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MOMENTUM TRANPORT, DISSIPATIVE HEATING, AND TURBULENCE STRUCTURE IN THE SURFACE LAYER OF LANDFALLING HURRICANES

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1. INTRODUCTION

A handful of data sets of in-situ based wind measurements during hurricane landfalls have been collected over the past several hurricane seasons as part of the Florida Coastal Monitoring Program (FCMP). These observations provide unique and valuable data sets to explore the behavior of winds during hurricane landfall and quantify their respective characteristics. This particular study investigates the turbulent momentum transport, dissipative heating, and structure of turbulence in the surface layer of 3 landfalling hurricanes from the 2004 hurricane season. Using high-resolution tower observations we are able to estimate momentum fluxes in the surface layer, as well as drag coefficient (C_D), and dissipative heating (DH).

2. DATA AND METHODOLOGY

Data for this study was collected using a set of portable wind towers (PWTs) equipped with instrumentation to measure 3-D wind velocities at frequencies up to 10 Hz at heights of both 5 and 10 meters. The towers, designed to resist a 90 ms^{-1} wind gust, are deployed in the path of landfalling hurricanes. Here we analyze data collected from the landfalls of Hurricanes Frances (2004), Ivan (2004), and Jeanne (2004).

Momentum flux is calculated using an eddy correlation method,

$$\bar{\tau} = \rho(-\overline{w'u'}\,\hat{i} - \overline{w'v'}\,\hat{j}) . \qquad (1)$$

The surface C_D is calculated from the frictional velocity ($u_* = |\hat{\tau}|^{1/2}$) and 10-m wind speed, U^2,

$$C_D = u_*^2 / U^2 . \qquad (2)$$

During the FCMP, only one regular temperature sensor was installed at 3 m on each tower preventing us from computing heat flux and atmospheric stability directly. Therefore, in this study, we estimated the stability of the surface layer and the surface effective aerodynamic roughness by applying the Monin-Obukhov Similarity Theory,

$$\frac{\kappa u}{u_*} = \ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right), \qquad (3)$$

to the 5m and 10m wind observations, and based on the assumption of a constant surface flux layer, it yields,

$$\frac{\kappa(u_{10} - u_5)}{u_*} - \ln\left(\frac{z_{10}}{z_5}\right) = -\Psi_m\left(\frac{z_{10}}{L}\right) + \Psi_m\left(\frac{z_5}{L}\right) \qquad (4)$$

where Ψ_m is the stability function. The Monin-Obukhov length, L can be determined by solving Eqn. 4, and then the surface effective aerodynamic roughness, z_0 can be derived from Eqn. 3.

Lastly, DH is estimated via two methods, one by direct method integrating the dissipation rate of turbulent kinetic energy (TKE), (ε) over the surface layer,

$$DH = \rho \int_0^{Z_1} \varepsilon dz = \rho \bar{\varepsilon} z_1 \qquad (5)$$

where ε is estimated from turbulence spectra,

$$\varepsilon = \alpha_u^{-3/2} \frac{2\pi f}{U} [f S_{uu}(f)]^{3/2} . \qquad (6)$$

Another method for estimating DH utilizes a study done by Bister and Emanuel (1998), (hereafter is the BE formula) who parameterized DH as,

$$DH = \rho C_D U^3 . \qquad (7)$$

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Bister and Emanuel (1998) were first to point out the importance of DH to the maintenance and intensification of a hurricane. They argued that DH is a non-negligible source of energy for hurricanes and needs to be considered in hurricane simulations. The BE formula can be derived from Eqn. 5 assuming there exists a balance between the shear production ($u_*^3 / \kappa z$) and dissipation rate (ε) in the TKE budget in the surface layer.

3. RESULTS & DISCUSSION

Momentum fluxes are shown in Figure 1. It is clear that momentum flux increases with increasing wind speed, consistent with previous studies for low to moderate wind regimes over both land and ocean. However, the magnitude of the momentum flux in Figure 1 is larger than over ocean conditions, attributed to the larger surface roughness for over land conditions.

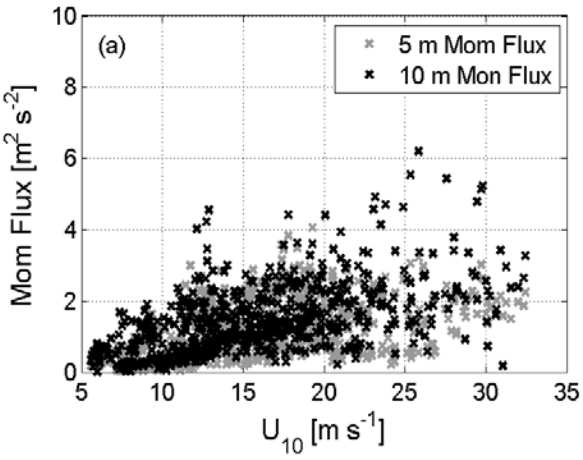

FIGURE 1. Plot of 5 and 10 meter momentum fluxes as a function of 10-m wind speed.

C_D vs. 10-m wind speed is plotted in Figure 2. The observed decrease in C_D with increasing wind speeds in the low to moderate wind speed range, and the leveling off of C_D at higher wind speeds is consistent with an analysis done by Mahrt et al. (2001). This behavior of C_D can be attributed to a decreasing role of viscous effects, and the increased roughness present in over-land conditions. The static surface roughness does not change with wind speed, but the effective aerodynamic roughness, z_0, will decrease due to the enhancement of streamlining of surface obstacles as wind speed increases.

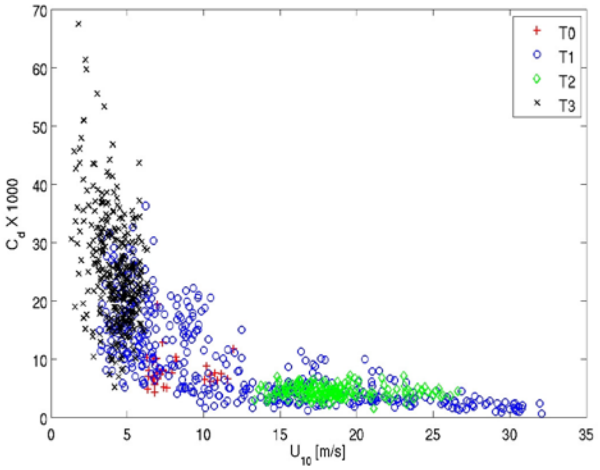

FIGURE 2. Plot of C_D vs. 10-m wind speed for the 4 towers deployed in Hurricane Ivan.

Further analysis of data collected during Hurricane Ivan shows that the effect of increased z_0 on C_D is offset by a change in atmospheric stability (estimated from Eqn. 4). As shown in Figure 3, before the eye of Ivan passed over tower T2, the surface layer was dominantly unstable, which enhanced the turbulent transport despite the small z_0. After the eye passes, the increased z_0 helped maintain the turbulent transport and thus the unchanged C_D, despite the evident near-neutral atmospheric stability.

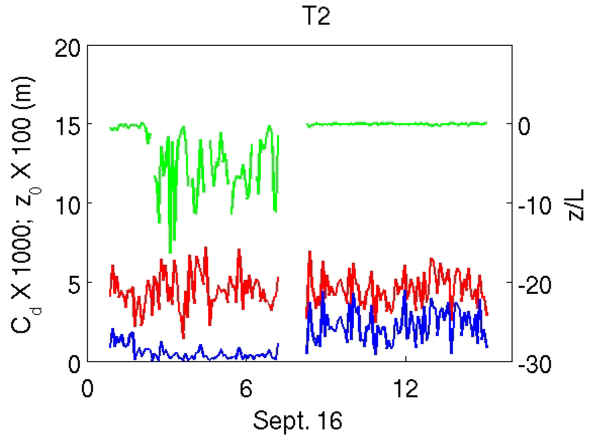

FIGURE 3. Time series of C_D (red), z_0 (blue), and the stability parameter $\frac{z}{L}$ (green) for tower T2 deployed in Hurricane Ivan.

Figure 3 suggests that atmospheric stability is an important factor to consider when estimating surface drag. In fact, the spread of C_D in Figure 2 can be partially attributed to different atmospheric stabilities. To isolate this effect, we categorized the data into different groups based on value of z_0. Figure 4 is a plot of C_D as a function of the stability parameter $\frac{z}{L}$ for different ranges of z_0. It clearly shows the dependence of C_D on atmospheric stability is very weak for small values of z_0, but strengthens as z_0 increases. These results strongly suggest that for heterogeneous coastal areas with a large static surface roughness, the effect of atmospheric stability on C_D needs to be considered in the parameterizations of surface drag.

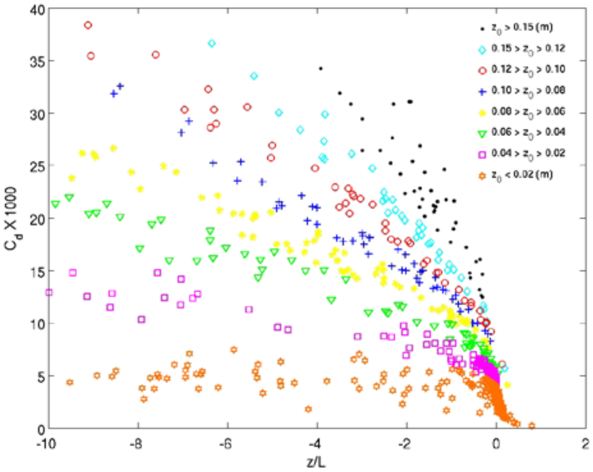

FIGURE 4. C_D as a function of the atmospheric stability parameter $\frac{z}{L}$ with different ranges of z_0 for all data collected in Hurricane Ivan.

DH is calculated using both the BE formula and the direct method. In the direct method we assume the dissipation of TKE, ε, to be constant with height, which agrees with previous studies showing that ε begins to decrease only above the surface layer (Zhang et al. 2009). Figure 5 shows DH estimated using both methods as a function of 10-m wind speed. There is a clear trend of increasing DH with increase in wind speed. Indisputably, higher wind velocities produce more heat because of the larger dissipation of TKE. When comparing the two methods, it is evident that the BE formula overestimates DH compared to the direct method. This (relative) overestimation is attributed to the BE formula being derived from the simplified TKE budget which assumes a balance between the shear production and dissipation rate. This balance suits near-homogeneous conditions, but oversimplifies the local TKE budget in hurricane conditions.

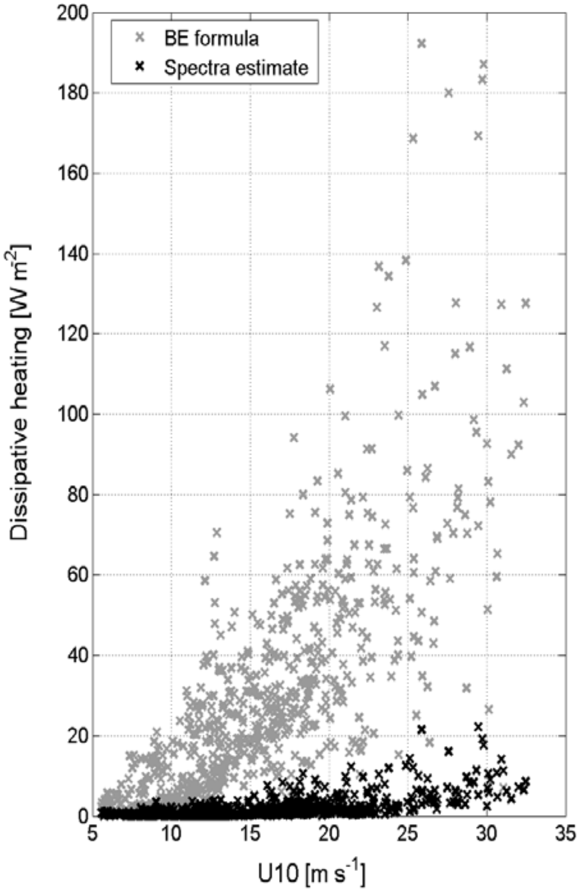

FIGURE 5. Plot of DH vs. 10-m wind speed for both the BE formula (gray) and direct method (black). It clearly shows the overestimation using the BE formula.

In order to confirm the (relative) overestimation of the BE formula, we computed the shear production and compared it to the dissipation rate estimated using the direct method (Figure 6.) It is evident that the shear production is substantially greater than the dissipation rate, especially for wind speeds greater than 10 ms^{-1}, thus providing one reason why the BE formula (derived from the simplified TKE budget) overestimates DH. Since turbulence in the surface layer of hurricanes is mostly shear-driven, and the boundary layer is typically under near-neutral stability (Drennan et al. 2007), we can assume the buoyancy term in the TKE budget to be of little contribution. Thus, it is presumed that other terms such as advection, pressure transport, and turbulent transport in the TKE budget are significant. We believe that the unsteady and inhomogeneous turbulent flow in the hurricane surface layer destroys the simplified TKE balance.

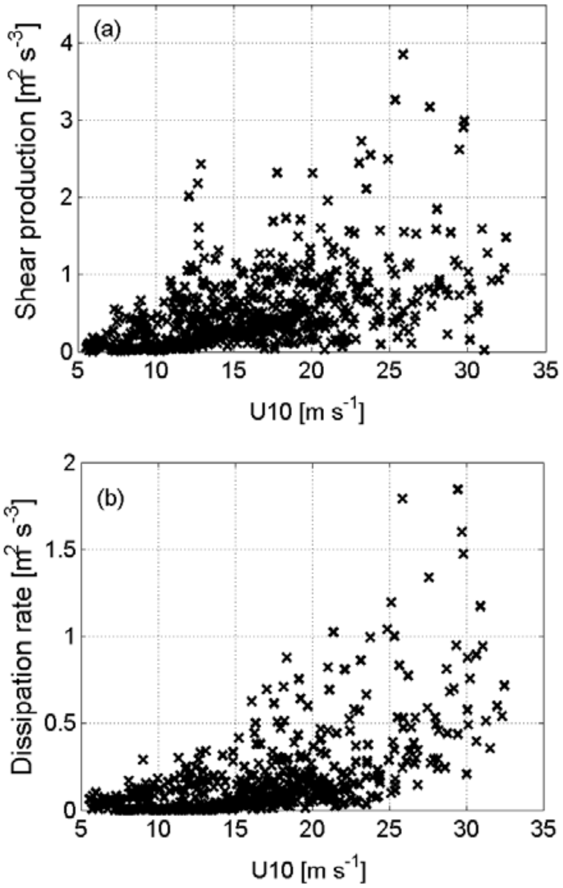

FIGURE 6. (a) Plot of shear production as a function of 10-m wind speed, (b) plot of dissipation rate as a function of 10-m wind speed.

4. FUTURE RESEARCH

This study and results derived from it are limited by the instrumentation that was used to collect the data from the tower deployments as part of the FCMP. In other words, the PWTs deployed in landfalling hurricanes up to the upcoming hurricane season were only equipped with wind sensors, or anemometers. Recently, upgrades have been made to one of the PWTs and we will now be able to collect high frequency temperature and humidity data. These instrumental improvements will allow us to look further into the moisture and buoyancy variables related to turbulence fluxes. We will be able to estimate the buoyancy production term in the TKE budget, analyze the (true) effect of stability on C_D, and determine the bulk transfer coefficients for heat and moisture (C_H and C_Q).

5. REFERENCES

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