On the Estimation of Planetary Boundary Layer Variables in Mature Hurricanes

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ABSTRACT

Using data from Hurricanes Daisy 1958 and Inez 1966, we have applied Deardorff's (1972b) planetary boundary layer parameterization scheme to compute the surface exchange coefficients for these storms. The drag coefficients compare quite well with previous budget study estimates provided we assume that Charnock's (1955) or Cardone's (1969) relation for the roughness length is valid.

1. Introduction

Hurricanes are strongly dependent upon air-sea exchange processes. Frictionally induced horizontal convergence at low levels provides the major part of the mass and water vapor that is transported upward in the hurricane convective clouds. Water vapor and sensible heat are supplied to the atmosphere by the ocean and maintain the low-level equivalent potential temperatures at values that are high enough to permit the existence of tall cumulus clouds despite rather large static stabilities in the middle and upper troposphere.

Despite the importance of these turbulent transports, knowledge of turbulent flux magnitudes in the hurricane's planetary boundary layer (PBL) is fragmentary and based upon indirect methods of analysis. Surface fluxes are usually computed as residuals from bulk momentum budgets (Miller, 1964; Hawkins and Rubsam, 1968; Hawkins and Imbembo, 1975), or bulk heat budgets (Riehl and Malkus, 1961). Drag or heat transfer coefficients are then computed from the fluxes using the bulk aerodynamic equations. The accuracy of these estimates is an open question since the bulk budget data are obtained from subjective analysis of relatively incomplete aircraft observations. Kraus (1972) suggests that the values of the drag coefficients estimated by these techniques may contain errors of a factor of two or three.

Data are usually available at only one level in the hurricane PBL. Thus a more direct estimate of these coefficients is difficult to obtain. The problem is similar to that encountered when one attempts to estimate surface fluxes and stresses in a numerical prediction model with a coarse vertical resolution. The latter problem has received considerable attention in recent years (Clarke, 1970; Deardorff, 1972b; Randall and Arakawa, 1974). In principle, Deardorff's scheme is readily adaptable to diagnostic studies with data of the type available for hurricanes. However, we must keep clearly in mind that Deardorff's method contains several elements that may or may not be applicable under hurricane conditions.

Specifically, the surface layer model he uses is based on the formulations of Businger (1966), and Businger et al. (1971) which, in turn, are derived from relatively low wind speed, land-based observations. Furthermore, the deficit law used to depict processes in the remainder of the PBL is based on Deardorff's (1970a, 1970b, 1972a) numerical simulations of surface generated turbulence. The relationship between the simulated turbulence and that encountered in hurricanes is an open question. Nevertheless, a comparison between exchange coefficients estimated by budget methods and those obtained from Deardorff's scheme seems to be a reasonable undertaking. In this pilot study, we have used bulk data from the mature stages of Hurricanes Daisy 1958 and Inez 1966. The data and their sources are given in Appendix A.

2. Computational procedure

a. Depth of the PBL

For this study, we adopt Deardorff's (1972b) definition of the PBL "... the region adjacent to the earth's surface where small-scale turbulence is induced by wind shear and/or thermal convection and occurs almost continuously in space and time. It includes in its lowermost portion the Prandtl or surface layer, where the vertical fluxes of heat, momentum, and moisture have nearly the same magnitudes as they do at the surface itself." As Deardorff (1972b) also points out, "The definition of the PBL has not here included the region of turbulence within towering cumuli but only the average height of surface induced turbulent fluxes outside of such clouds."
Hence, eddy fluxes produced by the cumuli are separated from those produced by surface induced turbulence. This separation removes conceptual difficulties that might arise in the definition of the PBL in areas of very active cumulus convection such as the hurricane’s eyewall. While the eyewall region is usually filled (or nearly filled) with visible cloud, much of this is cloud debris and not active cumuli. This has been verified by numerous eyewall penetrations by the NOAA research aircraft and by careful analysis of data obtained from cloud photography and from radar (Malkus et al., 1961). The latter study indicated that in Hurricane Daisy 1958 less than 10% of the eyewall area was covered by active cumulus updrafts.

The depth of the PBL as defined above, is a key parameter in the Deardorff (1972b) parameterization. In the published form of Deardorff’s scheme, this depth is a prognostic variable. When the scheme is adapted for diagnostic purposes, the depth of the PBL must be obtained from other considerations. To our knowledge, direct observational material relevant to this depth for mature hurricanes over the oceans does not exist. In fact, a plan to gather such data is currently part of our Laboratory’s field program.

On the other hand, observations are available for a variety of undisturbed and weakly and disturbed tropical situations (for example, Betts et al., 1974; Pennell and LeMone, 1974). Excellent summaries of this body of information are provided by Garstang and Betts (1974), Ogura and Cho (1974), and Arakawa (1975). These data indicate a close correspondence between cloud base and the top of the PBL. The validity of extrapolating these results to hurricane conditions is not immediately obvious. We will, however, present arguments to show that such a procedure is not entirely unwarranted. Furthermore, our computational results will provide some pragmatic support to our arguments.

The close correspondence between cloud base and the top of the PBL in the observations cited above appears to be too strong a relationship to be a coincidence as thought by some. This proximity may well be explained, to some degree, by the arguments presented by Deardorff (1972b) and Arakawa (1975). These investigators feel that the lifting condensation level is the limiting height for the PBL in the presence of cumulus clouds. Arakawa (1975) states, “The subsidence between the clouds keeps the PBL top from rising above the condensation level.” Deardorff (1972b) makes a similar statement.

Subsidence near cloud base between cumulus elements in weakly disturbed situations has been documented by several investigators (for example, Yanai et al., 1973, and Ogura and Cho, 1974). Whether this is also the case in hurricanes is a matter that requires further study. However, Rosenthal (1973) did find evidence in Hurricane Daisy 1958 of weak low-level subsidence between the cloud elements. The diagnostic technique devised by Yanai et al. (1973) was used to obtain this result. While Rosenthal’s (1973) study is by no means conclusive, it, together with the arguments of the last few paragraphs, should allow us to proceed with the working hypothesis that cloud base and the top of the PBL are in close proximity within the hurricane vortex. If we further assume that the cloud base is located at the lifting condensation level of the surface air, the iterative procedure described in Appendix B may be used to calculate the cloud base height and, hence, the top of the PBL.

b. Surface exchange coefficients

Deardorff (1972b) derives a bulk Richardson number of the form

$$RI_B = -\frac{gZ_B(\bar{\theta}_s - \bar{\theta}_{sea})}{\bar{\theta}_s(\bar{V} \cdot \bar{V})}. \quad (1)$$

The circumflex denotes averages over the depth of the PBL ($Z_B$). The symbol $g$ represents the gravitational acceleration. The virtual potential temperatures are given by

$$\bar{\theta}_s = \bar{\theta}(1 + 0.61\bar{q})$$

and

$$\bar{\theta}_{sea} = \bar{\theta}_{sea}(1 + 0.61\bar{q}_{sea}). \quad (3)$$

$\bar{\theta}$ and $\bar{\theta}_{sea}$ are the average and sea surface potential temperatures respectively, $\bar{q}$ is the average specific humidity, $\bar{q}_{sea}$ is the saturated specific humidity at the sea surface and $\bar{V}$ is the average horizontal velocity. Strictly speaking, the component of $\bar{V}$ in the direction of the surface stress should be used in (1). However, in view of the many uncertainties involved in these calculations, this correction, which is probably small, is ignored. Note that in our calculations the hurricane PBL was everywhere weakly unstable,

$$|RI_B| < 0.2 \text{ and } RI_B < 0. \quad (4)$$

This point will be discussed in more detail later. However, we can, at this point, exclude the mathematics relevant to the stable case and relevant to free convection.

The bulk momentum transfer coefficient is defined by

$$C_V = \frac{|V_*|}{|\bar{V}|} \quad (5)$$

and the bulk heat transfer coefficient by

$$C_0 = \frac{(-\bar{w}'\bar{\theta}_s)_{\bar{V}}}{|V_*|(\bar{\theta}_s - \bar{\theta}_{sea})} \quad (6)$$

where the numerator in (6) represents the eddy flux of virtual potential temperature at the “anemometer” level. (Following Deardorff (1972b), the “anemometer” level, $Z_a$, is defined by the expression $Z_a = 0.025Z_B$ and is the top of the surface layer.) The remaining equations
from Deardorff (1972b) of pertinence to our calculations are,

\[ C_V = \left[ C_{V_n}^{-1} - 25 \exp(0.26 \xi - 0.03 \xi^3) \right]^{-1}, \tag{7} \]

and

\[ C_0 = \left[ C_{0_n}^{-1} + C_V^{-1} - C_{V_n} \right]^{-1}, \tag{8} \]

where,

\[ \xi = \log_{10}(-RI_B) - 3.5 \quad \text{and} \quad RI_B < 0. \tag{9} \]

\( C_0 \) is the bulk heat transfer coefficient, \( C_{V_n} \) and \( C_{0_n} \) are the neutral values of the coefficients given by

\[ C_{V_n} = \left[ k^{-1} \log \left( \frac{0.025 Z_B}{Z_0} \right) + 8.4 \right]^{-1} \tag{10} \]

and

\[ C_{0_n} = \left[ k^{-1} R \log \left( \frac{0.025 Z_B}{Z_0} \right) + 7.3 \right]^{-1} \tag{11} \]

where \( k = 0.35 \) (Karman’s constant), \( R = 0.74 \), and \( Z_0 \) is the roughness length.

If \( Z_0 \) is known, equations (1) and (5–11) comprise a complete set for the variables \( RI_B \), \( |V_a| \), \( C_V \), \( C_0 \), \( (\omega' \Omega_a)' \), \( \xi \), \( C_{V_n} \) and \( C_{0_n} \). It should be noted that the transfer coefficients determined from the above procedure represent bulk layer estimates. We can extrapolate these estimates to the “anemometer” level by a straightforward application of Deardorff’s PBL deficit formulation as discussed below. The wind speed deficit formulation is given by

\[ \frac{|\hat{V}| - |V_a|}{|V_a|} = 8.4 \left[ 1 - \frac{50 Z_B}{L} \right]^{-0.16}, \quad (\omega' \Omega_a)' > 0 \tag{12} \]

where \( |V_a| \) is horizontal wind speed at the “anemometer” level and \( L \), the Monin-Obukhov length, is given by

\[ L = \frac{C_V Z_B}{k C_0 R I_B} \tag{13} \]

From (12) and (13) we can compute \( |V_a| \) and then evaluate the “anemometer” level momentum transfer coefficient via the expression

\[ C_{V_a} = \frac{|V_a|}{|V_a|}. \tag{14} \]

The “anemometer” level heat transfer coefficient is directly computed from the deficit formulation for the virtual potential temperature and is given by

\[ C_{0_a}^{-1} = \frac{|V_a| (\hat{\theta}_a - \theta_a)}{(\omega' \Omega_a)'}, \quad (\omega' \Omega_a)' > 0 \tag{15} \]

where \( \theta_a \) is the virtual potential temperature at the anemometer level.

\[ \text{FIG. 1. Track and central pressure evolution for Hurricane Daisy 1958.} \]

From the definition of \( |V_a| \), the surface stress, \( \tau_0 \), may be computed via the relation

\[ \tau_0 = \rho_0 |V_a| \tag{16} \]

where \( \rho_0 \) is the surface air density. Applying the bulk aerodynamic formulation, the “anemometer” level drag coefficient is given by

\[ C_{D_a} = \frac{\tau_0}{\rho_0 |V_a|^2}. \tag{17} \]

From (14), (16), and (17) it can be shown that the Deardorff (1972b) momentum transfer coefficient and the drag coefficient are related by the equation

\[ C_{D_a} = C_{V_a}^{-2}. \tag{18} \]

By similar reasoning, it can be shown that

\[ C_{H_a} = C_{V_a} C_{0_a} \tag{19} \]

where \( C_{H_a} \) is the “anemometer” level heat exchange coefficient.

The behavior of \( Z_0 \) over the oceans, especially at high wind speeds, is a controversial subject. From oceanic observations under nearly neutral conditions at the 10 m level, Wu (1969) composited values of the drag coefficient \( C_{V_a} \) for winds up to 30 m·s\(^{-1}\). His results showed that \( C_{V_a} \) (hence \( Z_0 \) for nearly neutral conditions) increased directly with wind speed up to 15 m·s\(^{-1}\) and was essentially constant thereafter. On the other hand, results from budget studies suggest a direct relationship...
between the wind speed and $C_v$ (and, therefore, $Z_0$ for the nearly neutral hurricane PBL) for the high wind speeds encountered in the hurricane.

Charnock (1955), from dimensional considerations, proposed that

$$Z_0 = a |V_*|^2 / g,$$  \hspace{1cm} (20)

where $a$ is an empirical constant. According to Kraus (1972), values of $a$ ranging from $8 \times 10^{-3}$ to $6 \times 10^{-2}$ have been estimated by different investigators. Cardone (1969) derived the expression

$$Z_0 = \frac{6.84 \times 10^{-5}}{|V_*|} + 4.28 \times 10^{-2} |V_*|^2 - 4.43 \times 10^{-3},$$  \hspace{1cm} (21)

from observations with winds ranging up to 20 m·s$^{-1}$. For the higher wind speeds, (13) gives values close to that obtained from (20) with $a = 0.035$. Kitagorodskii and Volkov (1965) found that Charnock's relation with $a = 0.035$ provided a best fit to data from laboratory experiments. In our computations, the system of (4), (5–11), and (21) is used to compute the surface exchange coefficients. The calculations become partially implicit, and the iterative procedure outlined in Appendix C is required. Several computations were made with constant values of $Z_0$. Since the results bore virtually no resemblance to those obtained from budget calculations, they are not presented here. On the other hand, as shown in the next section, good agreement with the budget studies is obtained when either (20) or (21) is used to estimate $Z_0$.

3. Results of PBL Computations

Daisy began to develop in the Bahamas on 23–24 August 1958, and attained hurricane strength on 26 August. By 27 August, the time from which we have extracted the data for this study, the surface winds reached their peak of approximately 100 kt and a central pressure of 947 mb (Colón and Staff, 1961). The track and central pressure for Daisy are shown by Fig. 1. Inez became a hurricane on 26 September 1966 about 500 n mi east of Antigua and attained maximum strength on 28 September, the day we have chosen to examine. Hurricane Inez was more intense than Daisy, with peak winds of approximately 120 kt and a central pressure of 927 mb (cf. Figs. 1 and 2).

Figure 3 illustrates the PBL depth as a function of the radius for both storms. The presence of smallest depths in the eyewall vicinity indicates relatively low cloud-bases. It is interesting to note that the PBL depths are generally less for the more intense Hurricane Inez.

Figure 4 compares the surface stresses obtained by Hawkins and Imbembo (1975) for Hurricane Inez with those obtained in this study. The agreement appears to be rather remarkable. For ease of interpretation, the remainder of the discussion will be in terms of the drag.
and heat exchange coefficients as defined in Section 2.

Tables 1 and 2 list the results obtained for the two hurricanes. In addition to the coefficients obtained from Deardorff's model, we have included estimates obtained from Deacon's equation (Roll, 1965),

$$C_{Da} = 1.1 \times 10^{-3} + 4 \times 10^{-3} |V_s|,$$

(22)

and from the equation suggested by Miller (1969),

$$C_{Da} = 10^{-3} + 7 \times 10^{-3} |V_s|.$$

(23)

Miller's equation is obtained from budget estimates for Hurricanes Donna (Miller, 1964), Helene (Miller, 1962), and Hilda (Hawkins and Rubsam, 1968).

At this point, we will limit our discussion to a comparison of the results obtained from Deardorff's method with those obtained from the budget studies. Note that the heat exchange coefficients obtained from Deardorff's model are 30–40% larger than the corresponding drag coefficients. This is an intrinsic property of the Deardorff scheme when the heat flux is from the ocean to the atmosphere (unstable PBL).

A cursory examination of Tables 1 and 2 indicates that there is reasonable agreement between Deardorff's method and the budget calculations. A more detailed examination of the data brings to light some very interesting points. We have already noted that the budget values for Daisy were obtained by Riehl and Malkus (1961) from the heat budget. Hawkins and Imbenbo (1975), on the other hand, obtained their drag coefficients for Inez from the budget of angular momentum. We may then ask whether, in the case of Daisy, the Deardorff heat transfer coefficients fit the budget values more closely than do the Deardorff drag coefficients and, in the case of Inez, whether the reverse is true.

For Daisy, the Deardorff drag coefficients are smaller than the budget coefficients. This result is consistent with Deardorff's model. However, the Deardorff heat transfer coefficients are larger than the values obtained.

### Table 1. Drag and heat exchange coefficients for Hurricane Daisy 1958.

| Radius from storm center (mi) | $|V_s|$ (m·s$^{-1}$) | $C_{Da}$ (10$^{-2}$) Riehl & Malkus | $C_{Da}$ (10$^{-2}$) Deardorff | $C_{Ha}$ (10$^{-2}$) Deacon | $C_{Da}$ (10$^{-2}$) Miller |
|-----------------------------|-------------------|----------------------------------|-------------------------------|--------------------------|--------------------------|
| 20                          | 29                | 2.4                              | 2.1                           | 2.9                      | 2.3                      | 3.0                      |
| 40                          | 22                | 1.9                              | 1.6                           | 2.2                      | 2.0                      | 2.5                      |
| 60                          | 18                | 1.8                              | 1.5                           | 1.9                      | 1.8                      | 2.3                      |
| 80                          | 16                | 1.6                              | 1.3                           | 1.8                      | 1.7                      | 2.1                      |
| Average                     | 21.3              | 1.9                              | 1.6                           | 2.2                      | 2.0                      | 2.5                      |
| Mean error                  |                   | -0.3                             | +0.3                          | +0.1                     | +0.6                     |
| Root mean square error      |                   | 0.3                              | 0.3                           | 0.1                      | 0.55                     |
| Standard deviation          | 5.09              | 0.3                              | 0.3                           | 0.4                      | 0.2                      | 0.3                      |
| Correlation coefficient with the wind | 0.97 | 0.99 |
from the heat budget. In the mean, the negative bias of the Deardorff drag coefficients is the same as the positive bias of the heat transfer coefficients. The root-mean-square error is the same for both of the Deardorff coefficients. Thus, for Hurricane Daisy, both of the Deardorff coefficients fit the budget values with about the same precision.

For Inez, however, the Deardorff drag coefficients provide a fit to the budget values that is clearly superior to that provided by the Deardorff heat transfer coefficients. This conclusion is supported by the average errors, the root-mean-square errors, and the individual values. In addition, the Deardorff heat transfer coefficients contain a clearly positive bias. If, for the moment, we assume that the budget values for Inez are relatively accurate, our computations indicate that Deardorff’s model, with a wind dependent roughness length, provides remarkably good exchange coefficient values.

As noted earlier, we were skeptical about the accuracy of the budget coefficients and also about the applicability of Deardorff’s model to hurricane situations. However, in view of the agreement between the two methods, particularly in the case of Inez, we now feel that we may have been overly pessimistic regarding both methods. The need for additional data and further comparisons is obvious.

In Section 2, we gave a brief summary of the controversy found in the literature relative to the wind dependence of the drag coefficient over the ocean. The budget coefficients shown in Tables 1 and 2 have a remarkably high correlation with the wind speed. Similar data have been obtained from other hurricanes (Summary, Hawkins and Rubsam, 1968). In agreement with budget calculations, the variability of the Deardorff coefficients is almost entirely dominated by the variability of wind. Evidence for this is given by the correlation coefficients listed in Tables 1 and 2.

| Radius from storm center (n mi) | $|V_0|$ (m·s$^{-1}$) | $C_{D_V}$ (10$^{-3}$) Hawkins & Imbenbo | $C_{D_V}$ (10$^{-3}$) Deardorff | $C_{D_A}$ (10$^{-3}$) Deacon | $C_{D_A}$ (10$^{-3}$) Miller |
|---|---|---|---|---|---|
| 10 | 48 | 4.5 | 4.0 | 5.8 | 3.0 |
| 20 | 36 | 2.6 | 2.8 | 3.8 | 2.6 |
| 30 | 29 | 2.1 | 2.1 | 2.7 | 2.2 |
| 40 | 26 | 2.0 | 1.9 | 2.5 | 2.1 |
| 50 | 23 | 1.3 | 1.7 | 2.3 | 2.0 |
| **Average** | 32.4 | 2.5 | 2.5 | 3.4 | 2.4 |
| **Mean error** | 0 | +0.9 | 0.1 | +0.7 |
| **Root mean square error** | 0.3 | 1.0 | 0.7 | 0.9 |
| **Standard deviation** | 9.08 | 1.1 | 0.8 | 1.3 | 0.4 |
| **Correlation coefficient with the wind** | 0.98 | 0.99 |

and Miller (23) corresponded to the drag coefficients obtained from the budget computations. Results are given in Tables 1 and 2. For Daisy, Deacon’s equation fits the budget values more closely than do any of the other calculations. Surprisingly, Miller’s equation provides the poorest fit of the three methods.

For Inez, Deacon’s method gives values that are too low at high wind speeds and too high at low wind speeds. Miller’s equation gives similar, but more extreme, results. Neither Deacon’s nor Miller’s equation fits the budget coefficients as well as Deardorff’s drag coefficients.

In summary, Deardorff’s model provides drag coefficients for Hurricane Inez that fit the values computed from the angular momentum budget remarkably well and substantially better than do values from either Deacon’s or Miller’s equation. For Hurricane Daisy, the results are less conclusive. Deacon’s equation provides the best fit to the coefficients obtained by Riehl and Malkus (1961) from the storm’s heat budget. Both Deardorff’s drag coefficients and heat exchange coefficients fit the budget values reasonably well. However, the former are somewhat too low (as is to be expected), while the latter are somewhat too high.

The magnitudes of the Monin-Obukhov lengths (Table 3) exceed the depths of the PBL (Fig. 3) in the inner core of both hurricanes. They are comparable to, but somewhat smaller than, the PBL depths at the

<table>
<thead>
<tr>
<th>Daisy 1958</th>
<th>Inez 1966</th>
</tr>
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<tbody>
<tr>
<td>Radius from storm center (n mi)</td>
<td>$</td>
</tr>
<tr>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>40</td>
<td>22</td>
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<tr>
<td>60</td>
<td>18</td>
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<td>80</td>
<td>16</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$-1104.25$</td>
</tr>
</tbody>
</table>
periphery of the two storms. Thus, close to the centers of these hurricanes, turbulence driven by forced mechanical mixing (due to wind shear) dominates over that driven by buoyant forces. At the larger radii, mechanically driven turbulence continues to make a substantial, if not dominant, contribution to the total turbulence.

With this strong contribution to the total budget of turbulent kinetic energy by mechanical effects, the very close correlations between drag coefficients and wind speeds that were cited above are not surprising. Furthermore, a rather interesting hurricane PBL property emerges from this chain of thought. Vast amounts of sensible and latent heat are transported from the ocean to the atmosphere in the inner regions of these storms. However, the intensity and structure of the turbulence is primarily determined by wind shear rather than by buoyancy forces. Thus, as noted earlier, the hurricane PBL may well be characterized as "weakly unstable."

4. Summary

Deardorff's (1972b) model of the PBL yields drag coefficients that agree remarkably well with those calculated from the angular momentum budget of Hurricane Inez, provided that Cardone's (1969) or Charnock's (1955) formula for the roughness length is used. Reasonable agreement is found between Deardorff's model and the drag coefficients computed from the heat budget of Hurricane Daisy. The results strongly indicate that further tests with Deardorff's model in hurricane conditions are warranted.

Acknowledgments. The writers thank Dr. Francis J. Merceret for a number of stimulating discussions on the subject, and Dr. Harry F. Hawkins for providing the data for Hurricane Inez.

APPENDIX A

Specific Bulk Hurricane Data Used in PBL Calculations (Tables A.1 and A.2)

APPENDIX B

Procedure for Computing the Pressure and Height at the Top of the PBL

The height of the LCL (top of the PBL) is estimated from the bulk data by the following iterative procedure: First, we guess the pressure ($p_B$) and the temperature ($T_B$) at the top of the PBL and compute tentative values of the moist static energy

$$ h_B = c_p T_B + g Z_B + L q_B, \quad (B.1) $$

mixing ratio of water vapor ($q_B$), and dry static energy

$$ S_B = c_p T_B + g Z_B. \quad (B.2) $$

Here, $L$ is the latent heat of vaporization and $c_p$ is the specific heat capacity at constant pressure, (the remaining symbols are defined in the main body of the text). If

<table>
<thead>
<tr>
<th>Variable</th>
<th>Radius (n mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea temperature (K)</td>
<td>301.1</td>
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<tr>
<td>Pressure (mb)</td>
<td>967.5</td>
</tr>
<tr>
<td>Wind speed (m·s⁻¹)</td>
<td>36.3</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>296.8</td>
</tr>
<tr>
<td>Mixing ratio (g·kg⁻¹)</td>
<td>18.3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>427</td>
</tr>
</tbody>
</table>

| Temperature (K) | 292.5 | 291.4 | 290.4 | 289.7 |
| Mixing ratio (g·kg⁻¹) | 15.3 | 14.4 | 13.5 | 13.0 |
| Height (m) | 1282 | 1367 | 1367 | 1453 |

$\rho_B$ is less than or equal to the pressure at the midpoint of the lowest layer at which the bulk data are available, ($\rho_B$), $h_B$, $S_B$, and $q_B$ are assigned the bulk values of the layer, because the static energies and specific humidities are considered to be invariant with height.

Table A.2 Bulk data for Hurricane Inez 1966.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Radius (n mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea temperature (K)</td>
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<tr>
<td>Pressure (mb)</td>
<td>965.0</td>
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<tr>
<td>Wind speed (m·s⁻¹)</td>
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</tr>
<tr>
<td>Temperature (K)</td>
<td>296.4</td>
</tr>
<tr>
<td>Mixing ratio (g·kg⁻¹)</td>
<td>18.1</td>
</tr>
<tr>
<td>Height (m)</td>
<td>298.5</td>
</tr>
</tbody>
</table>

| Temperature (K) | 291.8 | 290.4 | 290.0 | 289.8 | 289.6 |
| Mixing ratio (g·kg⁻¹) | 16.1 | 14.4 | 14.2 | 14.1 | 13.6 |
| Height (m) | 1090 | 1310 | 1370 | 1400 | 1409 |
in the mixed layer. If $p_B$ is greater than $p_B^0$, then $h_B$, $S_B$, and $q_B$ are estimated by linear extrapolation to $p_B$ using the bulk values of these variables in the lowest two layers. The techniques for estimating the static energies and specific humidity are schematically illustrated in Fig. B.1.

The second step is to determine the surface values of temperature and mixing ratio ($T_B$ and $q_B$). The surface temperature is obtained by assuming a dry adiabatic lapse rate from the LCL to the surface and the surface mixing ratio is simply assumed equal to $q_B$. Knowing $T_0$ and $q_0$, we reevaluate the PBL pressure by the relation

$$p_B = p_0 \left( \frac{T_B}{T_0} \right)^{c_p/R_d},$$

where $p_0$ is the surface pressure, $R_d$ the universal gas constant for dry air, and $T_B$ is now the temperature at $p_B$ for which the saturation mixing ratio at that level is equal to $q_0$. Thus, having obtained a new guess for $p_B$ (and $T_B$), we repeat the entire procedure until our convergence criterion on $p_B$ is satisfied. Once $p_B$ has been determined, we compute the height of the top of the PBL via the hydrostatic equation. The above procedure is schematically illustrated in Fig. B.2.

**APPENDIX C**

**Iterative Procedure to Compute Surface Fluxes**

Figure C.1 is a flow-chart of the iterative procedure for estimating the surface fluxes. Most of the information on this chart is discussed in the text. The first guess for the magnitude of the friction velocity, $|V_0|$, is obtained by applying Deacon's formula for the drag coefficient ($C_D^f$). Although we did not encounter any "stable" situations in our study, we include that possibility in the flow-chart to illustrate the flexibility of the procedure.
REFERENCES


