NUMERICAL EXPERIMENT OF THE EFFECT OF ENVIRONMENTAL FLOWS ON TROPICAL CYCLONE MOTION

Li Tianming (李天明) and *Zhu Yongti* (朱永禔)

Shanghai Typhoon Institute, Shanghai

Received October 28, 1989

ABSTRACT

A barotropic primitive equation model is used to simulate the tropical cyclone motion. Tropical cyclone movements under different environmental flow backgrounds were examined and sensitivity of tropical cyclone tracks were discussed. Conclusions of practical significance have been obtained in this paper.

Key words: numerical experiment, tropical cyclone motion, effect of environmental flow, tropical cyclone track, sensitivity experiment

I. INTRODUCTION

It is well known that tropical cyclone motion is confined by many factors (Demaria, 1985; Chan, et al., 1987), such as large-scale environmental flow field, Coriolis force, sea temperature, topography and the intensity and structure of the tropical cyclone (hereinafter abbreviated as TC) itself. The nonlinear effect of these factors determines the movement of TC.

It is shown (Li and Zhu, 1990) that the asymmetry of TC structure can affect TC movement and. in certain circumstances, may lead to the sudden change in the TC track. In this paper, a barotropic primitive equation model has been used to simulate and study the TC movement under several typical environmental flows and some sensitive questions of TC tracks have been analysed and discussed.

II. EXPERIMENT

A scheme (Wang and Zhu) of a barotropic primitive equation model is used in simulating TC track features under 5 typical environmental flows.

To avoid the effects of asymmetric structure of TC, axisymmetric tropical cyclone circulation were superimposed on the 5 typical environmental flows. Its height field is determined by

$$\phi(r)=\phi_E-\Delta\phi\cdot\exp(-4\cdot(r/R_0)^2)/\sqrt{1+1.55(r/r_m)^2},$$

where $\phi(r)$ is the axisymmetric geopotential height of the tropical cyclone; ϕ_E is the geopotential height of the environmental flow at the TC periphery, i. e., $\phi_E\approx\phi(R_0)$; $\Delta\phi$ is the difference between the geopotential height of TC centre and that of peripheral environment, characterizing the TC intensity, i.e., $\Delta\phi=\phi_E-\phi(0)$; r_m is the radius of TC maximum wind; and R_0 is the radius of TC circulation. In our experiment, $R_0=1000$ km, $r_m=200$ km, $\Delta\phi=3000$ m^2/s^2, and $\phi_E=584$ geopotential decameters. These parameters are close to real data.

The above-mentioned TC circulation heights are then embedded into the following 5 patterns of typical environmental fields which are quite close to the real ones:

a) Homogeneous Zonal Circulation Pattern: $\bar{U}(Y)=-\frac{1}{f}\frac{\partial\phi_E}{\partial Y}=U_0$, (1)

b) Linear Shear Flow Pattern: $\bar{U}(Y)=-\frac{1}{f}\frac{\partial\phi_E}{\partial Y}=U_0(Y-Y_0)/L$, (2)

c) Jet Stream Pattern: $\bar{U}(Y)=-\frac{1}{f}\frac{\partial\phi_E}{\partial Y}=U_0\cos\frac{\pi}{L}(Y-Y_0)$, (3)

d) ITCZ Pattern: $\bar{U}(Y)=-\frac{1}{f}\frac{\partial\phi_E}{\partial Y}=U_0\cdot\sin\frac{2\pi}{L}(Y-Y_0)$, (4)

e) Complicated ITCZ Pattern: $\bar{U}(Y)=-\frac{1}{f}\frac{\partial\phi_E}{\partial Y}$

$$=U_m\frac{Y-Y_0}{Y_m}\exp\left\{\frac{1}{2}\left[1-\left(\frac{Y-Y_0}{Y_m}\right)^2\right]\right\}, \quad (5)$$

where Y_0 and Y_m are the parameters to define the circulation patterns; U_0 or U_m is the maximum zonal wind, using the value close to the real wind: and L is the width of the zonal flow. The environmental height field ϕ_E is derived from the integration of the above equations when the parameters are given.

For illustration, Fig. 1 schematically shows the 5 flow patterns.

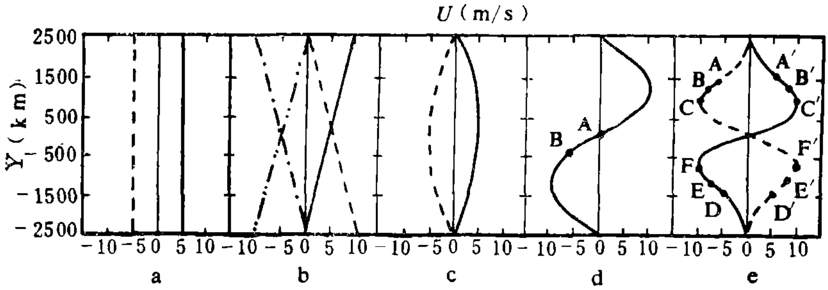

Fig. 1. Typical environmental flow fields (dots show TC locations).

We first examine the effects of the relative vorticity and vorticity gradient of the environmental flows on TC tracks. Set $\beta=0$, and the environmental wind at the TC centre is set to be 5m/s, it is shown from the calculation that under Circulation Pattern a, the direction and speed of the TC movement coincide with those of the environmental flow, and also under Circulation Pattern b, the direction and speed of the TC movement almost coincide with the environmental flow no matter whether the vorticity of the linear shear flow is cyclonic and anticyclonic.However,in Patterns c,d and e,due to the effects of the relative vorticity gradient of the environmental flows, which has the same contribution as the earth vorticity gradient, TC movement has a northward component when the gradient of the relative vorticity is positive and a southward component when the gradient is negative.Fig.2 gives the TC tracks under Circulation Patterns a and d. It should be noted that if TC is located at point B under Circulation Pattern d, though the vorticity shear of the environmental flow is negative, the TC does not show to move northward anticyclonically, instead, it appears to have a tendency of southward movement. This is because the vorticity gradient is negative. This means the vorticity gradient plays a greater role than the vorticity in TC movement. At point A in Pattern d, as the environmental flow speed is zero and the vorticity gradient is also zero, thus the TC at this point is shown to be stationary if the β-effect is not taken into account.

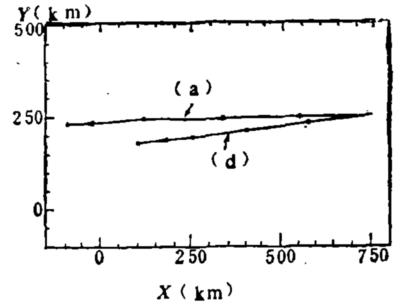

Fig. 2. The calculated tracks of TC for Circulation Patterns (a) and (d) when the β-effect is not considered (the initial TC position is at point B in Pattern d in Fig. 1).

Fig. 3 gives the calculated TC tracks for $\beta=0$ and $\beta\neq0$ in the Homogeneous Circulation Pattern a. It is seen from the figure that β-effect may cause the TC movement to have a northward component, i.e., the TC may move to the left of the westerly basic flow and move to the right of the easterly basic flow. Fig. 4 gives the calculated TC tracks when the initial TC position is taken as $Y=0$ and $Y=\pm200$ km respectively for 4 different linear shear flows ($U_0=\pm10$ m/s, $Y_0=\pm2500$ km) in Circulation Pattern b. It is seen from the figure that the 3 tracks have different features of confluence and dispersion. Note that the confluence means an unimportance of the initial TC positioning error under this circumstance while the dispersion of the tracks means the significant influence of the initial TC positioning error on TC movement. Therefore the effect of positioning error on TC track prediction depends on the environmental flows.

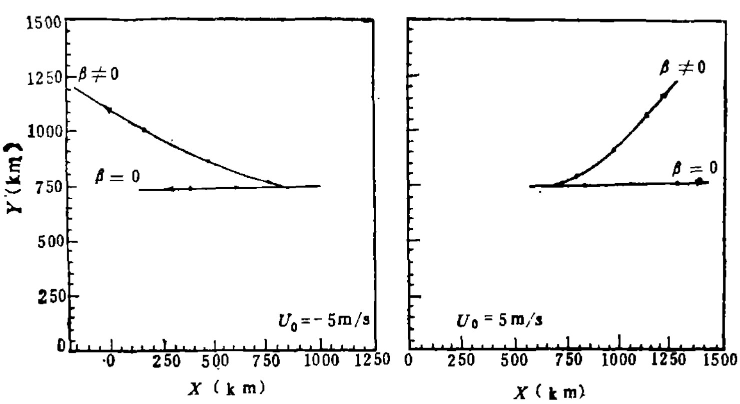

Fig. 3. TC track difference due to β-effect for Circulation Pattern a when $U_0=\pm5$m/s (dots are separated by 12 hours).

Fig. 5 gives the simulated tracks for Circulation Pattern b when $U_0=\pm10$m/s and $U_0=\pm50$ m/s; $Y_0=0$ and $Y=0$; and $\beta\neq0$. It is found that β-effect may cause TC to move northward when the relative vorticity gradient of the environmental flow is zero.Now a cyclonic vorticity,

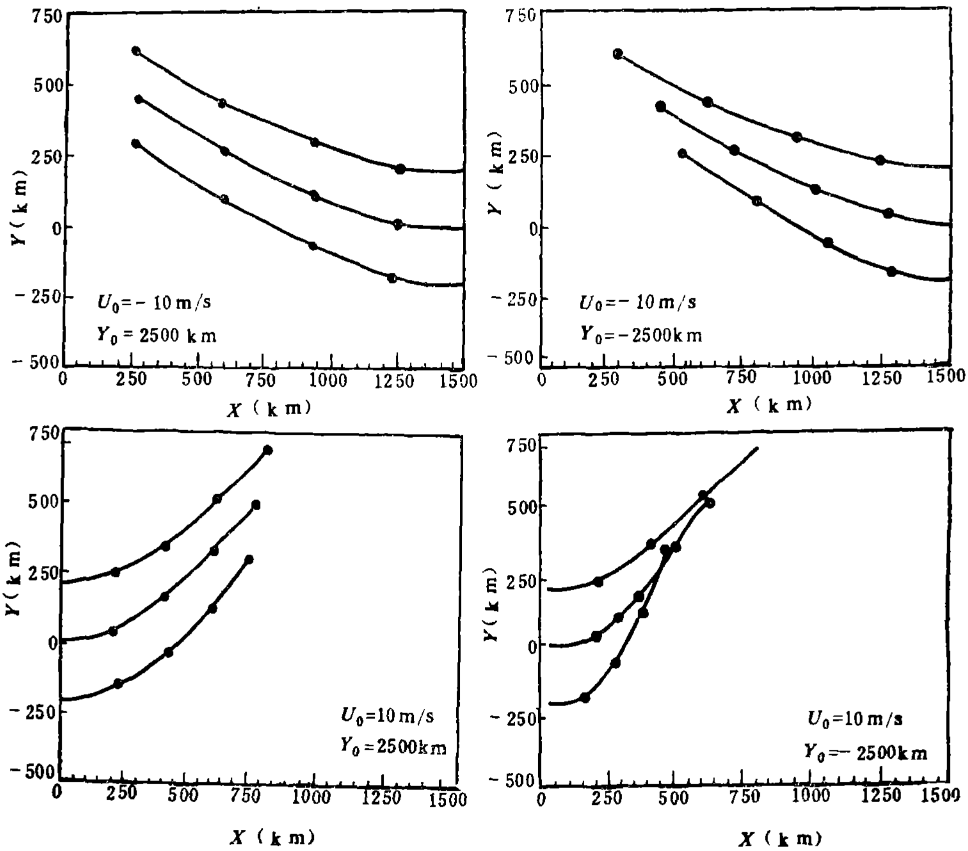

Fig. 4. Calculated TC tracks for different parameters and different TC initial positions for Circulation Pattern b (intervals between dots are 12 hours).

if exists, in the environmental flow could help the TC take a circuitous route cyclonically in its northward movement while an anticyclonic vorticity could cause an anticyclonic circuitous route for the north-moving TC track. These two kinds of tracks both show an arc shape. Fig. 6 gives the variation of TC wind field structure under environmental Circulation Pattern b, for $\beta\neq 0$, $Y=Y_0=0$ and $U_0=50$ m/s. It is found that the superimposition of the linear shear zonal basic flow over the TC circulation at the initial time causes the originally symmetric TC structure to change. Two maximum wind zones appear at the east and west sides of the TC and gradually approach to form one maximum wind centre.

Fig. 7 gives the calculated tracks for Circulation Pattern c when $U_0=\pm 5$ m/s, $Y_0=0$, $Y=0$ and $Y=\pm 200$ km. It is seen from the figure that the Westerly Jet Pattern causes the TC to move northward. Positive vorticity gradient enhances the north-moving component caused by the β-effect while the TC has a faster movement under Easterly Jet Pattern.

Fig. 8 gives the simulated TC tracks for Circulation Pattern e when $U_m=\pm 10$ m/s, $Y_0=0$, $Y_m=600$ km; and when the initial TC position is set to be at $Y=\pm 800$ km, ± 1000 km, and ± 1200 km respectively, corresponding to the same pattern in Fig. 1 when the initial TC positions are at A, B, C, D, E, and F; and at A', B', C', E', and F'. It must be pointed out that the relative vorticity gradient of the environmental circulation is zero at points B, E, B' and E',

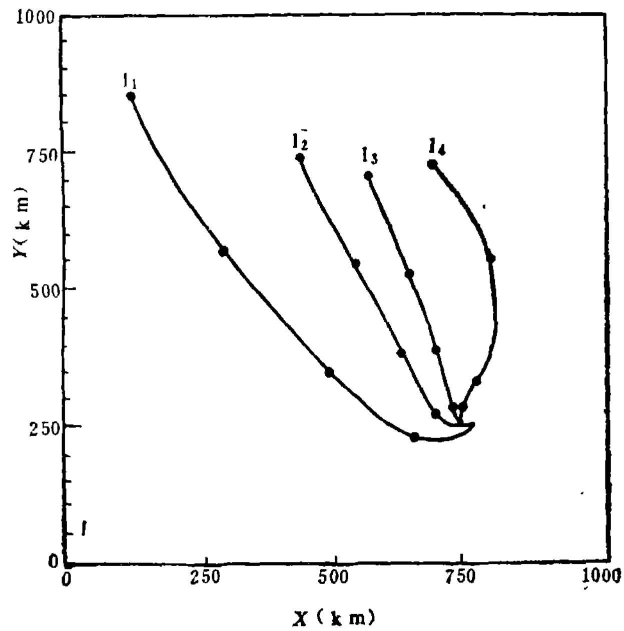

Fig. 5. The calculated track when the TC is located at $Y=0$ for Circulation Pattern b for $\beta\neq0$, $Y_0=0$. l_1: U_0=-50m/s, l_2: U_0=-10m/s, l_3: U_0=10m/s, l_4: U_0=50m/s.

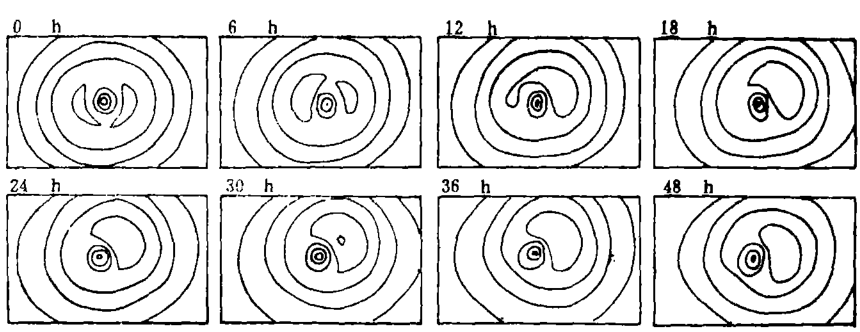

Fig. 6. Evolution of the wind field structure within the TC for Circulation Pattern b for $Y=Y_0=0$, $\beta\neq0$, U_0=50m/s (tangential isotaches are separated by 8m/s).

larger than zero at point A, and smaller than zero at point C; and the environmental wind speed at point C is larger than that at Point A, therefore the calculated TC tracks at points A, B and C are found to be separated to each other. That is to say, a smaller initial TC positioning error could cause a larger forecast error for the TC position. Thus the initial TC position in this case is shown to be very sensitive for the predicted track. The environmental relative vorticity gradient is larger than zero at point D, but smaller than zero at point F, and therefore the north-moving component of the TC movement at point D is larger than that at point F. In addition, as the environmental flow speed is faster at point F than that at point D,the 3 tracks have a greater trend of convergence. This means the TC track is not sensitive to the

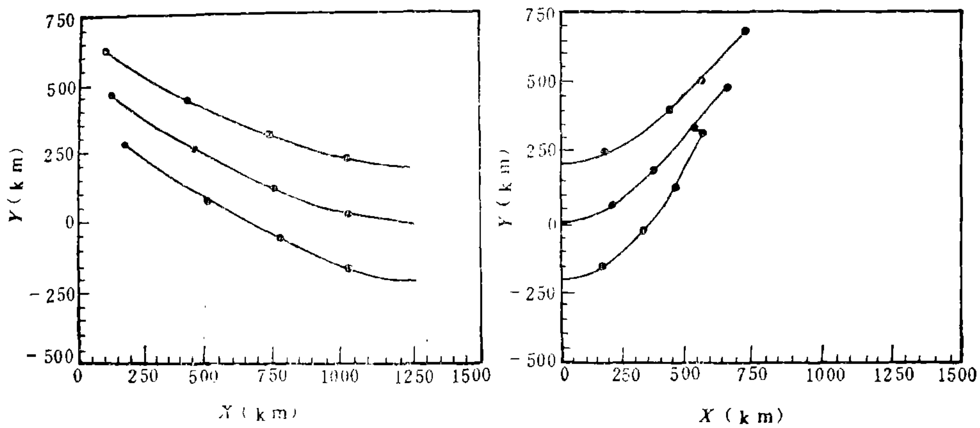

Fig. 7. The simulated TC tracks for Jet Pattern c when $U_1=5$m/s (left) and $U'_0=-5$m/s (right) (Intial positions are separated by 200km and intervals between dots are 12 hours).

initial TC positioning error under this circumstance. Even if the initial positioning has an error, its effect would decrease with the integration time. The relative vorticity gradient of the environmental circulation is smaller than zero at point A', but larger than zero at point C'. From this gradient distribution, the tracks should have a tendency of convergence. However, as the environmental wind is weak at point A', but strong at point C' and as the TC movement mainly depends on the environmental flow field and the absolute vorticity gradient (i.e., the combined forcing of β-effect and the environmental relative vorticity gradient), the north-moving component at point C' therefore weakens because of the superimposition of strong westerly basic flow. As a result, TC tracks with initial positions of A', B', and C' do not show any sign of convergence. Meanwhile the distance between calculated positions of 12, 24, 36 and 48 hours for TC at points D', E' and F' shows little difference from distance between the initial positions.

III. CONCLUSIONS

From various simulation results mentioned above, following conclusions can be made:

(1) The relative vorticity gradient of the environmental flow has the equal important role as the β-effect. When $\beta=0$, the positive relative vorticity gradient of the zonal basic flow makes the TC have a north-moving component while the negative gradient makes the TC have a south-moving component.

(2) When the north-south orientated gradient of the absolute vorticity of the environmental field is greater than zero and the zonal wind at the north side of the TC is smaller than or equal to that at the south side of the TC, the TC track would be sensitive to the initial TC position. On the other hand, when the north-south orientated gradient of the absolute vorticity gradient of the environmental field is smaller than zero, and the zonal wind at the north side of the TC is greater than or equal to that at the south side of the TC, the forecasted track is not sensitive to the initial positioning error of the TC. This is in agreement with other case analyses (Demaria, 1985).

These conclusions are made only from specific simulations and a simple model, but the obtained characteristics of the TC movement are in agreement with the observations.

Therefore, qualitatively speaking, these conclusions are helpful in practical applications.

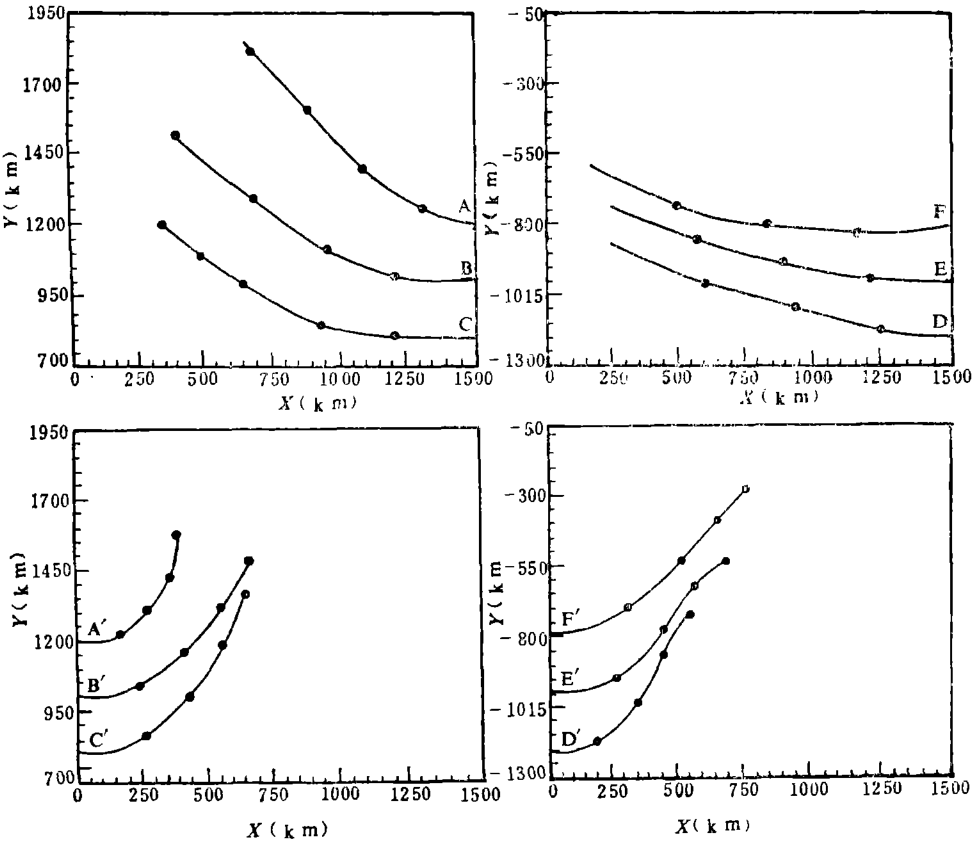

Fig. 8. Characteristics of confluence and dispersion of 4 groups of TC tracks for Circulation Pattern e taken β-effect into account (initial positions labelled by letters correspond to the TC positions in Fig. 1).

REFERENCES

Chan, Johnny, C.L.and Williams, R.T. (1987), Analytical and numerical studies of the beta-effect in tropical cyclone motion, Part I: Zero mean flow, *J. Atm. Sci.*, **44**:1257—1265.

Demaria, M. (1985), Tropical cyclone motion in a non-divergent barotropical model, *Mon. Wea. Rev.*, **113**: 1199—1210.

Li Tianming and Zhu Yongti (1990), Analysis and simulation of tropical cyclone movement,Part I: Asymmetric structure and the sudden change of the tracks, *Scientia Sinica*, (B series), No.**1**: 104—112 (in Chinese).

Wang Yuqing and Zhu Yongti, Mechanism analysis and numerical study of the interactions between two tropical cyclones (to be published in Chinese in Scientia Atmospherica Sinica).