

Climatological Characteristics of Rapidly Intensifying Typhoons

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ABSTRACT

The occurrence of rapid deepening of tropical cyclones (≥ 42 mb in 24 h) in the western North Pacific is examined to determine the statistics of these events and to identify features peculiar to their onset. Seventy-nine cases of rapid growth during the period 1956–76 were selected to study climatological characteristics. These data show that the majority (75%) of the deep central pressures (≤ 920 mb) in the region are attained through the rapid deepening process. The bulk (67%) of these pressure reductions occur over a time interval of 18 h or less with the first 6 h most likely to account for the steepest fall.

The statistics reveal that development of a tropical cyclone to typhoon intensity over warm waters (temperature $\geq 28^\circ\text{C}$ to a depth of 30 m) is a necessary (but not sufficient) prerequisite for rapid deepening. An eye dimension near 40 km also is a frequently observed feature at the onset of rapid deepening. The time of onset occurs most frequently at night. Investigation of typhoon track direction and speed (or changes of these two variables) in relation to abrupt intensification revealed little association.

1. Introduction

The forecast of intensity of a tropical cyclone (typhoon or hurricane) has proved to be difficult. Deepening and increasing intensity may occur very hesitatingly, somewhat more rapidly, or with almost explosive suddenness in a few hours. The proper prediction of intensity is of great significance to human activity in affected regions. Prediction techniques now in use mostly are based on climatology, extrapolation of trends, analog techniques or combinations of these procedures. But such procedures tend to be deficient for cases of abnormally rapid intensification. Part of the problem lies in an inability to recognize such cases prior to the onset of the rapid deepening. Furthermore, intensity forecast procedures are biased in that a dominant majority of the cases used to develop the techniques are not of the rapidly intensifying variety. Continued improvement of such forecast methods may be aided by an increased understanding of the characteristics of such tropical cyclones. This study describes an attempt to document further the climatological characteristics of rapidly deepening (RD)² typhoons.

2. Some earlier studies

Individual tropical cyclones have been studied in detail for several decades (e.g., LaSeur and Hawkins, 1963; Hawkins and Rubsam, 1968;

Hawkins and Imbebo, 1976). Not all such storms have undergone a period of unusually rapid fall of central pressure. Several studies have, however, examined the characteristics of the vigorously deepening tropical cyclone. Ito (1963) determined that the Philippine Sea south of 25°N was the area with greatest frequency of RD (2.0 mb h^{-1} pressure fall). Brand (1973) noted distinct geographic and seasonal preferences for changes in maximum wind exceeding 50 kt in 24 h.

Several investigators have examined the outflow mechanism at high levels as an explanation for changes in intensity of tropical cyclones. Miller (1958) and Colon and Nightingale (1963) examined flows near 200 mb. While all investigators noted some characteristics, all were hampered by lack of data at upper levels over the oceans. Sadler (1976, 1978), with more wind information available, was able to show the importance of multi-directional outflow channels for controlling the intensity changes of typhoons. The storm's interaction with the Tropical Upper Tropospheric Trough (TUTT) and also its outflow to the equatorial easterlies play important roles in a typhoon's ultimate intensity and associated development rate.

Shenk and Rodgers (1974), Ramage (1974) and Smith (1975) all examined individual cases of significant deepening. Their results are not particularly consistent with one another.

Dvorak (1975) and Dvorak and Wright (1978) used visible and infrared satellite pictures to obtain a tropical cyclone intensity analysis and forecast. While their schemes allow for varying rates of deepening, they place no emphasis on extreme rates.

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² In this paper the notation RD means rapid(ly) deepening or rapid(ly) intensifying or rapid intensification.

TABLE 1. Cases used to determine maximum 24 h deepening.

Years	1 Typhoon count in ATR†	2 Incom- plete data	3 Below typhoon intensity*	4 Total used
1956-76	365	53	27	305
Percent of Column 1		14	7	79

† ATR, Annual Typhoon Report, Joint Typhoon Warning Center (1960-77).

* Based on central pressure-maximum wind relationships.

3. The deepening stage

a. The data and procedures

Rapid deepening seems best evaluated in terms of the rate of fall of the central pressure of the typhoon. Central pressure is considered a more reliable and conservative measure of intensity than the maximum winds,³ and is not as likely to be biased by sampling procedures of aircraft reconnaissance (Colon, 1963).

Readings of central pressure obtained by aircraft reconnaissance in the western North Pacific area were extracted from copies of the *Annual Typhoon Report* published by the Joint Typhoon Warning Center (JTWC), Guam (1960-77). The period 1956-76 was selected for study. Central sea-level pressure (SLP) values were determined from dropsondes or by applying a regression equation developed by Jordan (1958) to the value of the minimum 700 mb geopotential height. A 24 h interval was chosen, as reconnaissance observations were available at least once a day during the earlier years. Of the 385 typhoons counted during the 21-year period, 80 were not used here; many of these storms were discarded because of incomplete reconnaissance, while others, despite being listed as typhoons, failed to meet minimum requirements for typhoon-strength winds based on the central pressure-maximum wind relationship recently developed by Atkinson and Holliday (1977). A breakdown of the 385 cases examined is presented in Table 1.

Maximum 24 h deepening rate was determined from the individual plot of the history of central pressure for each of the 305 typhoons retained. These 305 typhoons are considered to constitute a reasonable sample upon which to build reliable statistical conclusions.

b. Criterion for and types of rapid deepening

A frequency distribution of maximum 24 h deepening for the usable data is shown in the form of a

³ Large variations in actual wind speeds are often noted to occur on relatively small scales in time and space (Sheets, 1972).

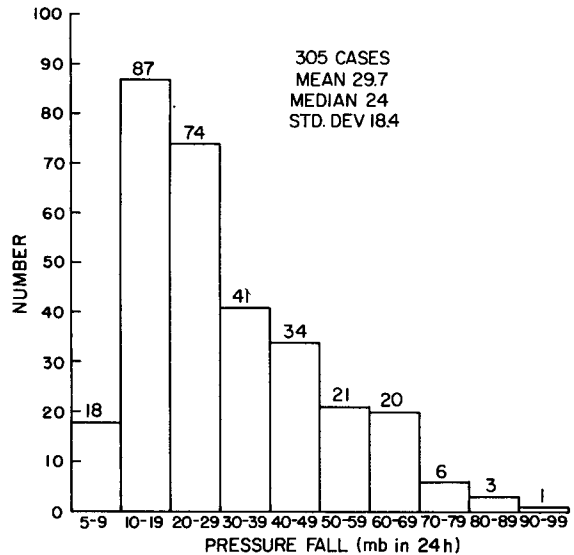


FIG. 1. Frequency distribution of maximum 24 h deepening of typhoons (1956-76).

histogram in Fig. 1, arranged into class intervals of 10 mb. The data show a distribution skewed toward the smaller deepening rates with maximum frequencies (53% of the sample) occurring in the 10-29 mb day⁻¹ interval. The observations ranged from 5 to 95 mb day⁻¹. Fig. 2 shows a cumulative frequency of the data with the median centered at 24 mb day⁻¹. It was felt appropriate to designate those cases in the upper 25% of the sample as rapid-growth systems. This portion of the sample was increased slightly (0.6%) to provide a convenient cut-off in the hourly deepening rate for classification purposes. Thus, a deepening rate of ≥ 1.74 mb h⁻¹

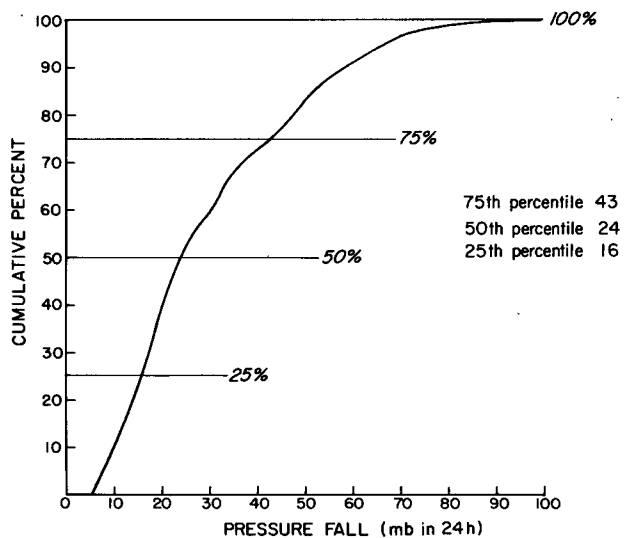


FIG. 2. Cumulative frequency distribution of maximum 24 h deepening of typhoons (1956-76).

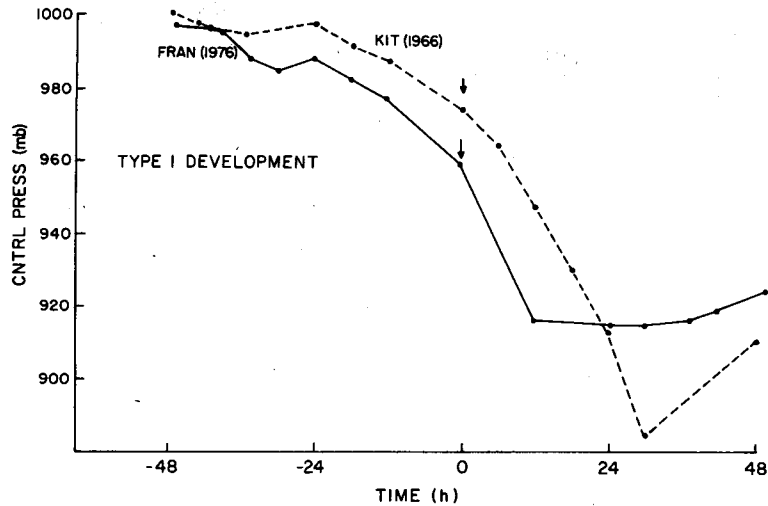


FIG. 3. History of central pressure readings for typhoons typical of type 1 development (Kit, June 1966; and Fran, September 1976). Arrow indicates onset of rapid deepening ($\geq 1.75 \text{ mb h}^{-1}$).

for 24 h or $\geq 42 \text{ mb day}^{-1}$ was chosen to identify RD. Of the 305 typhoons, 79 underwent RD.

Two basic categories of pressure profiles were noted. In type 1 the central pressure falls at a moderate rate ($\geq 0.8 \text{ mb h}^{-1}$) at least for 12–24 h, followed abruptly by accelerated development ($\geq 1.75 \text{ mb h}^{-1}$). The developments of Kit and Fran, shown in Fig. 3, are examples. This behavior was displayed by 36% of the sample. Type 2 behavior is characterized by slower initial development ($< 0.8 \text{ mb h}^{-1}$) suddenly followed by a surge of deepening ($\geq 1.75 \text{ mb h}^{-1}$). Fig. 4 shows two typical examples of this type, which accounted for 64% of the cases. Note that the maximum rate of deepening is about the same in

all four cases, though the time over which this rate persists differs. Virginia and Anita provide good examples of type 2 development. Note that the RD need not necessarily last a full 24 h provided that it exceeds 42 mb. The RD phase may last longer than 24 h; in that case the total deepening during the phase must exceed 42 mb.

c. Minimum pressures attained

A majority (75%) of case of RD resulted in very deep central pressures ($< 920 \text{ mb}$). This central pressure value was used by Frank and Jordan (1960) and later by Fung (1970) to identify extreme ty-

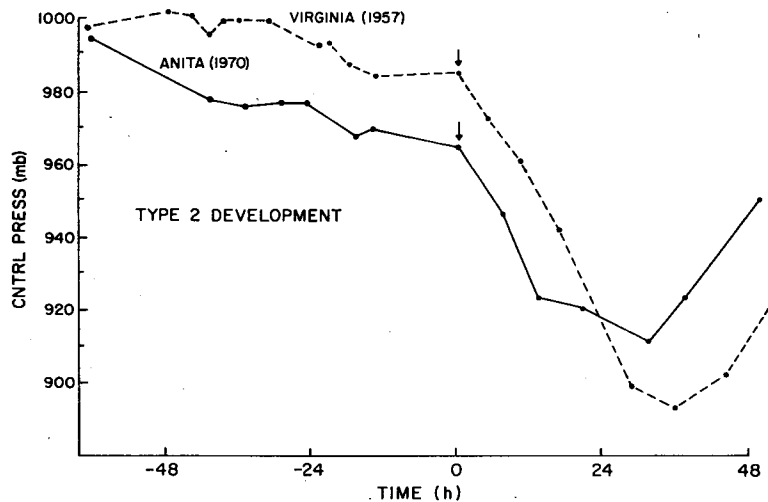


FIG. 4. History of central pressure readings for typhoons typical of type 2 development (Virginia, June 1957; and Anita, August 1970). Arrow indicates onset of rapid deepening ($\geq 1.75 \text{ mb h}^{-1}$).

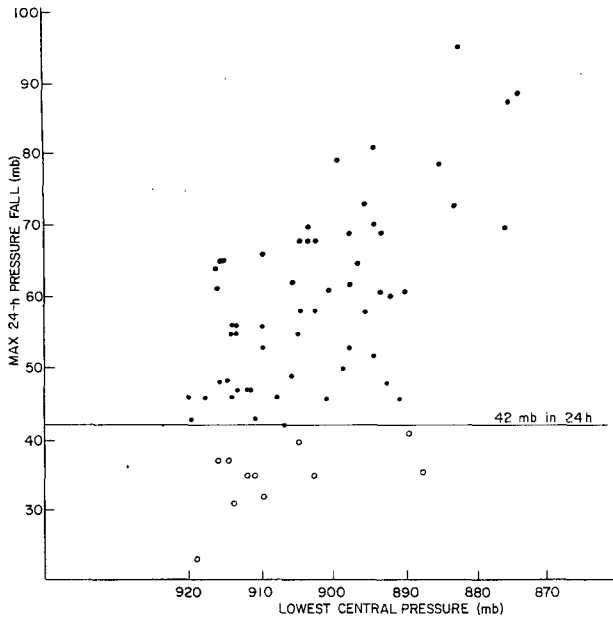


FIG. 5. Relation between minimum central pressure of deep typhoons (≤ 920 mb) and the maximum 24 h pressure fall.

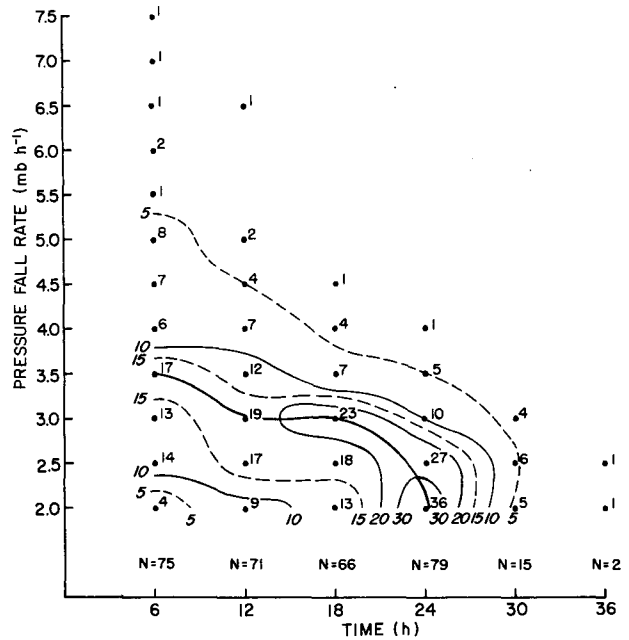


FIG. 6. Central pressure fall rates within given time periods for RD typhoons. (Isoleths are of equal numbers of occurrences.)

phoons. Of the typhoons occurring between 1956 and 1976, 71 reached intensities severe enough to be placed in this category. There was a strong preference for these very deep central pressures to follow a period of vigorous deepening. In fact, all minimum central pressures below 888 mb were attained following a period of RD, while only 14% of the 71 cases with minimum central pressure below 920 mb displayed a more gradual development rate (< 42 mb day⁻¹); see Fig. 5.

d. Duration and rates of development

The central pressure history for each typhoon was examined to determine maximum rates of fall over various time periods at 6 h increments to 36 h during the duration of RD. Not all consecutive 6 h fall rates were available, so the sample in Fig. 6 is incomplete (number of cases are noted at the base of each column). The general picture portrayed is that RD typhoons sustain the bulk of their pressure fall over short intervals, and durations of fall rates of 1.75 mb h⁻¹ beyond 24 h are relatively uncommon. A fall of 20 mb in 6 h is fairly common, and is already 48% of the minimum criterion for RD (42 mb) within a day. Table 2 shows that these peak falls are most likely to occur during the first 6 h of the period. Of 70 storms attaining minimum central pressures ≤ 920 mb, 59 experienced RD.

Extremes of rates of deepening are given by Opal 1967 (44 mb in 6 h), Iram 1971 (77 mb in 12 h and 85 mb in 18 h; also 95 mb in 24 h), Ida 1958 (95 mb in 30 h) and Elaine 1968 (83 mb in 36 h).

e. Relation of onset of intensification to time of day

Observers frequently have remarked that hurricanes appear more active at night than during the day (Sheets, 1969). A study by Sheets (1972) of maximum wind changes in hurricanes (1961–68), however, indicates no significant diurnal variation of hurricane intensity.

Of the 75 RD typhoons studied, 56 had sufficient consecutive 6 h observations to allow determination of the time of onset of the RD within 3 h. Most of the data were collected in 1957–59 and 1966 onward, as late night penetrations were not often conducted in the other years. The data were biased toward 0300, 0900, 1500 and 2100 GMT; the few other observations were included with the nearest standard time. A listing of the time of occurrence of the onset of RD is given in Table 3. Note that both GMT and local (Tokyo) times are indicated. The cases were also grouped into periods (1800–0000 and 0600–1200 LST) to emphasize either day or night periods. Greater frequencies (36 cases or 64% of all cases; coincidentally the same as the percent of Type 2 behavior) occur at night. This suggests that diurnal effect might be a contributing factor in the onset of intensification.

TABLE 2. Period when maximum central pressure fall occurs during RD.

Period of RD	1st 6 h	2nd 6 h	3rd 6 h	4th 6 h
Number of cases (75)	32	12	15	16

TABLE 3. Time of occurrence of onset of RD.

0300 (1200)	0900 (1800)	1500 (0000)	2100 (0600)	GMT (LST, Tokyo)
10	11	25	10	56 cases
Day (2100-0300 GMT)			Night (0900-1500 GMT)	
20 (36%)			36 (64%)	

One explanation of possible diurnal variations has been offered by Sheets (1969). He suggests that differences might exist in the stability of the day versus night hurricane conditions as a result of diurnal variation of temperature in the middle and upper troposphere. Diurnal variations are documented by Sheets (1969) for hurricanes and by Frank (1977) for typhoons. They find little evidence for diurnal changes except in upper tropospheric and stratospheric temperatures and related variables.

4. Aspects of storm organization

a. The formation period

Estimates of the organizational time required before commencement of the RD were made from the best track analyses for individual typhoons. Both the weak circulation stage⁴ and the time when tropical storm force was first attained were considered.

Evaluation of intensity and behavior of weak circulation systems was first performed systematically in 1967, when routine operational satellite data became available. This stage often begins two days before aircraft reconnaissance coverage. The time from the weak circulation stage to onset of RD could be estimated for 40 cases. A frequency distribution of various elapsed times appears in Fig. 7. RD onset began most frequently some 3.5-4 days following origin of the circulation. The range included Typhoon Nina (1975) which required only 3 days before entering the stage of explosive deepening (68 mb in 24 h) and Olga (1976) which delayed for 8 days until accelerated development took place (46 mb in 24 h).

The majority of locations of beginning of weak circulation were in the area bounded by longitudes 135 and 175°E and by latitudes 5 and 15°N. All but two of the 40 positions were east of 135°E and equatorward of 20°N. This indicates a geographic distribution well removed from topographic barriers (Philippines, Taiwan and Japan) and physical barriers (cooler sea surface temperatures and unfavorable upper tropospheric conditions). [This is dis-

⁴ The JTWC track analysis begins when a weak circulation is identifiable in the cloudiness pattern; this is classified as the disturbance stage. A depression classification is not assigned until the circulation has strengthened ($13-15 \text{ m s}^{-1}$) and central pressures have fallen to $\sim 1000 \text{ mb}$.

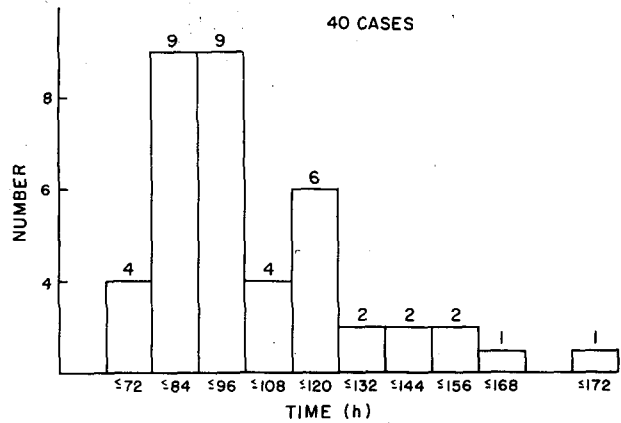


FIG. 7. Time elapsed from origin (weak circulation stage) to onset of RD.

cussed further in Section 5 (see also Gray, 1975, 1977; Sadler, 1976).]

A histogram of variations in time elapsed between tropical storm generation and RD, based on 54 cases with sufficient data, is shown in Fig. 8. Tropical storm intensity was considered to be reached when the central pressure reached 995 mb (Atkinson and Holliday, 1977). RD tends to occur 0.5-2 days (62% of the cases) after tropical storm generation. The majority of the cases shown in Fig. 8 were type 2 storms. At one extreme, both Ida (1969) and Wendy (1963) erupted into sharp pressure falls (61 and 49 mb in 24 h, respectively) within 6 h or tropical storm generation. Agnes (1968) and Olga (1976), on the other hand, took 4-4.5 days before RD began.

b. Intensity at onset of RD

Fairly accurate determination of the central pressure at the time ($\pm 3 \text{ h}$) of the onset of RD was possible in 75 of the typhoons. The distribution of these values is given in Fig. 9. The majority of cases of RD (81%) commenced in the interval 956-985 mb. Type 2 development predominates for higher values of central pressure, and type 1 becomes common for

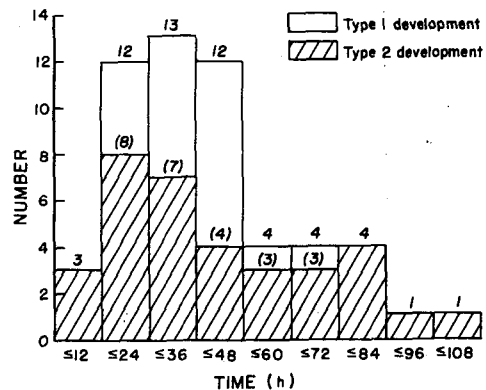


FIG. 8. Time elapsed from tropical storm generation to onset of RD.

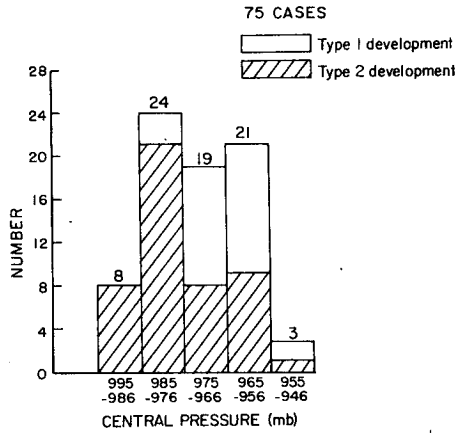


FIG. 9. Frequency distribution of central sea level pressure at onset of RD.

lower pressures. The cases ranged from Ida (1969) at 995 mb to Patsy (1973) with 950 mb at the onset of RD.

In the western North Pacific, as the central pressure falls to near 980 mb, the radar structure often undergoes significant transition toward typical hurricane-like features, suggesting cloud wall-eye formation and marking the transition from tropical storm to hurricane (Dunn and Miller, 1964). This pressure value is also required to produce typhoon force winds, according to the Atkinson and Holliday (1977) relationship. The time between reaching typhoon strength (assumed as the time when the central pressure reaches 980 mb) and the time of onset of RD was determined for the 73 cases for which the data were adequate. The values ranged from 6 h before attaining 980 mb to more than 72 h after (Fig. 10). For 62 (85%) of 73 cases, RD occurred during the period from 6 h before to 24 h after typhoon generation. The majority (67%) of the RD had commenced by 18 h after typhoon generation. Ida (1969) began RD 6 h before, and Agnes (1968) 3.5 days after, the time of typhoon generation.

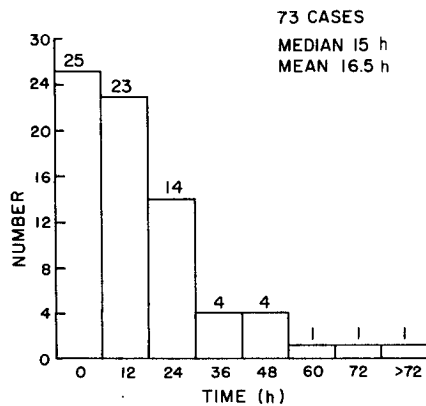


FIG. 10. Frequency distribution of interval elapsing between time of reaching typhoon strength and time of initiation of RD.

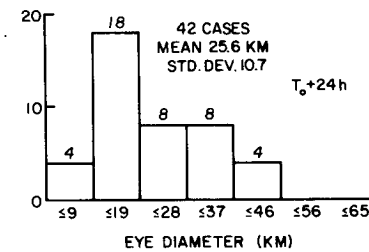
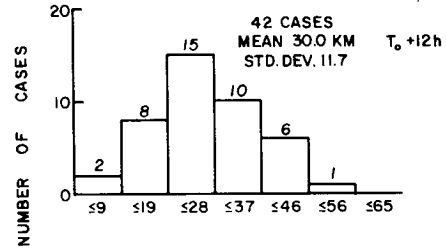
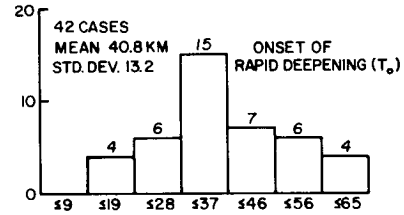


FIG. 11. Frequency distribution of eye diameter at onset of RD, and 12 and 24 h after that time.

c. Size of eye system

The onset of typhoon intensity was noted above as being related to the establishment of the eye system (including the eye wall) at the core of the storm. While this structure constitutes only 1–5% of the total storm volume (Gentry, 1969), it plays a major role in the intensity of the tropical cyclone (Riehl, 1954). Several investigators (Jordan, 1961; Gray and Shea, 1973; Bell, 1975) have noted that the smaller the eye-system radius, the more efficient is the reduction of central pressure. Thus, reports of eye diameter were examined to determine if RD occurs with a preferred size in the cloud wall-eye system, or with consistent changes in eye diameter.

Observations of eye diameter were not always made, nor, when made, were they necessarily adequate for our purposes, thereby leaving only 42 cases as a sample. Eye diameters were determined from radar or by measuring the radius of the ring of maximum winds. The eye diameter variations observed at the onset of RD and 12 and 24 h later are presented in Fig. 11.⁵ For the time of onset of RD, there is a preponderance of cases between 29 and 37 km

⁵ The peculiar class intervals result from conversion of the original data into SI units after classification.

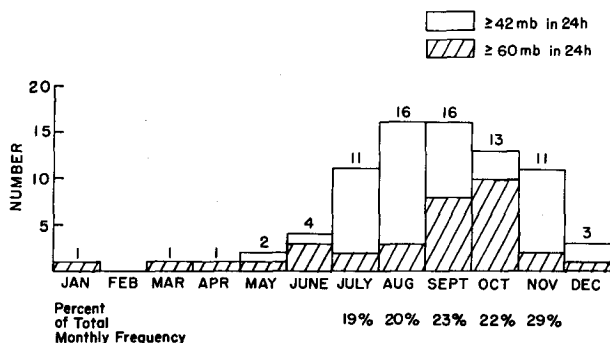


FIG. 12. Annual distribution of rapidly deepening typhoons (1956-76).

diameter with a mean of 41 km and a standard deviation of 13 km. Bell (1975), in a study of the eye diameter of western Pacific tropical cyclones developing to typhoon force, obtained an average diameter near 55 km for tropical cyclones with central pressures comparable to those of our sample.

The frequency distributions of eye diameter for 12 and 24 h after onset (Fig. 11) show a definite decrease in eye diameter with mean values of 30 and 26 km, respectively. This agrees with the ideas of Colon (1963), who suggests that eye size in early stages of hurricane development may influence intensification rate. He relates small size to rapid changes. Black *et al.* (1972) noted, in their study of Hurricane Debbie of 1969, that sudden significant changes in eye wall structure usually accompany RD.

5. Trajectory and seasonal-geographic aspects

a. Trajectory direction and speed

Trajectory direction and speed variations have been suggested by some as related to intensification (e.g., Dunn and Miller, 1964; Sugg and Pelissier, 1968). Thus, segments of the trajectories of the 79 sample cases were examined. Two adjacent 24 h segments of each path were selected, the first ending, and the second beginning, at the time of onset of the RD. Average 24 h direction and speed were determined by a straight line linking the initial and terminal point of each track segment. This eliminated some of the often considerable variability from one 6 h period to another.

The majority of cases in each time interval segment fell between the directions of 280° and 310° . Of the 26 typhoons of the sample that eventually recurved into the westerlies, none had reached recurvature point before the vigorous growth stage was completed. Almost half (48%) of the directional changes observed were relatively small ($\pm 10^\circ$). More directional shifts occurred to the right of the previous 24 h track (46) than to the left (28). Of the larger directional shifts ($>20^\circ$), more cases veered (21) after deepening commenced than backed (6).

Such behavior of tracks of tropical cyclones is well known (Tannehill, 1956; Dunn and Miller, 1964; see also Cressman, 1951).

Speeds were fairly evenly distributed from about 2.5 to 12 m s^{-1} , with a mean speed of 5.1 m s^{-1} before onset and 5.6 m s^{-1} after. An examination of individual changes in speed indicated that there were more cases of accelerating (39) than decelerating (28) systems. Twelve storms displayed no change in speed of movement. The majority of typhoons (56) showed changes $\leq 25\%$ of the 24 h speed immediately before RD. A greater number of accelerations $>25\%$ (18) were noted than decelerations (5). Changes in speed did not exceed 6 m s^{-1} .

No strong relationship appears evident in speed or speed changes in cases of RD. However, there is a slight tendency for storms traveling faster than normal to decelerate during the deepening process, while those initially moving at slow speeds display a gradual acceleration.

b. Seasonal distribution

RD occurs throughout the year (Fig. 12), with the main activity in July through November, the typhoon season. Incidents of extreme deepening ($\geq 60 \text{ mb}$ in 24 h) have been included for comparison. Values are given at the bottom of the figure for the percentage of RD as compared to the total monthly frequency of all typhoons.⁶ November has the highest percentage, with July-October not far behind.

A breakdown of the most active part of the year into 15-day periods⁷ is shown in Fig. 13. The bulk of cases is confined to summer and early fall (76%). Activity between mid-September and mid-October is at a peak for both rapid (21) and extreme (13) deepenings. It seems likely that the seasonal distribution displayed by all typhoons, regardless of deepening rates, is similar to that shown in Figs. 12 and 13 (except for the anomaly of October 16-31 in Fig. 13); however, we have not prepared statistics in a form comparable to these figures.

c. Geographic distribution

The trajectory segments (described in Section 5a) for summer and early fall (20 June-16 October) are plotted in Fig. 14. The midpoints of the track segments were identified as the points where typhoons intensified rapidly. The latitude and longitude of these points were averaged for each 5° Marsden square to represent the centroid of the points con-

⁶ Based on average frequency per month from data compiled by JTWC for period 1959-76 (1976 Annual Typhoon Report). Months must have at least 30 typhoons for comparison, thus resulting in exclusion of winter and spring months.

⁷ Thirty-one day months have the last day included in the latter 15-day period.

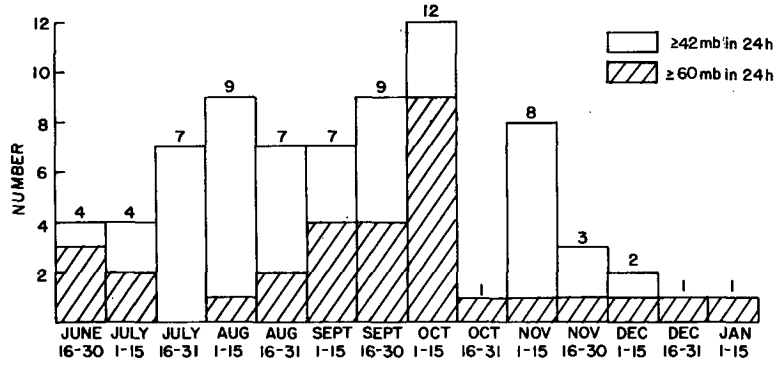


FIG. 13. Distribution of RD during main activity period by half-month periods.

tained in the square. Isoleths of these values were drawn to highlight areas of greatest activity (Fig. 15).

A large majority of all occurrences was concentrated in a 5° band between 15 and 20°N beginning some 550 km east of Luzon and stretching to near the northern Marianas. The South China Sea was almost free of rapid growth cases. This was not unexpected as typhoons that form in the South China Sea often reach landfall before they can intensify significantly. Storms entering from the Philippine Sea are weakened as their circulations are disrupted

by the rough terrain of the Philippine Archipelago, and have relatively little time for regeneration before landfall on the Indo-China Peninsula or southern China. The relatively few occurrences east of the Marianas are primarily the result of the normal absence of the low-level trough in this region. Eighty-five percent of all typhoons generate within the monsoon trough (Gray, 1977).

During late fall through spring, the area having preference for development shifts 5° equatorward and is concentrated between 10 and 15°N. The maxi-

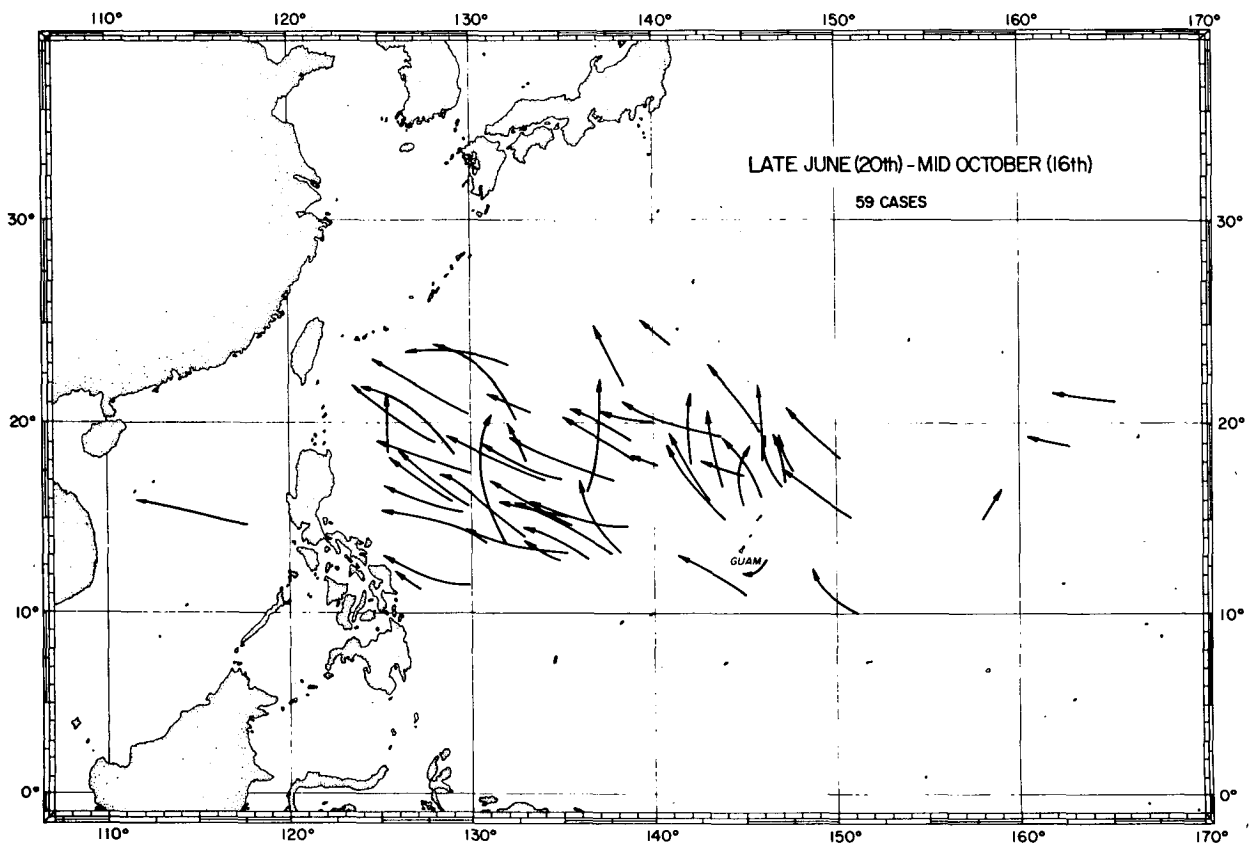


FIG. 14. Typhoon track segments (1956-1976) for period of RD (24 h) during summer and early fall (20 June-16 October).

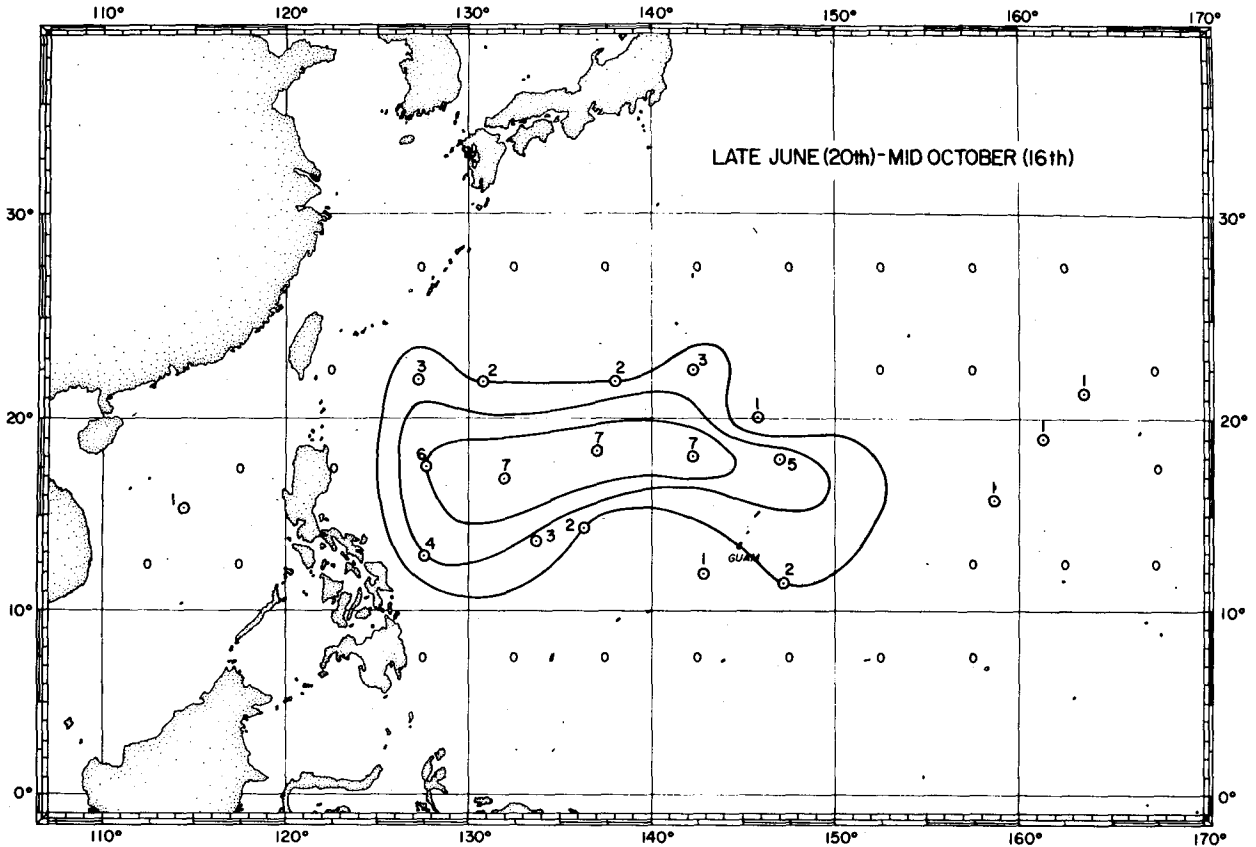


FIG. 15. Areas where typhoons intensified rapidly during summer and early fall (20 June–16 October)— number of occurrences (1956–76).

mum is not as longitudinally spread, being displaced further eastward from the Philippines and limited by the southern Marianas (not illustrated).

1) OCEAN TEMPERATURE INFLUENCE

Ten-day average sea surface temperatures over the region of each typhoon intensification immediately prior to arrival of the typhoon were determined for each point of onset and termination. (The maps of 10-day average sea surface temperatures were prepared by the Japan Meteorological Agency; averaging over several days minimizes the influence of

storm winds and upwelling of cooler water.) Table 4 shows the frequency of temperatures at commencement and termination of RD. The majority of cases was confined to values of 28–30°C. This corroborates the findings of Ito (1963) who found RD (2.0 mb h⁻¹) of typhoons (1954–60) associated with sea surface temperatures ≥28°C. The temperatures in the present sample seldom reached the theoretical values required for deep storms (30–31°C, central pressure ≤914 mb) as advanced by Miller (1958).

Several investigators (Perlroth, 1967; Leipper and Volgenau, 1972; Gray, 1977; among others) have emphasized the importance of considering the temperature of the upper ocean layer through several decameters at least. Gray even considers temperatures at a depth of 60 m in assessing ocean thermal energy. A climatological approach was necessary, as temperature versus depth measurements of the upper ocean layer are not routinely available ahead of a typhoon. Values at 30 and 60 m were extracted from an atlas of monthly subsurface ocean temperatures (Robinson and Bauer, 1971) at points where RD began and terminated. Table 5 displays the results for the 62 typhoons examined earlier for surface temperatures. Nearly all showed high tempera-

TABLE 4. Sea surface temperature variation associated with RD (1959–76)—62 cases.

Temperature (°C)	Number of cases	
	Onset	Termination
26–26.9	0	0
27–27.9	1	2
28–28.9	15	19
29–29.9	43	38
30–30.9	3	3

TABLE 5. Subsurface climatological temperature variation associated with RD (1959-76)—62 cases.

Temperature (°C)	30 m depth (cases)		62 m depth (cases)	
	Onset	Termination	Onset	Termination
23-23.9	0	0	0	2
24-24.9	0	0	0	1
25-25.9	0	0	2	1
26-26.9	0	0	1	8
27-27.9	0	3	8	20
28-28.9	13	31	28	20
29-29.9	49	28	23	10

tures ($\geq 28^\circ\text{C}$) to 30 m, though cooler temperatures often were in evidence at 60 m. Climatologically, these data suggest a mixed layer temperature of $\geq 28^\circ\text{C}$ to 30 m as a limiting criterion for RD.

Mean monthly 28°C isotherms for the surface and for 30 and 60 m depths were transferred from the atlas of Robinson and Bauer to maps of the western North Pacific Ocean. Track segments of RD typhoons within the month also were mapped. Figs. 16-18 show the results for August, October and November. With the exception of six storms, three of

which experienced rapid development for only 6-12 h, all tracks terminated at or equatorward of the position of the 28°C isotherm at 30 m depth; thus the climatological location of this isotherm might, in part, explain the poleward limit (and western demarcation line in the South China Sea) of the geographical distribution of storms displaying rapid growth. This does not say that a given typhoon will undergo RD: rather if the typhoon is in an area where the ocean temperature is below some limiting value ($\sim 28^\circ\text{C}$ at 30 m depth), the typhoon is very unlikely to display RD.

However, ocean temperature influences can be considered only as a necessary, but not sufficient, condition for abnormal intensity growth. The bulk of the typhoons traversing these warm waters displayed only normal development, and many weakened (Brand, 1973). It seems evident that upper tropospheric circulation features play the significant role (Ramage, 1974); these influences are examined in the next section.

2) UPPER TROPOSPHERIC INFLUENCE

Upper tropospheric outflow to the westerlies in the northern sector of a tropical cyclone has long

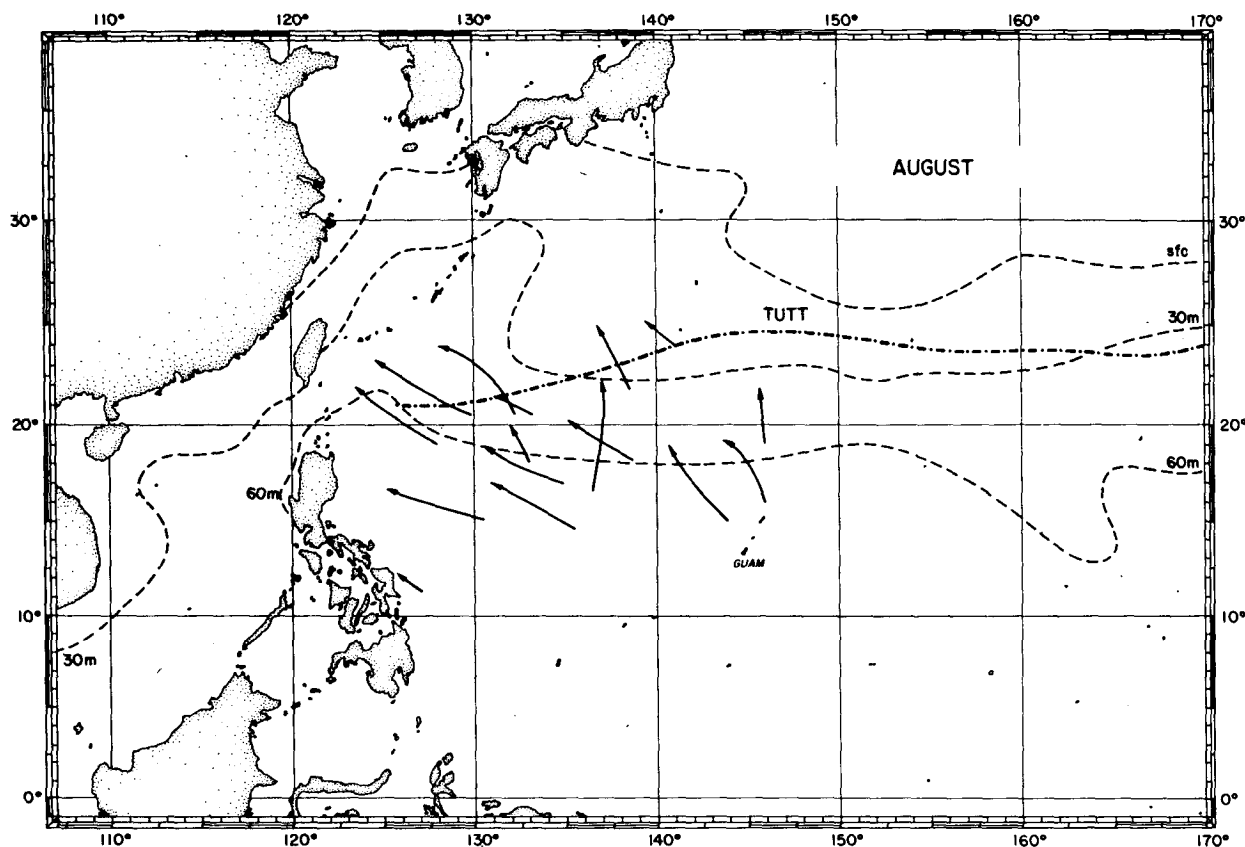


FIG. 16. August mean position of the 28°C ocean temperature isotherm (surface, 30 and 60 m depth), and the 200 mb Tropical Upper Tropospheric Trough (TUTT). Typhoon track segments during periods of RD for August are indicated.

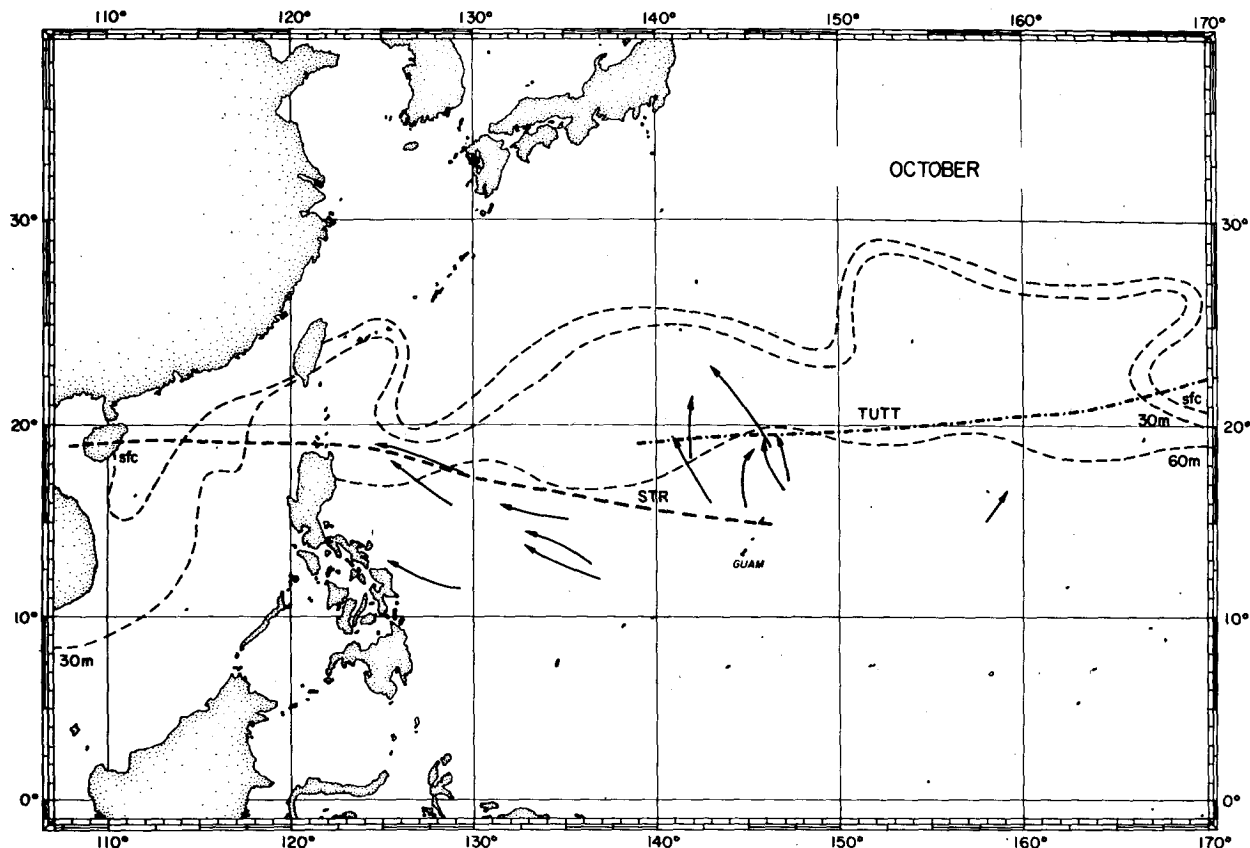


FIG. 17. October mean position of the 28°C ocean temperature isotherm (surface 30 and 60 m depth), the mean position of the 200 mb Subtropical Ridge (STR), and the average position (between September and October) of the Tropical Upper Tropospheric Trough (TUTT). Typhoon track segments during periods of RD for October (all within first 16 days) are included.

been recognized as a requirement for development (Riehl, 1954; Dunn and staff, 1964; Colon and Nightingale, 1963). Deep westerly troughs may aid this outflow in winter months. In summer, the Tropical Upper Tropospheric Trough (TUTT) provides a westerly channel for outflow (Ramage, 1959, 1971; Sadler, 1976, 1978).

The monthly climatological positions of the TUTT, and for some months the Subtropical Ridge (STR), as determined from an atlas of 200 mb circulation over the tropics (Sadler, 1975), were marked on our maps of sea temperature for the summer months (see the preceding subsection, including Figs. 16–18). From July into October the poleward limit of rapid deepening occurs within $\pm 3^\circ$ of latitude of the TUTT, with few exceptions. By early October subtropical westerlies prevail east of Asia, and the TUTT retreats eastward and disappears later in the month. The 200 mb STR becomes the latitudinal brake as suggested by the track segments of Figs. 17 and 18 and the equivalent map for December.

A slight seasonal preference in the geographic distribution of RD was noted (see also Brand, 1973).

In late June through August many tracks are located in the western portion of the Philippine Sea. During September and October, trajectories tend to be farther east, and a more meridional orientation of the tracks suggests the beginning influence of deep midlatitude troughs.

Although climatological features of the upper flow may be used to explain, in part, the geographical distribution of RD, recognition of the individual case with respect to particular upper tropospheric patterns is necessary if prediction skill is to be realized. The individual cases may best be examined by combining information from the meteorological satellites with the conventional upper troposphere data (e.g., Sadler, 1976, 1978). This should be investigated further, perhaps by using information from Japan's geosynchronous satellite launched in July of 1977 and located at 140°E.

The statistical-climatological approach used here does not distinguish clearly between RD typhoons and other typhoons. It only gives conditions and locations for which RD may occur. However, this implies regions and conditions for which a typhoon is not expected to undergo RD.

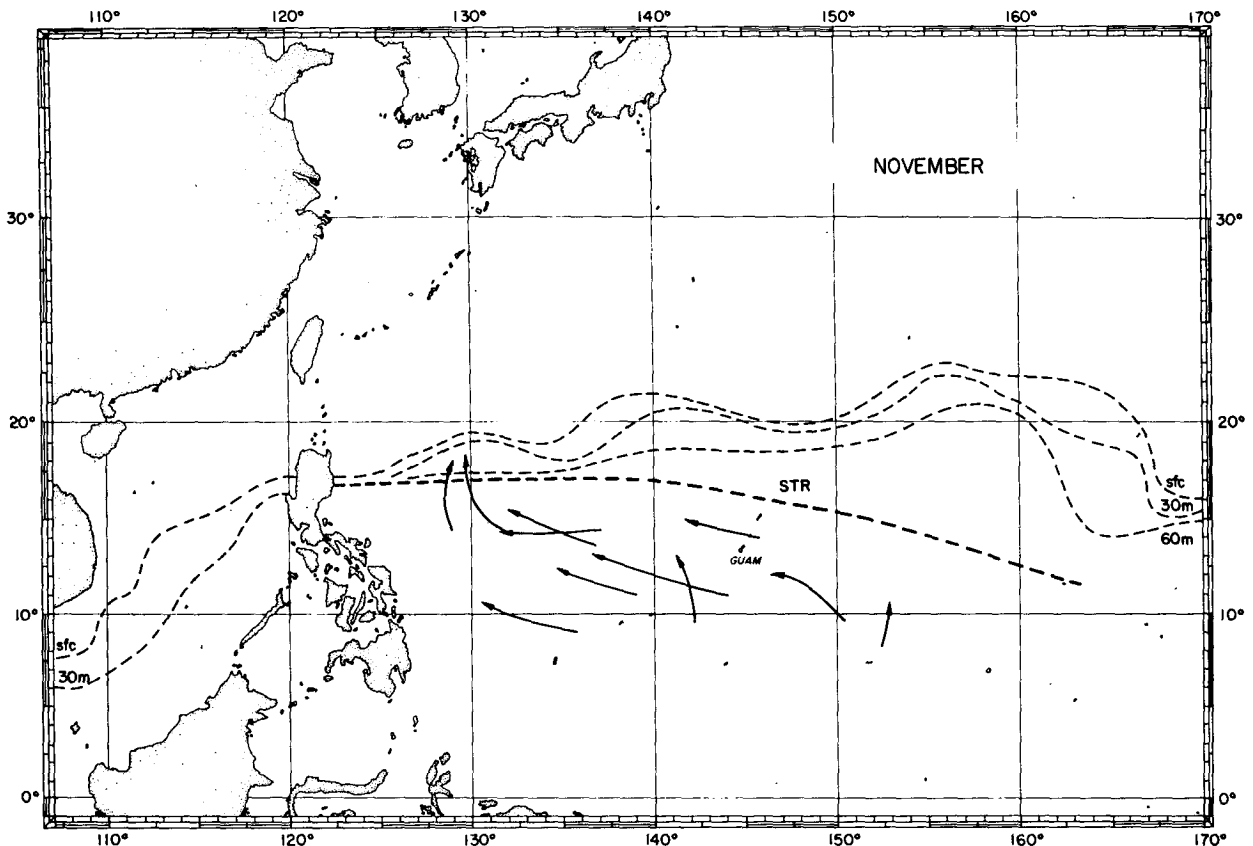


FIG. 18. November mean position of the 28°C ocean temperature isotherm (surface 30 and 60 m depth), and the 200 mb Subtropical Ridge (STR). Typhoon track segments during periods of RD for November are indicated.

6. Summary

Several characteristics regarding RD of tropical cyclones in the western North Pacific have been identified in this observational study. These include the following:

1) The majority (75%) of the deep central pressures (≤ 920 mb) recorded in the region are attained through the rapid growth process. The bulk (67%) of these pressure reductions occur over a short time span of 18 h or less, although occurrences of ≥ 1.75 mb h^{-1} in the remainder have extended to 36 h. The largest drop observed is most likely to occur during the first 6 h of the period. Relatively few typhoons exhibit a moderate rate of pressure fall preceding this phenomenon; the RD process is normally abrupt with sharp departures from extrapolation noted (characteristic of type 2 typhoons, 64% of cases).

2) RD is dependent on the organizational state of the storm circulation system. The majority (85% of cases) of onset of rapid development commenced 6 h before to 24 h after typhoon generation. The preceding development period for a weak circulation to strengthen before accelerated intensifica-

tion requires at least 3.5–4 days. Onset of this RD appears more frequently at night than during the day.

3) The size of the eye encompassed by the cloud wall has some bearing on future development. More frequently diameters between 29 and 37 km were observed, and always, diameters were ≤ 65 km at the onset of RD. This is in contrast to the average eye size of 55 km. Marked eye size reduction is also noted to be prevalent with vigorous intensification.

4) Little relation can be found between trajectory direction and speed (or changes of these two variables) and the RD of a typhoon. There is a tendency for storms traveling faster than normal to decelerate during the deepening process while those initially moving at slow speeds display a gradual acceleration.

5) Most cases of rapid growth of typhoons occur in the latitude bands 15–20°N during the summer and early fall in an area beginning some 300 n mi east of the Philippines and stretching eastward to the vicinity of the Marianas. During the rest of the year, less frequent activity is observed as the band shifts 5° equatorward. The peak seasonal frequency of significant intensification occurs between 16 September and 15 October. A conspicuous (but unexplained) absence of RD is observed for the last half of October.

6) Ocean temperature $\geq 28^{\circ}\text{C}$ at a depth of 30 m appears necessary to support rapid development.

7) The mean position of the Tropical Upper Tropospheric Trough during the summer and early fall and the Subtropical Ridge (November–May) appear to coincide with the poleward extend to RD over warm waters $\geq 28^{\circ}\text{C}$.

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