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Effect of the Interaction of Different Scale Vortices on the Structure and Motion of Typhoons①

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ABSTRACT

Five numerical experiments have been performed in this paper by using a quasigeostrophic barotropical model to investigate the interaction of different scale vortices on the structure and motion of typhoons. Results show that this interaction may arouse the irregular changes of the asymmetric structure of typhoons, thus leading to anomalous phenomena such as meandering tracks and sudden changes in the motion speed of typhoons; the effect of this interaction on the strucure and motion may be quite different when the smaller vortex is situated in different positions of the typhoon circulation.

Key words: Vortices, Interaction, Typhoon, Structure, Motion

I. INTRODUCTION

The meandering track is one type of anomalous tracks of tropical cyclones in the West Pacific and South China Sea (Chen, 1985). The earlier study on the dynamics of the oscillatory motion of tropical cyclones has been made by Yeh (1950), who treated the typhoon as the Rankine vortex in a southerly flow and found the oscillation solution of tropical cyclone motion with its amplitude and period dependent on the spatial scale and intensity of tropical cyclones and the strength of the southerly flow. Later, Syono (1955) and Futi (1956) held that the oscillations of the environmental flow may give rise to periodic and quasi–periodic oscillatory tracks. Those belong to mechanisms of tropical cyclone oscillatory tracks in the strong environmental flow.

In the real atmosphere,meandering tracks frequently occur in weak environmental flow fields. The mechanism of oscillatory track in this case differs from those in the circumstance of strong environmental flow fields. Recently Holland and Lander (1991) analyzed the interaction of meso–scale cloud clusters and tropical cyclones in the weak environmental flow field and its effect on tropical cyclone tracks, and successfully simulated a large amplitude oscillation of typhoon motion. However, it seems that they only presented the numerical results and did not go a step further to discuss possible physical causes in that paper.

This paper is going to show that the interaction of different scale vortices is able to trigger the irregular evolution of the asymmetric structure of typhoons in the weak environmental

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flow field, directly leading to irregular meandering oscillations of typhoon tracks. Besides, while the relative position of two different scale vortices is different, the amplitude of the oscillations is quite different. Therefore, what position of the typhoon circulation, where the smaller vortex lies, is also very important to the formation of meandering oscilations.

II. MODEL AND EXPERIMENT DESIGN

The quasigeostrophic barotropic vorticity equation

$$\frac{\partial}{\partial t}\nabla^2\psi + J(\psi,\ \nabla^2\psi) + \beta\frac{\partial\psi}{\partial x} = 0 \qquad (1)$$

is adopted, where ψ is geostrophic stream function, $\beta = df/dy$, f is the Coriolies parameter. The bisector of the beta plane is set on $\varphi = 25°$N.

The stream function is divided into the two parts of mean quantity $\bar{\psi}(y)$ and perturbation quantity $\psi'(x,y,t)$. Where the mean quantity describes stationary east or west wind environmental flow, which is usually set to be zero when weak environmental flow field problems are studied, such as in Chan and Williams (1987). In this paper, it is also set to be zero.

With regards to the initial condition, set

$$\psi'(x,y,0) = \psi'_1(x,y,0) + \psi'_2(x,y,0)\ , \qquad (2)$$

where $\psi'_1(x,y,0)$ delineates a circular symmetric typhoon vortex and is solved by the Poisson iteration method from the following initial vorticity field (see Chan and Williams, 1987):

$$\zeta' = (2V_m/r_m)(1-0.5(\tilde{r}/r_m)^b)\times \mathrm{EXP}\{(1/b)(1-(\tilde{r}/r_m)^b)\} \qquad (3)$$

where $\tilde{r} = \sqrt{(x-x_0)^2+(y-y_0)^2}$, (x_0, y_0) are the coordinates of the center of typhoons at the initial time. V_m is the maximum wind velocity, r_m the radius of maximum velocity, and b the shape parameter. The parameter values (see Chan and Williams, 1987) corresponding to the intense typhoon are adopted, i.e. set $V_m = 40.0$ m / s; $r_m = 100$ km; $b = 1$.

$\psi'_2(x,y,0)$ in Eq.(2) describes the small vortex in the peripheral region of the typhoon circulation. It is obtained from the following procedures: firstly, $\psi'_2(r,\theta,0)$ is specified, where r and θ are variables in polar coordinates. Set

$$\psi'_2(r,\theta,0) = Re\{\Phi(r)e^{in\theta}\}\ , \qquad (4)$$

where $\Phi(r)$ is a complex characteristic vector, representing the radial distribution of the amplitude of unstable mode with its maximum in the peripheral region of the typhoon circulation (Luo, 1994). n is the azimuthal wavenumber, set $n = 4$, i.e. there are four complete high / low value cycles in a circle. Then, interpolating $\psi'_2(r,\theta,0)$ into Cartesian coordinates yields the distribution of $\psi'_2(x,y,0)$. $\psi'_2(x,y,0)$ added $\psi'_1(x,y,0)$ makes the initial perturbation stream function field where different scale vortices coexist.

The computational domain for Eq.(1) is a square with the side length being 4000 km, horizontal grid–spacing $\Delta x = \Delta y = 40$ km, and 101×101 grid–points. Set $\psi' = 0$ on the south and north boundaries; a cyclic boundary condition on the east and west boundaries.

Five experiments, whose integration time is more than 120 hours, are performed with the time step being 10 minutes.

Experiment 1 is a standard experiment with $\psi'_2 = 0$, therefore no interaction of different scale vortices exists.

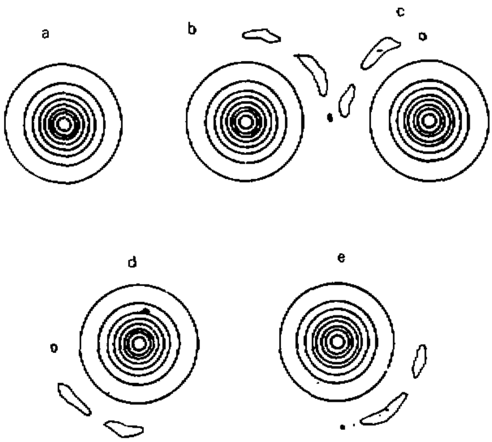

Fig. 1. Initial stream function fields of experiments 1–5. a). Experiment 1; b). Experiment 2; c). Experiment 3; d). Experiment 4; e). Experiment 5.

In experiments 2–5, set $\psi'_2(x, y, 0) \neq 0$ respectively in first, second, third and fourth quadrant of the typhoon circulation and $\psi'_2(x, y, 0) = 0$ in other quadrants. That is to say, there is a smaller vortex respectively in first, second, third and fourth quadrants. Fig. 1 shows the initial perturbation stream function fields of the five experiments performed in this paper. Because $\psi'_2(x, y, 0)$ presents an azimuthally symmetric four–wave distribution, the shape and intensity of smaller vortices in experiments 2–5 are virtually the same except different azimuthal positions in typhoon circulations.

It is necessary to explain that in Fig. 1 the scale of small vortex structures in the peripheral region of the typhoon circulations is very small. As mentioned above, those small vortices correspond to an unstable mode. With the lapse of time their spatial ranges rapidly increase. At 12th model hour, they have grown into quasicircular vortices with a diameter of 300–400 km (Figs. omitted here, see Fig. 1 in Luo, 1994), which is smaller than that of the typhoons, but is the same with the order of the horizontal characteristic scale, L (600 km), in this paper.Because the integration time in the five experiments is beyond 120 h, there exists the interaction of different scale vortices in the motion process of the typhoons.

III. COMPUTATIONAL RESULTS

1. *Interactions of Different Scale Vortices May Lead to the Oscillations of Typhoon Tracks*

In experiment 1,physical processes governing the motion of the typhoon are the beta effect and nonlinear advection. Under the effects of the two processes, a typhoon in a weak environmental wind field will move towards the northwest–by–north direction (see Chan and Williams, 1987). The typhoon track (Fig. 2a, dotted line) in experiment 1 is identical to that. Beyond 48 h, the track is very smooth, showing no oscillations.

After introducing a smaller vortex into first quadrant (experiment 2), the typhoon track shows distinct oscillations (Fig. 2a, solid line). Similarly, after introducing a small vortex respectively into second, third and fourth quadrants, all typhoon tracks exhibit to different extent oscillation phenomena (Figs. 2b, 2c, 2d).

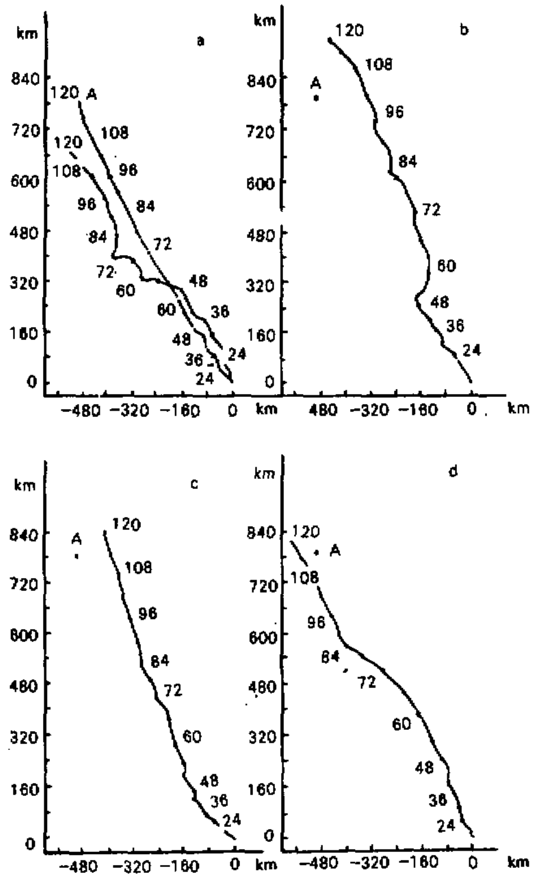

Fig. 2. Typhoon tracks in experiments 1–5. Numbers represent model hours and the position of typhoon centers is dotted evry 6 model hours. a. Experiment 1 (no interaction; dashed line) Experiment 2 (small vortex lying in NE quadrant; solid line) b. Experiment 3 (small vortex lying in NW quadrant) c. Experiment 4 (small vortex lying in SW quadrant) d. Experiment 5 (small vortex lying in SE quadrant) Point A denotes the position of the typhoon center at 120 h in experiment 1.

The comparison of the result of experiment 1 with those of experiments 2–5 shows that the interaction of different scale vortices is able to arouse the oscillations of typhoon tracks, which is in accord with the result of Holland and Lander (1991). In their paper, only the result of one numerical experiment was given, we present more numerical evidence here. Moreover, we shall further discuss the effect of the position of smaller scale vortices on the amplitude of track oscillations and its possible mechanism.

2. *Influences of the Relative Position of Different Scale Vortices on the Oscillation Amplitude and Motion Direction of Typhoon Tracks*

Among four experiments involved the interaction of different scale vortices, the oscillation amplitude of typhoon track (Fig. 2a solid line) in experiment 2 (small vortex lying *in NE quadrant) is the largest, and that (Fig. 2c) in experiment 4 (small vortex lying in SW* quadrant) the smallest, indicating that although shapes and intensities of the large and small vortices are all the same in experiments 2–4, the oscillation amplitude of typhoon tracks resulted from their interaction could be different due to the different relative positions.

Also seen on Fig. 2 are: when the small vortex lies in NE or SE quadrant, namely in the east side (FIg. 2a, solid line; Fig. 2d), the motion direction of typhoons has a west deviation from that (Fig. 2a, dashed line) in experiment 1 which contains no interaction of vortices; when the small vortex lies in NW or SW quadrant, namely in the west side (Figs. 2b, 2c), the motion direction of typhoons has an east deviation.

The interaction of different scale vortices also exerts some influences on the motion velocity of typhoons. When the smaller vortex lies in NW quadrant (Fig. 2b), the mean velocity obviously increases.

In experiments 2–5, tracks display oscillations mainly in the period from 48th to 84th hour. Based on the stream function charts at 6 hour interval in this period, we hereafter analyze the possible mechanism of the influence of different scale vortex interaction on typhoon tracks.

3. *Interaction of Different Scale Vortices and the Irregular Evolution of the Asymmetric Structure of Typhoons*

Under the joint effect of the beta and nonlinear advection terms, the initial Axisymmetric circular vortex gradually loses its symmetry, and shows an asymmeric structure of stream function isolines dense in NE quadrant and loose in SW quadrant (Chan and Williams, 1987; hereafter called as NE–SW direction asymmetric structure). After 36 model hours, this NE–SW direction asymmetric structure in experiment 1 has been apparent and continuously maintains. Correspondingly, the motion of the typhoon is always towards the northwest–by–north direction, i.e. neither motion direction changes, nor track oscillation takes place (Fig. 2a, dashed line). The left seven panels in Fig. 3 represent the perturbation stream function distributions in experiment 1 respectively at 48^h, 54^h, 60^h, 66^h, 72^h, 78^h, 84^h, all exhibiting a NE–SW direction asymmetric distribution.

After introducing a small vortex into NE quadrant (experiment 2, the middle panels in Fig. 3), the evolution of asymmetric structure differs widely from the case of no small vortex. Among the middle seven panels, there are only two showing a NE– SW direction asymmetric structure similar with those in experiment 1 (i.e. 60^h, Fig. 3h; 84^h, Fig. 3u). Correspondingly on the track chart (Fig. 2a, solid line), the typhoon moves northwards both in the two periods of 60^h–66^h and 84^h–90^h. The interior circulation of the typhoon at 54^h and 66^h exhibits a north–dense–south–loose pattern (Figs. 3e, 3k), the typhoon travels westwards (Fig. 2a, solid line). It is worth noticing that at 72^h the major axis of the typhoon vortex is along the NW–SE direction instead of the NE–SW direction, and isolines in SW quadrant are denser than those in SE quadrant (Fig. 3n); correspondingly the motion velocity rapidly reduces (Fig. 2a, solid line) in 72^h–78^h. The typhoon structures at 48^h and 78^h (Figs. 3b, 3q) also differ from the NE–SW asymmetric structure, therefore, the motion directions of the typhoon in the periods of $(48–54)^h$ and $(78–84)^h$ are different from those in experiment 1 in corresponding periods.

If we carefully compare the typhoon structures from the top to bottom in the middle panels in Fig. 3, It is easy to find out that after introducing a smaller vortex into NE quadrant the typhoon circulation does not always show the NE–SW direction asymmetric structure, and its asymmetric pattern irregularly involves with time. We have put forth the observational

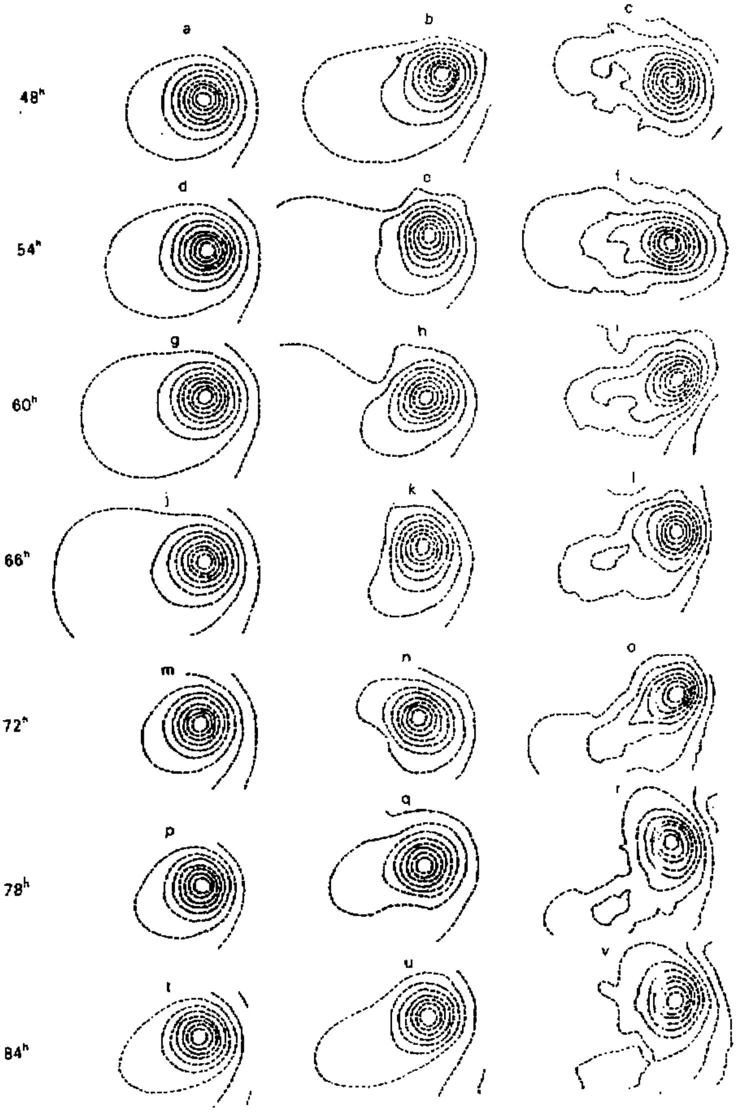

Fig. 3. Temporal evolution of the asymmetric structure of typhoons in experiments 1–3. The left panels for experiment 1; the middle panels for experiment 2; and the right panels for experiment 3.

and numerical evidence that the asymmetric structure of typhoons may affect their motion (Chen, 1991). The irregular variations of the asymmetric structure of the typhoon here are bound to induce the irregular changes in its motion direction and velocity, thus forming the oscillations deviated from the normal track. On these grounds, we preliminarily consider that the interaction of different scale vortices may be by way of changing the asymmetric structure of typhoons, then proceeding to cause oscillatory tracks.

After introducing a small scale vortex in NW quadrant (experiment 3; the right panels in Fig. 3), the evolution of asymmetric structure of the typhoon also differs widely from that in experiment 1. Among the seven right panels, there are also two showing a NE–SW direction asymmetric structure similar with experiment 1 (i.e. 60^h, Fig. 3i; 72^h, Fig. 3o). The difference between stream function fields at those two times is that the isolines in NE / SW quadrant are denser / looser in experiment 3 than in experiment 1, and therefore the stream function fields in Figs. 3i, 3o belong to the strong NE–SW direction asymmetry pattern. Correspondingly, the typhoon rapidly moves towards the northwest in the periods of $(60–66)^h$ and $(72–78)^h$ (Fig. 2b). At 48^h, the major axis of the typhoon vortex is not along the NE–SW direction, but turns to the NWW–SE direction (Fig. 3c). This is similar with the situation at 72^h in experiment 2 (Fig. 3n); at 78^h, the interior circulation of the typhoon also displays a NW–SE direction asymmetric structure. In correspondence to these two flow patterns the typhoon vortex suddenly slows down in the periods of $(48–54)^h$ and $(78–84)^h$ (Fig. 2b). At 54^h the isolines of stream function appear an east–dense–west–loose situation; in the interior region, the isolines are denser in SW quadrant and looser in NE quadrant (Fig. 3f). On the relevant track chart (Fig. 2b), the typhoon moves towards the NE direction. Thus it can be seen that after introducing a small vortex into NW quadrant, the evolution of the asymmetric structure of the typhoon in $(48–84)^h$ period also differs from the case of experiment 1, appearing the irregular variation of asymmetric structure, thus resulting in some irregular motions such as sometimes rapid advance; sometimes sudden deceleration; sometimes northwestward movement; sometimes northeastward movement. All those lead to the track oscillations shown in Fig. 2b.

It can be observed from the temporal evolution of flow patterns in the middle and right panels in Fig.3 that in the middle panels (experiment 2) flow patterns at 48^h, 60^h and 84^h are more or less the same, and the flow patterns at 54^h and 66^h are similar to each other; in the right panels (experiment 3), the flow patterns at 60^h and 66^h are similar to those respectively at 72^h and 78^h. Those can be looked upon as the reappearance of flow patterns after certain time intervals. Because the charts are plotted in 6 hour time interval, it is difficult to find out the accurate value of those time intervals. However, it can be estimated that they are within $(12–24)^h$, i.e. one day time scale. The reappearance of those flow patterns is only a local phenomenon in the temporal evolution of asymmetric structures, and the evolution process is still irregular on the whole.

IV. RESULTS AND DISCUSSIONS

The interaction of different scale systems is an important factor which affects the structure and motion of typhoons (Chen, 1985). There have been many studies on interactions between the subtropical high and the typhoon and between tropical cyclones. The problem of interactions between the small scale vortices and the typhoons has brought to meteorological forecastors' attention, and they tried to find out the forecasting criteria from characters of satellite cloud pictures. However the numerical studies on this problem are rarely seen so far. This paper uses a quasigeostrophic barotropical model, takes the typhoon circulation with a smaller scale vortex added to its different quadrants as the initial fields, and then traces the temporal evolution of those initial fields. By this way, the effect of the interaction of different scale vortices on the structure and motion of typhoons is investigated. Owing to that those smaller scale vortices correspond to the barotropically unstable mode, those vortices all grow with time. After more than 10 model hour integration,they start to influence the structure and track of typhoons.

On the basis of the results of the above five experiments, we preliminarily hold that under certain conditions, the interaction of different scale vortices is able to arouse the meandering oscillation track with the time scale of one day and the amplitude of 100 km; able to result in the deviations of the mean motion direction of typhoons from the normal tracks; and able to bring about the rapid movement and sudden deceleration of typhoons. The irregular temporal evolution of the asymmetric structure of typhoons, resulted from the interaction of different scale vortices, is the direct cause for the above oscillatory tracks.

The results in this paper also show that when a smaller scale vortex lies in different positions of a typhoon circulation, the effect of the interaction of different scale vortices on the structure and motion of the typhoon could be very different. This is benificial to the prediction of typhoon motion by using the satellite cloud picture data.

Generally,tropical disturbances of synoptic scale are barotropic and nondivergent, and therefore the quasigeostrophic barotropic nondivergent model is widely used to analyze the motion of typhoons (Holland and Lander, 1991; Chen and Williams, 1987). However, when the moisture condensation takes place in the typhoon circulation, a divergent term is required. The experience on numerical prediction suggests that the existence of this term may affect the velocity or even direction of typhoon motion. The physical process is not considered in this paper, so it is a limitation to be improved in future.

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