A STUDY ON THE RELATIONSHIP BETWEEN THE ROTATION OF BINARY TYPHOONS AND STEERING CURRENT

Bao Chenglan (包澄澜)

Department of Atmospheric Sciences, Nanjing University, Nanjing

Ruan Junshi (阮均石) and *Zhu Yaojian* (朱跃建)

Department of Meteorology, Nanjing Institute of Meteorology, Nanjing

Received October 17, 1984

ABSTRACT

Many studies show that, within a certain distance (ca. 700—800 n mi), two typhoons forming a binary typhoon (BT) system would rotate as a whole and attract each other, which is known as "Fujiwhara Effect" (FE). This paper indicates that only 30.3% of BTs has experienced remarkable cyclonic rotation with a 12-hr angle $\geqslant +10°$ when two components are less than 20° lat apart, and that the probability is much higher with the eastern component in the NE than in the SE quadrant for the western one, implying the steering effect of the enviromental flow field (EFF) on them.

47 observations from 13 BTs are separately used for calculating the angular velocity due to FE and EFF and the results are compared. The conclusion can be stated as follows: FE is dominant with the centers of two elements below 7° lat apart; the EFF steering current plays a major role when they are in the range of 7—15° and for a distance above 15° the principle of FE holds no longer.

I. INTRODUCTION

It is a well-known fact that BT (binary typhoon) is one of the major problems concerned with the typhoon's stagnation, looping and other behaviors in its course. As early as 1921—1923, Fujiwhara[1] noted that, when one vortex approaches the other, they will go around the common mass center counterclockwise in the Northern Hemisphere or attract each other, which is the famous FE (Fujiwhara Effect). Later, Haurwitz[2] calculated angular velocity of a BT by assuming the tangential wind speed distribution in a typhoon to be identical with that of Rankine Model. Brand[3] indicated in 1970, based on many case studies, significant increase in the angular velocity with reduction of the center-to-center distance for a BT system, thus giving a concept in synoptics that when two typhoons are close enough to each other, interaction occurs, but the rotation as a whole is prevalent.

In the 1960s Chinese meteorologists made preliminary study of the tracks of BTs[4,5] and since the 1970s much research has been done on it synoptically, dynamically and climatologically[6—12]. A general conclusion is achieved[13,14] that when typhoons' centers are within a distance of 20° lat, such interactions occur as stagnation, looping, cyclonic/anticyclonic rotation as a BT, mutual attraction and even mergence. But the track for each component is complicated. In addition, the BT's movement is significantly affected by the characteristics of the EFF (enviromental flow field)[15].

Since both the FE and the EFF steering effect are essential to the behaviors of a BT and they are hard to be separated, certain amount of difficulty arose in the past investigation and operational forecasting. The aim of this work is the attempt to make separate calculation of these two factors to examine their respective effect on the rotation of a BT.

II. STATISTICS

30 western North Pacific BTs from the 1961—1978 "Typhoon yearbook" are picked out with the western component close to China's coastline, to the waters west of 130°E and north of 20°N. The simultaneous appearance of two typhoons (if either of them has reached the intensity of a typhoon) is defined as the initial time of a BT whereas the time when one of them has dissipated or both merged into one is specified as the termination. A chart of the relative positions is shown with the eastern element as the origin of coordinates based on 0800 and 1200 data so as to get the 12-hr $\Delta\theta$ (positive if the rotation is cyclonic and negative if anticyclonic, hereinafter 12-hr $\Delta\theta$ is abbreviated to $\Delta\theta$) and the center-to-center distance d, with a total of 363 results. Fig. 1 depicts the relation of $\Delta\theta$ to d. When $d \geqslant 30°$ lat, $\Delta\theta$ is small and the rotation is anticyclonic, and as d decreases, $\Delta\theta$ increases rapidly, but not linearly. The rotation takes place mainly in the case of $d \leqslant 20°$ lat and the frequency of the anticyclonic type is relatively low with $\Delta\theta$ being 0 to $-10°$ for the most part. Also, the figure shows that with $d \leqslant 15°$ lat $\Delta\theta$ grows swiftly, giving a magnitude $\geqslant +10°$ in many cases, and the greater the $\Delta\theta$ is, the smaller the d is, and when $d \leqslant 10°$ lat, $\Delta\theta$ increases roughly linearly.

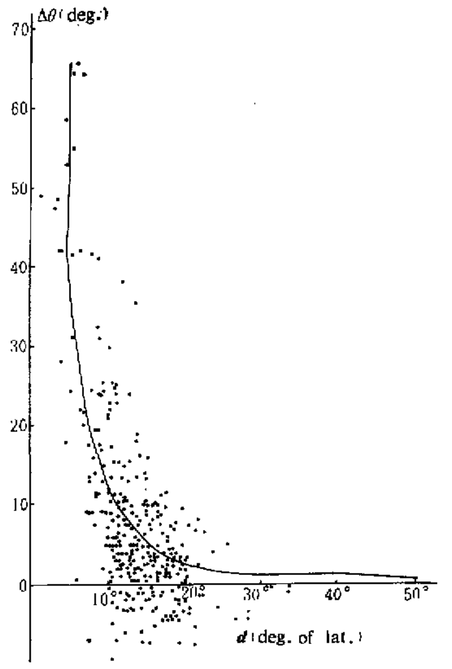

Fig. 1. Relationship between the distance d and $\Delta\theta$.

Table 1. Relationship between the Distance d and $\Delta\theta$

$\Delta\theta$ (deg.)	Distance d (in lat)			
	$d \leqslant 5°$	$5 < d \leqslant 10°$	$10 < d \leqslant 15°$	$15 < d \leqslant 20°$
$-10 < \Delta\theta < -7$	0	1	5	5
$-7 < \Delta\theta < +7$	0	7	87	83
$+7 \leqslant \Delta\theta < +10$	0	9	20	20
$+10 \leqslant \Delta\theta < +20$	1	23	29	6
$+20 \leqslant \Delta\theta < +30$	1	13	8	0
$+30 \leqslant \Delta\theta$	10	10	2	0
Total	12	63	151	141
Percentage of $\Delta\theta \geqslant 10$ (%)	100	73	25.8	5.3

For quantitative analysis of the d-$\Delta\theta$ relationship 340 from 363 cases are taken with $d \leqslant 20°$ lat. The results are indicated in Table 1. In view of the fact that $\Delta\theta$ represents the combined effect of Fujiwhara principle and the EFF current, $|\Delta\theta| \geqslant 10°$ is defined as the remarkable rotation (RR). As summarized in Table 1, out of 340 occasions only 103 have gone through RR. Further, when $d > 15°$ lat, cyclonic RR hardly happens and with $d \leqslant 15°$ RR frequency grows considerably, and if $d \leqslant 5°$ all rotations are clearly cyclonic with most $\Delta\theta$ higher than 30°.

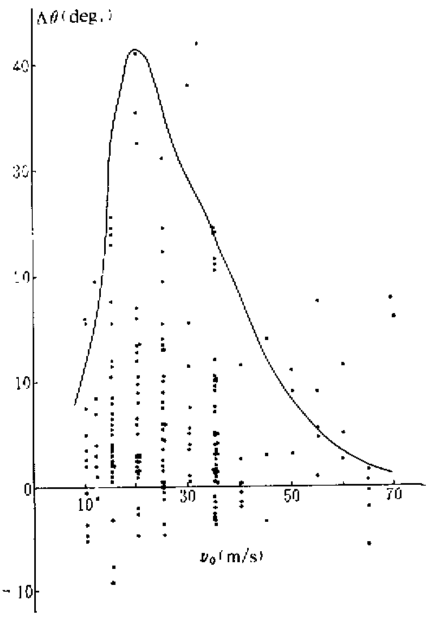

Fig. 2. Relation of $\Delta\theta$ to the intensity of western components v_0 with $5 \leqslant d \leqslant 15°$.

Alternately, it is found that RR of a BT depends on its strength. Fig. 2 gives $\Delta\theta$ in relation to the surface windspeed near the center of a western component (for denoting its intensity) under the condition of $5 \leqslant d \leqslant 15°$ lat. For BTs with RR almost all windspeeds of western tempests range from 15—35 m s^{-1}, the enveloping line showing a peak form, and those of eastern ones between 25 and 40 m s^{-1} (figure omitted). Similar characteristic distribution is exhibited in the dependence of $\Delta\theta$ on the pressure of both elements of a BT. About 80% of RR comes along when the pressure is between 960—1000 hPa in the cores (figure omitted). This fact shows that only when both components have moderate strength with small difference in between, is a favorable condition provided for RR, otherwise the process would be suppressed.

Statistics is therefore made of 210 in 340 data with maximal surface near-center windspeed difference of $\Delta v_m = 20$ m s^{-1}, a condition denoting both typhoons are of approximately equal intensity and we have Table 2.

Table 2. The Azimuth of the Eastern to the Western Typhoon Both Basically Identical in Strength in Relation to $\Delta\theta$*

d (in lat)	Eastern Typhoon in NE Quadrant		Eastern Typhoon in SE Quadrant**	
	RR	Not RR	RR	Not RR
$0 < d \leqslant 5°$	6	0	1	0
$5 < d \leqslant 15°$	41	50	7	32
$15 < d \leqslant 20°$	4	26	2	41
Total	51	76	10	73

* The azimuth of the eastern typhoon to the western is taken based on the 0800 and 1200 LST situations.
**Referring to the eastern typhoon located relative to the western one.

Thus the following summary can be given:

(1) Out of a total of 210 observations only 61 are with RR, accounting for 61/210=29.0%. On the 210 occasions there are 127 with eastern typhoons in the NE quadrant, with 51 cases having RR, making up 51/127=40.1% and 83 in the SE, with only 10 RR, 10/83=12.0%.

(2) When the distance is longer ($15 < d \leqslant 20°$ lat), the frequency of RR is 4/30=13.3% and 2/43=4.7% for the NE and SE quadrant, respectively. This means that the overwhelming majority of the BTs under study produce no RR in such circumstances.

(3) When two components are quite close to each other ($d \leqslant 5°$ lat), the BT will undergo RR with no exception regardless for the azimuth of the eastern typhoon.

(4) If $5 < d \leqslant 15°$ lat and the eastern typhoon is in the NE quadrant for its counterpart, then RR occurs with the frequency of 41/95=45.1% and, by contrast, it is only 7/39=17.9% when the eastern element is in the SE.

We have then come to the conclusion that FE is applicable to the BTs with $d \leqslant 5°$ but not to those having $d > 15°$, and for $5 < d \leqslant 15°$ lat the BTs will go through RR in close relation to the azimuth of its eastern component. It is assumed that in most cases the BT stays in the situation with the subtropical high in the E-W or SES-WNW direction; when the eastern typhoon is in the NE quadrant, it is acted upon by the EFF steering current which is directed towards the west or northwest whereas the western element is affected to less extent and irregularly so as to favor the cyclonic rotation of a BT (even so, the RR has probability of 45.1% only); when the eastern typhoon is in the SE quadrant, the line through both centers is parallel to the subtropical high ridge line so that both typhoons are steered equally by the current, a condition unfavorable to the BT's rotation, merely with the RR probability of 17.9%. It is obvious that the EFF steering effect is of vital importance to the track of a BT.

III. CALCULATION

Separate calculations are made for a particular BT to examine FE and the steering effect. This scheme is based on the assumption of Rankine Vortices. A typhoon can be divided into two parts: an inner core and outer belt. The radius of the core is set to be r_m. In the area of $r < r_m$ the windspeed regime satisfies the condition v/r = constant, and in the region of $r > r_m$ vr = constant. And v_{m1} and v_{m2} denote the maximal windspeed of Typhoon 1 and Typhoon 2, respectively (see Fig. 3). Thus we can get additional velocity of one component caused by the other (or residual velocity) through FE in the forms:

$$v_{F1} = \frac{v_{m2}\, r_{m2}}{d}, \quad v_{F2} = \frac{v_{m1}\, r_{m1}}{d}, \tag{1}$$

and the angular velocity $\Delta\theta_F$ can be obtained

$$\Delta\theta_F = \frac{r_{m1}v_{m1} + r_{m2}v_{m2}}{d^2}. \tag{2}$$

In our work both counterparts of a BT are calculated with data taken from the "Typhoon Yearbook". All values of 700 hPa maximal windspeed radii r_{m1} and r_{m2} as well as v_{m1} and v_{m2} are employed, which differs from the methods for mean values of relevant parameters of typhoons used by some investigators in their research.

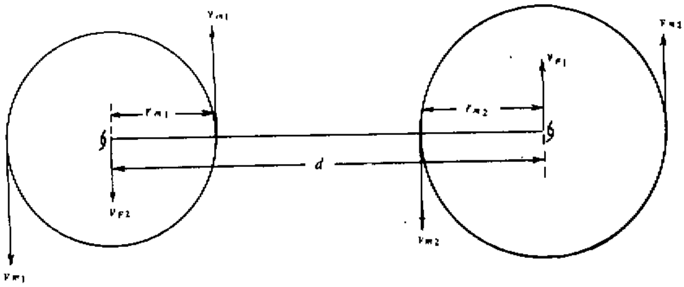

Fig. 3. The interaction of Rankine Vortices.

Next, the method developed by Abe and Najazawa[16] is employed for v_{s1} and v_{s2}, effect of 700-hPa steering current on both typhoons, respectively. This procedure can be described as follows: (1) to carefully analyse the 700-hPa contour pattern to locate m, the col point in the saddle field, near the typhoon and to draw a circle with the core as the center and the distance from the core to m as the radius; (2) to find M, a point of maximal geopotential height and the mean height between M and m, with these mean points a and b marked in the circle; (3) to connect a and both closest to the typhoon core, a line considered as showing the direction of steering current (generally M always to the right and m to the left of the line) and (4) to determine the speed of the steering current by the geostrophic wind formula on the natural coordinates with the M–m distance and their height values. An example is shown in Fig. 4.

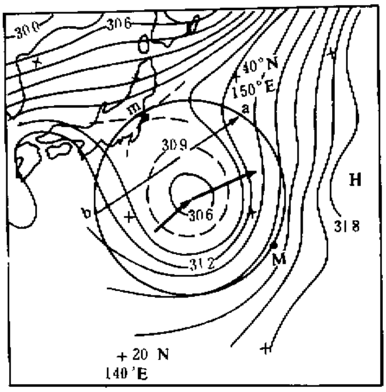

Fig. 4. Calculation of steering effect for Typhoon Wanda (7706) (from Abe and Nakazawa, 1982). Arrows denote the direction the typhoon was moved.

In view of a proportional relationship[17] between the actual speed of the components and the speed of the current, 1.2, 1.0, 0.8 and 0.6 v_s are taken for comparison. These two types of speed are made composite in the form of vectors:

$$\mathbf{v}_c = \mathbf{v}_s + \mathbf{v}_F \ . \tag{3}$$

Then we can have

$$\Delta\theta_c = \Delta\theta_s + \Delta\theta_F \ , \tag{4}$$

where $\Delta\theta_s$ is the 12-hr rotational angle of a BT due to steering effect obtained from the 12-hr relative position of both typhoons with v_{s1} and v_{s2} already known, and $\Delta\theta_F$ dentoes the angle produced by FE.

Table 3. Comparison of BT's Real Angular Velocity to That Obtained through Calculation

Difference in Angular Velocities	Mean Error (deg.)	Mean Relative Error* (%)
$\Delta\theta_F - \Delta\theta$	−13.0	+55
$1.2\Delta\theta_c$** $- \Delta\theta$	+11.2	+68.2
$1.0\Delta\theta_c - \Delta\theta$	+ 7.1	+48.3
$0.8\Delta\theta_c - \Delta\theta$	+ 3.7	+27.6
$0.6\Delta\theta_c - \Delta\theta$	−0.03	+ 2.7

* The mean relative error is the average of 47 $(\Delta\theta_F - \Delta\theta)/\Delta\theta$ or $(\Delta\theta_c - \Delta\theta)/\Delta\theta$.

** Such terms as $1.2\Delta\theta_c$ and $1.0\Delta\theta_c$ denote the total rotational angle consisting of $\Delta\theta_s$, which is obtained through v_s multiplied by an empirical coefficient, and $\Delta\theta_F$, e.g. $1.2\Delta\theta_s + \Delta\theta_F = 1.2\Delta\theta_c$.

Then $\Delta\theta_c$ and $\Delta\theta_F$ are compared separately with the observed 12-hr angle $\Delta\theta$. Calculation is made of 47 observations selected from 13 BTs experiencing RR with $5<d\leqslant 20°$ lat. The results are shown in Table 3. The angle caused by FE is considerably smaller than the actual one, and with steering effect included, it is apparently larger but the mean error diminishes. When the effect of the EFF is multiplied by an empirical coefficient of 0.6, the calculations are in good agreement with the real state of affairs. The mean error of the 12-hr rotational angle of a BT is only -0.03, implying that for most BTs ($5<d\leqslant 20°$ lat) the steering effect has at least the same order as FE or veen greater.

In calculating the 47 observations the mean rotational angle in 12 hours is figured out for different distances d. The relation of observed angles to the distances between centers is depicted in Fig. 5. Obviously, the curves of $\Delta\theta_c$ in the range between 7—15° lat not only have the same orientation as the observed trends but the (0.6—0.8) $\Delta\theta_c$ magnitude quite close to those of $\Delta\theta$ as well. By contrast, $\Delta\theta_F$ differs from $\Delta\theta$ in both aspects to a considerable extent. It follows that the EFF plays a major role when d is within 7—15° lat. For $d<7°$ very little improvement is achieved in the composited $\Delta\theta_c$ as compared with the actual $\Delta\theta$, suggesting a primary role of FE in these intervals. $\Delta\theta_F$ are all below 5° per 12 hr under the condition $d>14$—15° lat, indicating that this principle is no longer applicable.

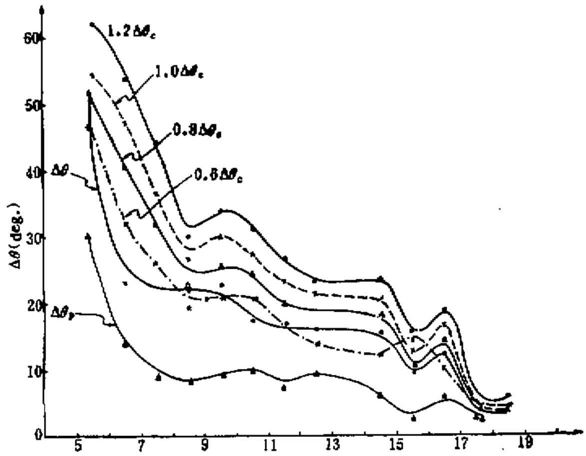

Fig. 5. Relationship between d and mean $\Delta\theta$.

It is also worth noting that both components of a BT can attract each other besides their rotation about the common mass center. As they become nearer, the 12-hr rotational angle grows appreciably large. As an example, a detailed analysis is carried out of the courses of extraordinary Typhoons 7009 and 7010[18], which have been taken from the "Typhoon Yearbook", and in the opinion of the editor, merged into one after 0600z, 6 September, 1979. Our calculations, however, showed that these tempests did not do so but experienced as a whole extremely RR when $d\leqslant 2°$ lat, whose rotational angle increased 3—5 times, amounting to 200° or so in 12 hr. In doing so, both moved towards the west under the action of the EFF steering current. In the end, they landed in different places of Fujian Province for 1800 LST, 7—0200 LST, 8 of the month. For 4 other BTs recorded for 1956—1968, on account of instensity the attractive force was greater than centrifugal effect and this led to the mergence of the counterparts into one.

IV. CASE STUDY

Three sets of typhoons are illustrated for the applicability of FE on these systems with $5<d\leqslant 15^\circ$ lat. (See Table 4).

Table 4. The Deviations of $\Delta\theta_F$ from $\Delta\theta$ for Three BTs (data taken at 0800 and 2000 LST only)

Set of Typhoons	Date/time	d	$\Delta\theta$	$\Delta\theta_F$	$\Delta\theta_F-\Delta\theta$
7203/7205	Jul. 13, 08	14.6	10.0	9.7	−0.3
	20	12.2	12.0	14.5	+2.5
	14, 08	9.8	21.5	15.5	−6.0
	20	10.0	21.0	17.2	−3.8
7203/7206	Jul. 22, 20	11.1	14.0	8.5	−5.5
	23, 08	9.8	12.0	10.1	−1.9
6413/6414	Aug. 15, 20	9.1	17.0	2.2	−14.8
	16, 08	8.6	32.5	2.7	−29.8
	20	7.8	41.5	3.3	−38.2
	17, 08	7.8	24.5	3.8	−20.7
	20	7.4	20.5	5.1	−15.4
	18, 08	6.7	20.0	8.9	−11.1

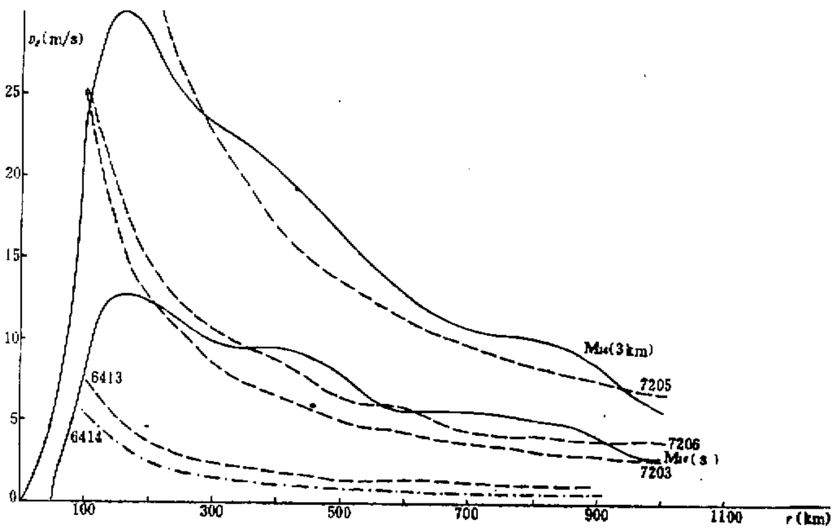

Fig. 6. Curves of tangential windspeed v_θ for some typhoons and their comparison with the mean.
M_{14}(3 km) refers to the mean at the level of 3 km for 14 typhoons from Izawa and M_{14}(s) that at the surface. The variations of v_θ with the typhoon radius r for the other cases are all in accordance to the model vr=const.

Fig. 6 depicts distributions of surface and 700-hPa tangential windspeed along the radius r for these typhoons and the mean one from Izawa[19] for comparison. It is apparent that Typhoons 7203 and 7206 well accord to the mean in surface windspeed curves and 7205 has a similar trend (based on model vr =constant) to that of the mean at the 700 hPa level, with the calculated $\Delta\theta_F$ rather close to observed $\Delta\theta$. On the contrary, Typhoons 6413 and 6414, according to the model just mentioned, give essentially different results from those of the mean of 14 observed systems and the calculated $\Delta\theta_F$, therefore, differ considerably from $\Delta\theta$. It appears that the surface tangential windspeed pattern similar to the results from vr= constant is one of the important conditions for applicability of FE.

With regard to the weather situation it is found that, the calculated $\Delta\theta_F$ has small deviation from $\Delta\theta$ mainly when the eastern component is in the NE quadrant. In this case, the typhoon is bordered on the N-NE by the stronger subtropical high whereas its counterpart is under the weaker influence of the EFF. Another situation is that the BT has the same pattern and both components are confined within a closed contour, implying that the steering effect has the same direction as FE, the strength being comparable to or even greater than the latter.

Greater difference between $\Delta\theta_F$ and $\Delta\theta$ occurs when a BT, for example, Typhoons 6413 and 6414, is within the E-W convergence belt. In this case the BT lies nearly in the WNW-ESE direction with a E-W subtropical high on the north side, thus facilitating faster rotation when it is in the N-S direction than when in the other[15]. This shows the importance of the steering effect on the rotation of a BT.

V. CONCLUSIONS

From the above the results can be summarized as follows:

(1) When within 20° lat, both typhoons composing a BT, will as a whole produce RR around the mass center and mutual attraction. The 12-hr rotational angle increases with the distance decreasing from center to center.

(2) The principle of the rotation due to the flow fields of both components, i. e. FE, is certainly applicable to the system with $d<5°$ and unapplicable if $d>15°$ lat.

(3) For $5<d\leqslant 15°$ lat both components depend strongly on their relative positions for RR. When the eastern one is in the NE quadrant with respect to the western one, RR accounts for about 45% while in the SE roughly 18%. In the latter situation both steering current and FE are effective, the former being dominant.

(4) The calculation results show that $\Delta\theta_c$ obtained with the EFF effect (multiplied by 0.6) considered is much closer to the observed $\Delta\theta$ than $\Delta\theta_F$ given by FE alone, indicating the momentous effect of the EFF, especially with d in the range 7—15° lat. If $d<7°$ lat, the improvement is not significant, that is, FE plays an important part in this case.

(5) If both counterparts are in close proximity (with $d\leqslant 2°$ lat), the rotational angular speed may increase 3—5 times, amounting to about 200° per 12 hr.

(6) It follows that FE is applicable only with $d<7°$ lat; when d is 7—15°, both types of effect come into action, but with the EFF predominant; If $d>15°$, FE inevitably goes out of action.

(7) Two determinant factors in judging the rotation are FE $\Delta\theta_F$ (inversely proportional to d) and the steering effect $\Delta\theta_s$ (the longer the d, the greater the effect on rotation as compared with $\Delta\theta_F$). Based on the statistics of 47 observations with $5<d\leqslant 15°$ lat an empirical formula is developed for predicting the 12-hr angle, i. e.

$$\Delta\theta_a=\frac{8}{d}\Delta\theta_F+\frac{d}{15}(\Delta\theta_s-\Delta\theta_F), \tag{15}$$

where $\Delta\theta_F$, $\Delta\theta$, and d are as indicated above and their values can be obtained from observational data.

This expression proves to be well-fitted after comparing the 40 observations with $5<d\leqslant 15°$ lat to the calculations. The total difference $\sum_1^{40}\Delta\theta_a-\sum_1^{40}\Delta\theta=952.8°-959.5°$ in which the error $\delta\theta=\Delta\theta_a-\Delta\theta\leqslant 5°$ lat occurs 18 times and $5<\delta\theta\leqslant 10°$ lat 11 times. It is suggested that this formula be used in operational forecasting.

REFERENCES

[1] Fujiwhara, S., *Quart. J. Roy. Met. Soc.*, 47(1921), 200.
[2] Haurwitz, B., The motion of binary tropical cyclone, *Archir for Met. Geophy. Bioklimat, Ser. A*, Band 4, 1951.
[3] 牟维丰，陆家珪，西太平洋双台风路径类型，气象通讯，1962, 11:10—18.
[4] 栾宝储，陆菁俊，气象通讯，1963, 7: 附刊，5—7.
[5] S. Brand, *J. Appl. Met.*, 9(1970), 3:, 433—441.
[6] 吴中海，大气科学，5(1981), 32—42.
[7] Khandeker, M.L. and G.V. Rao, *Mon. Wea. Rev.*, 99(1971), 11:840—846.
[8] 唐东昇，朱平，1983年全国台风会议文摘（预印本），全国台风会议技术组编.
[9] 魏丁文，张捷迁，双台风相互作用的流体力学模拟实验研究，国际台风讨论会 上海，1980.
[10] 上海中心气象台，天气预报技术经验汇编第三集，中央气象局编，1973.
[11] 陈企岗等，1981年全国台风会议文集，上海科学技术出版社，1983.
[12] 王作述，傅秀琴，大气科学，7(1983), 3:269—276.
[13] 陈联寿，丁一汇，西太平洋台风概论，科学出版社，1979.
[14] 包澄澜，热带天气学，科学出版社，1980.
[15] 董克勤，气象学报，39(1981), 3:361—370.
[16] Shiges Abe and Yasushi Nakazawa, *J. Met. Soc. Japan.*, 60(1982), 8:947—955.
[17] Gray W.M., 11*th Technical Conference on Hurricanes and Tropical Meteorology*, 1977.
[18] 包澄澜，气象学报，39(1981), 3:378—384.
[19] Izawa, T., Tech. Note, Typhoon Res. Lab., Met. Res. Inst., 1964.