14

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VERTICAL SHEAR OF THE HORIZONTAL WIND SPEED IN TROPICAL CYCLONES

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Weather Modification Program Office
Boulder, Colorado
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**UNITED STATES
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Juanita M. Kreps, Secretary**

NATIONAL OCEANIC AND
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CONTENTS

ILLUSTRATIONS

TABLES

VERTICAL SHEAR OF THE HORIZONTAL WIND SPEED IN TROPICAL CYCLONES

John Bates[1]

In this paper, we present a profile from 10 to 6000 m constructed from research aircraft, buoy, and tower data. These data are normalized so that different strength storms may be compared. The various wind-pressure relations and gust factors are also examined, particularly in relation to flight level winds and the profile constructed herein.

1. INTRODUCTION

As pointed out by Hawkins (1962), investigation of the vertical structure of the horizontal wind in hurricanes aids both the practical forecaster and the researcher. Saffir (1972), in the wake of Hurricane Camille, said, "At least 60%, and possibly as much as 75%, of the total structural damage... was due to wind or initiated by wind action." In addition, abnormally high tides and waves are a direct result of the wind so that a good estimation of surface wind speed from research flight data is necessary to optimize efforts to save life and property.

The theoretician is also served by hard data about the vertical structure of the horizontal wind in hurricanes. The ultimate test of any model under study must be its verification with actual observation. A number of investigators, Shea and Gray (1973), Hawkins and Rubsam (1968), and Gray (1967) have studied the effect that wind shear in the vertical has upon the various budgets and balances of forces in hurricanes. Enlargement of our knowledge of wind shear in the vertical is needed to properly scale the forces that are acting and to further refine hurricane models.

2. CONSTRUCTION OF THE VERTICAL PROFILE OF THE HORIZONTAL WIND SPEED

There are four types of data used in the construction of this profile: 1) overland data taken from Brookhaven National Laboratory and Tokyo Tower in the lowest 150 m, 2) over-water data from environmental buoy 10 (EB-10), and research aircraft, 3) planetary boundary layer profiles through Hurricanes Caroline (1975) and Eloise (1975) measuring horizontal wind speeds from 100 to 1000 m, 4) upper level data (> 1000 m) from previous years' research flights.

In the lowest layer (< 100 m) the expression for wind shear in the vertical over a roughened surface is given by

$$\frac{\partial \bar{u}}{\partial z} = \frac{u_*}{K(z + z_0)} \quad . \qquad (1)$$

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[1] Present affiliation: Florida State University, Department of Meteorology

Integration gives

$$\bar{u} = \frac{u_*}{K} \, \mathrm{LN} \left(\frac{z + z_o}{z_o} \right) \qquad (2)$$

in which, if $z >> z_o$,

$$\bar{u} = \frac{u_*}{K} \, \mathrm{LN} \left(\frac{z}{z_o} \right) . \qquad (3)$$

This is the familiar logarithmic profile (e.g., Charnock, 1955) in which $\bar{u}$ is the mean wind speed at height Z, $u_* = (\tau/\rho)^{1/2}$ is the friction velocity, and K is the von Kármán constant.

Examining the mean wind profiles from Brookhaven National Laboratory and Tokyo Tower, (fig. 1), we find that the logarithmic formula is quite well satisfied at these sites where the maximum mean winds were ~ 10 to 25 m s^{-1} The mean wind speed in these cases is defined as a time average of the total wind speed over a 10- to 15-min interval.

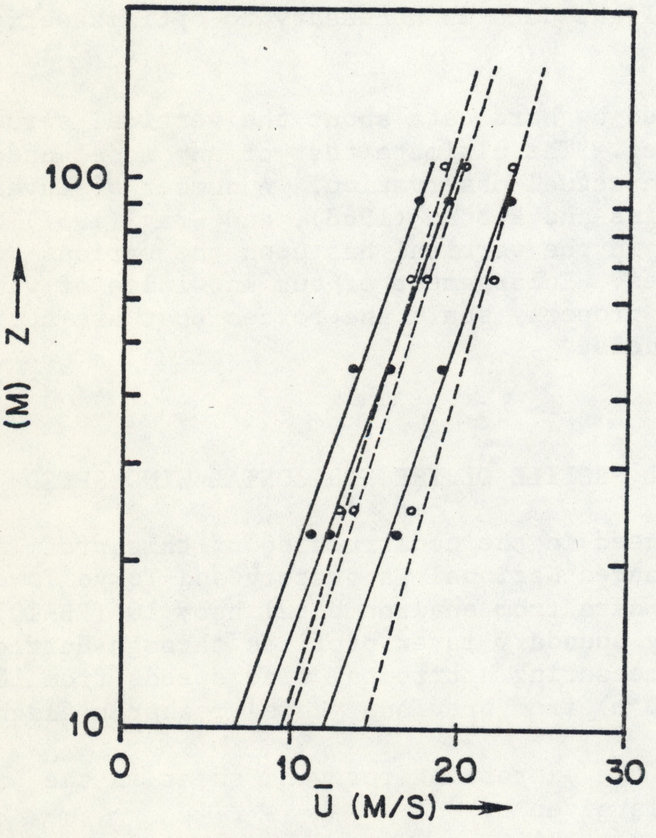

Figure 1. Profiles of mean horizontal wind speed from Brookhaven (solid lines) during three phases of Donna (1960) and from Tokyo Tower (dashed lines) during typhoons #15, 18, 24 (1964). (After Shiotani; Cohen et al.)

Using the logarithmic formulation, we obtained values of z_o ranging from 1.21 to 2.07 m, and values of u_* from 1.46 to 2.16 m s^{-1}. The profiles from Brookhaven and Tokyo were then normalized with respect to the 100-m level. These normalized profiles were in very good agreement with one another, the variance being less than 1%. *Note that none of the wind speeds in the overland profiles exceeded 25 m s^{-1} for a maximum mean wind.*

Problems of time and horizontal space differences have always hampered studies of wind shear in the vertical as measured from research aircraft. In an effort to minimize these problems, no time-space conversions were used to fill in data. All direct shear measurements used here were obtained from aircraft which flew legs at different elevations within 30 min of one another. Horizontal space differences were limited to a maximum of ± 25 n.mi. along the tangential and ± 5 n.mi. along the radial directions relative to the storm's center.

The over-water profile was more difficult to obtain. The data available for its construction were readings only from flight altitude (2-min space-averaged wind speed from 450 m) and from environmental buoy 10 (a 15-min average wind speed from the buoy with an anemometer height of 10 m) in Hurricane Eloise (1975). Because this did not provide much information about the shape of the low-level profile, some assumptions were necessary to construct this profile. We first assumed that the logarithmic profile shape was applicable in the layer from 10 to 100 m. This is an assumption which has yet to be validated, and which may fluctuate rapidly in the highly turbulent atmosphere of the hurricane's inner core. We await further research to document the actual structure there.

Notwithstanding these reservations, we constructed a profile according to the logarithmic relationship. A value of $z_o = 1$ cm, in agreement with measurements (Moss and Merceret, 1976) and recent models (Moss and Rosenthal, 1975), was chosen and a value of u_* computed so that the profile was normalized at 100 m and fell within the error limits of the EB-10 data (fig. 2).

In the layer from 100 to 1000 m, recent data from planetary boundary layer flights into Hurricanes Caroline (1975) and Eloise (1975) were used to construct the profile. These are 2-min space-averaged wind speeds obtained as a research aircraft flew a short leg at a constant altitude, then quickly ascended or descended to a new level, obtained readings there, and so on. The total time elapsed in obtaining a profile was approximately 30 min, so the profiles can be thought of as synoptic in time. Forthcoming reports will describe the structures of these storms in more detail. It suffices to say that we do not consider Eloise as very representative, since at flight time the storm was strongly influenced by nearby islands. The Caroline data we do consider representative of a mature hurricane, but the boundary layer traverses occurred at nearly 60 n.mi. from the storm's center. The actual tracks are shown in Appendix A. The profiles (fig. 3) show a vertical shear of < 8 m s^{-1} in the layer from 100 to 1000 m. These profiles were then normalized with respect to the 1000-m level and averaged to obtain a single profile.

Data for the uppermost layer, 1000 to 6000 m, were obtained from Gray (1967) who, in examining National Hurricane Research Laboratory flight data, found five occasions on which two aircraft flew simultaneously at different elevations. His data are presented as percentage shear per 225 mb (table 1), and defined as,

$$\text{PERCENTAGE SHEAR} = \frac{u_B - u_T}{\bar{u}} \times 100$$

where u_T = RELATIVE TANGENTIAL VELOCITY AT THE TOP OF THE LAYER,

u_B = RELATIVE TANGENTIAL VELOCITY AT THE BOTTOM OF THE LAYER,

and

$\bar{u} = \frac{1}{2}(u_B + u_T)$.

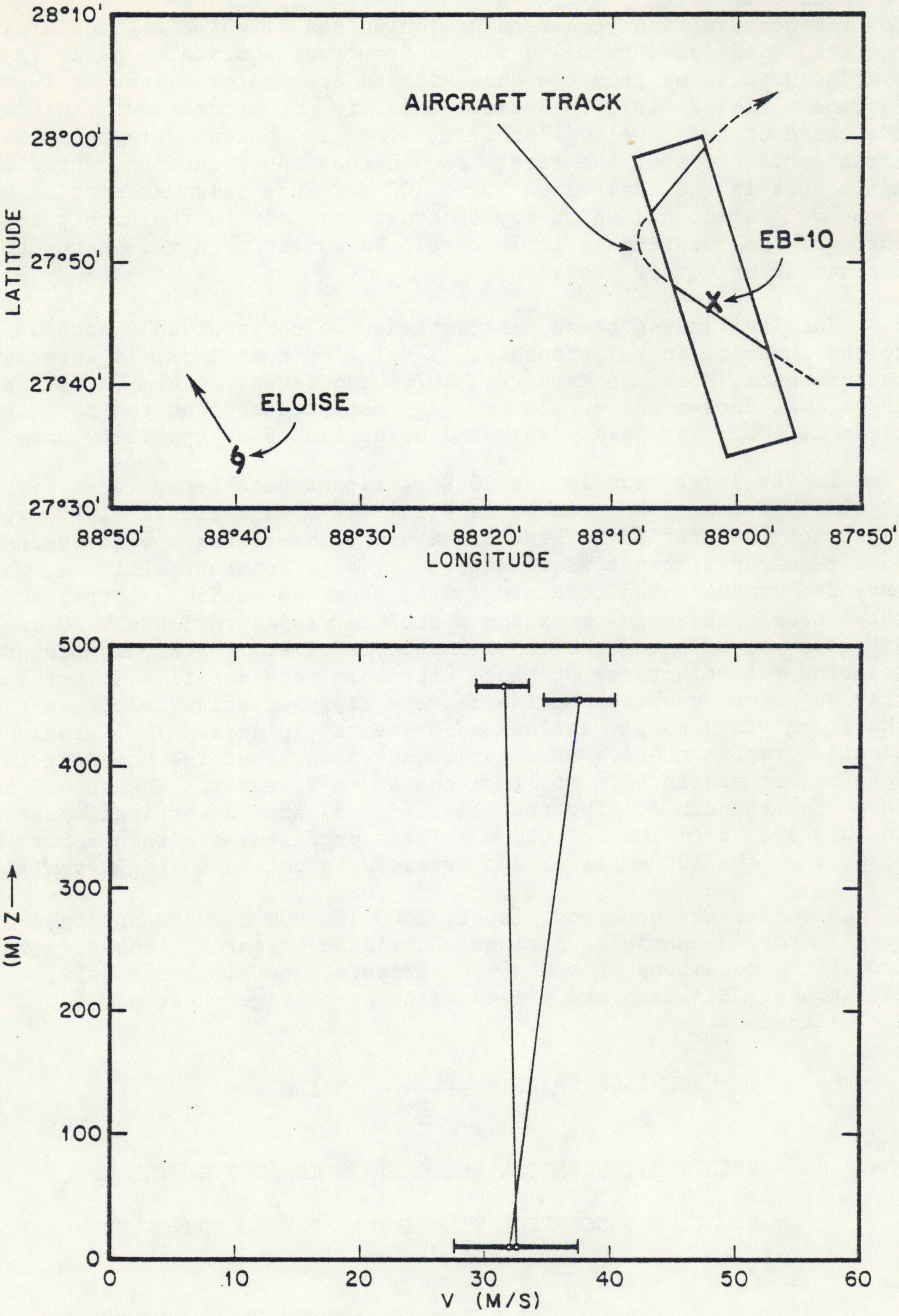

Figure 2. Above, flight track of research aircraft position of Eloise and EB-10 at 00Z, September 20, 1975. Below, measured wind speeds and deviations from research aircraft and EB-10.

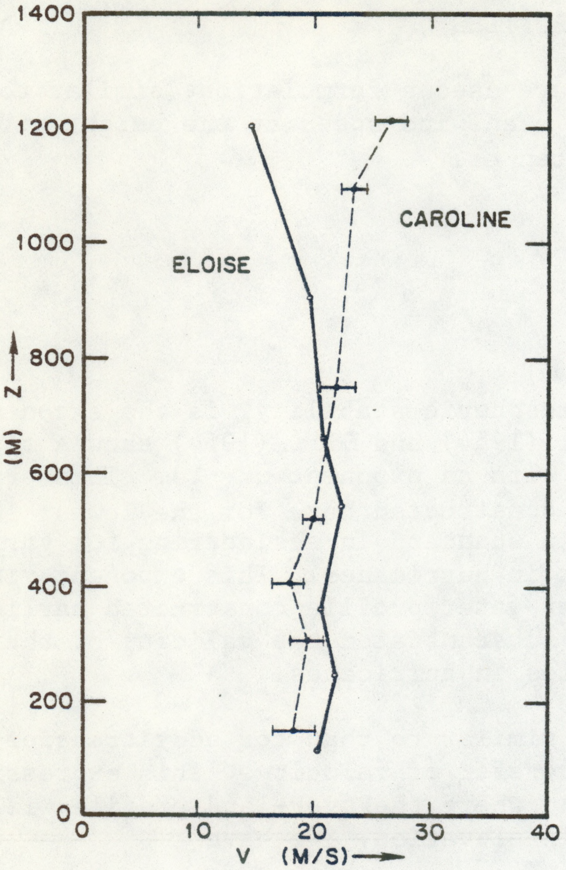

Figure 3. Planetary boundary layer profiles of mean horizontal wind speed in Hurricanes Caroline (1975) and Eloise (1975).

These data were normalized with respect to 1000 m. They were obtained with the Doppler Navigation System and must be treated with caution in regions of heavy precipitation.

In this uppermost layer, we find that the mean wind speed decreases with increasing height by 10% from 5000 to 15,000 ft. This is a slightly greater decrease than that found by Hawkins (1962), who found only a 5% decrease.

We formulated a composite profile by taking as the normalization point the layer from 150 to 350 m. This is where the profiles from Caroline and Eloise exhibited no change of wind speed with height in the normalized profile. The upper and lower profiles were then readjusted so that one continuous profile was obtained from 10 to 6000 m (fig. 4). Looking at the composite profile, we find that the normalization decreases from 150 to 10 m, to a value of .72 over water and to .4 over land. Above 350 m, the wind speed increases up to 1000 m and then slowly decreases up to 6000 m. It is important to keep in mind that all profiles were renormalized with respect to the Caroline and Eloise data and that any unrepresentativeness in those profiles will be propagated into the others.

Table 1. Ratio of Calculated to Observed Percentage Wind Shear Per 225 mb

Storm	Date	Between pressure levels (mb)	Radius (km)		
			18-36	36-54	54-72
Cleo	Aug 18, 1958	810-560	25/10	22/11	9/3
Daisy	Aug 25, 1958	825-555	32/6	6/-7	-9/-45
Donna	Sept 7, 1960	760-635	13/-2	8/8	5/1
Carla	Sept 6, 1961	905-585	26/19	20/12	13/21
Carla	Sept 8, 1961	860-720	16/6	16/12	11/13
		Avg:	22/8	13/7	6/6

3. OTHER PROFILES

For a number of years, engineers have used a formulation, similar to the logarithmic relationship, to relate the mean wind speed at one height with that at another. The power law is written as,

$$\bar{u}\,(z) = \bar{u}_1\left(\frac{z}{z_1}\right)^{x} = \bar{u}_1\left(\frac{z}{z_1}\right)^{n/2 - n} \tag{4}$$

where x or n, which is a function of atmospheric stability, is the exponent. Data from Brookhaven on Hurricanes Carol (1954) and Edna (1954) show a rapid increase of mean wind speed with height with an exponent x = .3. This profile compares well with the overland profile constructed here for the lowest 100 m. An exponent of x = 1/7 has been used as a standard in engineering for variation of mean horizontal wind with height in hurricanes. This exponent yields a profile in good agreement with the over-water profile constructed earlier. Recent data (Saffir, 1972) have further substantiated the validity of the 1/7 power for use in over-water shear profiles in hurricanes.

Sherlock (1952) used an expression similar to that for eddy transfer of heat to obtain an expression for eddy transfer of velocity. This expression can be used to obtain the distance inland where the over-land profile will match the over-water profile at a certain elevation. We have

$$z^2 = 4k\left(\frac{L}{u}\right) \tag{5}$$

where z is the height to which turbulence is significantly effective in time interval t, k is the eddy diffusivity, L is the distance inland from the coast line, and $\bar{u}$ is the mean wind speed at the reference height 10 m. Using the height $z = 150$ m for the level where the overland profile matches the over-water profile, we obtain $L < .5$ km for wind speeds of up to 60 m s^{-1}. Thus, the overland profile may be used reliably at all points further than .5 km inland.

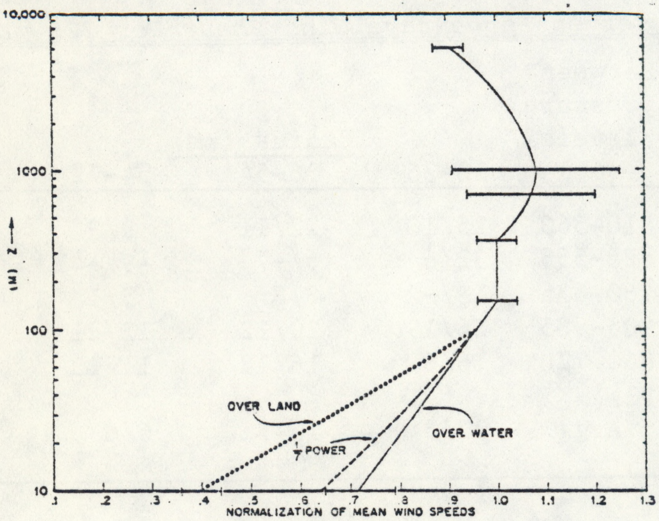

Figure 4. Normalized profile of variation of mean wind speed with height in tropical cyclones. (See text for discussion.)

The directly measured shear profiles for Hurricane Eloise (1975) are given in figure 2. These profiles were taken later than the PBL profile and occurred during the mature stage. Also included are the position of the EB-10 buoy, the position of Eloise, and the flight track of the aircraft. Since there were data at only two levels, this does not yield much information as to the actual shape of the profile. The shear appears to be small between flight altitude and the surface. Wind speed at 10 m is .86 to 1.02 of the speeds measured at 450 m. These factors are in excess of what the over-water profile would give, but it is of interest to note that these winds are near hurricane force or greater.

A sea-air interaction research flight into Hurricane Ava (East Pacific, 1973)[2] attempted to obtain profiles of horizontal wind speed in the vertical. However, the short time interval (20 to 30 sec) for data collection at one elevation, and other data reduction problems, made it unfeasible to use this data in constructing the profile of section 1. However, it is of interest to examine it for sake of completeness. Figure 5 shows two profiles from Ava, at different radial distances, normalized with respect to the wind speed in the 300- to 400-m level. These Ava profiles lie, for the most part, within the deviations given in the profile in section 1. The trend is also quite similar - an increase in horizontal wind speed from 400 to 1000 m, then a decrease from 2000 to 3000 m. If the lowest layers of these profiles are extrapolated to 10 m, the reduction in wind speed from the normalization point of 1 is also similar to the profile of section 1.

4. AN EXAMINATION OF THE WIND-PRESSURE RELATIONSHIPS

The cyclostrophic approximation in natural coordinates may be written,

$$\frac{v^2}{R} = \frac{-1}{\rho} \frac{\partial p}{\partial n} \qquad (6)$$

Equation (6) has been the impetus for a number of investigators (Fletcher, 1955; Kraft 1961) to obtain a relationship between the minimum sea level pressure (MSLP) and the maximum surface wind speed (MSW). Integration of (6) with respect to the radius and solution for v yields,

$$v = K\,(P_A - P_C)^{\frac{1}{2}} \qquad (7)$$

where $K^2 = \frac{1}{\rho}\,\frac{R}{r}$.

Here v is the wind speed in a frictionless environment, P_A is the ambient field pressure, P_C is the minimum central sea level pressure, and K is a constant to be determined empirically. Kraft (1961) has used a value of $P_A = 1013$ mb and $K = 14$ in his formulation for Atlantic tropical cyclones. Atkinson and Holliday (1975) have modified (7) to better fit observed data in western Pacific tropical cyclones.

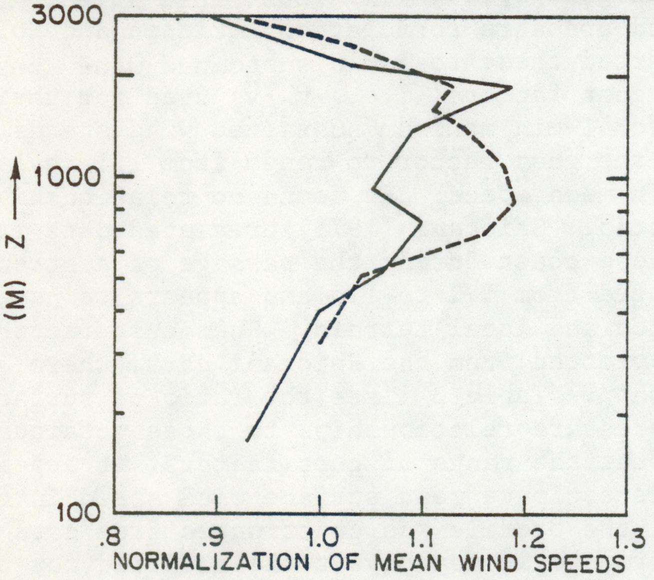

Figure 5. Normalized profiles of wind shear in Hurricane Ava at distances of 100 (solid lines) and 60 (dashed line) n.mi. (After Ross)

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[2] Duncan Ross 1976: personal communication.

They empirically determined the relationship

$$v = 6.7(1010 - P_c)^{.644} \qquad (8)$$

as a best fit curve to their data. The scatter diagrams for these relationships are given in Appendix B. Dvorak (1973), using satellite photos, has developed a scheme for relating MSLP in Atlantic tropical cyclones to MSLP in Pacific tropical cyclones of the same intensity. With this correction then, the Atkinson-Holliday MSLP-MWS formula can be used on Atlantic storms.

Radial profiles of D-values and relative wind speeds were available for a number of hurricanes from National Hurricane Research Laboratory flight data. From comparison of minimum D-value with the standard tropical atmosphere, we obtain a value for minimum sea level pressure. The maximum surface wind speed is then computed from the Kraft and Atkinson-Holliday formulas. These results are shown in table 2. Surface winds were also computed by means of the maximum wind speed recorded at flight level and the profile presented earlier. The ratio of surface wind speed to flight level wind speed was then computed. The profile always gives mean surface wind speeds less than those measured at flight level because of the frictional effect at the surface. Surface wind speeds obtained from the wind-pressure relations, however, are thought to hold for 1-min average winds. As such, they are less influenced by friction and often appear in excess of flight level wind speeds.

To put the wind speeds obtained from the profile and those obtained from the wind-pressure relationships on a more comparable basis, it is necessary to investigate the relationship between gust speed, 1-min sustained speed, and mean wind speed. For their wind-pressure formulation Atkinson and Holliday used only peak gusts and then converted these to 1-min sustained wind speed according to Atkinson (1973). The gust factors (i.e., $v_G/\bar{v}$) used for their conversion ranged from 1.2 to 1.1 for 1-min maximum sustained wind speeds of 70 to 140 kt. Gentry (1953) found the gust factor to range from 1.1 to 1.8 for the ratio of gust speed to 5-min mean speed. He found no relationship between mean wind speed and gust ratio. Shiotani (1975) presented data from a meteorological tower on the Japanese coast during the passage of a strong typhoon. The gust factor there ranged from 1.2 to 1.5 and appears to have been strongly influenced by wind direction and local terrain. When gust factor versus mean wind speed (fig. 6) is plotted from the Shiotani data, there appears to be no definite relationship. Table 3 lists the ratio of surface wind speed obtained from the wind-pressure relationships to those obtained from the profile. Taking into account the range of gust factors, it appears that the over-water profile may underestimate mean surface wind speed in the region of maximum winds. As noted, the profile was constructed from data not in the most intense part of the storm, so it may have to be modified for the most intense part. An examination of the overland ratios shows a large discrepancy. Again, one reason may be the low wind speeds from which the profile was constructed, but there are more serious effects which may bias these results. First, the profile was constructed from winds above 100 m measured over water, rather than over land. Second, we used wind speeds measured over the ocean for obtaining wind speeds over land according to the profile. These problems make it inappropriate to draw meaningful conclusions from the overland ratios.

Table 2. *Maximum Surface and Flight Level Wind Speeds* (Included are Parameters for Their Determination)

Storm	Date	Ht (ft)	D_{VAL} (min)	$MSLP_{ATL}$	V_K	$MSLP_{PAC}$	$V_{A\&H}$	V_W	V_L	V_{Ht}	Radius V_{Ht} (km)	V_W/V_{Ht}	V_L/V_{Ht}	V_K/V_{Ht}	$V_{A\&H}/V_{Ht}$
Debbie	8-20-69	11,780	-880	957	105	951	93	62	35	85	6	.73	.41	1.23	1.09
Debbie	8-18-69	11,780	-300	975	86	969	73	55	31	75	5	.73	.41	1.15	.97
Cleo	8-23-64	9,880	-1250	950	111	944	100	86	48	120	4	.72	.40	.93	.83
Betsy	9-3-65	11,780	-600	967	95	961	82	53	29	72	5	.73	.41	1.32	1.14
Hilda	10-1-64	3,470	-1900	942	118	936	107	63	35	95	10	.67	.37	1.24	1.13
Inez	9-28-66	1,770	-2500	922	133	916	125	86	48	125	4	.69	.38	1.06	1.0
Dora	9-4-64	3,240	-1200	965	97	959	84	50	28	75	8	.67	.37	1.29	1.12
Dora	9-5-64	3,240	-1500	955	106	949	96	64	35	95	7	.67	.37	1.12	1.01
Dora	9-9-64	3,240	-1500	955	106	949	96	60	33	90	6	.67	.37	1.17	1.06
Daisy	8-25-58	1,600	-300	998	54	990	46	35	19	50	5	.69	.38	1.08	.92
Daisy	8-26-58	6,400	-820	972	90	966	77	62	35	90	6	.69	.39	1.0	.85

KEY:

Ht	Flight altitude of research aircraft in feet
D_{VAL}	D = pressure altitude - standard tropical atmosphere pressure
$MSLP_{ATL}$	Minimum Sea Level Pressure in the Atlantic, computed with minimum recorded D-value
V_K	Maximum surface wind speed (fastest mile) according to Kraft (1969)
$MSLP_{PAC}$	Minimum Sea Level Pressure in the western Pacific converted from Atlantic values from Dvorak (1973)
$V_{A\&H}$	Maximum sustained 1-minute surface wind speed according to Atkinson and Holliday (1975)
V_W	Mean surface wind speed over water as computed from the profile with research aircraft wind speeds
V_L	Mean surface wind speed over land as computed from the profile with research aircraft wind speeds
V_{Ht}	Research aircraft wind speed at flight altitude
Radius V_{Ht}	Radial extent of maximum wind speed zone recorded at flight altitude
V_W/V_{Ht}, V_L/V_{Ht}, V_K/V_{Ht}, $V_{A\&H}/V_{Ht}$	Ratio of computed surface wind speed to maximum wind speed recorded at flight altitude

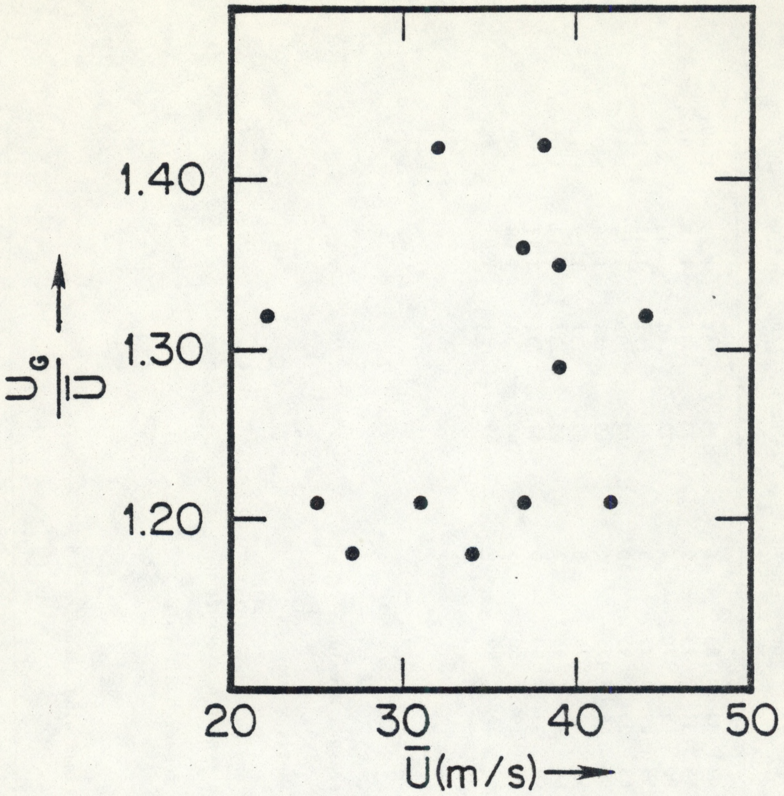

Figure 6. Scatter diagram of gust ratio versus mean wind speed for typhoon. (After Shiotani)

5. CONCLUSIONS

We have attempted to construct a standard profile of vertical shear of the horizontal wind speed in tropical cyclones. This was accomplished by linking data from the lowest 100 m to aircraft observations at higher levels. The different layers required only minimal readjustment to form one continuous profile. The intense convection associated with hurricanes acts to effectively exchange momentum in the vertical as demonstrated by Gray (1967). This momentum exchange then minimizes shear in the vertical. It also has a strengthening effect on the relationship between wind speeds at various heights.

While this attempt at a complete vertical profile appears to underestimate surface wind speeds of hurricane strength or greater, it is most important to realize that something different may be occurring at the higher wind speeds. That is, at higher wind speeds, the turbulent momentum exchanges may offset the effect of increasing surface drag. This would cause the wind speed profile not to fall off so rapidly with decreasing elevation as suggested by Cardone (1969).

Shear measurements in higher wind speeds show even smaller shear with height. While we await further measurements to substantiate this aspect, we can conclude that mean horizontal wind speed at one level is quite well related to that at another. It would also appear that the greater the wind speed, the less the shear between wind speeds at different altitudes.

Table 3. Ratio of Wind-Pressure Maximum Surface Wind Speed Versus Surface Wind Speed From Profile

$\frac{V_K}{V_W}$	$\frac{V_{A\&H}}{V_W}$	$\frac{V_K}{V_L}$	$\frac{V_{A\&H}}{V_L}$
1.69	1.50	3.00	2.65
1.56	1.33	2.77	2.35
1.29	1.16	2.31	2.08
1.79	1.55	3.27	2.82
1.87	1.70	3.37	3.06
1.54	1.45	2.77	2.60
1.94	1.68	3.46	3.00
1.66	1.50	3.03	2.74
1.76	1.60	3.21	2.90
1.54	1.31	2.84	2.42
1.45	1.24	2.57	2.20

See key, table 2.

6. ACKNOWLEDGMENTS

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APPENDIX A

CAROLINE AND ELOISE FLIGHT TRACKS

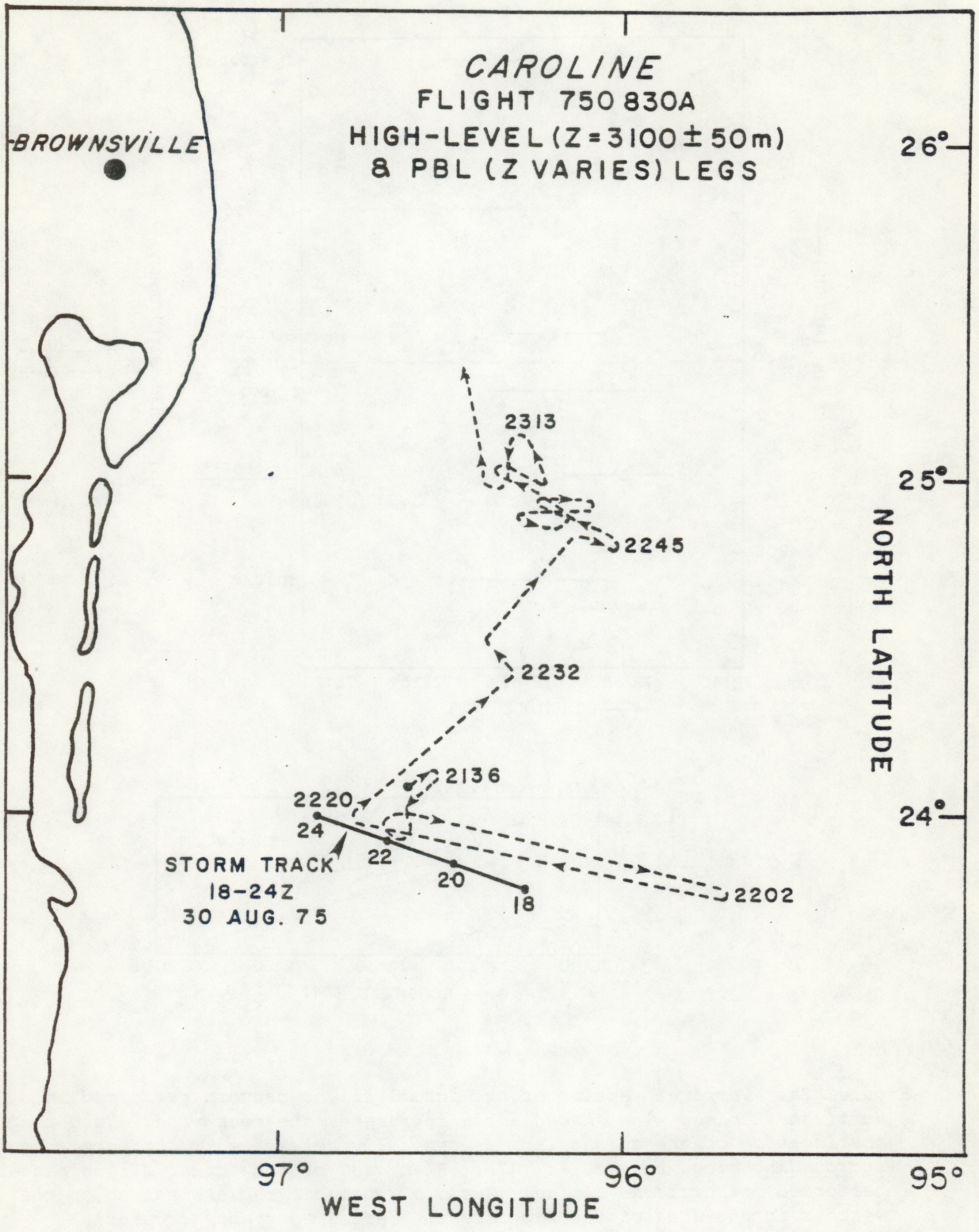


Figure A1. High altitude and PBL flight tracks. (After Merceret)

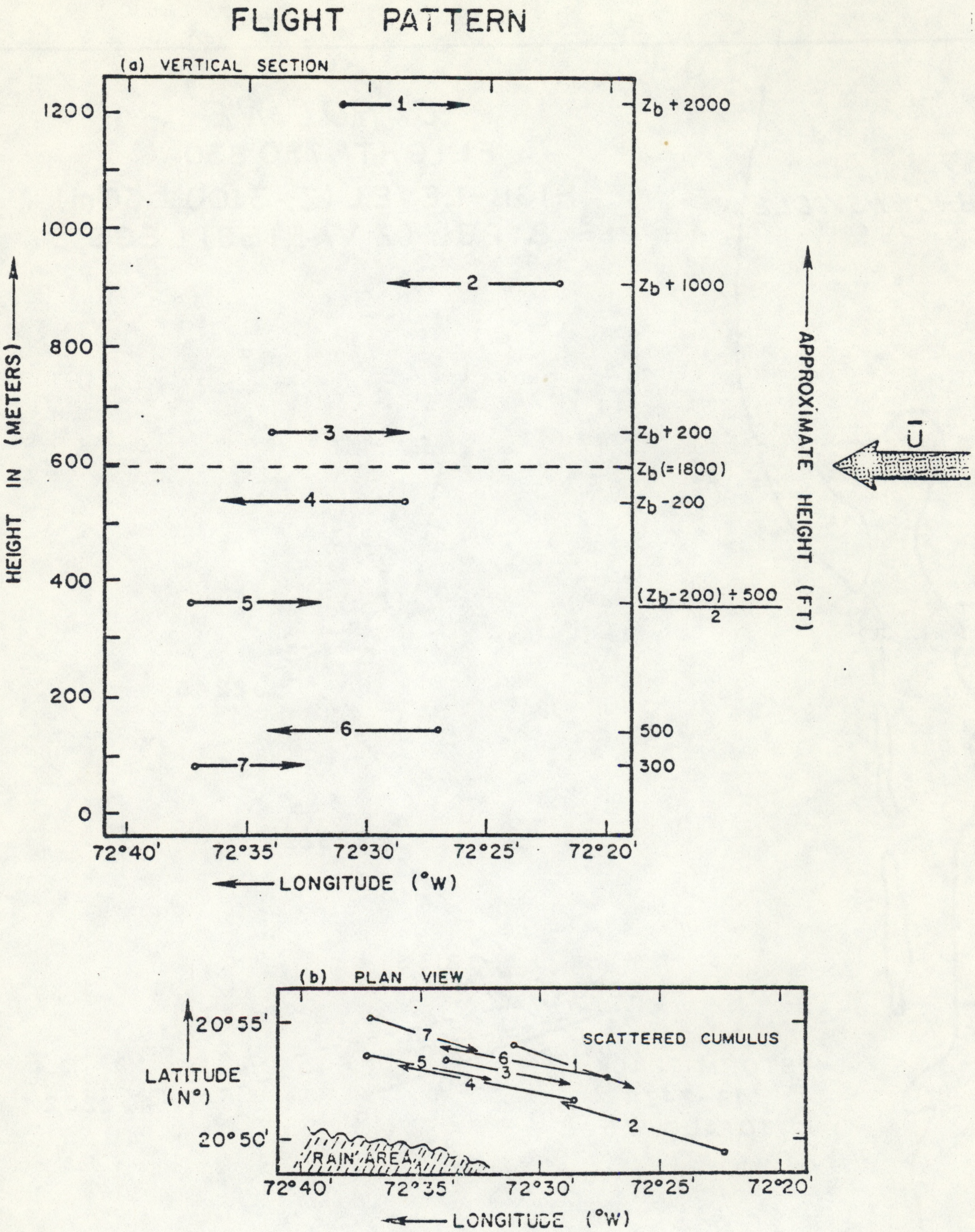


Figure A2a. Vertical section of the actual flight pattern performed in Hurricane Eloise. The shaded arrow represents the mean wind. Note that the location of the flight legs is generally referenced with respect to the surrounding cloud base (Z_b). A2b. Plan view of the actual flight pattern performed in Hurricane Eloise. Also, a schematic representation of the weather in the area of the experiment. (After Moss and Merceret)

APPENDIX B

MINIMUM CENTRAL SEA-LEVEL PRESSURE VERSUS MAXIMUM SURFACE WIND SPEED

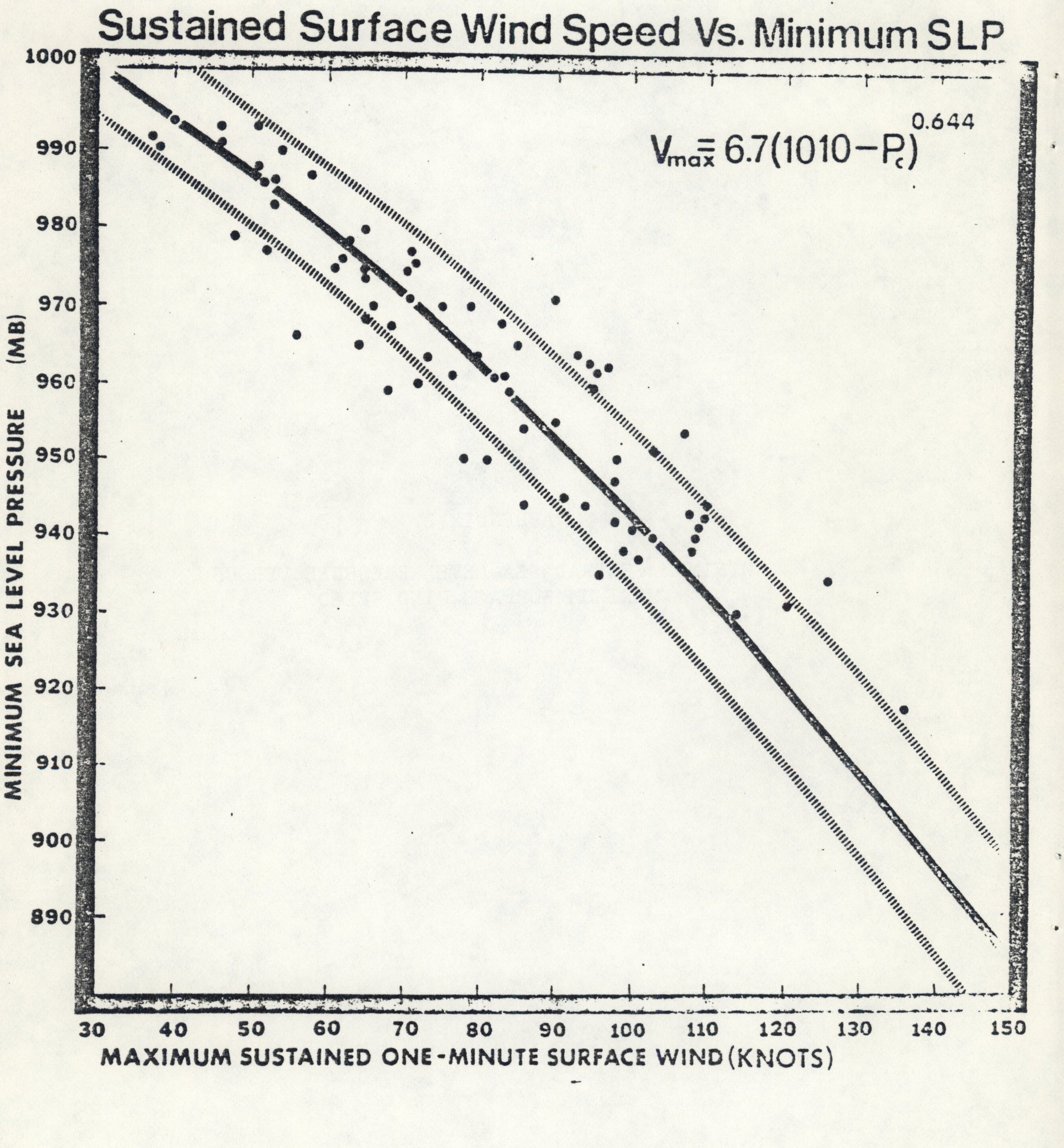
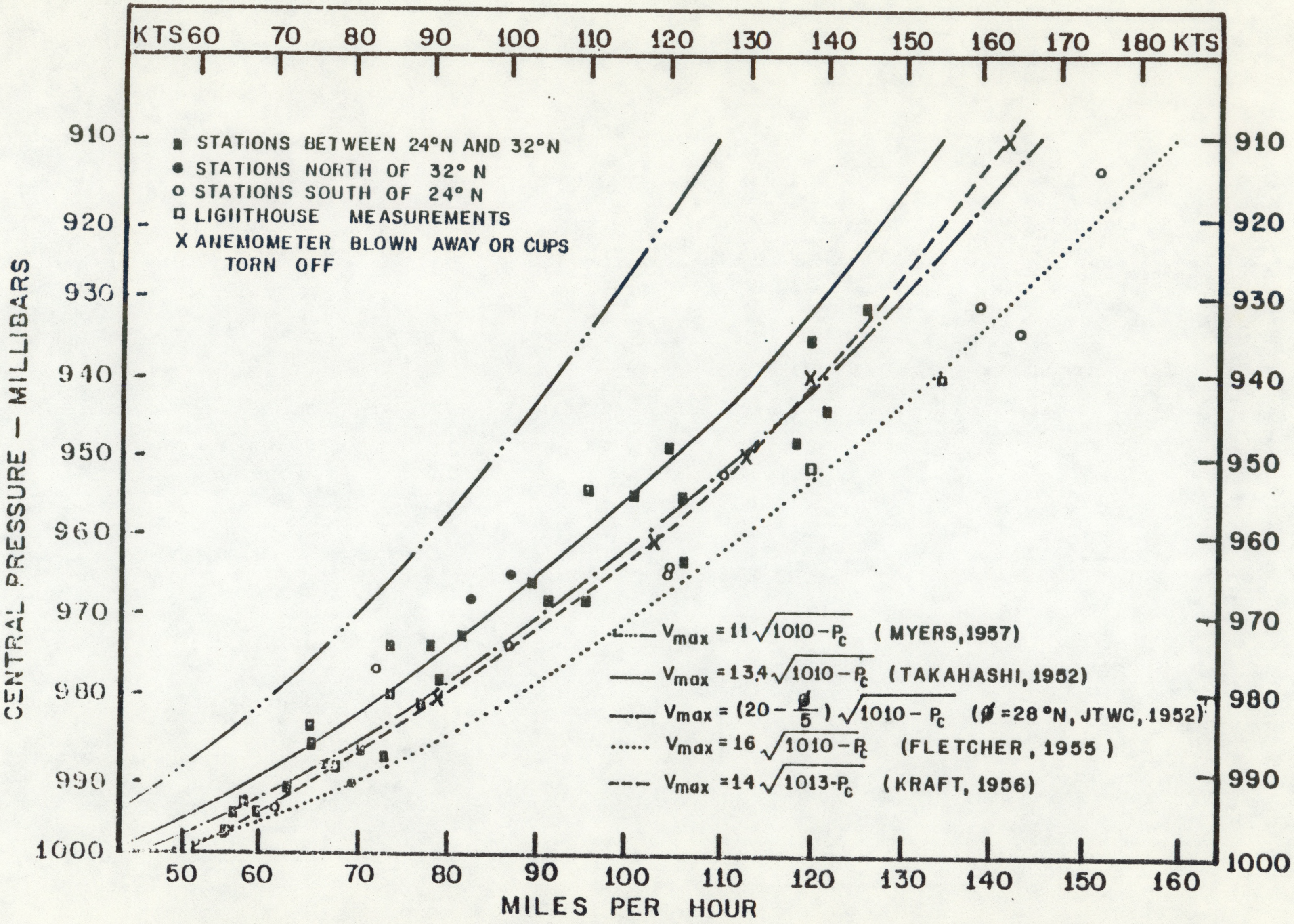


Figure B1. (After Atkinson and Holliday)



EQUATIONS USED FOR DETERMINING MAXIMUM SURFACE WINDS FROM CENTRAL PRESSURE IN TROPICAL CYCLONES

Figure B2. (After Holliday)