NUMERICAL EXPERIMENTS OF THE INFLUENCE OF DIABATIC HEATING ON TROPICAL CYCLONE ASYMMETRIC STRUCTURE

Lei Xiaotu(雷小途)

Shanghai Institute of Meteorological Sciences. Shanghai, 200030

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ABSTRACT

Using the barotropic vorticity equation that contains forcing from diabatic heating with appropriate parameterization. a number of numerical experiments are conducted for the tropical cyclone that is initially symmetric. The result shows that the diabatic heating has important effects on the asymmetric structure in addition to the roll of the β term and nonlinear advection term in its formation. It again confirms the conclusion that the diabatic heating is a possible mechanism responsible for such structures in the tropical cyclone.

Key words: tropical cyclone, asymmetric structure. diabatic heating

Ⅰ. INTRODUCTION

The fact that the tropical cyclone (to be shortened as TC hereafter) is an asymmetric vortex has been widely recognized and accepted. The current stress of the field is on the observational aspect of the research that aims at revealing the structure and form, the study of the mechanism for generating the asymmetric structure of TC and the numerical experiment of the effects on TC track and TC bogus technique in the numerical model. Due to the unavailability of the aircraft reconnaissance data and large variability of error in retrieved satellite data, the progress on the asymmetric TC structure is relatively slow while that on numerical experiments with the effects on the TC motion and the technique of TC bogus depends very much on how fully the asymmetric structure and form in TC are recognized.

Over the recent years, much work has been done with respect to the cause and effect for the asymmetry. Through case study, Black and Anthes (1971) relate it to internal dynamics while Madda and Piacsek (1975) and Ross and Kurihara (1992) link it to the β effect in numerical modeling. Holland (1983), Demaria (1985) and Fiorino and Elsberry (1989a) are successful in simulating the dipole circulation around the center of TC. Larr and Williams (1989), Peng and Willianms (1990) and Carr and Elsberry (1991) put forward the vorticity mechanism for asymmetric TC circulation. In his dynamics analysis, Liu and Liu (1993) document the 2-dimensional stationary flow field as being characteristic of a dipole-shaped asymmetric structure. Luo (1994) makes more extensive study of the effects on the TC structure given the β term and nonlinear advection. It is noted that the aforementioned work is all free of the effect of diabatic heating while it is evident in stages of TC evolution varying from the genesis, development and maintenance. Lei (1998) has dynamically proved that the diabatic heating might be a possible mechanism for the structure. It is just the purpose of the current work that the effects of diabatic heating on the asymmetric TC structure are studied and verified in a number of numerical experiments with the initially symmetric TC using the barotropic vorticity equation that is forced by diabatic heating.

II. BRIEF ACCOUNT OF THE MODEL

Following the work of Pedlosky (1981), a quasi-geostrophic barotropic equation that is incorporated with outward-source forcing is written as

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

where φ is the quasi-geostrophic stream function and Q the external forcing source. According to Lu (1994), Q can be the heating and it can be expressed by the vortex effect that it causes, as shown in Charney and Devore (1979):

$$Q=\alpha\nabla^2\varphi^* \tag{2}$$

where φ^* is the forced stream function and α the coefficient of forcing.

Generally, a greater diabatic heating is more favorable for TC to maintain and develop and the higher the intensity of TC, the larger the vorticity; in the meantime, a larger TC vorticity brings with higher intensity of TC and diabatic heating, i.e. Q is quasi-proportional to $\nabla^2\varphi$.

For the convenience of discussion, φ^* is substituted by φ, the forced stream function in Eq.(2). Then Eq.(1) becomes

$$\frac{\partial}{\partial t}\nabla^2\varphi+J(\varphi,\nabla^2\varphi)+\beta\frac{\partial\varphi}{\partial x}=\alpha\nabla^2\varphi \tag{3}$$

As the mean life cycle of TC is about 10 days, the forced stream function can be approximated by taking α=0.1 day=1.2$\times$10^{-6}1/s, or the order of magnitude being 10^{-6}1/s for α. Eq.(3) is then the basic model equation for the work.

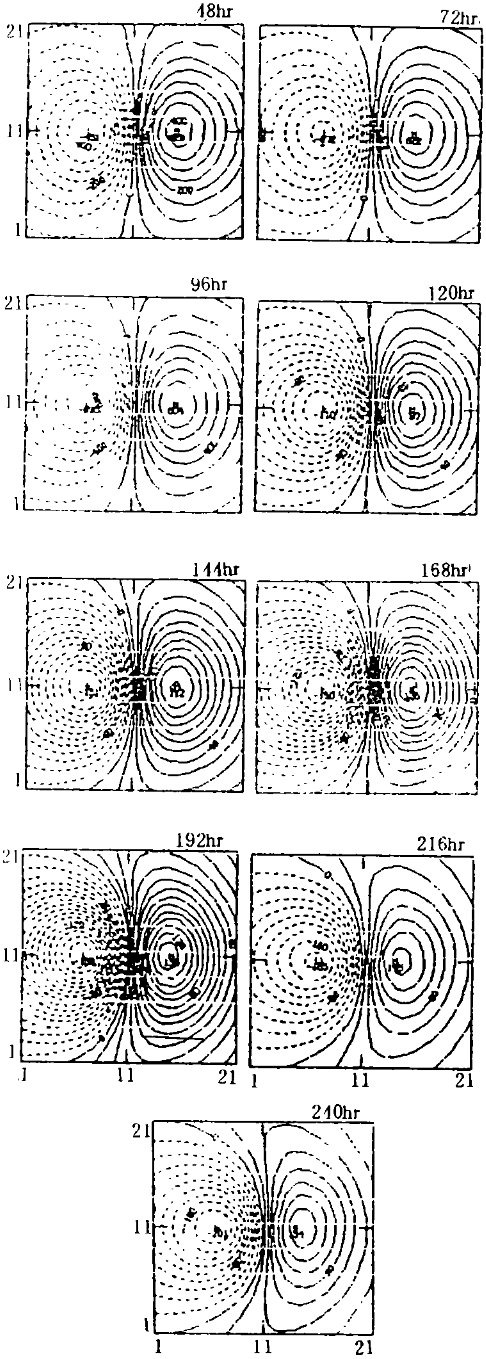
An initial TC vortex is assumed as follows.

$$\nabla^2\varphi=\frac{2V_m}{r_m}\left[1-0.5\left(\frac{r}{r_m}\right)^b\right]e^{\left[\frac{1}{b}\left(1-\frac{r}{r_m}\right)^b\right]} \tag{4}$$

where $r=\sqrt{(x-x_0)^2+(y-y_0)^2}$, and (x_0,y_0) is the coordinates of TC center at the initial time, v_m the maximum wind speed, r_m the radius of the maximum wind speed, b the parameter of shape. Here, r_m =100 km, v_m=20 m/s, b=1, and the grid interval is 50 km, the step is 12 min, with the domain of computation composed by 101$\times$101 grids and the TC center at (51, 51) at the initial time, without inclusion of the environmental field (Figures omitted for initial stream function and relative vorticity field).

III. ROLE OF β TERM AND NONLINEAR ADVECTION IN ASYMMETRIC TC STRUCTURE

Fig.1 and Fig.2 are the distribution of asymmetric components of stream function with 2 – 10



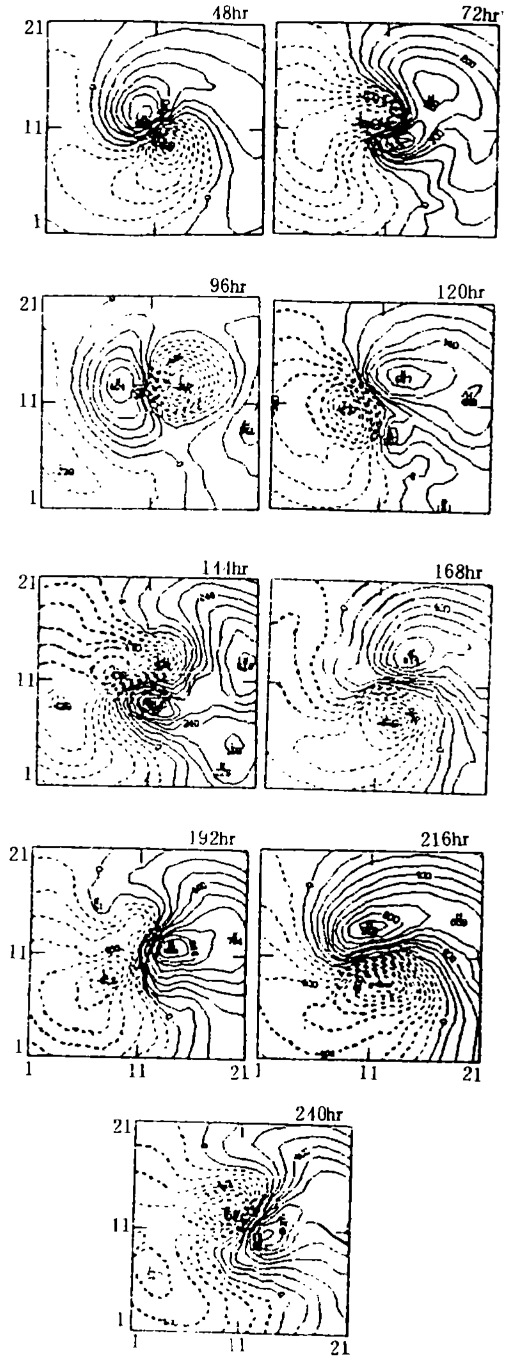


Fig.1. Distribution of asymmetric TC stream function with the inclusion of β term only.

Fig.2. Same as Fig.1 except for inclusion of non-linear advection and β term.

days of integration with the inclusion of β term only (the model equation becomes $\frac{\partial \nabla^2 \varphi}{\partial t} + \beta \frac{\partial \varphi}{\partial x} = 0$) and the day-to-day pattern of the asymmetric component of the TC stream function over the 2 – 10 days of integration, respectively.

It is known that there is a positive and a negative vortex center of stream function on the east and west sides of the TC center. Their absolute values of the vorticity against the central values are comparable in magnitude and all decrease with time. The contour of the positive vortex to the east side is marked by dense (loose) gradient in the east-west (north-south) direction while there is not any of such features for the western negative vortex. It is the well-known pair of β vortexes. Detailed analyses are given by Chan and William (1987) and Luo (1994).

With the consideration of nonlinear advection term only, the symmetry stays throughout the entire integration in the TC vortex that is initially symmetric, when the model equation then becomes $\frac{\partial \nabla^2 \varphi}{\partial t} + J(\varphi, \nabla^2 \varphi) = 0$. If both the nonlinear advection term and β term are both included in the model, the asymmetry will be much significant for the TC stream function during

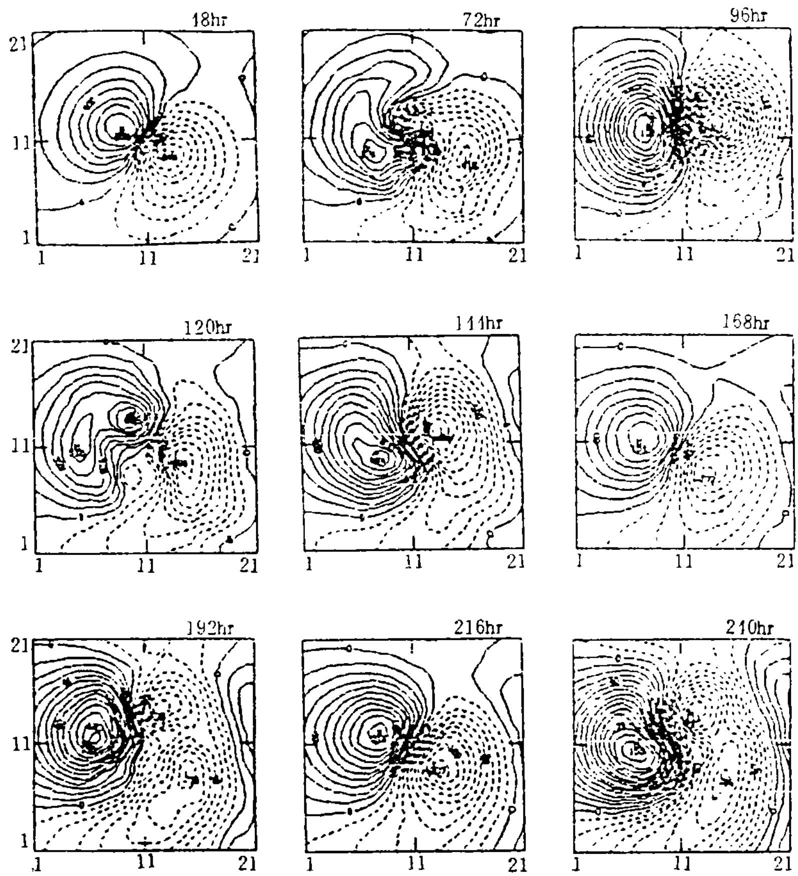


Fig.3. Contribution of nonlinear advection term to the asymmetric TC stream function co-acting with β terms

the integration, with the model equation changed to $\frac{\partial \nabla^2 \varphi}{\partial t} + \beta \frac{\partial \varphi}{\partial x} + J(\varphi, \nabla^2 \varphi) = 0$. Fig.3 is the distribution of stream function between the asymmetric components minus the pair of β vortexes with the condition of joined action of nonlinear advection and β terms. It is clear that the dipole structure as shown in the asymmetric components are with the TC and the line joining the dipole centers are variable in the integration, which is much different from the pair of β vortexes caused by the β term only. It suggests that with the combined action of β term, nonlinear advection term has important effect on the asymmetric distribution of TC stream function, generally agreeing with the conclusions of Liu and Liu (1993) and Luo (1994). It is known from Fig.3 that the structure of the dipole is well defined that the positive pole always stays in the upper left portion while the negative one in the lower bottom portion, which is consistent with Liu and Liu (1993).

IV. ROLE OF DIABATIC HEATING

When the diabatic heating is only the factor that is included (the equation model then becomes $\frac{\partial \nabla^2 \varphi}{\partial t} = \alpha \nabla^2 \varphi$), the TC remains symmetric over the integration process as it is at the initial time, only that the intensity keeps increasing. Fig.4 gives the initial field and the distribu-

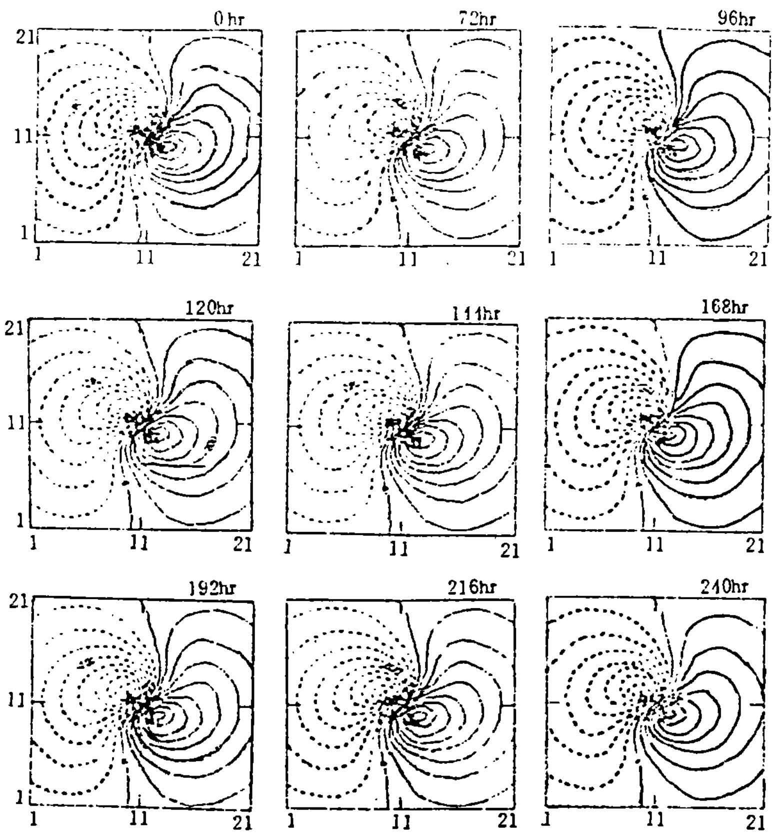


Fig.4. Distribution of stream function of initially asymmetric TC as affected by diabatic heating.

tion of asymmetric stream function over the 3 – 10 days of integration. Considering the joint action of nonlinear advection and β terms only, the initially symmetric TC is integrated for 24 h and the result of an asymmetric field is taken as the initial field for an integration of 10 days with an experiment in which only diabatic heating is included. Fig.5 is the difference of asymmetric stream function between the 3 – 10 days of integration and the initial field. The asymmetric TC structure is shown to maintain over most of the integration period, with increasing clear pattern of its dipole distribution and growing intensity. Similar conclusions are drawn with other forms of asymmetric TC fields as initial field of integration.

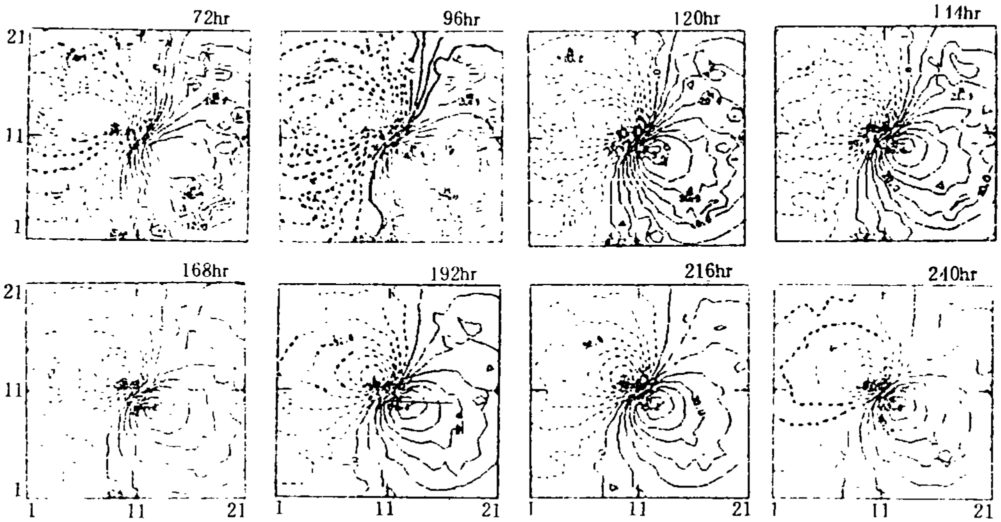


Fig.5. Effects of diabatic heating on initially asymmetric TC stream function.

Under the coaction of diabatic heating and the β term [(See Fig.6) the model equation is then changed to $\frac{\partial \nabla^2 \varphi}{\partial t} + \beta \frac{\partial \varphi}{\partial x} = \alpha \nabla^2 \varphi$], the TC stream function changes from the initial symmetry to asymmetry late in the time, though remaining much the same in the shape as the pair of β vortexes, with a much stronger intensity.

Fig.7 gives the contribution by diabatic heating to asymmetric structure of the TC stream function with the coaction of the β term, which is much the same as the pair of β vortexes. It suggests that the asymmetric distribution of the TC flow field is enhanced by diabatic heating in coaction with the β term. It is noted that there is no evidence of the effect of diabatic heating on the asymmetric TC structure before Day 3 in the integration.

With the joint action of diabatic heating and nonlinear advection, the initially TC always keeps symmetric during the integration, though with changes in intensity (Figure omitted); For an initially asymmetric TC, the asymmetry during the integration depends on the distribution of the initial field, which is not discussed here due to its complexity.

When the experiment includes diabatic heating, the β term and nonlinear advection (the model equation then becomes $\frac{\partial \nabla^2 \varphi}{\partial t} + J(\varphi, \nabla^2 \varphi) \beta \frac{\partial \varphi}{\partial x} = \alpha \nabla^2 \varphi$), the initially symmetric TC eventually changes into an asymmetric one (See Fig.8).

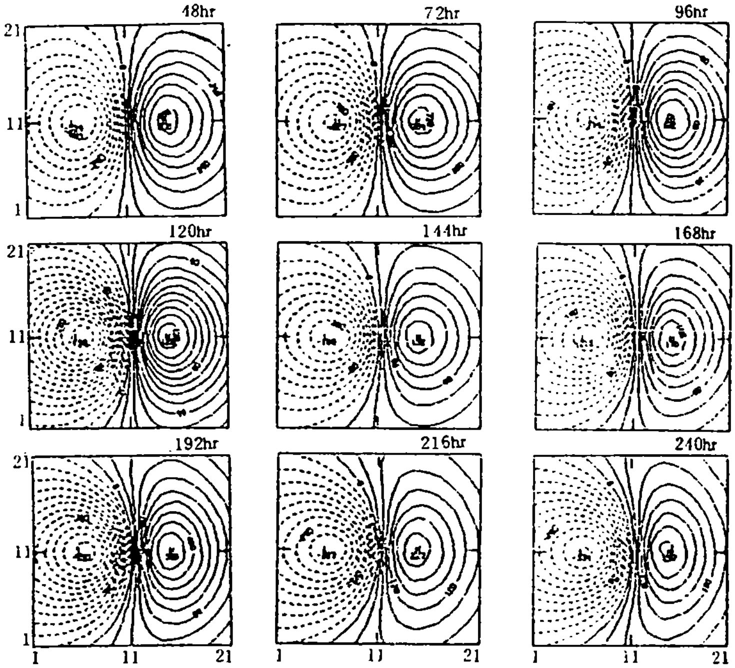


Fig.6. Distribution of asymmetric stream function in the coaction of diabatic heating and β terms.

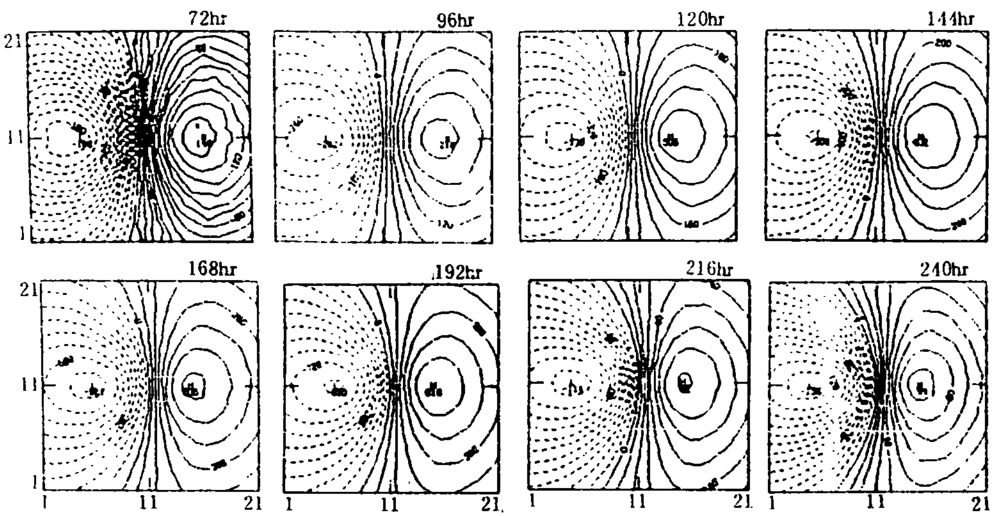


Fig.7. Same as Fig.3 except for the contribution of diabatic heating.

Fig.9 gives the contribution by diabatic heating to the asymmetric structure of the TC stream function with the joint action of the three factors presented earlier. The distribution is shown to have obvious pattern of a dipole and there is also the contribution of nonlinear advection to the asymmetric TC structure with the coaction of the β term (See Fig.3). The difference is that the dipole for the contribution of diabatic heating in this case varies by larger amplitude in the integration and both posi-

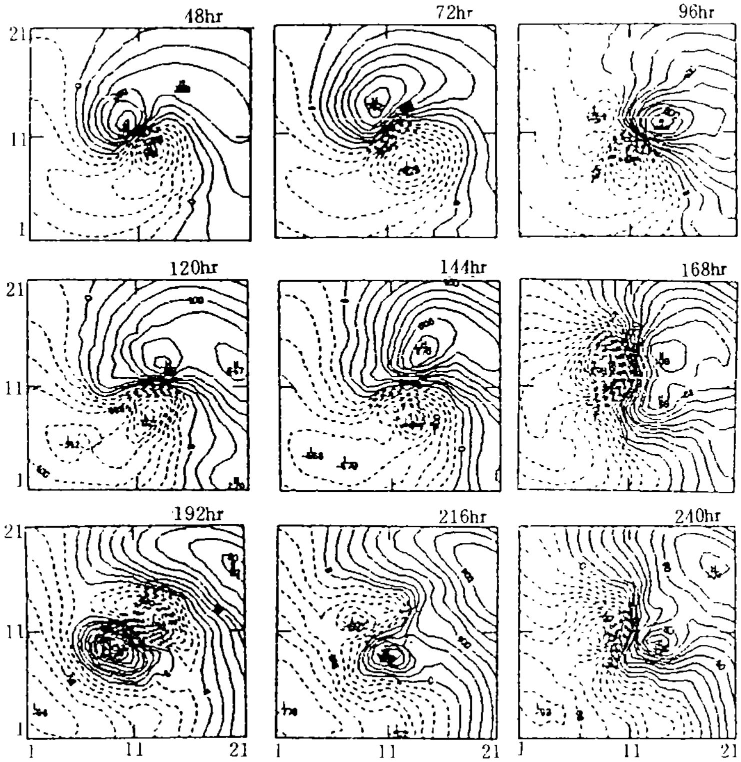


Fig.8. Same as Fig.6 except for the coaction of diabatic heating, β term and nonlinear advection term.

tive and negative dipoles appear in all quadrants of the TC center. It is then obvious that much larger influence is posed on the asymmetric TC structure if it is joined by the β term or by both the β term and nonlinear advection term, being consistent with the dynamic analyses in Lei (1998), which are, in effect, numerically verified here in this paper. Summing up, diabatic heating is shown to act as an additional possible mechanism for the formation of the asymmetric TC structure. It is noted, however, that such effect is not evident until after Day 2 in the integration, which is to be studied for the cause.

V. CONCLUDING REMARKS

a. With only the β term included in the experiment, the TC stream function is shown to be of the well-known pair of β vortexes, indicating that the β term is important for the asymmetric TC structure.

b. With the coaction of the β term, the nonlinear advection has significant influence on the asymmetric structure of TC with a contribution similar to the distribution of the dipole. The positive and negative dipoles are always on the eastern and western side of the TC center, respectively, suggesting that the nonlinear advection term is also important for the structure.

c. With the coaction of the β term, diabatic heating contributes to the asymmetric TC in a similar way the pair of β vortexes would do.

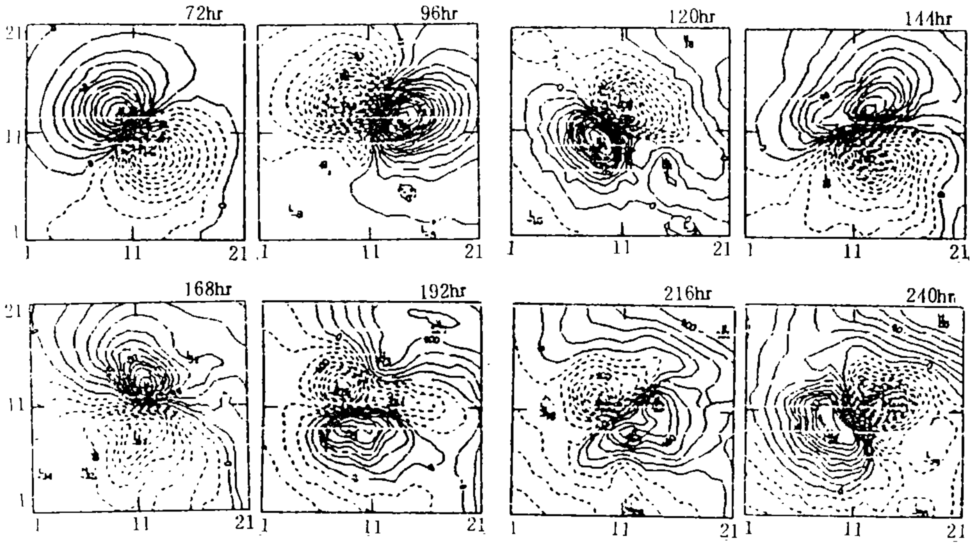


Fig.9. Contribution to TC asymmetric stream function by diabatic heating with the coaction of β term and nonlinear advection term.

d. With the coaction of the β term and nonlinear advection terms, diabatic heating exerts important influence on the asymmetric TC structure. Being different from the contribution by the nonlinear advection term with the coaction of the β term, the dipoles vary by larger amplitudes in direction during the integration.

e. With the coaction of the β term only or of both the β and nonlinear advection terms, diabatic heating has important influence on the asymmetric TC structure. It further justifies the conclusion in Lei (1998) with a dynamic study that diabatic heating is a possible mechanism for the formation of the asymmetric TC structure.

The conclusions above are drawn in an experiment with simplified quasi-geostrophic barotropic vorticity equations model and have to be further tested with a fuller model and a more reasonable parameterization scheme for diabatic heating.

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