The Speed of Recurving Typhoons over the Western North Pacific Ocean[1]

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ABSTRACT

Western North Pacific tropical cyclone data were evaluated for the period 1970–79 to determine characteristics of recurving typhoons near and after recurvature. Case studies revealed a good relationship between typhoon movement speed after recurvature and the upper tropospheric winds at and before recurvature observed along the future typhoon track. This relationship was then determined for a sample of 71 recurving typhoons from 1962 through 1978 and compared with operational forecasts for a subsample of 29 typhoons in 1972–78. The derived simple aid could have reduced the average forecast speed errors by more than 50% in the subsample.

1. Introduction

One of the most important aspects of typhoon track forecasting is recurvature. The largest errors in mean forecast position are associated with recurvature and are due mainly to acceleration after recurvature. In a statistical study of recurving typhoons for the period 1961–69, Burroughs and brand (1973) (noted hereafter as B and B) showed that 24 h forecast errors increased from 212 km for nonrecurving typhoons to 252 km for recurving typhoons and further to 306 km for forecasts after recurvature. Using a larger data sample (1945–69), they determined the seasonal frequencies and areas of recurvature and the movement velocities before and after recurvature and derived multiple regression equations to aid forecasting the speed of movement after recurvature. In addition, they examined synoptic situations during recurvature and devised some "rules of thumb" that related the large scale circulations to storms with greater or less acceleration than average after recurvature. However, since their study, the operational forecasts after recurvature have not improved. Twenty-four hour errors for 1978–80 typhoons were 193 km for nonrecurvers, 240 km for recurvers, and 340 km after recurving.

This paper, condensed from Bao and Sadler (1982), examines the statistics of recurving typhoons for the period 1970–79 and, through case studies, identifies features observed at and before recurvature for use as aids in forecasting speed after recurvature.

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2. Data sources

Movement velocity and intensity of typhoons are extracted from the Annual Typhoon Reports (1970–79) of the Joint Typhoon Warning Center (JTWC) at Guam. Selected periods of synoptic charts and additional data were obtained from: 1) Typhoon "data packages" from JTWC, containing analyzed operational charts for the surface, 700, 500 and 200 mb levels, satellite data, eye fixes, warning messages, etc.; 2) Daily synoptic charts on microfilm from the Royal Observatory, Hong Kong; 3) Daily synoptic charts and tabulated data published by the Japan Meteorological Agency; 4) 500 mb prognostic charts from the Fleet Numerical Oceanography Center (FNOC); and 5) Mean monthly wind charts from Sadler and Harris (1970) and Ramage and Raman (1972).

3. General features of recurving typhoons

From the Annual Typhoon Reports (1970–79), we considered only those 71 typhoons which recurved over the western North Pacific or the South China Sea, excluding those that crossed the coast of mainland China.

Recurvature is defined as a heading change from a basically westerly to a basically easterly direction (Burroughs and Brand, 1973).

a. Track types

The tracks of recurving typhoons can be classified into three general types (Fig. 1). The most frequent (a regular clockwise parabola) was followed by 50 typhoons. The motion changed uniformly from west-northwestward to northeastward. In the second type (10 cases) recurvature was delayed. Movement

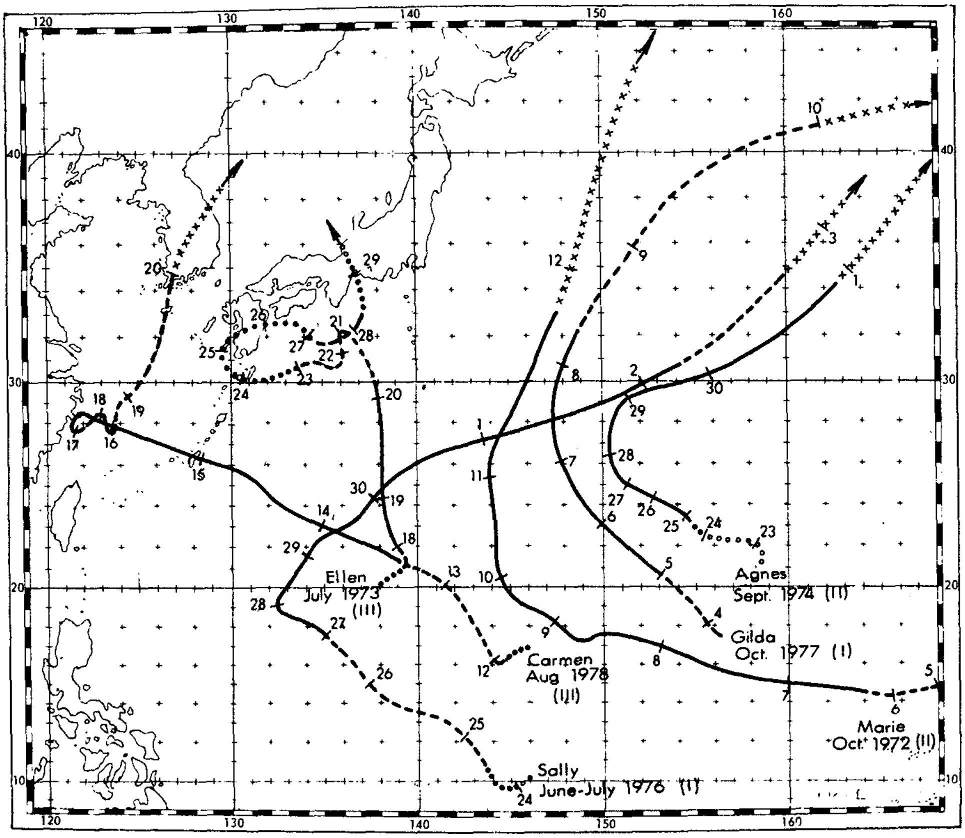

FIG. 1. Illustration of three common types of recurving typhoon tracks. See text for discussion of types.

changed gradually from west-northwestward to prolonged northward before becoming northeast. The third type (11 cases) had erratic behavior during recurvature by looping or stalling for a few days or weakening to less than tropical storm intensity or a combination of these.

b. Frequency

The monthly distribution of all typhoons and recurving typhoons during 1970–79 are shown separately in Table 1.

Types 1 and 2 were combined and listed as normal recurvers. Type 3, (the 11 erratic typhoons) 10 of which occurred in midsummer, are listed separately for they could not be used in some of the subsequent statistics. The frequency of recurving tropical storms and typhoons during May–December for the 25-year period 1945–69 from B and B comprises the last line of Table 1.

Forty-seven percent (71) of the 150 typhoons in our ten-year period recurved over the western North Pacific. Forty-nine (44%) of 112 recurved during the main typhoon season (July–October). Of 22 August typhoons, 14 (64%) recurved. In spring (March–June), the ratio is highest (12 of 17)—70%.

The monthly recurvature frequencies differed con-

TABLE 1. Monthly frequency of recurving typhoons for the years 1970–79.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total sample
Normal recurvers	1		1	5	3	3	6	10	13	10	6	2	60
Erratic recurvers	1						3	4	3				11
Total number of recurving typhoons	2	0	1	5	3	3	9	14	16	10	6	2	71
Total number of typhoons	4	1	1	6	4	6	26	22	34	30	11	5	150
Percent of typhoons recurving 1970–79	50	0	100	83	75	50	35	64	47	33	56	40	47
Percent of recurving typhoons and tropical storms (B and B)					58	35	20	34	43	55	49	38	40

siderably between the ten-year period and the preceding 25 years. The 30% increase in August and 22% decrease in October were the most dramatic. For the combined months of May–December the frequency of recurvers increased from 40 to 46%. These differences cannot be attributed to the inclusion of tropical storms by B and B for tropical storms have a higher recurvature rate than typhoons. Sixty percent of tropical storms recurved during 1970–79. The recurvature rate of typhoons was particularly high (65%) during the three years of 1978–80 and increased to 75% in 1981.

c. Maximum intensity relative to recurvature

In a statistical study of the intensity of recurving typhoons, Riehl (1972) showed that of 66 typhoons of 1957–68, 43 (65%) reached maximum intensity within ±12 h of recurvature, 22 (30%) reached maximum intensity one day or more before recurvature, and only one reached maximum intensity one day after recurvature. Our statistics differ (Table 2). Of 60 typhoons, only 24 (40%) reached maximum within ±12 h of recurvature, and 24 (40%) reached maximum intensity 18 h or more before recurvature. Twelve of the 60 typhoons reached maximum intensity 18 h or more after recurvature. Of the 10 typhoons which attained maximum intensity 54 h or more before recurvature, 8 were supertyphoons with wind speeds >65 m s^{-1}.

In this ten-year period, there were 31 supertyphoons—17 non-recurving and 14 recurving. Among the latter (Table 3), 13 attained an intensity of ≥65 m s^{-1}, then recurved ≥30 h later. Six of these 13 recurved ≥78 h later (the greatest lag was seven days). Only one typhoon attained supertyphoon intensity 12 to 24 h before recurving and none attained this status at or after recurvature.

d. Speed of movement relative to recurvature

Table 4 gives the change in typhoon movement speed within ±36 h of recurvature. More than half (52%) of the recurving typhoons were moving slowest on recurvature. Forty percent accelerated while only 7% slowed through the −36 to +36 h period about recurvature.

TABLE 2. Time of maximum intensity about the recurvature point* for the 60 type 1 and 2 recurving typhoons during 1970–79.

Time (h)	≤ −78	−72 to −54	−48 to −18	−12 to +12	+18 to +48	≥ +54	Total
Frequency	6	4	14	24	7	5	60
Percentage	10	7	23	40	12	8	100

* The point where the typhoon track attains an eastward component. If more than one, the most poleward is specified.

TABLE 3. Time of initial supertyphoon intensity about the recurvature point for the 14 recurving supertyphoons during 1970–79.

Time (h)	≤ −78	−72 to −54	−48 to −30	−24 to −12	Total
First time for $V \geq 65$ m s^{-1}	6	2	5	1	14

4. Case studies of typhoons which accelerated after recurvature

a. History of selected typhoons

Three 1979 typhoons were selected. Typhoons Irving in August, Owen in September, and Tip in October rapidly accelerated after recurvature, leading to greater than average forecast errors. Their histories are summarized in Figs. 2–4 and Table 5.

Irving was relatively weak (45 m s^{-1}); Owen was of moderate intensity (55 m s^{-1}); and Tip was a supertyphoon (85 m s^{-1}) with the lowest sea level pressure and largest circulation diameter on record (Dunnavan and Diercks, 1980). Irving recurved near time of maximum intensity, Owen three days after, and Tip more than five days later. Irving did not accelerate until 18 h after recurvature. Owen accelerated six h after recurvature and Tip was already accelerating at recurvature. The rate of acceleration, measured by the ratio of the average speed during four days before recurvature to that for 42 h after recurvature ($\bar{C}_a/\bar{C}_b$) shows that Tip (5.15) accelerated faster than Owen (4.22) and both accelerated much faster than Irving (2.84). The recurvature tracks were also quite different. Irving moved NNW for several days and recurved gradually; Owen also underwent prolonged recurvature with two distinct recurvature points (the most northern one was defined as the recurvature point); and Tip followed a parabola.

We first screened and studied the material available from JTWC—analyses, forecasts, prognostic reasonings, objective forecasts, etc.—to identify the major forecast problems and to reexamine the recurvature periods for any synoptic clues that may have been overlooked or misanalyzed under operational pressure and time limitations.

TABLE 4. Change in typhoon movement speed about recurvature for the 60 normal recurving typhoons during 1970–79.

	C increasing throughout −36 h to +36 h about recurvature	C is minimum −12 h to +12 h	C decreasing throughout −36 h to +36 h about recurvature	C is maximum −12 h to +12 h	Total
Frequency	24	31	4	1	60
Percentage	40	52	7	2	100

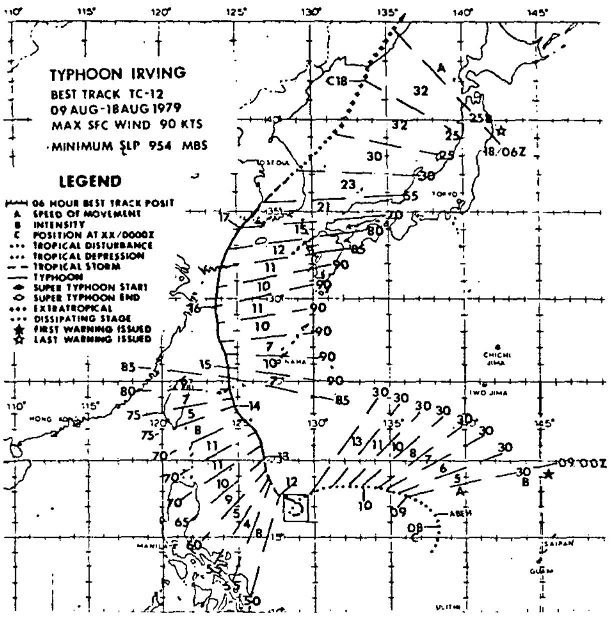

FIG. 2. Typhoon Irving track in 1979. Dates are shown for 0000 GMT positions. (From JTWC, 1979).

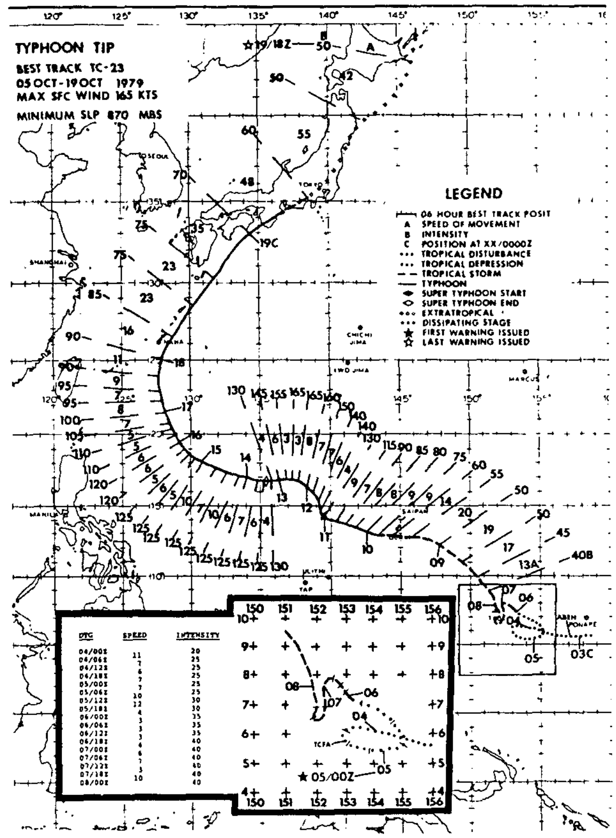

FIG. 4. As in Fig. 2 except for Typhoon Tip.

b. *Forecast errors relative to recurvature*

Forecasting for all three typhoons was more difficult than average. The average 24 h error (the distance between the forecast position and the best track position) for all tropical cyclones in 1979 was 230 km compared to 300, 270 and 250 for Irving, Owen and Tip, respectively. While still depressions or tropical storms (Figs. 2–4), all three had above average forecast errors due to erratic tracks; however, the largest errors were made after recurvature (Table 6). These were due mainly to acceleration because JTWC forecast the directions very well. Irving did not begin to accelerate until 18 h after recurvature and so the errors were below average for the 24 h forecast made at and 6 h after recurvature. Because it was moving slowly, the errors for Owen were also below average for the first two forecasts after recurvature. Tip accelerated through recurvature; the large forecast error of 535 km made at recurvature was more than twice the error of the forecast made 12 h earlier.

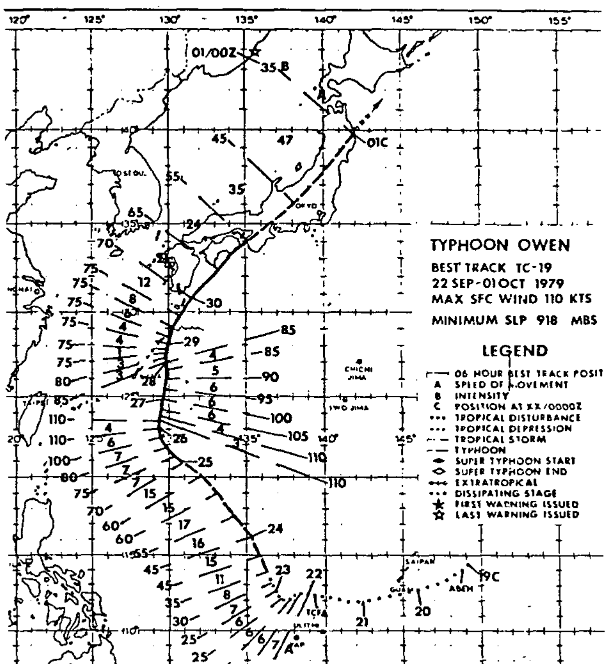

FIG. 3. As in Fig. 2 except for Typhoon Owen.

The "jogs" in the long northerly tracks of Irving and Owen produced some false recurvature forecasts with a few moderately large forecast errors. The tracks during this period probably reflect the complexity of the upper tropospheric circulation; for in summer the western Pacific experiences a double ridge system (subequatorial and subtropical) separated by the tropical upper tropospheric trough (TUTT). The 200 mb analysis (after JTWC) at 1200 GMT on 13 August (Fig. 5) near the beginning of Irving's northerly movement and when the first JTWC recurvature forecast

TABLE 5. Typhoon histories.

	Typhoon		
	Irving	Owen	Tip
Recurving time	0000 GMT 16 Aug	0000 GMT 29 Sep	1800 GMT 17 Oct
Recurving position	30°N, 124°E	28°N, 130°E	24°N, 128°E
V_{max}	45 m s^{-1}	55 m s^{-1}	85 m s^{-1}
Time lag of V_{max} to recurvature	−6 h	−72 h	−132 h
Average speed $\bar{C}_b$ for 4 days before recurvature	4.2 m s^{-1}	2.9 m s^{-1}	3.4 m s^{-1}
Average speed $\bar{C}_a$ for 42 h after recurvature	11.8 m s^{-1}	12.3 m s^{-1}	17.4 m s^{-1}
$\bar{C}_a/\bar{C}_b$	2.84	4.22	5.15

was made shows that Irving, at 22°N, had passed through the subequatorial ridge (SER) and was located between the latitudes of the SER and the TUTT with westerly flow to the east. However, although the subtropical ridge (STR) was in its normal latitude of 30°N over China, both the TUTT (33°N) and STR (38°N) near Japan were north of normal (Sadler and Harris, 1970; Ramage and Raman, 1972). A storm located between the SER and the TUTT usually drifts northwestward in the central Pacific (Sadler, 1976). Irving finally recurved at 30°N on the 16th after the TUTT and western Pacific segment of the STR had retreated southward to their normal positions.

At the first recurvature point of Owen (Fig. 6), the 200-mb circulation differed from that described for Irving. By 27 September, the STR over China had undergone its normal seasonal shift southward to near 22°N, and Owen began to recurve near this latitude; however, the western Pacific branch of the STR, north of the TUTT, was near 29°N, and Owen turned back to a northerly track and did not recurve until crossing the latitude of this ridge on the 29th.

TABLE 6. 24 h forecast errors (km) at and after recurvature for typhoons Irving, Owen and Tip.

Irving		Owen		Tip	
Forecast made at August/ GMT	Error	Forecast made at September/ GMT	Error	Forecast made at October/ GMT	Error
16/0000	72	29/0000	152	17/1600	535
16/0600	126	29/0600	156	18/0000	610
16/1200	405	29/1200	364	18/0600	800
16/1800	530	29/1800	613	18/1200	1000
17/0000	540	30/0000	772	18/1800	730
17/0600	670				
Average	390		410		750
Average error for total lifetime	300		270		250

During the recurvature of Tip, the upper tropospheric circulation was more simple than for either Irving or Owen. By mid-October, the TUTT had receded eastward of 150°E and the STR had moved southward to 24°N over the western Pacific southeast of Japan and tilted southwestward to link smoothly with the STR over east China near 21°N. Tip followed a smooth recurve path centered at 24°N on the 17th.

The subjective track forecasting of Irving and Owen using satellite pictures was discussed by Bao (1981).

c. Evaluation of objective forecast aids

The Fleet Numerical Oceanography Center (FNOC), using a tropical cyclone model (TCM) with interactive boundary conditions provided forecasts for operational testing at JTWC during the 1979 typhoon season. Typhoons Irving, Owen and Tip were positioned within the densest available data during and after recurvature and therefore ensured optimum model performance. TCM forecasts, available at 12

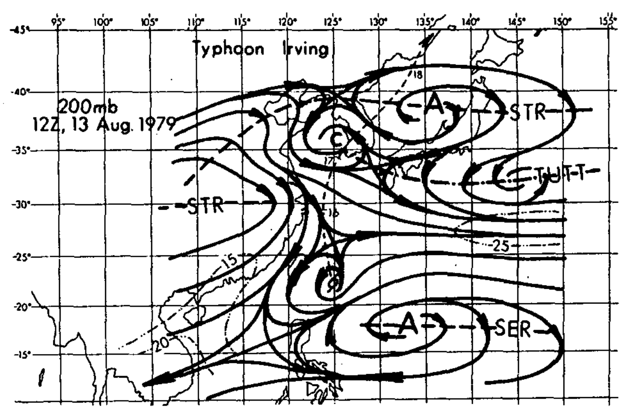

FIG. 5. 200 mb streamline analysis at 1200, GMT, 13 August (after JTWC). Wind speed in m s^{-1}. Position of Irving shown by tropical cyclone symbol and track is dashed line.

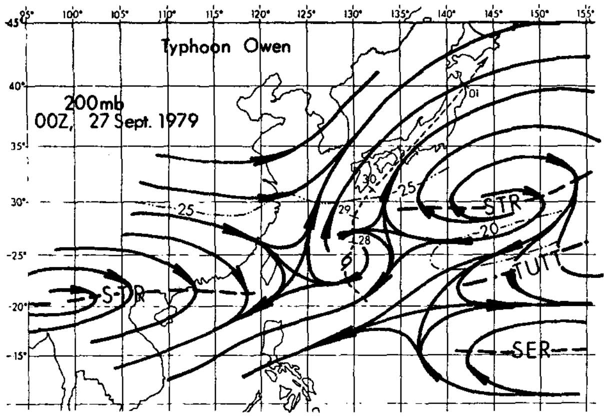

FIG. 6. 200 mb streamline analysis at 0000 GMT 27 September (after JTWC). Wind speed in m s^{-1}. Position of Owen shown by tropical cyclone symbol and track is dashed line.

h intervals, are compared to JTWC forecasts in Table 7. The model forecast errors greatly exceeded those of JTWC for every forecast during and after recurvature.

Also shown in Table 7 are forecasts using the statistical regression equations of B and B. The forecast for Irving was good but those for Owen and Tip were much too slow.

d. Upper tropospheric flow and typhoon acceleration after recurvature

1) 200 mb FLOW PATTERNS

Large forecast errors after recurvature, such as occurred with Typhoons Irving, Owen and Tip, are likely to be first attributed to a failure to forecast conditions *west* of the recurvature. This involves movement and/or deepening of an upper tropospheric trough which may greatly accelerate the southwesterly flow over and around the typhoon and cause it to rapidly accelerate.

A study of the JTWC 200 mb analyses and an evaluation of the FNOC 12, 24, 36 and 72 h, 500 mb wind forecasts showed definitely that such a forecast error was not a factor. No significant troughs formed in or moved across the regions of the typhoons (Figs. 7–9). Allowing for the normal southward seasonal shift of the jet from August to October, the position and time changes of the jet axis with respect to the typhoons were similar. For three days prior to recurvature, a slight ENE to WSW tilt of the jet axis remained unchanged as did the position of the jet core northwest of the typhoons in north central China. Also, the latitude of the 200 mb ridge over south China changed very little. Obviously, no trough perturbations traversed the areas west of the typhoons during the three-day periods prior to recurvature.

Near recurvature time, the jet axis started to rotate counterclockwise, shifting northward to the north and east of the typhoons, and slightly southward to the west. After recurvature, the typhoons moved parallel to the jet axis. The change in orientation of the jet axis during recurvature was not due to a transient trough in the westerlies but probably to the *effect of the typhoons* (see below).

Since no major transient systems in the westerlies were involved, we investigated the structure of the upper troposphere north of the typhoons in the vicinity of their future tracks. Vertical wind profiles along each typhoon track fall into three categories (Fig. 10). The first (area A of Fig. 10) is associated with the typhoon circulation in the tropics. The wind is strongest near the surface and sharply decreases with height while changing very little in direction. The second (area B) is associated with the subtropical ridge. An easterly component in the lower layers underlies a westerly component; speeds are normally moderate in both layers with a relative minimum in the transition zone. The third (area C) typifies the higher latitudes with westerlies increasing rapidly with height.

The influence of the environmental wind field changes as the typhoon recurves and moves northward. While south of the ridge and within the tropics, the typhoon dominates the circulation for a considerable radius and throughout the troposphere. As it moves northward through the ridge, usually at a weakness or break in the ridge, the typhoon usually weakens; perhaps of greater importance, the depth of the closed circulation decreases from the top. As it

TABLE 7. Evaluation of FNOC objective forecasts, JTWC subjective forecasts and B and B statistical forecasts.

	Average error of 24 h forecast made nearest recurvature time and 12 h later		Average 24 h error for subsequent forecasts		Speed at 36 h after recurvature (km)	
	JTWC	TCM	JTWC	TCM	Observed	B & B forecast
Irving	238	358	540 (1)*	730	12	12
Owen	61	215	430 (3)	650	8	3
Tip	268	374	626 (1)	930	24	12

* Number of comparable forecasts.

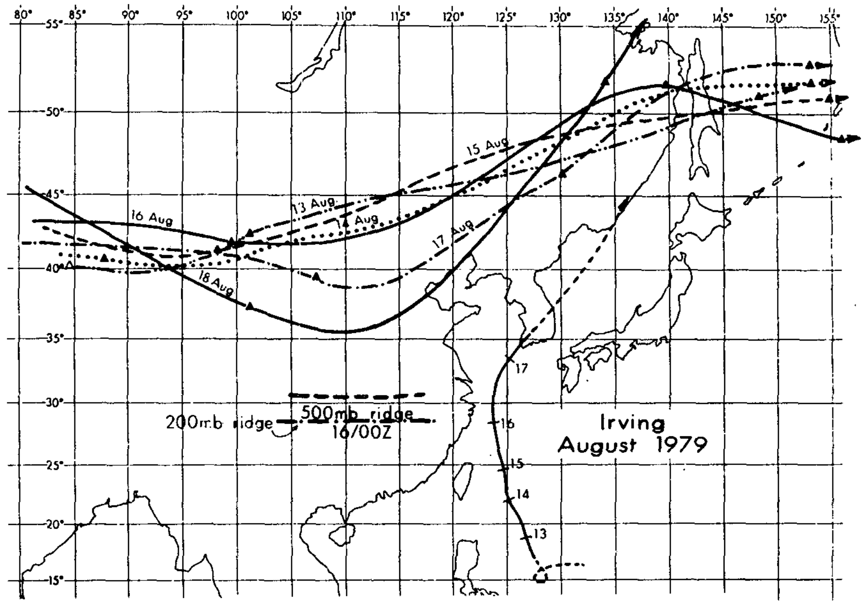

FIG. 7. The positions of the maximum wind core at 200 mb during the period of three days before, during and two days after the recurvature of Typhoon Irving. Solid triangles are positions of maximum wind centers along the core.

moves into the westerlies, while continuing to decrease in intensity and depth, the typhoon is engulfed by the environmental westerlies and its closed circulation is restricted to the lower troposphere. These rapid after-recurvature changes in typhoon dimensions and the increasing influence of the environmental flow on vortex movement, while important to forecasting, cannot be measured and furnished as an aid to the forecaster. However, since the weakening storm decreasingly affects its environment after recurvature, the environments along the tracks of Irving, Owen and Tip were analyzed around recurvature times to determine their space and time distribution and persistence.

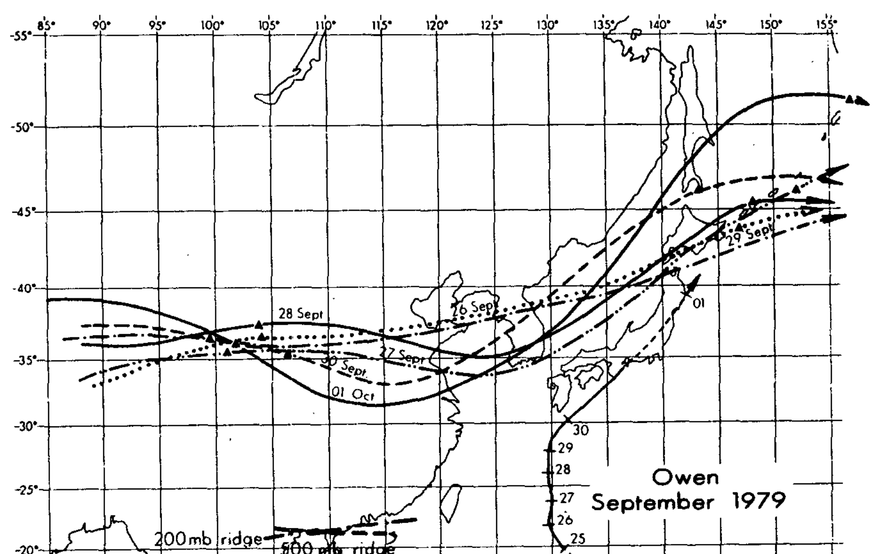

FIG. 8. As in Fig. 7 except for Typhoon Owen.

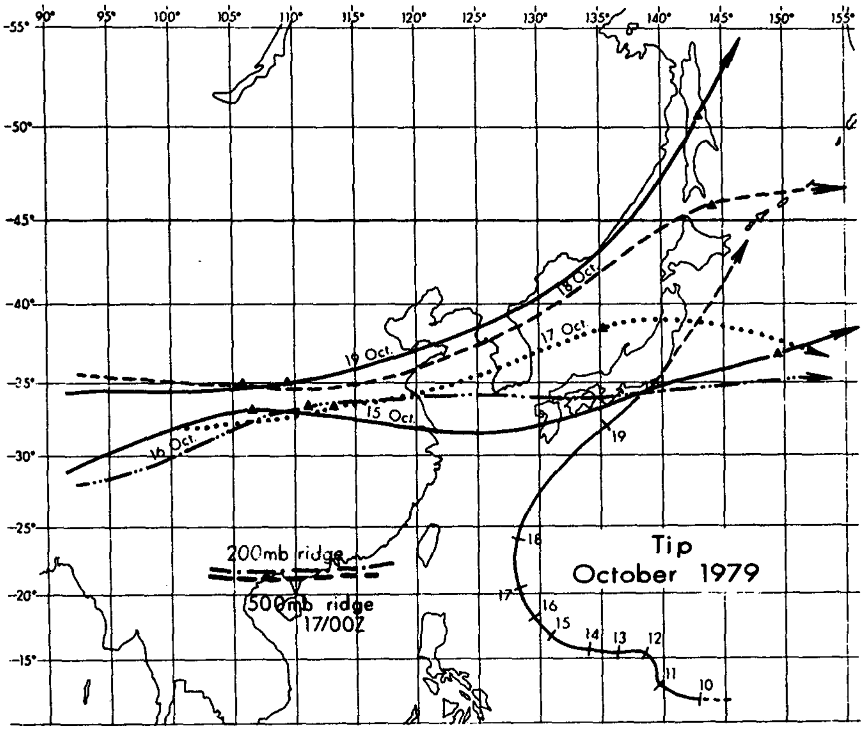

FIG. 9. As in Fig. 7 except for Typhoon Tip.

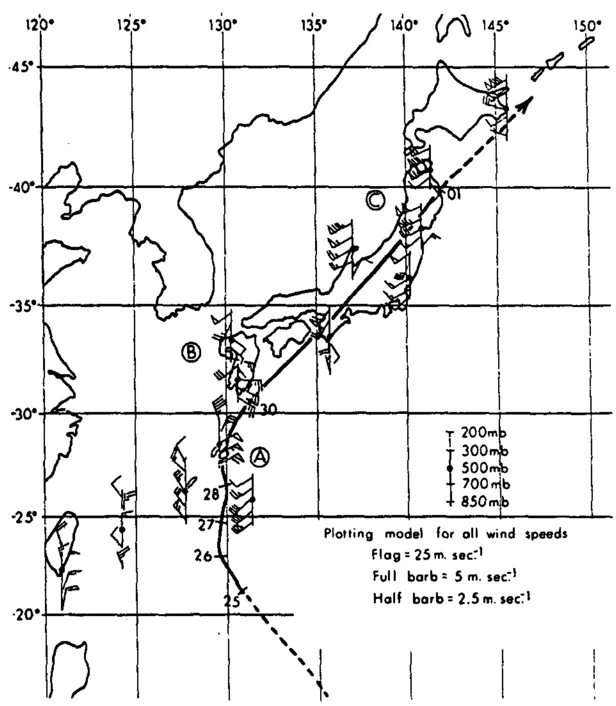

FIG. 10. Vertical wind profiles at 0000 GMT on 29 September 1979 for observing stations close to track of Typhoon Owen. Data levels range from 850 to 200 mb as indicated on the ladder. Wind speed plotting model as shown.

2) 500–200 mb THICKNESS

The warm-cored typhoon transports large amounts of latent heat of condensation to the middle and upper troposphere where the isobaric surfaces are inflated and ridges are enhanced. Maximum northward

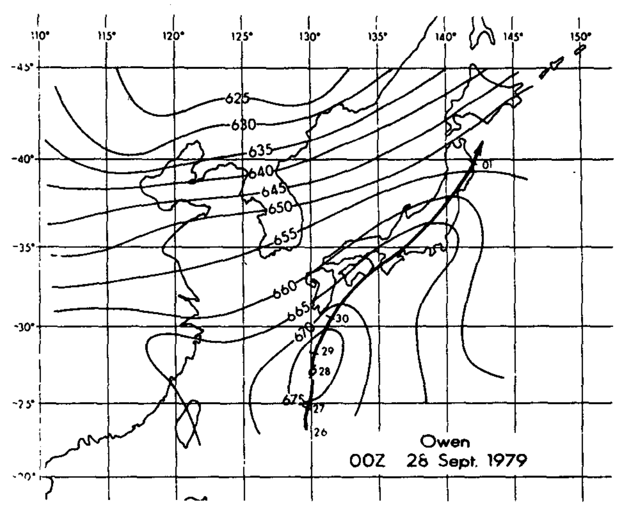

FIG. 11. 500 to 200 mb thickness at 0000 GMT on 28 September. Isopleths labeled in tens of meters. Position of Typhoon Owen indicated by the storm symbol. Subsequent track shown by heavy solid line.

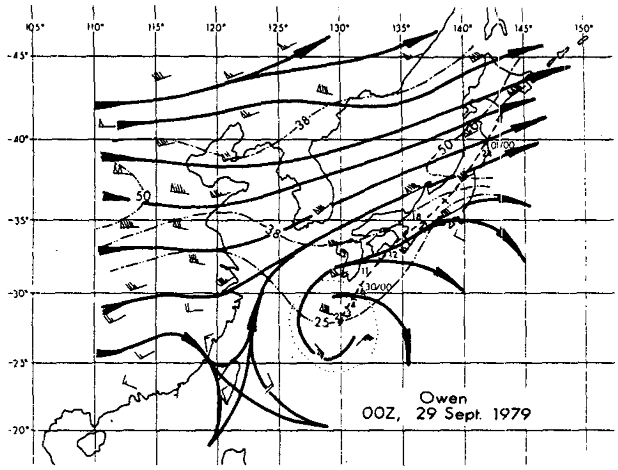

FIG. 12. Vertical wind shear (m s^{-1}) between 850 and 200 mb at 0000 GMT on 29 September. Area dominated by Typhoon Owen circulation is within dotted circle. Dashed line is subsequent typhoon track. Typhoon movement speed (m s^{-1}) shown in 6 h segments along track.

heat transport on the east side of a typhoon builds the ridge toward the northeast. We used the height difference between 500 and 200 mb as a measure of the mean upper tropospheric temperature.

At 0000 GMT on 28 September, just before Typhoon Owen recurved (Fig. 11), the thickness center over the typhoon and the ridge to the northeast are prominent. Note that Owen subsequently moved along the thickness ridge. One should exercise care in using this feature as a direction forecast aid for such good correspondence is not always observed. The thickness center and a ridge oriented to the northeast were also associated with Typhoons Irving and Tip (not shown) near recurving time; but, their future tracks were not always along the direction of maximum ridging. However, the forecaster should remember the probable effect of ridging in rotating the jet axis to a more southerly direction north of the typhoon, as was illustrated in Figs. 7–9. We found no persistent thickness feature related to a typhoon's *speed* after recurvature.

3) 850–200 mb WIND SHEAR

At the recurvature of Owen on 29 September (Fig. 12), anticyclonic shear surrounded the typhoon with westerly shear to the north. Except for the first 24 h, shear increased along the track with the maximum coinciding with the maximum of typhoon movement. Similar patterns were observed for all three typhoons and there may be some forecast value in the shear field. However, in the main area of concern north of the subtropical ridge, the greatest contributor to the 850–200 mb shear is the 200 mb wind; therefore, this should be as good as or perhaps better than the shear field as a forecasting aid.

4) 500–200 mb AVERAGED WIND SPEEDS

For Owen, correspondence between the speed field at recurvature (Fig. 13) and subsequent movement is better than for the shear field (Fig. 12). The speed gradient along the track is better defined than the shear gradient and the first 24 h after recurvature is better resolved since in the shear field this portion was dominated by excessive shears due to the typhoon circulation. The averaged wind speed increased from 15 m s^{-1} to 40 m s^{-1} between 33 and 40°N along the future track of Owen which accelerated rapidly to 24 m s^{-1} in less than 48 h before being discontinued as a depression at 40°N. Similar results were obtained for Irving and Tip and there appeared to be a useful forecasting relationship between the distribution of the upper tropospheric wind speeds *at* recurvature time and subsequent movement of the typhoon.

To test this relationship, we plotted the speed of typhoon movement against the 500–200 mb average upper tropospheric winds along the typhoon track. To test for persistence, the layer average wind was also averaged over three different time intervals: 1) At recurvature and 12 h prior to it; 2) at recurvature and 12 and 24 h prior to it; and 3) 12 and 24 h prior to recurvature (Figs. 14–16).

Owen and Tip traversed the data-rich area of Japan and fixed station data were used. As Irving remained over the sea for most of the time after recurvature, wind speeds were estimated from analyses by the Ja-

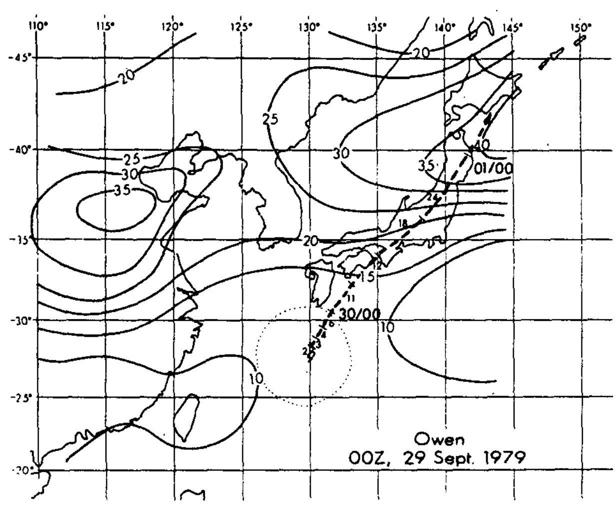

FIG. 13. Averaged wind speed (m s^{-1}) between 500 and 200 mb at 0000 GMT on 29 September. Area directly influenced by Typhoon Owen is within dotted circle. Dashed line is subsequent typhoon track. Typhoon movement speed (m s^{-1}) is shown in 6 h segments along track.

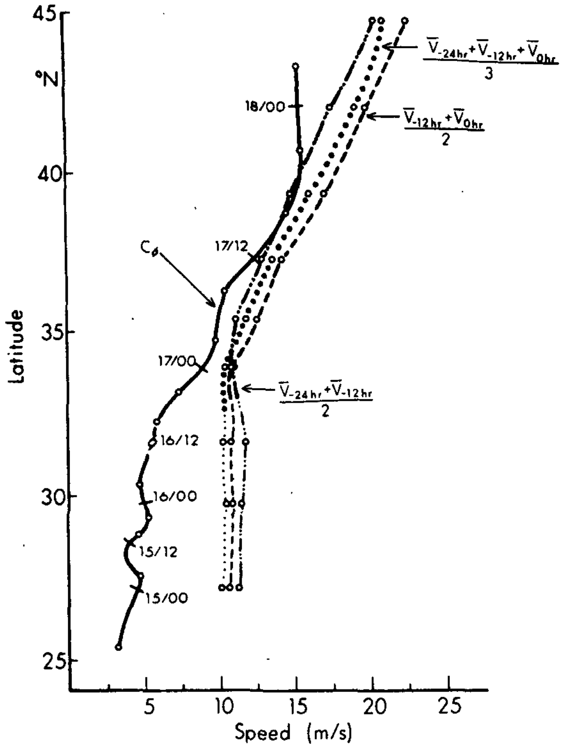

FIG. 14. Typhoon speed (c) and averaged wind speed between 500 and 200 mb ($\bar{v}$) along Typhoon Irving track. The times of averaging for $\bar{v}$ are relative to 1200 GMT on 16 August as time 0. The southern portion of the $\bar{v}$ curves dominated by the typhoon circulation are shown by thinner lines.

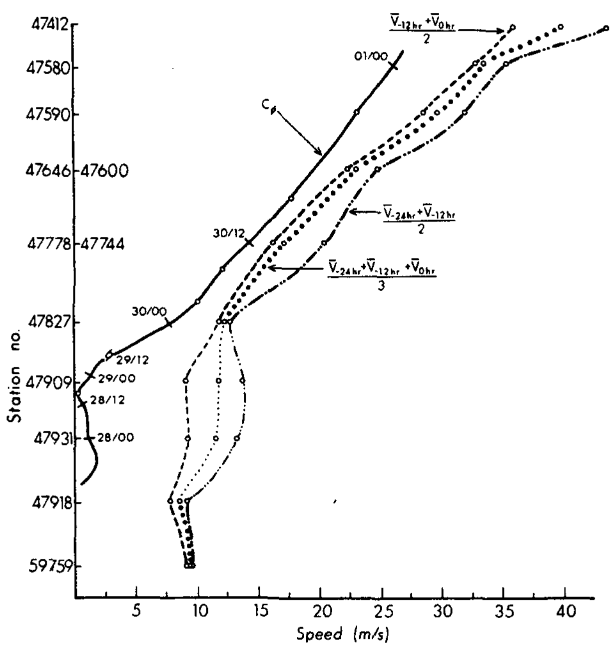

FIG. 15. As in Fig. 14 except for Typhoon Owen, 1200 GMT on 29 September as time 0 and ordinate is rawin stations on or near typhoon track.

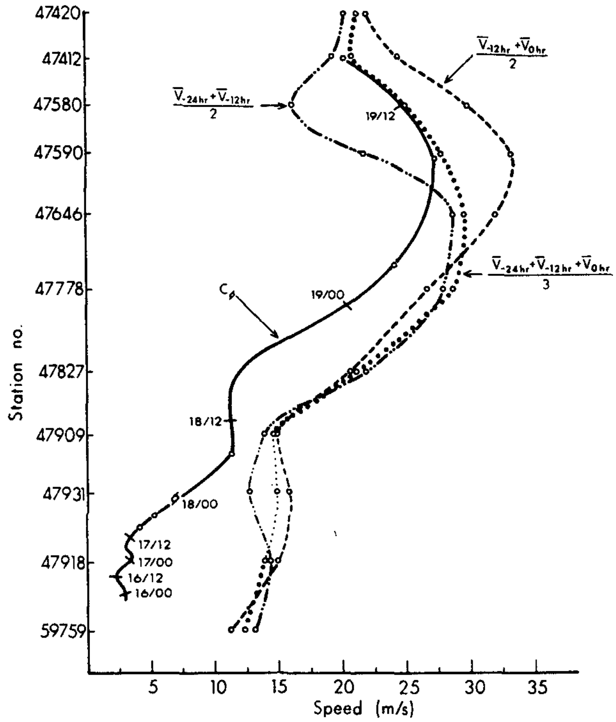

FIG. 16. As in Fig. 15 except for Typhoon Tip and 0000 GMT on 18 October as time 0.

pan Meteorological Agency and the Royal Observatory, Hong Kong. The curves for the three different time intervals are very similar, indicating persistence in the large-scale wind field for each typhoon around recurvature. The only exception was the slight northward shift of the minimum–maximum pattern north of Tip between 12 and 24 h, and 0 to 12 h prior to recurvature. The close relationship of the future movement of the typhoons *after* recurvature to the observed upper tropospheric wind field *at* and *before* recurvature is rather remarkable. The best overall correspondence, as would be expected, is with the averaged observations at recurvature and 12 h before. A movement forecast of $\sim$5 m s^{-1} less than the observed wind speeds at these times would have produced a good movement forecast for all three typhoons. These results warranted testing on a large sample of typhoons.

For the test, we used only the wind field at 250 mb because: 1) it is simple and easy to use, and 2) this level includes aircraft and satellite winds, and a good analysis is possible over the whole area. Results can therefore be used on typhoons recurving east of 140°E.

5) 250 mb WINDS AND TYPHOON SPEEDS AFTER RECURVATURE

We selected 71 typhoons that recurved within the good rawinsonde network west of 140°E from 1962–

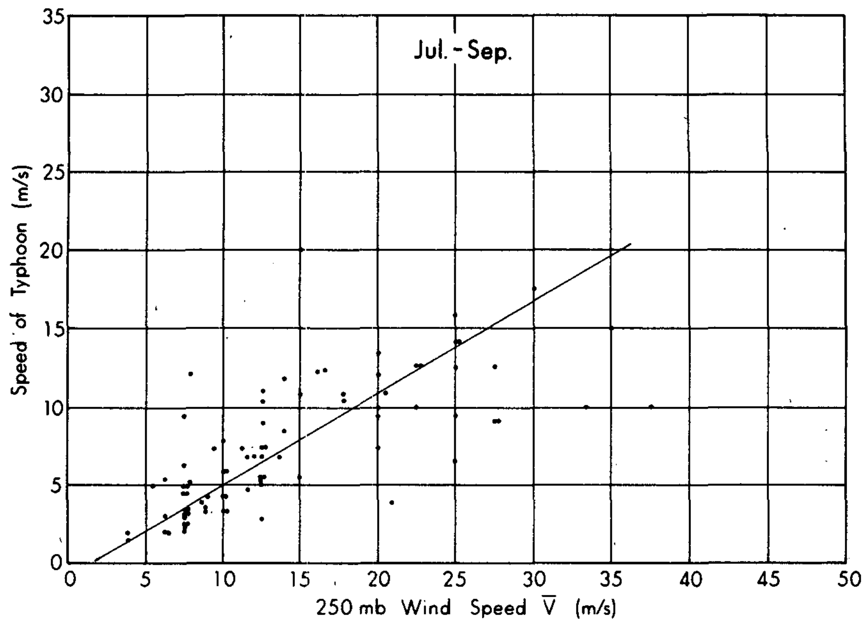

FIG. 17. The average 250 mb wind speed at and 24 h before recurvature at points along the typhoon track 24, 48, and 72 h after recurvature, versus the speed of the typhoon at the same points and times. Data sample is 32 typhoons during July–September for the years 1962–78.

78. Thirty-two recurved during July–September and 39 during October–June. The method of reporting wind observations varied over the period, so an observed 250 mb wind was defined as either the 250 mb wind or the 35 000 ft wind or an average of the 200 and 300 mb winds or an average of the 30 000 and 40 000 ft winds.

The observed 250 mb wind *at* recurvature and 24 h *before* were averaged and tabulated for points along the typhoon track at 24, 48 and 72 h *after* recurvature and compared to the corresponding moving speeds of the typhoon at those points. The combined data for all three time periods and their least squares line of best fit are shown in Figs. 17 and 18.

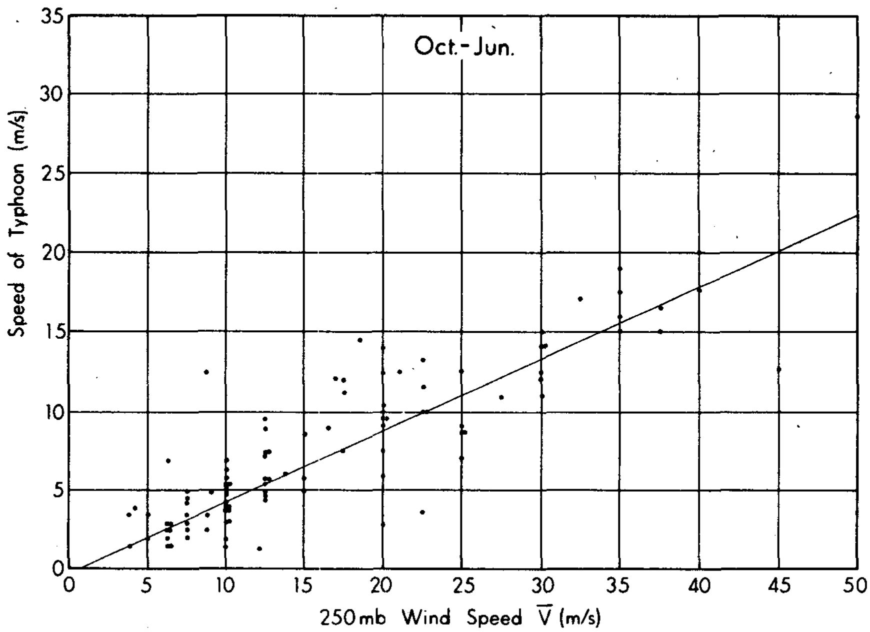

FIG. 18. As in Fig. 17 but for 39 typhoons during October–June.

TABLE 8. Errors (r) related to 250 mb wind speed and length of forecast period (Number of forecasts are in parentheses).

Forecast period	$\bar{r}$ for 250 mb $\bar{V}$ (m s^{-1}) ≤7.5	8–12.5	13–20	>20	Average $\bar{r}$ (m s^{-1})
		July–September			
24 h	0.8 (11)	1.6 (12)	3.1 (7)	0.3 (1)	1.6 (31)
48 h	1.3 (8)	1.8 (10)	2.6 (5)	3.3 (8)	2.3 (31)
72 h	2.6 (4)	2.5 (5)	2.1 (3)	4.0 (9)	3.0 (21)
		October–June			
24 h	1.3 (11)	1.2 (20)	2.6 (4)	1.8 (4)	1.4 (39)
48 h	1.1 (5)	1.8 (12)	2.0 (8)	1.9 (12)	1.9 (37)
72 h	0.7 (3)	1.9 (2)	2.1 (9)	2.2 (12)	2.0 (26)
		Average			
Average $\bar{r}$	1.2 (42)	1.6 (61)	2.5 (36)	2.6 (46)	2.0 (185)

Errors defined as the difference between the value determined from the linear line of best fit in Figs. 17 and 18, and the actual speed of the typhoons are shown in Table 8. The errors are stratified by forecast period, season and increments of the observed 250 mb wind speed. In general, the errors increase with forecast period length and with increasing 250 mb winds. For all three forecast periods, errors average less for October–June than for July–September.

Since the scheme depends on persistence of the 250 mb wind speed pattern, we determined whether most of the large errors stemmed from large wind field changes that could be identified by noting the change in 250 mb winds during the 24 h prior to recurvature. Large along-track errors were defined as 260, 430, 700 km for 24, 48 and 72 h, respectively. In 18 (25%) of the 71 cases, there were large errors in one or more of the forecast periods. There were 10 cases of large changes in the 250 mb winds defined as a change of 15 m s^{-1} or greater between the wind speed at and 24 h before recurvature. All 10 cases were associated with large errors in the speed of the typhoon. Thus, it appears that many of the potentially large errors can be anticipated at forecast time.

TABLE 9. Comparison of the after recurvature speed errors (m s^{-1}) between the JTWC forecasts and the curves of Figs. 17 and 18 for the typhoons of 1972–1978 (number of forecasts in parentheses).

	Forecast period 24 h (29)	48 h (21)	72 h (7)
JTWC forecast	3.4	5.2	4.6
Using Figs. 17 and 18	1.6	2.3	2.2

6) COMPARISON WITH JTWC FORECASTS

A subsample containing the 29 recurving typhoons during 1972–78 was used to compare the JTWC forecast speed and the forecast speed using Figs. 17 and 18. For all three forecast periods, the average speed error after recurvature using the 250 mb wind observed at and 24 h before recurvature was about half of the JTWC forecast error (Table 9). The overall improvement for this sample was 54%. No independent data sample was tested.

The JTWC forecasts had a definite slow bias. Seventy-two, 89 and 100% of forecasts for 24, 48 and 72 h, respectively, were too slow. An inspection of Figs. 17 and 18 indicate a small overall slow bias in our forecast scheme. For the combined 185 periods, 49% of the forecasts were slow and 43% were fast; however, in summer, with upper winds in excess of 20 m s^{-1}, most forecasts were too fast.

5. Summary

Western North Pacific tropical cyclone data were evaluated for the period 1970–79 to determine characteristics of recurving typhoons near and after recurvature. Some of the characteristics differed from those reported by Burroughs and Brand (1973) and Riehl (1972) in studies of earlier data sets.

Typhoons Irving, Owen and Tip, all occurring in 1979, were studied to determine relationships helpful to forecasting movement speed after recurvature. The typhoons differed in time of occurrence, maximum intensity, size, speed of movement, latitude and longitude of recurvature and rate of acceleration after recurvature; however, each produced greater than average forecast errors. Analyses of the upper troposphere within ±3 days of their recurvature revealed that: 1) a moving or developing trough in the midlatitude westerlies was not a significant factor during or after recurvature; 2) the heat export from each typhoon produced ridging to the northeast which probably caused the observed counterclockwise rotation in the westerly jet axis north of the typhoon near the time of recurvature; 3) common to all three typhoons was a good relationship between the speed of movement *after* recurvature and the observed upper tropospheric wind speed *at* and *before* recurvature averaged between 500 and 200 mb along the subsequent track. A variation of this last finding—using only the observed winds at 250 mb—was used to determine this relationship for 71 recurving typhoons during 1962–78. The results were tested by comparing with JTWC forecasts using a subsample of 29 recurving typhoons during 1972–78. The results indicate that the simple aid could have reduced the average forecast speed errors by ~50%. However, the true test, as with all aids, is the operational mode. Only if—when combined with the numerous aids and factors comprising an operational forecast—the slow bias is reduced in typhoon forecasts after recurvature can the scheme claim any success.

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