

## Tropical Cyclone Minimum Sea Level Pressure/Maximum Sustained Wind Relationship for the Western North Pacific

GARY D. ATKINSON<sup>1</sup> AND CHARLES R. HOLLIDAY<sup>2</sup>

*Joint Typhoon Warning Center, Guam*

(Manuscript received 4 June 1976, in revised form 10 January 1977)

### ABSTRACT

Determining the proper relationship between the minimum sea level pressures and maximum sustained winds in tropical cyclones has been a long-standing problem. The major obstacle has been the lack of sufficient ground truth, i.e., actual measurements of maximum wind speeds in tropical cyclones with a wide range of central pressures. In this study 28 years of maximum wind measurements made at coastal and island stations in the western North Pacific were collected and analyzed. Because of problems in measuring and interpreting sustained surface wind speeds, only recorded peak gust values were used. These peak gust values were reduced to a standard anemometer level of 10 m using a power law relationship and then converted to 1 min sustained wind speeds using gust factors representative of an overwater environment. The sample was restricted to cases where it was reasonably certain that the station experienced the cyclone's maximum winds during its passage. The resulting equation,

$$V_m = 6.7(1010 - p_c)^{0.644},$$

where  $p_c$  is the minimum sea level pressure (mb) and  $V_m$  the maximum sustained (1 min) wind speed (kt), indicates maximum wind speeds that are significantly lower than many previous studies.

### 1. Introduction

The maximum sustained surface wind in tropical cyclones is a function of the radius of maximum wind and the local maximum pressure gradient. While the maximum wind radius can be determined relatively accurately from aircraft data and meteorological satellite imagery, data to accurately determine the local maximum pressure gradient are seldom available. Therefore, most studies have concentrated on developing relationships between the minimum pressure (or pressure difference between the cyclone center and outer edge of the circulation) and the maximum winds. While numerous equations have been developed over the years, a stable equation for this relationship which can stand the test of time in operational use has remained elusive. Reliable center pressures from aircraft reconnaissance have been available for many years; however, accurate observations of the maximum overwater surface winds are seldom available. The major problems in obtaining maximum wind observations are the sparseness of oceanic observing stations and the lack of adequate wind equipment and exposure at existing stations, anemometers breaking or blowing away before recording the peak winds in intense ty-

phoons, the general avoidance of tropical cyclones by ships and lack of wind measuring equipment on board ships infrequently caught near cyclone centers, and the uncertainty of surface wind estimates from sea state observations made during aircraft reconnaissance flights.

In this article, previous studies on tropical cyclone pressure-wind relationships for the western North Pacific are briefly reviewed. A new relationship is developed based on maximum wind observations recorded at island and coastal stations in the western North Pacific area during tropical cyclone passages during a 28-year period.

### 2. Review of previous studies

Numerous minimum pressure/maximum wind relationships for tropical cyclones have been developed over the years for both the North Atlantic and western North Pacific areas. Holliday (1969) surveyed a number of these relationships, primarily for the North Atlantic area, and developed a new relationship for that area. Most of the relationships for the western North Pacific have been developed by Joint Typhoon Warning Center (JTWC) personnel and discussed in the Guam Annual Typhoon Reports (1952-75). Following is a review of the various relationships which have been developed for the western North Pacific area.

The first equation for relating maximum winds in typhoons to central pressure was developed by Takahashi

<sup>1</sup> Colonel, USAF. Present affiliation: HQ Air Weather Service, Scott AFB, Ill. 62225.

<sup>2</sup> Captain, USAF. Present affiliation: Department of Meteorology, Texas A&M University, College Station 77843.

(1939). He used wind data from ships and island stations near or in Japan during the late 1930's. Since central pressures often were not available, he estimated these by interpolation and a statistical horizontal pressure distribution model for typhoons. The following form of the cyclostrophic wind equation was used:

$$V_m = K(p_n - p_c)^{0.5}, \quad (1)$$

where  $V_m$  is the maximum surface wind speed (kt),  $p_n$  the environmental pressure (mb),  $p_c$  the central pressure (mb) and  $K$  is a constant. He chose an environmental pressure of 1010 mb as representative of the western North Pacific area and  $K$  was determined to be 13.4. Later, Takahashi (1952) indicated a constant of 11.5 may be more applicable for higher latitudes.

With the introduction of aircraft reconnaissance of Pacific typhoons, central pressure observations and estimates of maximum winds near cyclone centers became available. The Typhoon Postanalysis Board (McKown *et al.*, 1952) at Guam derived an equation based on 230 typhoon penetrations during 1951 and 1952. Using Fletcher's equation (published in 1955 but available earlier)

$$V_m = 16(p_n - p_c)^{0.5} \quad (2)$$

as a starting point, a family of curves was developed to fit the reconnaissance data. Fletcher's equation was modified such that the constant decreased linearly with increasing latitude. The resulting equation was

$$V_m = (20 - \theta/5)(1010 - p_c)^{0.5}, \quad (3)$$

where  $\theta$  is the latitude (deg).

Eq. (3) was based entirely on maximum surface wind estimates from sea state observations. No differentiation was made between estimates made from 1500 ft (44% of the data) and those from 700 mb (56% of the data). Flight level winds were not available as Doppler navigation systems were not installed on the WB-29's and double-drift wind readings were extremely difficult to obtain in typhoons. Procedures for estimating maximum winds from sea state were very subjective and lacked any ground truth verification data.

As reconnaissance flights at 700 mb became routine by the mid-1950's, Fortner (1958) derived an equation relating minimum sea level pressure (MSLP) to the minimum 700 mb height. This equation allowed modification of Eq. (3) so that 700 mb height values ( $h_7$ , m) could be used in lieu of  $p_c$  as shown below:<sup>3</sup>

$$V_m = (20 - \theta/5)(372 - h_7/8.54)^{0.5}. \quad (4)$$

This change facilitated operational use as the minimum 700 mb height was available and transmitted from the aircraft well before the MSLP computed from the dropsonde observation.

<sup>3</sup> 700 mb heights in Eqs. (4) and (5) originally given in feet were converted to meters.

Wacholtz (1961) modified the latitude constant based on reconnaissance data from 1956 to 1959. In his relationship, the maximum winds for a given central pressure (or 700 mb height) occurred at 15°N and decreased north and south of this latitude.

Seay (1964) also modified the equation using data through 1962. He changed the latitude factor to  $(19 - \theta/5)$ , close to that of the original 1952 equation. A year later the JTWC staff (1965) changed the 700 mb height term slightly, obtaining the equation

$$V_m = (19 - \theta/5)(364 - h_7/8.54)^{0.5}. \quad (5)$$

A later modification of Eq. (5) was made by the JTWC staff (1969) using land station reports during the 1964-65 and 1967-68 seasons. They noted that winds derived from Eq. (5) exceeded the maximum winds observed at land stations by 23.4 kt on the average. A modified graph was constructed by subtracting 20 kt from the values derived from (5); however, the graph was considered valid only for wind speeds >45 kt.

There was considerable uncertainty involved in the existing equations and a general belief among JTWC forecasters that they overestimated the maximum winds. Therefore, in 1973 a new pressure-wind relationship developed by Fujita *et al.* (1971) was adopted for operational use. While the Fujita relationship appeared to give more realistic wind values, a large-scale data collection effort (described in the next section) was initiated to obtain sufficient information to verify or refine the existing relationships.

In this review of previous studies relating maximum surface winds to the MSLP (or minimum 700 mb height), various problem areas became evident. These include 1) the lack of direct surface wind measurements near the cyclone centers; 2) the incompatibility of the surface wind observations used due to various averaging periods, different anemometer heights and terrain effects; 3) the neglect of boundary layer frictional effects when relating flight level and surface winds; 4) the attribution of wind speed variations for given central pressures to questionable latitude effects; and 5) the inability of the equations to produce realistic maximum winds for the higher pressure ranges.

### 3. Data collection

The high annual frequency of tropical cyclones in the western North Pacific (Crutcher and Quayle, 1974) coupled with a fair density of meteorological stations along the periphery of East Asia provide the best potential for gathering surface observations during tropical cyclone passages. A major problem, however, is that observations of peak wind speeds and minimum pressures are not readily available in routine publications from the various countries concerned. Therefore, contacts were made through correspondence and personal visits to the various national meteorological

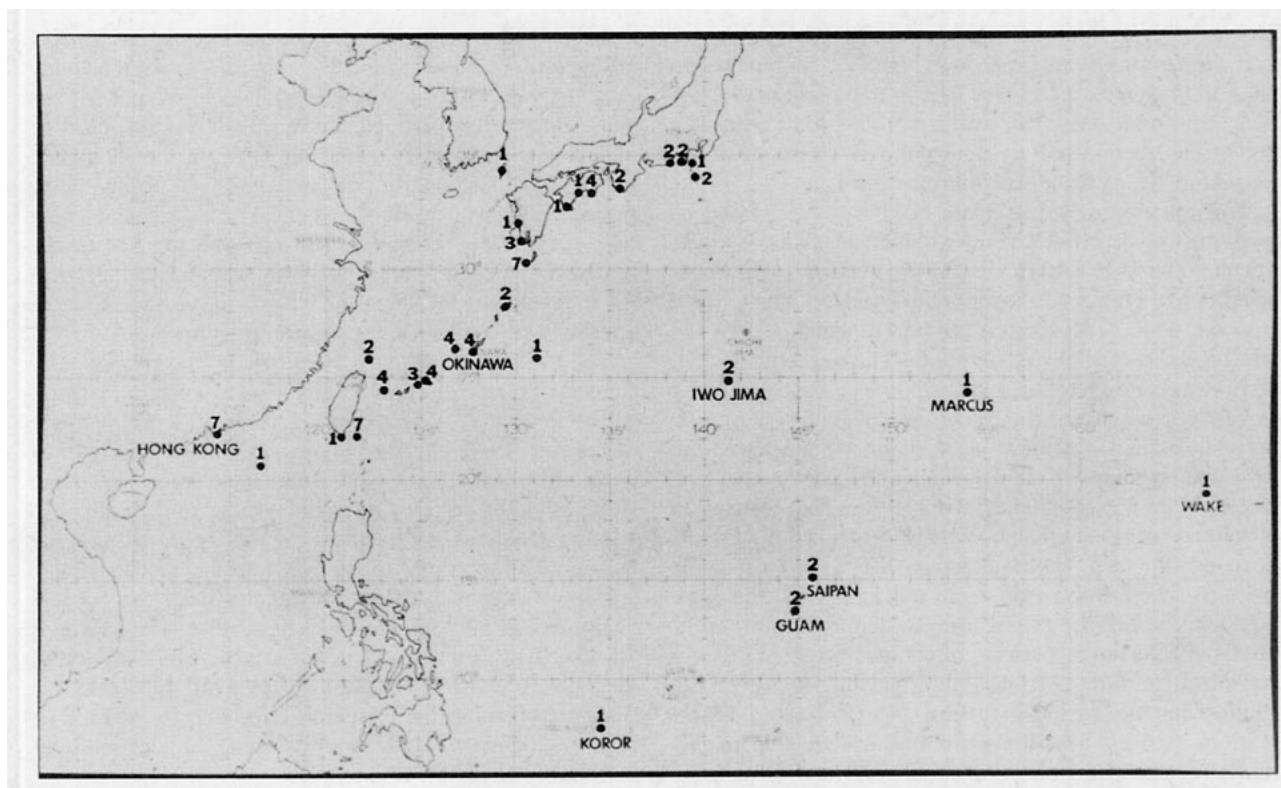


FIG. 1. Location of meteorological stations providing data for the study and the number of cases used for each station.

agencies to gather the required data. Some of the data were available in climatological summaries published by some countries since the early 1950's. Use was also made of annual reports of tropical cyclones affecting the Philippines (Philippine Weather Bureau, 1950-1970), Taiwan (1947-1971) and Hong Kong (Royal Observatory Hong Kong, 1960-1973). Earlier data from Hong Kong were obtained on request as were data for Pratas Island (from the Republic of China Navy). Special reports which compiled several decades of data on tropical cyclones affecting the Ryukyu and Japanese islands since the 1940's were obtained from the Japanese Weather Association, Tokyo (1973a,b). Occurrences of tropical cyclone passages at meteorological stations operated by U. S. government agencies in the western North Pacific area were screened and data were extracted from station records supplied by the National Climatic Center, Asheville, N. C. For recent years (1970 and after), station data were obtained on an annual basis by direct query to the various foreign meteorological services. Because of this extensive data collection effort, it is felt that most of the usable station data recorded since the late 1940's have been screened for possible inclusion in the data sample. Fig. 1 shows the location of stations used in the study and the number of cases used from each station.

#### 4. Methodology

Maximum wind observations associated with tropical cyclones occurring at meteorological stations in

JTWC's area of responsibility were analyzed and screened for possible inclusion in the data sample. A rigorous set of criteria had to be satisfied before any case was accepted. Out of hundreds of potential candidates occurring during the period 1947-74, only 76 were selected. Because of the relatively small number of cases meeting the criteria, further stratification of the sample was not considered advisable. As more cases become available in future years, separate relationships could be developed for various cyclone stages (e.g., deepening, filling or relatively steady state), various latitude zones, or other stratifications. Following is a discussion of the criteria used and the rationale for using these criteria.

The primary limiting criterion was that selection was restricted to cases where there was a very high probability that the station experienced the maximum winds in the cyclone during its passage. This meant that sometime during its passage, the eye wall cloud (where the strongest winds are normally found) must have been over the station. Additionally, since the strongest winds are usually found in the right-hand semicircle of the cyclone according to the direction of movement, selected cases were almost always restricted to cases where the cyclone passed directly over or just to the left of the station. Detailed mesoscale analyses of the cyclone's track and eye diameter as reported by aircraft reconnaissance and land radar observations were used in the selection process. In less intense tropical storms which lack a wall cloud, the maximum winds

are usually farther removed from the cyclone center and horizontal wind speed gradients are much less than in typhoons. For these cases, meteorological judgment and analyses of aircraft reconnaissance wind observations were used to determine if the station experienced the cyclone's maximum winds.

The maximum wind values used were restricted to peak gust observations taken at stations with recording anemometers. It is felt that peak gusts are the most reliable wind observations available during strong-wind periods. This is illustrated by Fig. 2 which shows the wind speed record during Typhoon Tilda at Kadena AB, Okinawa, on 2 October 1961. The peak gust of 108 kt is easily read from the recorder roll; however, estimates of the maximum sustained wind speeds for averaging periods of 1, 5, or 10 min could vary considerably among independent observers. The restriction of selected cases to stations with wind recording devices is to ensure that the peak wind speed was used. At stations where only wind dials are available, the peak gust could easily be missed due to demanding observer duties during such periods of violent weather. Many potential candidates from among cyclones striking the Philippines or various western North Pacific island stations had to be eliminated because of this uncertainty in the wind observational accuracy. Peak gust data used in the study were measured by different types of anemometers from various meteorological services. It is realized that varying sensitivities and response characteristics of different anemometers introduce another source of error. The magnitude of this error, however, is probably less than errors introduced by techniques/assumptions required to convert peak gust values to sustained winds at a standard height. Therefore, a rigorous analysis of anemometer characteristics and possible measurement errors was not made. Data used in the analysis were limited to wind observations from relatively small islands or to coastal stations where the peak winds blew from an onshore direction. This restriction was necessary so that, as much as

possible, the wind observations would be representative of undisturbed overwater flow. While even relatively small islands will reduce the sustained wind speeds from those of nearby open water, the peak gusts should be affected only slightly. This is because peak surface wind gusts in tropical cyclones invariably occur during periods of heavy rainfall, when maximum winds near the surface are transported downward to the surface in the downdraft caused by the convective activity. As a result, surface friction effects have less time to operate and reduce the maximum gust speeds.

The study was designed to develop the proper relationship between minimum sea level pressures in tropical cyclones and the maximum sustained 1 min average overwater wind speeds for operational warning purposes. Thus, the peak gusts for the selected cases had to be adjusted for elevation differences and reduced to 1 min sustained wind speeds using appropriate gust factors. The structure of the wind field near the earth's surface is extremely complex and has been the subject of numerous micrometeorological studies. Fortunately, an excellent survey of near-surface wind structure during strong wind conditions was available from the Air Force Cambridge Research Laboratories (AFCRL) (Sissenwine *et al.*, 1973) and used for determining reasonable adjustment factors.

Studies on the vertical variability of wind speed with height indicated that wind profiles tend to obey the power law

$$V/V_0 = (H/H_0)^P, \quad (6)$$

where  $V_0$  is the wind speed at some reference level ( $H_0$ ) and  $V$  the wind speed at level ( $H$ ). The exponent ( $P$ ) can vary considerably depending on the atmospheric temperature lapse rate, wind speed and surface roughness. A typical value of  $P$  for sustained wind speeds under neutral stability conditions is  $\frac{1}{7}$  (0.143). The exponent for peak gusts, however, should be much less because of the reduced frictional effects discussed earlier. For this study, a  $P$  value of  $\frac{1}{16}$  (0.0625) as

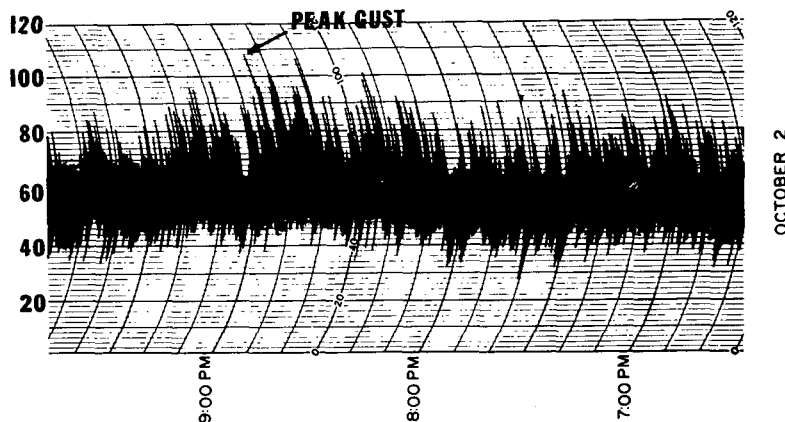


FIG. 2. Wind speed record (kt) during passage of Typhoon Tilda at Kadena Air Base, Okinawa, on 2 October 1961.

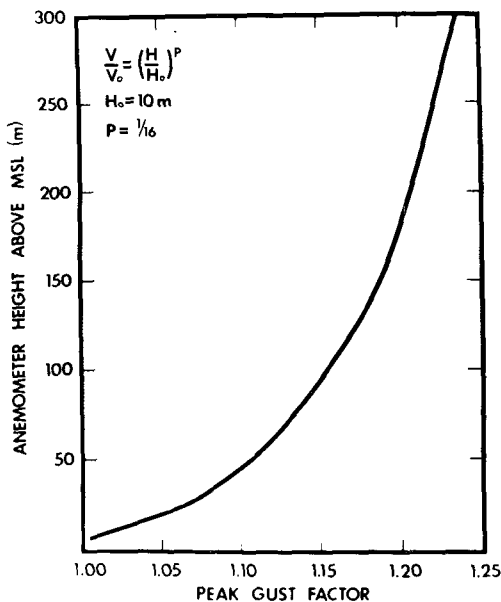


FIG. 3. Ratio of the peak wind gusts at various heights (m) to peak gusts observed at a standard level of 10 m using an exponent of 0.0625 in Eq. (6).

recommended by Sherlock (1953) was used to adjust all peak gust observations to a standard elevation of 10 m. This  $P$  value was the lowest observed in all studies surveyed by the AFCRL report and was chosen to be on the conservative side (i.e., its use gave the least reduction of peak gust speeds with decreasing height). A graph giving the ratio of peak gusts at various levels to the peak gusts at 10 m elevation using the exponent  $P=0.0625$  is shown in Fig. 3. The following example illustrates application of this height adjustment. The meteorological station at Andersen AFB, Guam, has an elevation of 191 m above sea level with an anemometer height of 4 meters. Entering the graph in Fig. 3 at 195 m elevation, a ratio of 1.20 is found. Thus, peak gusts observed at Andersen in tropical cyclones were divided by 1.20 to estimate the peak gusts that would be observed at the 10 m elevation.

Once peak gusts were adjusted for anemometer height differences, estimates of the corresponding sustained 1 min wind speeds were made. To do this, a graph derived from recommended gust factors given in Table 13 of the AFCRL report was used. Fig. 4 shows a graph of these gust factors plotted against sustained 1 min wind speeds. It shows the gust factors decreasing with increasing wind speed. This should be expected from physical considerations due to increased instability and turbulent mixing with increased wind speeds. The gust factors shown in Fig. 4 are less than the gust factors used operationally by JTWC which vary between 1.25 and 1.20 for winds exceeding 60 kt (Atkinson, 1974). Therefore, their use resulted in less reduction of the peak gusts to sustained winds than would have resulted from using the JTWC operational peak

gust factors. Again, the more conservative values were used so that the sustained winds would be overestimated in case any bias was present.

Once the maximum sustained winds were derived, estimates were made of the MSLP in the cyclone at the time the maximum winds were recorded. All available data were used to determine the MSLP. For cyclones that went directly over or very near the station, the MSLP could be determined from the station pressure observations. In cases where the center passed more than 10 n mi away from the station, the MSLP in the cyclone was interpolated from aircraft reconnaissance observations of MSLP. For island stations, these observations were generally available before and after center passage; however, for coastal stations, the last aircraft observation prior to landfall was used if it was reasonably close in time to the time of the maximum wind observation. Various sources of error can affect the MSLP observations, e.g., errors in instrumentation or measurement, errors in interpolating MSLP from nearby stations, and errors incurred when the aircraft dropsonde does not exactly hit the cyclone's surface center. To adjust for the last source of error, MSLP values were computed from minimum 700 mb heights in the cyclone (Jordan, 1957) and compared to the MSLP recorded from the dropsonde. The lowest of the two values was generally used for the MSLP. Even with these sources of error, most of the MSLP's used in the analysis are probably accurate to  $\pm 5$  mb.

5. Results

The derived maximum sustained wind speeds are plotted against the MSLP's in Fig. 5. Both linear and nonlinear regression equations were fitted to the data points. The bulk (95%) of the data falls between 994 and 935 mb. Statistically, little difference is noted between the linear and nonlinear equations in this range.

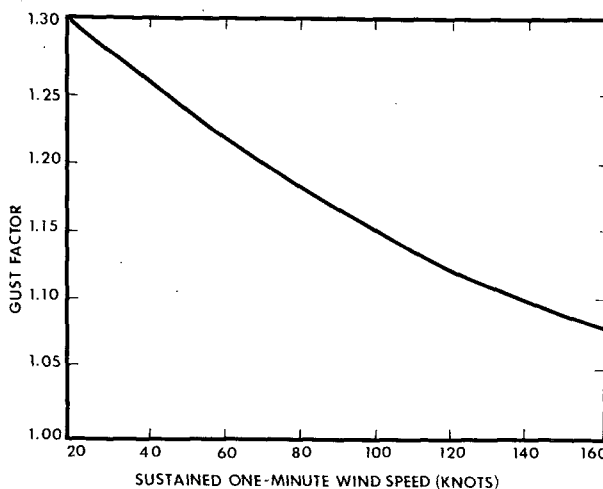


FIG. 4. Gust factors between the sustained (1 min) surface wind speeds and the peak wind gusts over water at 10 m elevation.

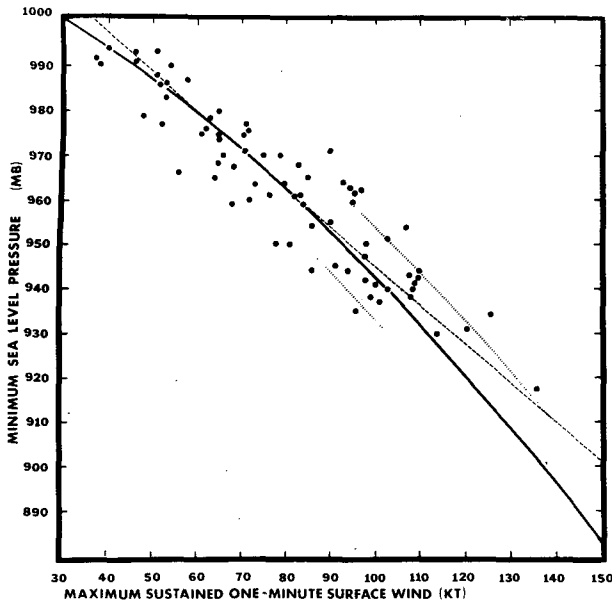


FIG. 5. Plotted data of derived sustained surface wind speeds in tropical cyclones versus minimum sea level pressures with nonlinear (solid) and linear (dashed) regression lines of best fit. Hatched lines show deviations of  $\pm 10$  kt from the nonlinear regression line.

Correlation coefficients are 0.92 for both relationships. Standard errors of estimate are the same at 8.8 kt. In the range of pressures below 930 mb the linear relationship appears to fit the data more closely than the nonlinear relationship. However, few data (four cases) are available to make any meaningful conclusions.

The nonlinear equation

$$V_m = 6.7(1010 - p_c)^{0.644}, \quad (7)$$

where  $V_m$  is the maximum sustained surface wind speed (kt) and  $p_c$  is the MSLP (mb) was selected for two reasons. First, from physical considerations the equation should be similar to the form of the cyclostrophic flow relationship shown by Eq. (1). Most studies of tropical cyclone wind-pressure relationships have used this form of the equation to estimate maximum surface winds. To simplify operational use with little loss of accuracy, a representative value of peripheral pressure is usually chosen. The value of 1010 mb used in several other studies is felt to be representative of the environmental pressure in the western North Pacific area; however, in other tropical cyclone regions other values may be more appropriate. For example, the average environmental pressures near the region of maximum tropical cyclone activity in the North Atlantic is about 10 mb higher than the corresponding area in the western North Pacific. The exponent of 0.644 is slightly higher than the 0.5 value used in other studies and implied by the cyclostrophic relationship. The other reason for selecting the nonlinear form of the equation is that it gives a better fit to the data at the higher

pressures and lower wind speeds. A rule of thumb used by JTWC forecasters is that tropical depressions with central pressures near 1000 mb normally have maximum winds around 30 kt and the systems usually develop tropical storm force winds as the pressures drop a few millibars below 1000 mb. In Eq. (7), 1000 mb corresponds to winds of 30 kt and 997 mb to winds of 34 kt (minimum tropical storm intensity). Conversely, the best-fit linear relationship ( $V_m = 1180.3 - 1.143p_c$ ) gives winds of 37 kt for a pressure of 1000 mb.

Seventy-five percent of the cases fall within  $\pm 10$  kt of the line of best fit (shown by the hatched lines in Fig. 5). While the scatter of data points about the regression line is larger than desired, it is considerably smaller than achieved in any previous studies of tropical cyclone wind-pressure relationships. It is felt that using the more reliable peak gust observations as the basic wind data input and applying standard adjustment factors for height differences to derive the maximum sustained winds significantly reduced the large scatter found in earlier studies. The remaining scatter is attributed to departures in individual cases from the standard height and gust factor adjustment values used, the errors in accurately determining the maximum winds and minimum pressures, and differences in wind-pressure relationships in individual cyclones. The last factor can be adjusted subjectively on an individual case basis. For example, a number of tropical cyclones develop each year in the  $20^\circ$ - $30^\circ$  latitude zone. These cyclones, which are normally induced by upper tropospheric lows in the tropical upper tropospheric trough (Sadler, 1976), form in areas of easterly trade wind flow where the environment peripheral pressure may be significantly above 1010 mb. For these cases, the maximum winds for any given pressure should be expected to be somewhat higher than those derived from Eq. (7). Conversely, cyclones which form in the monsoon trough near the Asian mainland may have environmental pressures below 1010 mb and lower maximum winds than indicated by the equation. These adjustments from the regression equation can be made operationally by considering mean monthly SLP distributions and the current synoptic pressure analysis. Even in these cases, however, it is not advisable to depart more than  $\pm 10$  kt from the regression equation value if reliable MSLP observations are available.

## 6. Summary

In contrast to previous maximum wind/minimum pressure relationships for tropical cyclones in the western North Pacific, the equation  $V_m = 6.7(1010 - p_c)^{0.644}$  is the only one derived on sufficient ground truth. This new relationship is noted to give lower maximum wind speeds for a specific central pressure than the previous equations. The most significant feature in the development of this equation was the use of peak gust observations which were converted to a standard anemometer

height and then to an estimated sustained 1 min wind speed. The derived equation proved suitable for both high and low wind speeds, a feature not found in previous relationships. Data scatter about the regression line is within limits for creditable operational use and is considerably smaller than in previous studies. Hopefully, this wind-pressure relationship can be refined and improved in future years as more cases are added to this sample and more accurate techniques for measuring surface winds in tropical cyclones are developed.

*Acknowledgments.* The authors acknowledge the computer programming assistance of Lt. O. R. Scrivener (USN) and the typing support of Mrs. Gail James.

#### REFERENCES

- Atkinson, G. D., 1974: Investigation of gust factors in tropical cyclones. Fleet Weather Central/Joint Typhoon Warning Center Tech. Note 74-1, 9 pp. [Available from FWC/JTWC, COMNAVMAR, Box 12, FPO SF 96630].
- Crutcher, H. L., and Quayle, R. G., 1974: *Mariners Worldwide Climatic Guide to Tropical Storms at Sea*. NAVAIR 50-1C-61, Asheville, N. C., Naval Weather Service Command, 114 pp plus 312 charts. [Available from Govt. Printing Office].
- Fletcher, R. D., 1955: Computation of maximum surface winds in hurricanes. *Bull. Amer. Meteor. Soc.*, **36**, 246-250.
- Fortner, L. E., Jr., 1958: Typhoon Sarah, 1956. *Bull. Amer. Meteor. Soc.*, **39**, 633-639.
- Fujita, T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Res. Pap. 91, The University of Chicago, 41 pp.
- Holliday, C. R., 1969: On the maximum sustained winds occurring in Atlantic hurricanes. Tech. Memo. WBTH-SR-45, Weather Bureau Southern Region, 6 pp. [NTIS PB 184609].
- Japanese Weather Association, 1973a: Reports of unusual weather investigation in Okinawa prefecture, Vol. 1.
- , 1973b: *Typhoon summary of Japan, 1940-1970*. Tokyo.
- Joint Typhoon Warning Center (JTWC), 1969: Annual Typhoon Report 1968. Fleet Weather Central/Joint Typhoon Warning Center, Guam M.I., pp 3-40 to 3-50 [NTIS Ref. AD 785251].
- , 1965: Annual Typhoon Report 1964. Fleet Weather Central/Joint Typhoon Warning Center, Guam M.I., pp. 26-27 [NTIS Ref. AD 786209].
- Jordan, C. L., 1957: Estimating central pressure of tropical cyclones from aircraft data. NHRP Rep. 10, U. S. Weather Bureau, Washington, D. C., 12 pp.
- McKnown, R. and collaborators, 1952: Fifth annual report of the typhoon post analysis board. Andersen AFB, Guam M.I.
- Philippine Weather Bureau, 1950-70: Tropical cyclones for 19-. Climatological Division Press, Manila.
- Royal Observatory Hong Kong, 1960-73: Meteorological Results —Part III, Tropical Cyclone Summaries.
- Sadler, J. E., 1976: Tropical cyclone initiation by the tropical upper tropospheric trough. NAVENVPREDRSCHFAC Tech. Pap. 2-76, 103 pp. [NTIS Ref. ADA 025456]
- Seay, D. N., 1964: Annual Typhoon Report 1963. Fleet Weather Central/Joint Typhoon Warning Center, Guam M.I., pp. 6-7, 10-11. [NTIS Ref. AD 786208]
- Sherlock, R. H., 1953: Variation of wind velocity and gusts with height. Pap. No. 2553, *Trans. ASCE*, **118**, 463-508.
- Sissenwine, N., Tattelman, P., Grantham, D. D. and Gringorten, I. I., 1973: Extreme wind speeds, gustiness, and variations with height for MIL-STD 210B. AFCRL-TR-73-0560, AFSG No. 273, Bedford, Mass. [NTIS Ref. AD 774044]
- Taiwan Central Weather Bureau, 1947-71: Reports on Typhoons.
- Takahashi, K., 1939: Distribution of pressure and wind in a typhoon. *J. Meteor. Soc. Japan*, Ser. 2, **17**, 417-421.
- Takahashi, K., 1952: Techniques of the typhoon forecast. *Geophys. Mag., Tokyo*, **24**, 1-8.
- Wachholz, E. R., 1961: Annual Typhoon Report 1960. Fleet Weather Central/Joint Typhoon Warning Center, Guam M.I. pp. 204-205 & 207. [NTIS Ref. AD 786148]