

Testing Turbulence Closure Models against Oceanic Turbulence Measurements

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Award Number: N000140010255
<http://www.whoi.edu/science/AOPE/cofdl/jtrow.html>

LONG-TERM GOALS

The long-term goals of this project are to quantify turbulence and to understand the dynamics and implications of turbulent mixing in the coastal ocean.

OBJECTIVES

The specific objectives of this project are to obtain a critical evaluation of turbulence closure models that are commonly used in the coastal ocean, and to identify ways to improve these models. Of particular interest are the MY-2.5 model (Mellor and Yamada, 1974, 1982) and the k - ϵ model (e.g., Rodi, 1987), which involve coupled equations describing turbulent kinetic energy and turbulent scale. Also of interest is the KPP model (Large et al. 1994), which determines the eddy viscosity and diffusivity in terms of boundary layer thickness and boundary fluxes of momentum and buoyancy. In the present applications, work to date has clarified the turbulence energetics (see below), so that the primary focus is on processes controlling turbulence scale, which is by far the most uncertain component of turbulence closure models.

APPROACH

The approach is to compare computations based on turbulence closure models with oceanic turbulence measurements obtained in ONR's Coastal Mixing and Optics (CMO) program and in an NSF-funded study in the Hudson estuary. Turbulence closure models produce estimates of turbulent fluxes, given the Reynolds-averaged profiles of velocity and density. In the CMO and Hudson observational studies, both turbulent fluxes and Reynolds-averaged profiles were measured. Thus the measurements permit direct tests of turbulence models, in contrast to the more common indirect tests, based on measurements of Reynolds-averaged profiles and the assumption of one-dimensional dynamics to infer turbulent fluxes. In addition to measurements of turbulent fluxes, the CMO and Hudson data sets include measurements of dissipation rates, which permits diagnosis of the turbulence energetics.

WORK COMPLETED

Work on this project has focused on two tasks. The first is comparison of computations based on turbulence closure models with measurements obtained in the CMO program. Some of this work is described by Shaw and Trowbridge (submitted). The second task is analysis of a unique set of measurements obtained from a spatial array of near-bottom velocity sensors, which were deployed in shallow water near Scripps pier, in California. Although not described in the original proposal for this

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2001		2. REPORT TYPE		3. DATES COVERED 00-00-2001 to 00-00-2001	
4. TITLE AND SUBTITLE Testing Turbulence Closure Models against Oceanic Turbulence Measurements				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) Woods Hole Oceanographic Institution,,Woods Hole,,MA, 02543				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 The long-term goals of this project are to quantify turbulence and to understand the dynamics and implications of turbulent mixing in the coastal ocean.					
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)	7	

project, the California measurements were pursued because they explicitly determine turbulence scale, which must be inferred from temporal variability in conventional turbulence measurements. The analysis of the California measurements is described by Trowbridge and Elgar (submitted).

RESULTS

Results of the analysis of CMO measurements include successful closure of simplified balances for turbulent kinetic energy and momentum (Figure 1) and an evaluation of MO similarity theory (a simple turbulence closure model) and the KPP model (Figure 2). Detailed explanations of these results are provided in the figure captions. Of particular interest is failure of MO similarity theory (Figure 2a), in contrast to crude but quantitative agreement between measurements and computations based on the KPP model (Figure 2b), because of incorporation of the effect of finite boundary layer thickness on turbulence scale.

Results of the analysis of the California measurements includes explicit determination of the scales contributing to the dynamically important alongshore component of the turbulent Reynolds shear stress (Figure 2). Of particular interest is demonstration that turbulence scales shorten during upwelling-favorable alongshore flows, probably because of the intensification of near-bottom stratification, which limits turbulence scales.

IMPACT/APPLICATIONS

This work will produce critical tests and ultimately improvements of turbulence closure models that are widely used in the coastal ocean.

TRANSITIONS

None.

RELATED PROJECTS

Trowbridge's and Y. C. Agrawal's participation in the ONR HYCODE program will capitalize on the insights about turbulence dynamics and measurements that will be obtained as part of this study.

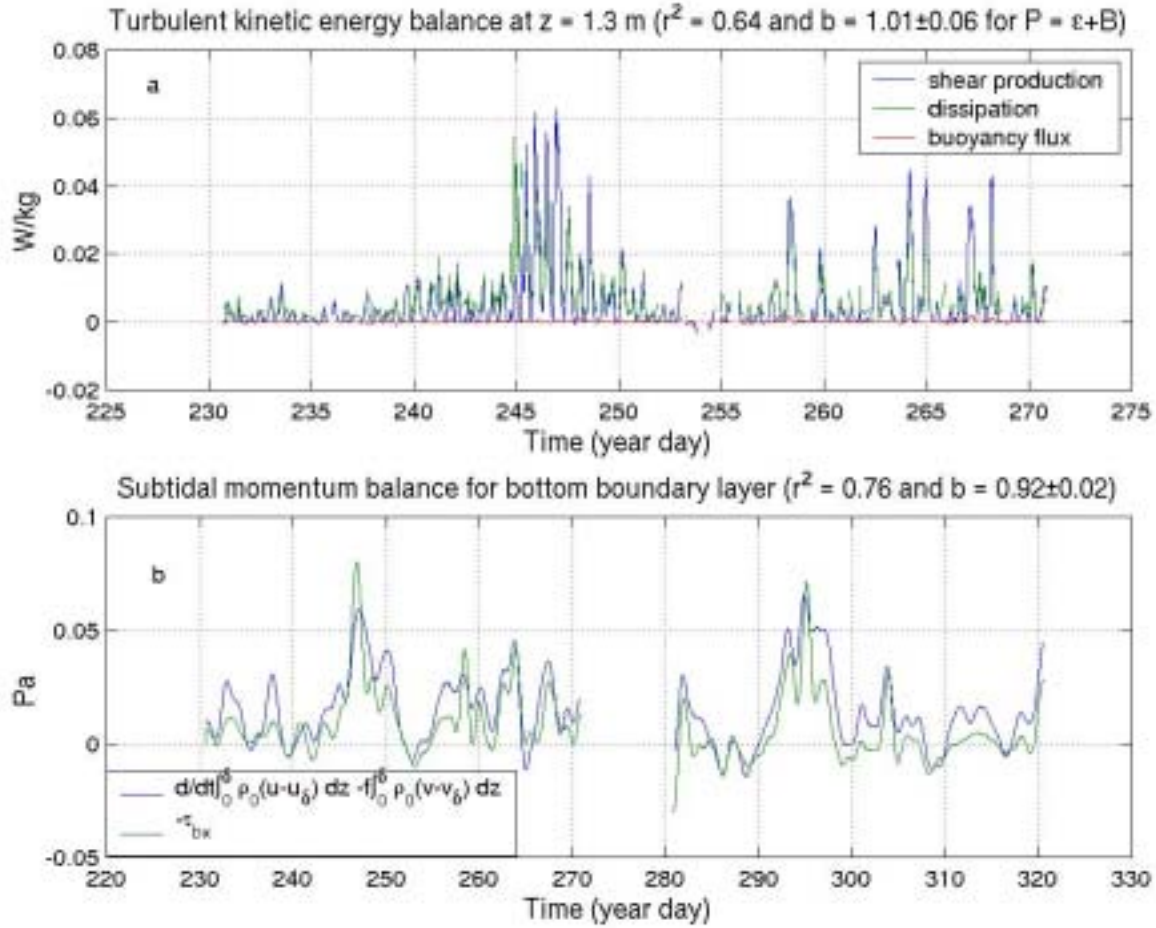


Figure 1. Tests of (a) a turbulent kinetic energy balance and (b) an alongshore momentum balance, based on measurements over the New England shelf during 1996 and 1997 as part of ONR's Coastal Mixing and Optics (CMO) program. The measurements were obtained with an array of BASS acoustic travel-time current meters (Williams et al. 1987) at heights between 0.4 and 7.0 m above bottom. The energy balance tested in (a) is shear production (P) equals dissipation (ϵ) plus buoyancy flux (B). In this example, shear production and dissipation are much larger than buoyancy flux. The balance $P = B + \epsilon$ closes well. The momentum balance tested in (b) is integrated over the thickness of the bottom boundary layer, and involves temporal acceleration, Coriolis acceleration, pressure gradient, and bottom stress. In (b), ρ_0 is a fixed reference density, f is the Coriolis parameter, z is height above bottom, t is time, v is cross-shelf velocity, subscript δ denotes evaluation at $z = \delta$, where δ is boundary layer thickness, and τ_{bx} is the alongshore component of the turbulent Reynolds shear stress, extrapolated to the sea floor. This calculation is based on $\delta = 40$ m. The momentum balance closes well. In both panels, r^2 is the squared correlation coefficient and b is the regression coefficient for the left and right sides of the equation. Successful closure of the turbulent energy and momentum balances implies that the measurements of stress, dissipation, and buoyancy flux are accurate and that the turbulence energetics and bottom boundary layer dynamics are relatively simple.

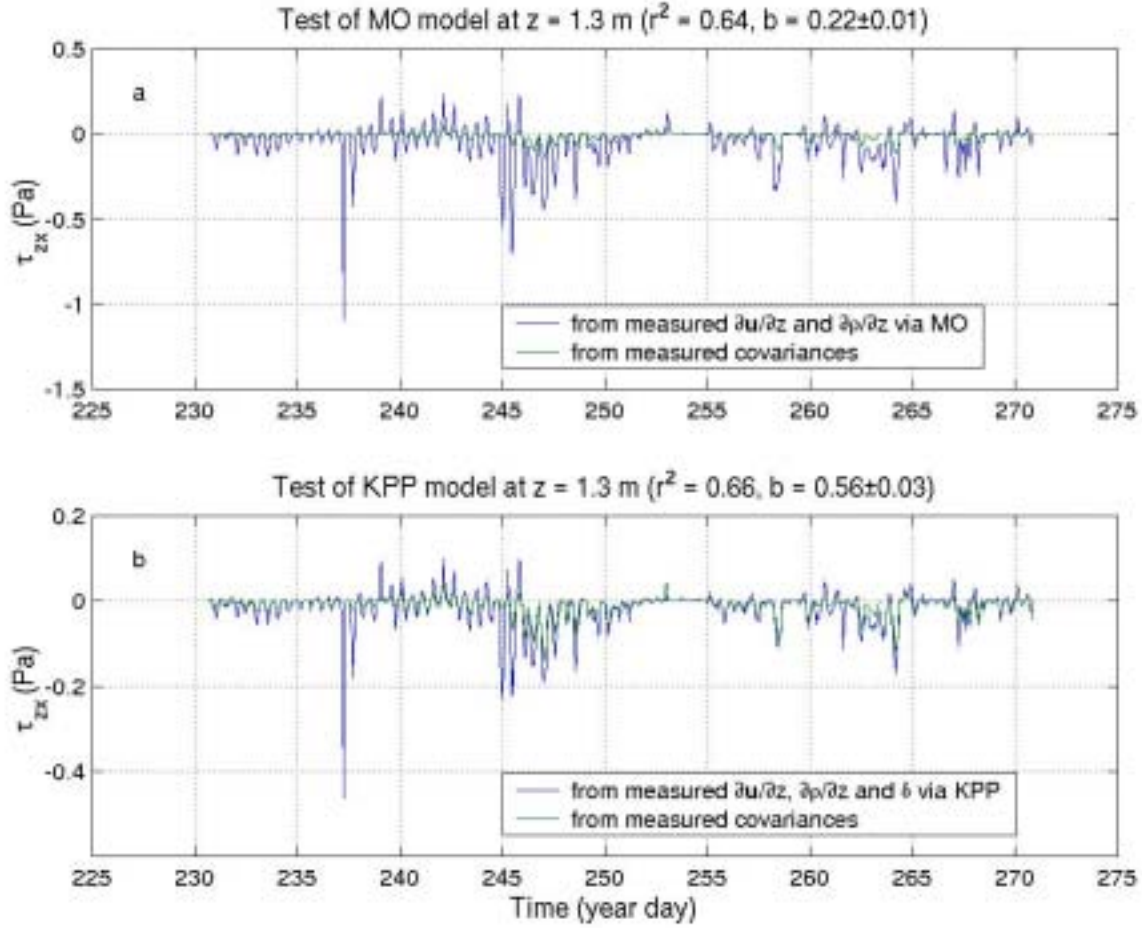


Figure 2. Tests of turbulence closure parameterizations, including (a) Monin-Obukhov (MO) similarity theory and (b) the K Profile Parameterization proposed by Large et al. (1994), based on measurements obtained during the CMO experiment. z is height above bottom, u is the Reynolds-averaged horizontal velocity vector, τ_{zx} is the alongshore component of the turbulent Reynolds shear stress, δ is boundary layer thickness, r^2 is squared correlation coefficient, and b is regression coefficient. In both panels, the Reynolds-averaged velocity and density profiles are inputs to the model, τ_{zx} is the model output, and model estimates of τ_{zx} are compared with estimates obtained directly from the turbulence measurements. In the MO model, τ_{zx} depends only on ρ_0 , z , $\partial u/\partial z$, and $g\partial\rho/\partial z$, where ρ is density and g is gravitational acceleration. In the KPP model, τ_{zx} depends, in addition, on the thickness of the boundary layer. Both MO and KPP estimates of stress are well correlated with measured stresses. The MO estimate is smaller by a factor of five than the measurements. The KPP estimate is better because it incorporating dependence on boundary layer thickness.

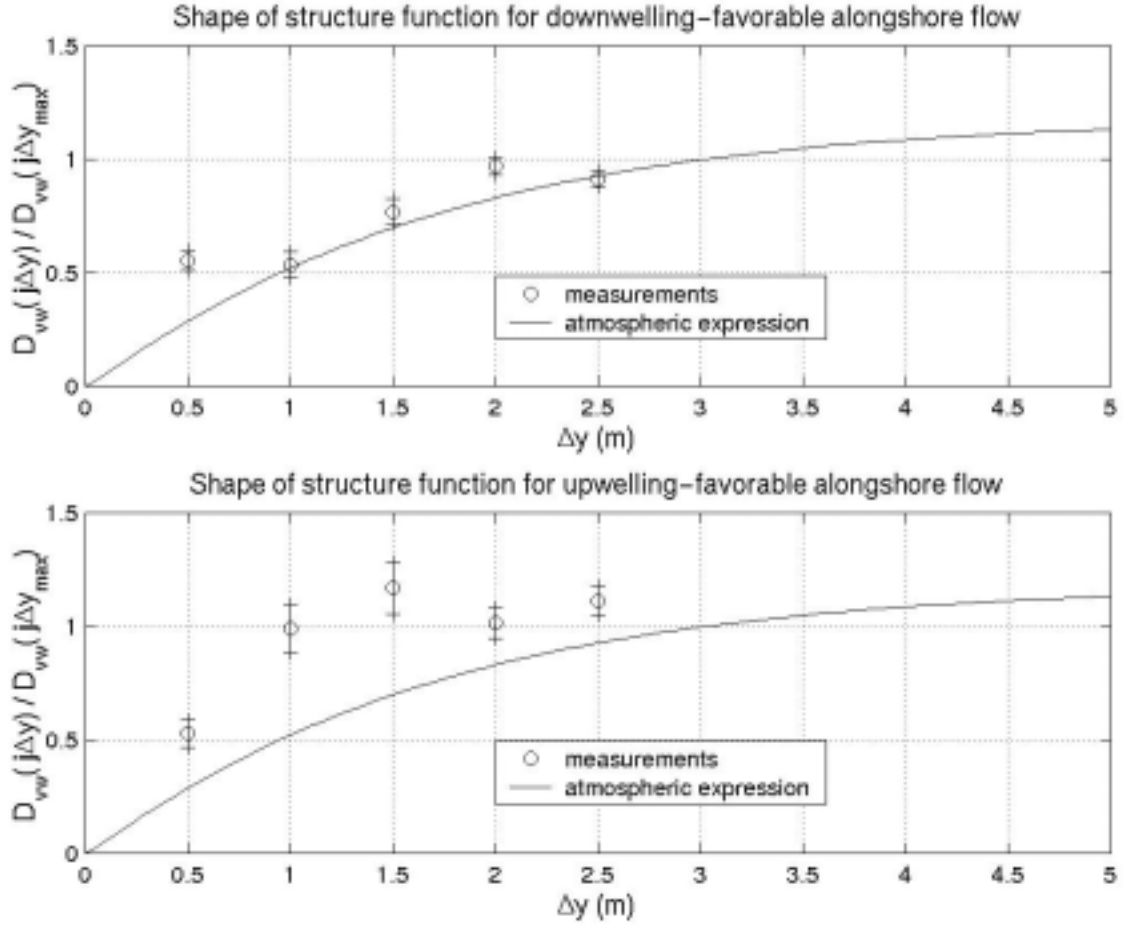


Figure 3. Estimates of the quadratic structure function $D_{vw}(j\Delta y)$, obtained from measurements at a water depth of approximately 4 m near Scripps pier, in California. In this application, the structure function describes the scales contributing to the alongshore component of the turbulent Reynolds shear stress. The measurements were obtained from an alongshore array of velocity sensors. Δy is alongshore separation, and Δy_{max} is the maximum separation resolved by the array. The measurements are compared with an expression based on measurements in the neutrally stratified atmospheric surface layer, in which the ratio of $D_{vw}(j\Delta y)$ to $D_{vw}(j\Delta y_{max})$ depends only on $\Delta y/z$, where z is height above bottom. During downwelling-favorable alongshore flows, the measured structure function is consistent with the atmospheric expression. During upwelling-favorable alongshore flows, however, turbulence scales are shorter than indicated by the atmospheric expression, probably because of near-bottom, stable stratification, which limits turbulence scale and intensifies during upwelling. Turbulence measurements from spatial array of sensors are nearly unique in the ocean, as is the explicit demonstration that turbulence scales shorten during upwelling.

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