7C.1 EVALUATION AND CONTINUED IMPROVEMENTS TO THE TOGA COARE 3.0 ALGORITHM USING CBLAST DATA

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1. INTRODUCTION

The transfer of momentum, heat, and water vapor across the sea surface couples the atmosphere with the ocean. From an atmospheric perspective, the transfer of heat and water vapor from the ocean to the atmosphere represents the energy that drives the atmospheric engine. In turn, the momentum exchange from atmosphere to ocean drives waves and currents and removing energy from the atmosphere. This exchange is a key component of the boundary conditions imposed in numerical formula. Therefore, to improve marine forecasts and coupled atmosphere-ocean models, we need to improve our understanding of these physical processes and the way they are simulated in these models.

The boundary conditions between the ocean and atmospheric models are often provided by parameterizations based on the bulk aerodynamic method. The bulk aerodynamic method is also the most widely used approach to estimate the fluxes from time series estimates over the ocean. This abstract describes ongoing efforts to improve parameterizations to estimate momentum and heat fluxes using data collected during the Coupled Boundary Layers and Air-Sea Transfer (CBLAST) experiments. Topics of interests include a discussion of wind-wave-swell interaction at low winds, equilibrium seas at high winds, and heat and moisture exchange in stratified conditions.

2. SURFACE FLUXES

There are three basic methods for obtaining time series of the air-sea fluxes: the direct covariance, bulk aerodynamic, and inertial-dissipation methods. The most direct estimate of the flux is the direct covariance (DC) method where the correlation between the turbulence fluctuations provides an estimate of the ensemble-averaged flux. The inertial dissipation method (ID) uses high frequency turbulence measurements of velocity, temperature, and humidity to estimate the scaling parameters from the corresponding dissipation estimates and empirical formula (Edson and Fairall, 1998). The bulk aerodynamic (BA) method estimates the fluxes using mean surface variables together with empirical formulae for the transfer coefficients. The empirical formulae for both the ID and BA methods are derived ideally from DC fluxes and mean profiles (e.g., Businger, 1988; Vickers and Mahrt, 1999; Edson *et al*., 2004).

The bulk aerodynamic formula parameterize the sensible heat, latent heat, and momentum fluxes in terms of the more easily measured mean or bulk quantities and are expressed:

$$Q_h = \rho c_p C_H S(T_s - \theta) \quad \textbf{(1)}$$

$$Q_e = \rho L_e C_E S(q_s - q) \quad \textbf{(2)}$$

$$\tau_i = \rho C_D S(u_{si} - u_i) \quad \textbf{(3)}$$

where θ, q, u_i and S are the average potential temperature, specific humidity, horizontal wind velocity in the i th direction, and instantaneous wind speed, respectively, at some height z; s denotes their surface values and $C_H, C_E,$ and C_D are the transfer coefficients for sensible heat (i.e. the Stanton number), latent heat (i.e. the Dalton number), and momentum (i.e. the drag coefficient) respectively. Therefore, estimates of heat, moisture, and momentum fluxes using the BA method require accurate measurements of wind velocity, surface currents,

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air temperature, sea surface temperature, barometric pressure, sea surface salinity, and relative humidity. The transfer coefficients have been shown to vary with height, stability, wind speed, and sea state (e.g., Fairall *et al.*, 1996, 2003; Donelan *et al.*, 1993; Grachev et al., 2003). Parameterizations that attempt to account for sea-state require additional measurement of surface waves.

Even if these measurements are available, the transfer coefficients or transfer velocities governing heat, mass and momentum exchange have large uncertainties, and the degree of uncertainty depends on the regime of interest. Information about the transfer coefficients at very high and extreme winds speeds is almost nonexistence due to the lack of direct flux estimates under these conditions.

To illustrate this point, the ratio of directly measured heat-exchange coefficients to drag coefficients from a decade of field observations in the 1990's is shown in Figure 1. Although a few momentum flux measurements have been made at wind speeds above 20 m/s, this figure provides a reasonable representation of the state of the science; i.e., there is little information about air-sea exchange in severe storms and no direct surface-layer measurements in tropical storms and hurricanes. The figure also illustrates the large uncertainties still exist below 20 m/s, primarily due to the difficulties associated with measuring the scalar coefficients (heat in this case) in all wind conditions and momentum flux at low wind conditions.

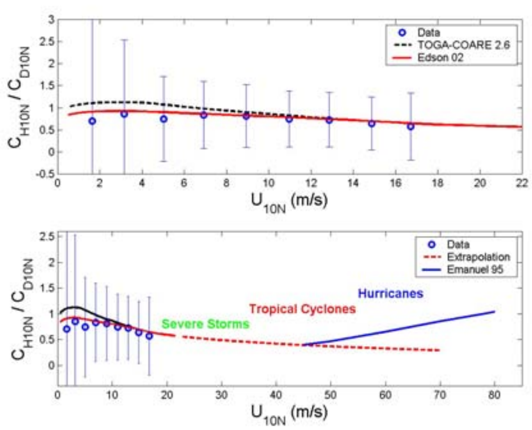

Figure 1. Ratio of the Transfer Coefficient for Heat to Drag Coefficient as a function of wind speed. The symbols represent bin-averaged data from a number of field experiments. The lines represent predictions from BA formula.

This represents a real impediment to accurately forecasting storm intensity, the surface wave field, the evolution of the upper ocean, and the feedback between the two boundary layers. In fact, numerical modelers have shown that extrapolation of current parameterizations (the broken red line) do not allow the formation of hurricanes due to too much drag and/or too little fuel exchange, and have postulated parameterizations like that shown in blue.

2. CBLAST

A major Office of Naval Research (ONR) sponsored investigation of the coupled ocean-atmosphere dynamics was conducted during the Coupled Boundary Layer and Air-Sea Transfer (CBLAST) program. The goal of the CBLAST program was to look at two extremes of the marine environment where coupled ocean processes have a clear impact on the response of both boundary layers. At one extreme, investigators in the CBLAST-Hurricane component are attempting to improve the long recognized shortcomings in hurricane intensity forecast and improve our understanding of OBL response under these extreme conditions. CBLAST-Low was designed to investigate coupled boundary layer processes at the low-wind extreme where the processes may be driven or strongly modulated by thermal forcing in the near-surface ocean and lower atmosphere. Little work has been done to explore air-sea interaction and upper ocean dynamics in very light winds, and few observations are available that describe the mesoscale and smaller scale horizontal variability of the upper ocean and lower atmosphere in such conditions.

2.1 CBLAST-Low

CBLAST-Low data are being used to investigate the relationship between the momentum, sensible heat, and latent heat fluxes and their associated mean profiles of velocity, potential temperature, and moisture, respectively. These investigations examine the validity of MO similarity theory as well as the departure from MOS due to the influence of the underlying wave field and other surface layer phenomena such as fog.

The investigations reported here rely on measurements made at the Air-Sea Interaction Tower (ASIT) built for CBLAST-Low. The ASIT is located 3.2 km south of Martha's Vineyard in the Atlantic and is directly cabled to shore via the Martha's Vineyard Coastal Observatory (MVCO).

The ASIT was specifically designed to provide a low profile, fixed structure to minimize the adverse effects of flow distortion and remove the need for motion correction.

The air-side components deployed during the 2003 CBLAST-LOW IOP are shown in Fig. 1 and include sensor to measure wind velocity, air temperature, water vapor, precipitation, solar and infrared radiation, pressure, sea surface temperature, and wave height. A wide range of oceanographic sensors was deployed beneath the surface on the ASIT as well as on the ocean bottom. These sensors measured ocean currents, waves, penetrating solar radiation, salinity, and temperature.

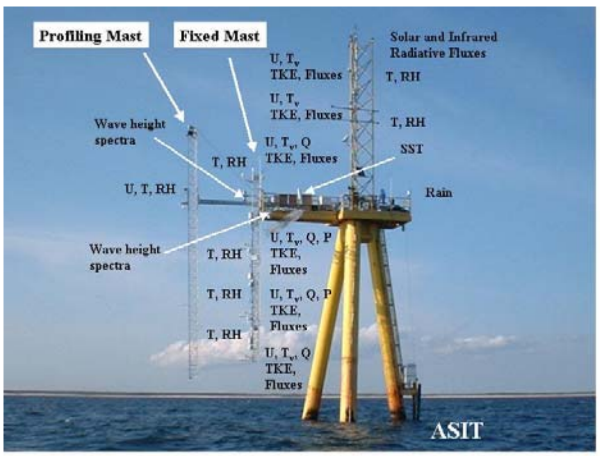

Figure 2. Experiment setup for the ASIT during CBLAST. The photo indicates where variables where measured on the met tower, fixed array, and profiling mast. The solar and infrared radiometers where measured 22-m above mean sea level.

Turbulence sensors were deployed at 6 levels to directly measure the fluxes of momentum, kinetic energy, temperature variance and sensible heat. The lowest 4 levels included sensors to measure the moisture variance and latent heat flux, while 2 levels were instrumented to measure the static pressure flux. A separate mast was deployed to support a moving package that measured the mean profiles of velocity, temperature and humidity.

2.2 CBLAST-Hurricane

Similar studies at extreme wind speeds are being conducted in CBLAST-Hurricane. The investigations reported here rely on a combination of airborne measurements in hurricanes and laboratory simulations. The airborne studies described in these proceedings include estimations of fluxes from budget evaluations of dropsondes near hurricane eyewalls (Emanuel) and direct covariance flux observations at low levels (100’s m) in clear areas between rainbands (Drennan and French). The airborne campaigns have also included measurements of water droplets using two different technologies (Fairall and Asher); here the goal is to obtain information on sea spray production. The University of Miami (Donelan) has done laboratory studies to examine the effective drag and moisture transfer coefficients at laboratory wind speeds that translate to equivalent to hurricane speeds. A second laboratory study was done in the wind-water tunnel in Australia (Banner, Asher, Fairall) where profiles of spray droplets were examined as a function of forcing.

3. BULK AERODYANIC FLUXES

The overall goal of CBLAST was to make observations over a wide range of environmental conditions that would be combined with numerical modeling and simulations to improve our understanding of upper-ocean and lower atmosphere dynamics. The uncertainty in the determination of the momentum and scalar fluxes remains one of the main obstacles to accurate marine forecasts particularly in coastal regimes and hurricane intensity forecasts.

A primary goal in the development of the TOGA-COARE bulk algorithm is to reduce the uncertainty of bulk flux estimates in all wind and stability conditions. The algorithm described by Fairall *et al*. (1996) was originally designed to provide accurate flux estimates in the tropical Pacific, i.e., a low-wind convective regime. The algorithm has since been modified to improve its performance in stratified conditions and at higher wind speeds between 10-20 m/s (Fairall *et al*., 2003).

3.1 CBLAST-Low

The drag coefficients computed from the CBLAST-LOW data set show very good agreement with the COARE 3.0 parameterization (Fig. 3). While there is some disagreement between the data and the parameterization at the highest wind speed (likely due to coastal/shoaling wave effects), the most significant disagreement is found at the lowest wind speeds. At these lower wind speeds naturally occurring variability and sampling problems cause uncertainty in the direct covariance flux measurements.

For example, use of conventional averaging times of 10 to 30 minutes to define the turbulent fluctuations in very weak turbulence often inadvertently includes mesoscale motions in the calculated flux. These mesoscale fluxes can be larger than the turbulence flux and are typically random and unrelated to the local wind shear or stratification. However, the flux calculation of Vickers and Mahrt (2005a) method carefully removes such mesoscale contributions to the flux. This approach is being implemented on the ASIT data to remove this bias.

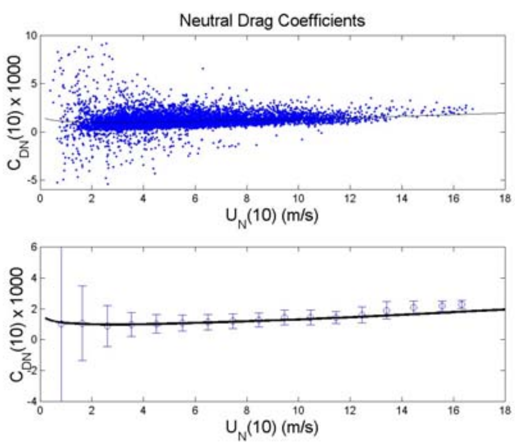

Figure 3. Individual and bin-averaged drag coefficient estimates. The black line is the TC3.0 parameterization.

In near-collapsed turbulence, the TC3.0 bulk model prediction of the momentum flux exceeds the observed momentum flux by a factor of ten for Long-EZ data and a factor of two for the ASIT data (Vickers and Mahrt, 2005b). The bulk model generally fails to predict the fluxes for near-collapsed cases observed by both the tower and the aircraft possibly due to wave state effects not included in the bulk model. For example, for conditions with weak wind following faster moving swell, the wind stress may be reduced relative to the bulk prediction. Recent investigations using the Long-EZ data are reported by Sun *et al*. and Vickers *et al*. in these proceedings.

Additionally, a number of recent studies by Sullivan *et al*. (2004) have indicated that some of this scatter is driven by stress-swell interaction over a range of stability conditions. The LES results clearly shown that fast moving swell in light winds can have a significant effect on the wind profile up to heights of O(10m). These conditions are known as old seas and are commonly found over the ocean whenever waves, generated non-locally, propagate into a low wind region or whenever local seas slowly decay as a storm moves out of the region. The former conditions were commonly observed during the CBLAST experiments.

We have begun to investigate these processes using the ASIT data to examine the vertical structure of the turbulence in the surface layer. A logical starting point for investigations of wind-wave coupling is to look for departure from law-of-the-wall scaling such as the dimensionless shear:

$$\phi_m\left(\frac{z}{L}\right) = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z} \qquad \textbf{(4)}$$

where κ is von Karman's constant, z is the height above mean sea level, u_* is the friction velocity, U is the mean wind speed, L is the MO length, and ϕ_m is the dimensionless shear.

The dimensionless function used in the TC3.0 algorithm is compared against measurements in Fig. 4. The ASIT data is in good agreement with this function in the mean, and gives a value of the von Karman's constant that is in good agreement with the canonical value of 0.4. The good agreement with the mean with "Kansas-like" functions is not overly surprising given the success of bulk formula in estimating the surface stress over a wide variety of conditions. However, our objective is to use the CBLAST data to move beyond MO similarity theory and begin to explain the departure from the mean in terms of sea state related variables.

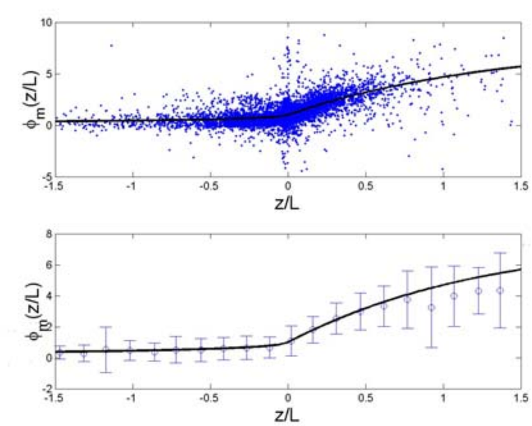

Figure 4. The dimensionless shear plotted versus the stability parameter z/L. The top panel plots individual estimates computed over 20 minute intervals while the bottom panel plots bin-averaged values.

Our initial attempts to investigate the cause for these low values have been aided by the Large-Eddy Simulations of Sullivan *et al* (2004). The LES models decaying wave conditions where the phase speed of the waves (i.e., swell) is moving faster than the wind. Appropriate boundary conditions are applied to correctly simulate energy and momentum exchange at the surface and thereby its effect on the overlying atmosphere. LES profiles of mean and turbulent variables show significant differences compared with classical boundary layers and flow over hills (i.e., stationary waves).

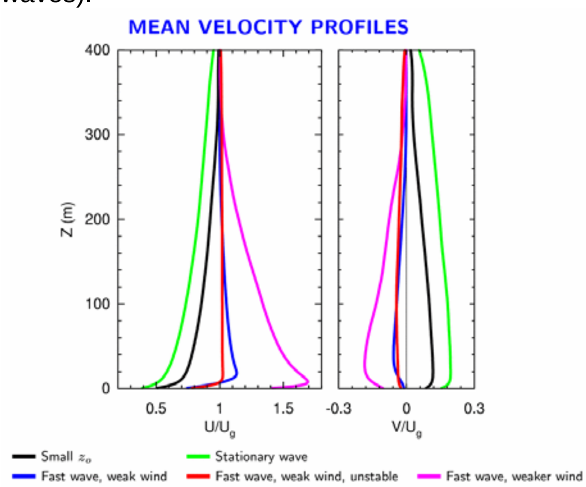

Figure 5. Profiles of horizontal velocity components normalized by their geostrophic values from LES over a variety of surfaces. The blue, red and magenta profiles simulate conditions over swell.

The LES suggests that this is a result of a wave-induced momentum flux divergence that accelerates the flow and a retarding pressure gradient, i.e., opposite to the momentum balance in classical boundary layers. Under these conditions, we observe positive upward momentum flux and low-level jets, signatures of wave driven winds as shown in Fig. 5. The LES is supported by the observations that provide clear evidence that variability in the drag coefficients at low winds is explained, in part, by the stress-swell interaction. The initial investigation is limited to periods when the direction of the wind and dominant waves were within 25^{o} of each other and binned averaged by a wave age parameter c_p / U_{10}, where c_p is the phase speed of the dominant waves.

Using this definition, previous studies have shown that fully developed, or mature, seas have a wave age of approximately 1.2. Developing, or young, seas have a smaller value, while decaying, old, seas have a larger value. As shown in Fig. 6, the bin-averaged profiles all depart from their MO similarity predictions as they approach the surface. The oldest wave show a velocity surplus while the youngest sea show a velocity deficit. Additional details about these ongoing investigations are provided by Sullivan *et al*. in these proceedings.

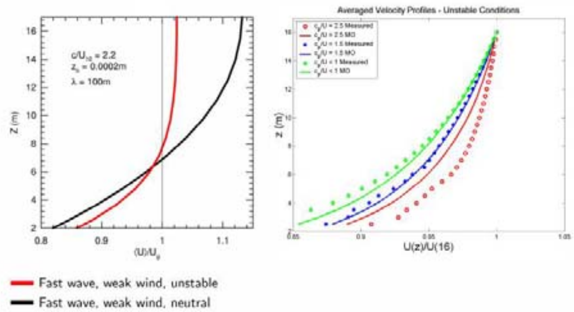

Figure 6. The left panel shows results from two of the LES runs for winds over swell in unstable and neutral conditions. The right panel shows measured and MO predicted velocity profiles average over 3 wave age classes denoting young, mature, and old seas.

The uncertainty in the determination of the scalar fluxes remains an obstacle to accurately numerical forecasts in low to moderate wind conditions. For example, latent heat fluxes computed from data using direct covariance and bulk aerodynamic methods show that there is good agreement in unstable conditions when the latent heat flux values are generally positive. However, the agreement is relatively poor in stable conditions, particularly when the moisture flux is directed downward. If the direct covariance measurements are accurate, then they clearly indicate that the bulk aerodynamic formula overestimate the downward moisture flux in stable conditions as shown in Fig. 7.

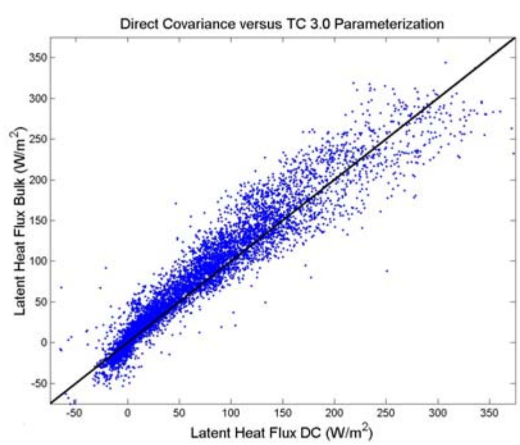

Figure 7. Comparison of direct covariance versus bulk aerodynamic fluxes measured from ASIT.

As a result, comparisons of the Dalton number for unstable and stable conditions indicate a marked difference in value between the two stability regimes. The individual estimates show reasonable agreement with the TC3.0 parameterization in unstable conditions as shown in Fig. 8. However, our investigations have found that Dalton numbers computed in stable, foggy conditions are substantially lower than the TC3.0 algorithm. The stable data are still slightly lower than the TC3.0 algorithm parameterization even after removal of the foggy periods (Fig. 8).

To investigate the cause for these differences, we begin with our definition of the neutral value of the Dalton number:

$$C_{EN} = C_{DN}^{1/2} C_{QN}^{1/2} = C_{DN}^{1/2} \frac{\alpha\kappa}{\ln(z/z_{oq})} \qquad \textbf{(5)}$$

where α accounts for differences in the scalar and velocity von Karman's constant, and z_{oq} is the thermal roughness length for humidity. The neutral value of the Dalton number is related to the measured value through

$$C_{QN}^{1/2} = C_{Q}^{1/2} \Big/ \left(1 + \frac{C_Q^{1/2}}{\alpha\kappa} \psi_q (z/L) \right) \qquad \textbf{(6)}$$

where C_Q is determined from measurements using Eqs. 2 and 3 and ψ_q is dimensionless profile function that corrects for stability affects. This points out that the neutral value of the Dalton should depend only on the scalar roughness length.

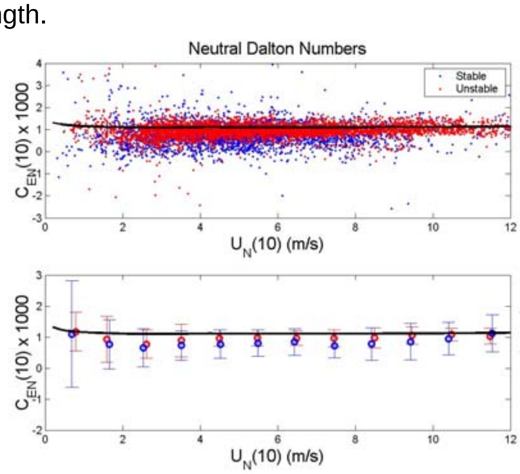

Figure 8. Dalton numbers calculated in the absence of fog. The upper panel plots the individual points where red and blue indicate unstable and stable conditions, respectively, while the bottom panel shows the bin-averaged results for each stability regime.

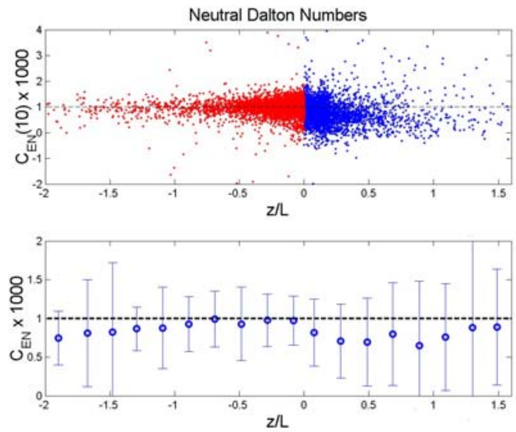

Figure 9. Neutral values of the Dalton number plotted versus z/L.

However, our results suggest that the dimensionless function used under stable conditions does not collapse the data to neutral values. This is clearly shown in Fig. 9, which plots the neutral value of the Dalton number versus z/L. The cause for this departure needs to be investigated before we can say anything about the roughness lengths from which the neutral values are computed.

Therefore, the behavior of the flux-profile relations and their boundary conditions are now a focus of investigation. For example, the dimensionless moisture profiles computed during fog-free periods are shown in Fig. 10. The individual estimates show good agreement with the TC3.0 parameterization and the function suggested by Edson *et al*. (2004) in unstable conditions. However, while the bin-averaged results agree reasonably well in stable conditions, the variability about the means is significant and the data suggest a lower value with increasing stratification. The goal of our ongoing work is to reduce this uncertainty in the dimensionless profiles by, e.g.:

- Varying the averaging time scale for individual flux calculations using the approach of Vickers and Mahrt (2005a).
- Investigation the treatment of gustiness in stable conditions.
- Investigating the impact of internal boundary layers in offshore flow.
- Investigating the structure of turbulence in very stable (shallow) boundary layers.

3.1 CBLAST-Hurricane

The CBLAST hurricane studies were extensive and very difficult observational efforts.

The budget analysis has yielded estimates of transfer coefficients up to 50 m/s with little or no wind speed dependence (albeit with large uncertainty). The direct covariance effort has shown the drag coefficient to level off at about 30 m/s; the latent heat transfer coefficient does not differ significantly from the HEXOS value. The airborne sea spray studies were inconclusive because the aircraft did not fly low enough to unambiguously encounter the sea spray layer near the surface.

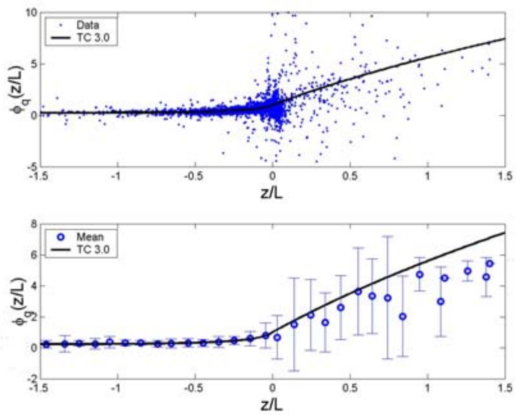

Figure 10. The dimensionless water vapor gradient plotted versus the stability parameter z/L in the absence of fog.

The investigations conducted at the RSMAS wind-wave facility imply that the drag coefficient levels off at 2.5 x 10^{-3} at a wind speed of 30 m/s; the enthalpy transfer coefficient is about 1.0 x 10^{-3} with little wind speed dependence. The Australian wind tunnel study showed that the sea spray source function depended very strongly on friction velocity but was essentially linearly dependent on the small-scale wave energy near the top of the breaking wave.

4. SUMMARY

An unprecedented data set was collected on both sides of the air-sea interface during CBLAST Low and Hurricane programs. These measurements are being used to investigate the processes that govern the exchange of momentum, heat, and mass across the CBLs. To date, we have focused our investigations on the traditional analysis of flux-profile relationship using MO similarity. However, these results have shown that there are significant differences between relationships developed over land versus those developed over the ocean. For example, we have already begun to shed light the physical processes governing, e.g., fog formation and stress swell interactions in low to moderate winds through a combination of process studies, numerical simulations, and mesoscale models.

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