A NUMERICAL ANALYSIS ON TYPHOON ASYMMETRIC STRUCTURE AND MOTION

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ABSTRACT

Five prediction experiments are carried out with two typhoons in 1992 using a limited-area primitive equations and two-way interactive model in a movable, nested mesh. The result indicates good agreement in terms of motion between the prediction and observation. Studying the asymmetric structure in the cases selected, a close link is uncovered between the temporal evolutions of the structure and the track of motion in a tropical cyclone. Understanding of real asymmetric structure will help to improve the skill of forecasting tropical cyclones.

Key words: typhoon asymmetric structure, typhoon track of motion, nested mesh model

I. INTRODUCTION

The forecasting of the track, especially those of abnormal nature, is a much interested subject of research for meteorologists at present. With the rapid development of numerical prediction techniques and progressive improvement of numerical predictive model for tropical cyclone motion in recent years, the forecasting skill has been increased considerably. Some difficulty, however, does exist operationally for abnormal track, especially so when the forecaster is going to decide when the typhoon is expected to recurve.

In the early 1980' s, an arguement is put forward that the asymmetric structure is an important factor having influence on abnormal motion of tropical cyclones. In their work coping with the motion and vortex structure of tropical cyclones, Fiorino and Elsberry (1989) find linkage between the velocity and direction of a vortex and the ventilation flow in its center. Symmetric vortex activating in constant planetary gradient of vorticity have been studied with the shallow water model (Wang and Li, 1994) on condition that there is no environmental flow. The result suggests that initial vortex governs the trajectory of its motion by structure, which is in response to the development of secondary asymmetric circulation. The circulation, consisting of a pair of β gyres that is related to planetary gradient of vorticity, determines the ventilation flow at the center of the vortex. Tian (1996) uses a simplified quasi-geostrophic 3-layer baroclinic model in his investigation of the relationship between the vector of ventilation flow and that of motion in a tropical cyclone in an asymmetric flow field and argues that the former vector may be taken a reference index in the forecast of typhoon motion together with the introduction of a method for improving the calculation of the vector of ventilation flow.

Higher resolution data have to be turned to if detailed asymmetric structure in a tropical cyclone is to be revealed (Reeder, Smith and Lord, 1991). On basis of it, analysis of the asymmetry is performed in the current work using forecasting cases from a mov-

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able and nested mesh numerical model in two-way interaction, followed by a discussion on links between the asymmetric structure and the track of motion.

Ⅱ. BRIEF DESCRIPTION OF MODEL AND FORECASTING EXPERIMENTS

1. *Brief description of the model*

In a σ-coordinated primitive equations model that is profiled at 15 layers in the vertical and homogeneous latitude/longitude mesh and C-type staggered grid differential scheme in the horizontal, physical processes included take account of horizontal diffusion, friction at the boundary layer, large-scale precipitation and parameterized cumulus convection, with Tatsumi's (1983) economic explicit scheme for temporal integration and the Davis' (1976) method in the treatment of the lateral boundary.

The coarse mesh model (shortened as CM below) is horizontally resolvable at 1.875° in a domain bounded by 0—48.75°N and 84.375—159.375°E for a total of 27×41 grid points. The fine mesh model (FM) is horizontally resolvable at 0.46875° in a domain sized 41×41 grid points. The ratio is 4:1 in terms of grid length between CM and FM, which have identical vertical structure. Detailed presentation of relevant model and bogus typhoon scheme is referred to Wang, Wang and Li (1996) and Wang and Wang (1996). The resolution of FM is approximately equivalent to 50 km which according to documentation (1991) is fine enough to identify the asymmetric structure of a tropical cyclone.

2. *Forecasting experiments*

Five case forecasts are made of two tropical cyclones in 1992 using the nested mesh model described above. Typhoon Eli, moving northwest, is initialized at 0000 GMT on July 11 and 12, denoted by A and B, respectively; Typhoon Janis, moving northwest before recurvature to the northeast, is initialized at 0000 GMT on August 5, 6 and 7, represented by C, D and E. To run the model in an environment consistent with operational forecast conditions, the lateral boundary solutions of the CM model are updated successively by 3-h interval interpolated tendencies from the global model output so that integrations for 48 h and forecast output fields at 00, 24, 36 and 48 h are produced. Good agreement is found between the prediction and the observation by displaying mean errors of 140.5 km and 272.7 km for 24 and 48 h, standing above what a general model can achieve now. It shows that the model is quite capable in forecasting the motion of a tropical cyclone.

Ⅲ. ISOLATION OF ASYMMETRIC COMPONENTS

Values of stream function on all isobaric surfaces are derived by the vorticity, which observe the relation as in

$$\nabla^2\psi = \xi. \tag{1}$$

The stream function is derived relative to Eq. (1) by the vorticity using the differencing method on the spherical coordinates. The derivation for FM is done first by obtaining the stream function on CM with corresponding predicted vorticity using Eq. (1), applying lateral conditions identical to Wang et al. (1996), i.e. letting $\psi = 0$ on poleward boundaries, and cyclic boundary conditions in the longitudinal direction, then by linearly interpolating the stream function of CM for boundary values on FM before solving for that of FM on the spherical coordinates using Eq. (1).

The center of the tropical cyclone is set at the grid point where the vorticity is the maximal on the 850 hPa surface of FM, around which meteorological elements field of stream function, vorticity and geopotential height are decomposed to axisymmetric and asymmetric components, i.e. the field $A\ (x, y, t)$ is decomposed to

$$A(x,y,t) = A_s(x,y,t) + A_a(x,y,t), \tag{2}$$

where $A_s\ (x, y, t)$ is the axisymmetric component (or angular oriented mean component) and $A_a\ (x, y, t)$ the asymmetric component.

For the FM grids, the field $A\ (x, y, t)$ is converted from the grid coordinates (x, y) to the polar coordinates (r, θ) setting the typhoon center as pole, which is expressed by $A\ (r, \theta, t)$. The axisymmetric component $[A\ (r_0, t)]_s$ at the range r_0 from the center is derived using the expression of

$$[A(r_0,t)]_s = \frac{\sum_{r_0 \leqslant r < r_0+\Delta r} A(r,\theta,t)}{N}, \tag{3}$$

where Δr is the increment in radial range (taken at 50 km) and the denominator N is the grid total within the annular band $r_0 \leqslant r < r_0 + \Delta r$.

Following Eqs. (2) and (3), asymmetric components of vorticity, stream function and geopotential field on the FM grids are determined. The small perturbation caused by separation is removed by a technique of nine-point running mean relative to the asymmetric components.

IV. ANALYSIS OF ASYMMETRIC STRUCTURE

1. *Temporal variation of asymmetric structure and its vertical distribution*

By examining the results of forecasting experiments, all but Case C are satisfactory. The failure in Case C may be caused by the weakening and retrogression to the east of the Subtropic High ridge at 24 h in the model output for the environment, leading to large discrepency in the motion of the tropical cyclones. The recurvature is well reproduced in Cases D and E, though some difference is found in Case D in terms of track forecast. The asymmetric structure and its evolutions have to be studied first in order to discuss the relationship between the asymmetric structure and the track.

The forecast of tropical cyclone motion is successful in Cases A, B and E (Figures of both forecast and observation omitted).

Figs. 2~3 give the graphic presentation of asymmetric stream function at 00, 24, 36 and 48 h on the 500 hPa isobaric surface in Cases C and D. The motion predicted in Case C is generally agreeable with the observation at 00 through 24 h, though differing much after 30 h i.e. Fig. 1. On its asymmetric stream function chart at 00 through 48 h at 500 hPa, Case C gives northwest oriented ventilation flow at 00-24 h for the storm center associated with the asymmetric structure, which is consistent with both reality and prediction. By 36 h, the structure has somewhat deflected clockwisely to cause some difference from the track predicted in the direction of the ventilation flow. Case D does well in the forecasting of the motion, especially of the recurvature. On its asymmetric strean function chart at 00-48 h of the 500 hPa surface, the ventilation is quite agreeable with the motion and the time of recurvature. The asymmetric stream function in Case D shows agreement between the recurvature predicted and that in the asymmetric gyre. Similarity

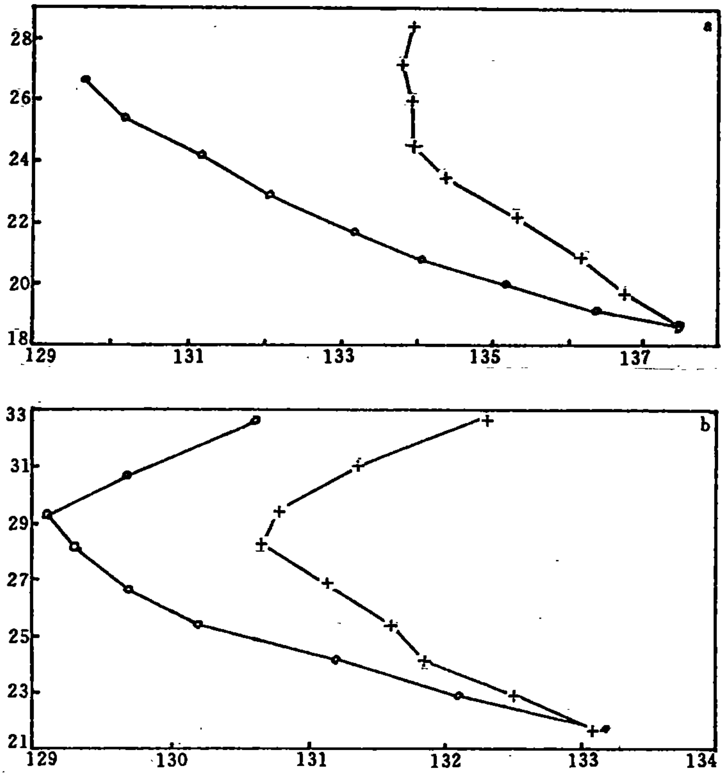

Fig. 1. Observational versus forecast typhoon track. (a) case B, (b) case E. Symbol "o" represents observational positions, symbol "+" denotes forecast positions. The time interval between symbols is 6 h. Numerals along abscissa and ordinate stand for longitude and latitude, respectively.

is also found in other cases (figure omitted).

For the cases above, the asymmetric geopotential field is mainly made up of a high-value maximum(anticyclone)and a low-value center(cyclone)and bears high resemblance to the asymmetric stream function in structure (Figures are omitted for individual cases).

Similarly, asymmetric temperature field is obtained by isolation of the individual cases applying the technique above. Fig. 4 gives the asymmetric temperature distribution at 00-48 h on the 500 hPa isobaric surface in Case D. As is shown, the asymmetry is so weak that it is barely identifiable at 00 h. For the 24-48 h section, however, significant cold and warm centers, their intensity, range and location vary much with time but much less with the motion of the tropical cyclone. It may be related to the asymmetric temperature structure and the typhoon rainfall and its associated process of release of latent heat condensed.

From the distribution of asymmetric stream function as shown in Fig. 5, it is known that the variation from 1000 hPa upward till 300 hPa remains mild with only light anticyclonic rotation with altitude.

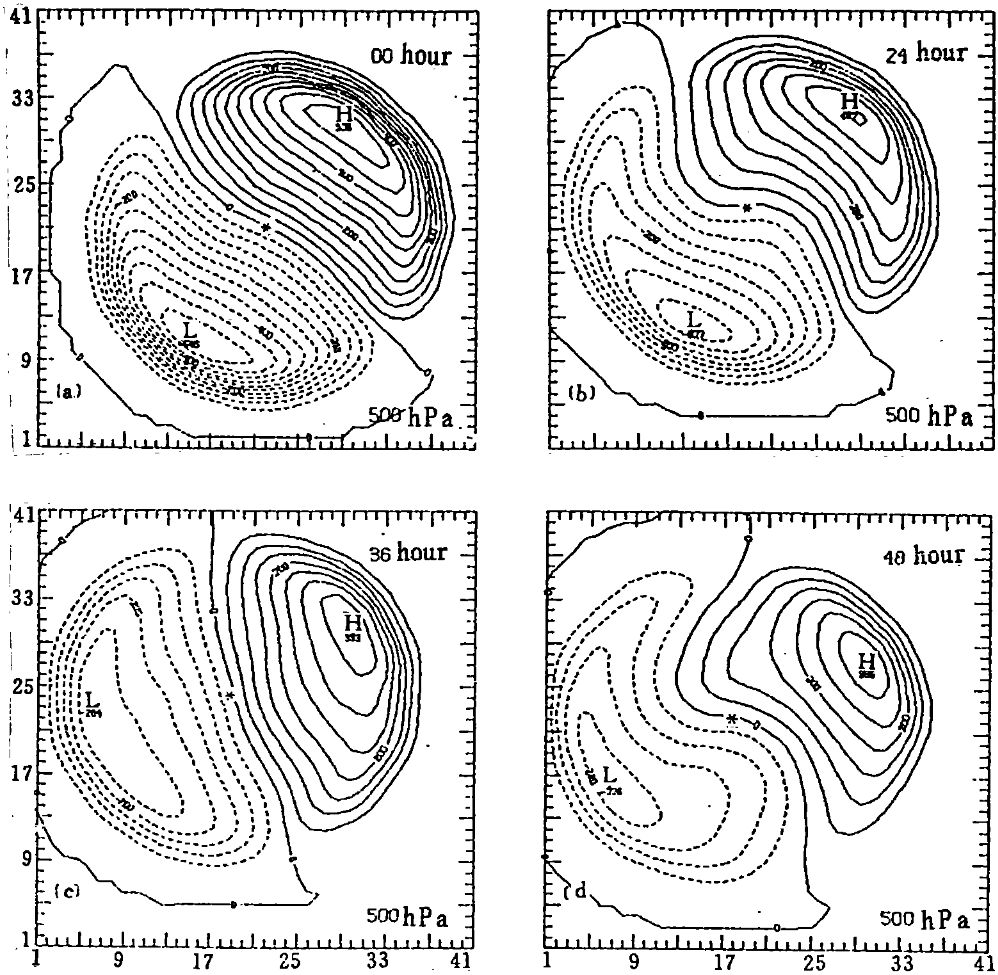

Fig. 2. Asymmetric stream function at 500 hPa in Case C at (a) 00 h, (b) 24 h, (c) 36 h and (d) 48 h. The contour interval is $5\times10^5 M^2S^{-1}$, and the symbol * denotes typhoon center position. The abscissa is numerals for FM longitudinal points and ordinate is numerals for FM latitudinal points with interval of 0.46875°.

The asymmetric structure is generally consistent vertically from 1000 hPa to 300 hPa and similar pattern is found in the geopotential field. As there is less consistence in regard to the vertical distribution of asymmetry with height in the temperature field, the relationship is more complicated between the structure and the motion of tropical cyclones (Figures for distribution of other asymmetric structures are omitted).

2. *Relationship between asymmetric structure and typhoon motion predicted*

The improved method in Tian (1996) is used to compute the vector of ventilation flow. First of all, a circular region is assumed by taking the center of the storm as the original point and the radius γ to be 400 km, for which the asymmetric wind components U_a and V_a are derived by asymmetric stream function. Then, the vectors of regional mean

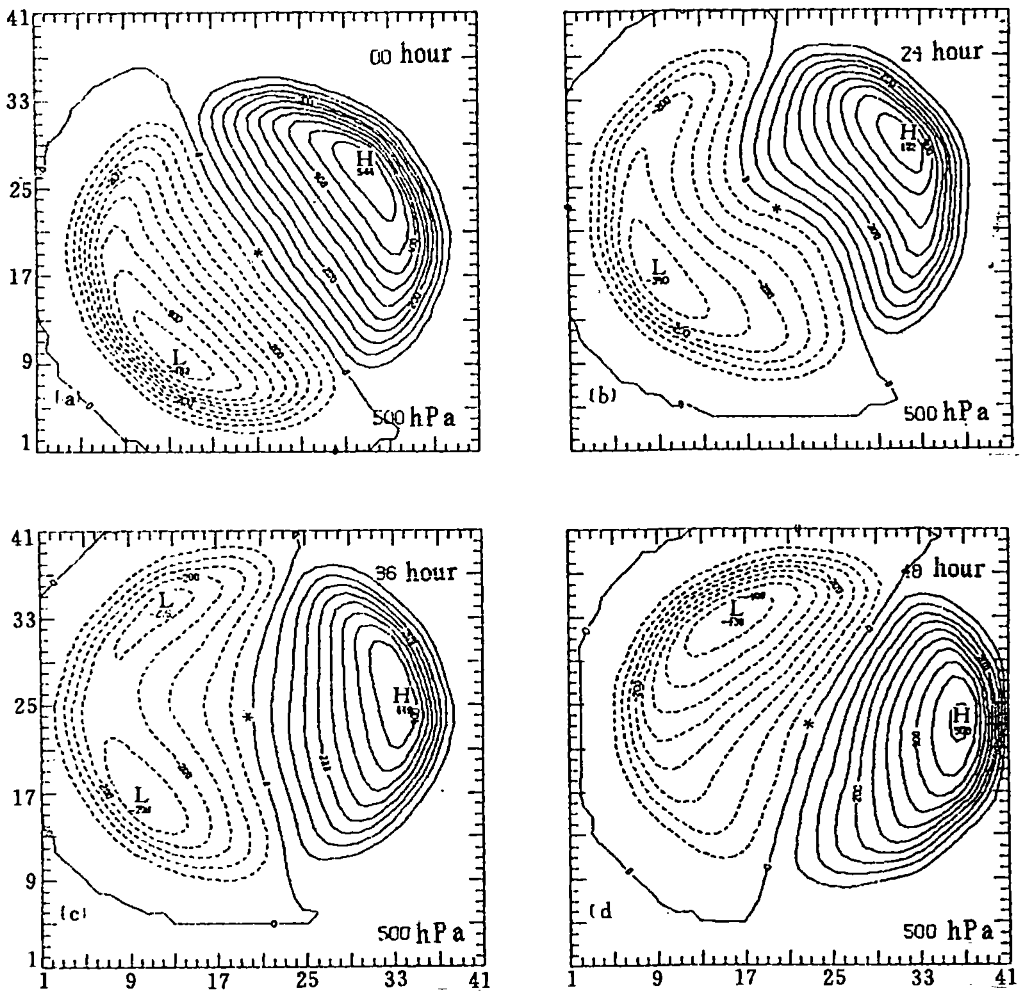

Fig. 3. Same as Fig. 2 but for Case C.

value of U_a and V_a are composed to have the vector of ventilation flow, whose magnitude and direction are denoted the way V_a and θ_a are (by setting the due north as zero degree and the clockwise direction as positive).

Following the method above, the ventilation flow vectors on the isobaric surfaces of 850, 700, 500, 400 and 300 hPa in all cases are computed for 00, 24 and 36 h. Then, the corresponding mean of ventilation flow is solved in terms of magnitude and direction expressed by V_a and θ_a for the particular moment. Using the track predicted for periods 00-03 h, 21-27 h and 33-39 h, the mean vectors of motion at 00, 24 and 36 h are determined with the magnitude and direction expressed by V_p and θ_p, respectively.

It is known from Table 1 that the magnitude and direction of the vector ventilation flow computed with asymmetric stream function of individual cases is close to those derived by predicted track for mean vector of motion. Judging from Cases D and E, recurvature of track has been well indicated and the predicted recurvature well coincided by directional variations of ventilation flow vector. The vector in the previous 24 hours in

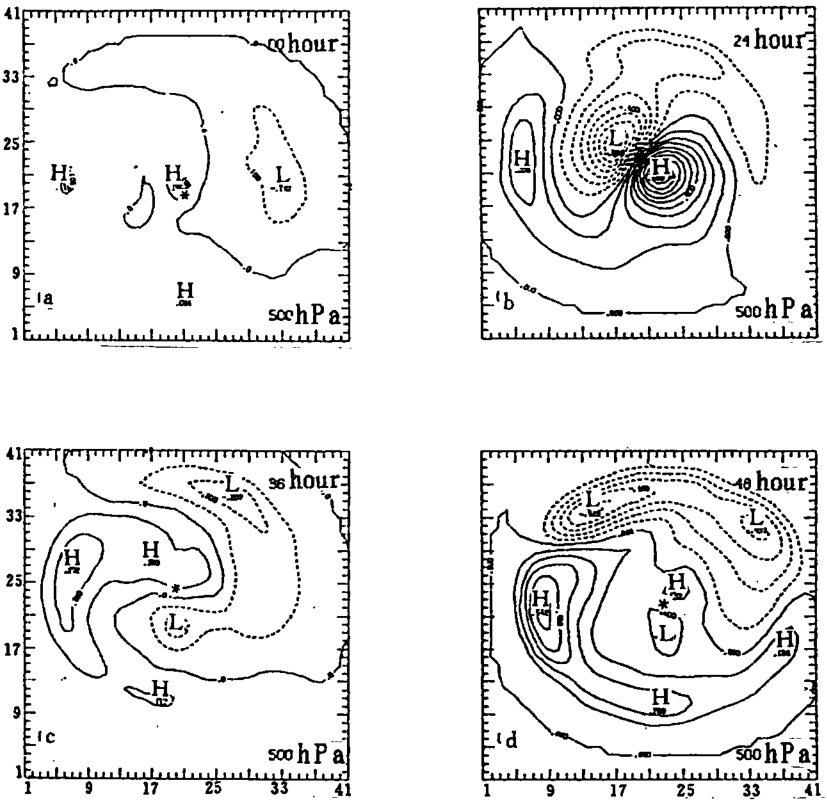

Fig. 4. Asymmetric temperature field at 500 hPa in Case C at (a) 00 h, (b) 24 h, (c) 36 h and (d) 48 h. The contour interval is 0.1 centigrade degree, and the symbol * denotes typhoon center position. The abscissa is numerals for FM longitinal points and the ordinate is numerals for FM longitinal points with interval of 0.46875°.

Table 1. Comparison of ventilation flow vector and mean vector of motion predicted for individual cases.

Case	00 hour				24 hour				36 hour			
	V_v (m/s)	θ_v (d.)	V_m (m/s)	θ_m (d.)	V_v (m/s)	θ_v (d.)	V_m (m/s)	θ_m (d.)	V_v (m/s)	θ_v (d.)	V_m (m/s)	θ_m (d.)
A	9.5	284	9.8	286	7.5	293	5.8	288	6.4	296	7.7	281
B	5.9	306	7.9	290	6.9	294	6.0	291	7.7	296	7.3	305
C	6.7	315	8.6	304	6.7	322	6.5	309	7.2	1	7.2	341
D	6.5	337	8.1	342	7.6	342	7.2	325	7.3	10	6.4	1
E	5.8	323	7.8	314	10.5	31	9.0	17	13.4	41	12.1	21

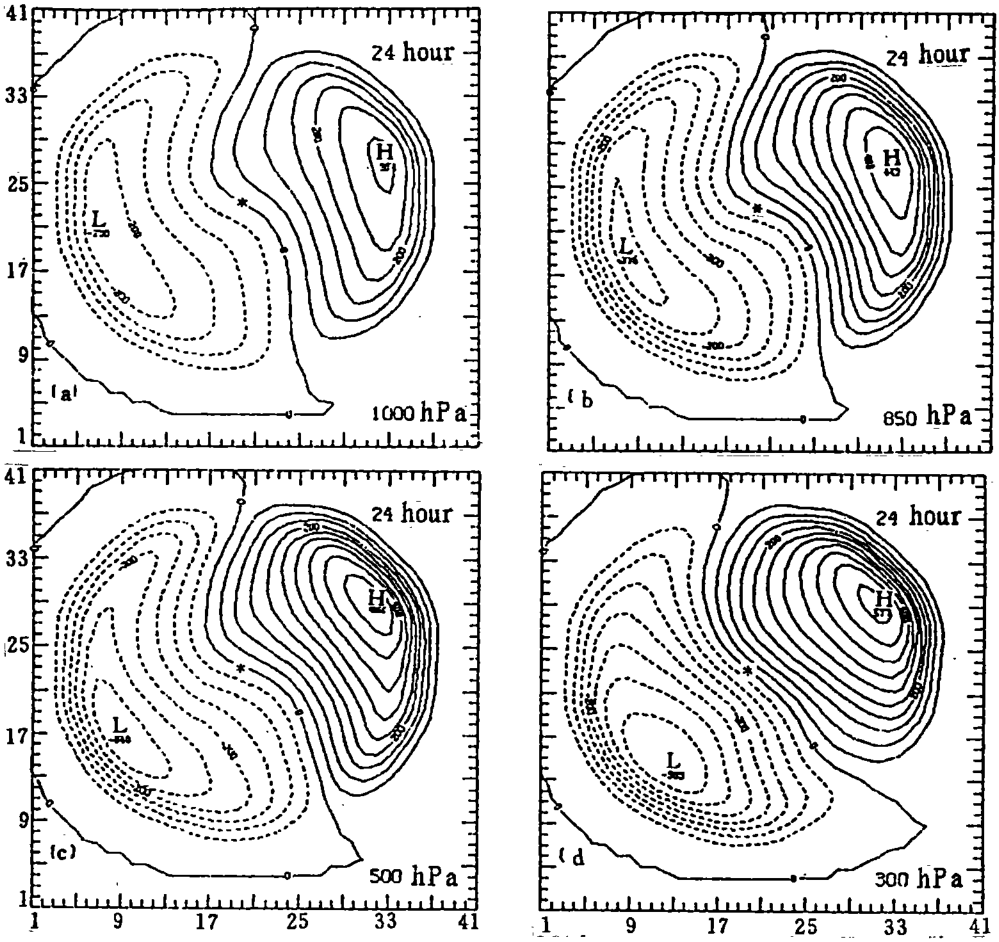

Fig. 5. Asymmetric 500 hPa stream function in Case D at 24 h on (a) 1000 hPa, (b) 850 hPa, (c) 500 hPa and (d) 300 hPa. The rest follows the same denotation of corresponding part in Fig. 2.

Case C and in the previous 36 hours in Cases A and B is also in coincidence with the northwest motion of the tropical cyclone predicted.

It is also suggestive by the computed results that the ventilation flow vector derived by a 5-layer mean is more efficient than by 500 hPa layer. It is an indication that there is closer link between the ventilation caused by the deep asymmetric structure and the moving speed of the tropical cyclone, which is helpful in the forecast of typhoon motion.

V. CONCLUSIONS

a. The asymmetric structure is relatively consistent between the stream function on all isobaric surfaces below 300 hPa. The mean vector of ventilation flow derived by the function on five surfaces between 850 and 300 hPa is agreeable with the track in which the tropical cyclone moves, indicating close relationship between the deep asymmetric structure and typhoon motion.

b. The asymmetric temperature structure of a tropical cyclone is multiply related to the motion, possibly due to precipitation by typhoon and associated release of latent heat condensed.

c. As the recurvature of asymmetric stream function and geopotential field is quite consistent with that of typhoon motion, understanding of the former is expected to be helpful in the prediction of abnormal track of the tropical cyclone.

As a matter of fact, there are more possible factors than those just acting internally, e.g. the effects of the environmental field and topographic features are equally important. They are left for further study in the future.

REFERENCES

Chan J C L. Williams K T. Analytical and numerical studies of beta-effect in tropical cyclone motion. *J. Atmos. Sci.* 1987, **44**: 1257—1265.

Davis H C, 1976. A lateral boundary formulation for multi-level prediction model, *Quart. J. Roy. Meter. Soc.*, **102**: 405—418.

Fiorino M, Elsberry R L, 1989. Some aspects of vortex structure related to tropical cyclone motion, *J. Atmos. Sci.*, **46**: 975—990.

Reeder M J, Smith R K, Lord S J, 1991. The detection of flow asymmetries in the tropical cyclone environment, *Mon. Wea. Rev.*, **119**: 848—854.

Tatsumi Y, 1976. An economical explicit time integration scheme for a primitive model, *J. Meteor. Soc. Japan*, **61**: 269—287.

Tian Yongxiang, 1996. Relation between ventilation flow and motion of tropical cyclone in a baroclinic vortex, *Acta Meteorologica Sinica* **54**: 83—93. (in Chinese)

Wang B, Li X, 1994. Barotropic dynamics of the beta gyres and beta drif, *J. Atmos. Sci.*, **51**: 746—756.

Wang Guomin, Wang Shiwen , Li Jianjun, 1996. A bogus typhoon scheme and its application to a movable nested mesh model, *J. Trop. Meteor.*, **12**: 8—17. (in Chinese)

Wang Guomin, Wang Shiwen, 1996. A two-way interactive movable nested mesh model for typhoon track prediction, *J. Trop. Meteor.*, **2**: 155—162.