Evaluations of Diagnostic Marine Boundary-Layer Models Applied to Hurricanes

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ABSTRACT

Four diagnostic marine boundary-layer models are evaluated for applicability to the hurricane regime. The goal was to develop an operational method of estimating surface variables with research aircraft flight-level (500 m) data. Evaluation consisted of comparing the four models plus two estimation methods with "ground truth" buoy and ship wind speed data from Hurricanes Eloise and Anita and vertically stacked several-level aircraft data in Eloise and Caroline. Three of the boundary-layer models are capable of estimating wind speed to 10% accuracy. Model results also include 10 m level neutral drag coefficients, which were compared with previous studies.

1. Introduction

Imminent landfall of a hurricane presents many problems. The likelihood of a major disaster in low-lying heavily populated areas is high. Accurate warnings from detailed forecasts must be given to save life and property and to cut down on the high costs of preparing relatively large coastal areas for hurricane occurrence. The National Hurricane and Experimental Meteorology Laboratory (NHEML) is investigating details of hurricane landfall in an effort to develop operational improvements of forecasts, warning procedures and damage potential estimates. Investigation of the hurricane boundary layer is a necessary part of the solution.

The object of this study is to evaluate and compare the capabilities of several boundary layer models for determining low-level wind structure in hurricanes. In addition, neutral drag coefficients are computed and compared with previous studies. The goal of this research is to develop an operational diagnostic model that is capable of using low-level (~500 m) aircraft data to estimate conditions close to the surface (~10 m).

The models investigated in this study are as follows:

- Moss-Rosenthal: An application of the Deardorff (1972) planetary boundary layer (PBL) parameterization scheme used by Moss and Rosenthal (1975).
- Powell: A surface-layer similarity model for unstable conditions developed by Powell (1978).
- Cardone I: A surface-layer wind reduction model developed by Cardone (1969).
- Cardone II: An application of Blackadar's (1965) two-layer neutral model to the marine boundary layer by Cardone (1969).

All models depend on the applicability of the Monin-Obukov (1954) surface-layer "similarity" theory. This theory applies in the lowest tens of meters of the planetary boundary layer (PBL). The PBL in tropical circulations, as defined by Moss and Merceret (1976), pertains to the region adjacent to the earth's surface where small-scale surface-induced turbulence occurs almost continuously in time, excluding convective turbulent regimes. The PBL height, for the hurricane circulation according to this definition, coincides with the lifting condensation level over all but the dry, cloud-free peripheral regions. The surface layer is defined as the region within which the stress is approximately constant with height. Since direct measurements of stress are difficult to make at >10–20% accuracy, the surface layer is determined to be the height at which the stress decreases to 80% of its surface value (Lumley and Panofsky, 1964). This height ranges from 20–200 m over land. Over water, on the periphery of 1975 Hurricane Eloise, it was estimated to be 175 m (Powell, 1978).

2. Models

The four diagnostic models require low-level (500 m) research aircraft input quantities, including potential temperature, mixing ratio, wind speed, radiometer or bathythermograph sea surface temperature, sea-level pressure and boundary layer height. These data are then used in iterative schemes that involve surface-layer similarity relationships. Wind speed is computed by

$$U = \frac{u_*}{k}\left(\ln\frac{Z}{z_0} - \psi_m\right), \qquad (1)$$

where u_* is the friction velocity, k the von Kármán constant, Z the height, z_0 the roughness length and ψ_m a stability function. The Moss-Rosenthal and Powell models reduce winds and temperatures from flight level to the top of the surface layer according to Deardorff's (1972) empirically derived deficit laws:

$$\frac{V_{\rm FL} - V_{\rm AN}}{u_*} = 8.4\left(1 - 50\frac{Z_{\rm BL}}{L}\right)^{-0.16}, \quad (2)$$

$$\frac{\theta_{\rm VFL} - \theta_{\rm VAN}}{H_v} = -\frac{7.3}{u_*}\left(1 - \frac{5.8Z_{\rm BL}}{L}\right)^{-0.47}, \quad (3)$$

where $V_{\rm FL}$ and $V_{\rm AN}$ and $\theta_{\rm FL}$ and $\theta_{\rm VAN}$ are wind speeds and virtual potential temperatures at flight and "anemometer" levels, respectively, $Z_{\rm BL}$ is the boundary-layer height, H_v the virtual heat flux and L the Monin-Obukov length. Anemometer level is estimated as 0.025 $Z_{\rm BL}$ and $V_{\rm FL}$ and $\theta_{\rm VFL}$ are assumed to be mean values in a well-mixed PBL. The Moss-Rosenthal model momentum and heat transfer coefficients are computed according to stability determined from the bulk Richardson number

$$\mathrm{Ri}_B = \frac{gZ_{\rm AN}\Delta\theta_V}{\theta V^2}, \quad (4)$$

where g is the gravitational acceleration, $\Delta\theta_V$ the air-sea virtual potential temperature difference, θ the bulk virtual potential temperature, and V the wind speed. The Cardone (1969) empirical expression for the variation of roughness length with friction velocity is employed in the Moss-Rosenthal model and also the Cardone I and Cardone II models. The Powell (1978) model employs the same deficit relationships for wind speed and temperature, but uses surface-layer similarity expressions as a method of parameterizing the unstable boundary layer, rather than bulk transfer coefficient relationships. The Powell model uses the Charnock (1955) relationship for roughness length

$$Z_0 = \frac{\alpha u_*^2}{g} \quad (5)$$

with $\alpha = 0.035$. The remaining two diagnostic models were developed by Cardone (1969); Cardone I is a surface layer model that employs similarity relationships, but which assumes that the surface layer extends to flight level. Cardone II is based on a two-layer neutral baroclinic model by Blackadar (1965). This model was used by Elsberry *et al.* (1974) in a semi-empirical model of the hurricane boundary layer and is essentially a modified Ekman spiral. In addition to the four models mentioned above, two wind speed estimation methods were employed: Bates (1977) developed hurricane wind profiles normalized by the 150–350 m level mean wind for over land and over water. These profiles are given in Fig. 1. A rough estimation of surface winds in hurricanes can be made by multiplying low-level aircraft winds (usually at 500 m) by 0.8. This estimation was used by the late Banner I. Miller to provide quick approximations of surface winds below flight level. A summary of the methods

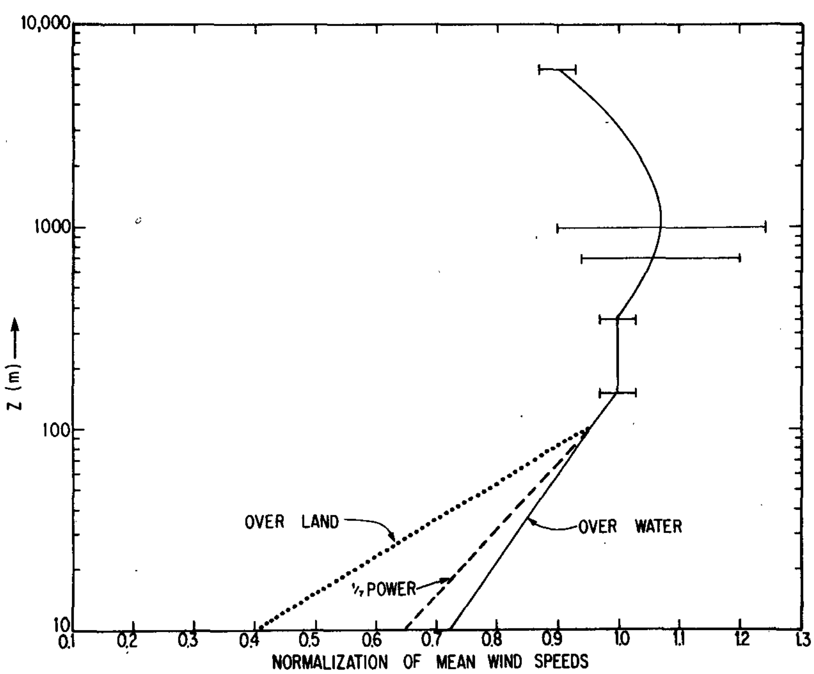

FIG. 1. Normalized profile of variation of mean wind speed with height in tropical cyclones (Bates 1977).

and input and output parameters of the models is given in Table 1.

3. Procedure

Data from three storms were available for analysis: Hurricane Caroline on 30 August 1975, Hurricane Eloise on 17, 22 and 23 September 1975, and Hurricane Anita on 30 and 31 August and 2 September 1977. Further details on these storms are available through the following works:

- Caroline—Merceret (1976), Hebert (1976), Moss (1978).
- Eloise—Moss and Merceret (1976), Moss (1978), Hebert (1976), Environmental Data Service (1975).
- Anita—Sheets (1977), Lawrence (1978), NOAA Data Buoy Office (1978).

Flight-level measurements of wind speed and other meteorological parameters from the NOAA Research Facilities Center aircraft were used as input data for the diagnostic models. Model computations were then compared with surface wind and other measurements made by NOAA environmental buoys and two ships in Hurricanes Eloise and Anita in the Gulf of Mexico. In Eloise (17 September) and Caroline, surface measurements were not available, but special PBL legs were flown at several levels. Measurements at one level were then compared with model results based on input data from another level. Measurements from the buoy, ships and PBL legs that were compared with model computations are hereafter called "reference data." Table 2 gives reference data sources for comparison to model results. The storm tracks and locations of data acquisition are presented in Figs. 2 and 3.

Two types of data measuring and recording platforms were used for this study—one airborne and one at sea. The NOAA Data Buoy Office operates and maintains the "EB" series of instrumented buoys. Wind speed and direction, air and sea surface temperature, dew point, pressure and accumulated precipitation were measured in Hurricane Eloise, but dew point and precipitation were eliminated from the 1977 measurements in Anita. An instrumented NOAA DC-6 was employed in Hurricanes Caroline and Eloise in 1975. In 1977, Hurricane Anita was flown with a WC-130B (Hercules) and a WP3-D (Lockheed Orion). These aircraft were equipped with inertial navigation systems and sensors for measurement of temperature, pres-

TABLE 1. Summary of models.

Model	Input parameters	Output parameters	Basic theory and method
Moss-Rosenthal	θ_{FL}, g_B, V_{FL}, $\theta_{\text{sea surface}}$, P_{FL}, Z_{FL}	U_*, z_0, Ri_B, Bulk momentum and heat transfer coefficients C_θ, C_v; Monin-Obukov length, L, ψ_H, and $U(Z)$.	Used in unstable and stable conditions. Uses Deardorff deficit laws to reduce flight level wind and temperature to anemometer level. Expressions for C_v, C_θ derived by curve-fitting results from numerical data by Deardorff. An implicit set of equations for Ri_B, U_*, z_0, C_v, C_θ, V_{AN}, θ_{VAN} is solved iteratively. Upon convergence of U_*, $U(Z)$ is computed from (1).
Powell	Same as above	U_*, T_*, g_*, Z_0, Ri_B, L, ψ_m, ψ_H and $U(Z)$.	Used in unstable conditions only, uses Deardorff deficit laws as above, but employs Monin-Obukov similarity expressions rather than the transfer coefficients above. An implicit set of equations for Ri_B, U_*, T_*, g_*, V_{AN}, θ_{VAN}, Z/L, ψ_m and ψ_H is solved iteratively. Upon convergence of U_*, $U(Z)$ is computed from (1).
Cardone I	Same as above	U_*, z_0, Ri_B, L, ψ_m and $U(Z)$.	Used in stable and unstable conditions. Uses Monin-Obukov similarity expressions. Assumes flight level is at the top of the surface layer. An implicit set of equations for Ri_B, U_*, z_0, L, and ψ_m is solved iteratively upon convergence of U_*, $U(Z)$ is computed from (1).
Cardone II	Above plus latitude and radial distance from storm center	U_*, z_0, L, ψ_m, inflow angle, several dimensionless parameters, and $U(Z)$.	Used in stable and unstable conditions. The model iteratively solves a set of equations for a modified Ekman spiral with a gradient wind departure. See Blackadar (1965) or Cardone (1969) for details. After convergence of U_*, $U(Z)$ is computed from (1).
Bates	V_{FL}, Z_{FL}	V_{10}	Wind data from several sources and levels were normalized by wind speeds measured in the 150–350 m layer. $V_Z = V_{FL}[N(Z)/N(Z_{FL})]$, where $N(Z)$ is the normalization at height Z.
0.8 estimate	V_{FL}	V_{10}	Flight level wind speed is simply multiplied by 0.8 to give surface wind speed.

TABLE 2. Model comparison data sources.

Source	Storm and date	Number of observations for comparison
NOAA Research Facilities Center aircraft DC-6, 39C Two levels: 267 m 394 m	Caroline 30 Aug 1975	1
NOAA Research Facilities Center aircraft DC-6, 39C Three levels: 86 m 153 m 362 m	Eloise 17 Sep 1975	3
U.S. Navy aircraft carrier anemometer height: 48 m	Eloise 23 Sep 1975	1
Exxon tanker anemometer height: 23 m	Eloise 22 Sep 1975 Eloise 23 Sep 1975	2
Environmental buoy EB-10 anemometer height: 10 m	Eloise 22 Sep 1975 Eloise 23 Sep 1975	4 (1 rejected)
Environmental buoy EB-4 anemometer height: 10 m	Eloise 23 Sep 1975	2
Environmental buoy EB-4 anemometer height: 5 m	Anita 30 Aug 1977 Anita 31 Aug 1977 Anita 02 Sep 1977	(4 rejected) 5 aircraft, 3 buoy 1 aircraft, 1 buoy 1 aircraft, 1 buoy
Environmental buoy EB-71 anemometer height: 10 m	Anita 31 Aug 1977 Anita 02 Sep 1977	3 aircraft, 1 buoy 1 aircraft, 1 buoy

sure, wind speed and direction, and dew point. In addition, the DC-6 aircraft in Eloise on 17 September 1975 and Caroline on 30 August 1975 was equipped with a hot-film anemometer and a gust probe to measure velocity fluctuations.

In Hurricane Eloise on 22 and 23 September, and in Hurricane Anita, aircraft data were prepared by averaging 10 s values of wind speed, potential temperature, mixing ratio, radar altitude and flight-level pressure over a period of 1–3 min during which

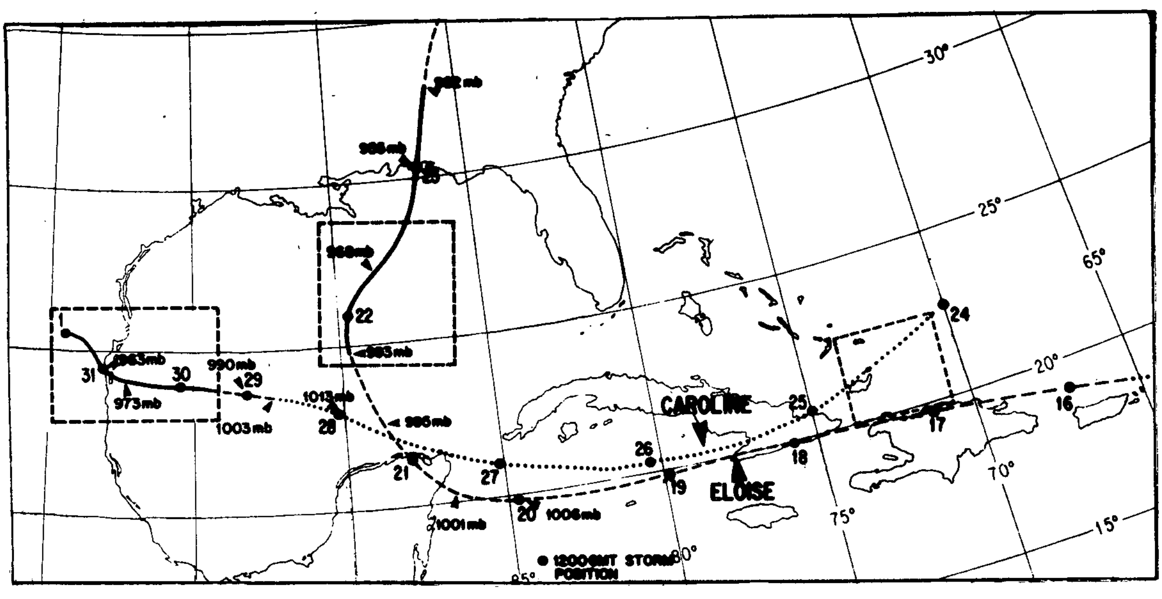

FIG. 2. Tracks of Hurricane Caroline and Eloise, including 1200 GMT position minimum surface pressure and aircraft experiment locations (in boxes). Depression and tropical storm stages are indicated by dotted and dashed lines, respectively.

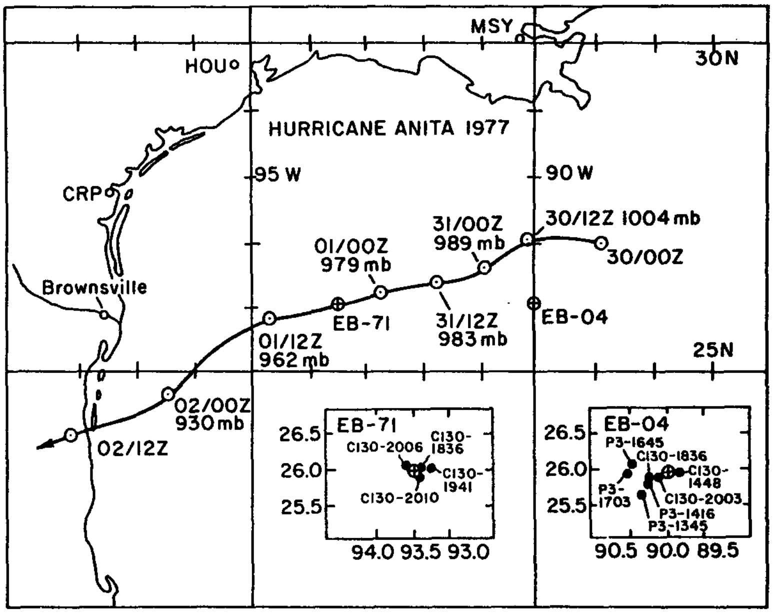

FIG. 3. Track of Anita including 12 h positions, environmental buoy positions and minimum sea level pressures. Insets give aircraft positions used for comparisons with respect to the buoys.

the aircraft was in the vicinity of the buoy position. Time and space differences between buoy and aircraft were minimized so that 16 out of 20 observations were within 1 h of each other and 15 of 20 observations were separated by <20 km. Information on the temporal and spatial observation differences is given in Table 3. Flight data for Eloise on 17 September and Caroline were averaged over the total length of each PBL leg for 2–4 min. Averaging times for buoys EB-10 and EB-4 in Eloise (22 and 23 September 1975) were 15 and 40 min, respectively, and 8.5 min for buoys EB-4 and EB-71 in Anita. Ship data[1] were available from the Exxon tanker *San Francisco* and the U.S. Navy aircraft carrier *Lexington*; these data were not averaged. Largest errors in low-level wind estimation should occur in locations close to the inner core of the eyewall where wind velocity and other variables change greatly with radial distance. Here it would be difficult for aircraft averages to correspond to portions of the storm measured by the buoys and ships.

4. Results

a. Wind speed estimations

Plots of reference wind speed (U_{ref}) versus model wind speeds (U_m) are given in Fig. 4 for the four diagnostic models and the Bates and "0.8 estimation" methods. Reference sources, anemometer heights and wind speeds, model errors, and time and space separation between the buoy or ship reference and aircraft data locations are in Table 3. The Cardone II model and the Bates profile appear to underestimate winds, as evidenced by the large number of points above the line. Large errors for the EB-10 (0200) observation in Eloise (22 and 23 September 1975) and the EB-4 (1400) and EB-4 (1700) observations in Anita occur because the aircraft was measuring portions of the storm that were different from those measured by the buoys. These observations are near the eyewall in Eloise and near a convective band in Anita and were eliminated from further analysis.

Table 4 lists average absolute error, root mean square (rms) error and percentage wind speed errors for each of the models for all the comparison sources in Table 2 and for the buoy data only. The Cardone I model is slightly more accurate than the Moss-Rosenthal and Powell models which achieved similar accuracy. The Cardone II model and the Bates profile give larger magnitude average absolute error due to wind speed underestimation.

The 0.8 estimation worked quite well for an absolute error of 1.8 m s^{-1} and a percentage error comparable to the Moss-Rosenthal and Powell models of 9%. The rms error of +2.5 m s^{-1} was large due to overestimates at high wind speeds (35 m s^{-1}), but this method provides a reasonable and quick estimate of surface wind from aircraft winds.

Table 4 also includes errors computed when only

[1] Ship data were made available by T. Inman, Exxon Corporation, for the Exxon Tanker *San Francisco* and by Lt. Cmdr. W. Peterson, U.S. Navy, for the aircraft carrier *Lexington*.

TABLE 3. Wind speed errors for each model (U_m) for ship and buoy reference observations (U_{ref}) $\Delta U = U_M - U_{ref}$.

	Reference and time (GMT)	Aircraft pass	U_{ref} (m s^{-1})	ΔU Moss-Rosenthal (m s^{-1})	ΔU Powell (m s^{-1})	ΔU Cardone I (m s^{-1})	ΔU Cardone II (m s^{-1})	ΔU Bates (m s^{-1})	ΔU 0.8 estimate (m s^{-1})	Δt** h:min	Δs** (km)
Eloise 22 Sep 1975	EB-10 2200		23.3	−2.9	−2.4	−3.0	−6.9	−3.6	−1.4	− :49	9.0
	Exxon 2200		5.5	−2.6	−2.3	−1.8	−2.8	−3.2	−2.9	−1:20	0–0.5
	EB-10 2300		25.5	−3.9	−3.3	−3.7	−7.8	−4.1	−1.7	:07	0–0.5
23 Sep 1975	Exxon 2400		36.0	7.0	7.8	5.2	2.0	2.3	9.5	−1:14	2.0
	Lexington 0037		18.0	1.4	1.8	1.1	−2.3	−3.2	−0.4	2:12	5.0
	EB-04 0100		17.6	−1.0	−0.4	−1.0	−4.3	−3.9	−0.4	−1:02	45.0
	EB-10 0100		35.1	0.8	1.8	−1.3	−7.2	−0.6	5.9	− :01	10.0
	EB-10 *0200		15.9	8.4	9.0	7.7	7.0	8.3	11.0	+ :54	3.0
	EB-04 0300		16.8	−1.3	−0.6	−1.1	−4.0	−3.1	−0.6	+ :38	15.0
	Reference	Aircraft pass									
Anita 30 Aug 1977	EB-4 1400	*P3 1345	18.5	−4.3	−4.6	−6.8	−7.0	−4.5	−3.2	+ :11	41.0
		*P3 1416	18.5	−3.0	−3.2	−5.5	−5.9	−3.0	−1.3	− :20	27.0
	EB-4 1700	*P3 1645	21.6	−6.8	−7.0	−9.1	−9.4	−6.9	−5.2	+ :11	55.0
		*P3 1703	21.6	−7.1	−7.3	−9.4	−9.7	−7.3	−5.7	− :07	54.0
		C130 2003	21.6	3.6	3.5	2.3	−2.3	1.7	4.3	− :07	12.0
31 Aug 1977	EB-71 2000	C130 1941	16.4	−0.6	−1.0	−0.8	−3.9	−3.3	−0.8	+ :15	18.9
		C130 2006	16.4	−2.6	−3.0	−2.4	−5.5	−4.5	3.2	− :10	6.0
		C130 2010	16.4	−1.0	−1.4	−1.3	−4.2	−3.7	−1.4	− :14	5.6
02 Sep 1977	EB-4 2100	C130 2119	12.3	+0.9	+0.6	0.5	−2.2	−0.9	1.3	− :23	11.1
	EB-4 1500	C130 1448	7.2	−0.9	stable case	−0.4	−1.5	−0.8	0.4	+ :08	20.1
	EB-71 1900	C130 1836	9.2	+0.5	+0.4	0.3	−1.1	−1.1	0.5	+ :20	8.7

* These comparisons are not included in the following results.

** Δt = time difference = $t_{reference} - t_{aircraft}$. Δs is the separation distance between buoy or ship, and aircraft with respect to the storm center.

the buoy data were considered and similar model performance is indicated (with smaller errors). Model errors (ΔU) were investigated for bias caused by wind speed and stability by plotting model error (ΔU) versus reference wind speed (U_{ref}) and model error versus air-sea virtual potential temperature difference ($\Delta\theta_v$) in scatter plots. Error increased with wind speed for the 0.8 estimation, since for high winds, the fractional speed decrease from flight level was greater than 0.8. Air-sea virtual potential temperature difference ranged from +0.9 to −4.1°C and indicated unstable conditions (negative $\Delta\theta_v$) in 21 out of 22 observations. No evidence of bias could be found in the stability plots.

Results from the PBL leg computations in Hurricanes Caroline and Eloise (17 September) indicate that winds computed by the models and compared with measurements below 175 m (the estimates surface layer height) were accurate to within 10%. Model winds [calculated by the logarithmic profile (1)] were overestimates of the aircraft-measured winds because the aircraft-measured PBL profiles exhibited negative vertical shear between 175 and 400 m.

Despite such inhibiting factors as the natural variability of hurricanes and the time and space differences between reference observations and input data aircraft observations, percentage errors of 9% for the Cardone I model and 10% for the Moss-Rosenthal, Powell and 0.8 models indicate that these models can estimate surface winds accurately from aircraft data.

b. Drag coefficients over water in hurricane winds

The neutral stability drag coefficient evaluated at anemometer level (10 m) is related to the friction velocity and is often used to calculate the surface stress

$$\tau = \rho C_{D_{10}} u_{10}^2, \tag{6}$$

where

$$C_{D_{10}} = \left(\frac{u_*}{u_{10}}\right)^2 \tag{7}$$

by definition (Kraus, 1972). This drag coefficient has also been used for the computation of heat and moisture fluxes. Several investigators have attempted to relate the drag coefficient to the mean wind

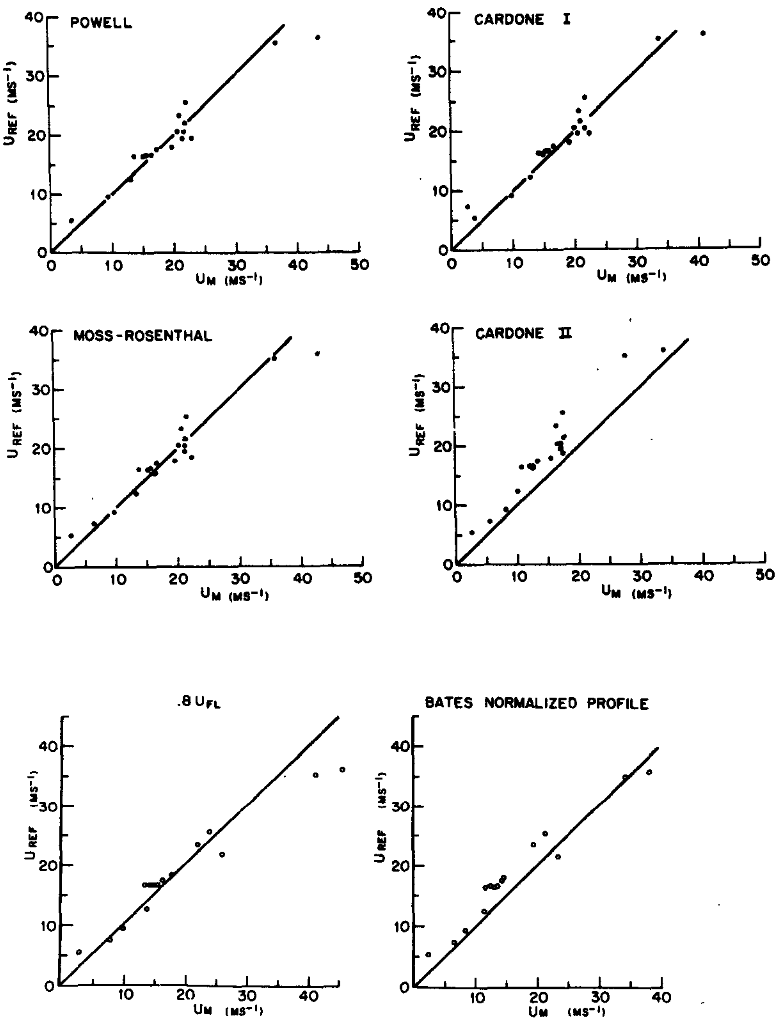

FIG. 4. Reference wind speed versus model wind speed. Solid line indicates perfect fit.

speed with varying results. Sheppard *et al.* (1972) found a linear increase of C_D with mean wind speed. Pond *et al.* (1971) reported a near-constant drag coefficient. Neumann (1956) measured a decrease in drag coefficient with increasing wind speed. Sethu-Raman and Raynor (1975) found a constancy of drag coefficient with mean wind speed for each of three roughness categories. Garratt (1977) combined results of 14 investigations and showed a linear dependence on wind speed. More than 85% of his data were for speeds < 10 m s^{-1}, however, and very little data are available for speeds > 15 m s^{-1}.

Investigators have calculated drag coefficients in hurricanes through several methods. Riehl and Malkus (1961) computed drag coefficients for Hurricane Daisy from heat and moisture budgets employing the bulk aerodynamic formulations

$$C_{D_{10}} = \frac{H}{\rho c_P U_{10} \Delta T} \tag{8}$$

or

$$C_{D_{10}} = \frac{Q}{\rho L_v U_{10} \Delta q}, \tag{9}$$

where ΔT and Δq are sea-air temperature and mixing ratio differences. These formulations assumed that heat and moisture and momentum exchange coefficients were equal, which is not necessarily true (e.g., Friehe and Schmitt, 1976). Miller (1962), Hawkins and Rubsam (1968), and Hawkins and Imbembo (1976) computed drag coefficients for Hurricanes Helene, Hilda and Inez, respectively, by integrating the tangential equation of motion through the inflow layer, i.e.,

$$\tau_\theta = \frac{1}{R^2} \frac{\partial}{\partial R} \int_{P_S}^{P_H} V_R R M \frac{dp}{g} + \frac{\omega_H M_H}{Rg}, \tag{10}$$

where τ_θ is the tangential surface stress component, R is radial distance, M is absolute angular mo-

TABLE 4. Model versus reference comparison errors.

Model	Wind speed comparison errors: Average absolute error (m s^{-1})	rms error ±(m s^{-1})	Percentage error (%)	
Cardone I	1.6	2.0	8.7	Based on 19 buoy, ship and aircraft comparisons
Moss-Rosenthal	1.8	2.4	10.6	
Powell	1.9	2.6	10.3	
Cardone II	3.8	4.2	21.5	
Cardone I	1.5	1.8	7.8	Based on 12 buoy comparisons
Moss-Rosenthal	1.7	2.0	9.3	
Powell	1.7	2.0	8.5	
Cardone II	4.2	4.7	22.8	
0.8 estimate	1.8	2.5	9.1	
Bates	2.6	2.9	14.9	

mentum and ω_H is vertical velocity; the subscripts H and S pertain to the top of the atmosphere and the sea surface, respectively. Miller (1964) made drag coefficient calculations from Hurricane Donna by integrating an approximate form of the tangential equation of motion

$$\tau_\theta = \int_{P_S}^{P_H} V_R \zeta_A \frac{dp}{g}, \qquad (11)$$

where V_R is the radial wind component and ζ_A the absolute vorticity of the tangential wind. After surface stresses in (10) and (11) were computed, drag coefficients were computed from (6). Neutral drag coefficients taken from the above studies are included in Fig. 5. Moss and Rosenthal (1975) found that drag coefficients computed by Deardorff's technique agreed well with those computed in the budget studies of Hurricanes Daisy and Inez mentioned previously.

Drag coefficients for Hurricanes Eloise, Caroline and Anita were computed from (7) and plotted with earlier hurricane computations in Fig. 5 to investigate the behavior of the neutral drag coefficient with increasing wind speed.

Model friction velocities and wind speeds were used for computing aircraft and ship reference cases and model friction velocities and 10 m level

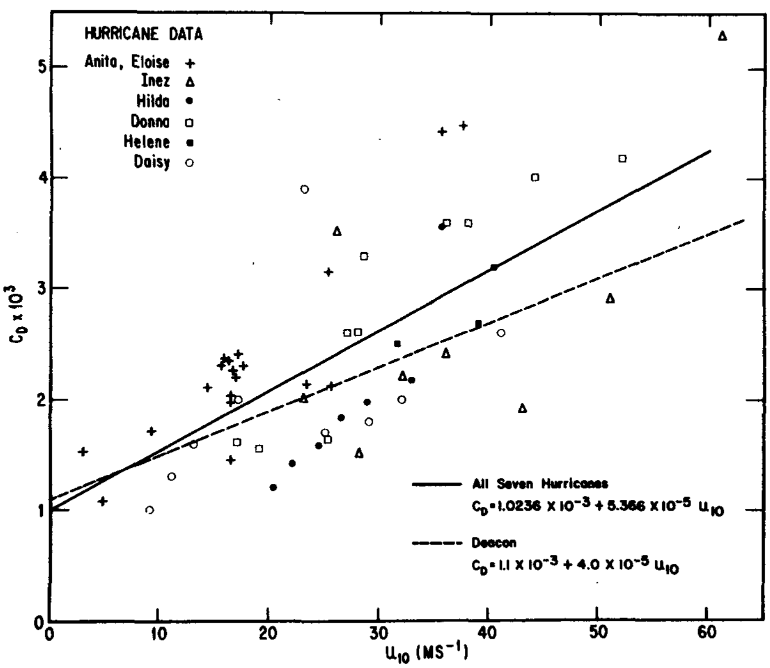

FIG. 5. Ten meter level neutral drag coefficient from several studies plotted versus wind speed.

measured wind speeds were used to compute the buoy reference cases.[2] Fig. 5 presents a scatter diagram of drag coefficient versus anemometer level wind speed for all of the storms mentioned above. Since model-computed sea surface roughness increases with friction velocity, which increases with wind speed, the drag coefficient computed with the model data shows an increase with wind speed. Comparison with other hurricane data in Fig. 5 indicates that Charnock and Cardone's relationships for roughness length are reasonable in the hurricane regime, although the larger scatter shows that the values of the constants may need to be refined. A linear least-squares fit to the data of Fig. 5 gives the relation

$$C_{D_{10}} \times 10^3 = 1.0236 + 5.366 \times 10^{-2}\, U_{10}, \quad (12)$$

which is plotted on the figure with the Deacon relationship used in NHEML numerical hurricane models (Rosenthal, 1971):

$$C_{D_{10}} \times 10^3 = 1.1 + 4 \times 10^{-2}\, U_{10}. \quad (13)$$

Much of the scatter in Fig. 5 can be attributed to differences in method of computation, i.e., from the models or the momentum budget, vorticity budget or heat budget, and to errors and differences in measurement systems. Previous hurricane studies involved aircraft wind data that were measured with a Doppler navigation system, while present studies make use of an inertial Omega updated navigation system. While it appears that the Deacon drag coefficients may be too low at speeds above 10 m s^{-1}, it is realized that more high-quality data will be required to determine the accuracy of (12).

5. Conclusion

Four diagnostic boundary layer models and two simple estimation models were evaluated for their ability to estimate wind speed near the surface by a comparison to buoy, ship and aircraft data in Hurricanes Caroline, Eloise and Anita. The Cardone I model was most accurate (9% error) and the Moss-Rosenthal, Powell and 0.8 techniques followed with 10% errors. The 10 m neutral drag coefficient was found to increase with wind speed to a greater extent than that shown by the Deacon relationship. It is concluded that three diagnostic marine boundary layer models and a simple empirical 0.8 law, when given low-level (~500 m) aircraft data as input, are able to estimate wind speed to 10% accuracy in hurricanes. Model determinations of neutral drag coefficients at the 10 m level may be made, but no direct measurements are available for comparison.

It is believed that the above models can be used on an operational basis to provide valuable low-level wind and surface layer information from research aircraft efforts in hurricanes and other high wind situations.

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[2] Drag coefficient computations of the Powell, Moss-Rosenthal and Cardone I models were averaged for each buoy wind speed observation.

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