

On the interaction of tropical-cyclone-scale vortices. I: Observations

By MARK LANDER¹ and GREG J. HOLLAND*²

¹*University of Guam, Guam and* ²*Bureau of Meteorology Research Centre, Australia*

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SUMMARY

A detailed analysis is made of the observed behaviour of interacting, tropical-cyclone-scale vortices in the western North Pacific region. It is found that all multiple-vortex interactions can be broken down into a common model of binary interaction. The classical Fujiwhara model of converging cyclonic rotation about a centroid followed by merger is rarely followed. Capture tends to occur rapidly, within several hours, and is followed by a period of relatively stable cyclonic orbit. Cyclone merger occurs by one vortex experiencing a loss of convective organization, followed by strong horizontal shearing and incorporation into the outer circulation of the other vortex. However, a substantial proportion of interacting cyclones escape from the interaction, and the changeover from a stable orbiting configuration occurs rapidly. A modified model of binary interaction is presented.

Cases where swarms of mesoscale vortices are formed in convectively active regions without tropical cyclones are also documented. These vortices have a much narrower range of influence (a few hundred kilometres) than that observed for tropical cyclones. When groups of vortices come within this range they are observed to conform to the same interaction model as observed for tropical cyclones.

1. INTRODUCTION

Interacting tropical cyclones have been of interest to weather forecasters for much of this century, partly because they are so easily observed and partly because of the inherent difficulty in forecasting their tracks. For example, Brand (1970) and Jarrell *et al.* (1978) found significant increases in forecast errors whenever two or more tropical cyclones were present. Such interactions are also of considerable research interest since they provide a relatively easily observable example of interacting atmospheric vortices.

Dong and Neumann (1983) presented comprehensive statistics on the interaction of binary tropical cyclones for the 36-year period 1946–1981. They indicated that, on average, binary-cyclone interaction occurs 1.5 times per year over the western North Pacific and 0.33 times per year over the Atlantic. The higher frequency over the western North Pacific was attributed to the greater number of tropical cyclones there (25 per year compared with 10 per year in the North Atlantic) and to differences in the character of the mean surface wind in each basin. The western North Pacific is dominated by a large monsoonal trough, which can spawn both tropical cyclones and several other types of mesoscale vortices, such as tropical depressions. A further climatological feature of this region is the Tropical Upper Tropospheric Trough, or TUTT (Sadler 1976), which can contain mesoscale cyclonic cells that interact with tropical cyclones. As a result, we consider that the frequency of tropical-cyclone interactions with surrounding mesoscale vortices is substantially higher than the purely binary-cyclone figures quoted by Dong and Neumann.

In a separate paper (Holland and Lander 1993) we investigated the meandering motion of tropical-cyclone tracks. Our conclusions were that the observed medium-scale meanders (period > 1 day and amplitude > 50 km) could not be explained by the earlier theories of Yeh (1950), Kuo (1950, 1969) and Syono (1955). We showed, using a detailed case study, that mesoscale vortices associated with convective complexes within the cyclone circulation, or vertically tilted circulations, could explain the observed behaviour.

* Corresponding author: Bureau of Meteorology Research Centre, PO Box 1289K, Melbourne, VIC 3001, Australia.

We hypothesized that the observed meander of many tropical cyclones would be due to such interactions.

Our aim in this paper is both to extend the work of Holland and Lander by examining the observed behaviour of interacting tropical cyclones and other mesoscale vortices and to provide an observational basis for the theoretical studies in the companion papers (Parts II and III) by Ritchie and Holland (1993) and Holland and Dietachmayer (1993) respectively. Several case studies of interacting systems in the western North Pacific are used to provide an indication of the types of interactions that occur. We first discuss the available data and our methodology in section 2. The interaction between relatively isolated binary tropical cyclones forms a major part of this paper and is presented in section 3; particular emphasis is given to the modes of capture, to differentiating types of interactions and to the modes of escape. In section 4 we consider the behaviour of three interacting tropical cyclones. We then examine in section 5 the mutual interactions that occur between members of two swarms of mesoscale vortices that develop from the convective activity in an active monsoon shear zone. Our findings are summarized in section 6.

2. DATA AND METHOD

(a) *Data sources*

We chose to concentrate our analysis on western North Pacific storms, because of the higher frequency of binary cyclone interaction there (Dong and Neumann 1983) and because of the enhanced interest in this region as a result of the recent international field experiments (Elsberry 1990). Tropical-cyclone data were obtained from a best-track archive of all tropical cyclones from 1945–1988 edited and collated at the Joint Typhoon Warning Center (JTWC), Guam, by J. Martin and J. Pickle (1990, personal communication). The best-track archive contains the position and intensity for each tropical cyclone at 6-hourly intervals. It is compiled from a subjective reanalysis of each cyclone based upon all available fix information, and is smoothed to a varying degree. This information, as well as the raw fixes, error statistics, official forecasts, and brief synoptic descriptions for each storm, is published in the *Annual tropical cyclone report**.

Synoptic data (e.g. surface and upper-air reports) were obtained from several sources:

- (i) Six-hourly hand-plotted surface charts of the North Pacific basin prepared at the National Weather Service Forecast Office, Honolulu;
- (ii) Twelve-hourly objective surface and upper-air analyses over the tropical domain archived at the Australian Bureau of Meteorology;
- (iii) Twelve-hourly hand-plotted and hand-analysed surface and 200 mb charts prepared operationally at the JTWC;
- (iv) Geostationary and polar-orbiting satellite visible and infrared imagery;
- (v) Individual storm folders from the JTWC which contain reconnaissance data, all official forecasts and aids, satellite fix reports, and a varied mix of relevant synoptic reports; and
- (vi) Narrative summaries of tropical depressions (regions of persistent organized convection with diameters ranging from 200–600 km and having a non-frontal migratory character) from the JTWC.

* Available from the Director, JTWC, COMNAV MARIANAS Box 12, FPO San Francisco, CA 96630-2926, USA.

These data, most of which are archived at the University of Hawaii, form a comprehensive research data base for the study of tropical cyclones in the western North Pacific.

The archives contain no objective information on the outer circulation of tropical cyclones, which is of considerable importance for the type of interactions that occur. As discussed by Weatherford and Gray (1988), there is little relationship between tropical-cyclone intensity and its outer circulation, so that intensity alone is not a good indicator of interaction potential. Hence, we relied on subjective judgment, based on available analyses, to estimate the scale of the outer circulation when needed.

(b) Method

The choice of an appropriate reference frame within which certain properties can be highlighted is important in the study of the behaviour of interacting tropical vortices. The best reference frame is that fixed to the centroid, weighted by the outer circulation strength of each vortex, which corresponds to the 'centre of mass' used by Haurwitz (1951) in an analogue to the astronomical many-body problem. Unfortunately, it is not possible to compute objectively the net circulation of the cyclones used in this study because of data limitations and the lack of a unique separation of environment and cyclone (Holland and Evans 1992). For general discussion, therefore, we use an unweighted approximation to the centroid defined by the average coordinates of each vortex. This average position was determined manually from storm tracks plotted on a Mercator projection map. The effects of different circulations are discussed in specific cases only.

3. BINARY TROPICAL CYCLONES

(a) Background

The interaction of binary tropical cyclones is generally referred to as the Fujiwhara effect after the pioneering laboratory and observational studies of Fujiwhara (1921, 1923, 1931). Fujiwhara demonstrated that the relative motion of two adjacent cyclonic vortices was composed of cyclonic orbit around their centroid, coupled with a mutual attraction. The rate of orbit steadily increases as the vortices spiral inward towards one another and eventually the two vortices coalesce into one vortex located at the centroid, which is the attractor for this system (for example, see Fig. 1(a)).

Dong and Neumann (1983) compiled statistics on the behaviour of tropical cyclones undergoing binary interaction. They defined binary interaction as the occurrence of two named tropical cyclones which co-existed for at least 48 hours during which time they approached within at least 13° latitude (1450 km) of great-circle distance and attained at least tropical-storm intensity. The separation criterion was based on other studies by Brand (1970), which showed that mutual interaction tended to dominate when storms approached within this distance. Brand further noted that mutual orbiting tended to commence suddenly. Dong and Neumann found that 70% of the binary tropical cyclones they studied continuously orbited one another in a cyclonic sense and with a speed of rotation that varied inversely with separation distance. Decreasing separation distance with time was noted in about 60% of those storms that were initially separated by less than 8° latitude (900 km). Several marked exceptions were found, however. Some cyclones orbited anticyclonically, even at quite small separation distances, and many cyclones did not converge towards each other. These cases were attributed to the dominating effect of the storm environment.

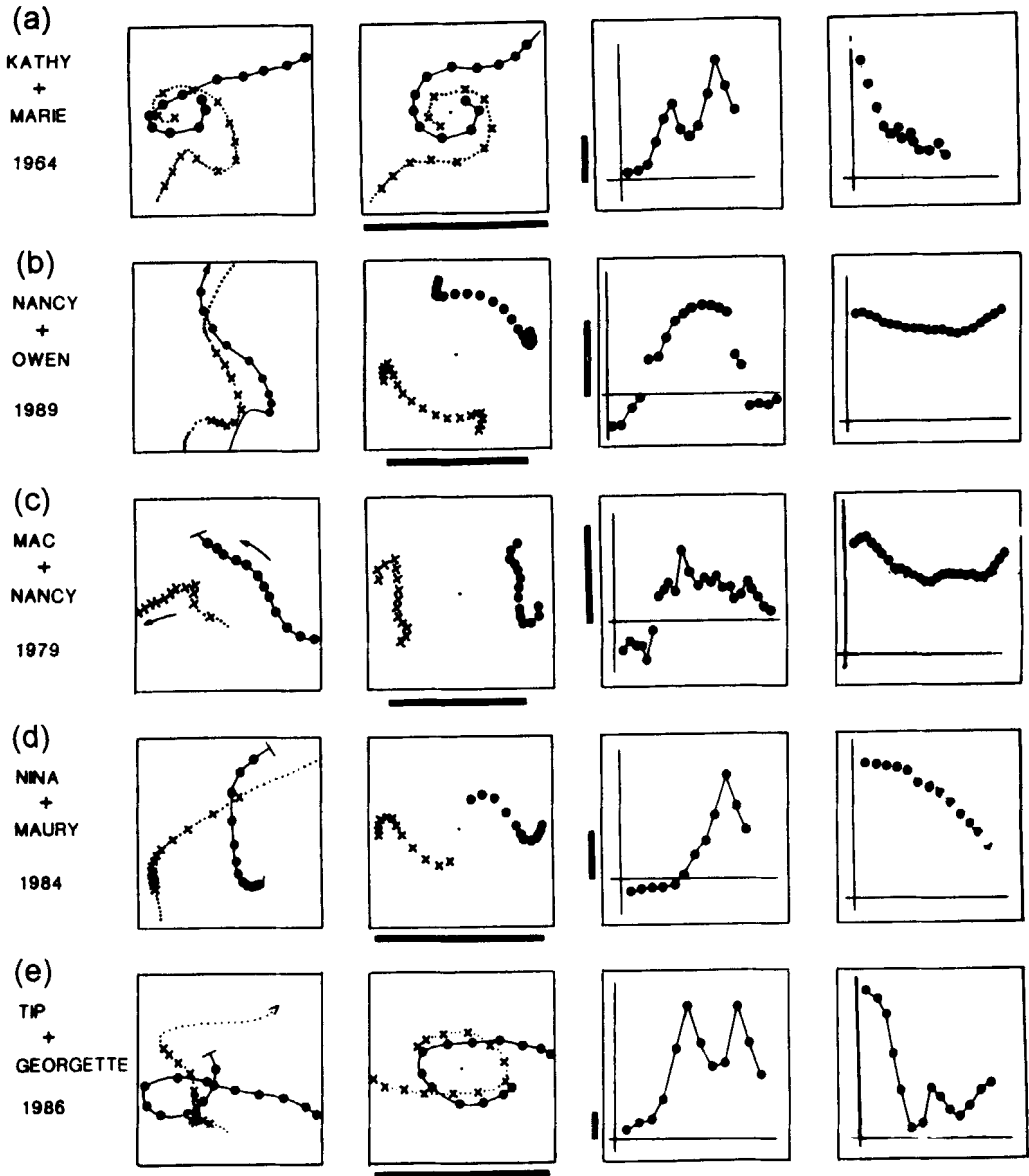


Figure 1. Summary of the binary interaction of ten tropical cyclone pairs from the western North Pacific. The cyclone names and year of occurrence are indicated on the far left; cyclone tracks are shown in the left panels, centroid-relative motion is indicated in the centre left panels, and the time change of orbital rate and separation distance are provided in the two right-hand panels, respectively. Each dot represents a 6-hourly time step and the scale is varied to emphasise relevant features. Horizontal and vertical bars represent 1000 km and 1° per hour rotation, respectively.

(b) Characteristic features

The ten cyclone pairs examined in this study were selected on the basis of their undergoing a clear and unambiguous period of mutual interaction. Their tracks and centroid-relative motion are summarized in Fig. 1, together with variations of orbital speed and separation distance.

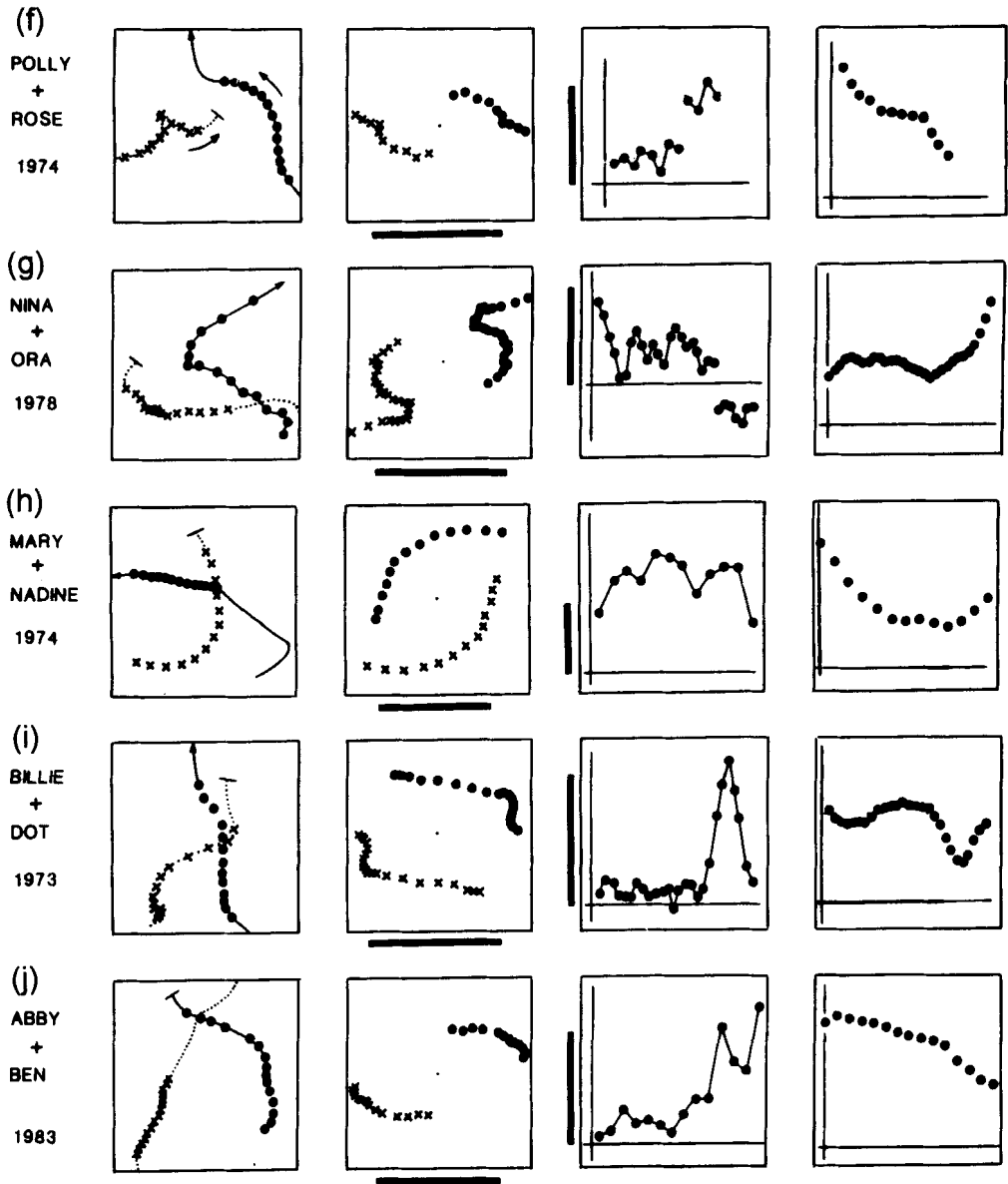


Figure 1. Continued.

Dong and Neumann used the example of tropical cyclones Kathy and Marie (Fig. 1(a)) as exhibiting classical Fujiwhara behaviour. However, most interacting cyclones deviate considerably from this idealized model, as is summarized in Fig. 1. The characteristic features are discussed below under the general headings of Approach and capture, Mutual orbit, Merger, and Escape.

Approach and capture. Most pairs of binary tropical cyclones are initially located too far apart to manifest a mutual cyclonic orbit. At first they approach toward the centroid before a mutual orbit sets in, as indicated by cyclones Kathy and Marie (Fig. 1(a)). Often the initial approach is accompanied by centroid-relative anticyclonic rotation (Figs. 1(b),(c),(d)). The rate of convergence of the two systems during this approach

phase is often faster than that which occurs once a steady cyclonic orbit is established (right panels of Figs. 1(a),(c)).

The mutual capture of the two cyclones is usually manifested as a sudden increase in angular rate of orbit, as has been noted previously by Brand (1970). The centre panels of Fig. 1 clearly show that capture typically occurs in less than 12 hours. Such rapid commencement of binary motion is not always apparent in geographical coordinates, however. For example, the centroid-relative motion of tropical cyclones Polly and Rose (Fig. 1(f)) contained an initial direct approach then a sharp change to cyclonic orbit, and this was readily apparent in the tracks (Fig. 2(a)). By contrast, the more marked onset of binary interaction between tropical cyclones Nancy and Owen (Fig. 1(b)) was not marked by any sharp changes in Owen's track (Fig. 2(b)).

Mutual orbit. The average duration of cyclonic orbit for the cyclones in Fig. 1 was 89 hours and was accompanied by 100° of angular rotation around the centroid. Considerable variation was observed, however. Some storms orbit for less than one day while others orbit for several days, particularly those that merge. For example, tropical cyclones Kathy and Marie (Fig. 1(a)) orbited through 360° during a period of five days.

The idealized Fujiwhara signature of an uninterrupted cyclonic orbit along an inward-spiralling path around the centroid is rarely achieved. Even the archetypal example of cyclones Kathy and Marie experienced marked cyclic fluctuations in their orbit rate (Fig. 1(a)). Some centroid-relative orbits are straight lines (Fig. 1(i)). Although the separation distance between interacting tropical cyclones generally decreases (Dong and Neumann 1983), in some cases it remains constant (Fig. 1(c)) whilst the cyclones clearly interact with one another. Dong and Neumann also found that some cyclones in close proximity orbit anticyclonically. These systems are strongly influenced by other factors and are not included in our analysis.

The interaction of tropical cyclones with different circulations is illustrated by Tip and Georgette (Fig. 1(e)). The cyclonic loop executed by Georgette was much larger than that for Tip, and the path of the centroid between Tip and Georgette executed a cycloidal loop (Fig. 3). Although this centroid motion could have occurred from other, synoptic, influences, it is most likely that it is due to the unweighted centroid not being the true centre of rotation for these cyclones. The path of a new reference centroid weighted in proportion to the observed intensities of the cyclones contains a smaller cycloidal loop than was executed by the unweighted centroid. A complete removal of the cycloidal loop required a reference centre with a weighting of seven to one in favour of Tip (Fig. 3). This indicates that Tip was approximately seven times more 'massive' than Georgette in the sense defined by Haurwitz (1951). Tip was more intense (maximum winds 30 m s^{-1}) and discernibly larger than Georgette (maximum winds 15 m s^{-1}) during their two-day period of mutual interaction. Since Georgette also experienced marked vertical shearing and loss of deep core convection during this period (not shown), the seven-fold weighting in favour of Tip is quite reasonable.

Merger. Coalescence of two tropical cyclones into a single cyclone located at the centroid has not been observed by us; the minimum separation distance found by Dong and Neumann (1983) was 180 km. Rather, merger typically occurs when one member of the interacting pair decays and loses its identity as it nears the centre of its companion. This decay typically occurs quite rapidly.

Escape. The escape of two interacting tropical cyclones typically occurs as abruptly as was found for capture. For example, with Nancy and Owen (Fig. 1(b)) a relatively long period of mutual rotation was interrupted in less than 12 hours. The centroid-relative paths of escaping cyclones are often straight outwards and some have a tendency for anticyclonic orbit (Figs. 1(b),(c),(g)).

All of the escape sequences in Fig. 1 occurred as a sharp bifurcation. The remainder either merged or made landfall. The rate of separation is on average much greater than the slow rate of approach seen during the orbit phase, and often is faster than the rate of initial approach.

One of the major escape modes occurs when the interacting pair move sufficiently poleward to come under the influence of the mid-latitude westerly airstream. This was observed in approximately half of the cases analysed here. The large majority of the remaining interacting storms also move steadily polewards during their lifetime, but their escape mechanisms are complex and difficult to identify from synoptic charts. Potential mechanisms are identified in Part III (Holland and Dietachmayer 1993).

(c) Discussion

The characteristic features of the interaction of the binary tropical cyclones that we have examined are contained in the tracks of Kathy and Marie (Fig. 1(a)) and Nancy and Owen (Figs. 1(b) and 2(b)). For those cyclones that develop more than 1400 km from each other the initial interaction consists of a direct approach then rapid capture during just a few hours. This is followed by a period of cyclonic orbit around the centroid of the cyclone pair, during which time the rate of approach typically decreases, or ceases, and oscillations in rotation rate occur. Some cyclone pairs merge, with one cyclone weakening and being absorbed into the other. Other cyclone pairs escape from the binary interaction with a cessation of mutual orbit that is as rapid as that which is observed for initial capture.

The average separation distance at the capture point was approximately 1000 km of great-circle arc. This distance is somewhat smaller than that noted by Brand (1970) and Dong and Neumann (1983) for the commencement of binary interaction. The small difference may easily be due to sampling error, or to the slightly different definition of capture used here*. The mean separation distance at the escape point was about 870 km. Escape usually occurred at, or within 6–12 hours after, the point of closest approach of the two vortices. This minimum separation distance averaged 820 km for non-merging cyclones. The range of separation distances about these mean values at capture, escape and closest approach was roughly 200 km. An interesting feature was that cyclones that captured each other at larger distances also tended to escape at larger distances.

Although the cyclonic orbit and mutual attraction of binary cyclones were reproduced in laboratory experiments by Fujiwhara (1923), there has been little theoretical examination of the precise mechanisms. Haurwitz (1951) used two Rankine combined vortices to develop a relationship between rotation rate, cyclone intensity and separation distance. But this relationship was based entirely on linear advection of each vortex by its partner, and Haurwitz provided no explanation of any of the other characteristic features described above. Both Brand (1970) and Dong and Neumann (1983) found a consistent relationship between separation distance and rotation rate. But Dong and Neumann also found that there is only a poor relationship between intensity and rotation rate, which they considered to be due to the effects of other synoptic systems and basic current variations. We suggest that a major contributing factor is that a Rankine combined vortex is a very poor model for the outer circulation of tropical cyclones (Holland 1980) and that there is little relationship between cyclone intensity and outer circulation (Weatherford and Gray 1988).

* A weak cyclonic orbit during the approach would have been catalogued as binary interaction in the previous studies.

Dong and Neumann suggested that the observed deviations from a classical Fujiwhara model were due to variations in the environment of the binary cyclones. They provide several typical examples. The oscillation in rotation rate was related to binary cyclones embedded in a zonal monsoon shear zone with westerlies (easterlies) on the equatorward (poleward) side. As a result, the binary pair orbited faster when their axis aligned meridionally and slower when they moved to a zonal alignment. Motion in a sheared environmental flow also seems to have produced the variations of orbit rate and separation distance that were observed in cyclones Tip and Georgette (Fig. 1(e)). All cases of anticyclonic orbit were attributed by Dong and Neumann to a single generic environment in which one storm is progressing westward south of a subtropical high while the other is accelerating northward on the west side of the same high.

The merger of two tropical cyclones also does not seem to follow the classical Fujiwhara coalescence to a single vortex located at the centroid. All of the merger cases observed in this study involved the decay and absorption of one cyclone into the circulation of its dominant partner. Thus initial differences of strength, size or intensity of the storms may decide much of the way in which the merger occurs.

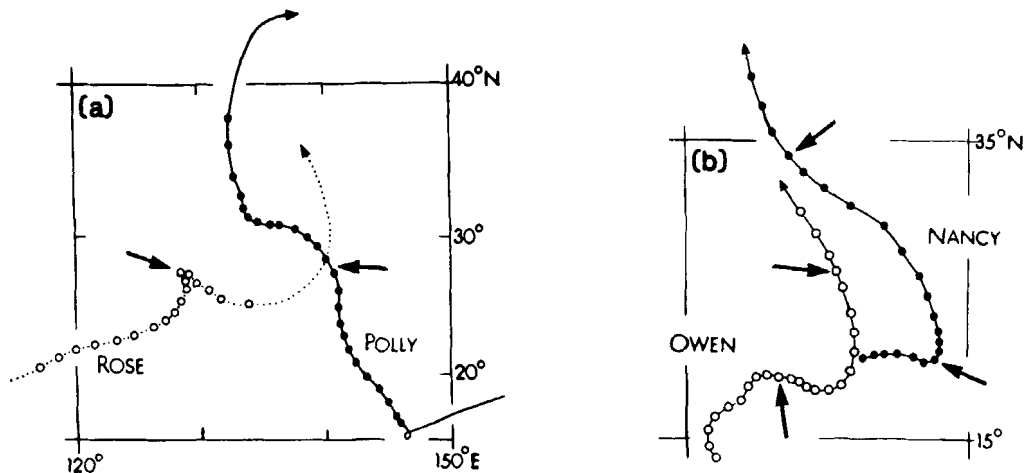


Figure 2. Cyclone tracks of (a) Polly and Rose and (b) Nancy and Owen. The arrows indicate the capture times for both pairs of cyclones and the escape time for Nancy and Owen. Additional information is provided in Figs. 1(b) and 1(f).

The action of deep, moist convection in each tropical cyclone also provides a strong forcing mechanism to counteract the destructive tendency of the strong horizontal shear of the partner vortex. In several of our observed merger cases, the deep convection of the dying vortex is virtually eliminated. The remnant low-cloud vortex is swept into the circulation of its partner, becomes sheared horizontally, and loses its identity as a distinct system. Consider the case of the absorption of cyclone Georgette into Tip (Figs. 1(e) and 3). The satellite imagery for the period (not shown) indicates a steady decrease and loss of organization of Georgette's convection that preceded decay. Georgette closed to within about 300 km of Tip's centre at the closest point of approach and was about 550 km away when last identifiable as a distinct circulation.

There has been no prior work on the short time period of only several hours during which both capture and escape seem to occur. The nature of this rapid bifurcation implies that it is dominated by nonlinear processes.

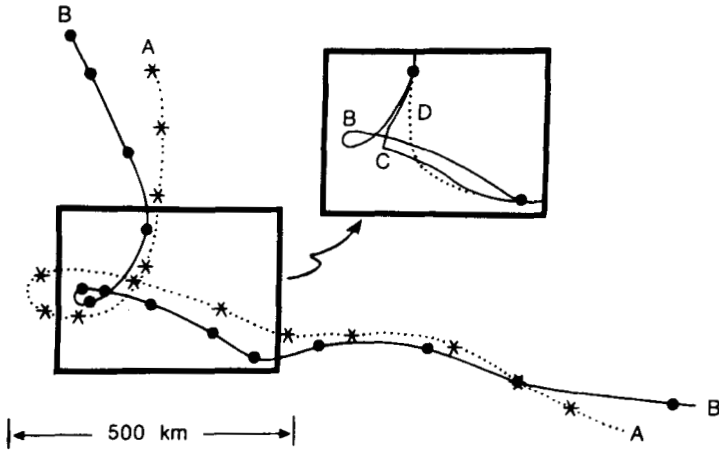


Figure 3. Track of the centroid of cyclones Tip and Georgette calculated with different degrees of weighting: unweighted (A), weighted in proportion to intensities (B), 3:1 in favour of Tip (inset, track C), and 7:1 in favour of Tip (inset, track D).

4. MORE THAN TWO INTERACTING TROPICAL CYCLONES

On occasion, three tropical cyclones will occur in close enough proximity to interact in a complex mutual orbit. Although this interaction is quite rare, it does provide additional insights into the processes operating in binary pairs. We illustrate the type of interaction and some of the relationships to binary cyclones in this section by using a detailed case study of cyclones Pat, Ruby and Odessa.

Cyclones Pat, Ruby and Odessa developed in the western North Pacific during late August 1985 in a zonally oriented monsoon shear zone. They subsequently followed the complex and climatologically unusual tracks shown in Fig. 4, during which both Pat and Ruby initially moved eastward before turning northward, then recurving into the mid latitudes.

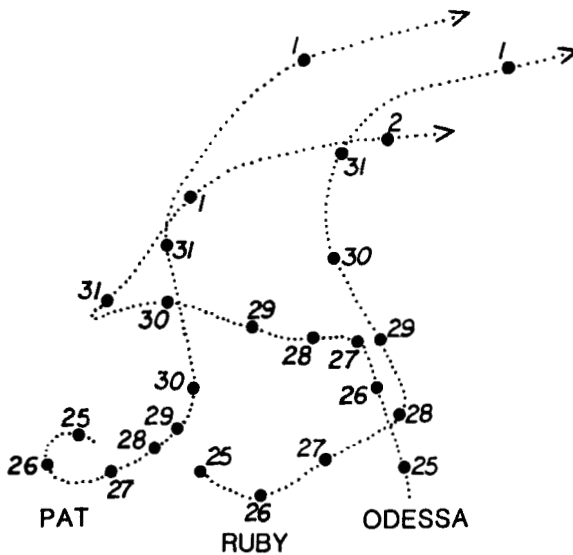


Figure 4. Tracks of cyclones Pat, Ruby and Odessa, August-September 1985. The dots represent 00 UTC positions, with dates.

The motion of these cyclones relative to their centroid (Fig. 5(a)) shows that they were undergoing a strong interaction. Initially, Ruby and Odessa seem to have been orbiting each other whilst Pat was orbiting both cyclones as a pair. As Odessa approached Pat, however, a sharp bifurcation occurred during which Pat appeared to capture Ruby whilst Odessa escaped and commenced an anticyclonic orbit.

When the motion of Pat, Ruby, and Odessa is examined separately as the three possible binary-pair permutations (Figs. 5(b), (c), (d)), the resulting interactions are seen to exhibit a behaviour similar to that found for general binary pairs in section 3. Pat and Ruby undergo a very slow cyclonic orbit at a large separation distance (Fig. 5(b)). Although this motion has some characteristics of the typical binary pair, it seems to have resulted from indirect, rather than direct interactions. Ruby and Odessa (Fig. 5(c)) began to orbit as they developed and executed a 200° rotation before experiencing a sharp escape. The initial orbit of Pat relative to the other pair appears as a cyclonic rotation at large distance in the centroid-relative motion of Pat and Odessa (Fig. 5(d)). These cyclones then execute a direct approach, a capture, an orbit through 180° , and a sharp escape.

Thus the behaviour of three spatially proximate tropical cyclones, which were known to have mutually interacted, is reducible to the common model of binary behaviour when

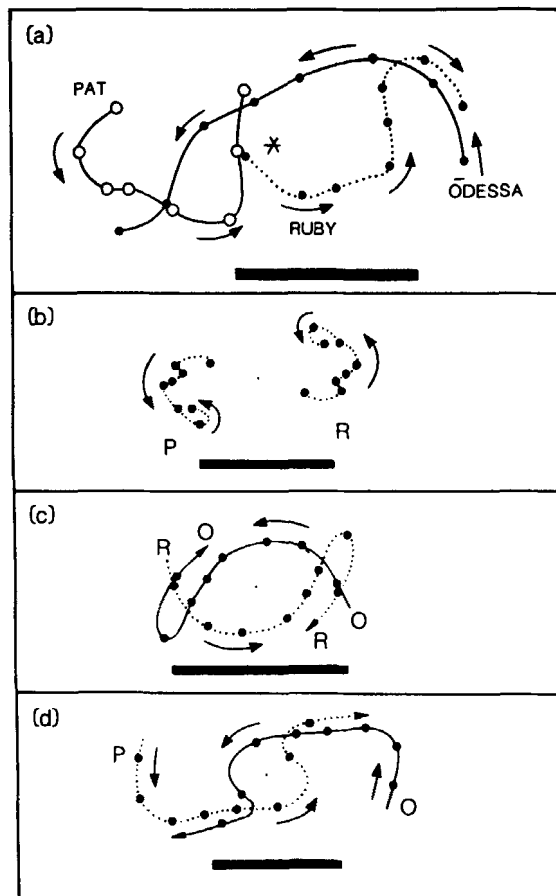


Figure 5. Centroid-relative motion of cyclones: (a) Pat, Ruby and Odessa, (b) Pat and Ruby, (c) Ruby and Odessa, and (d) Pat and Odessa. The direction of motion is shown. The horizontal bars are 1000 km long and dots indicate the same 00 UTC positions as in Fig. 4.

the storms are taken as separate pairs. This case study provides tentative evidence that the sharp bifurcation which accompanies capture and escape may be partially due to the influence of other systems that are interacting with the binary pair. Care needs to be taken, further, in attributing all mutual cyclonic rotation as being due to binary interaction, as has been shown by the tracks of Pat and Ruby in Fig. 5(d).

5. MESOSCALE VORTEX INTERACTIONS

It would be reasonable to expect that the features of interacting binary cyclones might also be reproduced during the interaction of other mesoscale cyclones. During the field component of Tropical Cyclone Motion-90 (TCM-90) (Elsberry 1990) we became aware of the development of large numbers of mesoscale vortices from an active monsoonal shear zone. These groups of vortices, which we refer to as 'swarms' because of their number and rapidity of development, last for a few days and can interact with each other. As far as we are aware, they have been given no attention in the literature and they are not routinely documented in tropical-cyclone summaries. Such vortices would seem to be of interest to the problem of tropical-cyclone genesis and also may provide clues to the structure of the mesoscale convective complexes observed to be interacting with tropical cyclones by Holland and Lander (1993). However, we shall limit our discussion here to their mutual interaction by presenting two case studies of vortex swarms that could be analysed unambiguously from available satellite imagery.

The first case study is of a vortex swarm that formed in a northward-displaced monsoon trough during the third week of August 1989. On 21 August, a swarm of three distinct vortices was observed on the satellite imagery. These vortices featured well defined low-level cumulus cloud lines and centrally located cumulonimbus clouds, but were not analysed on the large-scale analysis.

These three vortices and a fourth low-cloud vortex located further east (code named Alpha, Bravo, Charlie and Delta) were followed for as long as they could be found on satellite imagery. The tracks of Alpha, Charlie and Bravo (Fig. 6) exhibit a clear cyclonic rotation, but there seems to have been little, if any, interaction with Delta. Part of the cyclonic curvature in the tracks arose from the movement of all systems around the large-scale monsoon depression (not shown). However, when Alpha and Bravo are plotted in centroid-relative coordinates (Fig. 6(b)), they seem to undergo a transition to binary interaction when they approach to within around 200 km of each other.

The second example of a family of mesoscale vortices occurred during July 1990, just before the commencement of TCM-90. The overall synoptic situation consisted of a complex monsoonal trough that was gradually migrating poleward. During the week of 14 July–22 July a series of at least six mesoscale vortices developed in the eastern reaches of the monsoon trough, moved poleward away from the major cloud band, and tracked westward or north-westward. As shown by Fig. 7, these were long-lived systems that lasted for 3–5 days while travelling around 1000 km. No binary interaction was observed in these systems, however, probably because of their small size and relatively large separation distances. None of the vortices approached within 600 km of each other; this is substantially larger than the 200 km separation of Alpha and Bravo (Fig. 6).

6. CONCLUSIONS

We have examined the interaction of binary tropical cyclones that were reasonably independent of other marked influences, a group of three interacting tropical cyclones, and two swarms of mesoscale vortices. We find substantial differences from the commonly

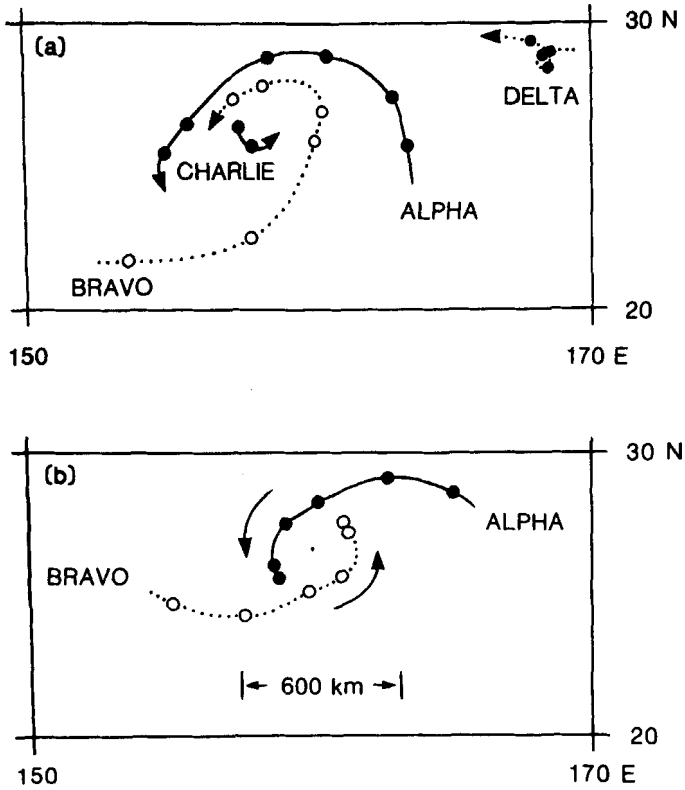


Figure 6. (a) Tracks of mesoscale vortices Alpha, Bravo, Charlie and Delta and (b) centroid-relative motion of Alpha and Bravo. Dots on the tracks are at irregular time intervals and show fixes obtained from visible satellite imagery.

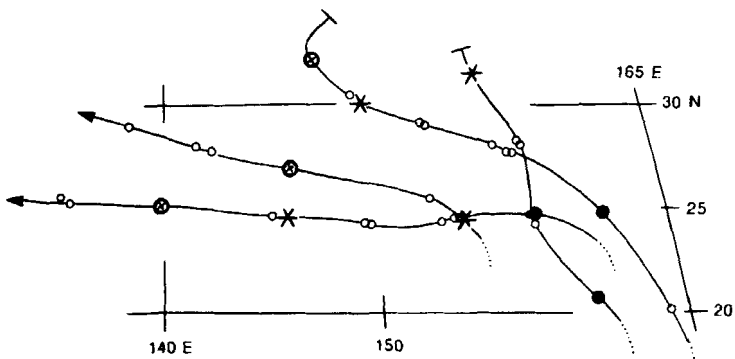


Figure 7. Tracks of four mesoscale vortices observed during late July 1990. Symbols on the tracks are at irregular time intervals and indicate fixes obtained from visible satellite imagery; different symbols show the relative positioning of the vortices at specific times.

used Fujiwhara model of sustained cyclonic rotation and mutual approach. Although there are differences in detail arising from the synoptic environment, the binary interactions tend to be comprised of several elements of the schematic model in Fig. 8. Those cyclones whose circulations do not overlap at formation, approach directly under the influence of the surrounding environment. Often this approach occurs with anticyclonic orbit of the cyclone pair, which we attribute to the tendency for tropical-cyclone tracks to follow an anticyclonic trajectory around and across the subtropical ridge.

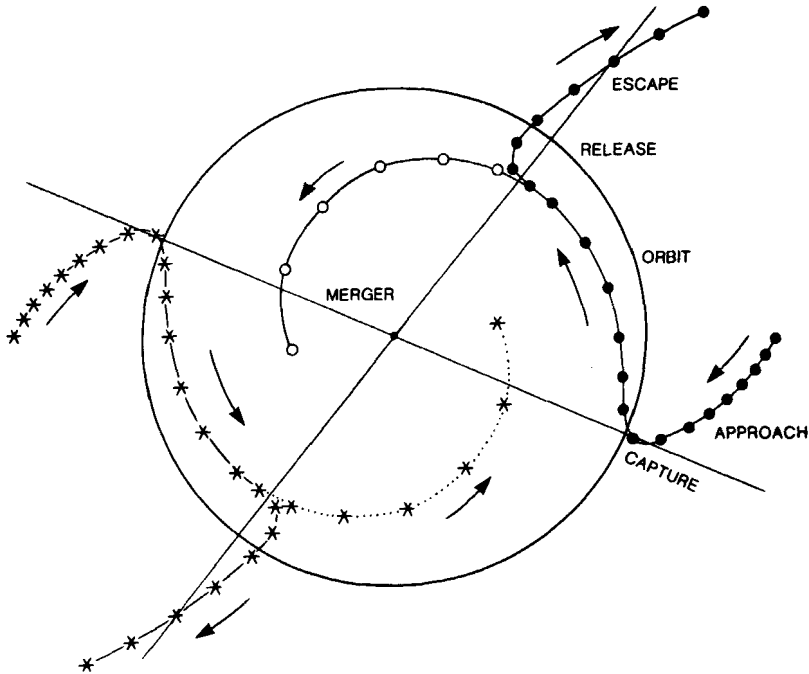


Figure 8. Model of binary interaction of two cyclonic mesoscale vortices that contain the major elements of approach and capture, followed by mutual orbit, then release and escape, or merger.

Capture occurs rapidly, usually in a few hours, and is marked by a sharp change in centroid-relative motion which may not be obvious in geographical coordinates. A period of relatively stable cyclonic orbit then ensues. During this time the cyclones tend to converge, but usually at a slower rate than the original approach, and a significant proportion maintain a constant separation distance. The orbital rate often fluctuates, and at least some of this fluctuation can be attributed to external influences, such as a sheared environmental flow.

The binary interaction may end by destruction of one vortex (by movement over land, for example), by merger of the two cyclones, or by escape. Merger does not follow the classical binary vortex model of coalescence at the centroid. Rather, one cyclone tends to lose its convective forcing and become sheared into the circulation of the other. Escape, when it occurs, is as rapid as capture; the cyclones then normally diverge at a faster rate than occurred during their original approach. We suggest that this is partially due to the escaping cyclones moving into strongly-sheared subtropical westerly flow. As with capture, escape is not always obvious in geographical coordinates.

The same binary interaction elements were observed for separate pairs of a three-cyclone interaction between typhoons Pat, Ruby and Odessa and between mesoscale vortices that approached within a few hundred kilometres. The interaction between typhoon Sarah and mesoscale convective complexes that developed within its circulation influence (Holland and Lander 1993) also followed the interaction model in Fig. 8. This ability of the model to describe the interactions between pairs of vortices in the presence of a large-amplitude environmental influence, such as another tropical cyclone, indicates its robustness in varying synoptic conditions. However, we note that many cases occur when cyclones in near proximity to each other are dominated by the synoptic flow conditions and do not enter into the binary interaction shown in Fig. 8.

Swarms of mesoscale vortices were observed to form in convectively active regions of the western North Pacific when no tropical cyclones were present. They were observed to move up to 1000 km over several days. These were small systems in comparison with tropical cyclones, with regions of influence restricted to around 200 km. Nevertheless, when vortices approached within this influence region, their movement conformed to the interaction model (Fig. 8) for interacting tropical cyclones. The observed presence of mesoscale vortices in such abundance supports the finding by Holland and Lander (1993) that such systems may be having a marked influence on the meandering motion of tropical cyclones.

The interaction model in Fig. 8 may be interpreted as follows: (1) cyclones approaching each other undergo a rapid and unstable transition to a stable attractor consisting of mutual cyclonic orbit, which may last several days; (2) unless one of the systems is destroyed by moving over land, equally rapid transition will then occur to one of two final stable states, merger or escape. The transitions arise from interactions with the environment, are not always obvious in geographical co-ordinates, and seem to be essentially chaotic and unpredictable in their character. The nature of this interaction is examined further in Parts II and III by Ritchie and Holland (1993) and by Holland and Dietachmayer (1993). The latter includes an overall summary of the findings of all three papers.

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