ON THE GENERATION AND MAINTENANCE OF ATMOSPHERIC DISTURBANCES *

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ABSTRACT

Blocking is one of the intensive atmospheric disturbances which can maintain for a long time. In this paprer we investigate the general conditions favorable for the generation and maintenance of the intensive disturbances. First, the evolutional process of disturbances superimposed on a jet-like zonal flow is studied by using the wave-packet representation and the WKBJ method. Second, the mechanism for generation and maintenance of disturbances is investigated by using the nonlinear equations and the general physical laws. Finally, some numerical experiments are given for illustration, showing the rapid absorption of disturbances by the jet-like zonal flow in one case and the maintenance of disturbances for a long time in the other case.

I. INTRODUCTION

Blocking is an important anomalous phenomenon in the atmospheric circulation. Currently, many intensive observational studies and theoretical investigations have been devoted to this problem. Owing to these worldwide intensive investigations we have got much better understanding of the mechanism for the generation and maintenance of the blocking. Blocking itself is a large scale flow pattern with intensive anticyclonic vorticity which maintains for rather long time. Other intensive disturbances are cut-off low, the abnormal intensive ultralong waves, strong asymmetricity of the circulation pattern, strong flow across the equator, the stratospheric sudden warming and so on. They are also associated with some kinds of anomalous states in the atmospheric circulation and are of practical importance in the middle and long range weather forecast and climate prediction. It seems that an extension of the investigation to including the mechanism of the generation and maintenance of the intensive disturbances is desirable, and this extension in its turn might help us to get a supplementary understanding of blocking.

It must be pointed out that in our atmosphere there is always a jet-like zonal flow and, thus, there generally exists interaction between the zonal flow and disturbances. As well known from many climatological observational studies (see, for example, Lorenz[1]), the quasi-stationary planetary waves are generated and maintained by the forcing, but the transient eddies by the baroclinic conversion from zonal to eddy available potential energy, while they both feed their kinetic energy to the zonal flow. Therefore, the generation and maintenance of atmospheric disturbances are very closely related to the interaction along with the forcing. In this paper, we will first summarize some results in the aspect of interaction, making emphasis on the evolutional process for the disturbances, and then indicate the general conditions favorable for their generation and maintenance with illustration by some numerical experiments.

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II. EVOLUTION OF DISTURBANCES SUPERIMPOSED ON A JET-LIKE ZONAL FLOW

Representing atmospheric disturbances by a wave-packet, the propagation of forced quasi-stationary disturbances and the mechanism of teleconnection have been investigated by Grose and Hoskins[2] and Karoly[3]. Taking the wave-packet representation and making emphasis on the energetic aspect the evolution of transient disturbances has been investigated[8,9] by Young and Rhines[4], Lu and Zeng[5,6], Lu[7] and Zeng[8,9].

For simplicity, we now take a linearized barotropic quasi-geostrophic model without forcing and dissipation (see, Zeng[8])

$$\left(\frac{\partial}{\partial t}+\bar{U}\frac{\partial}{\partial x}\right)\left(\frac{\partial^2\psi'}{\partial x^2}+\frac{\partial^2\psi'}{\partial y^2}-\left(\frac{l_a}{l_r}\right)^2\sin^2\theta\cdot\psi'\right)=-\frac{\partial\bar{q}}{\partial y}\frac{\partial\psi'}{\partial x}, \tag{1}$$

where $\bar{U}=V_\lambda/\sin\theta$, V_λ is the zonal flow, $\bar{q}$ its quasi-geostrophic potential vorticity, ψ' the perturbation of stream function, θ the co-latitude, l_r the Rossby deformation radius, and l_a the characteristic length for the disturbances. All the variables and coordinates are nondimensional.

Assume that $\bar{U}$ and $\partial\bar{q}/\partial y$ are slowly varying functions of y and t, let ε be a small parameter, introduce

$$X=\varepsilon x,\qquad Y=\varepsilon y,\qquad T=\varepsilon t, \tag{2}$$

and represent ψ' in the form of a wave packet

$$\psi'=\{\Psi_0(X,Y,T)+\varepsilon\,\Psi_1(X,Y,T)+\cdots\}e^{i\tilde{\theta}(X,Y,T)/\varepsilon}, \tag{3}$$

where $\tilde{\theta}$ and $\Psi_j\,(j=0,1,\cdots)$ are all slowly varying functions of (x, y, t). Using the WKBJ method, we obtain

$$(\sigma-m\bar{U})\gamma^2+m\tilde{\beta}=0, \tag{4}$$

and

$$\gamma^2 D_g|\Psi_0|/DT+\frac{|\Psi_0|}{2}D_g\gamma^2/DT+\frac{\gamma^2|\Psi_0|}{2}\nabla\cdot C_g-mn\frac{\partial\bar{U}}{\partial y}|\Psi_0|=0, \tag{5}$$

where $\sigma\equiv-\partial\tilde{\theta}/\partial T$, $m\equiv\partial\tilde{\theta}/\partial X$, $n\equiv\partial\tilde{\theta}/\partial Y$, $\gamma^2\equiv m^2+n^2+\rho^2$, $\rho^2\equiv(l_a/l_r)^2\cdot\sin^2\theta$, $\tilde{\beta}\equiv\partial\bar{q}/\partial y$, and

$$D_g/DT=\frac{\partial}{\partial T}+C_{gX}\frac{\partial}{\partial X}+C_{gY}\frac{\partial}{\partial Y}. \tag{6}$$

The components of group velocity are given by

$$\begin{cases} C_{gX}=\dfrac{\partial\sigma}{\partial m}=\bar{U}+\dfrac{2m^2}{\gamma^4}\tilde{\beta}, \\ C_{gY}=\dfrac{\partial\sigma}{\partial n}=\dfrac{2mn}{\gamma^4}\tilde{\beta} \end{cases} \tag{7}$$

From (5), we obtain the following integrals

$$\frac{\partial}{\partial T}\iint\limits_{W}\frac{1}{2}\gamma^2|\Psi_0|^2 dX dY=\iint\limits_{W}|\Psi_0|^2 mn\frac{\partial \bar{U}}{\partial Y}dX\, dY, \tag{8}$$

$$\iint\limits_{W}\bar{\beta}^{-1}\frac{\partial}{\partial T}(\gamma^4|\Psi_0|^2)dX dY=0, \tag{9}$$

$$\iint\limits_{W}\left[\frac{\partial}{\partial T}(\gamma^2|\Psi_0|^2)+\frac{\bar{U}_0-\bar{U}}{\bar{\beta}}\frac{\partial}{\partial T}(\gamma^2|\Psi_0|^2)\right]dX dY=0\,, \tag{10}$$

where the integration is taken over the whole wave packet W. $\gamma^2|\Psi_0|^2$ and $\gamma^4|\Psi_0|^2$ are the analogues of energy and enstrophy density respectively, and $\bar{U}_0$ is a constant.

From (4) and (7) and by using some kinematic relationships we obtain an equation for the change in the tilt of trough-ridge lines as follows

$$D_g\left(\frac{n}{m}\right)/DT=-\left(\frac{\partial \bar{U}}{\partial Y}+\frac{\bar{\beta}}{\gamma^4}\frac{\partial \rho^2}{\partial Y}-\gamma^{-2}\frac{\partial \bar{\beta}}{\partial Y}\right). \tag{11}$$

According to (8), a disturbance is intensified, i.e., its energy increases with time, if the averaged $mn\partial\bar{U}/\partial Y$ is positive, while it decays if the averaged $mn\partial\bar{U}/\partial Y<0$. On the other hand, the term $-\partial\bar{U}/\partial Y$ generally is the dominant on the right hand side of (11) if $\bar{U}$ is a jet-like zonal flow. Therefore, a growing disturbance, i.e., the averaged $mn\partial\bar{U}/\partial Y>0$, gradually turns its trough-ridge lines toward a meridian, then becomes a decaying disturbance with $mn\partial\bar{U}/\partial Y<0$, and after that its energy is absorbed by the zonal flow, and the trough-ridge lines become more and more tilted. Only in the unstable case, i.e., there exist $\bar{\beta}<0$, and $(\bar{U}_0-\bar{U})/\bar{\beta}<0$, in some areas included in the region occupied by the disturbance, can the disturbance maintain a large amplitude for a long time.

III. THE FAVORABLE CONDITIONS FOR THE MAINTENANCE OF DISTURBANCES IN A BAROTROPIC ATMOSPHERE

So far as the linearized Eq. (1) is a good approximation to a potential vorticity equation and the disturbance can be well represented by a single wave packet (3), the condition for maintenance of intensive disturbances is the instability of the zonal flow. However, if the nonlinear terms can not be omitted, or the disturbances can not be well represented by a single wave packet, the problem becomes complicated. For example, if the disturbances are represented by a linear combinatiom of several wave packets, we have to investigate their interference, and the Eq. (11), valid for a single wave packet, can not correctly predict the change in the tilt of the trough-ridge lines, hence the lifecycle of the disturbances.

It is better to directly use the nonlinear equations and the general physical laws. We have the conservation of potential vorticity, the conservation of the vector of the total atmospheric angular momentum and the inertial axis of atmospheric motion, if there is no orographic forcing and the energy source and sink. Therefore, we come to the following conclusion (see Zeng [9]).

Nonzonal disturbances will maintain and will not be completely absorbed by a jet-like zonal flow in a barotropic atmosphere without forcing and dissipation, if one of the following conditions is satisfied: (i) there are three or more centres of potential vorticity in the whole sphere, (ii) the atmospheric inertial axis does not coincide with the one of the earth's rotation.

The zonal flow has two potential vorticity centres, each at one pole in the two hemispheres. Note that a sufficiently intensive individual vortex (cyclone or anticyclone) is usually associated with a potential vorticity centre, hence there exist at least three centres, and the nonzonal disturbances can maintain to some extent. Second , the atmospheric inertial axis does not coincide with that of the earth's rotation if there is a strongly asymmetric flow pattern, for example, an intensive ultra-long wave with wavenumber 1. It is also interesting to point out that there are always several potential vorticity centres if the zonal flow is unstable and the disturbances are located in the area with $\bar{\beta}<0$. Besides, the existence of strong flow across the equator will create more potenial vorticity centres in the equatorial region. All these are the favorable conditions for the maintenance of nonzonal disturbances.

Along with the above-mentioned conditions, the orographic forcing and the energy source,of course, are the other factors for thr generation and maintenance of disturbances.

IV. BAROCLINIC CASE

In the baroclinic atmosphere we get the results similar to those obtained in Section II if the wave packet is located far away from the bottom boundary (see Zeng [10]). However, if a disturbance is located near the bottom boundary, the situation is complicated. Second, similar to the results in Section III, we have the conservation of potential vorticity, conservation of potential temperature, conservation of the vector of total atmospheric angular momentum, and conservation of the atmospheric inertial axis in the ideal baroclinic atmosphere without orographic forcing. However, the bottom boundary plays a special role. Namely, if at the bottom boundary the atmosphere has three or more centres of potential temperature or potential vorticity, the nonzonal disturbances will always be maintained. Besides, if at the bottom boundary, the atmosphere has only two centres of potential temperature and two centres of potential vorticity, but these two families of isoplethes do not coincide with each other, the advections of these two quantities always remain, hence some unsteady nonzonal disturbances exist all the time.

We come to the following conclusion:

Nonzonal disturbances will maintain and will not be completely absorbed by the jet-like zonal flow in a baroclinic atmosphere without orographic forcing and diabatic heating, if one of the following conditions is satisfied: (i) there are three or more centres of potential vorticity in some of the isentropic surfaces over the whole sphere, (ii) the inertial axis of the atmospheric motion does not coincide with the axis of the earth's rotation, (iii) at the bottom boundary either the potential temperature field or the potential vorticity field has more than two centres, or the two families of isoplethes do not coincide with each other.

This conclusion is valid for the ideal atmosphere. In the real atmosphere, the orographic forcing, the heat flux due to the ground and sea surface temperature anomaly, as well as the heating due to the condensation in the atmosphere play a very important role in the generation and maintenance of the disturbances as have been emphasized by many investigators. Here we would like to point out that the pure dynamical factors, the orographic and diabatic forcing usually interact strongly with each other. For example, high-level intensive vorticity centres are usually related to the condensation heating in the atmosphere and to the orographic forcing, or generated and maintained by the heat or energy fluxes from upstream or below, while the regions with strong surface advection are almost coincident with the distribution of surface heat sources and sinks. Thus, the orographic and diabatic forcing usually amplify the dynamical effects.

V. SOME NUMERICAL EXPERIMENTS

In order to test the theoretical results, we have carried out some numerical experiments. We use a hemispheric grid point model with conservation of the total energy for the barotropic primitive equations (Zeng et al.[11]). The initial zonal flow is taken as the climatological one at 500 mb in the Northern Hemisphere with a small correction near the pole and the equator. The initial nonzonal disturbances of geopotential field will be described in each experiment, and the initial wind field is calculated by the geostrophic relationship.

Experiment 1. The initial nonzonal part of geopotential field is a four-wave pattern (zonal wavenumber is 4), given by the following formulas

$$\begin{cases} \varphi' = A\sin\left(\pi\dfrac{\theta}{\theta_0}\right)\cdot\sin m\lambda, & (\theta<\theta_0<\pi/2) \\ \varphi' = O, & (\theta\geqslant\theta_0) \end{cases} \tag{12}$$

where the amplitude A is a constant. In Fig. 1 the dashed lines show the initial geopotential field, which has only one centre of potential vorticity at the pole (the potential vorticity field is not given in this figure). The solid lines are the calculated geopotential field on the 7-th day, showing a strong absorption of eddy energy by the zonal flow. The disturbances decay rapidly.

Experiment 2. The initial fields are taken by adding four intensive vorticity centres to those used in experiment 1, and the initial potential field is given by the dashed lines in Fig. 2. The solid lines represent the field on the 10th day, showing the maintenance of the intensive vortex centres.

Experiment 3. The initial fields are a superposition of an intensive vorticity centre on the initial field used in experiment 1 (Fig. 3(a)). The computed evolution is given in Fig. 3 (b), (c) and(d)), showing a very typical downstream effect and maintenance of some disturbances. Downstream troughs I, II, and III successively become very deep.

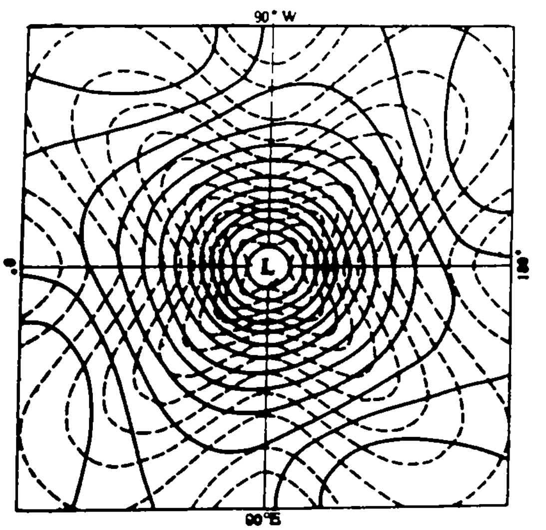

Fig. 1 Geopotential field.

Dashed lines – initial, solid lines—on the 7th day.

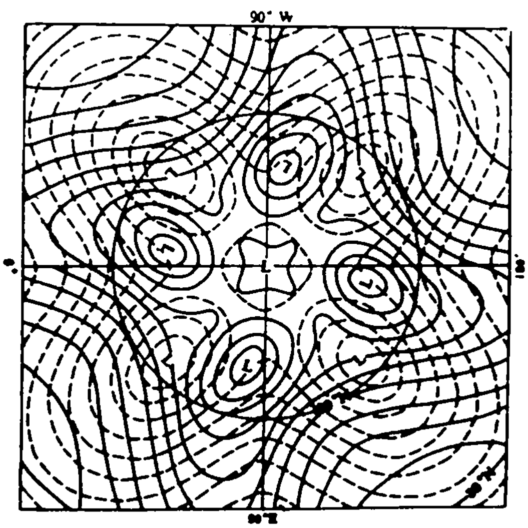

Fig. 2. Geopotential field.

Dashed lines—initial, solid lines—on the 10th day.

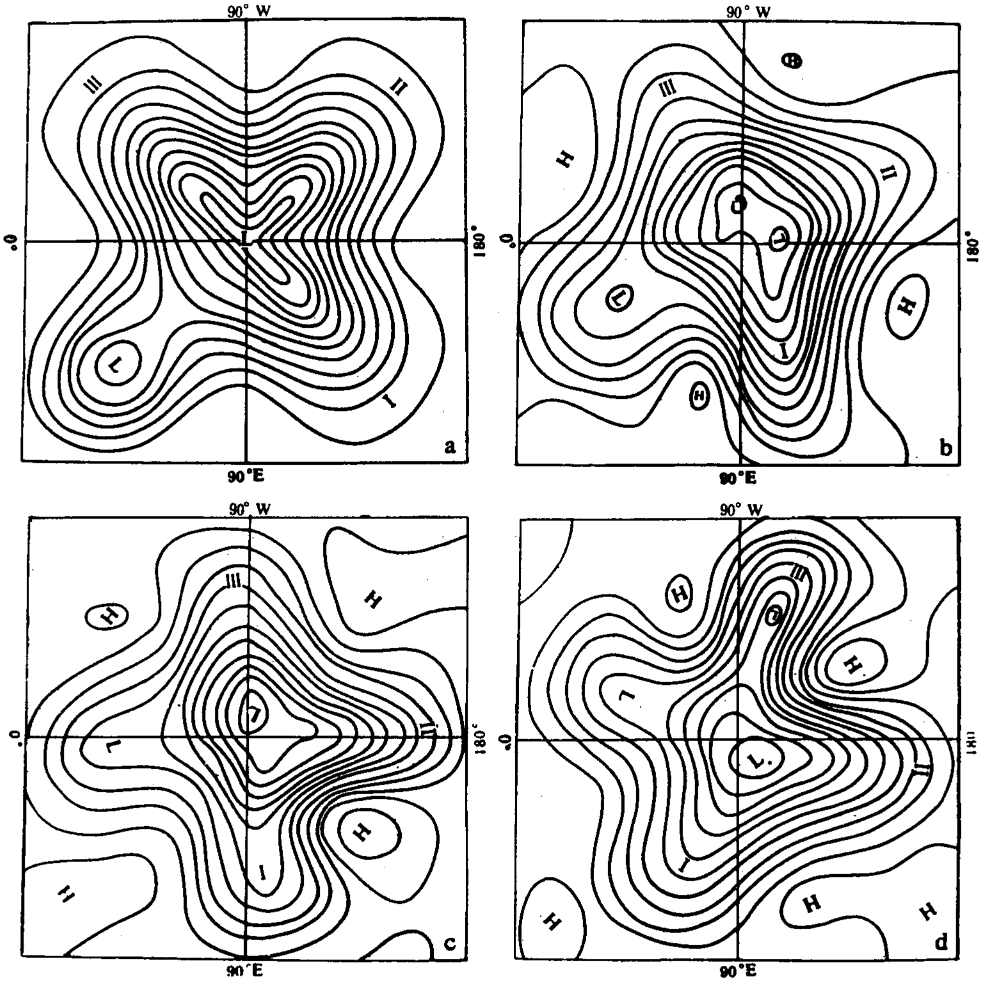

Fig. 3. Geopotential field.
(a) initial, (b) on the 4th day, (c) on the 8th day, (d) on the 13th day.

REFERENCES

[1] Lorenz, E.N., *The Nature and Theory of the General Circulation of the Atmosphere* WMO-No. 218. TP.115, 161,1967.

[2] Grose, W.L. & Hoskins B.J., *J. Atoms. Sci.*, **36** (1979), 223—234.

[3] Hoskins, B.J. & Karoly, D.J., *J. Atoms. Sci.*, **38** (1981),1179—1196.

[4] Young W.R. & Rhines, P.B., *Geophys. Astrophys. Fluid Dynamics*, **15** (1980), 39—52.

[5] 卢佩生，曾庆存，大气科学，**5** (1981), 1—8.

[6] Zeng Qingcun & Lu Peisheng, *Scientia Sinica*, **24** (1981), 508—520.

[7] 卢佩生，气象学报，**39** (1981), 141—149.

[8] Zeng Qingcun, *J. Met. Soc. Japan*, **60** (1982), 24—31.

[9] Zeng Qingcun, *Scientia Sinica*, **22** (1979), 945—957.

[10] Zeng Qingcun, *J. Atoms. Sci.*, **40** (1983), 73—84.

[11] Zeng Qingcun, Yuan Chongguang & Li Rongfeng, *Scientia Sinica*, **23** (1980), 1405—1416.