AD-A109 581 NAVAL OCEANOGRAPHY COMMAND CENTER/JOINT TYPHOON WARNI--ETC F/G 4/2
A STUDY OF RECURVING TROPICAL CYCLONES > OR = 34 KT (18 M/SEC) --ETC(U)
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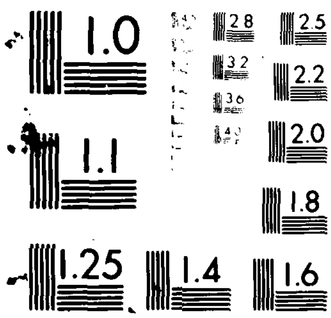

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A STUDY OF RECURVING TROPICAL CYCLONES ≥ 34 kt (18 m/sec) IN THE NORTHWEST PACIFIC 1970 - 1979

by

JACK E. HUNTLEY, LT, USNR.

PREPARED BY

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NAVAL OCEANOGRAPHY COMMAND
NSTL STATION, BAY ST. LOUIS, MS 39529

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NAVOCEANCOMCEN/JTWC
TECH NOTE 81-2

2. GOVT ACCESSION NO.
AD-A109 581

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
A Study of Recurving Tropical Cyclones > 35 kt (18 m/sec) in the Northwest Pacific 1970 - 1979

5. TYPE OF REPORT & PERIOD COVERED
TECH NOTE

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Jack E. Huntley, LT, USNR

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U. S. Naval Oceanography Command Center/Joint Typhoon Warning Center (NAVOCEANCOMCEN/JTWC)
FPO San Francisco 96630

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
U. S. Naval Oceanography Command Center/Joint Typhoon Warning Center (NAVOCEANCOMCEN/JTWC)
FPO San Francisco 96630

12. REPORT DATE
23 December 1981

13. NUMBER OF PAGES
22

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tropical Cyclone Speed of Movement
Tropical Cyclone Intensity
Recurvature

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Recurving tropical cyclones in the Northwest Pacific region were studied to observe their behavior relative to track and intensity. Tropical cyclones occurring from 1970 through 1979 were selected for this study and categorized into three groups based upon their maximum intensity. Parameters relating to point of recurvature, direction and speed of movement, and intensity were analyzed. The skill of forecasting speed of movement by a solution to a first order differential equation was investigated.

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CONTENTS

ABSTRACT

Recurving tropical cyclones in the Northwest Pacific region were studied to observe their behavior relative to track and intensity. Tropical cyclones occurring from 1970 through 1979 were selected for this study and categorized into three groups based upon their maximum intensity. Parameters relating to the point of recurvature, direction and speed of movement, and intensity were analyzed. The skill of forecasting speed of movement by a solution to a first order differential equation was investigated.

A STUDY OF RECURVING TROPICAL CYCLONES IN THE NORTHWEST PACIFIC 1970 - 1979

I. INTRODUCTION

Each year a significant number of tropical cyclones recurve in the Northwest Pacific region. In particular, almost half of the tropical cyclones that occurred from 1970 through 1979 recurved as graphically depicted in Figure 1. Yearly, more than 44 percent of all the tropical cyclones recurved, except in the years 1972 and 1973.

This paper presents a study of the intensity and speed of movement of recurving tropical cyclones. The importance of this paper lies not only in the frequency of occurrence, but also because tropical cyclones that do recurve characteristically have larger forecast position errors than straight-tracking (east to west) cyclones. Hence, there is a need to improve forecasts for recurving tropical cyclones. Increased errors associated with recurvature were evident in a recent study by Jarrell, Brand, and Nicklin (1977). In their analysis of forecast position errors for warnings issued by the Joint Typhoon Warning Center (JTWC), they found that greater errors were associated with northward tracking tropical cyclones (generally attributed to recurvature) than those tracking east to west. In another study, Burroughs and Brand (1972) found that typhoons that recurved from 1961 through 1969 had greater forecast position errors than the average error for all typhoons during the same period.

Specific topics discussed in this study are:

(1). The monthly frequency of recurvature.
(2). The monthly averaged latitude and longitude of the point of recurvature.
(3). The speed of movement at the point of recurvature.
(4). The direction and speed of movement 24 hours prior to and following the point of recurvature.
(5). The intensity of recurving tropical cyclones.

The intent of this paper is to familiarize forecasters with the motion and intensity of recurving tropical cyclones and compare the results of this study to those of previous studies.

There are generally three factors in the recurvature forecast which cause large errors: the point of recurvature, rapid acceleration following recurvature, and the direction of movement following recurvature. Of the three, rapid acceleration along the track poses the most difficult problem

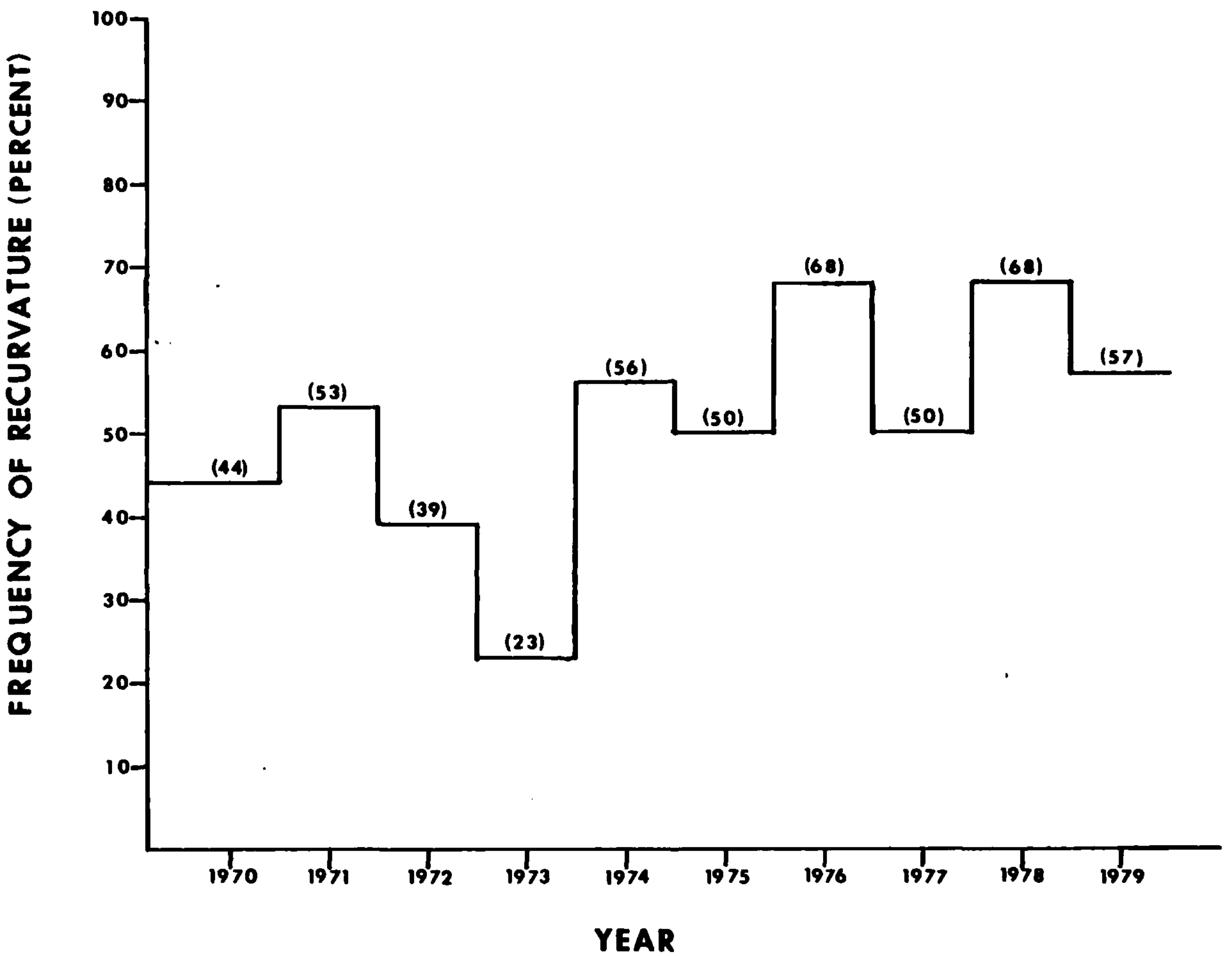

FIGURE 1

The frequency of tropical cyclone recurvature from 1970 through 1979 by year (Numbers in parentheses indicate the percent of total tropical cyclones that recurved in that year.)

to the forecaster. This problem was dramatically demonstrated in 1979 when Super Typhoon Tip accelerated from 11 kt (20 km/hr) to 48 kt (89 km/hr) within 30 hours after recurvature. This rapid acceleration greatly increased the error of an otherwise good forecast that had correctly shown the direction of movement on each of the 06-hourly warnings issued following recurvature.

The point of recurvature is equally difficult to forecast. Although many of the meteorological conditions necessary for a tropical cyclone to recurve may be readily recognizable to the forecaster, doubts still arise as to the actual time and point that the tropical cyclone will recurve. Occasionally, the conditions for recurvature are not evident. This was the case in 1978 when Typhoon Ora was forecast to track westward over China, but instead recurved and immediately threatened Taiwan and the Ryukyu Islands. Another example of the difficulty to forecast recurvature was Typhoon Lola in 1972. Lola was forecast to maintain a westward movement and pass across the Northern Marianas Islands. JTWC continued to forecast this track after she had recurved and was tracking northeastward; the forecasts on Lola did not reflect the change in direction until 24 hours after recurvature. The recurvature forecast is further complicated when uncertainty exists as to whether the tropical cyclone is undergoing erratic behavior, such as looping, especially when the system is close to the equator.

The direction of movement following recurvature also contributes to large position errors in the forecasts. However, once recurvature has occurred, the direction of movement is usually not as much a concern as is rapid acceleration due to the tropical cyclone having entered a regime of very strong steering currents. When this happens, there is little likelihood of the cyclone tracking in a direction significantly different than that of the steering current.

II. DATA SOURCE AND METHODOLOGY

Data used in this study were extracted from the 1970 through 1979 issues of the Annual Typhoon Reports, published annually by the U.S. Naval Oceanography Command Center/Joint Typhoon Warning Center (JTWC), Guam. These reports contain data on each tropical cyclone that JTWC issued warnings on. Included in the data set are forecast verification statistics, reconnaissance data and the systems "best track", ie., the path of the center of circulation on the earth's surface derived from position fixes received from aircraft, satellite, radar, and synoptic data.

The point of recurvature was defined for this study as the most westerly and northerly position that the tropical cyclone reached before tracking and maintaining an easterly direction.

Recurving tropical cyclones selected for the motion study met the following minimum criteria:

(1). Wind speeds greater than or equal to 34 kt (18 m/sec) during the time interval from at least 24 hours prior to recurvature to six hours or more following recurvature.
(2). Tropical cyclones that displayed erratic movements, e.g. looping, stalling, were excluded from the data set.

Furthermore, for the study of intensity the data set used in the motion study was reduced by deleting all tropical cyclones that tracked over any major land mass (ie., Taiwan, Philippines).

The data sets for the studies of motion and intensity were than categorized based upon the maximum intensity attained in the time interval used for this study.

(1). Super Typhoon, tropical cyclones greater than or equal to 130 kt (67 m/sec).
(2). Typhoon, tropical cyclones greater than or equal to 64 kt (33 m/sec) but less than 130 kt (67 m/sec).
(3). Tropical Storm, tropical cyclones greater than or equal to 34 kt (18 m/sec) but less than 64 kt (33 m/sec).

The months of July through November were each subdivided into two groups for better comparison with other months that had fewer recurvature cases and with the results of the earlier study by Burroughs and Brand (1972). Tropical cyclones in each data set were assigned to the month or half month of occurence determined by the midpoint of JTWC's best track, ie., the point on the track in time midway between the first and last warning times. Tropical cyclones that occurred from the 1st through the 15th of the subdivided months were assigned to the first half, the remaining cyclones were assigned to the second half of the month.

During the period of record, 224 tropical cyclones reached an intensity greater than or equal to 34 kt (18 m/sec). Of that number, 117 recurved. The number of tropical cyclones that met both criteria for the study of motion was 78 while the number for the study of intensity was 52. As shown in Table 1, typhoons were the largest number of tropical cyclones in the study of motion. Of the 123 typhoons that occured, 54

TABLE 1

The monthly number of cases of recurvature for the 224 tropical cyclones that occurred from 1970-1979. (Numbers in parantheses indiate the percent of total tropical cyclones that recurved during each time period).

MONTH	TOTAL	SUPER TYPHOON	TYPHOON	TROPICAL STORM
JAN	2 (28)		1 (14)	1 (14)
FEB	1 (50)		1 (50)	
MAR	1 (25)		1 (25)	
APR	6 (85)		5 (71)	1 (14)
MAY	6 (66)	2 (22)	2 (22)	2 (22)
JUN	3 (20)		2 (13)	1 (07)
JUL 1	2 (16)		1 (08)	1 (08)
JUL 2	2 (08)		2 (08)	
AUG 1	6 (35)		6 (35)	
AUG 2	8 (37)	2 (09)	5 (23)	1 (05)
SEP 1	8 (38)	1 (05)	7 (33)	
SEP 2	8 (34)	1 (04)	6 (26)	1 (04)
OCT 1	8 (42)	1 (05)	5 (26)	2 (11)
OCT 2	4 (31)		3 (23)	1 (08)
NOV 1	6 (54)	2 (18)	3 (27)	1 (09)
NOV 2	4 (57)	1 (14)	2 (29)	1 (14)
DEC	3 (33)		2 (22)	1 (11)
TOTAL	78 (35)	10 (05)	54 (24)	14 (06)

were evaluated. Likewise, 10 of 21 super typhoons and 14 of 80 tropical storms were evaluated in the motion study. For the study of intensity, 8 super typhoons, 34 typhoons, and 10 tropical storms were evaluated.

III. RESULTS

A. Motion

The monthly and semi-monthly percent frequency of recurving tropical cyclones is illustrated in Figure 2. Most notable is the minimum occurrence of recurvature for the months of June and July, while the maximum frequency occurs in April. There was nearly an equal occurence in the other months. These results are similar to the earlier findings of Burroughs and Brand (1972), whose study also revealed a minimum occurence of recurvature in July. Table 1 further breaks down the monthly distribution by classes. Typhoons accounted for the largest number, or 69 percent, of the cyclones that met the selection criteria. Typhoons were also the prevalent category of cyclone that recurved in the maximum and minimum months with the remainder being tropical storm. Further, although the occurrence of super typhoons and tropical storms was nearly equal in the study of motion, tropical storms were evenly distributed throughout most of the year, while super typhoons occurred mainly in the months of late August through November.

Figure 3 displays the seasonal variation for the point of recurvature with respect to latitude. The number of cases for each month and half month is listed in Table 2. The latitude of recurvature remained basically unchanged during the months of January through June, but moved northward dramatically in July. Thereafter, from August through December, the latitude of recurvature receded equatorward. The findings of this study agree well with the seasonal variation noted by Riehl (1971) who first reported this seasonal change in the latitude of recurvature. The seasonal variation for the point of recurvature with respect to longitude is shown in brackets along the abscissa of Figure 3. There was no trend observed in the longitude of recurvature in this study. However, Burroughs and Brand found that the average monthly longitude of recurvature moved eastward in November and December.

The speed of recurvature was investigated at three specific times for each tropical cyclone: 24 hours prior to recurvature (t_{-24}), at recurvature (t_0), and 24 hours following recurvature (t_{+24}). The mean monthly speed at t_0 was surprisingly different than observed by Burroughs and

Brand. Though the yearly mean speed at t_0 was slightly more than 10 kt (5 m/sec), the lower than average monthly speeds occurred from late July through November, rather than at the beginning of the season. The mean monthly speeds are shown in Figure 4. The highest speed of movement occurred in late July and the lowest speed in April and June. The speed of movement at t_{-24} was generally slower than at recurvature. Liechty (1972) found that recurving tropical cyclones between 1960 and 1969 exhibited a minimum in the speed of movement 12 hours prior to recurvature and then accelerated following recurvature, except in September when a minimum in speed occurred more than 84 hours prior to recurvature. He found that the speed of movement at t_{-24} was greater than at t_0, except, again, for September. In this study, the speed of movement at t_0 was greater than t_{-24}, except for June and early July as can be seen in Figure 4 and Table 2.

Table 2 also lists the number of cyclones per month and half month that recurved and met the selection criteria. The direction and speed of movement at t_{-24}, t_{+24}, and the speed of movement at recurvature are also listed. Differences in the number of cases at t_{+24} versus the number of cases for the study of motion are noted in parentheses. These differences arise because some tropical cyclones either dissipated or became extratropical earlier than 24 hours after recurvature.

The speed of movement increased between t_0 and t_{+24}, with marked acceleration occurring in November. This is also observed by Liechty (1972). Further, the results of this study showed that the speed of movement at t_{+24} was maximum in July, with a secondary maximum in October and November. The number of observations at t_{+24} were less than at t_0 or t_{-24} due to dissipation or extratropical transition of tropical cyclones earlier than 24 hours after recurvature. The speed of movement was lower at t_{+24} than t_0 during the months of September and October as seen in Figure 4, however, this may be only a result of the smaller data sample used in this study compared to Burroughs and Brand's data sample and not a general situation.

Burroughs and Brand (1972) used the ratio (Rs) to better examine the speed of movement of tropical cyclones after recurvature. This ratio normalizes the speed of movement following recurvature (S) at a specific time to the speed of movement at the point of recurvature (Sr) as shown below:

$$Rs = \frac{S}{Sr} \qquad (1)$$

The ratio Rs was then computed for the months of May-August, September-December, and May-December. This same

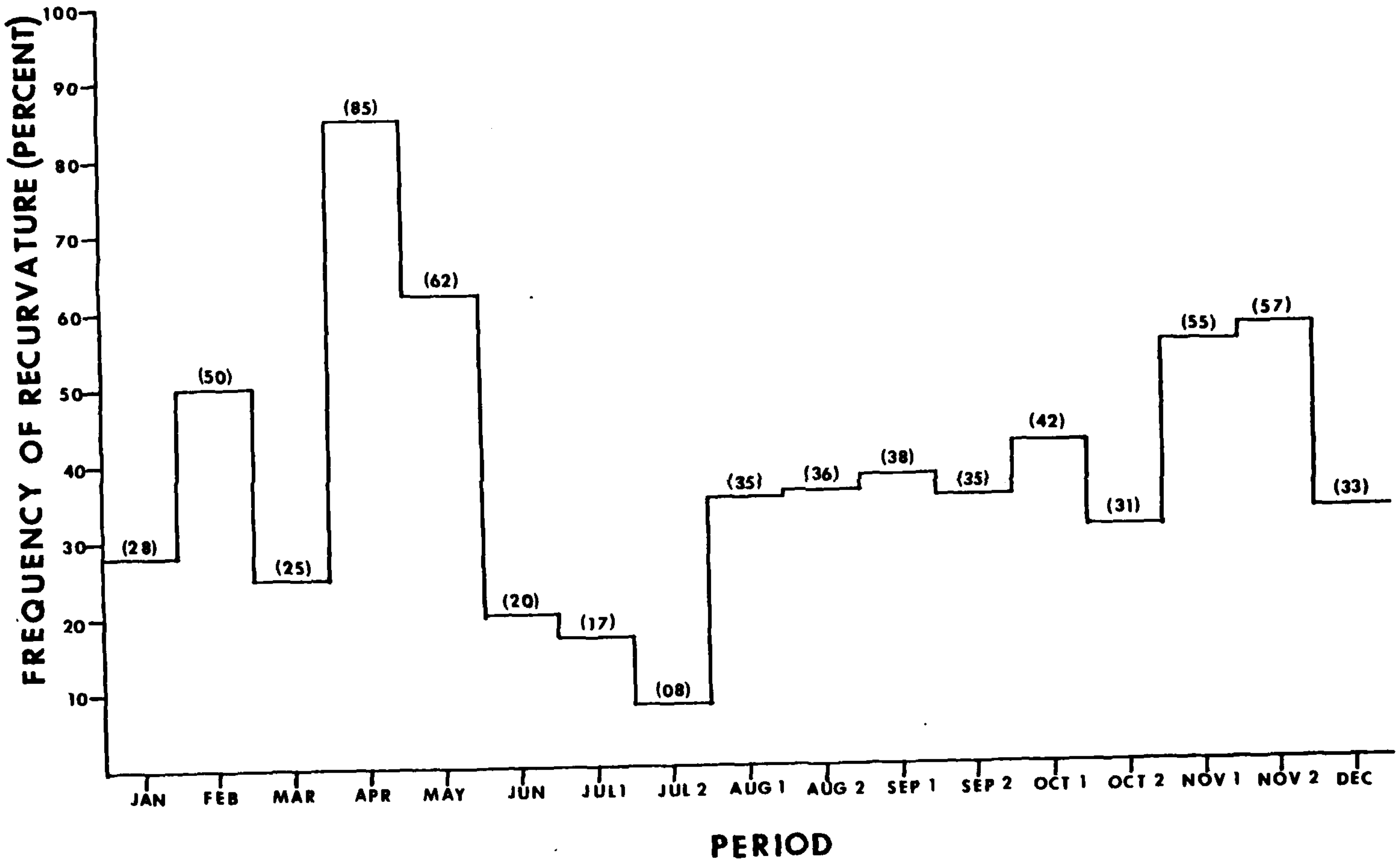

FIGURE 2

The montly frequency for tropical cyclone recurvature from 1970 through 1979. (Numbers in parentheses indicate the frequency of occurrence.)

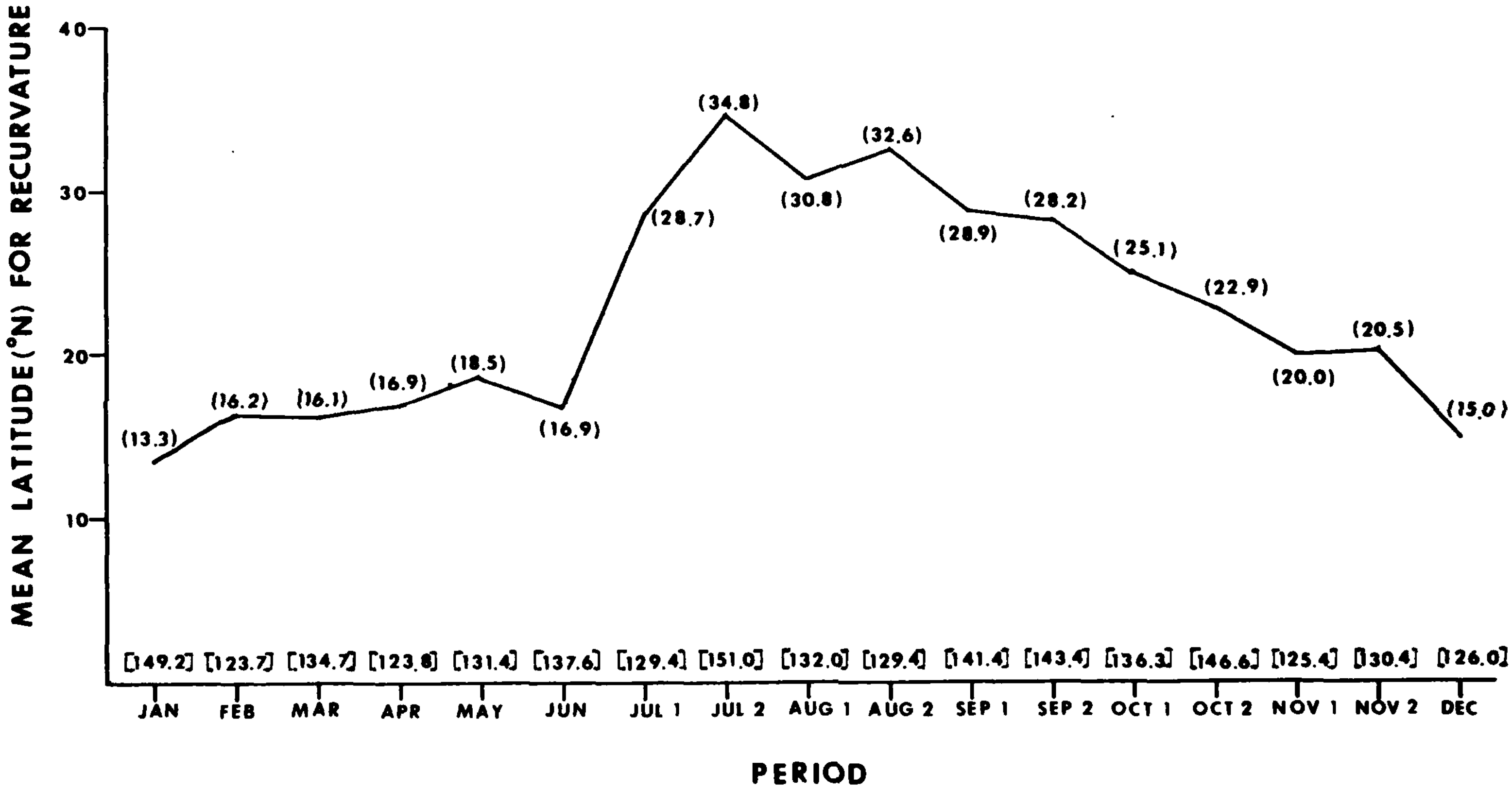

FIGURE 3

The mean latitude for recurvature from 1970 through 1979 as a function of months and half months. The monthly mean longitude for recurvature is shown in brackets along the abscissa.

TABLE 2

The month and half month averaged speed and direction of movement at t_{-24}, t_0, and t_{+24}.

MONTH	NUMBER OF CASES	DIRECTION (°T)/ SPEED (KT) AT t_{-24}	SPEED (KT) AT t_0	DIRECTION (°T)/ SPEED (KT) AT t_{+24}
JAN	2	339.6/ 9.4	10.6	038.7/12.2
FEB	1	329.1/ 9.9	10.0	018.7/11.1
MAR	1	340.1/ 6.4	10.2	041.9/11.4
APR	6	327.2/ 5.8	6.7	030.0/ 7.7 (4)[1]
MAY	6	339.2/ 6.4	9.9	023.6/ 9.9 (4)[1]
JUN	3	321.1/ 6.9	5.9	028.3/ 8.3
JUL 1	2	345.5/12.0	9.6	025.0/13.6
JUL 2	2	341.0/10.6	14.4	028.4/15.6 (1)[1]
AUG 1	6	338.9/ 8.8	11.6	020.5/11.8 (3)[1]
AUG 2	8	332.4/ 9.1	10.0	042.6/10.1 (5)[1]
SEP 1	8	339.9/ 9.0	10.2	030.9/10.1 (6)[1]
SEP 2	8	340.4/ 9.4	11.9	031.5/10.2 (6)[1]
OCT 1	8	332.7/11.2	12.5	021.2/14.5 (6)[1]
OCT 2	4	330.4/ 9.8	12.5	030.8/12.0 (3)[1]
NOV 1	6	325.2/ 9.3	9.9	023.9/14.9 (4)[1]
NOV 2	4	338.3/11.2	12.4	037.9/16.7
DEC	3	316.0/ 9.0	9.5	029.0/11.0 (2)[1]
AVERAGE SPEED DIRECTION FOR TOTAL ANNUAL VALUES	78	341.7/ 9.0	10.5	029.7/11.7 (57)[1]

[1] Numbers in parentheses indicate the number of cases if different from the data set for the study of motion shown in Table 1. The difference is a result of tropical cyclones dissipating or becoming extratropical earlier than 24 hours after recurvature.

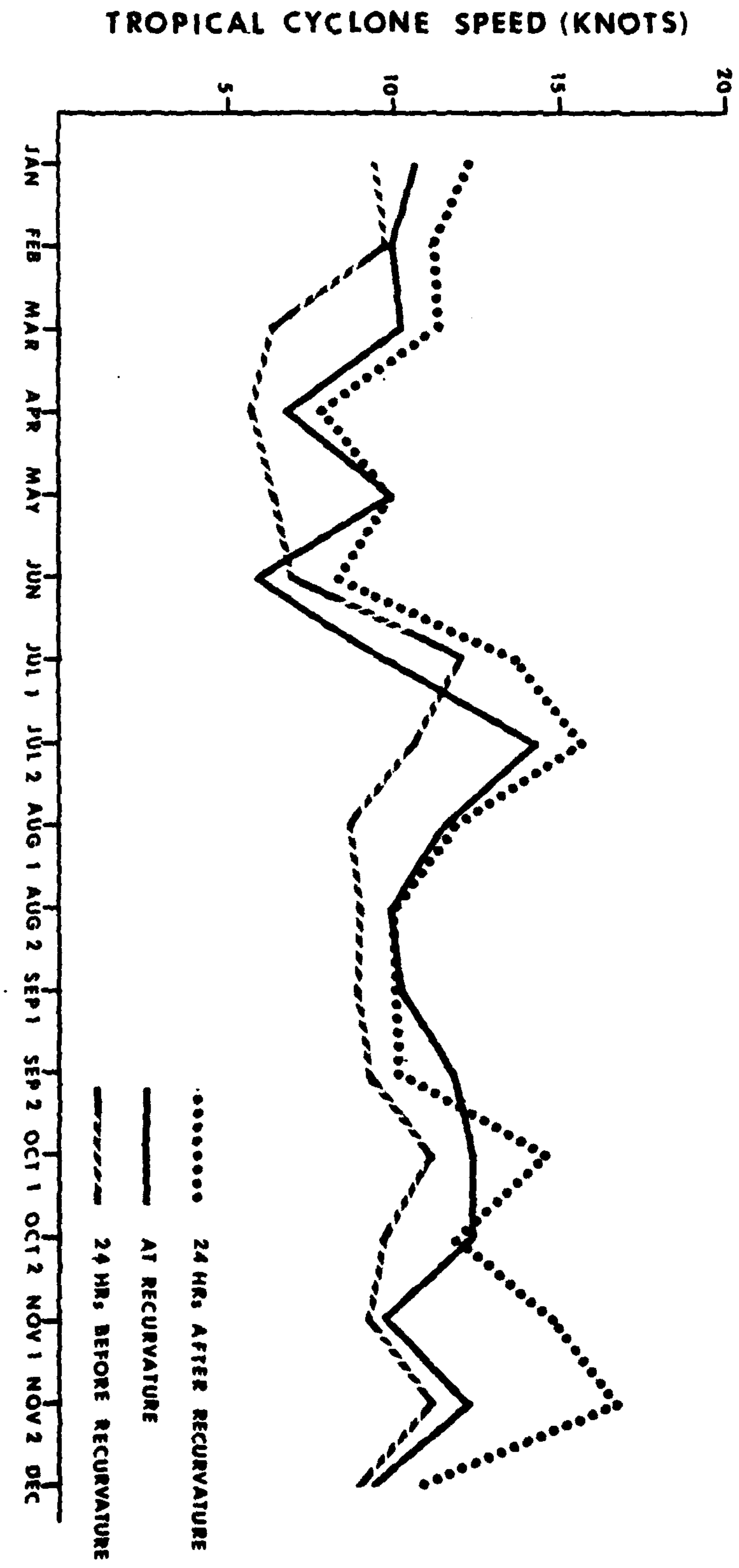

FIGURE 4

The speed of movement of tropical cyclones as a function of months and half months.

procedure was used in this study to compare the ratios of tropical cyclones in this data set to Burroughs and Brand's earlier findings.

Table 3a mean values of Rs for the periods of January-April, May-August, September-December and January-December. The number of cases for each period are shown in parentheses. Using the ratios as an indication of changes in the speed of movement, general statements can be made about the results of this study and how they differed from Burroughs and Brand (1972), Table 3b. The periods used for comparison are May-August and September-December. These general observations are:

(1). Tropical cyclones of this study period had a greater speed of movement following recurvature for both periods than those of Burroughs and Brand.

(2). The speed of tropical cyclones did not increase as much 36 hours and 48 hours after recurvature during the two periods being compared as did those in Burroughs and Brand's study.

The values of Rs can be used by the forecaster to determine the speed of movement following recurvature simply by multiplying Rs for the period and time desired.

The ratios of this study and those of Burroughs and Brand provide a helpful tool in developing forecast of accelerating tropical cyclones after recurvature. However they are not adequate to forecast the sudden and rapid acceleration observed in some tropical cyclones (cf. Super Typhoon Tip, 1979). In an effort to better forecast rapid acceleration the following solution to a first order differential equation of motion was investigated and compared to the forecasts issued by JTWC during this ten year study,

$$Sf = (Sr)\exp(\tau\alpha), \quad \text{where } \alpha = \frac{S\chi}{Sr\ t\chi}, \tag{2}$$

$S\chi$ is the speed of the tropical cyclone during the interval $t\chi$, in hours, following recurvature, Sr the speed at recurvature and τ the time interval, in hours, after $t\chi$ used to compute the forecast speed, Sf.

A modified form of equation (2) was also investigated to remove transient changes in α where $\bar{\alpha} = \overline{\Sigma\alpha}$ was substituted for α. $\bar{\alpha}$ was computed by averaging α for each 6-hour interval between the time of recurvature and $t\chi$. The modified and unmodified forms of equation (2) were then compared against forecasts issued by JTWC for each recurving tropical cyclone used in this study.

TABLE 3a

The average values of Rs by season with respect to time after recurvature. (Numbers in parentheses indicate the number of cases.)

PERIOD	Rs at $t+_{12}$	Rs at $t+_{24}$	Rs at $t+_{36}$	Rs at $t+_{48}$
JAN-APR	1.31 (9)	1.46 (8)	2.14 (7)	2.14 (4)
MAY-AUG	1.46 (21)	1.77 (14)	2.21 (14)	2.24 (8)
SEP-DEC	1.51 (34)	1.96 (26)	2.13 (20)	2.08 (14)
JAN-DEC	1.47 (64)	1.82 (48)	2.16 (41)	2.14 (26)

TABLE 3b

The early and late season average monthly values of Rs given as a function of time after recurvature for tropical storms and typhoons from 1945-1969. (Extracted from Burroughs and Brand, 1972.)

PERIOD	Rs at $t+_{12}$	Rs at $t+_{24}$	Rs at $t+_{36}$	Rs at $t+_{48}$
MAY-AUG	1.25 (80)	1.49 (69)	1.81 (53)	2.08 (38)
SEP-DEC	1.38 (150)	1.89 (127)	2.43 (101)	2.63 (70)
MAY-DEC	1.34 (230)	1.75 (196)	2.22 (154)	2.44 (108)

Table 4 lists the mean speed error and standard deviation for JTWC and for Sf, equation (2), using α and $\bar{\alpha}$ for tropical storms, typhoons, super typhoons, and the total data set. Overall, JTWC 24-hour forecasts underestimated the speed of movement by 1.5 kt while $\bar{\alpha}$ and α over estimated the speed by 1.7 kt and 1.3 kt respectively. At 48 hours, all forecasts underestimated the speed of movement by approximately the same amount. Thus, in comparison with JTWC, the two methods did not warrant further consideration as a forecast aid due to the nearly equal magnitude of error and standard deviation for each method. Burroughs and Brand (1972) also developed regression equations that forecast the speed of movement after recurvature to which the reader is referred.

The mean direction of movement for all tropical cyclones 24 hours prior to recurvature is listed in Table 2 for each month and half month. As might be expected, each period had a mean heading between 300°T and 360°T 24 hours prior to recurvature. Following recurvature, the mean direction of movement exhibited no systematic trend from month to month.

B. Intensity

The data set used for the study of motion was reduced to 52 cases for the study of intensity by excluding those tropical cyclones that tracked over land. This data set used for the study of intensity was then grouped into three categories based upon their maximum intensity, as discussed earlier.

Table 5 lists the results found in this study. Most notable was that all super typhoons reached their maximum intensity more than 24 hours prior to recurvature. A majority of tropical storms and a large percentage of typhoons reached their maximum intensity more than 24 hours after recurvature. Generally, super typhoons and tropical storms reached their maximum intensity more than 24 hours before recurvature while typhoons reached their maximum intensity within ±24 hours of recurvature.

Reihl (1971) and Liechty (1972) conducted similar studies. Reihl found that from 1957 through 1968, 43 of 66 tropical cyclones reached their maximum intensity within 12 hours of recurvature, 22 cyclones 24 hours or more before recurvature and 1 more than 24 hours after recurvature. In Leichty's

TABLE 4

The averaged speed of movement error and standard deviation of the errors for JTWC's forecast and Sf, using $\bar{\alpha}$ and α, for the 24 hour and 48 hour forecast times.

			JTWC		$\bar{\alpha}$		α	
CLASS	TIME	# OF CASES	AVG. ERROR(kt)	STD DEV(kt)	AVG. ERROR(kt)	STD DEV(kt)	AVG. ERROR(kt)	STD DEV(kt)
SUPER TYPHOON	24HR	37	.6	2.4	-1.3	1.8	- .4	1.8
TYPHOON	24HR	182	- .6	2.1	2.5	2.6	1.6	2.2
TROPICAL STORM	24HR	17	-5.1	1.9	- .4	1.8	1.2	2.3
TOTAL	24HR	236	-1.5	2.2	1.7	2.5	1.3	2.2
SUPER TYPHOON	48HR	15	-1.7	2.5	-5.9	2.1	-4.8	2.3
TYPHOON	48HR	43	-2.2	2.8	-2.3	3.0	- .8	3.2
TROPICAL STORM	48HR	4	-5.7	1.7	4.8	3.0	.1	3.5
TOTAL	48HR	62	-2.3	2.7	-2.7	2.9	-1.7	3.1

TABLE 5

Number of tropical cyclones that reached maximum intensity during specified periods.

CLASS	# OF CASES	PRIOR TO RECURVE	AT RECURVE	AFTER RECURVE	≥ 24HR PRIOR TO RECURVE	≥ 24HR AFTER RECURVE
SUPER TYPHOON	8	8	0	0	8	0
TYPHOON	34	18	2	14	11	4
TROPICAL STORM	10	6	2	2	6	1
TOTAL	52	32	4	16	25	5

study, which covered the period from 1960 through 1969, the monthly mean maximum intensity occurred more than 24 hours prior to recurvature. The results of this study for the entire sample agree more with Liechty than with Reihl, except that few tropical cyclones were observed to reach a maximum intensity 24 hours or more following recurvature.

Figure 5 shows a cyclic trend in tropical cyclone intensities at recurvature. In July and August, the intensities were at a minimum, gradually increasing to a maximum in the winter months. Maximum intensities of tropical cyclones 24 hours prior to recurvature were generally less than at recurvature, except during those months when super typhoons are common. This is reflected in Figure 5 by the trace for the average monthly maximum. The maximum intensity was observed during the occurrence of a super typhoon in late August.

In Liechty's study, the months of September and November had the highest mean intensity, whereas, in this study the maximum occurred in February, late August, and November. However, because there was only one case each for February and August, it is likely that these maxima would shift if a larger data sample had been available for this study.

IV. CONCLUSION

This study indicated that few differences exist in the motion and intensity of recurving tropical cyclones compared to the findings of previous studies. It was found in this study that tropical cyclones from 1970 through 1979 had a slightly greater speed of movement at recurvature but the same intensity in comparison with cyclones occurring from 1960 through 1969 (Liechty, 1972). Further, dividing the intensity data set of this study into three classes revealed that the maximum intensity for all super typhoons occurred more than 24 hours prior to recurvature.

The use of equation (2) to forecast the speed of movement after recurvature was found to have little value as a forecast aid. This is due to the comparible magnitude of error of JTWC's forecast during the 24 hour and 48 hour periods to that of equation (2) as well as the large standard deviation of these errors. The ratios of this study and those of Burroughs and Brand (1972) provide a helpful aid to generally describe the speed of movement following recurvature, but they are not adequate in forecasting the most rapid acceleration observed in some tropical cyclones. Thus, new methods for describing such rapid acceleration should be further investigated.

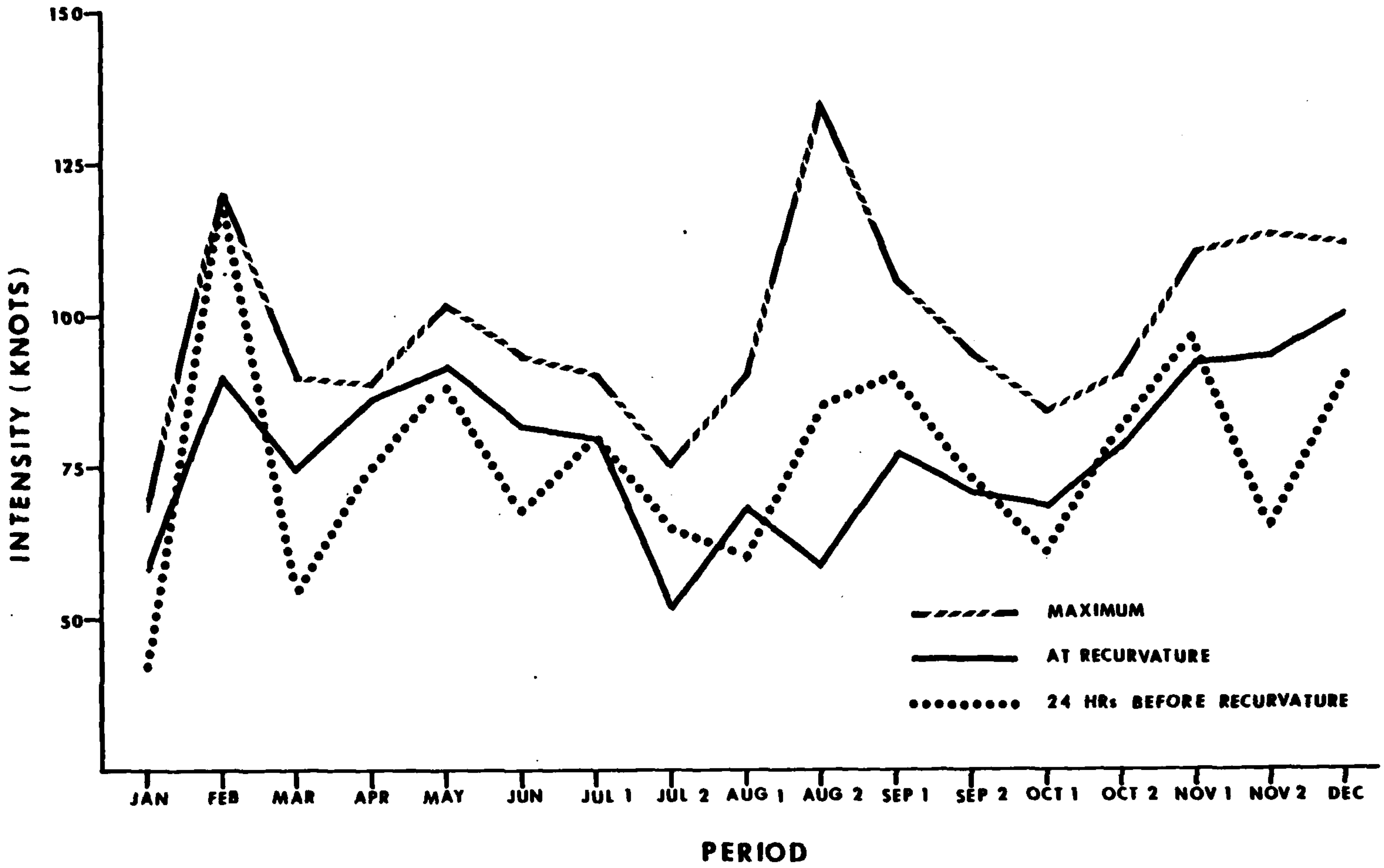

FIGURE 5

The average intensity of recurving tropical cyclones as a function of month and half month.

Although the mean motion and intensity of recurving tropical cyclones appears to be conservative with respect to earlier studies, it is the large variability about the mean which causes the high forecast errors associated with recurvature. A study of this variability, rather than the mean motion and intensity, would be of great benefit to further understand recurving tropical cyclones.

ACKNOWLEDGEMENTS

The author wishes to thank Colonel John W. Diercks, USAF, and Lieutenant Colonel Dean A. Morss, USAF, for their constructive suggestions and review of the manuscript. Also, special thanks are due to Aeorgrapher's Mate Third Class Beverly A. McCreary, USN, for her work on the graphics and assistance with typing. Finally, the author is indebted to Sergeant Konrad W. Crowder, USAF, and Senior Airman Randy G. Quinto, USAF, for their help in compiling the data for this study and to Mrs. Tammi Price for the final typing of the manuscript.

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