Extended Analysis of Near-Bottom Turbulence Measurements Obtained During the Coastal Mixing and Optics Experiment

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LONG-TERM GOALS

The long-term goals associated with this project are to quantify turbulence and to understand the mechanisms and implications of turbulent mixing in the bottom boundary layer of the coastal ocean.

OBJECTIVES

The specific objectives of this project are to test, in the continental shelf bottom boundary layer, (1) simplified budgets for turbulent kinetic energy and scalar variance, (2) simplified flux-profile relationships for momentum and scalars, and (3) vertically integrated momentum and heat balances.

APPROACH

The approach is analysis of a year-long set of near-bottom, time-series measurements of velocity, sound speed, temperature and conductivity, which were obtained between August 1996 and August 1997 as part of ONR's Coastal Mixing and Optics (CMO) program.

WORK COMPLETED

A. J. Williams, a principal investigator on this project during the last funding period, had overall responsibility for obtaining the measurements.

He supervised construction of the "SuperBASS" tripod, which supported a vertical array of seven BASS acoustic travel-time velocity sensors (Williams et al., 1987), a pressure sensor, a vertical array of thermistors, a horizontal array of three of Sontek's acoustic Doppler velocimeters (ADVs), and two temperature-conductivity sensors. The bottom-most and top-most sensors were approximately 0.3 and 7.0 m above bottom, respectively. The BASS sensors were modified to measure absolute as well as differential acoustic travel time, so that they determined sound speed (a surrogate for temperature) and velocity in a single sample volume. The ADVs were all at the same height (approximately 0.3 m above bottom), and they were separated horizontally to permit a technique for removing contamination by surface waves from estimates of turbulent Reynolds stress by differencing measurements from spatially separated sensors (Trowbridge, 1998). The sensors were sampled rapidly (25 Hz for the ADVs and approximately 2 Hz for the other sensors) and the measurements were recorded by synchronized in-situ loggers. G. Voulgaris, a post-doctoral investigator, assisted with preparing the

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ADVs, and W. J. Shaw, a graduate research assistant, assisted with reducing the noise floor in the BASS measurements of sound speed to an acceptable level. Williams deployed the tripod at the central CMO site on the New England shelf, at a water depth of approximately 70 m, in August 1996. He recovered and redeployed the tripod, for the purpose of offloading data and changing batteries, in October 1996, January 1997, April 1997, and June 1997. The final recovery was in August 1997. An array of moorings with velocity, temperature and conductivity sensors extending from surface to bottom were maintained at the same site during the same period by S. Lentz, J. Edson, A. Plueddemann, and S. Anderson. Manuscripts describing the SuperBASS measurement program, the modification of the BASS sensors to produce low-noise measurements of sound speed, and preliminary analysis of the SuperBASS data were published in conference proceedings by Shaw et al. (1996), Trowbridge et al. (1996) and Voulgaris et al. (1997).

Analysis to date has focused on (1) obtaining direct covariance estimates of turbulent momentum and heat fluxes and indirect inertial-range estimates of turbulence dissipation rate for turbulent kinetic energy and scalar variance from ADV and BASS measurements; (2) using the estimates of fluxes and dissipation rates to test simplified budgets for turbulent kinetic energy and scalar variance; (3) using the flux estimates and Reynolds averaged velocity and sound speed measurements to test Monin-Obukhov (MO) similarity theory, a simple flux-profile relationship (i.e., turbulence closure model) developed in the atmospheric literature; and (4) use of the turbulence measurements and moored velocity measurements to test simplified vertically integrated momentum balances for the bottom boundary layer. Portions of this work appear in W. J. Shaw's PhD thesis and in Trowbridge (1998), Shaw and Trowbridge (accepted), Shaw, Trowbridge and Williams (in press), and Shaw and Trowbridge (in preparation).

RESULTS

A simplified budget for turbulent kinetic energy, in which production balances dissipation plus buoyancy flux, is consistent with the SuperBASS measurements (Figure 1). At all heights within the BASS array, production and dissipation are the dominant terms in this balance. Near the bottom of the array ($z \simeq 1$ m), the flux Richardson number (ratio of buoyancy flux to production) is much smaller than 0.2, which is often cited as a critical value, above which turbulence cannot exist. At the middle of the array ($z \simeq 3$ m) and above, the flux Richardson number maintains a roughly fixed value of approximately 0.2, suggesting control of the turbulence by buoyancy effects, even though the buoyancy term in the energy balance is not large.

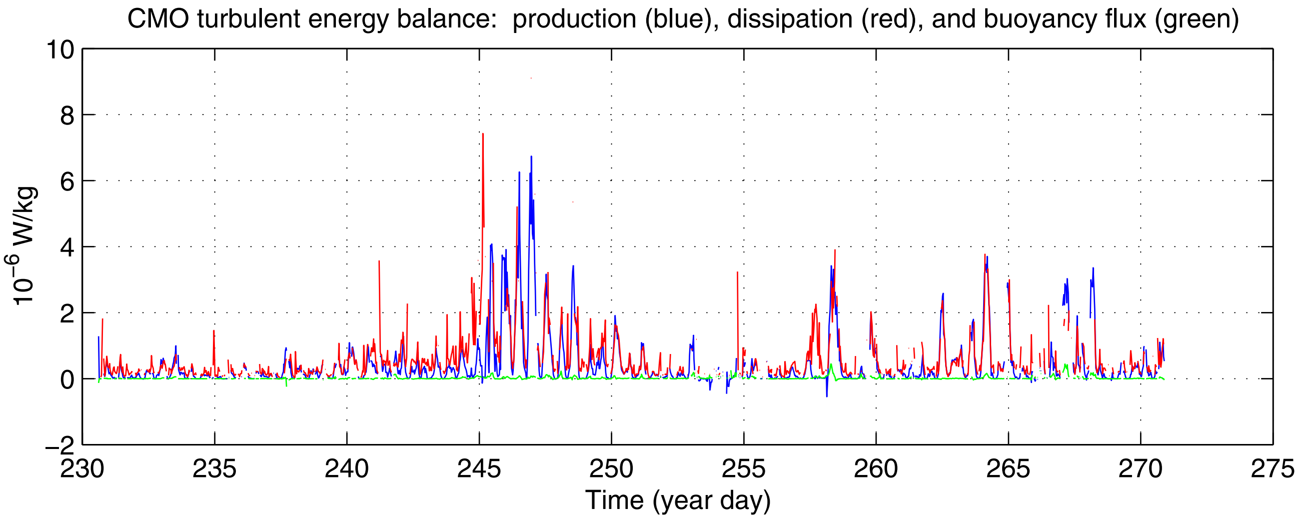

Figure 1. Time series of terms in the turbulent kinetic energy equation based on CMO SuperBASS measurements. Height above bottom for this calculation is 1.6 m. Note that production approximately balances dissipation (squared regression coefficient r^2 = 0.60, regression slope b = 1.2 ± 0.1), and that buoyancy flux is much smaller than production and dissipation.

The SuperBASS estimates of turbulent Reynolds stress and the moored velocity measurements are consistent with an Ekman balance, in which along shore bottom stress balances density times Coriolis parameter times vertically integrated cross-shelf velocity in the bottom boundary layer, relative to the cross-shelf velocity in the overlying flow (Figure 2). Although a cornerstone in geophysical fluid dynamics and shelf dynamics, an Ekman balance has not previously been tested with direct measurements of turbulent Reynolds stress. Successful closure of this balance indicates that the bottom boundary layer dynamics are consistent with classical theory and that the stresses estimated from BASS velocity measurements are representative of the bottom drag experienced by the entire bottom boundary layer. Successful closure of the bottom Ekman balance indicates that estimates of turbulent Reynolds stresses are meaningful, which is important because these stress estimates are an order of magnitude smaller than concurrent wind measurements and an order of smaller than previous estimates of bottom stress in this region, obtained indirectly from an assumed depth-averaged momentum balance.

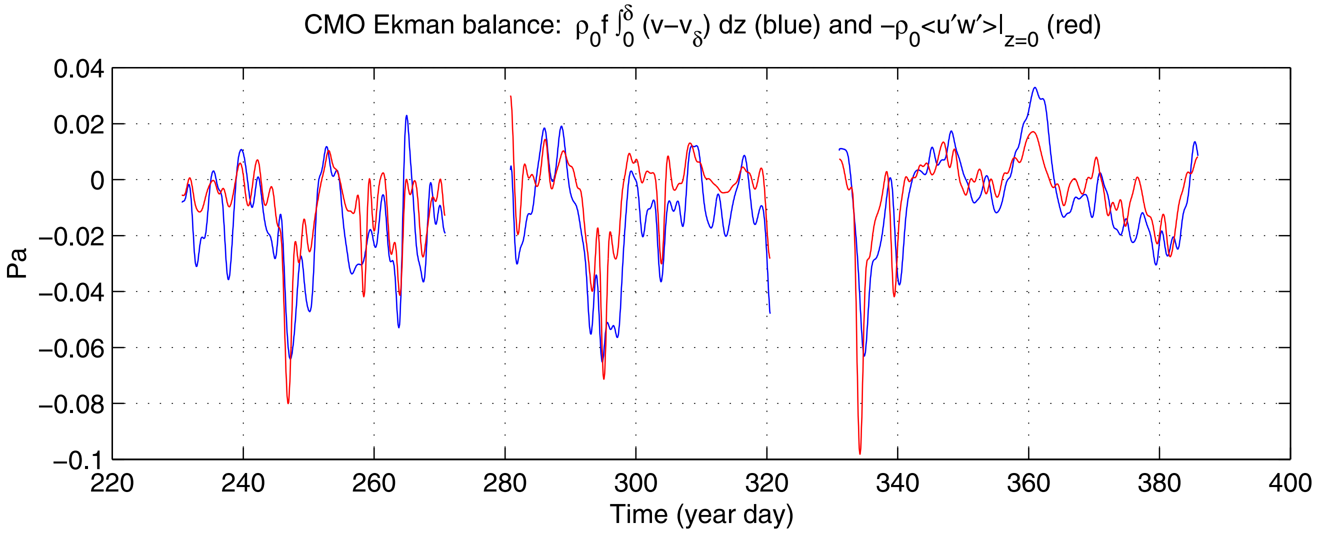

Figure 2. Time series of terms in an Ekman balance, which is a vertically integrated alongshore momentum balance for the bottom boundary layer. Here ρ_0 is a fixed reference density, f is the Coriolis parameter, z is height above bottom, v is cross-shelf velocity, v_δ is cross-shelf velocity at $z = \delta$, where δ is boundary layer thickness, and $-\rho_0 < u'w' > |_{z=0}$ is alongshore component of the turbulent Reynolds shear stress extrapolated to the sea floor. This calculation is based on $\delta = 40$ m. The terms in the Ekman balance agree well ($r^2 = 0.62$, $b = 0.84 \pm 0.05$).

Monin-Obukhov (MO) similarity theory is a simple turbulence closure, which relates velocity gradient ($\partial u/\partial z$), stratification ($N^2 = -g/\rho_0 \partial \rho/\partial z$) and height above bottom (z) to turbulent Reynolds shear stress and turbulent buoyancy flux. Estimates of stress obtained from measured $\partial u/\partial z$, z and N^2 via MO similarity theory are poorly correlated and much larger than direct estimates of stress obtained from covariances of turbulent velocity fluctuations (Figure 3). Thus MO similarity theory fails in this application. A likely explanation is that the boundary layer thickness, a parameter that does not appear in the MO formulation, has an important effect on the near-bottom turbulence dynamics. Future research will address this issue by means of more general turbulence closure models.

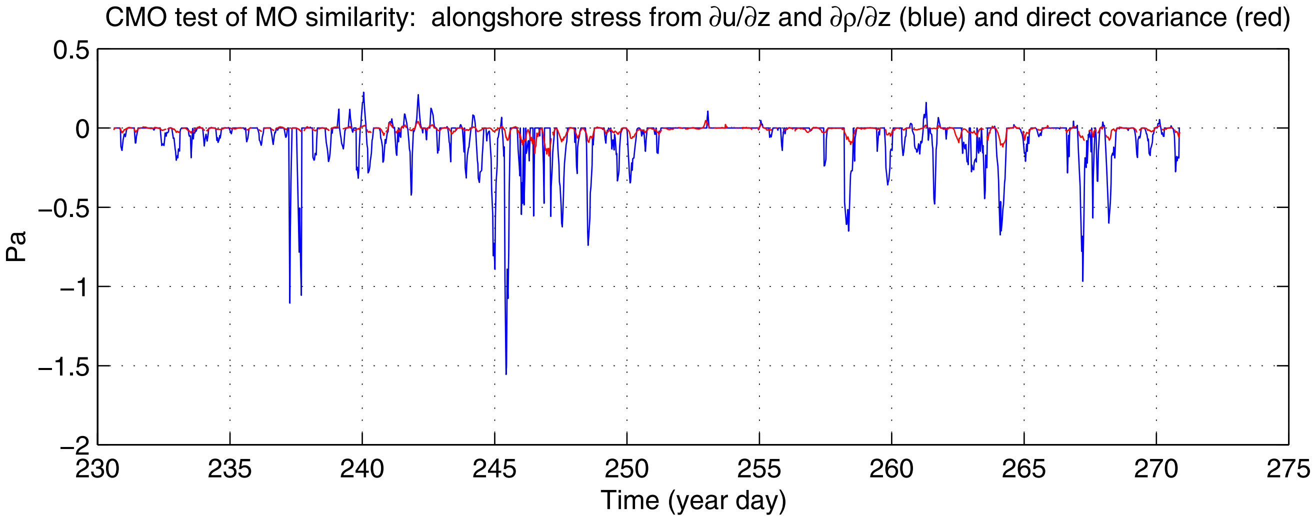

Figure 3. Time series of alongshore bottom stress based on direct covariance estimates of Reynolds stress and based on measured velocity and density gradients via Monin-Obukhov (MO) similarity theory. Height above bottom is 1.6 m. Note that two stress estimates are poorly correlated and dramatically different in magnitude, indicating a failure of MO similarity theory in this application.

IMPACT/APPLICATIONS

This study has demonstrated successful measurement of turbulent fluxes and dissipation rates and their interpretation in the continental shelf bottom boundary layer. This work will lead ultimately to critical tests and improvements of turbulence closure models (such as the widely used Mellor-Yamada model).

TRANSITIONS

The estimates of turbulence statistics obtained during this study are being used in companion studies of sediment transport and particle dynamics by P. S. Hill (of Dalhousie University), Y. C. Agrawal (Sequoia Scientific, Inc.), and P. Traykovski (Woods Hole Oceanographic Institution) (Hill et al., submitted, Agrawal and Traykovski, submitted).

RELATED PROJECTS

Trowbridge's and Y. C. Agrawal's participation in the ONR program HYCODE will capitalize on the techniques for turbulence measurement and analysis that have been developed during this study.

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