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Vortex dynamics in the studies of looping in tropical cyclone tracks

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Abstract

This paper proposes criteria for predicting the tendency of looping in tropical cyclone tracks using the approach of vortex dynamics. We model the asymmetric structure of a cyclone by a system of vortex patches. The evolution of such system of vortices is simulated by the method of contour dynamics. A new set of exact analytic formulas for contour dynamics calculations is derived, which is shown to be more computationally effective. Based on point-vortex models, we derive analytic formulas for the criteria of looping in a cyclone track. From numerical experiments, the simulated trajectories obtained from the point-vortex system and vortex patch system agree quite well. Hence, the looping criteria obtained from the point-vortex system can be applied by forecasters to stay alert for tendency of looping in a cyclone track. To demonstrate the applicability of the proposed criteria, the trajectory of Typhoon Yancy (9012), whose field data are available from "TCM-90", is simulated. The case study shows that the asymmetric structure similar to the pattern of a beta gyre is responsible for its recurvature when Yancy landed Fujian Province, China on 20 August 1990.

Keywords: Tropical cyclone; Anomalous track; Contour dynamics; Beta gyres; Asymmetric structure

1. Introduction

At present, we have been quite successful to certain extent in predicting the normal track of a tropical cyclone by remote sensing and numerical simulation. However, forecasters still hardly enhance the accuracy of forecasts beyond a certain limit (for instance, the average error of forecasting where the center of a tropical cyclone would be 24 h later is about 200 km), despite the arduous efforts in improving algorithms and increasing the resolution of simulation. Besides poor representation of initial data as there are not enough measurements to feed into the simulation models, and inadequate understanding of mechanisms such as cloud physics, the accuracies of cyclone forecasts may be much deteriorated by occasional occurrence of anomalous behaviors, whereby the cyclones alter their tracks and intensities all of a sudden. Such anomalous changes always render people

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in an entirely unprepared state and may lead to serious disasters. Hence, the understanding of the mechanisms for such anomalous tracks, even qualitatively, is of practical significance on avoidance of disasters (Holland and Elsberry, 1992).

Generally speaking, such anomalous tracks may be attributed to beta effects, topography influences, underlying surface conditions, existence of binary vortex system, interaction with other weather systems, etc., when the environmental steering flows are weak enough (Chen and Xu, 1992). In efforts for trying to gain insight into the genuine causes for unusual recurvature of typhoon motion, researchers have paid special attention to the asymmetry of the inner structure in a tropical cyclone. For example, Holland and Lander (1993) investigated a number of varieties of meandering tracks of tropical cyclones under different length scales, which range from a few to hundred kilometers; in particular, they analyzed the potential mechanisms of such meandering behaviors for storms of medium sizes. They showed that such meandering is always accompanied by some marked asymmetric evolution of tropical cyclones. Moreover, recent observations support the argument of the existence of a dipole circulation, which is commonly called the beta gyres, around the typhoon center (Gray, 1991). Fiorino and Elsberry (1989) and Li and Wang (1994) made careful studies on the beta gyres and beta drift by observing the interaction of a symmetric vortex with the existing environmental absolute potential vorticity gradient. The studies reveal the formation, evolution (growth or decay) and radial and azimuthal motions of the vortices, and the motion (propagation) of the principal symmetric vortex along ventilation flows. Using the above approaches, they explained different cyclone tracks within the framework of barotropic dynamics.

Vortices may be considered as "sinews and muscles" of fluid motion. Tropical cyclones are indeed vortices in the atmosphere and over the oceans. The studies of tropical cyclones by vortex dynamics can be traced back as early as the works of Yeh (1950) and Kuo (1969). They only regarded a tropical cyclone as an undeformable cylinder or a vortex patch in an imposed steering flow. In a recent work on aspects of vortex structure related to cyclone motion, Willoughby (1988) considered the path of a pair of rotating masses of sink and source in a stream flow. Further, recent numerical simulation of initially symmetric vortex imbedded in zonal flows predicts the distortion and development of vortices with different wave numbers (Williams and Chan, 1994). More recently, Holland and his collaborators (1993a–c; 1995a, b) performed thorough investigation on the motions of tropical cyclones using the vortex dynamics approach for both continuous and discrete vortex models. Also, Smith (1992) proposed an approximate theory to analyze vortex motions in a shear flow, and applied the theory to estimate the roles played by various convective processes in tropical cyclones, when the total wind field is appropriately decomposed into an axis-symmetric vortex, an asymmetric circulation and the environmental steering flows. Nevertheless, the theory has been applied only to situations with relatively weak shear. Other applications of vortex dynamics in cyclone studies can be found in the study of Fujiwhara effects for binary tropical cyclones (Chan, 1992) and the bogusing of initial flow fields by different vortex models (Leslie and Holland, 1992).

Not only a cyclone can be considered qualitatively as a mass of remarkably swirling vortex in the atmosphere, the pressure and tangential velocity profiles of a cyclone are quantitatively similar to that created by a vortex patch, or so-called Rankine vortex, when the Coriolis force is negligible in comparison to the pressure gradient and centrifugal force (Holland, 1980). Furthermore, observations by drop sonde data exhibit an apparent dipole structure consisting of a pair of cyclone and anticyclone gyre. This suggests that any tropical cyclone, either symmetric or asymmetric, can be suitably represented by a few vortex patches with constant values of vorticity. Although various discrete vortex methods are commonly used in hydrodynamics to investigate the nonlinear behaviors of vortex interaction, the method of contour dynamics initiated by Zabusky et al. (1979) has gained much popularity in the past decades as an effective tool for the numerical simulation of vortex interaction. Here, the system of vortex patches with constant vorticities in the above cyclone model allows the effective use of the method of contour dynamics. One may argue that the two-dimensional formulation appears to be a limitation to restrict the model to be in the framework of barotropic dynamics. However, if we only consider motions (rather than genesis) of a relatively slowly changing cyclone in a short period, the two-dimensional model is considered well acceptable. In addition, meterologists commonly regard barotropic models as a nice approximation since the main steering flows are usually at the middle layer of the non-divergent troposphere. Recently, some researchers have initiated studies on the influences of baroclinic effects, namely, environmental shear, vertical structure and degree of diabatic heating. They observed that the baroclinic structures may tilt the vortex, amplify or reduce the beta effects and speed up or slow down northwest movement of a typhoon (Holland and Wang, 1995). Nevertheless, such influences tend to be secondary. For this reason, the simulation of tropical cyclone tracks by barotropic models seem to be meaningful.

In this work, we attempt to reveal a feasible mechanism causing the anomalous track of a cyclone so that recurvature behavior of a tropical cyclone may be predicted. We employ the method of contour dynamics to analyze vortex interaction in the model. The paper is organized as follows. In the next section, we propose a new set of *exact* analytic formulas for contour dynamics calculations. After then, based on the point-vortex models, we derive analytic formulas for the criteria of *tendency of looping* in a cyclone track. The criteria depend on the ratio of the strengths of the principal vortex and the beta gyres and the magnitude of the steering flow. Next, we model the cyclone by a system of vortex patches with uniform vorticities and simulate the trajectories of the vortices by contour dynamics. Comparison of the trajectories obtained from the vortex-patch model and point-vortex model are made. Finally, as a case study, we examine qualitatively the looping tendency of Typhoon Yancy (9012) in light of the criteria proposed in this paper.

2. Analytic formulas for contour dynamics calculations

According to Pullin (1992), contour dynamics (CD) refers to the numerical solution of initial value problems for piecewise constant vorticity distributions by the Lagrangian method of calculating the evolution of the vorticity jumps, that is, the two-dimensional Euler equation is converted into the one-dimensional Lagrangian form. As explained in the last section, since a cyclone can be suitably represented by vortex patches, it appears that the motion of a tropical cyclone can be effectively simulated by CD. In the past decades, the techniques of CD have been much advanced. The improvements include tangential regularization (Zabusky and Overman, 1983), node replacement (Zou et al., 1988), and contour surgery (Dritschel, 1989), and they serve to overcome the difficulties which arise from the drastic distortion of the contours. A comprehensive review of the method of contour dynamics was written by Pullin (1992).

To simulate the evolution of steep-sided finite-area vortex patches in our cyclone model, we follow the Zabusky et al. (1979) CD method of solution for two-dimensional inviscid, incompressible fluids. Discrete nodes are placed along the circular contour surrounding a vortex patch so that the patch is approximated by a polygon with the nodes as vertices. Let (ξ_j, η_j), $j = 1, 2, \ldots, n$ denote the nodes and $P(x, y)$ be an arbitrary point in the flow field. Let K denote the uniform vorticity inside the vortex patch. The velocity components at $P(x, y)$ induced by the n-sided polygonal patch are given by

$$U(x,y) = -\frac{K}{2\pi}\iint_{\mathscr{D}} \frac{y-\eta}{(x-\xi)^2+(y-\eta)^2}\,\mathrm{d}\xi\,\mathrm{d}\eta, \tag{2.1a}$$

$$V(x,y) = \frac{K}{2\pi}\iint_{\mathscr{D}} \frac{x-\xi}{(x-\xi)^2+(y-\eta)^2}\,\mathrm{d}\xi\,\mathrm{d}\eta, \tag{2.1b}$$

where $\mathscr{D}$ denotes the polygonal domain approximating the patch. In the Zabusky et al. CD method, the above integrals are transformed into line integrals, which are then integrated *approximately*. However, following the conjugate complex variables formulation proposed by Kwok (1989) on calculation of the gravitational potential due to a two-dimensional mass anomaly, the above integrals can be evaluated *exactly*. The exact analytic formulas for evaluating induced velocities due to the polygonal vortex patch are

$$U(x,y) = \frac{K}{2\pi}\sum_{j=1}^{n}\left[S_j \ln\left|\frac{w_{j+1}}{w_j}\right| - C_j(\operatorname{Arg} w_{j+1} - \operatorname{Arg} w_j)\right], \tag{2.2a}$$

$$V(x,y) = -\frac{K}{2\pi}\sum_{j=1}^{n}\left[C_j \ln\left|\frac{w_{j+1}}{w_j}\right| + S_j(\operatorname{Arg} w_{j+1} - \operatorname{Arg} w_j)\right], \tag{2.2b}$$

where

$$|w_j| = \sqrt{(\xi_j - x)^2 + (\eta_j - y)^2}, \quad j = 1, 2, \ldots, n,$$

$$\operatorname{Arg} w_j = \tan^{-1}\frac{\eta_j - y}{\xi_j - x}, \quad j = 1, 2, \ldots, n,$$

$$C_j = \frac{[(\eta_{j+1} - \eta_j)(\xi_j - x) - (\xi_{j+1} - \xi_j)(\eta_j - y)](\xi_{j+1} - \xi_j)}{(\xi_{j+1} - \xi_j)^2 + (\eta_{j+1} - \eta_j)^2}, \quad j = 1, 2 \ldots, n,$$

$$S_j = \frac{[(\eta_{j+1} - \eta_j)(\xi_j - x) - (\xi_{j+1} - \xi_j)(\eta_j - y)](\eta_{j+1} - \eta_j)}{(\xi_{j+1} - \xi_j)^2 + (\eta_{j+1} - \eta_j)^2}, \quad j = 1, 2 \ldots, n.$$

Note that $\xi_{n+1} = \xi_1$ and $\eta_{n+1} = \eta_1$.

We have checked that numerical results obtained from the Zabusky et al. approximate formulas agree favorably well (with relative difference less than 0.01%) with the above exact formulas. Since the exact expressions are more concise, saving of computation time is obvious (about 30% saving in CPU time in numerical tests).

3. Criteria of looping derived from point-vortex models

As discussed in previous sections, an asymmetric tropical cyclone can be represented by a system of vortex patches. First, we consider a three-vortex system which consists of a principal vortex at the center and a pair of weaker vortices, which are of equal but opposite strength, on the left and the right sides. Such a configuration resembles a beta gyre. In this section, we assume them to be point vortices so that analytic solutions for their motions can be derived. The numerical simulation of the evolution of a system of vortex patches by CD will be discussed in the next section. Further, the vortices are convected by an underlying steering flow.

Here, two assumptions are made in the present model. First, the vortex patches are replaced by concentrated vortices. Such an approximation is acceptable when the patches are not too much deviated from the circular shapes. Second, the strengths of the secondary vortices are small compared to that of the principal vortex so that we can neglect the mutual interaction between the two secondary vortices.

For convenience, we assign the coordinate axes such that the initial position of the principal vortex is at $(0,0)$ and the secondary vortices are at $(-r,0)$ and $(r,0)$, respectively. Let the strengths of the principal vortex and the secondary vortices be $K_{\rm L}$ and $K_{\rm S}$, respectively, and define a small parameter $\varepsilon = K_{\rm S}/K_{\rm L} \ll 1$. Let (x,y) denote the position of the principal vortex and (x_j, y_j), $j = 1,\ 2$ denote the positions of the left and the right secondary vortices, respectively. Assume the underlying steering flow to be a function of y only, which is then denoted by $U(y)$. Define the complex quantities: $z = x + {\rm i}y$, $z_j = x_j + {\rm i}y_j$, $j = 1,\ 2$. Using complex variable notation, the governing equations for the motions of the vortices are

$$\frac{{\rm d}\bar{z}}{{\rm d}t} = \frac{K_{\rm S}}{2\pi{\rm i}}\left(\frac{1}{z - z_1} - \frac{1}{z - z_2}\right) + U(y), \tag{3.1a}$$

$$\frac{{\rm d}\bar{z}_1}{{\rm d}t} = \frac{K_{\rm L}}{2\pi{\rm i}}\left(\frac{1}{z_1 - z} - \varepsilon\frac{1}{z_1 - z_2}\right) + U(y_1), \tag{3.1b}$$

$$\frac{{\rm d}\bar{z}_2}{{\rm d}t} = \frac{K_{\rm L}}{2\pi{\rm i}}\left(\frac{1}{z_2 - z} - \varepsilon\frac{1}{z_2 - z_1}\right) + U(y_2), \tag{3.1c}$$

where a bar denotes complex conjugate and U is a real quantity. The $O(\varepsilon)$ terms in both Eqs. (3.1b) and (3.1c) represent the mutual interaction between the two secondary vortices. One can deduce that

$$\frac{{\rm d}\bar{z}}{{\rm d}t} = U(y) + \varepsilon\frac{{\rm d}}{{\rm d}t}(\bar{z}_2 - \bar{z}_1) + \varepsilon[U(y_1) - U(y_2)] + O(\varepsilon^2) \tag{3.2}$$

so that the zeroth-order approximation for z is given by $z(t) = U(0)t + O(\varepsilon)$. The zeroth-order approximation for z_1 is obtained by solving

$$\frac{{\rm d}}{{\rm d}t}[\bar{z}_1 - U(0)t] = \frac{K_{\rm L}}{2\pi{\rm i}}\frac{1}{z_1 - U(0)t} + [U(y_1) - U(0)] \tag{3.3}$$

and a similar equation for z_2. Now, we assume the steering flow to be uniform, that is, $U(y) = U_0$. In such a case, the last term in Eq. (3.3) vanishes so that Eq. (3.3) becomes integrable. The solution is given by

$$z_1(t) = -r{\rm e}^{{\rm i}\omega t} + U_0 t + O(\varepsilon), \tag{3.4a}$$

where $\omega = K_{\rm L}/2\pi r^2$ is the angular velocity of the motion. Similarly, we obtain

$$z_2(t) = r{\rm e}^{{\rm i}\omega t} + U_0 t + O(\varepsilon). \tag{3.4b}$$

To the first-order approximation, the solution for $z(t)$ is

$$z(t) = U_0 t + 2r\varepsilon(e^{i\omega t} - 1) + O(\varepsilon^2). \tag{3.4c}$$

The parametric representation of the curve traced by the principal vortex is then

$$x(t) = U_0 t + 2r\varepsilon(\cos\omega t - 1), \tag{3.5a}$$

$$y(t) = 2r\varepsilon \sin\omega t, \tag{3.5b}$$

which happen to be the defining equations for a trochoid. Here, it represents the curve traced by a point distant $2r\varepsilon$ from the center of a disc of radius $|U_0|/\omega$ rolling along a flat plane with angular velocity ω. When $|U_0| = 2r\varepsilon\omega = K_S/\pi r$, the curve reduces to a cycloid; otherwise, the trochoid is a snakelike or looping curve depending on $|U_0|$ being greater than or less than $K_S/\pi r$, respectively.

From the looping condition $|U_0| < K_S/\pi r$, the tendency of looping in a cyclone track is seen to increase with increasing strength of the secondary vortices, decreasing distance of separation between the vortices and decreasing velocity of steering flow.

We would like to remark that though a three-point vortex system in a uniform flow is still an integrable system (Aref, 1983), the corresponding full solution for Eqs. (3.1a)–(3.1c) without the above asymptotic approximation would appear to be analytically intractable for extracting a simple looping condition as what has been successfully done in the above.

In the above three-vortex system, we consider the influences of the two secondary vortices on the motion of the principal vortex, neglecting the mutual interaction between the secondary vortices. For a two-vortex system with a principal vortex and a secondary vortex, the derivation of the looping condition is similar. Indeed, the two-vortex system can be integrated exactly. Employing the same set of notations, the exact solution for the position of the principal vortex is

$$z(t) = U_0 t + r\varepsilon(e^{i\omega t} - 1). \tag{3.6}$$

Hence, the condition for looping to occur for a two-vortex system becomes $|U_0| < K_S/2\pi r$. The looping condition differs from the previous one by a factor of $\frac{1}{2}$ since we have only one secondary vortex influencing the principal vortex in a two-vortex system.

4. Numerical examples

In this section, we perform numerical simulation of the evolution of various systems of vortex patches by CD. We also compare the trajectories of the center of the principal vortex computed by CD and asymptotic/analytic formulas of point-vortex models, the purpose of which is to assess the accuracy of the point-vortex models and their asymptotic/analytic formulas. In the following numerical examples, the non-dimensional physical quantities used in the computation are

Length, L:	1000 km
Time, T:	24 h
Velocity, $V = L/T$:	41.67 km/h or 11.57 m/s
Vorticity, $\zeta = 1/T$:	0.0000115 1/s

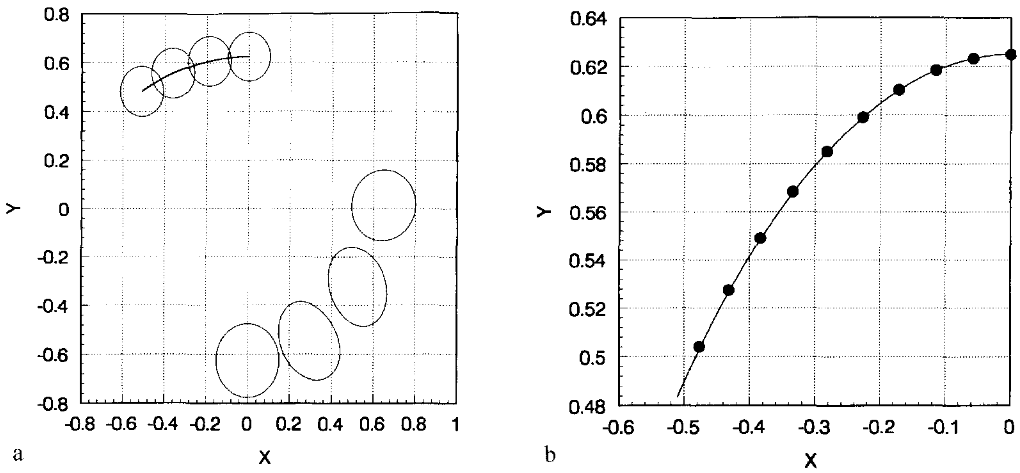


Fig. 1. (a) Interaction of a two-vortex system with the principal vortex of uniform vorticity $\zeta_L = 50.0$ and radius $R_L = 0.2$ and the secondary vortex of uniform vorticity $\zeta_S = 5.0$ and radius $R_S = 0.3$. The initial separation is $r = 1.25$. The trajectory of the center of the principal vortex is traced by the solid line. The strengths of the principal vortex and secondary vortex are given by $K_L = \pi R_L^2 \zeta_L$ and $K_S = \pi R_S^2 \zeta_S$, respectively. (b) Comparison of the trajectory of the center of the principal vortex (system in Fig. 1a) computed by CD (solid line) and analytic solution of the point-vortex model (line with circles).

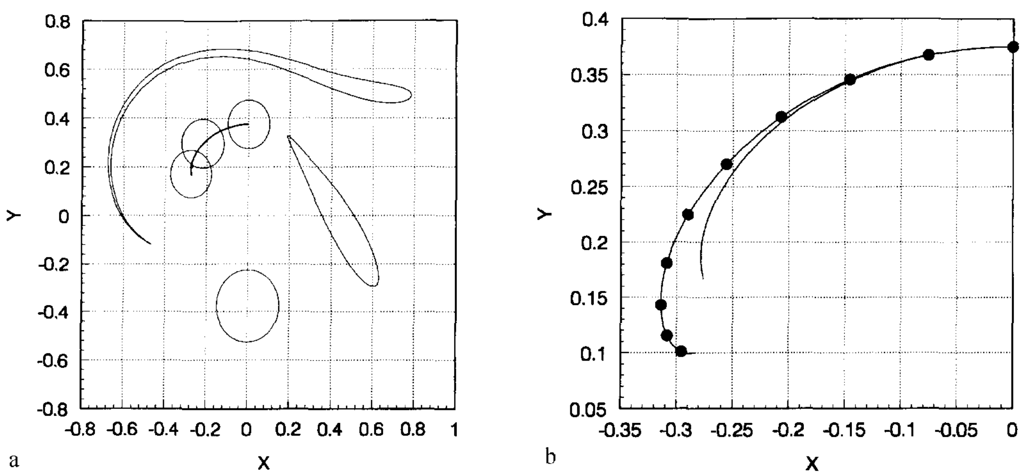


Fig. 2. Captions are the same as in Figs. 1a, 1b, respectively, except that the initial separation is now closer with $r = 0.75$.

The values of the above parameters are chosen within the range of values for conventional tropical cyclones. In both Figs. 1a and 2a, we show the evolution of the vortex patches in a two-vortex system. When the initial distance of separation is closer, we observe a drastic distortion of the secondary vortex (Fig. 2a). However, the agreement of the trajectories of the principal vortex computed by CD and analytic solution of the point-vortex model appears to be reasonably good (Figs. 1b and 2b). In Figs. 3a and 3b, we show the trajectories of the principal vortex under different uniform easteries flow in a two-vortex system when the secondary vortex is of opposite sign and same

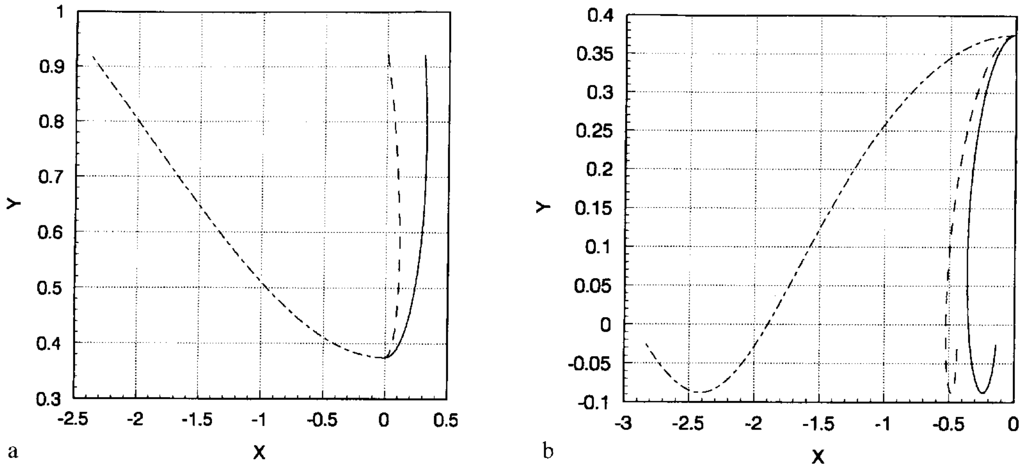


Fig. 3. (a) Comparison of the trajectories of the center of the principal vortex ($\zeta_L = 50.0$, $R_L = 0.2$) interacting with a secondary vortex of opposite sign ($\zeta_S = -10.0$, $R_S = 0.3$) under different uniform easteries flows (i) $U = -0.5$ (solid line), (ii) $U = -0.1$ (dotted line), (iii) $U = -0.05$ (dashed line). The initial separation is 0.75. (b) Same caption as in Fig. 3a, except the secondary vortex is of the same sign ($\zeta_S = 10.0$) as the principal vortex.

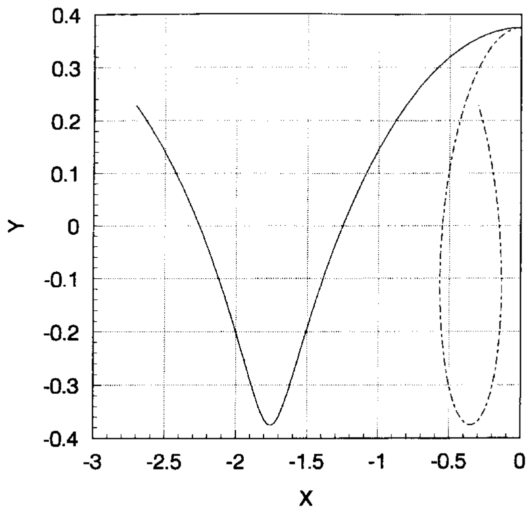


Fig. 4. Comparison of the trajectories of the center of a vortex ($\zeta = 50.0$, $R = 0.2$) interacting with another vortex of the same sign and same strength ($\zeta = 50.0$, $R = 0.2$) under different uniform easteries flows: (i) $U = -0.1$ (solid line), (ii) $U = -0.5$ (dotted line). The initial separation is 0.75.

sign, respectively. The two-vortex system in Fig. 4 contains two vortices of the same strength and same sign. We observe that looping trajectory occurs when the steering flow is weak ($U = -0.1$) and zig-zag trajectory occurs when the steering flow is strong ($U = -0.5$).

Finally, we simulate the evolution of a three-vortex system with no steering flow, as shown in Fig. 5a. We also compare the trajectory of the principal vortex using various methods: (i) the

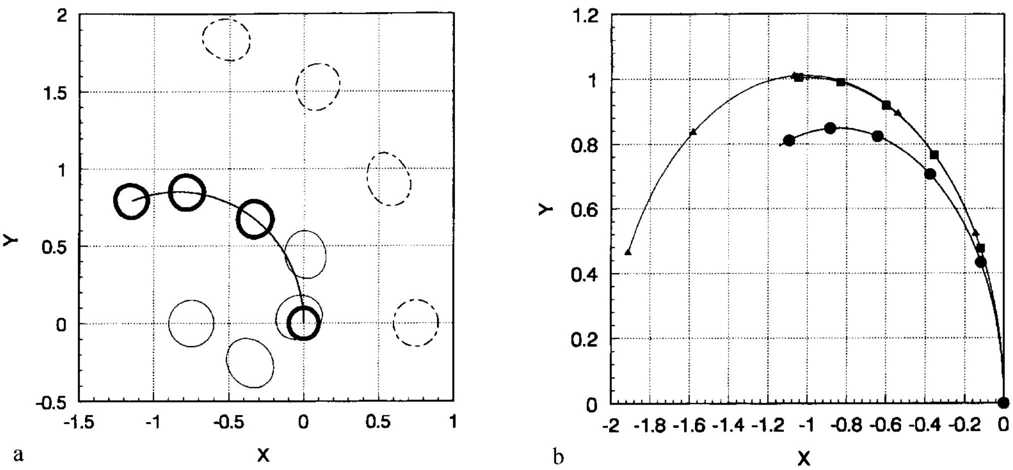


Fig. 5. (a) Interaction of a three-vortex system with no steering flow. The principal vortex (thick line) is of vorticity $\zeta_L = 50.0$, radius $R_L = 0.2$ and with initial position at (0, 0). The two secondary vortices are of opposite sign ($\zeta_{S1} = 15.0, \zeta_{S2} = -15.0, R_{S1} = R_{S2} = 0.3$) and with initial positions at (0.75, 0) and (−0.75, 0), respectively. The trajectory of the principal vortex is traced by the solid line. (b) Comparison of the trajectory of the center of the principal vortex (system in Fig. 5a) computed using (i) CD (line with circles), (ii) point-vortex model (line with triangles), (iii) asymptotic solution of point-vortex model (line with squares). The symbols on the lines represent the position of the principal vortex at regular time intervals.

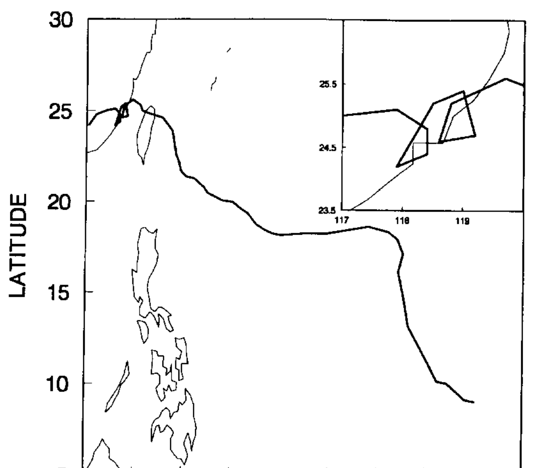


Fig. 6. Observed trajectories of Typhoon Yancy (9012) from 18 to 22 August 1990 (from Meterological Bureau, China). The inserted figure in the upper right corner shows in more detail the looping motion around the Fujian Province after its landing.

method of CD, (ii) the solution of the full set of equations for the corresponding point-vortex model (Eqs. (3.1a)–(3.1c)), (iii) asymptotic solution of the point vortex model (formula (3.4c)). These results are shown in Fig. 5b. We conclude that the agreement of the trajectory calculations is less promising for three-vortex systems, in comparison with that for two-vortex systems.

5. Case study: Typhoon Yancy (9012)

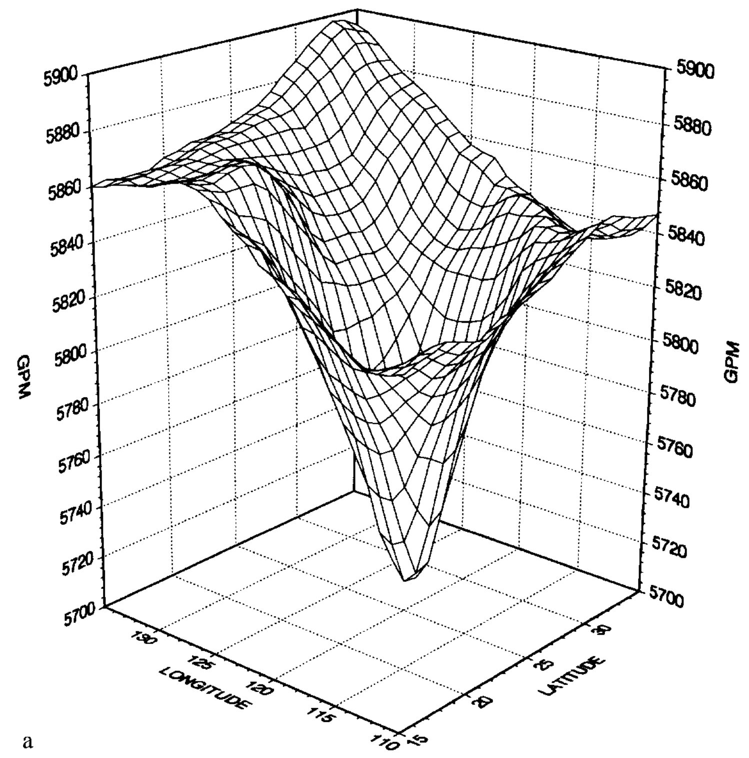
In this section, we perform a case study on Typhoon Yancy (9012) on its anomalous recurvature and apply the criteria presented in the previous section to predict at least qualitatively for such recurvature behavior. Typhoon Yancy has been chosen to be one of the seven target tropical cyclones of "SPECTRUM-90 "(Special Experiment Concerning Typhoon Recurvature and Unusual Movement) launched in 1990.

Yancy first emerged as a tropical depression on 11 August at 1200 km east–southeast of the Guam and was then intensified further into a tropical storm in the evening of 13 August around 630 km north–northeast of the Guam. Subsequently, it went through Taipei, Taiwai Strait, South China Sea and finally landed on the east coast of the Fujian Province, China. After lingering there for three days, Yancy ultimately weakened to a tropical depression again (see Fig. 6).

Due to the peculiar nature of its anomalous track, Typhoon Yancy has drawn interest from meterologists in the past few years, in particular, on the two anomalous behaviors during its life. The first event is its sudden turn to the north at 00 UTC on 18 August; another event is the looping motion around Fujian Province after its landing (Fang et al., 1991).

Here, we concentrate our study to the looping in Yancy's track. Meteorologists regard the internal asymmetry inside Yancy as the main cause for the looping of the typhoon. For instance, Niu et al. (1994) presented figures for the contour of the tangential component of the observed wind speed for the period from 00 UTC 20 August to 12 UTC, 22 August, which show asymmetric structure in flow field and anticlockwise rotation of its maximum contour. Furthermore, Yancy's vertical distribution in the troposhere (700–300 hpa) and outflow level (200 hpa) exhibited similar asymmetry behaviors. Zhu and Chen (1994) have also arrived at the same conclusion by comparing numerical simulations with or without considering typhoon's structure.

Our augument is based on the fact that around 00 UTC, 20 August, the typhoon gradually formed a flow field pattern which seemed to resemble a beta gyre and the steering current at that time happened to become weak enough. With such conditions, it is possible for the tropical cyclone to have a tendency to assume a looping track according to our criterion presented in Section 3. This is also a kind of dynamic rather than thermodynamic asymmetries in its inner structure. Figs 7a and 7b show the potential height and velocity vector field at middle level (500 hpa). Besides the principal vortex along the track of Yancy at (25.2°N, 120.6°E), a pair of vortices can be easily identified too. There are one cyclone to the northwest and another anticyclone to the southeast in the neighborhood of the typhoon center. On this occasion, weakening of the steering flow was due to the change of synoptic circulation: we observe that the subtropical high over the northwest Pacific broke into two cells, thus reducing the easterlies at its southern side to a great extent. It happened that Yancy was right in the saddle field as well. In order to estimate the steering flow quantitatively, we need a separation algorithm to separate these cyclones and anticyclones from the observed TCM-90 field data either by using the velocity component directly or using the data on potential height indirectly. In the present study, the latter method is preferred over the former to avoid inaccuracy due to numerical differentiation operation, whereby components due to cyclone or anticyclone were subtracted by making an average over the tangential components of wind speed at specified positions along the respective circles or ellipses within the influencing range of the cyclone or anticyclone. Hence, the method for potential height in a circular region suggested by Dong (in Wang et al., 1987) is extended in this study to that for the velocity field in a tilted elliptic region.



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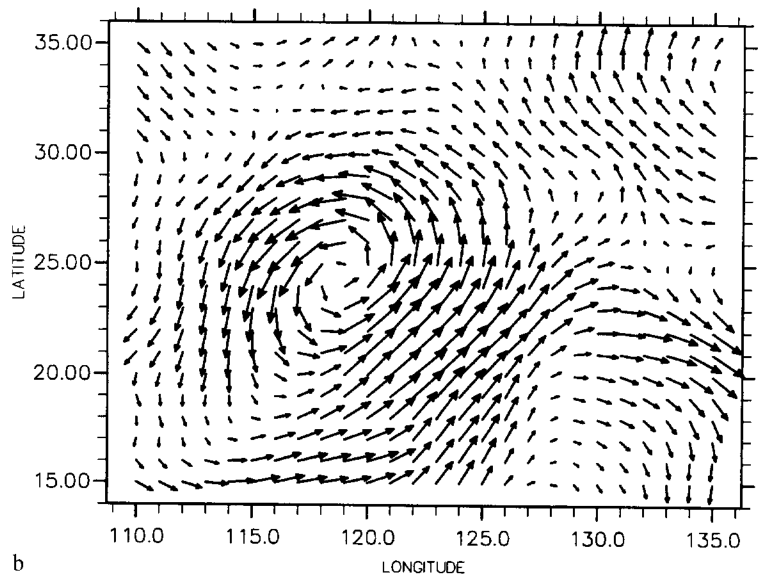

b

Fig. 7. (a) Observed potential height (GPM) of Typhoon Yancy (9012) at 00 UTC, 20 August 1990 (from TCM-90 field program). (b) Observed velocity plot of the same typhoon at the same time as that in Fig. 7a.

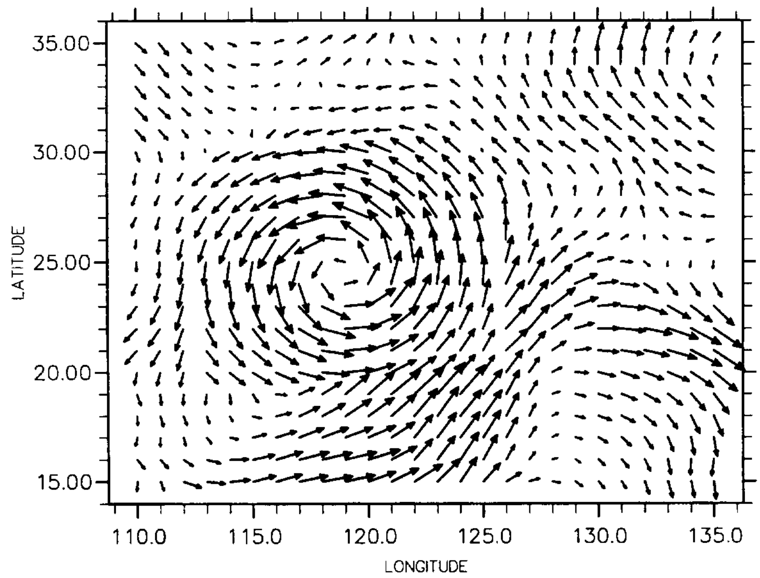

Fig. 8. Plot of the approximating initial velocity vector field adopted for the simulation of the trajectory of Typhoon Yancy.

This is accomplished by subtracting a velocity component which can be obtained by interpolation of this series of average values from the total observed field at each grid. The steering flow field can be written as

$$V(r)_{\text{steer}} = V(r)_{\text{obs}} - \sum_{n=1}^{N} V_{\text{ave}}^{(n)}(r)\,\hat{t}^{(n)}, \tag{5.1}$$

where $V_{\text{ave}}^{(n)}(r)$ is the magnitude of average velocity and $\hat{t}^{(n)}$ is the unit tangential vector of the nth cyclone or anticyclone. The number N represents the total number of influencing cyclones and anticyclones in the region. As expected, we find that the flow field at 00 UTC, August 20 is sufficiently weak (the averages of u, v components are less than 0.1) and has no definite direction. As a check, an experiment to obtain the composite flow field by superposing the steering flow on top of the cyclones and anticyclones is carried out (see Fig. 8). We observe that the composite field is indeed a good approximation of the observed field which serves as an additional confidence on our separation algorithm. When calculating the steering flow by (5.1), a concurrent by-product is the velocity profile as a function of radius r (see Fig. 9) of the respective cyclones and anticyclones, which can be used to determine the respective radius and strength of the vortex patches. Now the motion of Yancy in an averaged steering flow of $u = -0.091$ and $v = -0.062$ can be simulated by CD with data actually based on the observed field (as listed in Table 1):

The numerical simulation of Yancy's motion around landing in the Fujian Province by the above three-vortex system by CD shows that the simulated trajectory of Yancy indeed exhibits a looping (simulated location shifted about one degree to the north of the actual looping position) and the second recurvature tendency (see Fig. 10). Hence, we conclude that the present method based on

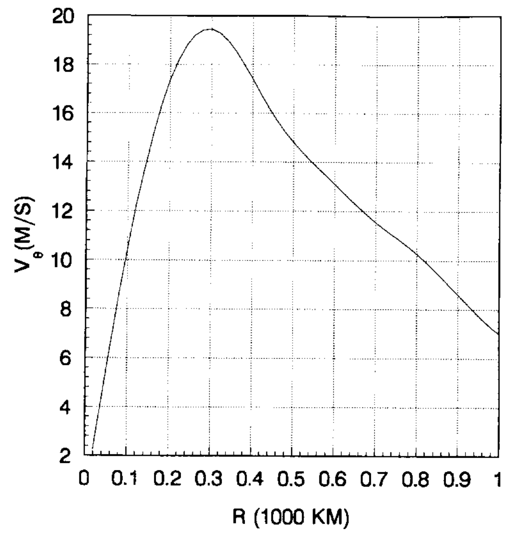

Fig. 9. Profile of the tangential velocity component of the radially symmetric cyclone (principal vortex) used in the simulation, which is obtained from averaging of observed cyclone centered at (25.2°N, 120.6°E) from data in Fig. 7b.

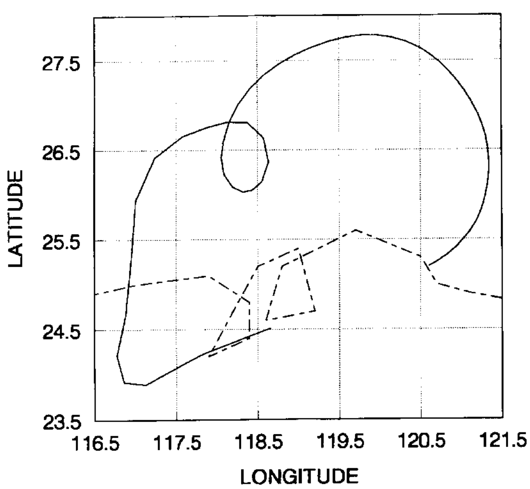

Fig. 10. Illustration of the looping trajectory of Typhoon Yancy from CD simulation. The simulated looping trajectory is shown by a solid line while the actual observed trajectory is shown by a dashed line.

Table 1
Strengths, sizes and locations of the principal and secondary vortices adopted for the simulation of looping in Typhoon Yancy's track

	Vorticity	Radius	Location
Principal vortex	11.2	0.3	(25.2°N, 120.6°E)
Secondary vortex 1	7.0	0.2	(32.0°N, 116°E)
Secondary vortex 2	−7.0	0.2	(12.9°N, 128.2°E)

CD in vortex dynamics is capable of predicting anomalous track (looping) due to asymmetry in inner structure qualitatively.

6. Discussion and conclusion

Forecasting the course of typhoons is extremely difficult as mentioned in the introduction. Modern weather forecasting relies on complicated computer models of the atmosphere. Meteorologists feed in up-to-the-minute measurements of temperature, air pressure, wind direction and the like. The model's mathematical formulas calculate how these factors interact to influence the weather, and produce a forecast of how a particular weather system will evolve. The present study was undertaken to investigate the possibility to forecast the looping in tropical cyclone tracks under certain weather condition without prohibitive cost in computing time.

First we have shown that though the point-vortex theory is merely a simplified model, the results of numerical simulation of a system of vortex patches showed that the qualitative behaviors of their tracks computed using the exact theory or CD agree reasonably well with that obtained by the approximated point-vortex model. Hence, the looping criteria obtained analytically from the point-vortex system can be easily used by meteorologists to make judgement whether recurvature or looping motion may occur. Evidently, such criteria are of significance to cyclone forecasters which enable them to stay alert for possible looping to occur.

Secondly, the looping trajectory of Typhoon Yancy (9012) with asymmetric structure is simulated by using CD with the steering flow whose input data are based on the observed field. The qualitative agreement between the observed track and the simulated one shows that it is a promising approach if the observed data are available instantly during typhoon's motion. One may consider to incorporate the present criterion for looping into existing numerical codes.

Finally, we would like to emphasize that the mechanisms leading to an anomalous track for a tropical cyclone are rather complicated. Hence, a comprehensive analysis of various factors when making operational forecasting is absolutely necessary.

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