Thermodynamic and Flux Observations of the Tropical Cyclone Surface Layer

Alex M. Kowaleski and Jenni L. Evans[1]
The Pennsylvania State University, University Park, PA

1. INTRODUCTION

Understanding tropical cyclone (TC) intensity and the factors that govern it remain major challenges for forecasting these systems. While TC track forecast errors have decreased markedly in the last twenty-five years, intensity forecast errors have improved only slightly during this period (National Hurricane Center 2013). Improved understanding of the factors governing TC intensity is a first step toward improving TC intensity forecasts and so reducing societal vulnerability to these dangerous storms. As the surface layer is the source of the ocean-air energy exchange that powers the TC, the thermodynamic characteristics of this layer can substantially affect cyclone intensity.

According to Emanuel Potential Intensity (EPI) Theory (Emanuel 1986, 1988, 1995; Bister and Emanuel 2002), sea surface temperature (SST) and tropopause temperature matter most in determining the upper limit of TC intensity (wind speed and central pressure). EPI theory models a hurricane as a Carnot engine, in which entropy is acquired under the eyewall from latent and sensible heat fluxes, and exported at the much colder tropopause. This means that surface layer thermodynamic conditions outside the eyewall determine the maximum entropy increase from heat fluxes under the eyewall. The maximum entropy increase and tropopause temperature determine the eyewall wind speed at which energy production from fluxes balances frictional dissipation, and thus maximum TC intensity.

In EPI theory the TC boundary layer is idealized as radially isothermal outside the storm's radius of maximum winds (R_{MAX}). One R_{MAX} is assumed to be the outer edge of the eyewall and the environment is many R_{MAX} from the center. As air spirals inward, sensible heat fluxes are expected to balance adiabatic cooling from falling pressure. Relative humidity is assumed to remain at its environmental value outside R_{MAX}, as turbulent fluxes and dry air entrainment at the top of the boundary layer are expected to balance ocean-air moisture fluxes (Emanuel 1995). Thus, an inward-spiraling air parcel experiences no moisture increase from fluxes until it reaches 1 R_{MAX}. Inside 1 R_{MAX} (in the eyewall) ocean-air fluxes are expected to overwhelm dry air entrainment so that relative humidity increases rapidly. As a result, in the idealized EPI profile equivalent potential temperature (θ_e, a proxy for moist entropy) increases slowly with decreasing radius outside R_{MAX} due to falling pressure, but increases rapidly inside R_{MAX} due to latent and sensible heat fluxes combined with rapidly falling pressure. Because the maximum ocean-air energy flux at and inside R_{MAX} depends on conditions outside R_{MAX}, if the observed boundary layer differs substantially from EPI theory (for example, if the boundary layer is not isothermal), this will affect the maximum entropy input at R_{MAX}, and hence maximum TC intensity.

Here the fundamental EPI boundary layer assumptions are evaluated against a composite profile of hurricane observations. The goals of this study are to (i) diagnose the radial distributions of temperature, moisture, and θ_e (entropy) in the TC surface layer, and (ii) explore the radial distributions of sensible and latent heat fluxes and how these flux values vary with the calculation method used. In a companion paper, EPI values calculated with the observed boundary layer characteristics are compared to EPI values calculated using the idealized EPI boundary layer profile.

---

[1] Corresponding author address: Jenni Evans, Department of Meteorology, The Pennsylvania State University, 503 Walker Building, University Park, PA 16802.
E-mail: jle7@psu.edu

2. METHODOLOGY

Data are obtained from 88 time series of 38 Atlantic hurricanes that passed near a buoy or C-MAN station between 1995 and 2012. A total of 3871 observations are obtained; 3715 (85 time series) contain SST data for flux calculations. Observations inside the eye are excluded from the dataset. Data are also excluded if they are obtained after a landfall that caused the hurricane to weaken by more than 10 m s^{-1}.

Near-surface air pressure, temperature (T_a) and dew point temperature are obtained at each observation time. Temperatures are adjusted from their observed value to 10-meter temperatures using the dry adiabatic lapse rate (-0.0098K m^{-1}) and dew point temperatures are adjusted so that the temperature adjustment causes no change in relative humidity. Potential temperature (θ), specific humidity (q), relative humidity (RH), and equivalent potential temperature (θ_e) are calculated. The TC's position at each observation time is found by linearly interpolating between vortex data messages and/or best-track positions to the time when each observation was taken. In a small number of cases microwave satellite images are used to refine storm position. Then, the distance between the observation location and the TC's position is calculated for each observation.

Ocean-air fluxes are calculated for the 85 of 88 time series for which SST data are available. Fluxes are calculated using three methods. In the first method, the standard bulk formulas for sensible (H_{Sbulk}) and latent (H_{Lbulk}) heat exchange are used:

$$\mathrm{H_{S_{bulk}}} = \rho_a c_P C_H(\theta_{SST} - \theta)V_{10} \quad (1),$$

$$\mathrm{H_{L_{bulk}}} = \rho_a L_V C_E(q_{SST} - q)V_{10} \quad (2).$$

C_H and C_E, the coefficients of heat and moisture exchange, are set to a constant $1.2\text{x}10^{-3}$, consistent with the nearly constant values found at both low wind speeds and high-wind hurricane conditions (Zhang et al. 2008; Haus et al. 2010).

The second and third flux calculation methods use the formulas for interfacial and spray fluxes from Andreas et al. (2008) and Andreas (2010), with a formula for friction velocity from Andreas et al. (2012).[2] In these formulations, spray drops are lofted by the hurricane's winds, where they rapidly cool to their equilibrium temperature, causing a net enthalpy input into the air. In the Andreas et al. (2008) formulation, sensible (H_{Sspray}) and latent (H_{Lspray}) heat fluxes from spray are calculated as:

$$\mathrm{H_{S_{spray}}} = 3.92 \times 10^{-9}\rho_w c_w\left(SST - T_{EQ,100}\right) \qquad u_* < 0.148\ \mathrm{m\ s^{-1}} \quad (3),$$

$$\mathrm{H_{S_{spray}}} = 5.02 \times 10^{-6}{u_*}^{2.54}\rho_w c_w\left(SST - T_{EQ,100}\right) \quad u_* > 0.148\ \mathrm{m\ s^{-1}} \quad (4),$$

$$\mathrm{H_{L_{spray}}} = 1.76 \times 10^{-9}\rho_w L_V\left[1 - \left(\frac{r(\tau_f)}{50}\right)^3\right] \qquad u_* < 0.1358\ \mathrm{m\ s^{-1}} \quad (5),$$

$$\mathrm{H_{L_{spray}}} = 2.08 \times 10^{-7}{u_*}^{2.54}\rho_w L_V\left[1 - \left(\frac{r(\tau_f)}{50}\right)^3\right] \qquad u_* > 0.1358\ \mathrm{m\ s^{-1}} \quad (6),$$

---

[2] The full code for calculating fluxes using this method is available for free download, courtesy of Dr. Ed Andreas, at http://www.nwra.com/resumes/andreas/software.php

where $u_{*,}$ the friction velocity, is calculated from the neutral-stability 10-meter wind speed (Andreas et al. 2012). T_{EQ} is the equilibrium temperature of an evaporating droplet, with 100 ηm estimated as a representative size for spray droplets. The $r(\tau_f)$ term relates the time it takes for a droplet to fall to the ocean surface with the time it takes a droplet to evaporate (thorough descriptions are available in the full code).

In the Andreas (2010) formulation, total enthalpy from spray is calculated, rather than separate sensible and latent spray fluxes:

$$\mathrm{E_{spray}} = 6.84 \times 10^{-8} \rho_w c_w (\mathrm{SST} - \mathrm{T_{EQ,100}}) \quad u_* \; < 0.1435 \text{ m s}^{-1} \; (7),$$

$$\mathrm{E_{spray}} = 1.8 \times 10^{-5} {u_*}^{2.87} \rho_w c_w (\mathrm{SST} - \mathrm{T_{EQ,100}}) \; u_* \; > 0.1435 \text{ m s}^{-1} \; (8).$$

This total spray enthalpy flux can differ substantially from the sum of the sensible and latent heat fluxes from spray calculated using the Andreas et al. (2008) method, especially at high relative humidity values.

In both the Andreas et al. (2008) and Andreas (2010) flux formulations, interfacial sensible and latent heat fluxes are calculated as:

$$\mathrm{H_{S_{interfacial}}} = \rho_a c_P u_* T_* \; (9),$$

$$\mathrm{H_{L_{interfacial}}} = \rho_a L_V u_* q_* \; (10),$$

where T_* and q_* are the flux scales of sensible and latent heat fluxes.

After all thermodynamic and flux variables are calculated, radial profiles of each variable are compiled for a composite of the 88 hurricane events. Data are assigned to radial bins by (i) distance between the observation and the hurricane center, and by (ii) distance between the observation and the hurricane center divided by that hurricane's radius of maximum winds, obtained from the Tropical Cyclone Extended Best-Track ("R_{MAX} space").

3. RESULTS AND DISCUSSION

Near-surface air temperature (T_a) in the composite hurricane decreases between the environment and the TC core in both radial and R_{MAX} space (Fig. 1). Between 9.5 R_{MAX} and 1.5 R_{MAX} $T_{\underline{a}}$ decreases by 2.5 °C (from 28.0 °C to 25.5 °C). It then increases by 0.3 °C between 1.5 R_{MAX} and 0.4 R_{MAX}, though this increase is not statistically significant (95% confidence interval) and is not observed in radial space (Fig 1, left panel). This temperature profile is consistent with the observations of Cione, Black and Houston (2000; CBH00), though we observe slightly higher temperatures between 450 km and 150 km from the hurricane's center.

The R_{MAX} space profile of T_a derived for the composite hurricane differs from the radially isothermal boundary layer assumed in EPI theory; the observed T_a at 1 R_{MAX} averages over 2°C lower than environmental T_a. This indicates that in observed hurricanes the region beyond 1 R_{MAX} does not maintain the isothermal balance between adiabatic expansion and ocean-air sensible heat fluxes assumed in EPI theory. A lower temperature at R_{MAX} signifies greater ocean-air temperature disequilibrium under the eyewall, where the most important ocean-air energy exchanges occur. This lower temperature under the eyewall may lead to greater maximum sensible heat fluxes under the eyewall than predicted by EPI theory, and hence a higher potential intensity.

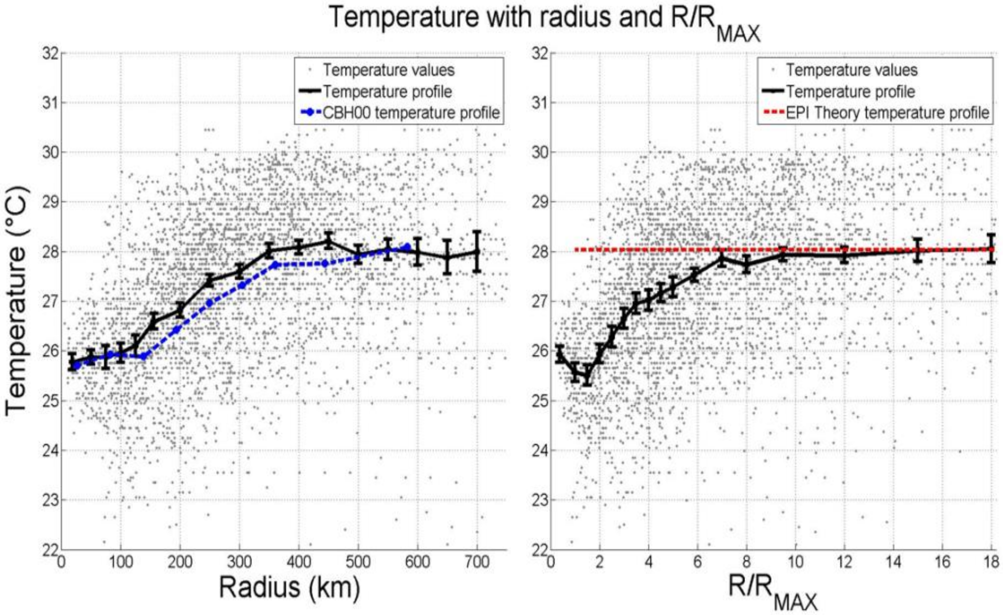

Figure 1: Near-surface air temperature (T_a) with radius and R/R_{MAX} in this study, CBH00, and the idealized EPI profile. Temperature decreases with decreasing radius between 7 R_{MAX} and 1.5 R_{MAX}, and increases slightly inside 1.5 R_{MAX}. This is substantially different from the idealized EPI temperature profile, which is radially constant outside R_{MAX}.

The composite hurricane's specific humidity is relatively constant outside 3 R_{MAX}, then increases by 0.7 g kg^{-1} (18.8 g kg^{-1} to 19.5 g kg^{-1}) between 3 R_{MAX} and 1 R_{MAX}, and by an additional 1.0 g kg^{-1} between 1 R_{MAX} and 0.4 R_{MAX} (Fig. 2, bottom right panel). Dew point, which unlike specific humidity, does not increase with decreasing pressure, shows a similar profile, indicating that the moisture increase outside 1 R_{MAX} is not simply due to pressure fall. Dew point increases from 24.0 °C at 3.5 R_{MAX} to 24.3 °C at 1.0 R_{MAX} and 24.9 °C at 0.4 R_{MAX} (Figure 2, top left panel). While the sharpest moisture increases occur inside 1 R_{MAX}, moisture begins to slowly increase with decreasing radius outside R_{MAX}, suggesting that important moisture (latent heat) fluxes occur beyond the eyewall.

Relative humidity in the composite hurricane increases with decreasing radius as far as 7 R_{MAX} (Fig. 2, top right panel). It rises from 79.6% at 7 R_{MAX} to 85.1% at 3 R_{MAX}, and then increases rapidly to a maximum of 94.2% at 0.4 R_{MAX}. However, the relative humidity increase between 7 R_{MAX} and 3 R_{MAX} is primarily due to a 1.2° C drop in T_a, not a moisture increase, as specific humidity at 3 R_{MAX} is slightly lower than at 7 R_{MAX}. Therefore, the relative humidity increase outside 3 R_{MAX} is primarily due to falling temperatures, not ocean-air moisture (latent heat) fluxes. Only inside 3 R_{MAX} do ocean-air moisture fluxes drive increasing relative humidity values.

Equivalent potential temperature decreases slightly with decreasing radius between 9.5 R_{MAX} and 3 R_{MAX} (356.9 K to 354.8 K; Fig. 3, bottom left panel), primarily due to falling temperatures (T_a decreases by 2.3 K in this range). Equivalent potential temperature increases by 2.4 K between 3 R_{MAX} and 1 R_{MAX}, and by an additional 4.8 K between 1 R_{MAX} and 0.4 R_{MAX}. These results confirm the θ_e profile found by CBH00, in which θ_e decreases slowly with decreasing radius far from the hurricane center, and increases rapidly near the center.

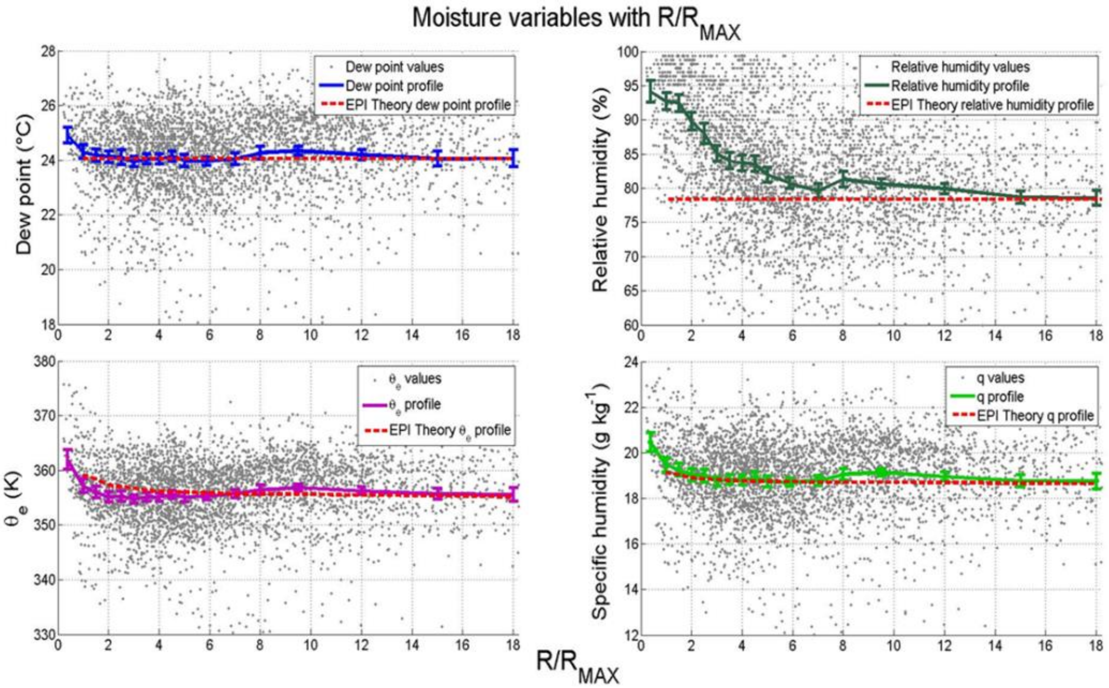

Figure 2: Dew point, relative humidity, equivalent potential temperature, and specific humidity with radius. Relative humidity begins to increase with decreasing radius far from the hurricane center due to decreasing temperature. The other quantities begin to increase with decreasing radius near 3 R_{MAX}, suggesting that ocean-air fluxes outside the eyewall contribute to total entropy input.

Bulk sensible and latent heat fluxes increase with decreasing radius. Total energy flux for the composite TC increases from about 230 W m^{-2} at 15 R_{MAX} to a maximum of 500 W m^{-2} at 1 R_{MAX}. However, it should be noted that binning the data by radial or R_{MAX} space inevitably leads to smearing of the most intense winds, reducing the maximum flux values calculated.

In the Andreas et al. (2008) flux formulation, in which latent and sensible spray fluxes are calculated separately, total fluxes are substantially higher than in the bulk flux formulation, especially at small radii. Total flux increases form 250 W m^{-2} at 15 R_{MAX} to 690 W m^{-2} at 1 R_{MAX}, and a maximum of 710 W m^{-2} at 0.4 R_{MAX} (Fig. 3, center panel). The larger flux increases in the Andreas et al. (2008) formulation arise from the non-linear effects of sea spray. As winds increase beyond tropical storm force (17.5 m s^{-1}), spray rapidly increases, causing greater ocean-air energy transfer. This results in greater flux increases with decreasing radius and the larger fluxes in the hurricane core (37% higher at 1 R_{MAX} than calculated using the bulk formulation).

The Andreas (2010) flux formulation, in which enthalpy flux from sea spray is calculated as a single quantity, gives even greater total fluxes than the Andreas et al. (2008) formulation. Total ocean-air heat flux is 990 W m^{-2} at 1 R_{MAX} and reaches a maximum of 1140 W m^{-2} at 0.4 R_{MAX}, 128% greater than the maximum bulk flux and 60% greater than the maximum Andreas et al. (2008) flux (Fig. 3, right panel).

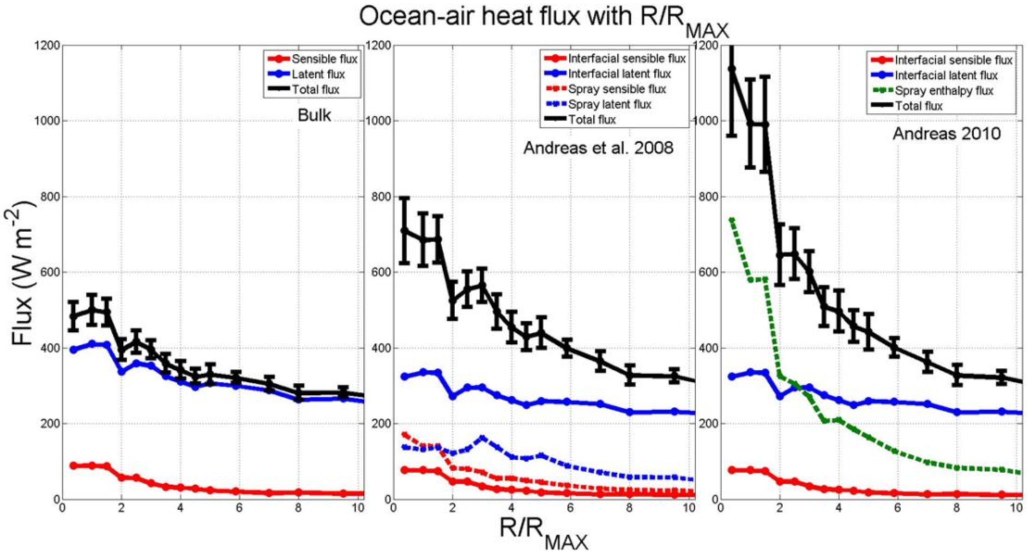

Figure 3: Ocean-air heat fluxes with radius produced by the bulk, Andreas et al. (2008) and Andreas (2010) formulations. Total ocean-air heat flux varies greatly among the three schemes chosen, with the Andreas (2010) formulation giving a total flux over twice as great as the bulk formulation and 60% higher than the Andreas et al. (2008) formulation at 1 R_{MAX}.

When the bulk formulation is used to calculate ocean-air fluxes, observationally-based near surface conditions yield a substantially higher total energy flux than the idealized boundary layer conditions of EPI theory (T_a and relative humidity constant at environmental values), especially near 1 R_{MAX} (520 W m^{-2} vs. 440 W m^{-2}; Fig. 4, left panel). The observationally-based conditions produce a higher total energy flux at small radii because of their much larger sensible heat flux due to the lower observed temperatures near the hurricane center.

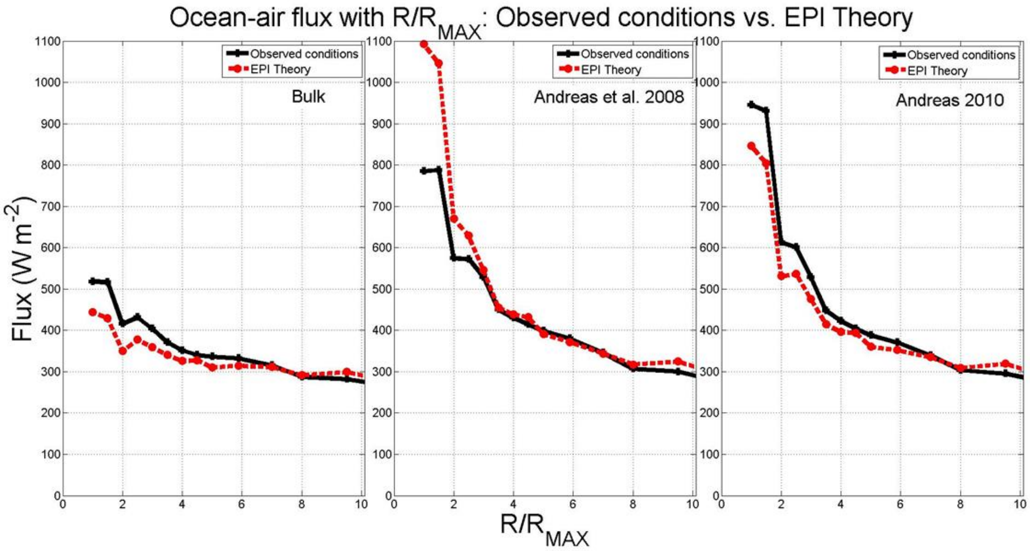

Figure 4: Total ocean-air heat fluxes calculated from each flux formulation and the observed conditions (solid) and idealized EPI conditions (dashed). Using the bulk formulation and Andreas (2010) formulation, observed conditions yield higher total fluxes at 1 R_{MAX}, but using the Andreas et al. (2008) formulation EPI conditions yield much higher total fluxes at 1 R_{MAX}.

Using the Andreas et al. (2008) method, in which sensible and latent heat flux from sea spray are calculated separately, the EPI-based conditions produces much higher total fluxes at 1 R_{MAX} than the observationally-based conditions (1040 W m^{-2} vs 770 W m^{-2}; Fig.4, middle panel). These higher total fluxes from EPI-based conditions are driven by the much higher latent heat flux from sea spray, a result of the constant relative humidity in the EPI boundary layer.

Using the Andreas (2010) formulation, in which enthalpy flux from spay is calculated as a single quantity, the observationally-based conditions produce higher total heat fluxes at 1 R_{MAX} than the EPI-based conditions (930 W m^{-2} vs 800 W m^{-2}; Fig. 4, right panel).

The method used to calculate ocean-air fluxes determines whether observationally-based near-surface conditions produce higher ocean-air energy fluxes than the idealized conditions of EPI theory. Nevertheless, these results suggest that observationally-based conditions may allow for greater energy input under the eyewall than EPI theory because of the lower observed temperatures there. This could cause higher calculated potential intensity values, a result explored in a companion paper.

4. REFERENCES

Andreas, E. L., 2010: Spray-mediated enthalpy flux to the atmosphere and salt flux to the ocean in high winds. *Journal of Physical Oceanography*, 40: 608-619.

Andreas, E. L., P. O. G. Persson, and J. E. Hare, 2008: A Bulk turbulent air-sea flux algorithm for high-wind, spray conditions. *Journal of Physical Oceanography*, 38: 1581-1596.

Andreas, E. L., L. Mahrt, and D. Vickers, 2012: A new drag relation for aerodynamically rough flow over the ocean. *Journal of the Atmospheric Sciences*, 69: 2520-2537.

Bister, M. and K. E. Emanuel, 2002: Low frequency variability of tropical cyclone potential intensity: 1. Interannual to interdecadal variability. *Journal of Geophysical Research-Atmospheres*, 107: 26-1-26-15.

Cione, J. G., P. G. Black, and S. H. Houston, 2000: Surface observations in the hurricane environment. *Monthly Weather Review*, 128: 1550-1561.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: steady-state maintenance. *Journal of the Atmospheric Sciences*, 43: 585-604.

Emanuel, K. A., 1988: The Maximum Intensity of Hurricanes. *Journal of the Atmospheric Sciences*, 45: 1143-1155.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *Journal of the Atmospheric Sciences*, 52: 3969-3976.

Haus, B. K., D. Jeong, M. A. Donelan, J. A. Zhang, and I. Savelyev, 2010: Relative rates of sea- air heat transfer and frictional drag in very high winds. *Geophysical Research Letters*, 37: L07802.

National Hurricane Center, cited 2013: National Hurricane Center Forecast Verification. [Available online at http://www.nhc.noaa.gov/verification/verify5.shtml].

Zhang, J. A., P. G. Black, J. R. French, and W. M. Drennan, 2008: First direct measurements of enthalpy flux in the hurricane boundary layer: The CBLAST results. *Geophysical Research Letters*, 35: L14813.