U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

NOAA Technical Memorandum NWSTM PR-24

RELATIONSHIP OF MAXIMUM SUSTAINED WINDS TO MINIMUM SEA LEVEL PRESSURE IN CENTRAL NORTH PACIFIC TROPICAL CYCLONES

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February 1982

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Introduction

The intensity of a hurricane is closely related to its central pressure with the lower the pressure the more intense the storm and its maximum sustained winds. Central pressure values are more reliably measured than sustained winds through the use of dropsondes during reconnaissance flights or from surface observations from ships or from coastal stations that happen to be under the eye during landfall. Wind estimates from aerial reconnaissance are often very subjective and may be based on the sea state or the winds at flight level. In the case of surface observations, wind measuring equipment frequently fails during the violent winds of an intense tropical cyclone whereas the barograph trace usually survives. Wind observations from ships may also be questionable in many cases as it may not be known whether the ship passed through the narrow band of the storm's maximum sustained winds.

Tropical cyclones occur in a wide range of intensities with the flow near the center considered to be approximately in cyclostrophic balance. These cyclones are observed in most cases to occupy a very limited area as compared to their extratropical counterparts. When several tropical cyclones are present in close proximity to each other, they move along their tracks separated by a distance of 15 degrees latitude or 900 miles. Thus a ring of subsidence can be assumed to be present about 7½ degrees from the centers. As a sidelight, the next step up the scale of atmospheric vortex hierarchies takes us to the common extratropical cyclones where the gradient wind relationship predominates. Here the preferred separation between like vortices is 30 degrees. Casual observations will confirm that other scales of flow, larger as well as smaller, occur in the atmosphere. In a way it is not surprising that when you deal with a thin fluid like our atmosphere held in place by gravity on our globe that such an arrangement of preferred scales exists where vortices occupy space that is separated by discrete fractions of 2π radians or 360 degrees.

Previous Studies

With this limited space occupancy of tropical cyclones in mind, it should be possible from knowledge of a storm's central pressure and its peripheral pressure to arrive at a reliable estimate of the maximum sustained winds circling the center just outside the eye and the wall clouds. Numerous studies have been done over the years with studies by Takahashi (1939), Myers (1954), Fletcher (1955), Kraft (1955) and Holliday (1969) often quoted. These relationships are all of the form

$$V_{MAX} = C\,(p_w - p_o)^{1/2} \tag{1}$$

where C is a constant, and the quantity $(p_w - p_o)$ is the pressure drop across the cyclone from a peripheral or ambient value, p_w, where the curvature of the isobars turns anticyclonic, to the central pressure, p_o, within the eye. The exponent 1/2 is arrived at from the cyclostrophic relationship

$$\frac{V^2}{r} = -\frac{1}{\rho}\,\frac{dp}{dr} \tag{2}$$

which tells us that the wind speed is a function of the pressure gradient to the 1/2 power, or the square root.

Atkinson and Holliday (1977) in a recent Monthly Weather Review article reviewed some of the work done in earlier investigations, and on the basis of their experiences at the Joint Typhoon Warning Center (JTWC) and data gathered from within the western Pacific suggested a statistical relationship between central pressure and maximum winds of the following form

$$V_{MAX} = 6.7\,(1010 - p_o)^{0.644} \tag{3}$$

for winds in knots and pressures in millibars. The ambient or peripheral pressure of 1010 mb fitted well in the western North Pacific, while the exponent, 0.644, seemed to give better results with the many intense cyclones where the square root relationship tended to underestimate winds when C was chosen as a linear constant.

Central North Pacific Hurricanes

The peripheral pressure values of 1010 mb for the western North Pacific and 1013 mb used by Kraft for the Atlantic, are somewhat lower than those common to the Central Pacific Hurricane Center's (CPHC) area of responsibility. As a result, these empirical relationships tend to demonstrate a bias toward lower wind speeds in the central North Pacific which is dominated by the sprawling subtropical high pressure system. This bias is particularly pronounced for the less intense cyclones. Whereas a peripheral pressure value of 1010 mb worked quite well for western portions of the Pacific, a value of 1017 mb was found to fit the data better for the CPHC area. These CPHC data consist of a total of 109 central pressure/maximum wind reports from dropsondes, ships, and land stations for the 1950-78 period. The data were obtained from the JTWC Annual Typhoon Reports, Mariners Weather Log, Monthly Weather Review, and the CPHC individual tropical cyclone files. Regression analysis was done on the data sample which is reproduced in the scatter diagram on Figure 1, and the result was a regression equation in the form

$$V_{MAX} = 1.176\,(1017 - p_o) + 30 \tag{4}$$

shown in Figure 2. The units are in knots and millibars. Again an exponent somewhat larger than 1/2 was needed to give a good fit for the stronger winds and lower pressures. The exponent in this linear relationship is, of course, 1.

Some overestimation of wind speeds is likely in the case of strong winds where sea conditions and damage effects are proportional to the kinetic energy of the wind, which in turn relates to the wind speed squared (and to the density of the air). However, it was difficult to reconcile the large differences that exist between wind speed estimates by experienced observers and the values computed from the square root relationship. The constant C of equation (1) therefore may not be a true constant; or perhaps, as in the case of Atkinson's and Holliday's statistical relationship, the exponent should be chosen somewhere between 1/2 and 1.

Next a gradient wind/cyclostrophic wind relationship used by Schwerdt, Ho, and

Watkins (1979) was tested on CPHC tropical cyclones. The equation relates maximum winds to central pressure in the following way

$$V_{MAX} = \left[\frac{1}{\rho e} (p_w - p_o) \right]^{1/2} - \frac{r_{xw} f}{2} \qquad (5)$$

Here ρ is the density of the air, $(p_w - p_o)$ is again the pressure drop across the storm, r_{xw} is the radius of maximum winds, and f is the Coriolis parameter. The number $e \simeq 2.71828$, the base of natural logarithms, is included from Schloemer's (1954) parametric log/linear profiles derived for nine Florida hurricanes. The $\frac{r_{xw} f}{2}$ term is a small term that appears due to the gradient wind relationship which includes the Coriolis force and which amounts to about a $0.5 ms^{-1}$ or 1 knot correction in maximum sustained wind speeds for a typical hurricane with a maximum wind radius of 20 km (2×10^4m) at latitude 20°N ($f = 5 \times 10^{-5}\ s^{-1}$). In the computations, air density was varied with pressure only, and p_w was held constant at 1017 mb. Very good central pressure/maximum wind relationships were arrived at using this equation for weak and moderate hurricanes, but for severe cyclones there again appeared to be a systematic underestimation of the actual wind speeds according to the data sample. An average translation speed, V_{TRANSL}, was added into equation (5) to explain the asymmetry caused by the motion of the cyclone and to alert the forecaster to this important contribution to maximum sustained winds at high forward motion speeds. The results are plotted in Figure 3.

Holland's Model

As can be seen from the cyclostrophic wind relationship in equation (2), the radius of the winds also enters into this equation. Thus cyclostrophic winds depend on the radius or distance from the center, and the radius of the maximum winds will likely not coincide with the radius of maximum pressure gradient. Holland (1980), in a recent study of Australian tropical cyclones, modified Schloemer's simple log/linear profile by incorporating two scaling parameters A and B. Holland was able to reproduce the pressure profile across the entire hurricane circulation by using the relationship

$$p = p_o + (p_w - p_o)e^{-A/r^B} \tag{6}$$

Within the central core of the cyclone, through the cyclostrophic wind relation, the wind profile then becomes

$$V_{cycl} = \left[\frac{AB}{\rho r^B}(p_w - p_o)e^{-A/r^B}\right]^{1/2} \tag{7}$$

By setting the derivative $\frac{dV_{cycl}}{dr} = 0$, the radius of maximum winds is found at

$$r_{xw} = A^{1/B} \tag{8}$$

or, in other words, $A = r_{xw}^B$

This relationship, when substituted into equation (7), gives the expression for the maximum wind speeds, namely,

$$V_{max} = C(p_w - p_o)^{1/2} \tag{9}$$

where

$$C = \left(\frac{B}{\rho e}\right)^{1/2} \tag{10}$$

It is notable that the maximum wind intensity is independent of the radius of maximum winds but information about the pressure profile through parameter B is required.

Physically, B defines the shape of the wind profile and A determines the location of the radius of maximum winds, through equation (8), relative to the origin. The scaling parameter B was found to vary between 1 and 2.5 in most hurricanes. Some examples of pressure and wind profiles with varying values of B are shown in Figure 4 taken from Holland's paper. Also shown from Holland's paper in Figure 5 is a plot of the parameter B against various ratios of the radius of maximum pressure gradient to the radius of maximum winds in cyclones. The maximum pressure gradient in the cyclone thus appears to be located in most cases somewhere between the radius of the maximum winds and half the distance to the center of the eye. This ratio is related to B in the following fashion.

$$\frac{r_{xpg}}{r_{xw}} = \left[\frac{B}{B+1}\right]^{1/B} \tag{11}$$

From equation (6) or by substituting the relationship from equation (8) into (11) we arrive at the following expression for the location of the radius of the maximum pressure gradient involving the parameters A and B, namely

$$r_{xpg} = \left[\frac{AB}{B+1}\right]^{1/B} \tag{12}$$

Pressure/Wind Profiles

In a vortex, like a hurricane, we find, to a large extent, some conservation of angular momentum. As a hurricane suddenly intensifies, as favorable divergence aloft stretches the circulation vertically, the pressure and wind profiles change much like the series of curves in Figure 4 where B is shown to vary from 0.25 to 2.25. The growth of the eye and the sharpening up of the maximum wind area just outside the wall cloud region at the expense of the peripheral winds is very well represented. It is therefore our opinion that increasing values of B can be assigned to decreasing central pressure values. In Table 1 a central pressure/maximum wind relationship was developed where a range of p_o values from 1010 mb to 890 mb, at 10 mb intervals, was assigned B-values ranging from 0.95 to 1.55. The resultant curve of central pressure/maximum winds superimposed on the scatter diagram of the data set of central pressure versus maximum sustained winds for the CPHC area of responsibility is shown in Figure 6. It is believed that this range in B-values is a reasonable one, and as can be seen, it produced an excellent fit to the observed values. Holland lends support to this choice of B-values ranging mostly between 1 and 1.5 since he found that this was exactly the range of climatological values derived from Atkinson's and Holliday's estimates of 1 minute maximum sustained surface winds.

Assumptions Used

In computing the data presented in Table 1, the convenient m, t, s system of units was used. Some assumptions were made. Among these, the air temperature T in the relation

$$C = \left[\frac{BRT}{P_{xw}\,\varrho}\right]^{1/2} \tag{13}$$

was kept at a constant T = 298°K or 77°F. With the small variations in sea surface temperature across the CPHC region, air temperatures in hurricane circulations at sea level are rather constant near 298°K as heat added from the agitated ocean surface and from latent heat releases in the nearly moisture saturated air counter-balances the cooling due to expansion as the air spirals toward lower pressure. Actually, a slight adjustment for moisture by using the virtual temperature might be attempted but this difference would amount to less than a meter per second in the derived wind speeds. The pressure at the maximum wind radius was computed from the relation

$$P_{xw} = p_o + 1/3\ (p_w - p_o) \tag{14}$$

as a rough estimate of the pressure at that particular location. The translational wind speed addition, V_{transl}, was held constant at 5.0 m s $^{-1}$ or 10 kt. This value was used since it is an average of forward motion speeds in the CPHC region. It would be a simple matter for the forecaster to vary this value for stationary as well as fast moving storms. The peripheral pressure, p_w, was held at the constant 1017 mb. This value could also be varied by the forecaster should the peripheral pressure be somewhat different from 1017 mb. The peripheral pressure is found by taking the value of the first isobar, spaced 1 mb apart, where the curvature turns anticyclonic in the periphery of the cyclone.

Summary

A quite reliable relationship exists between the values of the central pressure of a tropical cyclone and its simultaneously observed maximum sustained winds. Several authors have computed regression equations for these values utilizing data

from the Atlantic hurricanes and western North Pacific typhoons. These relationships are based on the pressure difference between the center and the peripheral environment of the cyclone. This peripheral pressure is somewhat higher in the central North Pacific area, and as a result somewhat stronger winds are reported with CPHC cyclones than with cyclones in the Atlantic or western North Pacific having the same central pressures. Regression analysis produced a linear curve which gave a good fit over the entire range of cyclone intensities. Since hurricane winds in the central core of the cyclone are cyclostrophic and therefore related to the square root of the pressure gradient, such a relationship was developed. Schloemer's parameterization of pressure profiles as log/linear functions was first tried, but for intense cyclones the correlation with observed data was not satisfactory. A slight modification of Schloemer's pressure profiles by Holland, who substituted families of rectangular hyperbolas and scaling parameters, produced better relationships for the entire spectrum of intensities. These relationships were therefore utilized to construct a table and graph of central pressure versus maximum sustained wind speed estimates from observed values of central pressure.

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Notes to Table I - Constants, Variables and Units

V_{max} = $C(\Delta p)^{1/2} + V_{TRANSL}$

V_{max} in $m\ s^{-1}$ or knots ($1\ m\ s^{-1}$ = 1.943 kt)

C $= \left(\frac{B}{\rho e}\right)^{1/2} = \left(\frac{BRT}{P_{xw} \cdot e}\right)^{1/2} = \left(\frac{B \cdot 287 \cdot 298}{P_o + \frac{1}{3}(P_w - P_o) \cdot 2 \cdot 71828}\right)^{1/2}$ in $\left[m^{3/2} t^{-1/2}\right]$

B = Holland's scaling parameter

R = gas constant = 287 kj t^{-1} deg^{-1}

RT/e = 31463.3 kj t^{-1}

T = cyclone air temperature = $298^{o}K$

P_{xw} = pressure at maximum wind radius = $p_o + \frac{1}{3}(P_w - P_o)$

ΔP = $P_w - P_o$ = pressure drop across cyclone

P_w = peripheral cyclone pressure = 101.7 cb

P_o = central cyclone pressure in cb

e = 2.71828 = base of natural logarithms

V_{TRANSL} = cyclone forward motion speed held constant at 5 m s^{-1} (additive in right hand semicircle)

TABLE I

Central Pressure Versus Maximum Sustained Wind Speeds
for Central North Pacific Hurricanes as Computed From the Relationship

$$V_{max} = \left[\left(\frac{B}{\rho e}\right) (P_w - P_o) \right]^{1/2} + V_{TRANSL}$$

P_o		B	$P_{xw} = P_o + \frac{1}{3}(P_w - P_o)$	$C = \left(\frac{B}{\rho e}\right)^{1/2} = \left(\frac{BRT}{P_{xw} \cdot e}\right)^{1/2}$	$(\Delta P)^{1/2} = (P_w - P_o)^{1/2}$ $cb^{1/2}$	$C \cdot (\Delta P)^{1/2}$ $m \cdot s^{-1}$	V_{TRANSL} $m\ s^{-1}$	$V_{MAX} = C(\Delta p)^{1/2} + V_{TRANSL}$ $m\ s^{-1}$	V_{MAX} KT
mb	cb								
1010	101	0.95	101.2	17.18	0.84	14.43	5.0	19.43	38
1000	100	1.00	100.6	17.68	1.30	22.98	5.0	27.98	54
990	99	1.05	99.9	18.19	1.64	29.83	5.0	34.83	68
980	98	1.10	99.2	18.68	1.92	35.87	5.0	40.87	79
970	97	1.15	98.6	19.16	2.17	41.58	5.0	46.58	91
960	96	1.20	97.9	19.64	2.39	46.94	5.0	51.94	101
950	95	1.25	97.2	20.12	2.59	52.11	5.0	57.11	111
940	94	1.30	96.6	20.58	2.77	57.01	5.0	62.01	120
930	93	1.35	95.9	21.05	2.95	62.10	5.0	67.10	130
920	92	1.40	95.2	21.51	3.11	66.90	5.0	71.90	140
910	91	1.45	94.6	21.96	3.27	71.81	5.0	76.81	149
900	90	1.50	93.9	22.42	3.42	76.68	5.0	81.68	159
890	89	1.55	93.2	22.83	3.56	81.42	5.0	86.42	168

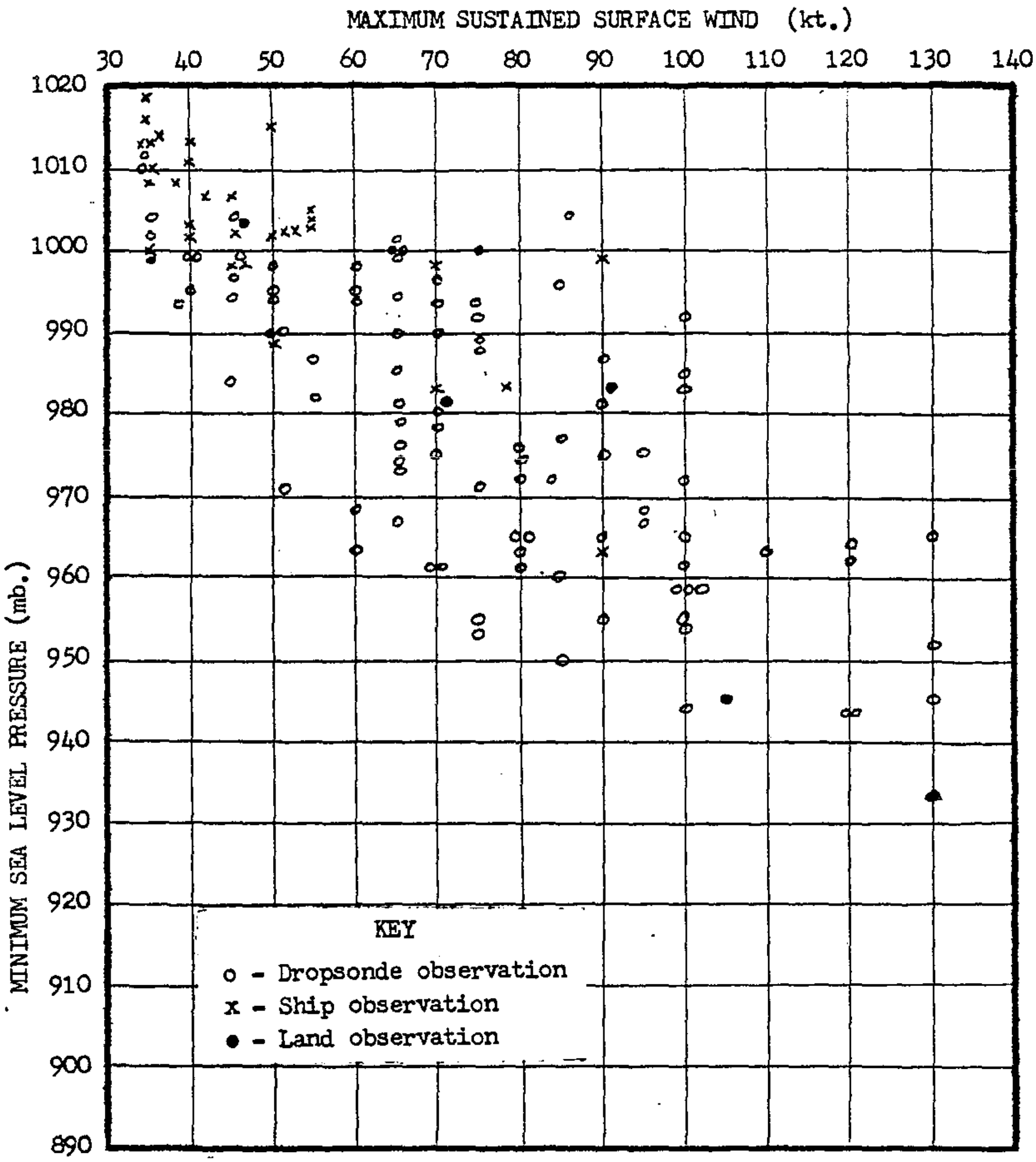

Figure 1. Scatter diagram of simultaneously observed Central North Pacific tropical cyclone sea level pressure minima and maximum sustained winds 1950-1978.

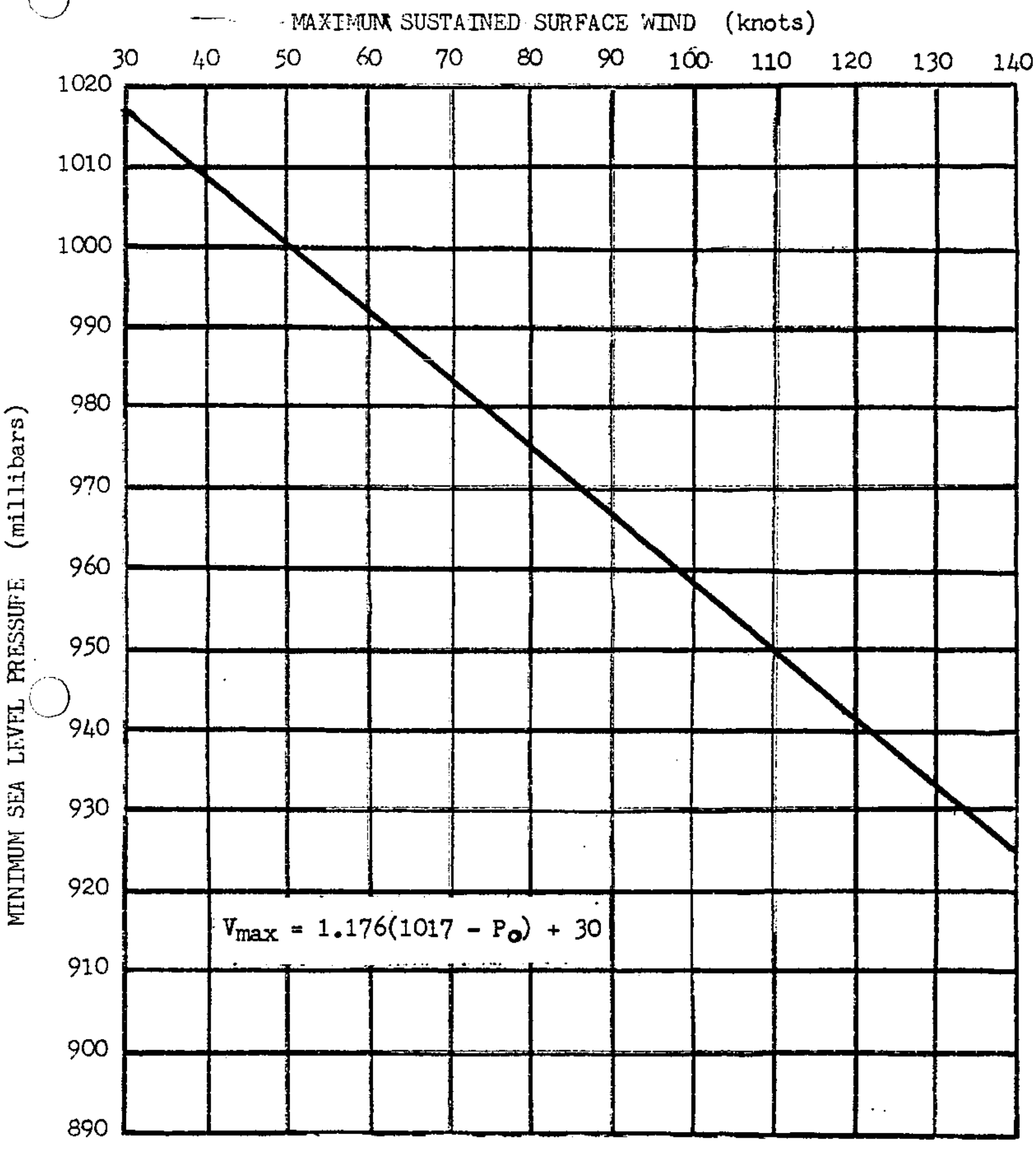

Figure 2. Linear regression curve computed from CPHC region 1950-1978 data base of tropical cyclone central pressure vs. maximum sustained winds plotted in scatter diagram on Figure 1. (Use of this curve is not recommended since winds in the central core of tropical cyclones are cyclostrophic and related to the square root of the pressure gradient).

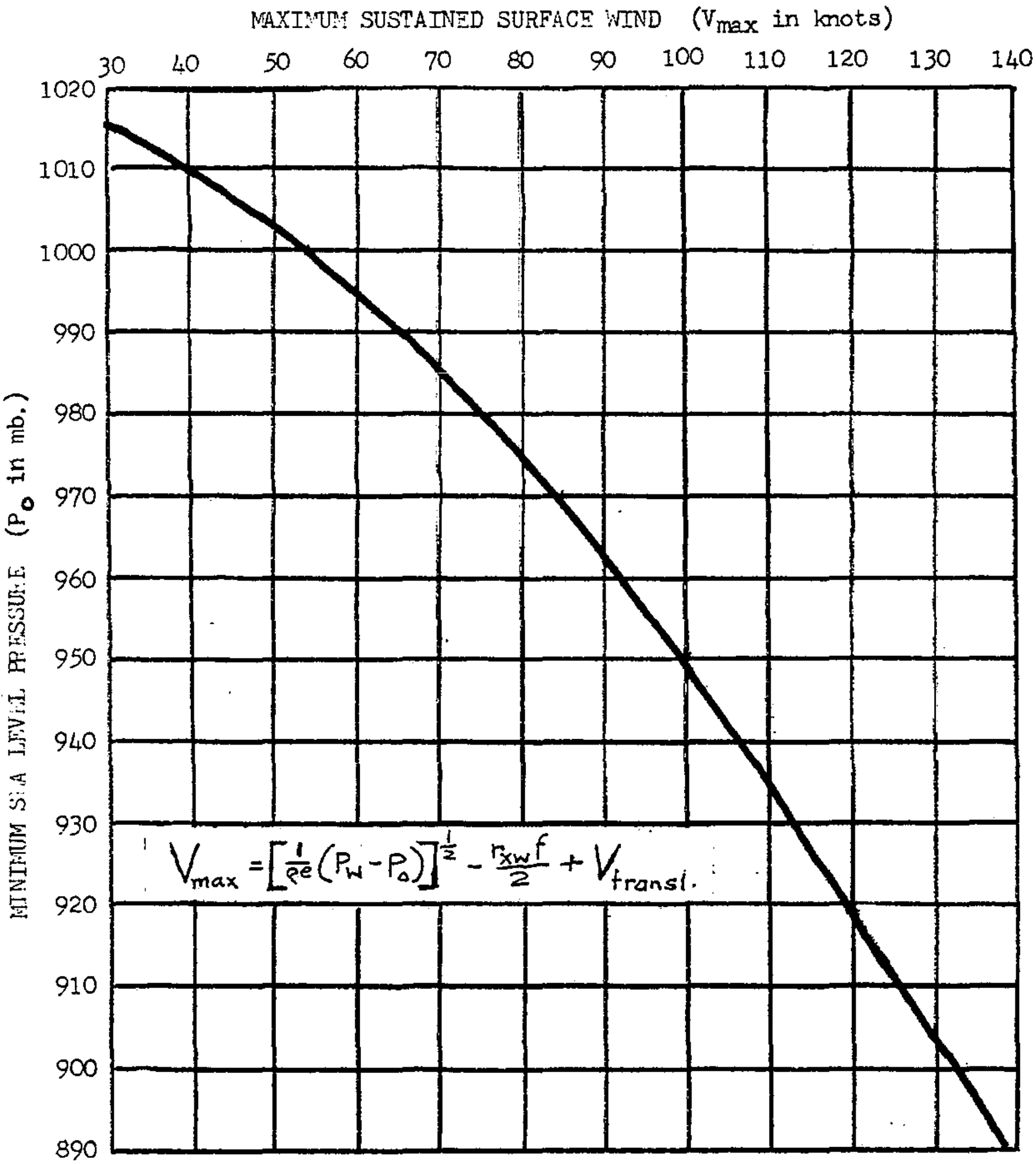

Figure 3. Maximum sustained surface wind speed vs. minimum sea level pressure relationship for Central North Pacific tropical cyclones. This curve was found to underestimate winds in the more intense Central North Pacific tropical cyclones. It utilizes gradient wind and Schloemer's log/linear pressure profile relationships.

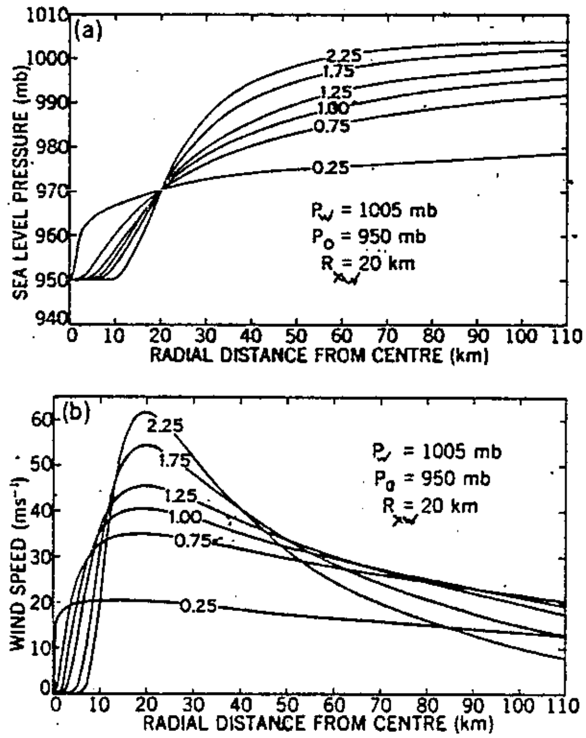

Fig. 4. The effect of varying the parameter B on (a) the sea level pressure profile and (b) the gradient wind profile (After Holland, 1980).

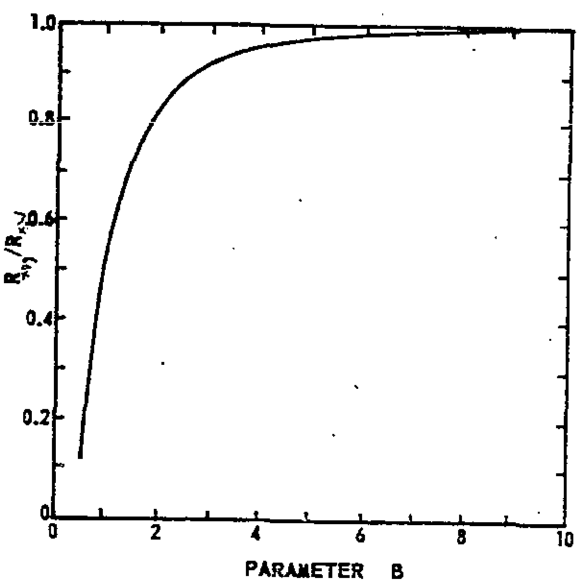

Fig. 5. The variation with B of the ratio of radius of maximum pressure gradient (r_{xpg}) and radius of maximum winds $(r_{x}w)$ as expressed in EQ (11) (After Holland, 1980).

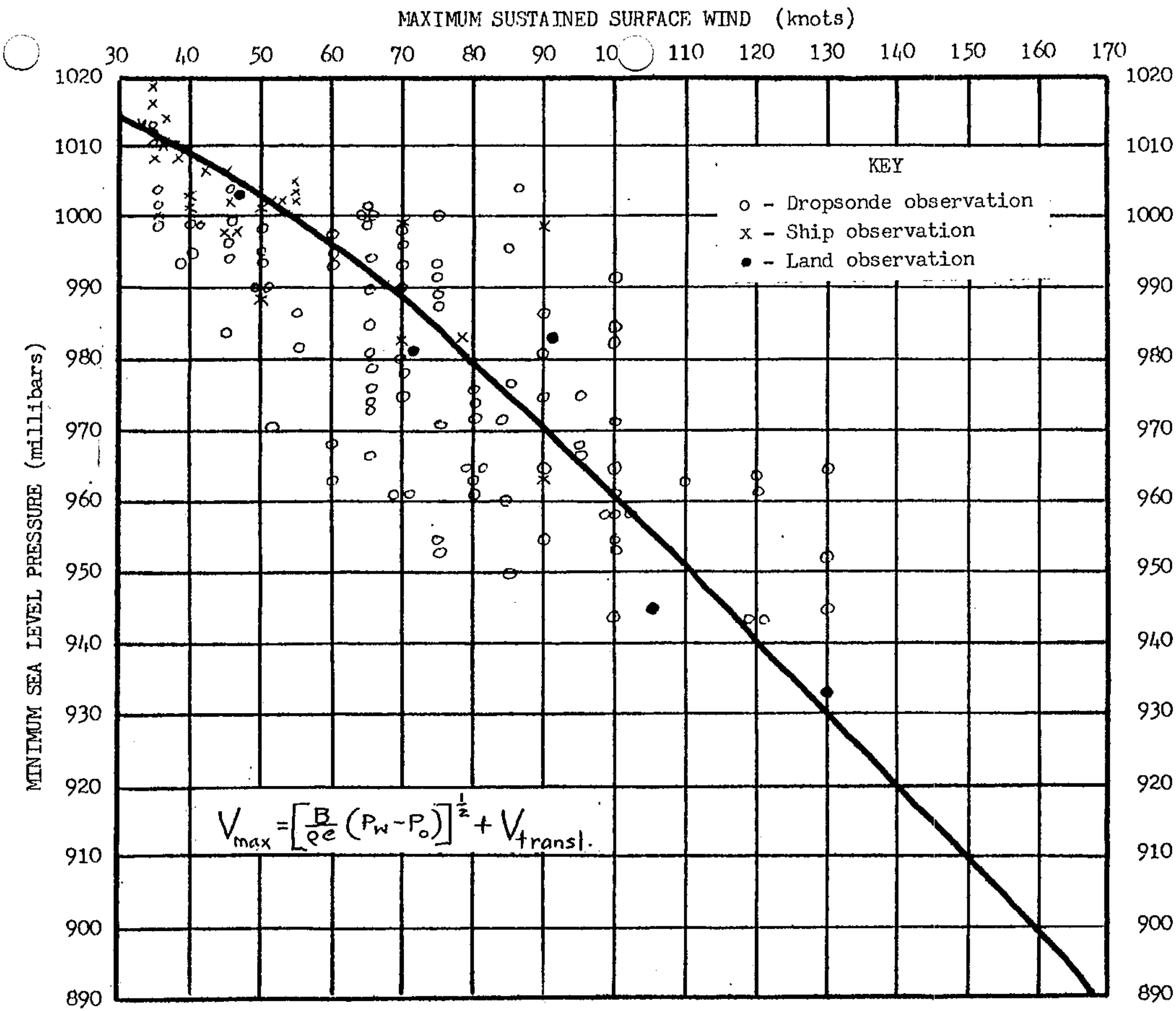

Figure 6. Operational chart relating maximum sustained surface winds to given central pressure values of tropical cyclones in the Central North Pacific.