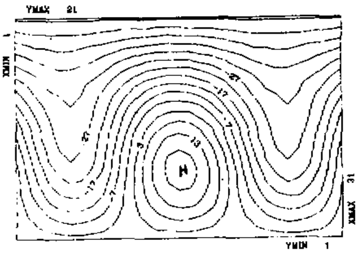

Fig.4e. The atmospheric streamline field for day 8, the others same as Fig.4a.

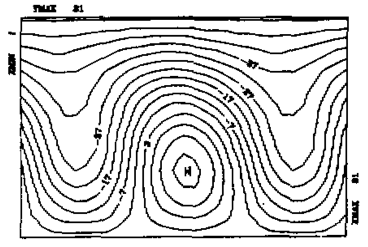

Fig.4f. The atmospheric streamline field for day 10, the others same as Fig.4a.

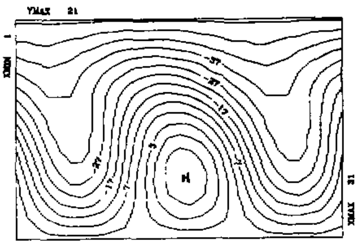

Fig.4g. The atmospheric streamline field for day 12, the others same as Fig.4a.

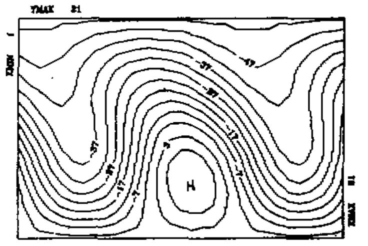

Fig.4h. The atmospheric streamline field for day 14, the others same as Fig.4a.

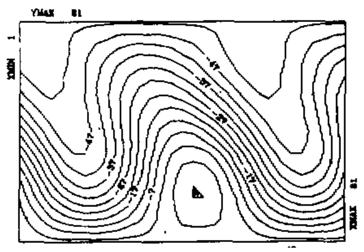

Fig.4i. The atmospheric streamline field for day 16, the others same as Fig.4a.

The figures show that the blocking might be developed into strong omega type blocking with the development of Rossby wave disturbance. The omega type blocking lasted for ten days and then it decayed and extended toward the west with time. This process resembles the *evolution of blocking in the real atmosphere very well. White and Clark (1975) pointed out* that the development of blocking over the Pacific was caused by baroclinic instability, Schilling (1982) also demonstrated the baroclinic instability might produceblocking. However, the *baroclinic instability might be not only one of the reasons of blocking formation. From the* above discussions, it is found that the barotropic instability of topographically forced Rossby wave is of importance for the development of blocking, this mechanism had been discussed by Charney and Devore (1979). They proposed *the form–drag instability forced by topography* in studying multiple equilibria of planetary waves in the atmosphere. This instability is similar to the topographically forced Rossby wave instability in the present paper. However, they only obtained a kind of state blocking and did not discuss the development process of blocking. Here, the author discussed Rossby wave instability forced by topography from another aspect, and pointed out that the topographically forced Rossby wave instability is a possible mechanism for the development of blocking.

V. THE CONCLUSIONS

In this paper, the barotropic instability of topographically forced Rossby wave is discussed, and pointed out that the topographically forced Rossby wave is a possible mechanism of the development of blocking over the Pacific.

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