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14. ABSTRACT

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. Therefore, observational components of this program will investigate the temporal and spatial evolution of the Coupled Boundray Layers (CBLs) over vertical scales of centimeters to hundreds of meters, horizontal scales of 10 meters to 10's of kilometers, and time scales of minutes to months. Mesoscale models, large eddy simulations (LES), and direct numerical simulations (DNS) will provide nowcasts, forecasts, and simulations over similar scales. The numerical results will provide a context for interpreting our measurements, while our measurements will provide a means to initialize and evaluate the estimates of turbulent fluxes and dissipation rates calculated by these models. The objective of the *Coupled Boundary Layers and Air-Sea Transfer (CBLAST) DRI Program Office* is to assist the CBLAST principal investigators in their research and publication efforts in all aspects of the program.

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LONG-TERM GOALS

The long-range goal of the proposed research is to understand air-sea interaction and coupled atmospheric and oceanic boundary layer dynamics at low wind speeds where the dynamic processes are driven and/or strongly modulated by thermal forcing. The low wind regime extends from the extreme situation where wind stress is negligible and thermal forcing dominates up to wind speeds where wave breaking and Langmuir circulations are also expected to play a role in the exchange processes. Therefore, the CBLAST-LOW investigators seek to make observations over a wide range of environmental conditions with the intent of improving our understanding of upper ocean and lower atmosphere dynamics and the physical processes that determine both the vertical and horizontal structure of the marine boundary layers.

OBJECTIVES

The objectives of the *Flux Profile Relationships Across the Coupled Boundary Layers* component (N00014-01-1-0029) are to obtain direct measurements of vertical fluxes (transfer) of momentum, heat and mass across the coupled boundary layers (CBLs); to map the 3-D structure of the CBLs over a range of spatial and temporal scales, to identify the processes that drive the flux and CBL structure; to develop and evaluate parameterizations of the flux-producing processes; and to test the mean and variance budgets for momentum, heat, mass, and kinetic energy.

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. Therefore, observational components of this program will investigate the temporal and spatial evolution of the CBLs over vertical scales of centimeters to hundreds of meters, horizontal scales of 10 m to 10's of km, and time scales of minutes to months. Mesoscale models, large eddy simulations (LES), and direct numerical simulations (DNS) will provide nowcasts, forecasts, and simulations over similar scales. The numerical results will provide a context for interpreting our measurements, while our measurements will provide a means to initialize and evaluate the estimates of turbulent fluxes and dissipation rates calculated by these models.

The objective of the *Coupled Boundary Layers and Air-Sea Transfer (CBLAST) DRI Program Office* is to assist the CBLAST PIs in their research and publication efforts in all aspects of the program.

APPROACH

To achieve some of these objectives, the array component deployed a 3-D mesoscale array to simultaneously observe the horizontal and vertical structure of the oceanic surface boundary layer south of the tower as shown in Figure 1. This mooring component also conducted ship-based surveys during the intensive operating period (IOP). The ship-based surveys were coordinated with the two aircraft-based efforts that investigated spatial variability of the atmospheric boundary layer and sea surface temperature field. The combined data sets will be used in conjunction with the modeling studies to seek answers to unresolved questions about how the vertical as well as the horizontal structure of the coupled boundary layers evolve.

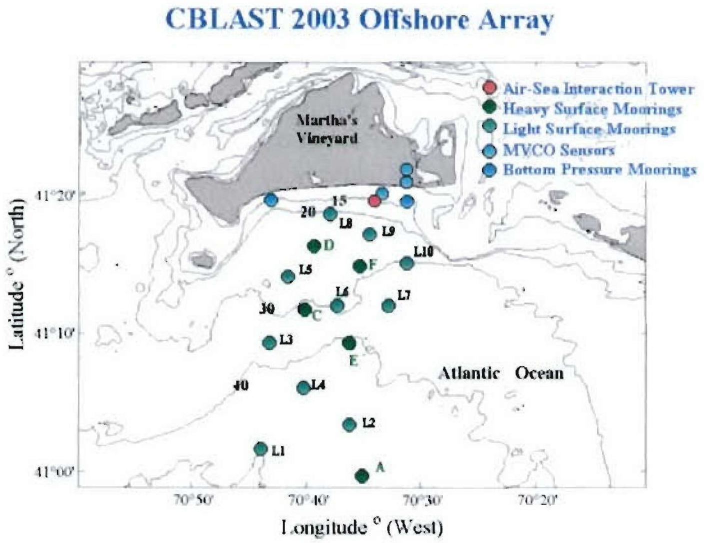

Figure 1. A diagram of the CBLAST region showing some of the assets that were deployed during the main experiment IOP in the summer of 2003.

The tower component has deployed an Air-Sea Interaction Tower (ASIT) spanning the water column and the lower 22-m of the atmosphere at a water depth of 15-m at the Martha's Vineyard Coastal Observatory (MVCO) shown in Figure 1. The 37-m tower has been instrumented with velocity, temperature, conductivity, pressure, humidity, solar radiation, turbidity, precipitation and wave sensors. The tower is connected directly to shore using a fiber-optic-conductor cable, which provides Gbyte bandwidth and kWatts of power to the researchers. The velocity and temperature arrays span horizontal and vertical scales of O (1-10) m to resolve vertical structure and to permit separation and quantification of processes associated with shear- and buoyancy-generated turbulence, surface waves, and Langmuir-like coherent structures.

The IOP of the main experiment was recently completed in August of 2003 with some components continuing into the fall. The field work during the IOP involved substantial collaborations with Tim Stanton (NPS) deploying complementary sensors at the ASIT; Larry Mahrt and Dean Vickers (OSU), Jielun Sun (NCAR), Djamal Khelif (UCI), and Haf Jonsson (CIRPAS) obtaining atmospheric measurements of turbulent fluxes, vertical profiles and horizontal variability from the LongEZ aircraft in 2001 and the CIRPAS Pelican aircraft in 2003; and Andy Jessup (UW) and Chris Zappa (LDEO) obtaining IR remote-sensing measurements. In addition, we have had substantial collaborations with regional-scale modeling groups at Rutgers University and NRL-Monterey, as well as LES investigations by Eric Skyllingstad at OSU and Peter Sullivan at NCAR. The regional-scale models are providing a context for interpreting our measurements, and our measurements will provide a means of testing estimates of turbulent fluxes and dissipation rates calculated by these models. The tower measurements of horizontal and vertical variability spanned a range of scales similar to those resolved by LES simulations and will permit a quantitative evaluation of LES model calculations. The proposed study will produce a unique set of simultaneous measurements of turbulent fluxes and dissipation rates on both sides of the air-sea interface, as well as critical evaluations and improvements of turbulence parameterizations used in atmospheric and oceanic models. The mooring and ship survey measurements spanned a range of scales required to investigate processes on the mesoscale and, in combination with the aircraft measurements, will permit a quantitative evaluation of the coupled mesoscale model results.

WORK COMPLETED

Detailed measurements of the vertical structure of the upper ocean and lower atmosphere were successfully conducted from the ASIT during the IOP. The atmospheric arrays on ASIT were deployed in late June and recovered in early November, 2003. During this period, direct measurements of momentum, heat and mass fluxes were measured at 3-6 levels on the tower. These measurements where complemented by fixed sensors and a profiling package of sensors to compute mean profiles of velocity, temperature, and humidity. Additional measurements of the radiative fluxes, sea surface temperature, precipitation, and the wave field were collected to provide estimates of the net heat flux to the ocean and the significant wave height and period.

The subsurface boom was deployed on the ASIT and instrumented during the second half of the IOP. The sensors included a horizontal array of ADVs paired with thermisters. These measurements were used to compute subsurface stresses and heat fluxes during the IOP (Trowbridge et al., 2004a; 2004b). To obtain these fluxes, a technique that relies on differencing velocities obtained from horizontally separated ADVs is used to remove the irrotational motion of the surface waves. To our knowledge, this is the first comparison of coincident direct covariance Reynolds stresses and heat fluxes measured on both sides of the interface. An upward looking, high resolution ADCP was deployed to measure the near surface current profile and an array of CTDs was also deployed to quantify the stratification (Plueddemann, 2004a). Bottom mounted instrumentation was deployed in July 2003 and recovered with the horizontal array in the spring of 2004. The instrumentation included an ADCP to measure current profiles throughout the water column and a Fanbeam ADCP to quantify the strength of Langmuir circulations (Plueddemann, 2004b).

The Nobska conducted 4 cruises during the IOP in a wide variety of conditions. The Nobska was outfitted with a direct covariance flux system (DCFS), IR radiometers to measure the SST, and a towed thermistor chain to measure upper ocean temperature structure at very high vertical resolution during transects in the CBLAST region. The Nobska also deployed a series of drifters to document the trajectories and the evolution of temperature structure within a water mass. Some of the towed and drifting array results have been processed and combined with the DCFS results that clearly show that the surface fluxes are rapidly responding to the spatial variability in the SST field.

Basic processing and application of post-deployment calibrations to our data from the 2003 IOP is complete and further processing and quality control is ongoing. Relevant portions of the data have been transferred to John Wilkin (Rutgers) for initialization and testing of the high resolution Regional Ocean Modeling System (ROMS), to Shouping Wang (NRL) for comparison with COAMPS (Coupled Ocean/Atmosphere Mesoscale Predictions Systems), to Larry Marht (OSU) for comparison with aircraft measurements, and to Peter Sullivan (NCAR) for comparison with Large Eddy Simulations of wind-swell interactions.

A technical report has been written for the 2001 pilot experiment (Pritchard *et al.*, 2002) and for the 2002 mooring deployments (Hutto *et al.*, 2003). Data from the 2001 pilot revealed the presence of energetic solitons south of Martha's Vineyard (Pritchard and Weller, 2002; Pritchard and Weller, 2004a, b). Results based on analyses of our data have been presented at the 2004 AGU Ocean Sciences Meeting (Weller *et al.*, 2004; Farrar *et al.*, 2004a; Pritchard and Weller, 2004a, Crofoot et al., 2004; Edson et al., 2004b; Trowbridge et al., 2004b; Plueddemann, 2004b), the 2004 AMS Boundary Layers and Turbulence Conference (Farrar *et al.*, 2004b; Wang *et al.*, 2004; Edson et al., 2004a; Trowbridge et al., 2004a; Plueddemann, 2004a), and the 2004 International Geoscience and Remote Sensing Symposium (Thompson *et al.*, 2004).

The research efforts lead by the PI (Edson) have focused on the following topics:

Bulk Formulae and Flux-Profile Relationships

The analysis of atmospheric measurements has focused on evaluation of bulk aerodynamic formulae and flux-profile relationships. Bulk aerodynamic formulae relate turbulent fluxes of momentum, sensible heat, and latent heat to the Reynolds-averaged velocity, temperature, and humidity, and are expressed in terms of dimensionless, empirical coefficients (e.g. Fairall et al. 2003), which may depend on quantities such as wind speed and wave age. Flux-profile relationships relate turbulent fluxes of momentum, sensible heat, and latent heat to the vertical derivatives of the Reynolds-averaged velocity, temperature and humidity, and are expressed in terms of dimensionless, empirical functions, which depend on the ratio of the distance from the boundary to the Monin-Obukhov (MO) length (e.g. Businger 1988). Bulk aerodynamic formulae and flux-profile relationships are a cornerstone of numerical weather predictions, and their uncertainty is one of the primary obstacles to accurate marine forecasts in low to moderate wind conditions. The high-quality direct-covariance measurements of turbulent fluxes obtained during CBLAST-low provide a unique opportunity for evaluation of these relationships. Work during 2004 has led to intriguing results related to (1) latent fluxes and fog formation and (2) stress-swell interaction.

Latent Heat and Fog

CBLAST-Low measurements indicate that the standard TOGA-COARE 3.0 bulk aerodynamic formulation (Fairall et al. 2003) represents direct-covariance measurements of latent heat flux accurately when the latent heat flux is positive (corresponding to an upward moisture flux), but poorly when the latent heat flux is negative (corresponding to a downward moisture flux). Similar results were reported by Edson et al. (2000). Lieutenant Crofoot, a Navy student in the MIT/WHOI educational program, recently completed a case study of an eight-day period characterized by light winds, a stably stratified atmospheric boundary layer, and swell-dominated waves. The case study (Crofoot 2004) shows that failure of the bulk aerodynamic estimate occurred when advection of warm moist air over cooler water resulted in a downward flux of moisture and fog formation (Figure 2). Measurements during the entire record show that Dalton numbers (the transfer coefficient for humidity) computed in stable conditions are substantially lower than the standard TOGA-COARE 3.0 algorithm (Figure 3a). As a result, averaged Dalton numbers computed under all stability conditions are biased low (Figure 3b). Corresponding estimates of the MO flux-profile function for humidity indicate small variability during unstable conditions, but much larger variability during stable conditions; formation of fog is likely related to some of this variability. The intriguing relationship between fog formation and failure of standard expressions for humidity flux is not understood and is a subject of continuing investigation.

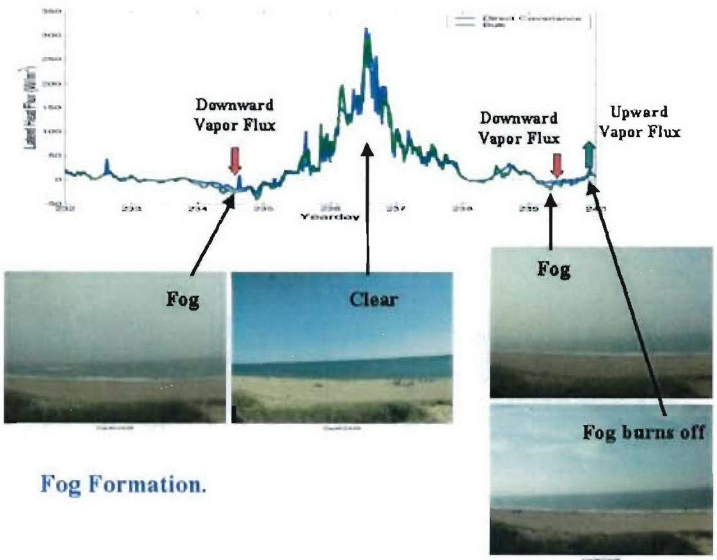

Figure 2. Time series of the latent heat fluxes and visual evidence for the presence of fog during periods of downward moisture flux.

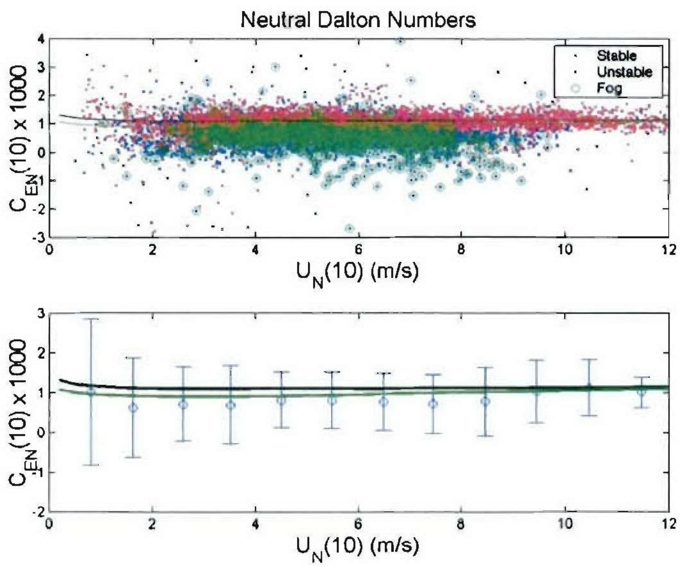

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Figure 3. Measurements of the Dalton number plotted versus wind speed. Runs characterized by unstable, stable, and stable with fog are denoted by different symbols. The black line is from TOGA-COARE 3.0 while the green line is from Edson (2002).

Wind-Swell Interactions

MO similarity theory is often assumed to hold within the lowest 10% of the atmospheric boundary layer, but recent observations (Miller et al. 1997, Vickers & Mahrt 1999, Smedman et al. 1999) indicate effects of surface waves on the Reynolds stress and velocity profile over the sea surface, and detailed LES results show that fast moving swell in light winds can have a profound effect on wind profiles up to heights of O (10 m) above the sea surface (Sullivan et al. 2004). Motivated by the parallel investigation of Sullivan et al. (2004), we limited our initial investigation to periods when the direction of the wind and dominant waves were within 25° of each other; velocity profiles during these periods were normalized by their MO predictions and then bin averaged by a wave age parameter c_p / U_{10}, where c_p is the phase speed of the dominant waves. Previous studies have shown that fully developed (mature) seas have a wave age of approximately 1.2, while developing (young) seas have a smaller value and decaying (old) seas a larger value. The bin-averaged profiles all depart from their MO similarity predictions as they approach the surface, the oldest waves showing a velocity surplus and the youngest indicating a velocity deficit (Figure 4). These results are qualitatively similar to the LES results of Sullivan et al. (2004).

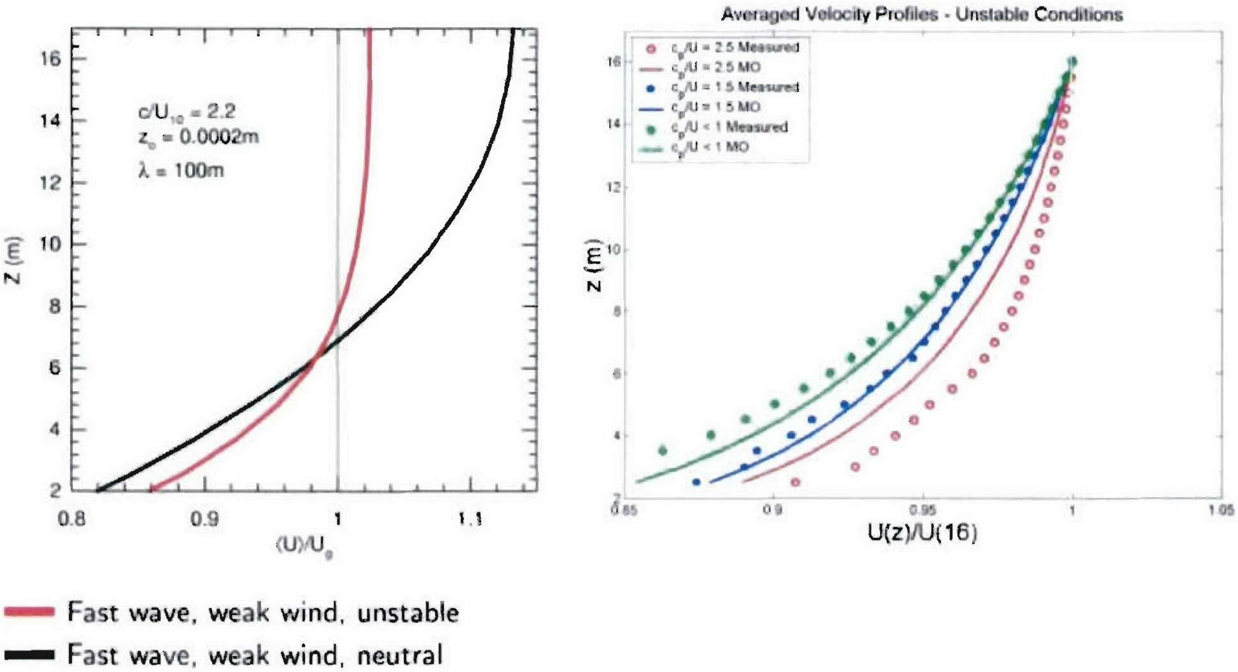

Figure 4. A comparison of the LES results (left panel) reported by Sullivan et al. (2004) with CBLAST results (right panel). The LES results are normalized by the value geostrophic wind used in the simulation while the CBLAST results are normalized by wind speed at 16 m.

RECENT RESULTS

Our recent efforts have focused on improving the bulk formulae required for forecast models such as COAMPS. Our previous work has shown that the bulk formulae fail to accurately estimate the flux in stable conditions in the presence of fog. This is not surprising as these formulas are based on MO similarity theory, which should not be applied in these conditions. Therefore, our current efforts are focusing on the unstable and stable stratification in the absence of fog where MO similarity for scalar fluxes is expected. These efforts have shown that parameterizations used in the TOGA COARE 3.0 bulk formula for momentum and scalar fluxes:

- Provide accurate momentum fluxes in the mean for moderate winds between 3-10 m/s.

- Underestimate the momentum fluxes at high winds due to the effects of shoaling.
- Have large uncertainties for momentum fluxes at low winds due to stress-swell interaction.
- Slightly overestimate the upward latent and sensible heat fluxes in the mean for unstable flows with large uncertainties.
- Overestimate the often downward latent heat fluxes in the mean for stratified flows with large uncertainties.
- Underestimate the downward sensible heat fluxes in the mean for stratified flows.

We are now working to properly incorporate these observations into an improved version of the TC algorithm. Our focus will be on improvements to the scalar flux estimates in stratified flows and an attempt to incorporate the effects of swell into the momentum flux formulations. It is important to note that the CBLAST parameterizations shown on Figures 6 and 7 do not represent our final results. Specifically, we expect to determine dimensionless profile functions that cause the neutral values of the Dalton and Stanton numbers to collapse for both stable and unstable conditions. We are also looking into the possibility that mass and heat exchange are not explained by identical functions.

Lastly, the project office is coordinating efforts to publish CBLAST summary papers in *the Bulletin of the American Meteorological Society* for both the hurricane and low wind components. The PI is leading the effort on the low wind component and is working closely with Drs. Peter Black (NOAA) and Shuyi Chen (RSMAS) on the hurricane component.

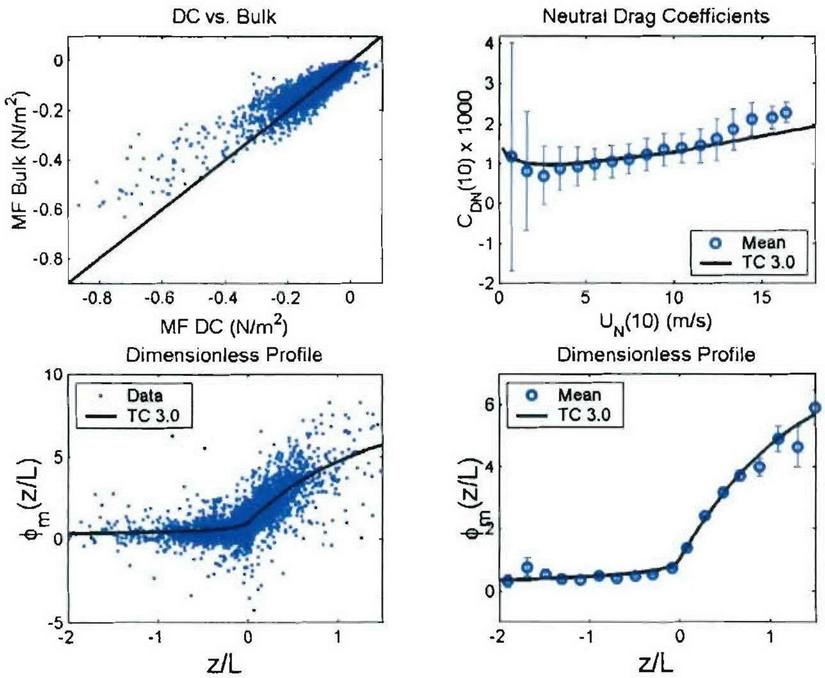

Figure 5. A composite showing CBLAST results for the momentum flux: a) direct covariance measurements versus TC 3.0 bulk aerodynamic estimates; b) measured neutral drag coefficients versus TC 3.0; c) measured dimensionless shear versus TC 3.0 parameterization; and d) averaged values versus parameterization.

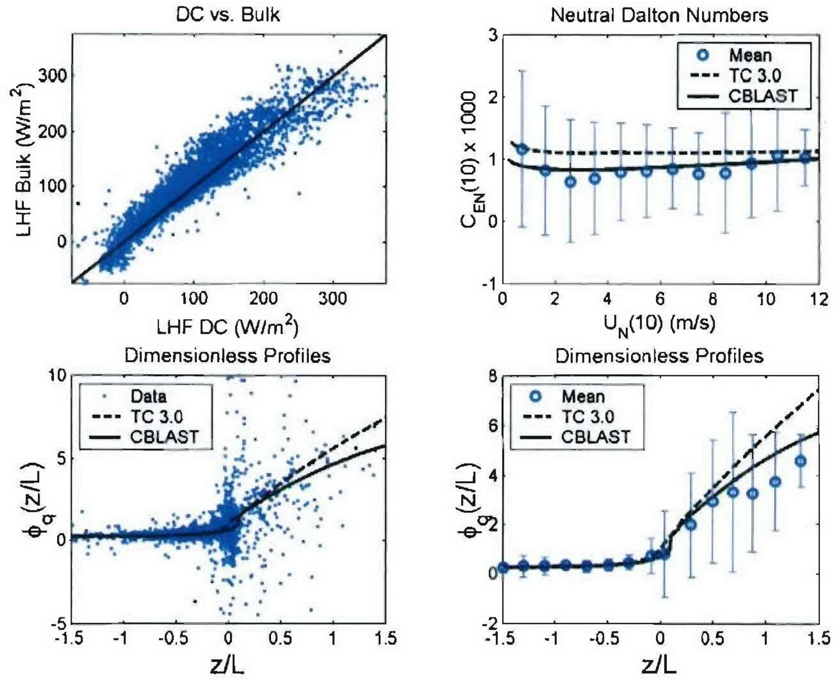

Figure 6. The same information as shown in Figure 5 for the latent heat (mass) fluxes and water vapor profiles.

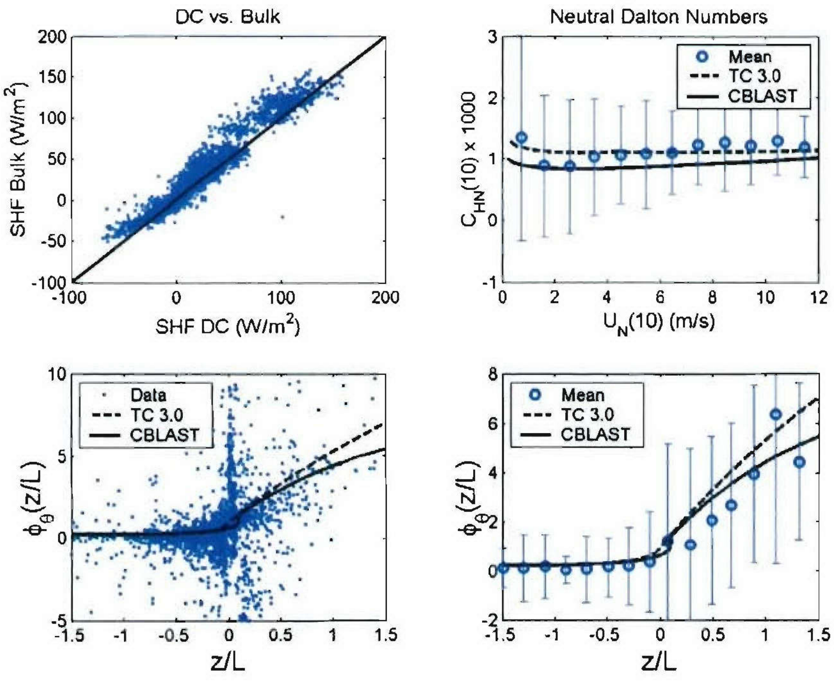

Figure 7. The same information as shown in Figure 5 for the sensible heat fluxes and temperature profiles.

IMPACT/APPLICATIONS

The 2003 IOP component of the CBLAST field program was successfully completed in October, 2003. Data quality and return have been excellent, and a wide variety of conditions were sampled, including low-to-moderate wind conditions and the passage of strong atmospheric and oceanic fronts through the study region. The ASIT and the fifteen moorings deployed provide a complete time series of the passage of oceanic fronts and other processes with a spatial resolution on the order of 4 km, while the ship-based measurements complement this data by providing a spatial resolution of about 8 m. In conjunction with aircraft-based measurements and satellite data, the *in situ* measurements collected during the 2003 IOP constitute an unprecedented record of the evolution of the coupled air-sea boundary layers. These measurements will facilitate a more complete understanding of the relative roles of local air-sea interaction and other processes (e.g. ocean fronts and advection) in influencing the evolution of the coupled air-sea boundary layer in low-to-moderate winds. Through ongoing collaboration with numerical modeling groups, we anticipate that this data and improved understanding of air-sea interaction will contribute directly to improving the skill of marine forecasts.

TRANSITIONS

In addition to several ongoing ONR projects, the ASIT is being used by investigators funded by the NSF and NASA to conduct their research. The ASIT has become a component of the MVCO.

RELATED PROJECTS

James Edson, in collaboration with Peter Sullivan (NCAR) and John Wyngaard (PSU), has used the ASIT in an NSF and ONR jointly sponsored program entitled *Ocean Horizontal Array Turbulence Study (OHATS): An Investigation of Subfilter-Scale Fluxes in the Marine Surface Layer.* Detailed information about this project is provided in the ONR annual report submitted by Sullivan.

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