Analysis of Near-Surface Atmospheric Measurements Obtained During CBLAST-LOW

James B. Edson
University of Connecticut, Avery Point, 1080 Shennecossett Road, Groton, CT 06340
phone: (860) 405-9165 fax: (860) 405-9153 email: james.edson@uconn.edu

Award Number: N00014-05-1-0139*
http: www.whoi.edu/science/AOPE/dept/CBLAST/lowwind.html
*This report presents results that are a continuation of the research conducted under N00014-00-1-0409 and N00014-01-1-0029.

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 of the physical processes that determine both the vertical and horizontal structure of the marine boundary layers.

OBJECTIVES

The goal of CBLAST-LOW is therefore to improve our understanding of the processes that couple the marine boundary layers under these conditions using observations, numerical simulations and models. The ultimate goal is to incorporate new and/or improved parameterization of these processes in coupled models to improve marine forecasts of wind, waves and currents. For example, the boundary conditions between the ocean and atmospheric models are often provided by parameterizations based on the **bulk aerodynamic method**. This method is also widely used to estimate the fluxes from time series measurements over the ocean. This briefing describes ongoing efforts to improve bulk formula using data collected during CBLAST-LOW. Topics of interests include a discussion of wind-wave-swell interaction at low winds and heat and moisture exchange in stratified conditions.

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 intensive 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.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Analysis of Near-Surface Atmospheric Measurements Obtained During CBLAST-LOW**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Connecticut,Avery Point,1080 Shennecossett Road,Groton,CT,06340**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

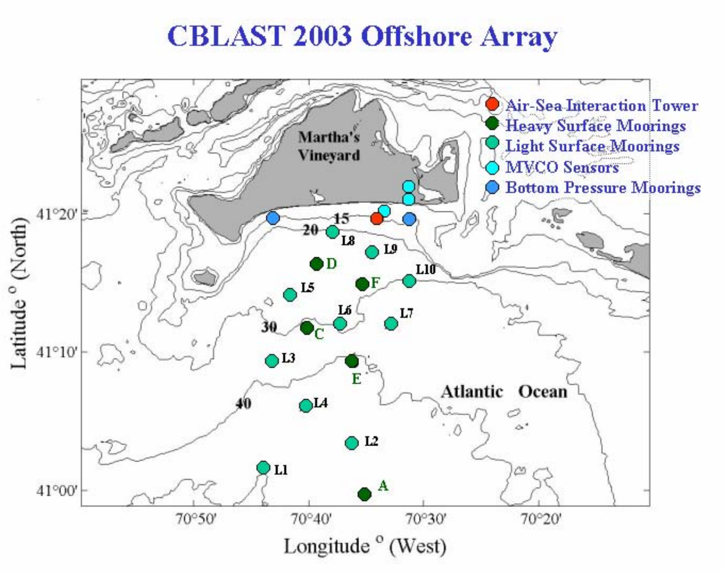

Figure 1. A diagram of the CBLAST region showing some of the assets that were deployed during the main experiment IOP in the summer 2003.

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) and 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., 2004; Gerbi et al., 2006). 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.

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.

Results based on analyses of our data have been presented at the 2004 AGU Ocean Sciences Meeting (Farrar *et al.,* 2004; Crofoot et al., 2004; Edson et al., 2004b; Hristov et al., 2004b; Mahrt et al., 2004), the 2004 AMS 16th Symposium on Boundary Layers and Turbulence (Edson et al., 2004a; Hristov et al., 2004a; Sullivan et al., 2004; Trowbridge et al., 2004; Wang *et al.,* 2004a, 2004b), the 2005 Gordon Research Conference on Coastal Ocean Circulation (Edson, 2005), 2006 AGU Ocean Sciences Meeting (Gerbi *et al.,* 2006), and 2006 AMS 27th Conference on Hurricanes and Tropical Meteorology (Edson et al., 2006; Sullivan et al., 2006; Sun *et al.,* 2006).

An overview of the CBLAST-LOW program has been accepted to the Bulletin of the American Meteorological Society (Edson *et al*, 2006).

RECENT RESULTS

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.

Heat Fluxes: 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).

The uncertainty in the transfer coefficients for heat remains one of the main obstacles to accurate numerical forecasts. In particular, our initial investigations have shown significant differences between direct covariance and bulk fluxes in stable conditions, particularly when the moisture flux is directed downward (Fig. 3). These periods of downward moisture flux are often associated with foggy conditions. However, the CBLAST data indicates that the Dalton numbers (i.e., the transfer coefficient for latent heat) remain lower than the COARE algorithm parameterization even after removal of downward fluxes and foggy periods (Fig. 4). Therefore, ***the CBLAST algorithm proposes a neutral Dalton number that is 25% lower than the COARE algorithm at low winds speed***. On the other hand, the Stanton numbers (i.e., the transfer coefficient for sensible heat) is in reasonable agreement with COARE (Fig. 5). This result argues against the commonly held assumption that the neutral transfer coefficients for heat and mass are equal.

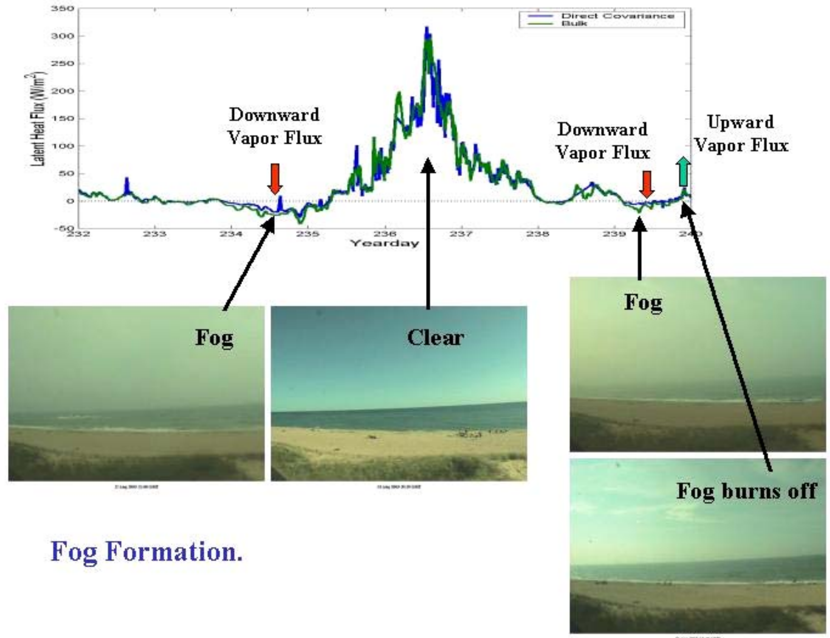

Figure 2. Time series of the latent heat fluxes and visual evidence for the presence of fog during periods of downward moisture flux.

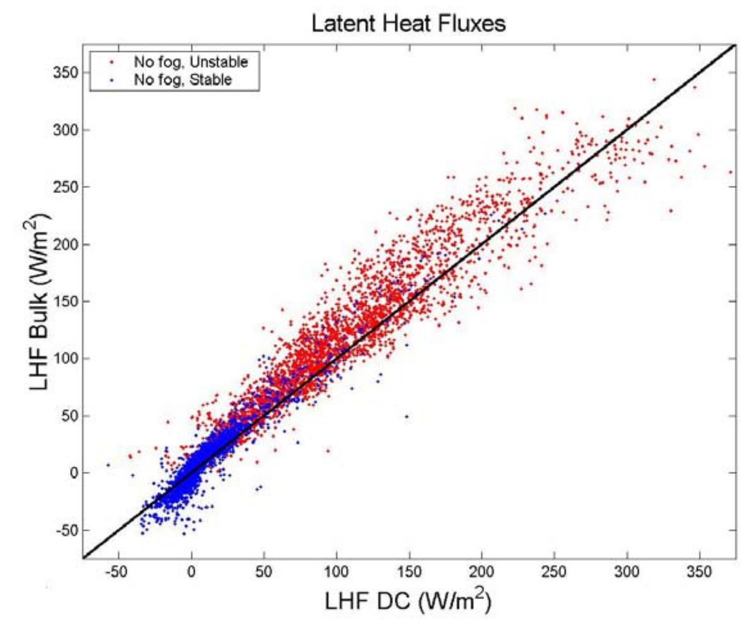

Figure 3. Comparison of bulk aerodynamic versus direct covariance latent heat fluxes measured from ASIT. The red dots indicate unstable conditions (i.e., positive buoyancy flux) while the blue dots indicate stable conditions (i.e., negative buoyancy flux).

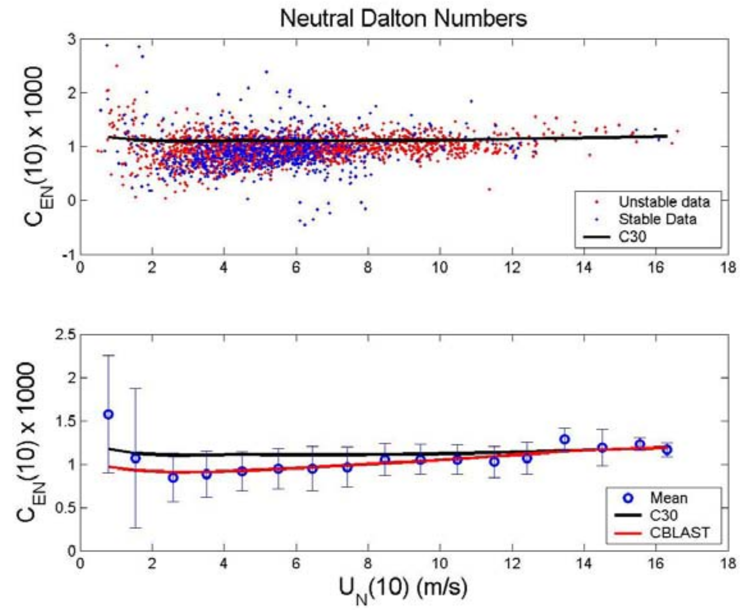

Figure 4. Individual and bin-averaged estimates of the neutral Dalton number. The black lines labeled with C30 represents the COARE 3.0 parameterization from Fairall et al. (2003), while the red line represents the proposed CBLAST parameterization.

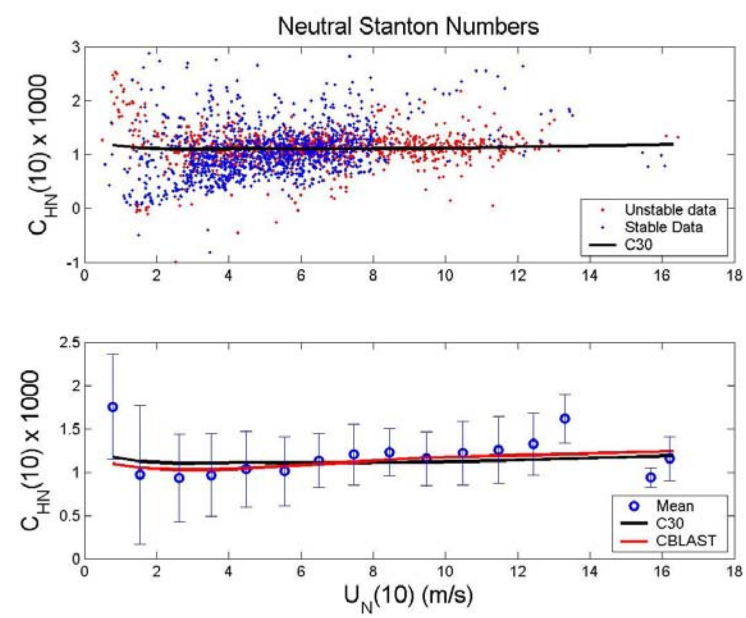

Figure 5. Individual and bin-averaged estimates of the neutral Stanton number. The black lines labeled with C30 represents the COARE 3.0 parameterization from Fairall et al. (2003), while the red line represents the proposed CBLAST parameterization.

Momentum Fluxes: The transfer coefficient for momentum, i.e., the drag coefficient, computed from the CBLAST-LOW data set show good agreement in the mean with the COARE 3.0 algorithm (Fairall et al., 2003), particularly between 4 and 12 m/s as shown in Fig. 6. However, there is significant disagreement between the bin-average data and the parameterization at the lowest and highest wind speeds. At low winds, we hypothesize that wind-swell interaction is the leading cause. For example, for conditions with weak wind following faster moving swell, previous studies have indicated that the wind stress may be reduced relative to the bulk prediction. These conditions are known as old seas and are commonly found over the ocean whenever non-locally generated waves propagate into a low-wind region or whenever local seas slowly decay as a storm moves out of the region. The lowest panel of Fig. 6 plots the bin-averaged results for three subsets of the data that were measured in young (developing), mature (developed) and old (decaying) seas. If the COARE parameterization is correct for mature seas at all wind speeds, ***then the bin-averaged results indicate that the drag coefficients of the younger seas are enhanced while those of the older seas are suppressed***.

Although these results as not conclusive, we have reason to believe that swell impacts air-sea exchange at low winds based on the CBLAST LES studies conducted by Peter Sullivan (NCAR). The LES clearly show that fast moving swell in light winds can have a significant effect on the wind field up to heights of O(100m). Under these conditions, the wave driven winds produce a low-level jet and a rapid decay of the momentum flux with height. The ASIT data is now being used to verify these results and investigate the vertical structure of the turbulence in the surface layer as a function of wave-age and sea-state. For example, previous studies have shown that fully developed (mature) seas have a wave age of approximately c_p / U_{10} =1.2 (where c_p is the phase speed of the dominant waves), 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 7). These results are qualitatively similar to the LES results of Sullivan et al. (2004, 2006).

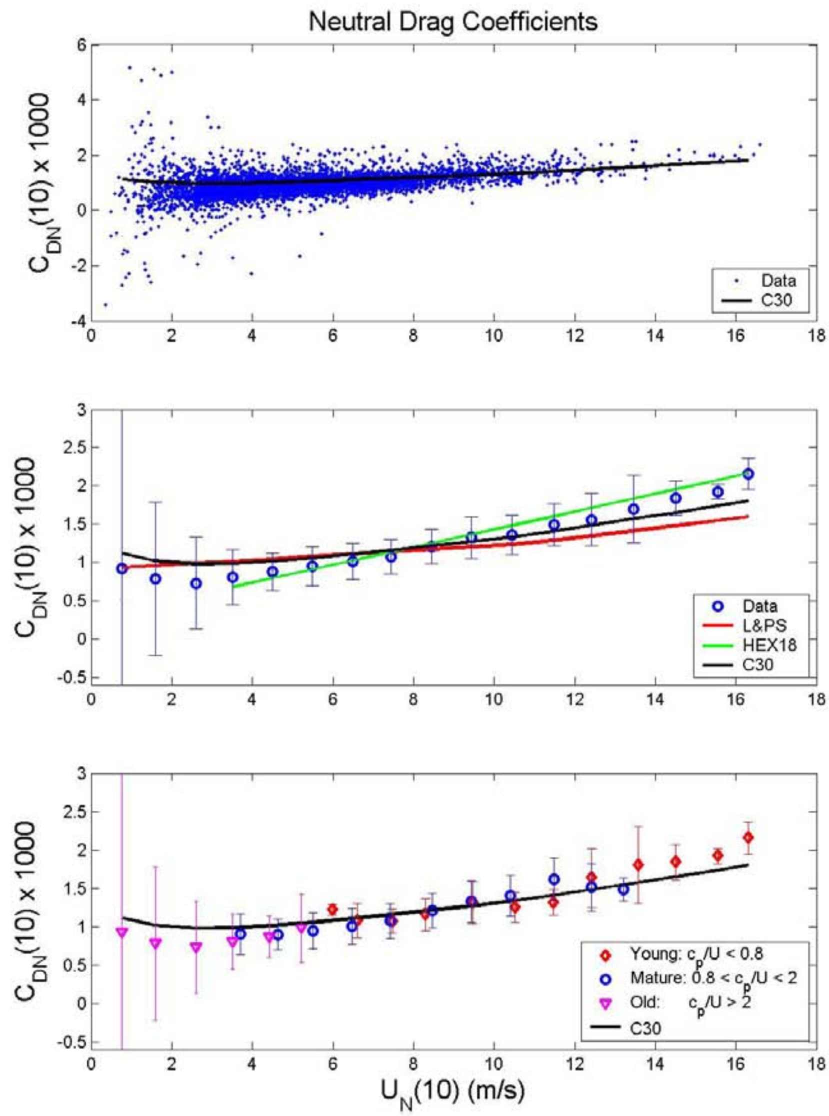

Figure 6. Individual (top panel) and bin-averaged (middle and lower panel) estimates of the neutral drag coefficient. The black lines labeled with C30 represents the COARE 3.0 parameterization from Fairall et al. (2003). The bin-average estimates in the middle panel are also compared with an average parameterization derived from Large and Pond (1981) and Smith (1980) denoted by L&PS, and the HEXOS parameterization given by Smith et al. (1992) denoted by HEX18. L&PS and C30 were developed using open ocean data sets, while HEX18 was developed from data taken in coastal waters where the water depth was 18-m. The lower panel provides bin-average results for subsets of the data that were measured in young, mature and old seas as characterized by the wave age parameter c_p/U.

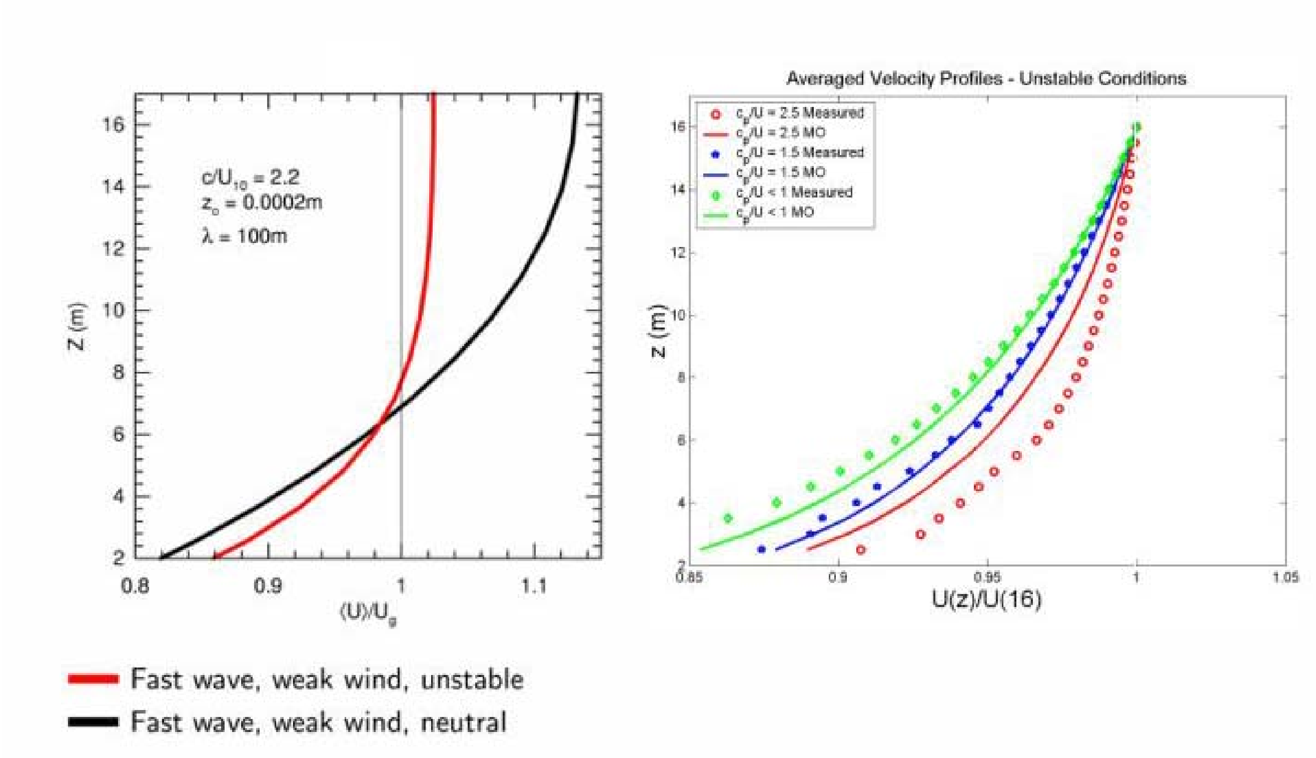

Figure 7. A comparison of the LES results (left panel) reported by Sullivan et al. (2004) with CBLAST results (right panel). The LES results are normalized by the value geostrophic wind used in the simulation while the CBLAST results are normalized by wind speed at 16 m.

REFERENCES

Businger, J. A., 1988: A note on the Businger-Dyer profiles, *Bound.-Layer Meteorol.*, *42*, 145-151.

Edson, J., 2002: Air-sea fluxes in high winds, Ocean Sci. Mtg., Honolulu, HI, OS51C-01.

Edson, J. B., et al., 2000: Downward Flux of Moisture over the Ocean, *Proc. 14th Symp. on Boundary Layers and Turbulence*, Aspen, CO, Amer. Meteor. Soc., 511-513.

Fairall, C. W., E. F. Bradley, J. E. Hare, A. A. Grachev, J. B. Edson, 2003: Bulk parameterization of air–sea fluxes: Updates and verification for the COARE algorithm, *J. Climate*, *16*, 571–591.

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 that were 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, and 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.

PUBLICATIONS RESULTING FROM THIS PROPOSAL

Crofoot, R. F., 2004: Investigations of scalar transfer coefficients in fog during the Coupled Boundary Layers and Air-Sea Transfer experiment: A case study, *M.S. Thesis*, WHOI/MIT Joint Program.

Crofoot, R., J. B. Edson, W. R. McGillis, and C. Zappa, 2004. Investigations of transfer coefficients in the marine atmospheric boundary layer during CBLAST-Low. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS32A-09.

Edson, J. B., 2005. Contrasting air-sea exchange in the coastal versus open ocean: Are there significant differences? *4th Gordon Research Conference on Coastal Ocean Circulation*. Invited presentation, Colby-Sawyer College, New London, NH, June 5-10, 2005.

Edson, J., T. Crawford, J. Crescenti, T. Farrar, N. Frew, G. Gerbi, C. Helmis, T. Hristov, D. Khelif, A. Jessup, H. Jonsson, M. Li, L. Mahrt, W. McGillis, A. Plueddemann, L. Shen, E. Skyllingstad, T. Stanton, P. Sullivan, J. Sun, J. Trowbridge, D. Vickers, S. Wang, Q. Wang, R. Weller, J. Wilkin, A. Williams, D.K.P. Yue, and C. Zappa, 2006. The Coupled Boundary Layer and Air-Sea Transfer Experiment in Low-winds (CBLAST-LOW). *Bulletin of the American Meterological Society*, in press.

Edson, J. B., R. F. Crofoot, W. R. McGillis, and C. Zappa, 2004a. Investigations of flux-profile relationships in the marine atmospheric surface layer during CBLAST. *16th Symposium on Boundary Layers and Turbulence.* Portland, ME, Ref. 8.2, AMS, Boston, MA.

Edson, J. B., R. Crofoot, R., S. M. Faluotico, W. R. McGillis, F. T. Thwaites, C. Zappa, and T. Hristov, 2004b. Flux-profile relationships in the marine atmospheric surface layer during CBLAST-Low. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-09.

Edson, J. B., C. Fairall, and P. P. Sullivan. 2006. Evaluation and continued improvements to the TOGA COARE 3.0 algorithm using CBLAST data. *27th Conference on Hurricanes and Tropical Meteorology.* Monterey, CA, Ref. 7C.1, AMS, Boston. MA.

Farrar, J. T., R. Weller, and J. Edson. 2004. Observations of the coupled air-sea boundary layers during the 2003 CBLAST-Low field program. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-02.

Gerbi, G. P., J. H. Trowbridge, E. A. Terray, J. B. Edson, and A. J. Plueddemann. 2006. Direct covariance measurements of near surface turbulent momentum flux in the coastal ocean. *Eos Trans. AGU*, Ocean Sci. Meet. Suppl., Abstract OS34O-02**.**

Hristov, T., K. D. Anderson, J. B. Edson, and C. A. Friehe, 2004a. Dynamics of the surface layer over the ocean as revealed from field measurements of the atmospheric pressure. *16th Symposium on Boundary Layers and Turbulence.* Portland, ME, Ref. P8.3, AMS, Boston, MA.

Hristov, T., K. D. Anderson, C. A. Friehe, and J. B. Edson, 2004b. Atmospheric pressure fluctuations over the ocean: Analysis of field experiment data. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS52G-06.

Mahrt, L., D. Vickers, and J. B. Edson, 2004. The very stable boundary layer. *Eos Trans. AGU*, 84(52), Ocean Sci. Meet. Suppl., Abstract OS51G-01.

Sullivan, P. P., J. B. Edson, T. Hristov, and J. C. McWilliams. 2006. Momentum flux structures and statistics in low-wind marine surfaces layers: Observations and large-eddy simulations. *27th Conference on Hurricanes and Tropical Meteorology.* Monterey, CA, Ref. 7C.6, AMS, Boston. MA.

Sullivan, P. P., J. B. Edson, J. C. McWilliams, and C.-H. Moeng, 2004. Large-Eddy Simulations and Observations of Wave-Driven Boundary Layers. *16th Symposium on Boundary Layers and Turbulence.* Portland, ME, Ref. 8.12, AMS, Boston, MA.

Sun, J., S. P. Burns, J. B. Edson, D. Dhelif, L. Mahrt, D. Vickers, and T. Hristov. 2006. Contributions of swell to air-sea interactions under weak wind conditions. *27th Conference on Hurricanes and Tropical Meteorology.* Monterey, CA, Ref. 7C.2, AMS, Boston. MA.

Trowbridge, J. H., G. Gerbi, J. B. Edson, and G. Terray, 2004. Momentum and heat fluxes across the air-sea interface during CBLAST-low. Portland, ME, *16th Symposium on Boundary Layers and Turbulence.* Ref. 8.1, AMS, Boston, MA.

Wang, S., Q. Wang, Z. Gao, J. Edson, R. Weller, and C. Helmis, 2004a. Evalutaion of COAMPS Real Time Forecast for CBLAST-LOW Summer Experiments 2002/2003. *16th Symposium on Boundary Layers and Turbulence.* Portland, ME, Ref. P8.2, AMS, Boston, MA.

Wang, S., Q. Wang, J. Edson, and R. Crofoot, 2004b. COAMP fog forcast during 2003 CBLAST-Low. *16th Symposium on Boundary Layers and Turbulence.* Portland, ME, Ref. 8.10, AMS, Boston, MA.