On the interaction of tropical-cyclone-scale vortices. III: Continuous barotropic vortices

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Summary

The interaction of cyclonic vortices in spherical geometry is investigated using a shallow-water model on an adaptive grid. It is found that the mutual approach and merger of binary cyclones support the compound vortex-patch findings of Part II. As interaction commences, distortion of the weak outer vorticity fields leads to a change in the advecting flow over each vortex core, which leads to mutual approach or retreat depending on the shape of the vorticity fields. Rapid merger occurs when the cyclone cores approach within the critical separation distance defined in Part II.

The core merger of cyclones seems to be largely independent of the environment and the rotation of the earth. The initial approach can be quite sensitive, however. Non-merging binary cyclones sweep equatorial parcels of air over long trajectories towards the pole to create exceptionally strong anticyclonic gyres. These can be of sufficient strength to capture the nearest cyclone and induce the escape mode described in Part I. Some sensitivity to latitude (and hence strength of the earth-vorticity gradient), therefore, is found. A large anticyclone in a subtropical ridge location is found to be sheared and torn apart by the interacting cyclones, with little effect on merger.

The observations in Part I that interactions of three cyclones could be broken down into separate binary interaction sequences is supported by experiments with three vortices. When two of the vortices merge, the interaction evolves to a small/large cyclone situation. When no merger occurs, each pair of cyclones proceeds through a distinctive orbit/escape cycle.

1. Introduction

This paper extends the two-dimensional theoretical examination of the observational findings in Part I (Lander and Holland 1993) and those of Holland and Lander (1992). In Part II (Ritchie and Holland 1993) a contour-dynamics method was used to examine merging and non-merging vortex patches of various sizes and intensities. This study supported earlier work that showed that the bifurcation between merging and non-merging vortices occurs at a well defined separation distance, which is a function of vortex size and intensity. Small-scale track meanders also were found to be superimposed on the orbits of interacting cyclones, and arose from vortex asymmetries occurring from the mutual interaction.

We now examine the effects of introducing continuous vortices into a field of varying earth-vorticity gradient. We are particularly concerned with testing the more general applicability of the merger mechanisms that were isolated using the vortex-patch analysis. We also investigate potential mechanisms for the escape mode described in Part I.

The vortex structure and numerical model are described in the following section. The numerical experiments are summarized in Table 1. Two pairs of interacting vortices are examined in section 3, with separation distances designed to provide conditions under which the vortices merge and remain separate. These are compared with the findings in Part II. In section 4 we utilize two experiments with three interacting vortices to examine the effects of environmental features, and for comparison with the study of tropical cyclones Pat, Ruby and Odessa in Part I; potential escape-mode mechanisms identified in Part I are also described. A discussion of the major findings from the overall study is given in section 5.

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2. Method

(a) Vortex profiles

The tropical-cyclone profiles defined by Holland (1980) were used to derive the initial vortex structure in all numerical experiments. The radial profile of the perturbation geopotential is given by

$$\phi = \phi_c (1 - e^{-(r/r_m)^b})$$

(1)

where $\phi_c$ is the maximum geopotential perturbation, $r$ is the radius, $r_m$ is the radius of maximum winds and $b$ is a scaling parameter that was set to 1.5 for this study. The corresponding wind profile is found from the gradient-wind relation, and for a cyclonic circulation

$$v = \left( \frac{br_m^b \phi_c}{r^b} e^{-(r/r_m)^b} + \frac{r^2 f^2}{4} \right) - \frac{rf}{2}$$

(2)

where $f$ is the Coriolis parameter.

Radial profiles of azimuthal wind and relative vorticity for the cyclonic and anticyclonic vortices used in this study are shown in Fig. 1.

(b) Numerical model

Multiple-vortex interaction is difficult to handle numerically as both a large computational domain and very high resolution over the vortices are required. The large domain avoids contamination by the artificial lateral boundary conditions (Shapiro and Ooyama 1990). As shown in Part II (see also Carr and Williams (1990) and Smith et al. (1990)), the vortex interaction process involves the development of a very fine structure, with marked filamentation of the vortices due to the strongly sheared horizontal flow fields. These problems are overcome by use of the somewhat unconventional numerical techniques described in Dietachmayer (1992).

The numerical model consists of the shallow-water equations in the form:

$$\frac{du}{dt} - \left( f + \frac{u \tan \theta}{a} \right) v + \frac{1}{a \cos \theta} \frac{\partial \phi}{\partial \lambda} = 0$$

$$\frac{dv}{dt} + \left( f + \frac{u \tan \theta}{a} \right) u + \frac{1}{a \cos \theta} \frac{\partial \phi}{\partial \theta} = 0$$

$$\frac{d\phi}{dt} + \frac{\phi}{a \cos \theta} \left( \frac{\partial u}{\partial \lambda} + \frac{\partial v \cos \theta}{\partial \theta} \right) = 0$$

(3)

(Bates 1984), where $a$ is the radius of the earth, $\theta$ is latitude, $\lambda$ is longitude, $u$, $v$ are the zonal and meridional components of fluid motion, and $\phi$ is the geopotential height of the fluid layer. The geopotential field for each experiment consists of a 4.2 km deep background state with superimposed vortices as given by Eq. (1). This fluid depth and the latitude range used here result in a Rossby deformation radius of approximately 2000 km.

Numerical integration utilizes the continuous dynamic grid-adaption technique first adapted for meteorological applications by Dietachmayer and Droegemeier (1992). The objective of the grid adaptation is to improve the accuracy of numerical solutions of partial differential equations by the use of non-uniform grids which have higher local resolution in regions of interest where detailed information is required. Conceptually,
the procedure is related to the well known technique of grid-stretching, but its power lies in its ability to determine an appropriate spatial distribution of grid points automatically, and to update this distribution in response to changes in the evolving numerical solution.

Application of the technique is facilitated by transforming the governing equations from physical space, in which the grid is non-uniform, non-orthogonal, and for which the individual grid points are in continuous motion, to computational space, which, by definition, has both a regular and stationary distribution of grid points. A user-defined 'weight function', $W(\lambda, \theta; t)$, is introduced to provide a quantitative guide as to the desired distribution of grid points; high local weight-function values require maximization of grid resolution in that region, and zero weight indicates that a sparse allocation of grid points is sufficient. A 'grid generator' algorithm is used to distribute the grid points in response to the weight function. In the current work the weight function is defined as a linear combination of the magnitude of the geopotential perturbation and the square of the wind speed. It is thus loosely related to the total energy of the flow. The presence of both potential- and kinetic-energy terms ensures that grid resolution is enhanced in the core of the vortices, as well as in the surrounding regions of strong winds. (An example is shown in Fig. 2(b)).

One advantage of the grid-adaptation approach in the current application is that no changes to the model are required in dealing with one, two or three vortices; indeed the number of vortices (and hence the number of zones of high resolution) may vary even within a single experiment (as is the case in vortex merger). Traditional nested models, with separate, high-resolution grids for each vortex, for example, would experience some difficulty in the vortex-merger case, as this would require the merging, in some sense, of two previously independent grids.
Model efficiency is further enhanced by the use of an operator-splitting technique to deal with the slow (advective) and fast (inertia-gravity) modes separately (see, for example, Gadd 1978). Most spatial derivatives are approximated using fourth-order differences, with the exception of the advection terms which are approximated by fifth-order upwind differencing. The high-order upwind scheme has considerably better phase-properties than its even-order counterparts. The associated increased level of dissipation has little or no disadvantage in practice as it is so scale-selective that it impacts on the solution little more than many of the filters that are currently used to control noise in centred-difference models.

The boundary conditions consist of a low-order radiation condition, together with a strongly damped time-stepping scheme in the near vicinity to help control noise (Dietachmayer 1992). These conditions perform moderately well, the major difficulty being that the vortices tend to introduce parallel flow at some parts of the boundaries and this violates the normal flow assumption implicit in the radiation boundary conditions. Fortunately, the implementation of the grid-adaptation technique has enabled us to use very large computational domains and thus avoid much of the impact of boundary-condition errors. Several experiments were conducted with boundaries at various distances to ensure that minimal contamination occurred in the regions of interest for this study.

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The configuration shows, schematically, the relative distances between the cyclonic vortices, shown $. ‘A’ represents an anticyclonic vortex.

3. Interactions of two cyclonic vortices

(a) Previous studies

The interaction of two cyclonic vortices in a barotropic model has been studied by Chang (1983, 1984), DeMaria and Chan (1984), and in a comprehensive series of experiments by Wang and Zhu (1989a, b, 1992a, b, 1993). The conclusion from these studies is that each vortex is advected cyclonically by the swirling flow from the other system. Further, that the movement of each vortex is affected by the magnitude and sign of the vorticity gradient from the other system across the vortex core. On an f-plane, when each vortex is placed in a region where the relative-vorticity gradient is cyclonic towards the other centre, the pair spiral on a converging path until merger occurs. When the relative-vorticity gradient is cyclonic away from the centre, the vortices diverge; and in regions of zero gradient, they rotate steadily at a constant radius. Wang and Zhu also show that including a variable earth vorticity can introduce some changes in the degree of mutual approach of the vortex centres. These changes can be related directly to the total vorticity gradient.
(b) Vortex merger: Experiment CC5

The initial configuration for experiment CC5 consisted of two cyclonic vortices of equal strength located 550 km apart at 20°S (Table 1, Fig. 2(a)). This separation distance placed each vortex centre close to the zero relative-vorticity gradient of the other (Fig. 1).

Figure 2. Initial conditions for experiment CC5: (a) relative-vorticity contour (maximum $1.7 \times 10^{-3} \text{s}^{-1}$), (b) grid for the numerical model after adaptation, weighted by the perturbation height and kinetic energy.

The vortex tracks (Fig. 3(a)) consisted of a south-westward drift with mutual cyclonic rotation as the vortices approached then merged. In centroid-relative coordinates (Fig. 3(b)) the vortices approached with an increasing rate of rotation and convergence until very rapid merger occurred between 21 and 22 hours of integration. Superimposed on the smooth tracks in Fig. 3 were a series of cyclonic oscillations of period around 6 hours and amplitude of the scale of the eye diameter. Thus, as noted in Part II, the interaction of two systems can be expected to produce high-frequency oscillation superimposed on the mutual orbit.

Figure 3. Motion of the vorticity centres in experiment CC5: (a) actual trajectories, (b) centroid-relative motion. Hourly vortex positions are marked on (b).
At 12 and 18 hours (Fig. 4) the cores of both vortices retained their basic symmetric shape, though trailing spirals of cyclonic vorticity had developed in the outer regions. Merger was well developed by 24 hours, and by 30 hours a new, stable vortex configuration had emerged in the shape of a Kirchoff ellipse (Kirchoff 1876). This composite vortex subsequently returned to a circular shape and continued to move poleward and westward.

![Diagram](image)

Figure 4. Six-hourly evolution of the relative-vorticity field from 12–30 hours for experiment CCS. The white dots indicate the cores of the original vortices.

Most of the merger process occurred in the three-hour period from 21–24 hours (Fig. 5) and involved substantial distortion of the original vortices. At 21 hours the vortices became flattened and began to slide past each other. Substantial amounts of fluid with cyclonic vorticity was being lost to filamentation in the spiralling wake. The two vortices merged at 23 hours and the quasi-stable Kirchoff ellipse had emerged by 25 hours. The remnants of the cores of the original two vortex cores also retained a separate identity and orbited within the core of the new composite vortex.

We compare the merger of these continuous vortices with that of the compound vortex patches in Part II by examining the shearing deformation of a set of concentric circles at constant vorticity for one of the vortex pair (Fig. 6(a)). After 6 hours integration (Fig. 6(b)), the outer vorticity lines have been strongly distorted and wrapped around
the second vortex. A trailing vortex filament has started to form and the cores of both vortices are virtually unchanged. This field is nearly identical to that for the compound vortices in the third panel of Fig. 10 in Part II.

Notice that the cores of the continuous vortices maintain their basic shape until a few hours before merger (Figs. 4 and 5). The final merger occurs rapidly as the cores distort and slide towards and along each other, then roll up to form the loci of a Kirchoff ellipse with trailing vortex filaments. Again this is closely analogous to the vortex-patch findings in Part II. Using Eq. (5) of Part II, and assuming an equivalent patch radius for the continuous vortices of 100 km (Fig. 1), a critical separation of around 350 km is indicated before merger of the cores can be accomplished by mutual distortion. This correctly predicts the barotropic modelling results here (Figs. 4 and 5).

Figure 6. Evolution of concentric circles representing constant vorticity lines for one vortex in experiment CC5 for comparison with the compound vortex-patch results in Part II: (a) initial condition, (b) after 6 hours integration. The two smallest circles indicate the core of each vortex.
The structure of the composite vortex is indicated by the cross-sections of vorticity, winds and height in Figs. 7(c), (d) and (e), which were taken through the remnant cores of the original vortices at 27 hours (Fig. 7(a)). Because of the weakly divergent nature of the model used, relative vorticity is approximately conserved in the merger process, and the results are quite similar to those for the merging vortex patches discussed in Part II. The area of the composite vortex has approximately doubled from that of each of the original vortices. As a consequence, the maximum winds have increased by approximately 40% to 70 m s\(^{-1}\) at a mean radius of 125 km, and a secondary wind maximum has developed in association with the spiral vortex filament. This secondary wind maximum and most of the asymmetric structure of interest is barely noticeable in the height field (Figs. 7(b) and (e)).

Figure 7. Experiment CC5 at 27 hours: (a) relative-vorticity field, (b) height field, and cross-sections along the line in (a) of: (c) relative vorticity, (d) wind speed, (e) height.

The above observations lead to a modified model of vortex merger which blends the findings of Part II with those of DeMaria and Chan (1984) and Wang and Zhu (1989a, b). We start with two continuous vortices at larger than the critical core separation distance of Part II, but within the influence or each other’s outer cyclonic vorticity gradient (Fig. 1). Initially, the rotational stiffness of each core is sufficient to withstand the imposed strain (Fig. 4 at 12 and 18 hours), but the strain on the outside edge of each vortex causes marked distortion. This outer region distortion brings a radial advection over the vortex cores and causes them to move along a converging path* (Fig. 3(b)). The strain on each

* Note that although qualitatively similar, this mechanism is quite different to the 'beta gyre' generation of Fiorino and Elsberry (1989), in which there is no distortion of the background vorticity gradient.
vortex core increases as they approach, and eventually exceeds the critical value described in Part II. At this time the two cores rapidly distort and merge to form a new composite vortex (Fig. 5). This merger is faster than that observed in the discrete patches. We suggest that this is due to the progressive distortion that is occurring on the edge of the continuous vortex. All of the merging-vortex experiments conducted by us resulted in broad agreement with the above model.

The earth-vorticity gradient seems to have had negligible effect on the above merger, other than to induce a poleward and westward drift on the overall system. Additional model experiments, where we kept the vortex circulations constant but varied the background earth-vorticity gradient from 10° latitude to 30° latitude, produced nearly identical tracks to those in Fig. 3. When the other vortex profiles were tried, however, the earth-vorticity gradient was found to inhibit merger. Marked sensitivity was found in some cases, so that identical vortices which merged at 30° latitude tended to diverge at 10° latitude. The major cause seemed to be that the earth term tends to dominate the weak relative-vorticity gradients in the outer regions of tropical cyclones, especially in low latitudes. However, a detailed analysis has not been made at this stage.

(c) Non-merging vortices: Experiment CC10

Experiment CC10 consisted of two cyclonic vortices, named Russ and Bob for convenience, initially located 1100 km apart but with all other parameters the same as in CC5 (Table 1). The tracks (Fig. 8) consisted of weakly diverging cyclonic orbit for the first 48 hours, followed by a rapid change to sharply diverging anticyclonic relative

Figure 8. Tracks of the vorticity centres in experiment CC10, superimposed on the residual winds, derived by removal of the initial vortex structure, at 24, 48 and 72 hours, together with the centroid-relative motion. The vortices are named Bob and Russ for ease of identification.
motion. This motion is remarkably similar to the orbit and escape sequence discussed in Part I.

The deformation of concentric circles surrounding one vortex (Fig. 9) indicates that the initial vortex interaction closely followed that of the compound vortices shown as Fig. 9 in Part II, for the first 24 hours or so. The longer-term evolution is quite different, however. Regions of anticyclonic and cyclonic relative vorticity soon develop to the east and west, respectively, of the cyclone pair by the differential advection of earth vorticity. The resulting wind gyres (Fig. 8) tend to move Russ poleward faster than Bob and contribute to the weakly divergent relative motion. As the vortices move into a meridional alignment, increased advection of earth vorticity from Bob causes the anticyclonic gyre to intensify and lag behind Russ (Fig. 8, 48 hours). The flow across the centre of Russ associated with this gyre approaches the magnitude of that from the outer circulation of Bob. Russ, therefore, turns and moves around the gyre. As Bob and Russ diverge, the gyre circulation dominates, so that escape of the two vortices from their captured orbit is rapidly accomplished (Fig. 8, 72 hours). In section 4(b) the mechanisms contributing to the formation of the gyre are discussed for the more general case.

Figure 9. Evolution of concentric circles representing constant vorticity lines for one vortex in experiment CC10 for comparison with the compound vortex-patch results in Part II: (a) initial condition, (b) after 24 hours integration. The two smallest circles indicate the core of each vortex.

4. THREE-VORTEX INTERACTION

The previous two experiments indicated that the superimposed gradient of earth vorticity affected both the merger and non-merger modes of binary cyclone interaction. Escape of the two non-merging cyclones, in particular, was due entirely to the nonlinear interactions between the vortices and the background vorticity field. Here we examine the effects of other systems in the vicinity of the binary cyclones by introducing an additional vortex.

(a) Two cyclonic, one anticyclonic vortex: Experiments CCA10 and CCAS

Tropical cyclones are often moving in the vicinity of an anticyclone and the potential interactions are investigated by the addition of an idealized subtropical anticyclone directly poleward of the eastern-most cyclone (Experiments CCA10 and CCAS in Table 1). For the anticyclone we used the same analytic profile as the cyclonic vortices, but with 10% of the intensity and a radius of maximum winds of 550 km (Fig. 1). For ease of discussion, we identify the two cyclonic vortices as Bill and Chip.

Experiment CCA10. The original anticyclone (A in Fig. 10) was sheared and moved rapidly westwards ahead of the approaching Chip to become caught up in the circulation
surrounding Bill. A more intense anticyclonic gyre (G) developed on the poleward and eastern side of the cyclone pair.

The complex interactions that lead to both the shearing of the original anticyclone and the generation of the dominant anticyclonic gyre are illustrated by the sets of particle trajectories in Fig. 11. Forward trajectories from a grid of points lying across the anticyclone (Fig. 11(a)) clearly show that the system was rapidly sheared by the outer circulation of the approaching cyclones. The equatorward half was advected westward then equatorward around Bill (Fig. 10). The remainder of the anticyclone literally disintegrated, with some parts being advected eastward, then equatorward around the developing gyre.

An indication of the complexities of formation of the large gyre (G in Fig. 10) and the sharp vorticity gradient to its south-east is provided by the trajectories in Fig. 11(b). The source for the gyre was relatively anticyclonic equatorial fluid that had been advected over a long trajectory around both Bill and Chip. Local fluid advected into close proximity to these equatorial parcels provided the sharp vorticity gradients in Fig. 10 and also the strong winds needed to provide the means of escape of Chip from the interaction with Bill. A similar process occurred during the interactions of Bob and Russ (section 3(c)).

Trajectories of parcels initially in the near vicinity of the cyclones (Fig. 11(c)) clearly show that parcels within a few hundred kilometres of each vortex centre remain trapped there. These parcels execute many orbits of the cyclone and provide a means of maintenance of the symmetric core (Carr and Williams 1990; Shapiro and Ooyama 1990; Smith et al. 1990). Parcels in the near vicinity, however, have quite complex trajectories, in which they execute large cycloidal loops or escape the influence of the vortex.
Figure 11. Parcel trajectories for experiment CCA10: (a) forward trajectories showing the destruction of the anticyclone (A in Fig. 10), (b) backward trajectories showing the equatorial source for fluid in the developing anticyclonic gyre (G in Fig. 10), (c) forward trajectories indicating the complex interactions in the vicinity of the two cyclones.

The westward extension of a subtropical ridge that often causes significant forecast problems could be occurring, therefore, from shearing associated with the outer circulation of an approaching typhoon. Differential advection of earth vorticity by the typhoon could also be responsible for the development of a stronger anticyclone (G in Fig. 10), which ultimately captures the typhoon. Importantly, including a weak anticyclone made virtually no difference to the vortex escape mechanism described in section 3(b) for experiment CC10. The same sequence of steady cyclonic orbit followed by rapid escape was observed and the final residual wind-field was very similar to that for experiment CC10 (Fig. 8), but displaced slightly westward. The implication is that large, intense cyclones, such as used here, will dominate nearby subtropical anticyclones, at least from a barotropic perspective. Further, the presence of reasonable-amplitude anticyclones in the environment may not necessarily have a significant influence on the orbit/escape model described in Part I.
Experiment CCA5. With the addition of a weak anticyclone, the merging vortex pair moved on a much more westward trajectory, but no significant differences were found from the merger processes described in section 3(b) for experiment CC5; the cyclonic pair merged within a few hours after 21 hours integration. However, the environmental changes that occurred were quite different to those which were found in experiment CCA10 above.

Because of the rapid coalescence of the two cyclones, the anticyclone was not caught up in the strong shearing flow associated with Chip (Fig. 10). As a result, it distorted only gradually (Fig. 12) and continued to influence the net motion of the cyclone pair whilst moving slowly westward and being reinforced from advection of earth vorticity by the circulation associated with the merging vortices.

Figure 12. Relative-vorticity field for experiment CCA5 at 0 and 24 hours (contour interval $5 \times 10^{-5}$ s$^{-1}$).

(b) Three cyclonic vortices; Experiment CCC10

Several experiments were conducted with three cyclonic vortices of equal size and intensity to investigate the potential interactions that can occur, following the analysis in Part I. As with the two-vortex experiments, the major features arose from two basic configurations in which two of the vortices were initially sufficiently close to merge, or in which initial interaction followed by escape occurred.

The interaction of three cyclonic vortices, Joanne, Peggy and Liz from experiment CCC10 (Table 1), produced the meandering paths shown in Fig. 13(a). Breaking these down into a series of centroid-relative binary interactions (Figs. 13(c), (d) and (e)) produced the characteristic interaction and escape sequence as described in Part I for tropical cyclones Pat, Ruby and Odessa. As with the two-vortex interaction discussed in previous sections, the sequence consisted of a long period of mutual interaction and cyclonic orbit followed by a rapid escape. In this experiment, the escape of binary pairs occurred at different times.

The basic mechanisms of both interaction and escape for Joanne and Peggy were the same as for the two-vortex experiment (Fig. 8). Trajectory analyses (not shown) indicated that the development of G1 (Fig. 14) resulted from equatorial fluid moving around the two cyclones in a similar manner to that shown in Fig. 11(b). The sharp anticyclonic turning of Peggy’s track during the escape mode (Fig. 13) followed the development of this gyre in a very similar manner to that for both Russ (Fig. 8) and Chip (Fig. 10).
Figure 13. (a) Tracks of cyclonic vortices Joanne, Peggy and Liz from experiment CCC10, together with centroid-relative tracks of: (b) all three vortices, (c) Joanne and Peggy, (d) Peggy and Liz, (e) Joanne and Liz.

Figure 14. After 72-hours integration, fields of: (a) relative vorticity (contour interval $5 \times 10^{-6}$ s$^{-1}$), and (b) residual flow after removal of the cyclonic vortices (maximum vector length 23 m s$^{-1}$). Gyres G1 and G2 are indicated and the vortex tracks are superimposed on (b).

Because the third vortex (Liz) was very intense, it did not experience the shearing that occurred for the weaker anticyclone described in section 4(a). Instead the circulation associated with all three cyclones brought equatorial fluid from just east of Peggy over an extended poleward trajectory to produce an intense second anticyclonic gyre (G2 in Fig. 14). This intensifying gyre ultimately captured Liz, which diverged rapidly away from the other cyclones.
5. CONCLUDING DISCUSSION

This paper concludes our initial examination of the interaction between mesoscale vortices and tropical cyclones. The topics covered have included the impact of mesoscale circulations on the meandering motion of tropical cyclones (Holland and Lander 1993), and in this series: the observed interaction between tropical cyclones in Part I (Lander and Holland 1993), and in Parts II and III an examination of the manner in which barotropic vortices interact, using vortex patches (Ritchie and Holland 1993) and continuous vortices (this paper).

(a) Summary

We have shown in Part I that the classical Fujiwhara (1921) model for binary tropical cyclones of cyclonic orbit, mutual approach and merger, rarely, if ever, applies. Our modified model (Part I, Fig. 8) consists of several quasi-stable states, consisting of mutual approach, orbit, and merger or escape. The changes between these states tend to be very rapid, occurring in a few hours. The same model was shown to apply to all combinations of two vortices during interaction of three typhoons, and to the interaction of swarms of mesoscale vortices that did not reach tropical-cyclone strength. It was noted that merger normally occurred by the dominance of one system and the loss of convection and shearing destruction of the other.

The investigations of barotropic vortex interactions in Part II and in this paper have indicated potential mechanisms involved in the observed cyclone interactions. Discrete vortices, which approximate the core structure of tropical cyclones, exhibit a critical separation distance inside which merger occurs rapidly, and outside which merger never occurs. Merger occurs by rapid distortion of the vortices, which move towards each other by mutual advection, and amalgamate whilst trailing one or more vortex filaments. Equal vortices initially form a quasi-stable Kirchoff ellipse, with the original vortex centres at each focus. Generally, however, one vortex dominates and the other is sheared horizontally on to a long spiral that wraps around the dominant system. In either case, the composite vortex gradually adjusts back to a symmetric vortex, which is larger, and has a stronger circulation, than either of the original systems, and often is surrounded by a tangle of vortex filaments.

The attraction of two vortex patches during merger resulted entirely from changing advection as the vortices became distorted. The experiments described in Part II contained no net environmental convergence, the vortex patches were not touching, and there were no gradients of vorticity apart from the discontinuity at the edge of each vortex. Thus the boundary-layer convergence mechanism proposed by Chang (1983) and the propagation of vorticity gradients discussed by DeMaria and Chan (1984) are not essential for cyclonic vortices to approach each other and to merge. Further, the spiral vortex filaments move outward from the composite-vortex core entirely by advection. The presence of these spirals and their observed movement raises interesting questions on the mechanisms responsible for the development and movement of spiral bands in tropical cyclones.

Order-of-magnitude calculations in Part II and the modelling experiments in this paper have indicated that tropical cyclones must approach to within at least 300 km of each other before their cores can merge by the above mechanisms. Experiments with interacting vortices of different sizes and intensities indicate that merger will normally occur by shearing destruction of one vortex whilst the other retains much of its original identity. This finding supports the observations in Part I that merger normally occurred by loss of identity of one system. We note, however, that although baroclinic and
convective processes may be important, they are not essential to produce the observed interaction.

Tropical cyclones consist of a central core of very strong vorticity surrounded by a weaker, but not insignificant, field of vorticity. Our analysis of piecewise continuous vortex patches in Part II and the full modelling studies in this paper suggest that the initial attraction of vortices outside the critical separation arises from distortion of the weak vorticity field in their outer circulation. This supports the findings by DeMaria and Chan (1984) with two important qualifications. First, the approach of the two vortices results from the mutual distortion of the vorticity fields that produces a changed advective motion over each vortex. Thus this is a different process to the generation of the 'beta gyres' arising from rotation across a gradient of earth vorticity. Second, the gradients at the vortex centre do not necessarily define the ultimate motion. The mutual advection and distortion of asymmetric vortices can produce a range of behaviours.

The imposition of an earth-vorticity gradient or nearby environmental features, such as another tropical cyclone or a large anticyclone, can have a marked impact on the type of vortex interaction that will occur. For example, the mutual approach of two cyclones due to distortion of their outer-region vorticity fields can be substantially affected by surrounding systems, and a stronger earth-vorticity gradient generally inhibits approach. In this paper, we showed that the dynamical development of anticyclonic cells (also called beta gyres) to the east of a group of interacting cyclones is enhanced by the resulting long poleward-trajectory air parcels. The anticyclone developed sufficient intensity to capture one of the interacting cyclones in a manner which compared very well with the escape mode found in Part I. These experiments indicate the importance and complications of dynamical interactions between the cyclone and its environment in defining the track. For example, an anticyclone placed on the poleward side of non-merging cyclones was sheared apart and had little impact on the overall binary interaction, dynamical anticyclone development and escape mode. For merging cyclones the same anticyclone remained intact and was reinforced by the dynamical development. We find that external influences have a minor effect once core merger commences.

Using the terminology from Part I, the binary tropical-cyclone interaction and associated dynamical developments are able to reproduce many of the observed features of approach, merger and escape. The capture component has not been adequately explained, however. It may be due to the effects of an evolving environment, such as the movement of one cyclone into a strongly sheared westerly flow as noted in Part I. Changes of intensity and size of the tropical cyclones may also be important. More work is needed, however, especially to quantify the rapidity of the capture process.

We have shown in this paper that the interaction of binary tropical cyclones can induce both cyclonic and anticyclonic track meanders. In Holland and Lander (1993) we found that the large-amplitude sinusoidal and looping motion of typhoon Sarah (1989) could be attributed to formation and direct interaction of mesoscale convective complexes within the cyclonic circulation. This has been supported by experiments in Part II which showed that the amplitude and period of the meanders scaled linearly with the relative size and intensity of the cyclone and secondary vortex.

Three important results from this paper and from Part II indicate potential mechanisms for the long-lived, small-scale oscillation of some tropical cyclones. First, a smaller and weaker system than the main vortex will be stretched out into a thin spiral, which may continue to affect the vortex motion long after it would be impossible to detect using current observing methods. Thus a small perturbation in the tropical-cyclone circulation may produce longer-lived oscillations of the cyclone centre than would a larger perturbation, which will tend to merge with the cyclone to form a new composite system.
INTERACTION OF VORTICES. III

Second, vortex distortion associated with the interaction of binary tropical cyclones, or similar large-amplitude systems, may induce small-scale meanders superimposed on the mutual orbit. Third, interactions of a tropical cyclone with a nearby large, weak vortex (such as a monsoon trough) produces a complex motion consisting of different scale meanders as the weak vortex is wound up around the more intense cyclone.

(b) Further questions

The studies summarized above have identified several important mechanisms that contribute to the meandering motion of tropical cyclones, and to the interactions that occur between tropical-cyclone-scale vortices. Several questions have arisen, including the potential influence of more realistic environments, the effects of vertical structure, the contributions of the above mechanisms to the development of spiral bands in tropical cyclones, the potential for mesoscale vortices in convectively active regions (as shown in Part I) to contribute to the cyclogenesis process, and our capacity to observe and predict the relevant mechanisms. These aspects are currently being studied and will be reported at a later date.

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