Vol. 2 No. 1 ADVANCES IN ATMOSPHERIC SCIENCES February 1985

A NUMERICAL SIMULATION OF TYPHOON GENERATION

Li Chongying (李崇银)
Institute of Atmospheric Physics, Academia Sinica, Beijing

Received December 6, 1983

ABSTRACT

By using a two-dimensional axisymmetrical PEM in which two physical processes (the Ekman pumping and the vertical transportation of cumulus momentum) are included, the genesis and development of typhoons have been simulated. The results of numerical simulation show that the generation and structure of the typhoon simulated by the model involving both the physical processes are much close to a real one in the atmosphere as compared with that involving either the Ekman pumping or the cumulus momentum transport. Therefore, it can be suggested that the cumulus momentum transport and Ekman pumping together play an important role in the genesis and development of typhoons through the CISK mechanism.

I. INTRODUCTION

The conditional instability of the second kind (CISK) proposed by Charney[1] can reasonably explain the dynamic mechanism on the developing of the tropical disturbance into deep vortex-typhoons theory. The cooperation between the cumulus convection and synoptic scale perturbation is considered in this theory. The moisture requisite for the development of the system is considered as coming from the frictional convergence of the boundary layer (i. e., the Ekman pumping). Therefore, this kind of CISK can be referred to as the Ekman-CISK. By using a numerical model, some numerical simulations of the genesis and development of typhoons have been completed on the basis of the above-mentioned theory[2-4]. The process of the development and primary structures of typhoons have been simulated successfully.

Some analyses on the satellite photograph indicated that a part of typhoons can also grow from the tropical cloud cluster[5]. The computation of the convergence field of typhoons showed that the moisture convergence in the bounday layer does not absolutely dominate but the moisture convergence above 900 hPa is still considerable[6]. Therefore, another mechanism to cause the genesis and developing of typhoons may exist besides the Ekman pumping. Mak introduced the cumulus friction (the cumulus momentum transport) into a simple theoretic model in his study1). Since the cumulus momentum transport can cause a cyclonic frictional torque in the upper troposphere and an anticyclonic frictional torque in the lower troposphere, there will occur the radial inflow at the lower levels and the outflow at the upper levels. Thus a secondary circulation will be formed. In other words, the cumulus momentum transport would lead to a positive feedback process of the cooperation between the cumulus convection and synoptic scale perturbation. Thus, the CISK is produced, causing the typhoon to generate and develop.

---

1) Mak, M., 13th Technical Conference on Hurricanes and Tropical Meteorology, A. M. S., Miami Beach, Fla., December 1—5, 1980.

In an axisymmetrical PEM which only included the cumulus momentum transport but neglected the Ekman pumping, a numerical simulation on the genesis and development of the typhoon was performed[2]. The computed results showed that, like the action of the Ekman pumping, the convective heating and cumulus momentum transport also enable a weak depression to develop into a "typhoon". And the structures of the simulated typhoon is more similar to a real typhoon, but the sea-level pressure in the typhoon center is higher. In this paper, the same model as used in that study is adopted. The cumulus momentum transport and the Ekman pumping are simultaneously introduced. The numerical simulation on the genesis and development of a typhoon from a weak surface depression is carried out.

II. MATHEMATICAL MODEL

According to the characters of active deep cumulus in the tropical atmosphere, Schneider and Lindzen[7] suggested that the fractional raea covered with active clouds is much smaller than the whole, then clouds and environment may be treated separately. And the vertical velocity in the cloud is sufficiently large, then drag forces will not have time sufficient to modify significantly the horizontal velocity (V_c) in the cloud and V_c will therefore be approximately conserved. They represented the cumulut momentum transport by cumulus friction as

$$F_c=\frac{1}{\rho}\frac{\partial}{\partial z}[M(V-V_c)], \tag{1}$$

Where M is the vertical cumulus mass flux, ρ the density and V the environment velocity.

Under static equilibrium, the axisymmetrical primary equations in r, θ, ζ, and t coordinate system may be written as

$$\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\dot{\zeta}\frac{\partial v_r}{\partial \zeta}=v_\theta\left(f+\frac{v_\theta}{r}\right)-\frac{\partial \phi}{\partial r}-H\frac{\partial P}{\partial r}+D_r+F_{cr}, \tag{2}$$

$$\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\dot{\zeta}\frac{\partial v_\theta}{\partial \zeta}=-v_r\left(f+\frac{v_\theta}{r}\right)+D_\theta+F_{c\theta}, \tag{3}$$

$$\frac{\partial H}{\partial t}+v_r\frac{\partial H}{\partial r}+\dot{\zeta}\frac{\partial H}{\partial \zeta}=\frac{R}{C_p}H\left(\frac{\dot{\zeta}}{\zeta}+\dot{P}\right)+Q+D_H, \tag{4}$$

$$\dot{P}\equiv\frac{dP}{dt}=\frac{\partial P}{\partial t}+v_r\frac{\partial P}{\partial r}=-\left(\frac{\partial r v_r}{r\partial r}+\frac{\partial \dot{\zeta}}{\partial \zeta}\right), \tag{5}$$

$$H\equiv RT=-\zeta\frac{\partial \phi}{\partial \zeta}, \tag{6}$$

where v_r and v_θ are the radial and tangential velocity components, respectively; $\dot{\zeta}\equiv\frac{d\zeta}{dt}$ is the vertical velocity; $\zeta=p/p_s$, p is the pressure, p_s the surface pressure; $P=\ln p_s$; T is the temperature, R the gas constant, C_p the specific heat; Q the convective condensational heating; f is Coriolis parameter; ϕ is the geopotential; F_{cr} and $F_{c\theta}$ are the momentum exchange caused by the cumulus friction and may be written in the light of formula (1); D_r and D_θ are the turbulence friction terms and D_H is the heating exchange term by turbulence.

---

2) Li Chongyin and Zhang Ming, A numerical simulation on the typhoon——the action of the cumulus momentum transport, Acta Meteorologica Sinica (in press), 1983.

They can be written as follows respectively:

$$D_r = K_H\left(\nabla_2^2 v_r - \frac{1}{r^2} v_r\right) + K_\zeta \frac{\partial^2 v_r}{\partial \zeta^2}, \tag{7}$$

$$D_\theta = K_H\left(\nabla_2^2 v_\theta - \frac{1}{r^2} v_\theta\right) + K_\zeta \frac{\partial^2 v_\theta}{\partial \zeta^2}, \tag{8}$$

$$D_H = K_H \nabla_1^2 H + K_\zeta \frac{\partial^2 H}{\partial \zeta^2}, \tag{9}$$

where K_H and K_ζ are the horizontal and vertical diffusion coefficients, resectively; $\nabla_2^2 \equiv \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}$.

In Charney's paper, the condensational heating of cumulus convection was parameterized and assumed to be proportional to the frictional convergence of moisture. Therefore, the convection heating may also be parameterized by means of the vertical velocity at the *top of boundary layer when the Ekman pumping is introduced. In this study, since both* the cumulus momentum transport and the Ekman pumping are considered simultaneously, the convection heating may be separated into two parts and written as

$$Q = \alpha Q_{c1}\eta(p) M_* \xi_* + \beta Q_{c2}\eta(p)\xi_E \tag{10}$$

The first term represents the condensational heating caused by the cumulus momentum transport through the secondary circulation, and the second term is the condensational heating caused by the Ekman pumping. Where α and β are the adjustment parameters respectively and their values may indiate the heating intensity; Q_{c1} and Q_{c2} are the proportional coefficient respectively; M_* and ξ_* are the cumulus mass flux and the vorticity *at the reference level* p_* *respectively;* ξ_E *is the vorticity at the top of the Ekman boundary* layer; η (p), a distribution function of condensational heating. According to Ref. [8], the parameterization of convective condensational heating by means of the vorticity is more reasonable than that by means of the vertical velocity in the CIKS mechanism, therefore the condensational heating is written as Eq. (10).

Based on the analysis of the observation data, the cumulus mass flux $M(p)$ and the condensational heating function η (p) can be shown as in Fig. 1. They express the general character of the deep cumulus in the typhoon. At the same time, we have $M_{*0} =$ 5.0 hPa/hr according to note (1).

III. COMPUTATIONAL SCHEME

The computational scheme used in this paper is the same as in note (2), and its speciality may be simply mentioned as follows:

The equi-spaced difference is taken for ζ in the vertical direction. The vertical interval $\Delta\zeta = 0.2$. $\zeta = 0.1$, 0.3, 0.5, 0.7 and 0.9 are respectively corresponding to the level number $L = 1$, 2, 3, 4 and 5. The quantities v_r, v_θ and H are defined at the levels mentioned above. But the quantities ϕ and $\dot{\zeta}$ are defined at the middle levels between the levels mentioned above (see Fig. 2). The equi-spaced points are taken in the radial too ($j = 0$, 1, 2,...20) and interval $\delta = 50$ km.

For saving computational time, the splitting algorithm is used, i. e., the computations of the adjustment process and the advective process are performed separately. When the computation of the adjustment is in progress, the time step is taken to be 120 seconds.

And every 3-steps later, one step of the computation for the advective process with the time step of 360 seconds is started.

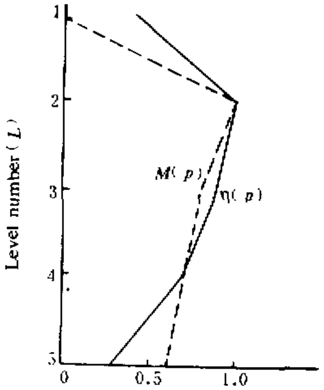

Fig. 1. Reference profiles of the cumulus mass flux $M(p)$ and the condensational heating function $\eta(p)$.

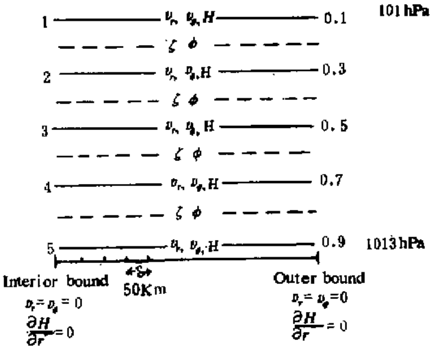

Fig. 2. Computational grids.

The radial boundary conditions are taken to be: (1) $v_r = v_\theta = 0$ and $\partial H/\partial r = 0$ at the center; (2) $v_r = 0$, $v_\theta = \text{const.}$ (very small) and $\partial H/\partial r = 0$ at $r = r_f$. The vertical boundary conditons are taken to be: (1) $\dot{\zeta} = 0$ at p_{top}; (2) at the low boundary level the drag of the sea surface and the transport of sensible heat are taken into consideration.

The initial conditons may be given arbitrarily. We take the initial temperature to be the climatic average values, i. e., $T_1 = -77.9$ °C, $T_2 = -35.0$ °C, $T_3 = -5.4$ °C, $T_4 = 9.9$ °C, $T_5 = 21.8$ °C and the sealevel temperature $T_s = 28.0$ °C. A weak initial depression is present at the sea-level and the center pressure is 1005 hPa. The initial wind field represents a cyclonic circulation being in adjustment to the initial pressure. The initial maximum tangential velocity is about 11.5 m/s at 300 km from the center but the initial radial velocity is zero.

When the convective condensational heating Q is computed, the fourth level in the model is taken as a reference level. Then vorticity ξ_4 and cumulus mass flux M_4 at the fourth level is used instead of ξ_* and M_*, respectively. Taking the fifth level in the model as the top of Ekman layer and the base of the cumulus, we have $\vec{V}_5 = \vec{V}_c$ and $\xi_5 = \xi_E$

In addition, several basic parameters are prescribed with the following values in all the computations: $f = 5.0\ 10^{-5}\ \mathrm{s}^{-1}$, $C_D = 1.2\ 10^{-3}$, $K_H = 10^2\mathrm{m}^2\mathrm{s}^{-1}$, $K_\xi = 10^{-6}\mathrm{s}^{-1}$, $p = 1013$ hPa, $\rho_s = 1.29\ 10^{-3}$ g cm^{-3}.

IV. RESULTS OF NUMERICAL SIMULATION

Numerical simulation shows that the simulated typhoon depression has a considerable development with the lapse of computational time. The surface pressure at the center decreases clearly. The tangential velocity at the periphery of the centeral area increases and reaches more than 50 m/s after 42 hours. The centeral area of the depression becomes warm gradually, so that the warm core structure is presented. In other words, due to the feedback of convective condensational heating the depression can be gradually developed into a typhoon vortex.

The variations of the center surface pressure (dashed) and the tangential velocity (solid) at the periphery of the center in the modeling typhoon depression with time are shown in Fig. 3, where curve I represents the result caused only by the Ekman pumping; curve II the result caused only by the cumulus momentum transport; and curve III is resulted from both the Ekman pumping and the cumulus momentum transport. In each case, the maximum convection heating rate is about 20°C/day. When both the Ekman pumping and the cumulus momentum transport are included in the model, the heating parameters (α and β) should be adjusted to keep the heating rate the same as that when only either of the processes is included. In fact, the heating is different since the process of typhoon development is a positive feedback. Fig. 3 shows that the development of the typhoon depression is the fastest and strongest when both the Ekman pumping and the cumulus momentum transport are introduced into the model. But the decrease of the surface pressure is not sufficient when the cumulus momentum troport is only considered in the model as Ref. [8].

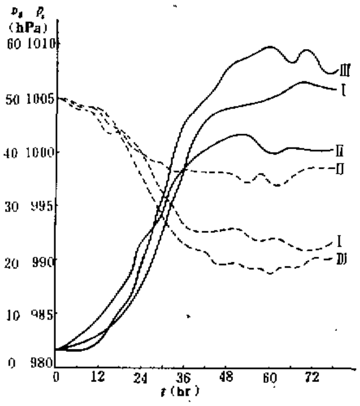

Fig. 3. The variations of the center surface pressure (dashed) and the tangential velocity (solid) at the periphery of the central area in the simulated typhoon depression with time.

The vertical cross sections of the vertical velocity in the simulated typhoon (at 48 hours) are shown in Fig. 4a—c for three cases. The comparision shows that when only the Ekman pumping is taken into account in the model, the maximum vertical velocity is at the center of the simulated typhoon and the speciality of the typhoon eye is not represented, so that it is different from a real typhoon; the maximum vertical velocity occurs at about 50 km from the center of the simulated typhoon and there appear weak vertical motions in the center area when only the cumulus momentum transport or together with Ekman pumping is considered in the model, thus the character of the typhoon eye has been represented.

Therefore, we may suggest that the cumulus momentum transport has a fundamental influence on the structures of typhoons under formation.

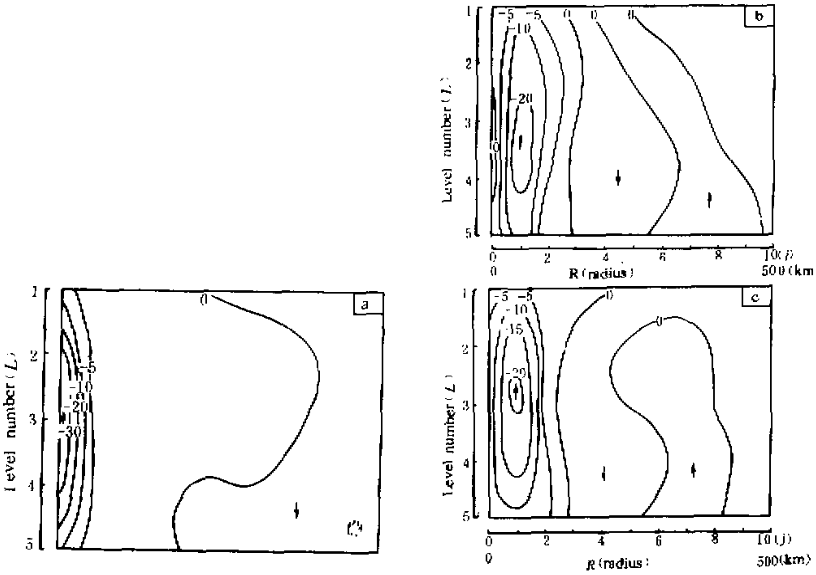

Fig. 4. The vertical cross sections of the vertical velocity (10^{-6} s^{-1}) in the simulated typhoon (at 48 hours) considering a. the Ekman pumping only; b. the cumulus momentum transport only; c. both the Ekman pumping and the cumulus momentum transport. The abscissa in (a) is the same as in (b) and (c).

Fig. 5 is the vertical cross section of the tangential velocities of the simulated typhoon at 48 hours. It is clear that there occurs a strong cyclonic circulation in the low-middle troposphere with a maximum tangential velocity at about 40 km from the center. A naticyclonic circulation is presented in the upper troposphere. It is worth indicating that the decrease of the tangential wind velocities with height is faster when only the Ekman pumping is considered in the model, but slower and more close to a real typhoon when the cumulus momentum transport is introduced into the model.

The vertical cross section of the radial velocities of the simulated typhoon (Fig. 6) shows that there is stronger inflow in the lower troposphere with a maximum influx in the range of about 250 km from the centre; the outflow is in the upper-middle troposphere and the maximum outflow locates about 50—100 km from the center in the upper troposphere. In addition, there is a weak influx layer in the middle troposphere. Whether the Ekman pumping is considered or not, stronger inflow is always present in the lower troposphere. Obviously, this convergence of the moist air in the lower troposphere plays an important role in the genesis and development of typhoons. No wonder that some early researchers studying the formation theory of the typhoon still emphasize the important influence of the convergence in the boundary layer up to now[9-10]. The influx in the middle troposphere is even more a reflection of the cumulus momentum transport process.

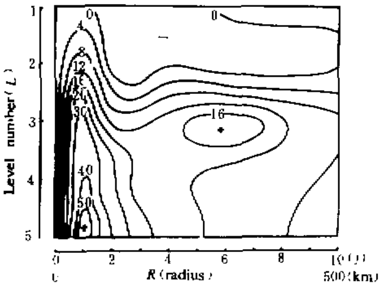

Fig. 5. The vertical cross section of the tangential velocities (m/s) of the simulated typhoon (at 48 hours).

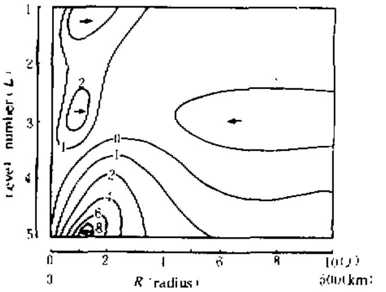

Fig. 6. As in Fig. 5, except for the radial velocities (m/s).

As we know, the warm core, as a fundamental feature of the typhoon structure, is one of successful signs for the numerical simulation. Fig. 7 is a cross section of the temperature variation of the simulated typhoon at 48 hours. Here, the solid curve represents the variation at the second level ($L=2$) and the dashed curve the variation at the fourth level ($L=4$). The following two features are very clear in Fig. 7: (1) the strongest increment of the temperature is nearby the centre, i. e., the maximum heating is in and near the simulated typhoon center; (2) the heating (temperature increment)at the upper level is stronger than at the lower level, which represents a character of the cumulus convection heating. These two features are very similar to thermodynamic structures of a real typhoon.

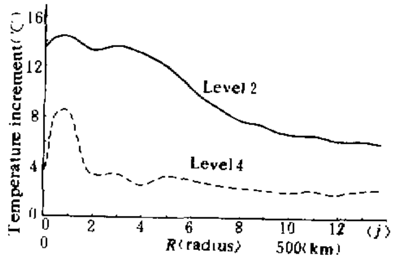

Fig. 7. As in Fig. 5, except for the temperature variation.

The variations of the radial distribution of the tangential velocities at the 5th level of the simulated typhoon depression with time are shown in Fig. 8a. Clearly, the maximum tangential velocity increases with the development of the depression; the location of the maximum tangential velocity gradually moves to the center; the variation of the tangential velocities mainly appears within the range of 250 km from the center. The above-mentioned features in developing process of the simulated typhoon is quite similar to a real typhoon. For example, the variation of the tangential velocities of the Anita hurricane (1977) shown in Fig. 8b has the aforesaid characters[11]. Obviously, the kinetic energy has an organized and centralized process in the development of typhoons. This process depends not only on the effects of the environmental field, but more on the self-feedback process of the typhoon depression system. The enhancement of the circulation is mainly produced within the limits of 250 km from the center. This suggests that the development of the typhoon depression mainly depends on the convective condensational heating, i. e., the CISK mechanism.

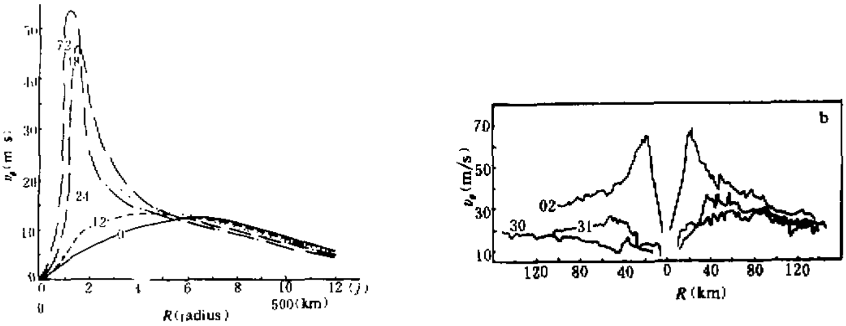

Fig. 8. a. The variation of the radial distribution of the tangential velocities at the 5th level of the simulated typhoon with time.
b. The cross section of wind velocity in the Anita hurricane on August 30, 31 and September 2, 1977.

V. DISCUSSION AND CONCLUSIONS

When only the Ekman pumping is included in the model, the structure of the simulated typhoon has some differences from a real one, espicially,the range of the eye is not clear[12]. If only the cumulus momentum transport is considered in the model, although the structure of the simulated typhoon is similar to a real typhoon, the surface centric pressure is too high and the simulated typhoon is also different from a real typhoon. In this paper, the Ekman pumping and the cumulus momentum transport are introduced into a model together. The results show that the surface centric pressure and the structure is very close to a real typhoon. It is therefore simply suggested that both the cumulus momentum transport and the Ekman pumping are important physical processes for the genesis and development of typhoons, and should be considered together in the dynamical study of typhoons.

Li and Kyo performed a numerical simulation of the development of the tropical cyclone[13]. Their numerical model is similar to ours and the one used in Ref. [12]. The differences are that in their model the parameterization of the cumulus convection is more complex, and that the vertical eddy exchange term is additionally included, especially, the influence of the cumulus on vertical momentum transport is investgated in the cumulus parameterization. The simulation experiments show that the result in Ref. [13] is more similar to a real typhoon than that in Ref. [12], especially, there is the typhoon eye pattern in their experiment. In this paper, when the cumulus momentum transport is included, the structure is greatly improved and become more similar to a real typhoon as in Ref. [13]. Therefore we could say that the cumulus momentum transport process is very important for the genesis and development of typhoons, especially for the formation of typhoon structure.

The cumulus momentum transport and the Ekman pumping are able to cause the secondary circulation, with the result that the cumulus convection and the convective condensational heating are produced, and the positive feedback to the development of the depression circulation can occur. Another experiment is carried out by adjusting the heating parameter to investigate the relative importance of the above two physical processes. In consideration of the outstanding characters of the structure of a typhoon, the coumulus momentum transport seems to be important. The environmental conditions of typhoon formation are not the same in the atmosphere. Hence, there would not be confirmed standards to distinguish which process is more important than another. In general, the Ekman pumping may be conspicuous in the initial stages of typhoon development, then the cumulus momentum transport becomes to be more important.

For typhoon formation it is important that the isolated cumulus action develop into the organic and systematic cumulus convection. Since the parameterization of the cumulus convection is very simple in this paper, the process of the evolution of the cumulus convection is not simulated. But the centralized phenomenon of the kinetic energy (the tangential velocity) of the simulated typhoon not only represents the feedback between the convective condensational heating and the depression vortex, but also reflects the processes developing into the organic and systematic cumulus convection.

The convergence of the moisture in the lower troposphere is very important to the genesis and development of typhoons. This convergence is not only forced by the friction in the boundary layer but also driven by the cumulus friction (the cumulus momentum transport).

The author is grateful to Mr. Zhang Ming for his helps with the computation in the present study.

REFERENCES

[1] Charney, J. G. & Eliassen, A., *J. Atmos. Sci.*, **21**(1964), 68—75.
[2] Ooyana, K., *J. Atmos. Sci.*, **26**(1969), 3—40.
[3] Rosenthal, S. L., *Mon Wea. Rev.*, **98**(1970), 463—653.
[4] Rosenthal, S. L., *J. Atmos. Sci.*, **35**(1978), 258—271.
[5] 陈隆勋等，中国科学院大气物理研究所集刊（第2号），科学出版社， 1974 年， 1—12.
[6] Gray, W. M., *Quart. J. Roy. Meteor. Soc.*, **105**(1979), 155—218.
[7] Schneider, E. K. & Lindzen, R. S., *J. Geophy. Rev.*, **81**(1976), 3158—3160.
[8] Mak, M., *Tellus*, **33**(1981), 531—537.
[9] Kuo, H. L., *13th Technical Conference on Hurricanes and Tropical Meteorology, A. M. S., Miami, FL.*, 1980, (selected papers) 63—64.
[10] Ooyama, K. V., *Intense Atmospheric Vortices*, Springer-Verlay Berlin Heidelbert, New York, 1982, 21—34.
[11] Sheets, R. C., *Intense Atmospheric Vortices*, Springer-Verlag Berlin Heidelberg, New York, 1982, 35—50.
[12] 张铭，曾庆存，第二届亚洲流体力学会议论文集，北京， 1983, 912—917.
[13] Li Peng & Kuo, H. L., *Tellus*, **27**(1975), 133—144.