On the Relative Motion of Binary Tropical Cyclones

KEQIN DONG[1]

Central Meteorological Bureau, Academy of Meteorological Science, Beijing, People's Republic of China

CHARLES J. NEUMANN

National Hurricane Center, Coral Gables, FL 33146

(Manuscript received 17 March 1982, in final form 31 January 1983)

ABSTRACT

The interaction between spatially proximate (binary) tropical cyclones is such that relative rotation in the counterclockwise sense and decreasing separation distance between the two storm centers can be expected. This is referred to as the *Fujiwhara effect.* This study analyzes this effect for 43 binary tropical cyclone systems which occurred over the western North Pacific, 1949–78. It is shown that most demonstrated mutual interaction according to Fujiwhara expectations. However, there were notable apparent exceptions.

Further analysis of these exceptional cases shows that environmental currents in which the storms were embedded had a significant effect on relative motion and masked the Fujiwhara effect. Additionally, it was found that storms exhibiting behavior most in accordance with Fujiwhara expectations were located in or near the Intertropical Convergence Zone. The main conclusion of the study, in confirmation of earlier studies, is that forces relative to environmental steering must be determined and filtered before one can determine forces attributable to the Fujiwhara effect alone.

1. Introduction

For both North Atlantic (Neumann, 1982) and western North Pacific (Jarrell *et al.*, 1978) tropical cyclone basins, it has been shown that errors in the forecasts of tropical cyclone motion are related to a number of factors. One of these factors is the presence of two spatially proximate storms (hereafter referred to as binary tropical cyclones or binary systems). The Jarrell study as well as an earlier study (Brand, 1970) cite significant increases in western North Pacific forecast error whenever binary systems are present.

Binary tropical cyclones are considerably more common to the western North Pacific than to the North Atlantic. According to records of tropical cyclone tracks maintained on magnetic tape at the National Hurricane Center, storm pairs subject to binary interaction[2] averaged 1.5 annually over the western North Pacific and 0.33 annually over the Atlantic for the 36-year period 1946–81. The higher frequency over the western Pacific is at least partially attributable to the overall higher tropical cyclone frequency over that basin compared to the Atlantic; i.e., 25 versus 10 storms annually (Crutcher and Quayle, 1974). However, it is also attributable to different characteristics of the Intertropical Convergence Zone (ITCZ) between the two basins (See Section 4b).

The increase in forecast error with the presence of binary tropical cyclones is understandable. Even with the presence of a single storm, data inadequacies over the tropical cyclone basins lead to analyses and numerical prognoses uncertainties (Neumann, 1982). These uncertainties translate into forecaster uncertainty as to environmental steering forces and how these forces are changing. Given the presence of another storm in close proximity, an already complex problem is compounded by still additional uncertainties concerning vortex interaction.

Through laboratory experiments and geophysical observations, Fujiwhara (1923, 1931) studied the interaction of adjacent vortices. These studies demonstrated that relative motion was composed of counterclockwise revolution of one vortex about the other and that there was a tendency for the approach of circulations with the same sense of rotation. In meteorological application, this is commonly referred to as the *Fujiwhara effect.*

Haurwitz (1951) derived a mathematical expression for the rotation of the axis connecting the centers of a tropical cyclone pair by considering that each storm behaved as a simple Rankine vortex. However, when applying his equation to actual observations, many discrepancies were noted which, as pointed out

---

[1] Portions of this study were completed while author was assigned to the National Hurricane Center, Coral Gables, Florida, as a WMO Fellow.

[2] Here, binary interaction is defined as two coexisting tropical cyclones, separated at some point by less than 1334 km and with associated maximum surface winds of both systems of at least 18 mps.

by Haurwitz, were presumably due to paucity of observations, analysis deficiencies, shear of the large scale environmental steering current or combinations thereof.

Hoover (1961) conducted an observational study of binary tropical cyclones for both Atlantic and Western Pacific basins. For the former, he noted that the predominant relative motion was clockwise whereas in the latter, much better agreement with Fujiwhara expectations of counterclockwise rotation was noted. Hoover suggested that the Atlantic discrepancies were due to different large-scale circulation (steering) patterns between the two basins.

Brand (1970) studied 15 years (1953–67) of Western Pacific binary tropical cyclone tracks and derived a regression equation for rotation rate Y as a function of cyclone separation distance X,

$$Y = 119.06 - 0.162X + 0.000055X^2, \quad X \leqslant 1500, \tag{1}$$

where Y is in units of angular degrees of rotation per 12 hours with positive Y indicating counterclockwise rotation and where X is in km. In the derivation of (1), Brand noted some large Y residual errors at recurvature latitudes. These were attributed to the mutual interaction between two storms being overshadowed by the effects of shear in the steering current. He excluded these recurvature cases in the final derivation of (1).

The three authors cited above either alluded to or specifically called attention to possible contamination of binary interaction by large scale horizontal shear in the steering current but, except in the subjective sense, did not account for these in their calculations. Indeed, such accountability would have been difficult considering the upper-air observational deficiencies one finds in the tropics and difficulties in distinguishing between background flow and storm circulation. In the present paper, we treat the effects of associated shear somewhat less implicitly than heretofore although, admittedly, we are still constrained by similar observational deficiencies; much must be inferred from indirect observations.

2. Basic statistical features

Over the 30-year period, 1949–78, 43 pairs of tropical cyclones (binary) were observed over the western North Pacific Ocean. Some of these cases have been previously discussed by Dong (1980, 1981). In our study, a binary case is defined as two named tropical cyclones which: 1) have coexisted for at least 48 h, 2) were separated, at some point, by less than 1334 km, and 3) had attained, at some point, at least tropical storm ($\geqslant$18 mps) status.[3] All data were obtained from files maintained and published periodically by the Central Meteorological Bureau (1972) of the People's Republic of China (PRC). Storm tracks given therein (best-tracks[4]) are nearly identical to those issued annually[5] by the United States Joint Typhoon Warning Center (JTWC).

a. *Overall relative rotation of binary systems*

To determine separation distance and relative motion, polar coordinate charts were prepared for each of the 43 binary systems. Four of these charts (to be subsequently discussed) are included as Figs. 3, 5, 7 and 10. From these charts, the following statistical data are noted:

1) In 30 (69.8%) of the pairs, relative motion of one storm about the other was continuously counterclockwise about the pair midpoint. For each pair, the maximum angular rate of rotation (degrees of arc per 24 hours) was at least 20°.

2) In five (11.6%) of the pairs, a continuously clockwise rotation with a maximum 24 h rotation rate of at least 20° was also noted.

3) In the remaining eight pairs (18.6%), rotation rates were either very small or the sense of rotation varied between clockwise and counterclockwise; that is, assignment to category (1) or (2) was not possible. In this study, these will be referred to as *indeterminate* cases.

For the western Pacific basin, the above statistical summary confirms that most binary systems, during their coexistent period, do indeed exhibit relative counterclockwise rotation. However, five pairs clearly rotated in the opposite sense. This apparent contradiction to Fujiwhara expectation provided much of the impetus for this study.

b. *Rotational sense at 12-hour intervals*

The 43 pairs of tropical cyclones coexisted for periods of up to five days. This provided a total of 319 12-hourly periods. Rotational sense between each 12-hourly period was determined and, if measuring at least five degrees of arc, was assigned as being either counterclockwise or clockwise; otherwise as indeterminate. The average separation[6] distance between pair members was also noted. These data are summarized in Fig. 1. Clearly, from the figure, when the separation distance is less than ~11 units (~1225

---

[3] This definition is somewhat different than that used to compute long-term climatology of binary systems (see footnote 2).

[4] Best-track is defined as the accepted track and associated intensity of a tropical cyclone after a post-analysis of all available data.

[5] For example, *Annual Typhoon Report,* 1978, U.S. Fleet Weather Central, Joint Typhoon Warning Center, Guam.

[6] In this study, the separation distance between tropical cyclone centers will be specified in terms of "separation distance units," or simply, "units," each unit being equal to 111.2 km. This is equivalent to one degree of great-circle arc on the earth's surface.

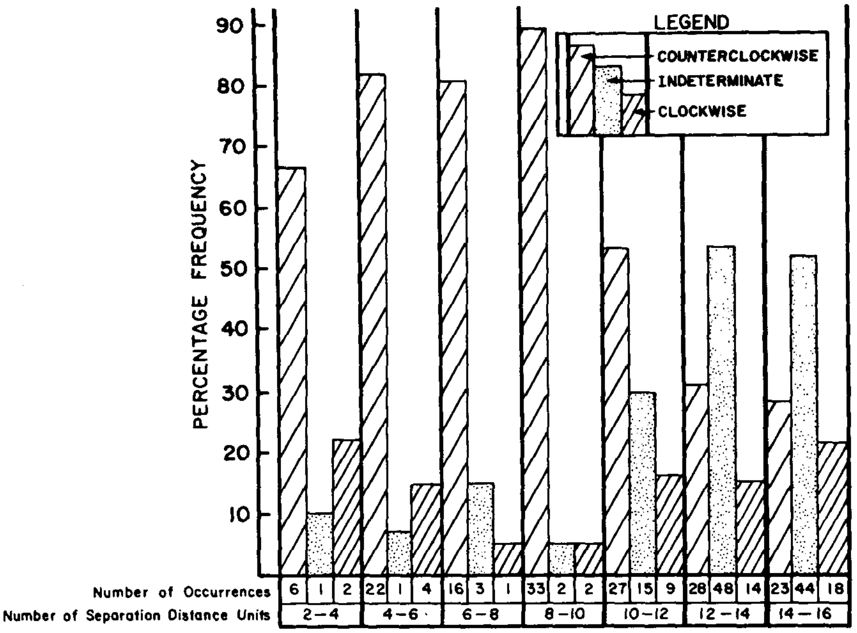

FIG. 1. Frequency distribution of relative motion. Percentage frequency refers to cases within each specified class interval. A separation distance unit is defined in footnote 6.

km) counterclockwise rotation becomes predominant. It is also noted, however, that even when separation distance is less than 4 units (~450 km) cases do exist where rotation is clockwise.

c. Changes in separation distance

Similarly, changes in separation distance of the 319 individual 12-hourly cases were subdivided into three categories of *approaching* (decrease in separation distance not less than 0.5 units per 12 h); *separating* (increase in separation distance not less than 0.5 units per 12 h); and *indeterminate* (not belonging to either class). These data are shown in Fig. 2.

Also contrary to Fujiwhara expectation, separation distances were not always observed to decrease. Only when these were initially less than 8 separation dis-

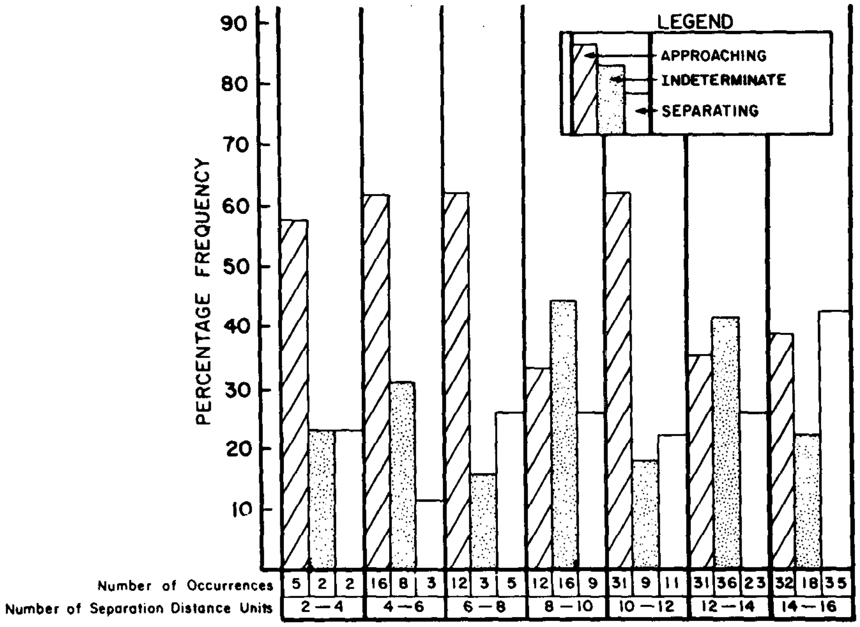

FIG. 2. As in Fig. 1 except frequency distribution of changes in separation distance.

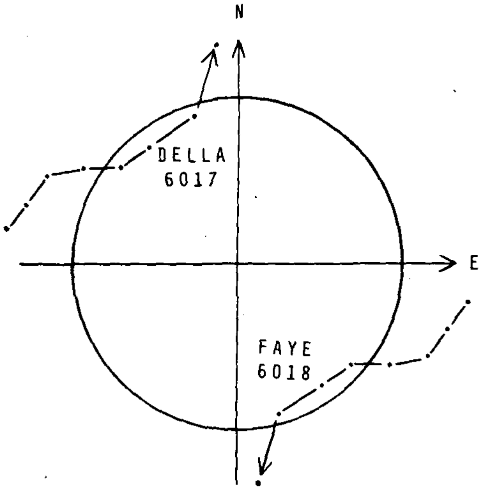

FIG. 3. Relative motion of the tropical cyclone pair Della and Faye (27–30 August 1960). Storm center positions are given every 12 h. Radius of circle is six separation distance units (~650 km, see footnote 6) and origin represents mid-point of line connecting storm centers.

tance units (~900 km) did decreases in storm separation clearly exceed increases.

3. Clockwise relative rotation

Among the five cases of mutual clockwise rotation noted in Section 2a(2), there were three instances when separation distance of the binary pair exceeded 10 separation distance units and the steering of each pair member was apparently under the influence of the same subtropical high; one system was to the south of the high and generally progressing westward then northwestward while the other system was to the west of the high and generally progressing northward. Examples of this pattern for tropical cyclone pair Della (6017)[7] and Fay (6018) are shown in Figs. 3 and 4.

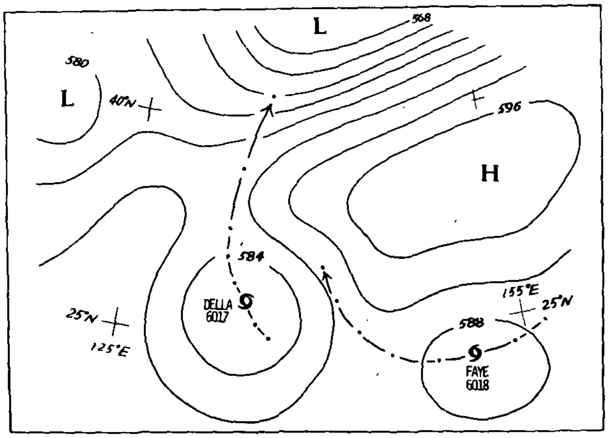

FIG. 4. The 500 mb geopotential height field (decameters) for 1200 GMT 27 August 1960 and the tracks of Della and Faye. Designated storm positions (dots) are at 12 hourly intervals.

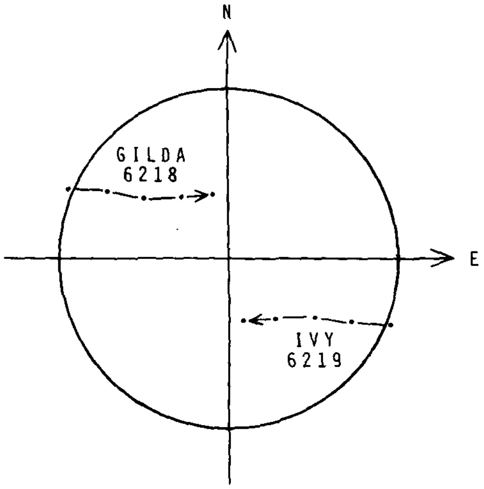

FIG. 5. As in Fig. 3 except for Gilda and Ivy (27–29 October 1962).

The tracks of both of these systems are seen to be consistent with the implied 500 mb steering forces. Relative motion from this implication is such that a net clockwise mutual rotation would be expected. Mutual interaction (Fujiwhara effect, presumably in the counterclockwise sense) is completely masked by the large scale steering forces. However, the separation of these storms is large enough that binary interaction would be small.

Consider now the remaining two cases of mutual clockwise rotation. These occurred with binary tropical cyclones Lucretia[8] and Missatha in 1950 where minimum storm separation was only 2.6 separation distance units and with Gilda and Ivy in 1962 where minimum separation was 4.6 units. Again, both tropical cyclone pairs were embedded in a similar large-scale environmental flow pattern: one of the pairs moved rapidly towards the northeast ahead of a strong trough in the westerlies and the other pair member moved slowly northward in the west side of the subtropical high. For example, Figs. 5 and 6, respectively, show the relative motion of binary pairs Gilda (6218) and Ivy (6219) and the associated 500 mb geopotential height field.

As depicted in Fig. 6, the environmental currents within which the storms were embedded would lead to mutual rotation in the clockwise sense as well as a decrease in separation distance. Here, however, the two systems are close enough that the rotational aspect of the Fujiwhara effect should have been quite active but, if present, is again masked by the back-

---

[7] The designation (6017) refers to the 17th storm of 1960. This accounting system is used in some Far Eastern countries.

[8] This storm eventually weakened and was renamed Nancy.

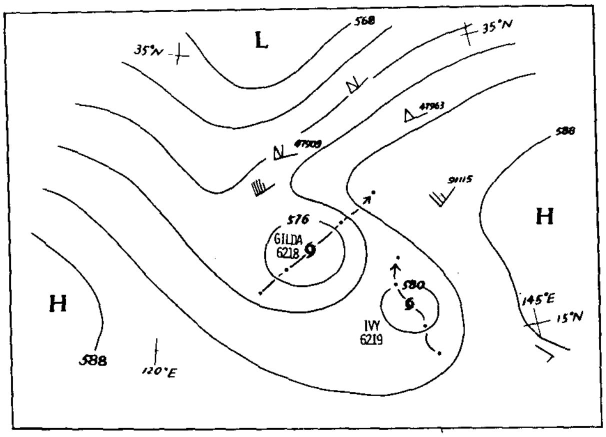

FIG. 6. As in Fig. 4 except for Gilda and Ivy 1200 GMT 28 October 1962. Observed winds have been plotted at selected locations, three of which are identified by International index numbers.

ground flow. The separation distance between the two storms, as in the Fig. 4 Della/Faye example, did decrease in accordance with Fujiwhara expectation. Obviously, however, this is due principally to steering shear.

4. Counterclockwise relative rotation

a. Western Pacific

Of the 30 cases of counterclockwise rotating binary pairs noted in Section 2a, 14 were contained within the Intertropical Convergence Zone (ITCZ)[9]; six were contained within the ITCZ during their earlier stage and were influenced by a westerly trough at their later stage while an additional nine pairs were located on the western side of the subtropical high. A final case was located on the southern side of the subtropical high.

The eight pairs in which 24 h counterclockwise rotation was at least 60 degrees of arc, the minimum distances between pair members were less than five separation distance units and these distances were continuously decreasing, are listed in Table 1. All of these, it can be noted, were within the ITCZ. Tropical cyclone pair Marie (6413) and Kathy (6414) present a classic example of the Fujiwhara effect in that the counterclockwise revolution and mutual approach of the two centers continued for a long period (Fig. 7). Indeed, vortex behavior was much like Fujiwhara's (1931) photographic documentation.

The near perfect Fujiwhara-like characteristics of the Marie/Kathy pair prompted further analyses. Twelve-hour rotation rates for each of the 13 datapairs (26 points) on Fig. 7 were computed and an isoline analysis (Fig. 8) was prepared. It is seen that the rotational pattern is not circular but elliptical with the major axis slightly counterclockwise from meridional and the minor axis slightly counterclockwise from zonal. The interpretation, here, is that for a given separation distance, the two systems revolve at a faster rate when in a nearly meridional orientation.

TABLE 1. The eight pairs of tropical cyclone in which 24 h counterclockwise rotation was at least 60° of arc, minimum separation distance was at least 5 units (see footnote 6) and separation distances continually decreased.

Typhoon pair	Coexistence period	Minimum separation distance (tens of km)	24 h maximum angular rotation rate (deg)	Synoptic pattern
Unnamed (5010) Helen (5011)	25–27 Jul	33.3	70	ITCZ
Helen (6113) Ida (6114)	28–31 Jul	40.0	106	ITCZ
Marie (6413) Kathy (6414)	14–20 Aug	35.6	121	ITCZ
Ivy (6511) Jean (6512)	30 Jul–1 Aug	17.8	90	ITCZ
Susan (6610) Tess (6611)	13–16 Aug	46.7	104	ITCZ
Nadine (6803) Olive (6805)	4–26 Jul	33.3	69	ITCZ
Ellen (7009) Fran (7010)	4–6 Sep	20.0	173	ITCZ
Polly (7415) Rose (7417)	23–31 Aug	52.3	60	ITCZ

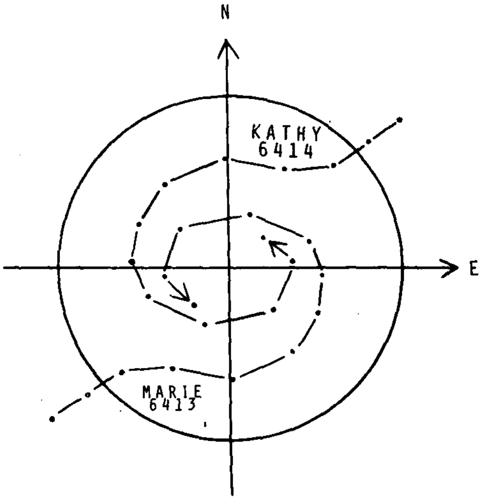

FIG. 7. As in Fig. 3 except for Marie and Kathy (14–20 August 1964).

---

[9] ITCZ positions were obtained from charts analyzed at the Central Meteorological Bureau, PRC. During the main portion of the typhoon season, there is typically easterly component flow north of the zone and westerly component flow south of the zone. This is sometimes referred to as the monsoon trough (Atkinson, 1971).

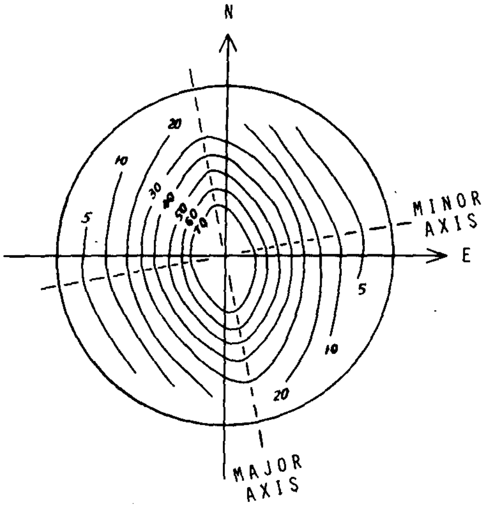

FIG. 8. Spatial pattern of angular rotation rates (degrees of arc per 12 hours) for the tropical cyclone pair Marie and Kathy (14–20 August 1964). Coordinate system as in Fig. 3.

It can also be shown that the 12-hourly changes in the separation of tropical cyclone pair Marie/Kathy are closely related to orientation of the line between the two centers (Fig. 9). When the two systems are positioned in nearly a northeast–southwest orientation, the tendency to approach is more pronounced whereas when they are positioned 90 degrees from this mode, there is even a slight tendency for the distance between centers to increase.

Ellen (7009) and Fran (7010) represent another pair with apparent classic Fujiwhara relative motion characteristics (Fig. 10). In consideration of the shorter coexistence of these two systems, computations are presented at 6-hourly rather than at 12-hourly intervals (Figs. 11 and 12). Results are quite similar to those of binaries Marie and Kathy, 1964, illustrated in Figs. 7, 8 and 9.

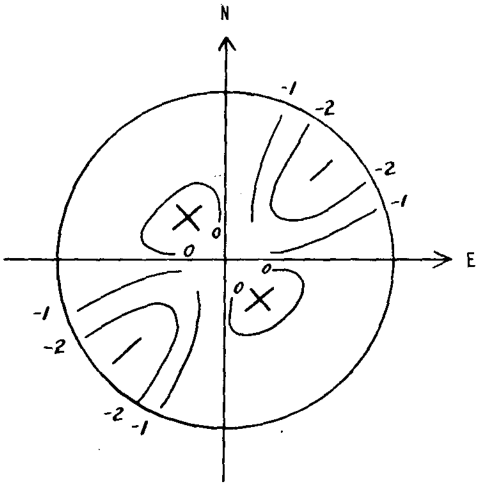

FIG. 9. Distribution of 12 h changes in separation distance between tropical cyclone pair Marie and Kathy (14–20 August 1964). Isolines are given in units of separation distance (see footnote 6), where positive indicates separating and negative indicates approaching. Coordinate system as in Fig. 3.

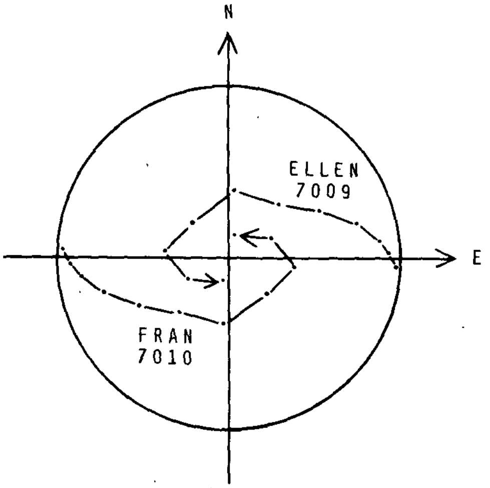

FIG. 10. As in Fig. 3 except for Ellen and Fran (4–6 September 1970).

As before, the motion profiles of Marie and Kathy (Figs. 7, 8 and 9) and of Ellen and Fran (Figs. 10, 11 and 12) cannot be interpreted from the Fujiwhara effect alone. One must also consider environmental steering patterns. Figs. 13 and 14 show these patterns for the binary systems Marie/Kathy and Ellen/Fran, respectively. Both pairs are seen to be embedded in the ITCZ which, in the former case, is positioned well into the Northern Hemisphere.

In accordance with Fig. 15, which shows a schematic of typical wind shear north of the ITCZ, pairs

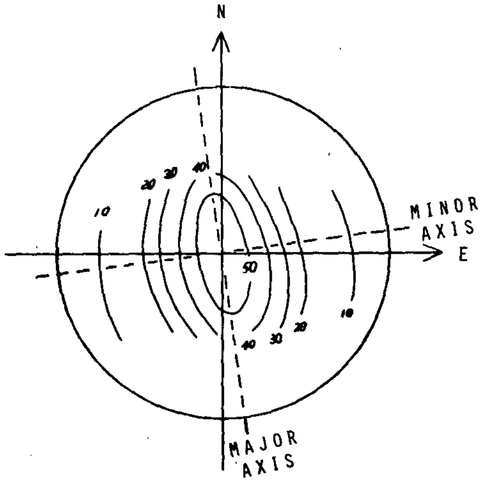

FIG. 11. As in Fig. 8 except for tropical cyclone pair Ellen and Fran (3–6 September 1970) and rotation rate in degrees of arc per 6 hours rather than 12 hours.

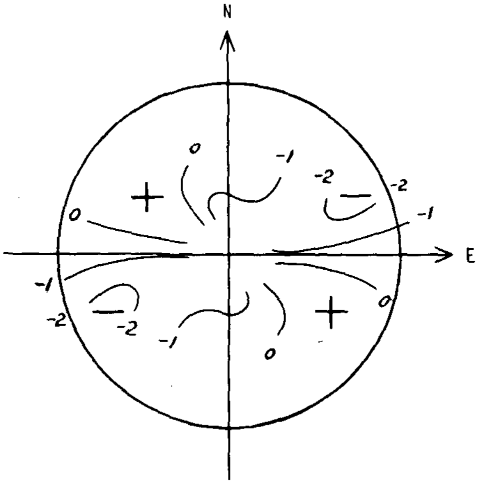

FIG. 12. As in Fig. 9 except for tropical cyclone pair Ellen and Fran (3–6 September 1970) and for 6 h rather than 12 h changes in separation distance.

A/B or C/D would be expected to increase their relative counterclockwise rotation when oriented meridionally (as in Fig. 14) and pairs A/C or B/D would be expected to decrease their rotation when oriented zonally (as in Fig. 13).

Using similar reasoning, when binary pairs are positioned in nearly a northeast–southwest orientation (as pair B/C in Fig. 15), they will mutually approach but when in nearly a northwest–southeast orientation (as pair A/D in Fig. 15), they will mutually separate (as depicted in Fig. 9).

In summary, these ITCZ results show that the observed distribution of angular rotation rates and separation distances between binary pairs may be satisfactorily interpreted as the steering effect of basic ITCZ currents on the embedded tropical cyclone pair.

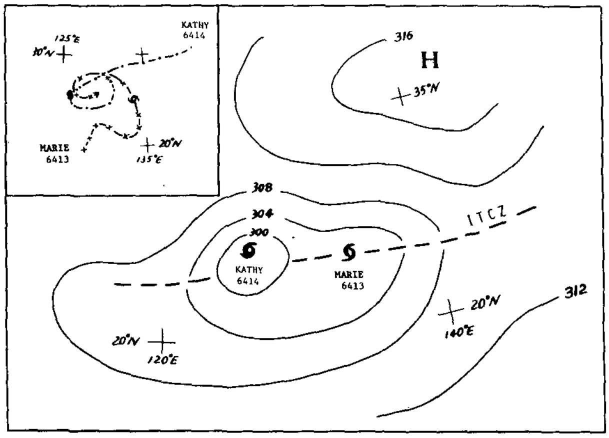

FIG. 13. The 700 mb geopotential height field (decameters) for 1200 GMT 17 August 1964 and the tracks of Marie and Kathy. Insert shows tracks of Marie (6413) and Kathy (6414) from 0000 GMT 14 August to 0000 GMT 20 August 1964.

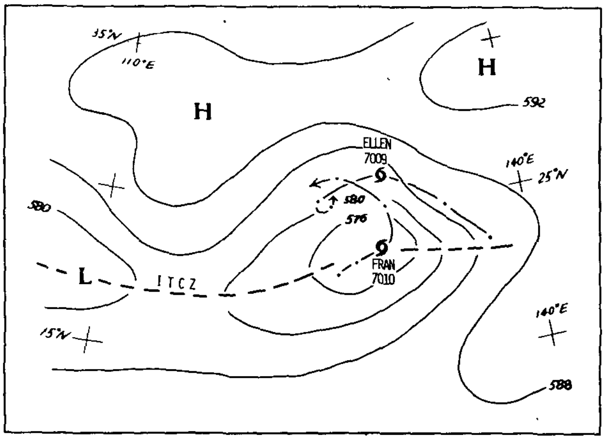

FIG. 14. The 500 mb geopotential height field (decameters) for 0000 GMT 5 September 1970 and the tracks of Ellen and Fran.

These currents, in addition to Fujiwhara forces, have been subjectively shown to have had an influence on the relative motion of binary systems.

b. *Atlantic*

The foregoing discussion and Table 1 point out that Western Pacific systems most likely to exhibit relative motion in accordance with Fujiwhara expectations are located in or somewhat north of the ITCZ. The Atlantic ITCZ is, on the average, not as well-defined as the western Pacific ITCZ and does not very often lead to tropical cyclone formation. Rather, most Atlantic tropical cyclones form on perturbations which regularly move off the west coast of Africa (Frank and Clark, 1979). Consequently, the type of binary system listed in Table 1 does not have a counterpart in the Atlantic. This is consistent with Hoover's (1961) observation that most Atlantic binary systems, being farther north and subject to greater steering shear, rotate in the clockwise sense. It is also consistent with the infrequency of binary systems in the Atlantic.

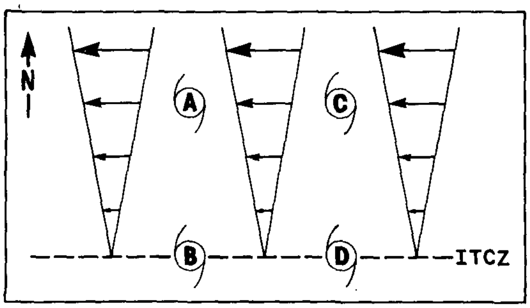

FIG. 15. A schematic diagram showing the influence of ITCZ-type horizontal wind shear on the relative motion of binary tropical cyclones.

5. Some quantitative estimates

For a number of reasons, including observational deficiencies, it is obviously difficult to distinguish between motion caused by binary interaction and that caused by the large-scale environmental steering forces. However, some semi-quantitative estimates for ITCZ disturbances can be made.

As previously depicted in Figs. 8, 11, 13, 14 and 15, when pairs were oriented along a nearly meridional axis, relative rotation was strongly influenced by shear in the environmental steering forces. Conversely, when pairs were oriented in a nearly zonal sense and aligned with a likewise nearly zonally oriented ITCZ, steering shear was small and relative rotation was influenced more by interaction of the pairs themselves.

Fig. 16, having been derived from Fig. 8 by noting the analyzed rotation rate along the major and minor axes, shows that within 4 to 10 separation distance units there is a range of approximately 19 degrees of arc rotation (distance *ab* = 18 at *x* = 10, distance *ab* = 20 at *x* = 4) which is attributable to non-Fujiwhara forces. At separation distances of less than 6.5 units (for this case), the net rotation was predominantly caused by the Fujiwhara effect (i.e., distance *bc* always exceeds distance *ab*) whereas at separation distances more than 6.5 units, the net rotation was predominantly caused by differences in environmental steering forces (i.e., distance *ab* always exceeds *bc*. For the ITCZ binary pair Ellen and Fran, illustrated in Figs. 11, 12 and 14, the crossover distance computes to ~5.8 units.

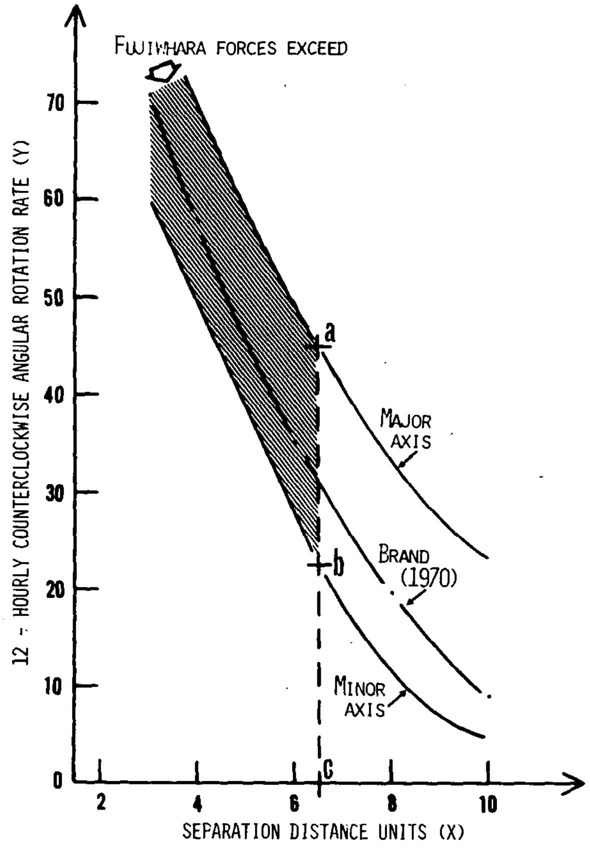

FIG. 16. Twelve-hour counterclockwise angular rotation rates as a function of separation distance (a unit of separation distance is 111.2 km, see footnote 6) for tropical cyclone pair Marie and Kathy (1964) as derived from Fig. 8. Upper curve gives rotation rate along major axis (where mutual rotation is caused by Fujiwhara and environmental steering shear) and lower curve gives rate along minor axis (where mutual rotation is caused by Fujiwhara forces alone). Center curve is Brand's (1970) regression estimate as derived from Eq. (1). Crosshatching depicts area where, in this example, Fujiwhara forces will always exceed environmental forces (distance *bc* exceeds distance *ab*).

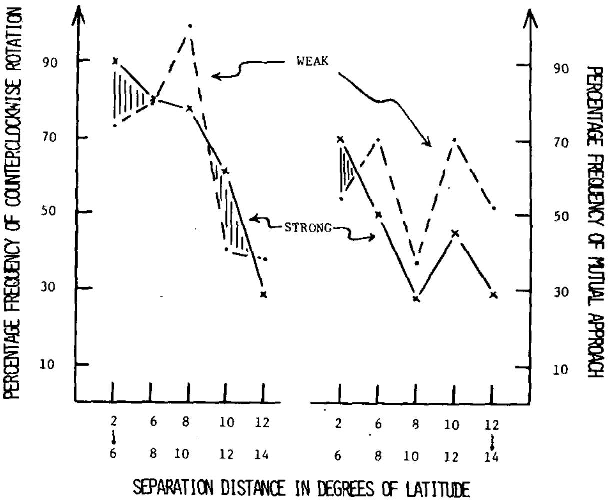

FIG. 17. Frequency distribution of counterclockwise rotation (left scale) and mutual approaching (right scale) for "strong" and "weak" pairs. Shading delimits area where higher percentages at given separation distances occurred with strong sample.

Also included in Fig. 16 is Brand's (1970) regression estimate (1) of the relationship between angular rotation rate and separation distance. In this example, it appears that the regression equation overestimates the Fujiwhara rotational forces by ~6–8 degrees of arc per 12 hours.

6. The effect of storm intensity

In order to determine the effect, if any, of storm intensity (as defined by maximum surface wind) on the computations, the sample (319 cases) was divided into two sub-groups: 1) a "strong" group where the two-storm average intensity at any given 0000 GMT or 1200 GMT synoptic hour was over 32 mps and 2) a "weak" group where the average intensity was between 20 and 32 mps. Computations similar to those displayed in Figs. 1 and 2 were made. A summary of the results is given in Fig. 17.

In accordance with accepted theory (Haurwitz, 1951), one would expect the strong sample to show greater Fujiwhara effect than the weak sample. That is, the tendency for counterclockwise rotation and for the two circulation centers to approach should be greater in the former. However, Fig. 17 shows that this is true only at small separation distances (less than 6 units). The scatter of the data at greater separation distances is presumably caused by environmental forces which mask the Fujiwhara effects. These data, when considered collectively with other evidence already cited, tend to support the overall theme of this paper: that differential environmental forces have a significant effect on the mutual behavior of binary systems.

7. Summary

1) The relative motion of tropical cyclone pairs is a function of both the Fujiwhara effect and differences in large scale environmental steering forces acting on each system. This confirms the suggestion originally made by Haurwitz (1951) and later cited by other authors as well.

2) Under certain conditions, larger-scale clockwise atmospheric forces can exceed the always counterclockwise Fujiwhara force and a net clockwise relative rotation may occur. This is sometimes true even with separation distances of less than five units (~550 km) where Fujiwhara forces are quite large.

3) Most binary tropical cyclones over the western North Pacific showed counterclockwise relative rotation and were situated in the ITCZ. When the separation distance of two ITCZ tropical cyclones is more than about six units (~650 km) the influence of ITCZ flow on relative rotation exceeded the Fujiwhara effect. When the separation distance was less than about six units, the Fujiwhara effect exceeded.

4) The infrequency of binary systems and the smaller frequency of counterclockwise rotating pair members over the Atlantic compared to the Pacific is probably related to different ITCZ structure between the two basins.

5) When considering environmental forces, estimation of binary tropical cyclone interaction in the ITCZ is shown to be reasonably close but somewhat less than that given by Brand (1970).

Acknowledgments. The authors wish to thank Judy Kraus of the National Hurricane Center for editorial work in restructuring the original manuscript. Additional editorial, drafting and photographic support was provided by the ERL National Hurricane Research Laboratory (NHRL). Appreciation is also directed to Professor Chen Chunshu for his helpful suggestions.

REFERENCES

Atkinson, G. D., 1971: *Forecasters Guide to Tropical Meteorology.* Tech. Rep. No. 240, Air Weather Service (MAC), 360 pp.

Brand, S., 1970: Interaction of binary tropical cyclones of the western North Pacific Ocean. *J. Appl. Meteor.,* **9,** 433–441.

Central Meteorological Bureau, 1972: *Northwest Pacific Typhoon Track Maps,* 1949–1969. Peking, PRC, 378 pp.

Crutcher, H. L., and R. G. Quayle, 1974: *Mariners Worldwide Guide to Tropical Storms at Sea.* (NAVAIR 50-1C-G1), National Climatic Center, 144 pp. + 312 charts.

Dong, K., 1980: On the clockwise co-rotation of typhoon twins, *Meteor. Monogr.,* No. 6, 18–19 [In Chinese].

——, 1981: On the relative rotation and the amalgamation of binary typhoons 6413 and 6414, *Acta Meteor. Sin.,* **39,** 361–370 [In Chinese].

Frank, N. L., and G. B. Clark, 1979: Atlantic tropical systems of 1978, *Mon. Wea. Rev.,* **107,** 1035–1041.

Fujiwhara, S., 1923: On the growth and decay of vortical systems. *Quart. J. Roy. Meteor. Soc.,* **49,** 75–104.

——, 1931: Short note on the behavior of two vortices. *Proc. Phys.-Math. Soc. Japan,* Ser. 3, **13,** 106–110.

Haurwitz, B., 1951: The motion of binary tropical cyclones. *Arch. Meteor. Geophys. Bioklim.,* **A4,** 73–86.

Hoover, E. W., 1961: Relative motion of hurricane pairs. *Mon. Wea. Rev.,* **89,** 251–255.

Jarrell, J. D., S. Brand and D. S. Nicklin, 1978: An analysis of western North Pacific tropical cyclone forecast errors. *Mon. Wea. Rev.,* **106,** 925–937.

Neumann, C. J., 1982: Trends in forecasting the tracks of Atlantic tropical cyclones. *Bull. Amer. Meteor. Soc.,* **62,** 1473–1485.