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14. ABSTRACT
Measurements obtained during the low-wind component of the Coupled Boundary Layers and Air-Sea Transfer program (CBLAST-Low) were used to elucidate the energetics of the ocean surface boundary layer. This work addressed the closure of the turbulent kinetic energy (TKE) budget, the relationship between TKE and dissipation, and the roles of wave breaking and Langmuir circulation in controlling turbulent diffusivity. The measurements occurred primarily during conditions in which shear, buoyancy and wave breaking were important energy sources, while Langmuir circulation was present but not dominant. The primary results were (1) The observed dissipation rate of TKE was enhanced relative that expected near a rigid boundary, and in good agreement with a scaling which assumes that TKE is extracted from the surface waves via breaking and dissipates as it is transported downward, (2) The dissipation rate of TKE was not balanced by local production or growth, indicating that the divergence of the flux of TKE was important, (3) The vertical distribution of TKE was reasonably well explained by a one-dimensional model incorporating the effects of surface gravity waves and shear instabilities, (4) Langmuir circulation did not appear to play a distinct role in boundary layer energetics.

15. SUBJECT TERMS
Coupled Boundary Layers and Air-Sea Transfer program (CBLAST-Low), energetics, ocean surface boundary layer, turbulent kinetic energy (TKE), Langmuir circulation

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Analysis of Near-Surface Oceanic Measurements Obtained During CBLAST-Low

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LONG-TERM GOALS

- Improve our understanding of the turbulent processes that drive the vertical exchange of momentum, heat and mass across the coupled atmosphere-ocean boundary layers
- Evaluate and improve parameterizations of vertical fluxes of momentum, heat and mass in collaboration with modelers.

OBJECTIVES

- To quantify and understand the relative importance of shear-generated turbulence, buoyancy, Langmuir circulations, and wave breaking in accomplishing vertical transport of momentum and heat beneath the air-sea interface.
- To quantify the dominant balances in the turbulent kinetic energy and temperature variance equations.
- To quantify the characteristics of Langmuir circulations and understand their relationship to wind and wave forcing.

APPROACH

Atmospheric and oceanic measurements obtained during the summer and fall of 2003 as a part of the low-wind component of the Coupled Boundary Layers and Air-Sea Transfer program (CBLAST-Low; Edson et al., 2007) were used to address the objectives. This project was a follow-on to Award Number N00014-03-1-0681 “Analysis of Near-Surface Atmospheric and Oceanic Measurements Obtained during CBLAST-Low” and had similar objectives. The focus of this work was on understanding the turbulent processes (e.g. wind-driven shear, wave induced turbulence, Langmuir circulation) that control vertical fluxes of mass, heat, and momentum, and evaluating existing parameterizations of these processes. Greg Gerbi, a doctoral degree recipient in physical oceanography from the Massachusetts Institute of Technology (MIT) – Woods Hole Oceanographic Institution (WHOI) joint program, was funded by the project. The research was done in collaboration with Jim Edson (University of Connecticut).

TASKS COMPLETED

The CBLAST-low measurement program was conducted off the southern coast of the island of Martha's Vineyard, Massachusetts. Observations of interest here were obtained from the Air-Sea Interaction Tower (ASIT), at a water depth of 15 m, which was constructed with CBLAST-low funding during 2002. The intensive observational period for the CBLAST-low program occurred during summer and fall of 2003.

Atmospheric measurements were obtained from the Air-Sea Interaction Tower (ASIT; water depth 15 m) using a variety of sensors that provided profiles of temperature, humidity, velocity, momentum flux, sensible and latent heat flux, kinetic energy, pressure and scalar variance, as well as dissipation rates for turbulent kinetic energy, temperature variance, and humidity variance. The downwelling radiative heat fluxes were measured by solar and infrared radiometers. The heat fluxes were combined to compute the net heat flux into or out of the ocean.

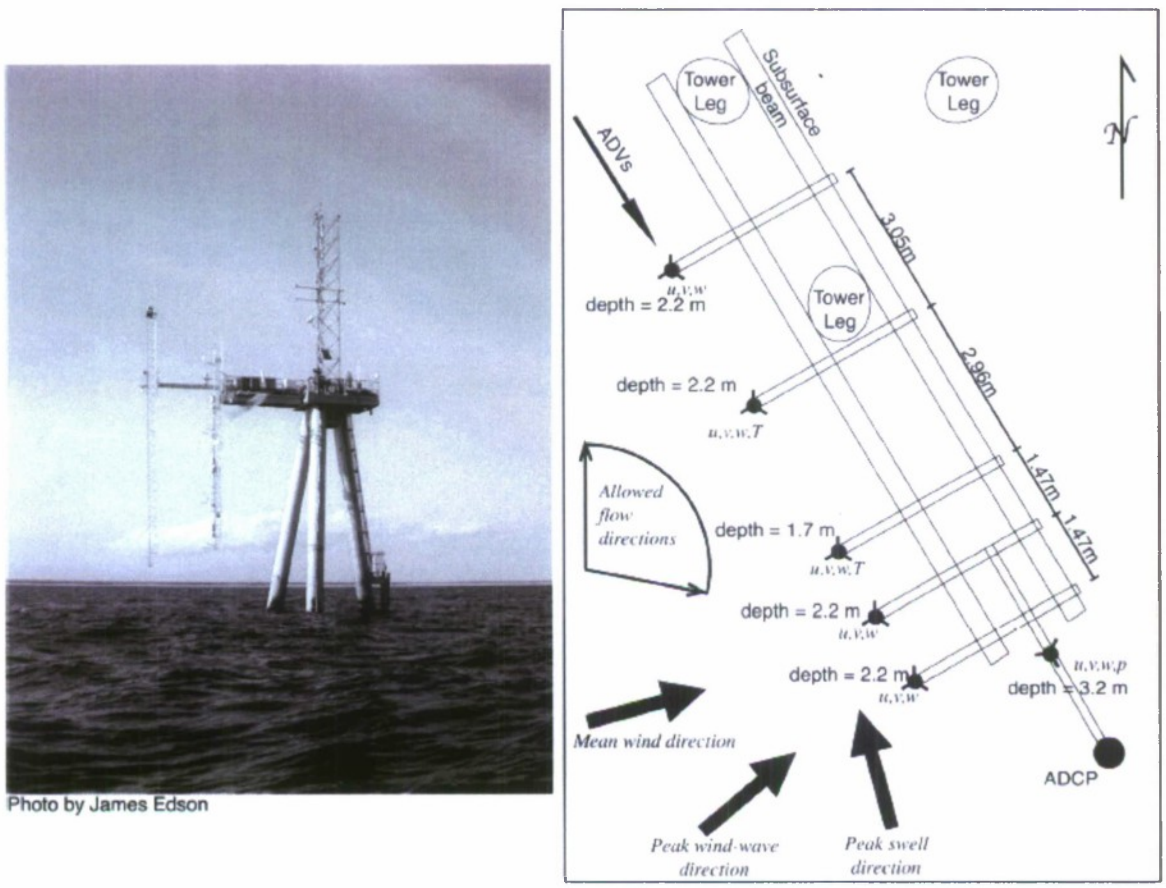

Figure 1. Photograph of the Air Sea Interaction Tower at the MVCO (left) and schematic drawing of the oceanic observation platform (right) located about 4 m below the sea surface. Small filled circles with three arms represent ADVs and thermistors. The large filled circle represents the mid-depth ADCP. Mean wind and wave directions (bold arrows) and the range of flow directions (0°–120°) used in this study are shown.

Oceanic measurements were obtained from instruments mounted on and near the ASIT, and from sensors routinely maintained as part of the Martha's Vineyard Coastal Observatory (MVCO; water depth 12 m). Estimates of dissipation rates for turbulent kinetic energy and temperature variance, as well as direct covariance estimates of turbulent momentum and heat fluxes were obtained from near-surface and near-bottom horizontal arrays of co-located coherently sampled acoustic Doppler velocimeters (ADVs) and thermistors. Estimates of Langmuir circulation intensity and cross-wind spatial scale were obtained with a "fanbeam" acoustic Doppler current profiler. Vertical profiles of horizontal velocity were obtained from ADCPs and stratification was determined from an array of conductivity-temperature-depth (CTD) sensors. Directional wave spectra were estimated from the ADCP measurements at the MVCO (Churchill et al., 2006) and partitioned into dominant swell and locally generated wind-wave components following the method of Hanson and Phillips (2001).

Previous analysis of CBLAST ASIT observations (Gerbi et al., 2008) produced a successful closure of the turbulent momentum budget spanning the air-sea interface. This is an important observational milestone because it means that the oceanic turbulence observations are suitable for characterization and quantification of the flux-carrying processes on the water side of the air-sea interface. Among the intriguing results form Gerbi et al. (2008) was the observation that temperature gradients were significantly smaller than those predicted by Monin-Obukhov theory, suggesting that turbulence in the ocean surface boundary layer is generated by mechanisms in addition to those found in the bottom boundary layer of the atmosphere. Likely candidates for these additional mechanisms are Langmuir circulation and wave breaking.

RESULTS

This project was designed to address the closure of the TKE budget, our understanding of the relationship between TKE and dissipation, and the determination of the role of wave breaking and Langmuir circulation in setting the turbulent diffusivity in the ocean surface boundary layer. In the process, an analytical model of the vertical structure of TKE (Craig 1996; Burchard 2001) was tested.

The observed dissipation rate of TKE was enhanced relative that expected in turbulence near a rigid boundary. According to the scaling of Terray et al. (1996), our measurements (significant wave heights less than 1 m and measurement depths between 1.35 and 2.55 m) were confined to the wave-affected surface layer and were not shallow enough to reach the wave breaking layer. The dissipation rates showed good agreement with the scaling of Terray et al. (1996) for the wave affected surface layer, which assumes that turbulent kinetic energy is extracted from the surface waves via breaking and dissipates as it is transported downward.

Estimation of terms in the TKE equation showed that local production of TKE was not sufficient to balance the observed dissipation rates (Fig. 2). In particular, both the buoyancy production and Stokes shear production terms were consistently small compared to dissipation. We were unable to measure the storage term consistently, but when measurable, the storage term was also small compared to dissipation. Only shear production (actually an upper bound due to measurement uncertainties) occasionally approached the magnitude of the dissipation rate, suggesting that a local balance could hold for low dissipation rates. For dissipation rates greater than about 2 m^2/s^3, the dissipation rate greatly exceeded even the upper bound on the shear production (Fig. 2).

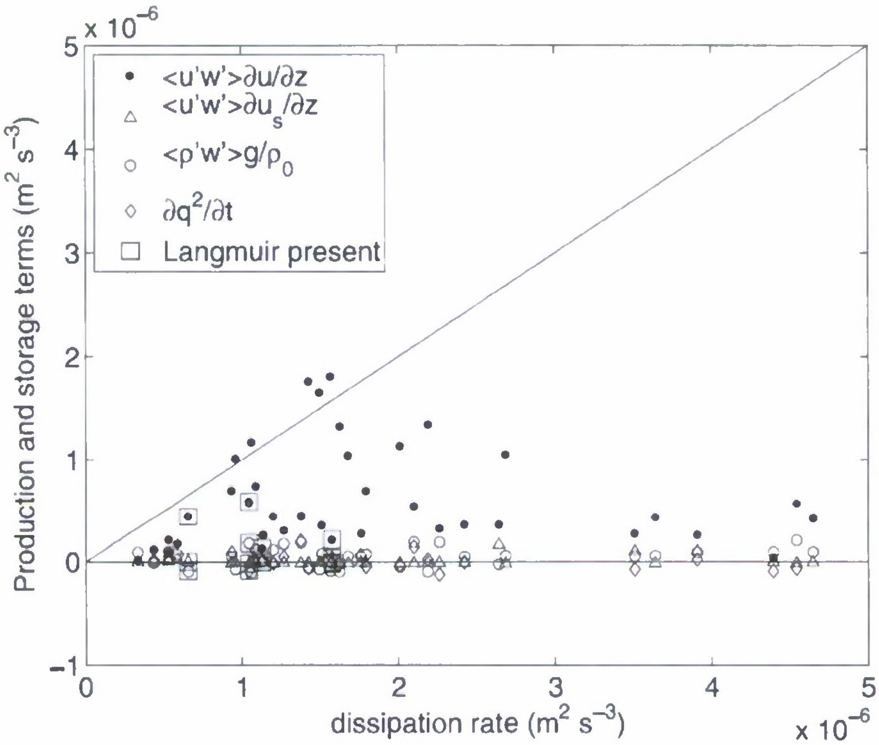

Figure 2. Estimates of shear production (solid circles), Stokes production (triangles), buoyancy production (open circles), and growth (diamonds) terms in the TKE budget vs. TKE dissipation rate. The dissipation term is usually larger than the sum of the other terms, suggesting that terms not included here—the transport terms—are important in the TKE balance. Boxes show times when Langmuir turbulence was detected.

Estimates of the TKE balance showed that the dissipation rate of TKE was not balanced by local production or growth, so that it must be balanced by the divergence of the flux of TKE. To investigate this further, we compared our results to an analytic model developed by Craig (1996) and Burchard (2001) that predicts the vertical structure of TKE by solving the TKE equation and assuming a balance of dissipation, shear production, and transport. This solution has been shown to be consistent with numerical solutions using the full k–epsilon model (Burchard 2001).

As assumed in simplified turbulence closure models, TKE and the dissipation rate in the ocean surface boundary layer are related through a length scale proportional to the distance to the sea surface. However, a proportionality constant smaller by a factor of about 2 than that in rigid-boundary turbulence relates the dissipation rate, depth, and the three-halves power of TKE in the ocean surface boundary layer. With suitable adjustments based on the ocean boundary layer observations, the vertical distribution of TKE is reasonably well explained by the Craig-Burchard one-dimensional model that incorporates the effects of surface gravity waves and shear instabilities (Fig. 3). In particular, this model does a credible job of reproducing the increase in energy at depths shallower than 5 times the significant wave height. The details of the agreement are sensitive to the choice of model constants. As suggested for other constants in closure models (Burchard 2001), the best values may be functions of the relative importance of the local TKE production and flux divergence in the TKE balance.

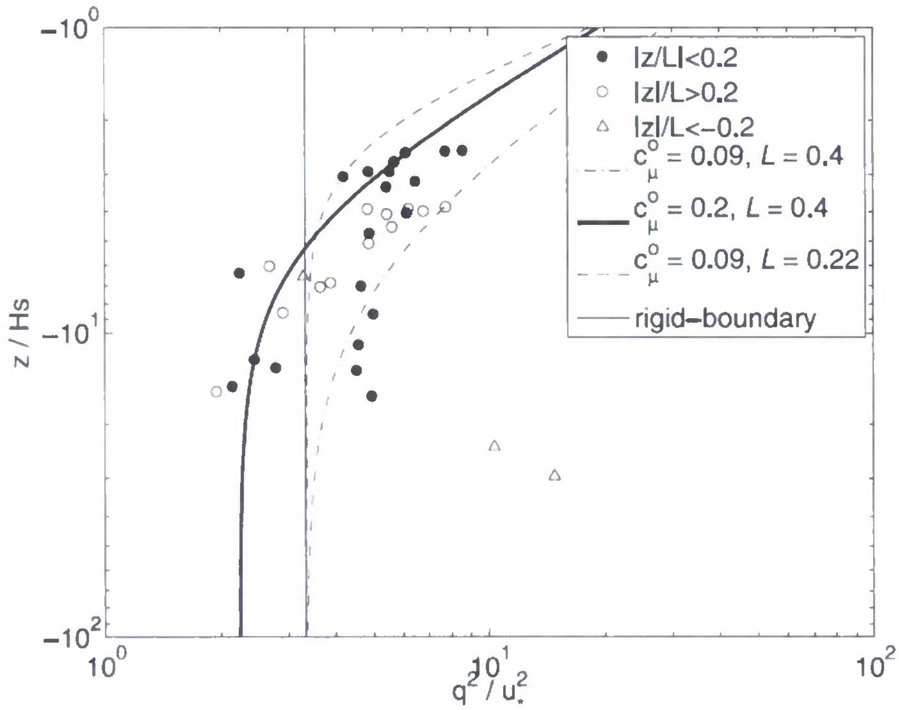

Figure 3. Comparison of the observed TKE profile (symbols) with that expected from analytic solutions to the TKE equation by Craig (1996) and Burchard (2001). Solutions were evaluated with different model parameters (solid, dash and chain-dash curves). The thin vertical line shows the rigid-boundary scaling used in the k–epsilon model (Burchard 2001).

Estimates of boundary layer turbulence properties from the CBLAST ASIT observations were restricted to times of weak to moderate surface forcing. As a result, there were few times when robust Langmuir turbulence was detected concurrently with turbulence energetics. Highlighting the times when Langmuir turbulence was detected did not indicate that it played a distinct role in the energetics or diffusivity. The times when Langmuir turbulence was present did not stand out from the overall distributions when examining the TKE balance (Fig. 2) or comparing observed and modeled heat fluxes. Questions of whether, at what depths, and under what forcing conditions, Langmuir turbulence plays a significant role in surface boundary layer energetics are topics for future research.

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PUBLICATIONS

Gerbi, G.P., J.H. Trowbridge, E.A. Terray, A.J. Plueddemann and T. Kukulka, 2009. Observations of turbulence in the ocean surface boundary layer: Energetics and transport, J. Phys Oceanogr., 39(6), 1077-1096. [published]