REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 5/8/2008	**2. REPORT TYPE** Final Technical	**3. DATES COVERED** *(From – To)* 1/1/06-6/30/08

4. TITLE AND SUBTITLE
Quantifying Turbulence in the Coastal Environment

5a. CONTRACT NUMBERS

5b. GRANT NUMBER
N00014-06-1-0292

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Trowbridge, John

5d. PROJECT NUMBER
130292SP

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
266 Woods Hole Rd.
Woods Hole, MA 02543

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
One Liberty Center
875 North Randolph Street Suite 1425
Arlington, VA 22203

10. SPONSORING/MONITORING ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimite

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long-term objective of our research is to quantify the structure of turbulence in fluvial and estuarine environments, in order to develop remote-sensing tools for environmental assessment as well as to improve numerical simulations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		6	John Trowbridge
					19 b. TELEPHONE NUMBER *(Include are code)* 508-289-2296

Quantifying Turbulence in the Coastal Environment

Dr. W. Rockwell Geyer
phone: 508-289-2868 fax: 508-457-2194 email: rgeyer@whoi.edu

Dr. John Trowbridge
phone: 508-289-2296 fax: 508-457-2194 email: jtrowbridge@whoi.edu

Woods Hole Oceanographic Institution
Applied Ocean Physics and Engineering
98 Water Street, MS #11
Woods Hole, MA 02543

Award Number: N00014-06-10292

Period of Performance: 1/1/2006—6/30/2008

LONG-TERM GOALS

The long-term objective of our research is to quantify the structure of turbulence in fluvial and estuarine environments, in order to develop remote-sensing tools for environmental assessment as well as to improve numerical simulations.

OBJECTIVES

The objectives of this program were:

- to quantify the turbulence length scale and turbulent dynamics in an estuary under varying stratification conditions and geometries, including relatively uniform boundary-layer flows and highly disrupted wake flow conditions;
- to quantify the key properties of observed coherent structures, including horizontal and vertical scales, intensity of vertical motions,
- to provide a field-scale test of turbulence closure models and large-eddy simulations via direct measures of turbulent kinetic energy, length scale and turbulent dissipation rate combined with accurate measures of the Reynolds-averaged quantities.
- to work with the other COHSTREX investigators to ascertain the relationship between surface signatures of the turbulence and the characteristics of the Reynolds-averaged flow, turbulence, density structure and bathymetry.

APPROACH

The Mobile Array for Sensing Turbulence (MAST) is a 10-m long aluminum structure with 6 sets of instruments for measuring the turbulent quantities and Reynolds-averaged velocity and density at multiple depths. The instrument is deployed off the side of a research vessel (fig. 1), either in

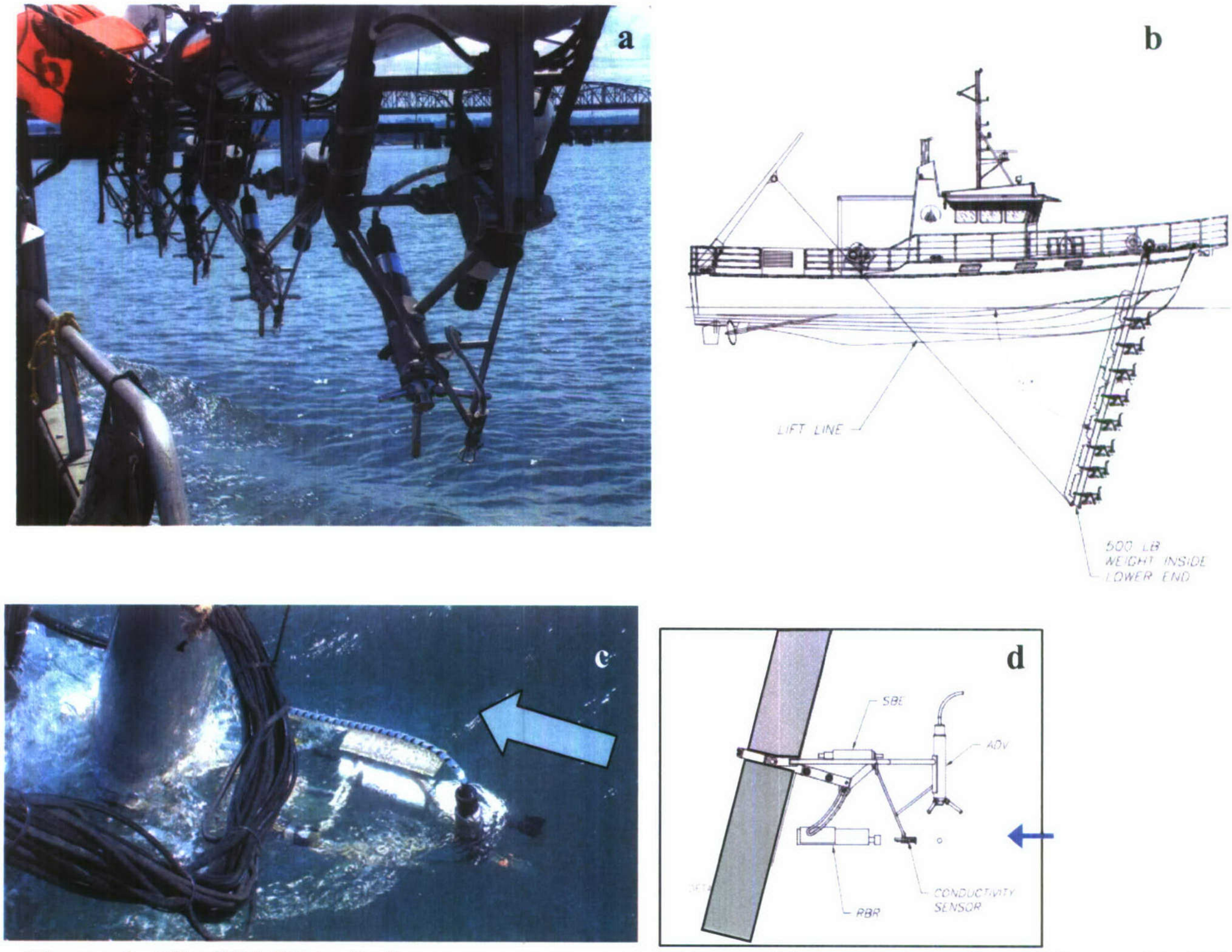

Figure 1. The MAST turbulence measurement system. a) in stowed configuration on the R/V Centennial in the Snohomish River (June 2006); b) schematic of deployed configuration; c) close-up of top sensor bracket; d) schematic of sensors in deployed configuration.

underway mode or at anchor. The depths of the sensors are varied by the tilt of the mast, with the sensor spacing 1-1.5 m in the vertical. Turbulence quantities are measured with co-located Seabird SBE-7 micro-conductivity sensors and Sontek ADVs (fig. 1). The stratification is measured with RBR T-S sensors. The spatial resolution of turbulence measurements is 5-10 cm for velocity (limited by the 25 Hz sampling rate of the ADVs and flows past the sensors of 50-100 cm/s), and less than 1 cm for conductivity (effective sampling rate 200 Hz).

The first field deployment of the MAST was the 2006 COHSTREX experiment in the Snohomish River (Fig. 2). There were three modes of observation: one was a set of anchored measurements in close proximity to a submerged jetty where Jessup and colleagues collected infrared observations; the second was a 30-hour anchor-station to observe the transitions between unstratified and stratified boundary-layer turbulence in the estuarine channel, and the third mode was a set of along-river and across-river transects of the velocity and water properties.

Figure 2. The Snohomish River estuary, showing the locations of the anchor-station observations. The triangle indicates a uniform reach of the estuary, where stratified and unstratified boundary-layer conditions were observed. The circles indicate observations near the jetty, where "wake" conditions were observed.

The turbulence analysis follows Kaimal et al. (1972), fitting the velocity and conductivity spectra to universal shape functions, in order to identify the turbulent length scale and to quantify the turbulent kinetic energy (tke) and dissipation rate. The vertical velocity spectrum was found to provide the cleanest fits to the Kaimal spectrum, and most of the length scale analysis focused on the vertical velocity spectrum. With reliable estimates of the turbulent length scale, the turbulent kinetic energy and the dissipation rate, the scaling of turbulence for different flow conditions—unstratified boundary layers, stratified boundary layers, and wakes—could be tested.

RESULTS

Methodological Advances

The study confirmed that the MAST provides an effective tool for quantifying turbulence in estuarine and fluvial environments. The inertial subrange method is well suited to the high-energy conditions of rivers and estuaries, due to the high Reynolds number of the turbulence and the correspondingly wide intertial subrange. The MAST is well suited to quantifying vertical distributions of the Reynolds averaged and turbulence quantities, which is essential for determining the influence of stratification and proximity to boundaries. It is also effective for quantifying buoyancy and momentum fluxes, which in conjunction with the measurements of Reynolds-averaged vertical gradients provide explicit tests of turbulence closure formulations.

Turbulence Length-Scale

The Kaimal spectral analysis provides robust estimates of the turbulence length-scale L_w, based on the horizontal wavenumber spectrum of vertical velocity variations (hence the subscript w; Fig. 3). The

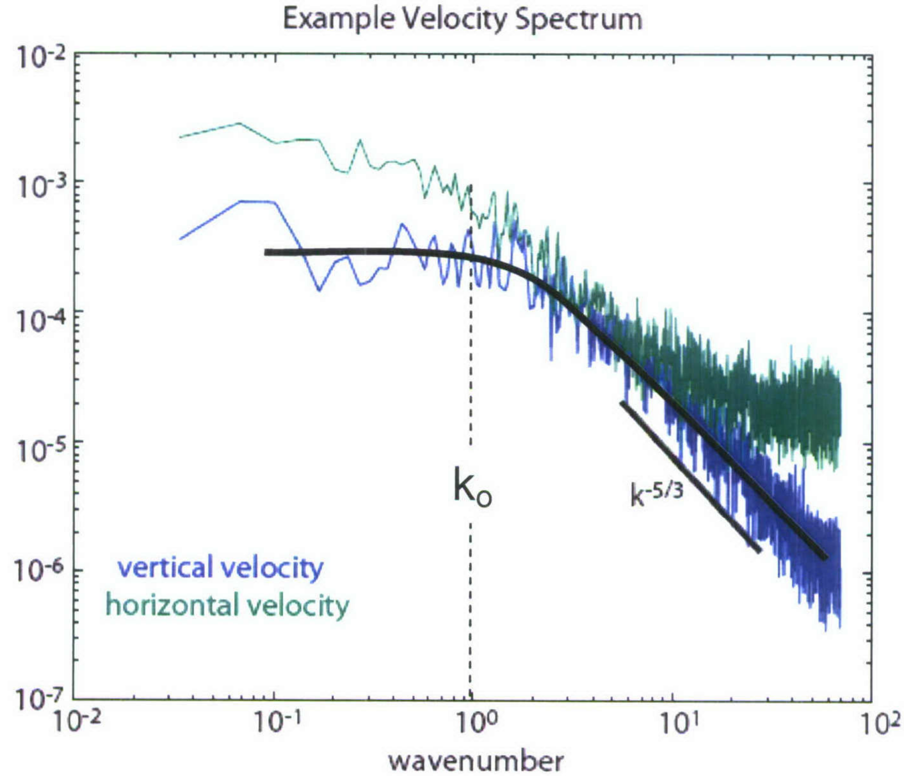

Figure 2. Wavenumber spectra of vertical (blue) and horizontal (green) velocity during the Snohomish field study. The Kaimal fit to the vertical velocity spectrum is shown, with the roll-off wavenumber k_o indicated. The turbulence lengthscale is estimated as $L_T = 0.56/k_o$.

length-scale L_w should provide a key diagnostic as to the nature of the turbulence. Specifically, L_w should vary as the distance from the boundary for unstratified, boundary-layer turbulence, and it should vary as the Ozmidov scale $L_o = (\varepsilon/N^3)^{1/2}$ within stratified shear layers. Deviations from these scaling relationships should indicate non-equilibrium conditions, for example wakes and fronts.

The length-scale analysis confirmed that in "normal" circumstances, i.e., relatively homogeneous and stationary flow conditions, the turbulence length-scale is set by either the Ozmidov scale or the distance to the boundary, depending on which is smaller. In figure 3, the Ozmidov scale is plotted against the MAST estimate of the turbulent length scale, where both quantities have been non-dimensionalized by boundary layer scaling. These two quantities show roughly a linear relationship for values on the x-axis less than one, where the Ozmidov scale is smaller than boundary layer scaling. The data asymptote to a value of roughly one where the Ozmidov scale exceeds the distance to the boundary, consistent with traditional boundary layer theory. This result provides a confirmation that the MAST can reliably quantify the turbulent length scale, and it also provides field confirmation for the Ozmidov scaling of the length scale in highly stratified conditions, for which there are few field observations.

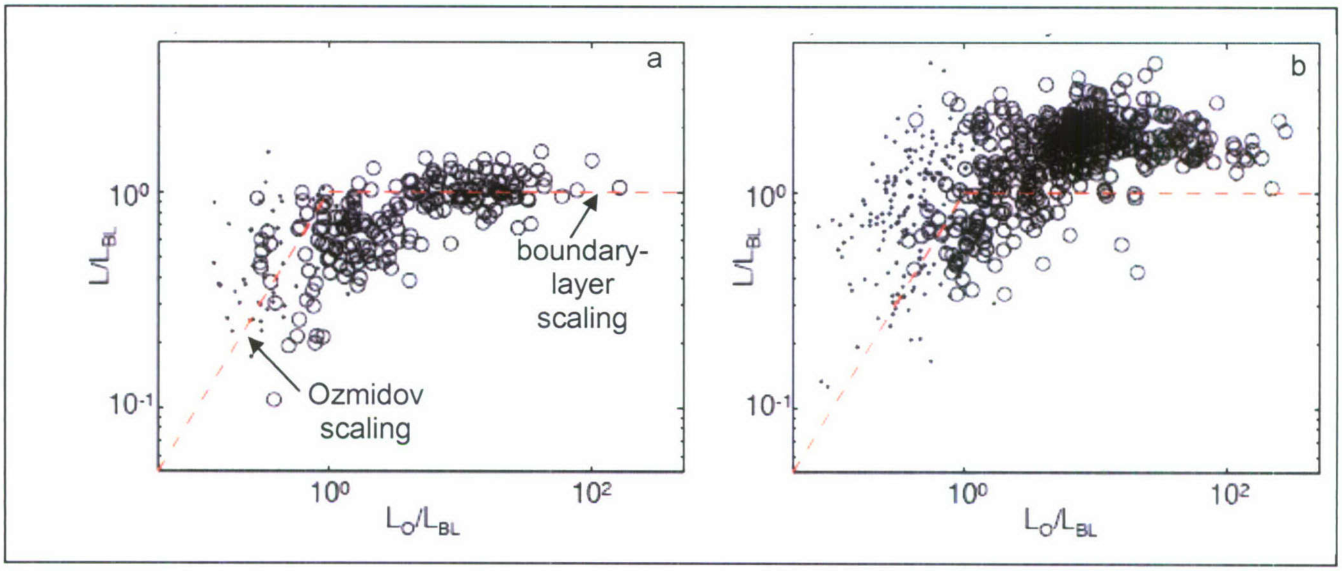

Figure 3. Turbulence lengh-scale non-dimensioanalized against the boundary-layer length-scale $L_{bl} = \kappa z(1-z/h)$ (y axis), compared to L_o / L_{bl} (x-axis), for the uniform boundary layer (a) and the wake of the jetty (b). The uniform boundary layer data confirm the conventional scaling for the lenthscale, whereas the wake data indicate that the turbulence lengthscale is generally greater by roughly a factor of 2.

The data collected in the vicinity of the jetty provide a marked contrast to the data collected during 30-hour anchor station. MAST estimates of the turbulent length scales exceed those expected based on boundary layer theory by roughly a factor of 2 (figure 3). Near surface estimates of length scale are in good agreement with estimates obtained from the infrared observations by Jessup and colleagues. Whereas the 30-hour anchor station data are consistent with either Ozmidov or wall layer scaling, the presence of the jetty imposes an additional length scale on the flow, increasing the turbulent length scale relative to the local production scale.

Another departure from conventional scaling for the lengthscale was observed during the passage of the salinity front during the flooding tide. The turbulence scale exceeded the Ozmidov scale by roughly a factor of two, indicating non-equilibrium turbulence conditions.

Both the jetty data and the observations in the front indicate that in non-equilibrium conditions, the turbulence lengthscale may significantly exceed its equilibrium value. Both the jetty data and the observations in the front indicate that in non-equilibrium conditions, the turbulence lengthscale may significantly exceed its equilibrium value. These results are consistent with the hypothesis that turbulence production exceeds dissipation in regions of rapid transitions in flow conditions, either as a result of changes in flow geometry or the presence of fronts.

IMPACT/APPLICATIONS

The MAST provides unprecedented resolution of turbulence length scale and turbulent kinetic energy through the water column in a coastal environment. Whereas microstructure measurements (e.g., Peters and Bokhorst, 2000) are effective for estimating dissipation, they provide little information about the energy-containing scales of the turbulence or the total tke. The ability of the MAST to obtain continuous timeseries at fixed levels provides the statistical information required to obtain the information about the outer scales of the turbulence.

The key scientific results of this study are 1) confirmation of the Ozmidov scaling of the turbulence lengthscale for uniform, stratified-flow conditions, but 2) significant deviations from either boundary-layer or Ozmidov scaling in regions of flow transitions, consistent with local excess of turbulence production. These observations indicate that non-equilibrium turbulence is important at the scales relevant to rivers and estuaries, and therefore turbulence closure must properly account for departures from a production-dissipation balance. Second-order turbulence closure models include non-equilibrium dynamics, but few measurements have heretofore been available to test model performance under non-equilibrium conditions. Additional analysis of these data will provide a valuable test of second-order closure models.

PUBLICATIONS

Geyer, W.R., M.E. Scully and D.A. Ralston, 2008. Quantifying vertical mixing in estuaries. Environmental Fluid Mechanics (in press).

REFERENCES

Kaimal, J.C, J.C. Wyngaard, Y. Izumi, and D.R. Cote, 1972. Spectral characteristics of surface-layer turbulence. *Quart. J. Royal Meteorological Society*, **98**, 563-589.

Peters, H. and R. Bokhorst, 2000. Microstructure observations of turbulent mixing in a partially mixed estuary. Part I: dissiapation rate. *J. Physical Oceanography*, **30**, 1232-1244.