First direct measurements of enthalpy flux in the hurricane boundary layer: The CBLAST results

Jun A. Zhang,[1,2] Peter G. Black,[3,4] Jeffrey R. French,[5] and William M. Drennan[1]

Received 16 April 2008; revised 19 June 2008; accepted 26 June 2008; published 30 July 2008.

[1] Hurricanes extract energy from the warm ocean through enthalpy fluxes. As part of the Coupled Boundary Layer Air-Sea Transfer (CBLAST) experiment, flights were conducted to measure turbulent fluxes in the high-wind boundary layer of hurricanes. Here we present the first field observations of sensible heat and enthalpy flux for 10m wind speeds to 30 ms^{-1}. The analyses indicate no statistically significant dependence of these bulk exchange coefficients on wind speed. As a measure of hurricane development potential, we compute the mean ratio of the exchange coefficient for enthalpy to that for momentum and find it to be significantly below the lowest threshold estimated by previous investigators. This suggests that the enthalpy flux required for hurricane development may come from sources other than turbulent fluxes, such as lateral fluxes from the vortex warm core, or sea spray. Alternatively, it demands a re-evaluation of the theoretical models used to derive the threshold. **Citation:** 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, *Geophys. Res. Lett.*, *35*, L14813, doi:10.1029/2008GL034374.

1. Introduction

[2] The fluxes of enthalpy and momentum play a vital role in the development and maintenance of tropical cyclones. Theoretical study [*Emanuel*, 1986] and numerical experiments [*Ooyama*, 1969] suggest that the intensity of a hurricane depends strongly on the ratio of C_K/C_D, where C_K is the exchange coefficient of enthalpy flux and C_D is the exchange coefficient of momentum flux (also called drag coefficient). Results from numerical simulations using an axisymmetric tropical cyclone model [*Emanuel*, 1995] demonstrate that to achieve realistic intensity of the simulated hurricanes, the ratio C_K/C_D mostly lies in the range of 1.2–1.5 with C_K/C_D = 0.75 as a lowest bound to ensure model consistency.

[3] Typically the fluxes of momentum, sensible heat and enthalpy are directly given by:

$$\hat{\tau} = -\rho\left(\overline{u'w'}\hat{i} + \overline{v'w'}\hat{j}\right), \quad (1)$$

$$F_H = \rho c_p \overline{\theta' w'}, \quad (2)$$

$$F_K = \rho \overline{k'w'} = \rho c_p \overline{\theta' w'} + \rho L_v \overline{q' w'}, \quad (3)$$

respectively, where w', u', v', θ', q' and k' are the turbulent fluctuations of vertical velocity, horizontal along-wind and cross-wind velocities, potential temperature, specific humidity, and specific enthalpy, respectively. The air density is given by ρ, L_v is the latent heat of vaporization and c_p is the specific heat of air (at constant pressure). An overbar refers to time averaging over a suitable period. Note that specific enthalpy is the sum of the sensible heat and latent heat, in the form of $k = c_p\theta + L_v q$. In numerical models, the fluxes of momentum, sensible heat and enthalpy are usually parameterized in terms of the mean neutrally stable 10 m wind speed (U_{10N}), potential temperature at 10 m and surface (θ_{10N} and θ_0), and specific enthalpy at 10 m and sea surface (k_{10N} and k_0) through C_D, C_H and C_K, respectively, as follows:

$$\tau = \rho C_D U_{10N}^2, \quad (4)$$

$$F_H = \rho c_p C_H U_{10N}(\theta_0 - \theta_{10N}), \quad (5)$$

$$F_K = \rho C_K U_{10N}(k_0 - k_{10N}). \quad (6)$$

[4] Over the last several decades, much effort has been made to determine empirically the values of the momentum and heat exchange coefficients through measurements [*Large and Pond*, 1981, 1982; *DeCosmo et al.*, 1996; *Fairall et al.*, 2003], however, one clear limitation of the observational results for C_K and C_D is that few direct flux data are available for wind speeds over 20 m s^{-1}. *Drennan et al.* [2007] and *French et al.* [2007] review previous field and laboratory experiments of turbulent flux measurements including the recent results of *Powell et al.* [2003] and *Donelan et al.* [2004] showing C_D leveling off at wind speeds over 30 to 40 m s^{-1}. They also summarize the results of the first direct measurements of latent heat and momentum flux in high winds using the data collected during the ONR-sponsored Coupled Boundary Layer Air-Sea Transfer (CBLAST) hurricane experiment. Measurements of enthalpy

[1]Division of Applied Marine Physics, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA.
[2]Now at Hurricane Research Division, Atlantic Oceanographic and Meteorological Laboratory, National Oceanographic and Atmospheric Administration, Miami, Florida, USA.
[3]Hurricane Research Division, Atlantic Oceanographic and Meteorological Laboratory, National Oceanographic and Atmospheric Administration, Miami, Florida, USA.
[4]Now at Science Applications International Corporation, Monterey, California, USA.
[5]Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming, USA.

0094-8276/08/2008GL034374

flux are rarely reported, and it is usually assumed that $C_K = C_E$. This assumption is tested below.

[5] In this study, we extend the works by *Drennan et al.* [2007] and *French et al.* [2007] and report the first direct measurements of sensible heat and enthalpy fluxes in the high wind hurricane boundary layer. As part of the CBLAST experiment, data presented in this study were obtained from aircraft measurements within the boundary layers of Hurricanes Fabian and Isabel, 2003. A brief description of experiment and instrumentation is presented in the following section. In section 3 we present our results. A discussion and conclusions are given in section 4.

2. Description of the Experiment

[6] The goal of the CBLAST experiment is to provide new physical understanding that would improve model predictions of hurricane intensity and intensity change [*Black et al.*, 2007]. Major field campaigns were conducted during the Atlantic hurricane seasons of 2002, 2003, and 2004. As part of CBLAST, measurements within boundary layers of hurricanes were obtained by a specially instrumented NOAA WP-3D Orion aircraft. Low-level flight legs were used specifically to investigate turbulence and energy transport in the boundary layer. These legs consisted of along- and cross-wind stepped descents of around 30 km in length at altitudes as low as 60 m above the sea surface. Details of the flight patterns related to storm position and motion are discussed by *Drennan et al.* [2007] and *Black et al.* [2007].

[7] Precise measures of the three dimensional wind velocity are crucial for the direct measurements of turbulent fluxes using the eddy correlation method. In this study, the wind vector was measured using two independent systems: the first utilizes two Rosemount 858Y sensors mounted on the fuselage, and a second system utilizes a 9-hole "Best Aircraft Turbulent" (BAT) probe system installed at the end of a 2m boom in front of the nose. In both cases, the velocity data were corrected for aircraft motion (measured using an Inertial Navigation System and Global Positioning System, GPS) following *Lenschow* [1986]. Descriptions of the instrumentation, corrections and calibration are detailed by *French et al.* [2007].

[8] From equations 2 and 3, the turbulent fluctuations of specific enthalpy require precise measures of both potential temperature and water vapor. Fast response humidity data were obtained using a modified LICOR-7500 infrared gas analyzer installed in the radome [*Drennan et al.*, 2007]. Details of the system calibration, potential sources of error and comparison with other measurements of environmental moisture are given by *Drennan et al.* [2007]. Temperature data were measured using fast response Rosemount 102a temperature thermistors, as discussed by *Khelif et al.* [1999].

[9] Surface (10 m) wind speeds were determined through measurements made by the Stepped Frequency Microwave Radiometer (SFMR). The SFMR provides brightness temperatures that are strongly correlated with 10 m neutral wind speeds that have been calibrated against measurements from GPS dropsondes [*Uhlhorn et al.*, 2007]. Sea surface temperature (SST) was measured using a Barnes PRT-5 (Precision radiation thermometer) radiometer with corrections described by *Drennan et al.* [2007].

3. Results

[10] The enthalpy flux data presented herein are from measurements made during six flights in two storms in 2003. The flights occurred on September 2, 3, and 4 into Hurricane Fabian, and September 12, 13, and 14 into Hurricane Isabel. During all six flights the hurricanes were either category 4 or 5. A total of 37 suitable boundary layer flux runs from these storms were made for enthalpy flux computation following equation 3. Details of the criteria for flux run selection are given by *French et al.* [2007]. Five runs from *French et al.* [2007] were not used here as they were near the edge of the cold wake: SSTs measured below the aircraft were found to be significantly different from those in the flux footprint several kilometers upwind. For all of the flux runs passing the aforementioned quality control, leg-averaged mean flight level wind speeds vary from 21 m s^{-1} to 40 m s^{-1}. The 10 m neutral-stability wind speed, U_{10N}, varies from a minimum of roughly 17 m s^{-1} to a maximum of 30 m s^{-1}.

[11] Figure 1a shows vertical profiles of $\overline{\theta' w'}$ in the boundary layer, where each profile represents a stepped descent. Only profiles with four or more points are used. A statistical analysis of the profile slopes indicates that $\overline{\theta' w'}$ decreases with increasing height, in the similar manner as the *DeCosmo et al.* [1996] HEXOS aircraft data, and also those of *Nicholls and Readings* [1979]. In this study, a different linear regression for each stepped descent is used to obtain the surface sensible heat fluxes. Note that of the 6 stepped-descents, 3 suggest negative sensible heat flux at the surface. This is consistent with the observed air-sea temperature differences, as these three descents were conducted over the cold wake induced by the storm [*D'Asaro et al.*, 2007].

[12] Figure 1b shows vertical profiles of $\overline{k' w'}$ in the boundary layer where each profile represents a stepped descent. The mean and standard deviation of these regression slopes are calculated as -0.0001 ± 0.00033. A least-squares analysis indicates that, at 95% confidence, there is no significant height dependence of $\overline{k' w'}$ in the boundary layer. In the same way as the treatment of surface latent heat flux [*Drennan et al.*, 2007], the measured enthalpy flux is regarded as indicative of surface values.

[13] Ten meter potential temperature, θ_{10N}, and specific enthalpy, k_{10N}, are extrapolated from flight level measured mean values assuming logarithmic profiles following similar methods used by *Drennan et al.* [2007] for the 10m humidity computation. Potential temperature and specific enthalpy at the surface (θ_0 and k_0, respectively) are calculated using the corrected SST and the computed specific humidity assuming saturation at the surface.

[14] Figure 2 shows the 10 m neutral Stanton numbers, C_H, plotted as a function of U_{10N}. The mean value of the 37 points is $1.09 \pm 0.11 \times 10^{-3}$, showing 1 standard error. These results do not differ significantly from the HEXOS results with the mean of $C_H = 1.12 \times 10^{-3}$ [*DeCosmo et al.*, 1996]. A least squares analysis on the slope (t-test, with 95% confidence) shows that there is no dependence of the Stanton number on the surface wind speed.

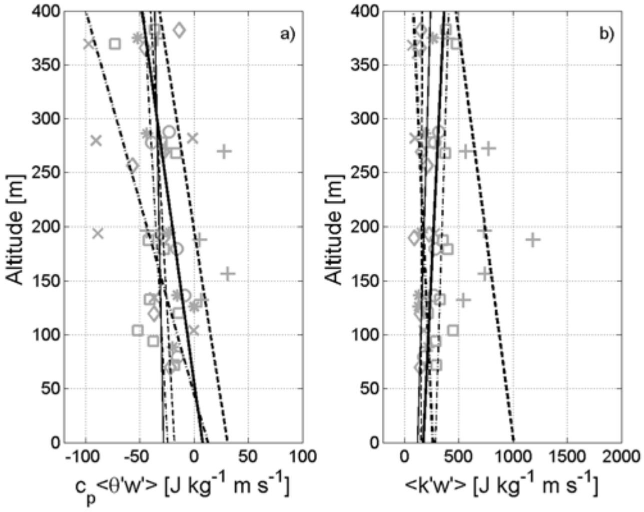

Figure 1. Plot of the (a) sensible heat and (b) enthalpy flux versus altitude z for CBLAST stepped descents. The symbols (lines) represent the different descents: September 02: circles (thick solid), 03: plusses (thick dashed), 04: crosses (thick dash-dotted), 12: asterisks (thin solid), 13: diamonds (thin dashed), 14: squares (thin dash-dotted).

[15] Figure 3 shows the CBLAST 10-m neutral exchange coefficients of enthalpy, C_K, versus wind speed. The mean value of the 37 points is $1.16 \pm 0.07 \times 10^{-3}$, showing 1 standard error. The HEXOS results are also shown. Here C_K from HEXOS are calculated based on the sensible and latent heat flux data. The mean value of the HEXOS data is $1.18 \pm 0.04 \times 10^{-3}$. Note that *Webb et al.* [1980] correction has been made for both CBLAST and HEXOS data. The small observed decrease in C_K with wind speed is not significant (at 95% confidence). Following the error analysis methods described by *Drennan et al.* [2007], the overall uncertainty of C_k is around 20%. That for C_H is approximately 5% higher due to uncertainties in radiometer SSTs, and the small magnitude of $|\theta_{10}-\theta_0|$, typically under 2K. A further analysis shows that, with 95% confidence, $C_H = C_E = C_K$ for these data.

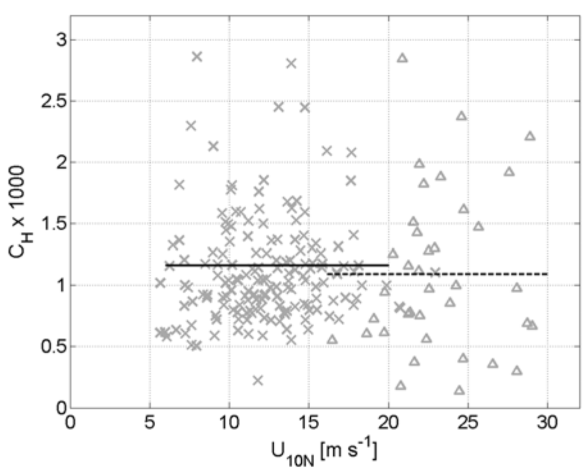

Figure 2. Plot of exchange coefficient of sensible heat versus wind speed, both neutral 10 m. The CBLAST data points and mean value are shown with triangles and dashed line, respectively. The HEXOS data [*DeCosmo et al.*, 1996] and mean value are shown with crosses and the solid line.

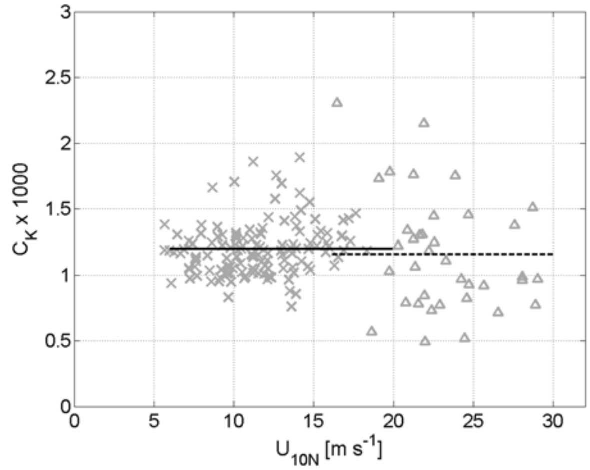

Figure 3. Plot of exchange coefficient of enthalpy versus wind speed, both neutral 10 m. The CBLAST data points and mean value are shown with triangles and dashed line, respectively. The HEXOS data [*DeCosmo et al.*, 1996], shown with crosses and the solid line, have been corrected according to *Fairall et al.* [2003].

4. Discussion and Conclusions

[16] In this study, we present the first-ever direct measurements of sensible heat and enthalpy flux within the atmospheric boundary layer of a hurricane. The CBLAST hurricane program has yielded an unprecedented data set for exploring the coupled atmosphere and ocean boundary layers during an active hurricane. The results presented

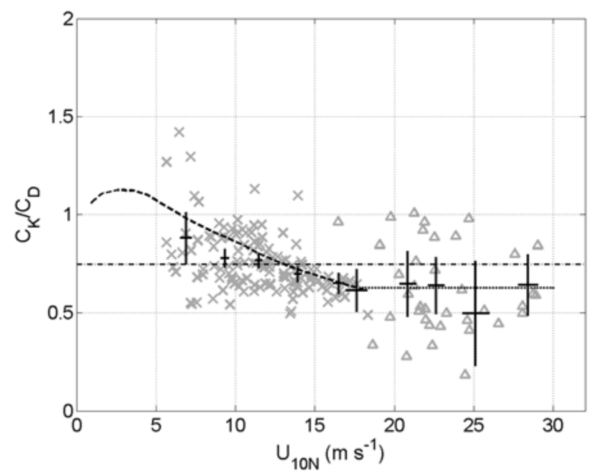

Figure 4. The ratio of C_K/C_D as a function of 10-m neutral wind speed. Data from CBLAST (triangles), and HEXOS (crosses) are shown. Solid black lines show the mean and 95% confidence intervals of the combined HEXOS and CBLAST field data after binning average by wind speed. The dotted black line shows the mean of the CBLAST data. The dashed line shows the ratio based on COARE 3.0 results. The dash-dotted line shows the threshold value of 0.75 suggested by *Emanuel* [1995].

herein extend the range of air-sea flux measurements significantly and allow enthalpy exchange coefficients to be estimated in wind speeds to nearly hurricane force.

[17] Results from this study are in good agreement with results from the earlier studies such as *DeCosmo et al.* [1996] and *Fairall et al.* [2003]. The exchange coefficient of enthalpy flux shows no significant dependence on wind speed up to hurricane force with a value of 0.00116. Figure 4 shows the ratio of C_K/C_D versus wind speed for the flux runs with both momentum and enthalpy flux measurements. Results of the momentum flux measurements of the same dataset used here are from *French et al.* [2007]. The average of the C_K/C_D values is 0.63, significantly below the 0.75 threshold for hurricane development suggested by *Emanuel* [1995], given the 20% uncertainty of C_k. This suggests that the enthalpy flux into the hurricane boundary layer required to initiate and sustain hurricane development may have to come from sources other than air-sea turbulent fluxes, or alternatively that the Emanuel model assumptions should be revisited.

[18] *Montgomery et al.* [2006] have shown that the entrainment from the higher entropy air inside the eye to the eyewall by enhanced frictional inflow and eyewall mesovortices could be an extra energy source to maintain a 'superintense' CAT 4 and 5 hurricane, if the ratio of C_K/C_D is less than the threshold of Emanuel. Recently, *Smith et al.* [2008] pointed out that a major deficiency of Emanuel's steady state model is using the assumption of gradient balance in the boundary layer. They also pointed out that the interactions between the eye and eyewall region through shear instability, and the energy entrainment processes from the top of the boundary layer in the outer region should be accounted for in hurricane intensity theory.

[19] At higher wind speed, sea spray becomes ubiquitous, which complicates the enthalpy transport at the air-sea interface and may result in different behavior of the exchange coefficients with increasing wind speed. Future efforts to improve our understanding of intensity theory for tropical cyclones will require quantitative estimates of the contributions of spray effects, dissipation heating and entrainment processes near the top of the boundary layer.

[20] **Acknowledgments.** This work is supported through the ONR (grant N00014-01-F-0090) CBLAST-Hurricane program and the NOAA OAR/USWRP program (NA17-RJ-1226) as well as through the NOAA/OAR laboratories AOML and ARL. The lead author also acknowledges support from the National Research Council's Research Associateship Program of The National Academies, administered in cooperation with NOAA/AOML.

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P. G. Black, Science Applications International Corporation, Monterey, CA 93940, USA.

W. M. Drennan, Division of Applied Marine Physics, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149-1098, USA. (wdrennan@rsmas.miami.edu)

J. R. French, Department of Atmospheric Science, University of Wyoming, Laramie, WY 82071, USA.

J. A. Zhang, Hurricane Research Division, Atlantic Oceanographic and Meteorological Laboratory, NOAA, 4301 Rickenbacker Causeway, Miami, FL 33149-1097, USA.