Shear Production and Dissipation in a Stratified Tidal Flow

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LONG-TERM GOALS

The long term goal of this work is to understand the physics of turbulent stratified shear flows as might be found in coastal regions and estuaries where both shear and stratification are strong. Because these regions are characterized by strong gradients in water characteristics (temperature, salinity and turbidity), the dynamics are influenced by the interaction of tidally-driven flows with the local density field – both vertical and horizontal gradients. We anticipate that such an understanding will permit the development of accurate predictive models of turbulence dynamics for energetic coastal flows. In addition to the interaction of tidal flows with the density field, we are also interested in how the resulting dynamics and stratification affect sediment dynamics.

OBJECTIVES

This project has as its objective analyzing a relatively complete set of observations of turbulence structure and variability in Suisun Cut, a tidal channel in Northern San Francisco Bay collected in October 1999 in collaboration with Mike Gregg of the University of Washington. The strong tidal forcing and density variability in this location are typical of coastal zone flows. Current work builds on our earlier work (Stacey et al. 1999) by including direct measurements of profiles of turbulence dissipation rates (Gregg) and bottom stresses using Acoustic Doppler Velocimeter (ADV) to water column ADCP derived turbulence measurements. Further, in the ONR supported work, we obtained nearly 2 weeks of observations spanning a complete neap-spring tidal cycle. This data set will allow us to both examine longer timescale variability – including the net, long-term circulation – and examine higher order turbulence quantities through additional averaging. The analysis done under the current grant focuses on the interaction of turbulence and stratification and the effects on sediment dynamics.

APPROACH

A comprehensive study of the tidal and spring-neap variability in turbulent mixing and stratification was carried out in October, 1999. The analysis we are carrying out examines the large-scale turbulence dynamics, including the Turbulent Kinetic Energy (TKE), Reynolds stresses, and the shear production,

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14. ABSTRACT

The long term goal of this work is to understand the physics of turbulent stratified shear flows as might be found in coastal regions and estuaries where both shear and stratification are strong. Because these regions are characterized by strong gradients in water characteristics (temperature, salinity and turbidity), the dynamics are influenced by the interaction of tidally-driven flows with the local density field ??? both vertical and horizontal gradients. We anticipate that such an understanding will permit the development of accurate predictive models of turbulence dynamics for energetic coastal flows. In addition to the interaction of tidal flows with the density field, we are also interested in how the resulting dynamics and stratification affect sediment dynamics.

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and how these quantities vary and interact with stratification. We are also attempting to detail the bottom boundary layer structure including sediment flux using a set of bottom mounted ADVs.

WORK COMPLETED

As in previous years, analysis of the data collected in 1999 has proceeded along two fronts:
1. Analysis of ADCP-derived turbulence data including density stratification (U.C. Berkeley). This analysis has proceeded along several parallel tracks, mostly focused on developing publications. First, we have worked out the analysis to quantify the non-local transport of TKE, which resulted in a manuscript submitted to *JAOT*. Second, we have completed the analysis of the structure and dynamics of the benthic boundary layer, which is to be submitted as a manuscript to *JPO* later this fall. Third, the net circulation (timescales longer than the tidal cycle) and the variation of estuarine circulation and mixing on the spring-neap timescale has been examined and the conclusions are being worked into a second manuscript, also for submission to *JPO*. Finally, new analysis of turbulent correlation scales is underway, which will be compared to other lengthscales derived from the shear production. In all cases, we seek to understand how the stratifying forces in the estuary come into balance with the tidally-produced turbulence to define the levels of stratification and mixing observed.

2. Analysis of bottom turbulence and sediment dynamics (Stanford). Analysis of sediment dynamics in the bottom boundary layer has continued to examine the field data from Suisun Cut, but has now been combined with laboratory analysis to examine ADV performance in detail. The laboratory experiment used a submerged turbulent jet seeded with particles to focus on the ADV's ability to resolve turbulent fluxes. The field observations, which have been analyzed to produce time series of fluctuating sediment concentration, have been further analyzed to focus on the effects of stratification and topography on the tidal-timescale sediment dynamics.

RESULTS

Stratified turbulence dynamics

The analysis of turbulence in the bottom boundary layer of this strongly-forced estuarine flow has indicated a strong ebb-flood asymmetry. It appears that the dominant source of the asymmetry is the reversal of the horizontal advective buoyancy flux between ebb and flood tides – during ebbs, the strain induces a stabilizing buoyancy flux, while on floods, the buoyancy flux is destabilizing and the boundary layer is forced by convective instabilities in addition to the traditional shear instabilities. This asymmetry in the forcing of turbulence indicates that the TKE budget will be fundamentally different between ebb and flood tides. This dynamic is summarized in Figure 1, which shows profiles of Reynolds stresses (Figure 1a) and TKE (Figure 1b) for ebb and flood tides (floods have positive mean velocity). The lower panels (Figure 1c and 1d) establish that this asymmetry is not due to the vertical stratification, since the gradient Richardson number is actually smaller on ebbs than on floods. The difference between turbulence on ebbs and floods is instead due to the reversal in sign of the horizontal advective flux, which is a source of energy on floods and a sink of energy on ebbs. Further, the role of diffusive turbulent transport in the TKE budget, as estimated using the triple correlations of the ADCP data, is different between ebbs and floods – with a more distributed diffusive flux on ebbs than on floods; again likely due to the fact that turbulence on flood tides is driven convectively.

At the longer timescale, the transition from neap tides, with reduced turbulent energy, to spring tides results in a decrease in the estuarine circulation. Using the two-week record of turbulent kinetic energy and Reynolds stresses, however, we have been able to directly quantify changes in the turbulence, including the tidally-averaged turbulent fluxes. The implications for the estuarine circulation are currently being considered, but it appears that the up-estuary flow at the bed is much less variable than is the mean shear in the water column. We conclude that water column mixing is more variable than the bed stress, which is most likely due to variable vertical stratification.

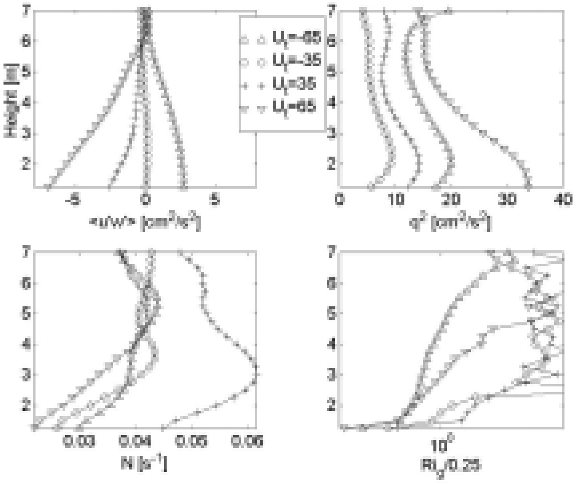

Figure 1: Average profiles of (a) Reynolds stress, (b) turbulent kinetic energy, (c) buoyancy frequency, and (d) gradient Richardson number. Averaging based on depth-averaged mean velocity (as noted in legend, floods are positive). Asymmetry between ebbs and floods is due to horizontal density gradients and associated buoyancy flux, not vertical stratification.

Sediment dynamics – Laboratory Analysis

To complement our use of Sontek ADVs in the field, we tested the turbulent particle flux measurement capabilities of an ADV in the laboratory with a submerged turbulent jet. The jet was seeded with suspended particles at a concentration on the order of 100 mg/L at the jet orifice. In view of the changing background concentration, the acoustic backscatter intensity (*I*) will serve as a direct surrogate for particle concentration. An experimental run consisted of multiple bursts, spaced 1 cm apart to obtain a vertical profile of velocity and particle concentrations within the jet. Overall, the profile demonstrates the expected behavior of a particle-laden jet (Figure 2B), with a centerline peak at z=0 cm (similar to the streamwise velocity, Figure 2A). The asymmetry in <*I*> above and below the jet's centerline is due to the increase in the background concentration over the course of the traverse. Spectra of *I* for half of the bursts (Figure 2C) have the expected -5/3 structure from 0.9 to 3 Hz, but the noise floor evident at approximately 3 Hz is considerably less than the noise floor for velocity spectra, which was above 10 Hz for the same data. The turbulent particle flux (<w'*I*'>) is radially outward on both sides of the jet's centerline (Figure 2D), as is expected in a particle-laden jet. The asymmetry in <w'*I*'> across the centerline is actually determined by the flow dynamics (in contrast to the case of <*I*>). From Figure 2A, the jet's velocity decays less rapidly below the centerline, perhaps because of the constricting effect of the tank bottom, creating asymmetry in the turbulent structure.

Sediment dynamics – Field Analysis

This study examines the effect of complex topography and intermittent stratification on estuarine suspended sediment, which can cause variations in suspended sediment concentration (SSC) on the same order as the predominant erosion flux from tidal currents. During a typical neap tidal day (not shown), which includes a large diurnal inequality in the tidal currents, the only significant resuspension occurs during the stronger ebb and flood tides. Stratification strengthens during the weaker tides, damping the turbulence and hence reducing the bed shear stress to the point where the water column remains almost completely clear of suspended sediment on the weaker tides.

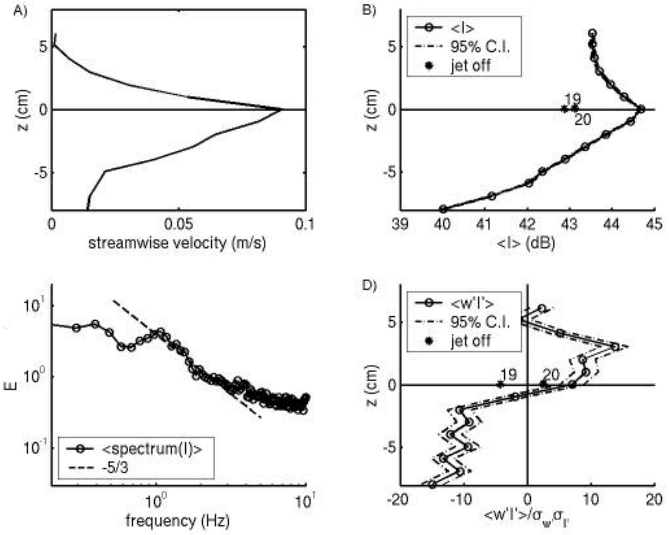

Figure 2: Velocity and acoustic backscatter intensity measurements from an ADV in a turbulent particle-laden jet A) streamwise mean velocity, B) mean acoustic backscatter intensity, C) mean spectra of acoustic backscatter intensity fluctuations, and D) turbulent particle flux. The particle flux is as expected for a high concentration jet at z=0 cm.

In contrast, the stronger currents and reduced diurnal inequality on spring tides produced significant resuspension on all phases of the tidal day (Figure 3A). However, local resuspension cannot explain all of the observed features of SSC, but instead there are three features in the SSC data that can be attributed to non-local transport along the estuary. First, the brief peak in SSC at the beginning of flood tides (t=294.04 and t=298.45), which is limited to the bottom of the water column, is likely due to a near-bed convergence zone associated with a short-lived baroclinic exchange (Figure 3B). The suspended sediment which is trapped in the bottom layer of this exchange flow most likely originated 1.5 km down-estuary (upstream on flood) of the study site at a submerged sill which generates a topographic estuarine turbidity maximum. Second, the large sustained peak in SSC at the end of the weakest tide (t=298.35-29.40) is likely sourced in an up-estuary shoal region, Honker Bay (which is about a tidal excursion away). Finally, the SSC unexpectedly decreases just before the peak currents on flood tides (t=298.1 and t=298.55). The dynamics of this period are dominated by the lateral mixing of water exiting a down-estuary shoal (Grizzly Bay) across the channel, stratifying the water column and decelerating the upper flood currents (analysis presented in Lacy et al., submitted to JGR).

It appears that these waters are also less turbid, such that the water column clears of sediment quite rapidly in the second half of the flood in spite of the strong flood currents.

IMPACT/APPLICATIONS

The data collected during our experiment are advancing our ability to predict the structure and mixing of stratified tidal flows, including sediment resuspension and erosion. In particular, the data will be made available to the coastal physical oceanography community (see websites on page 1) and will be also be used by the PIs in collaboration with colleagues at Stanford (Koseff, Ferziger, and Street) along with LES studies in the development of new parameterizations of stratified turbulence. Moreover, new methods for turbulence measurement using ADCPs and sediment fluxes using ADVs should lead to improved understanding of coastal and near-shore dynamics.

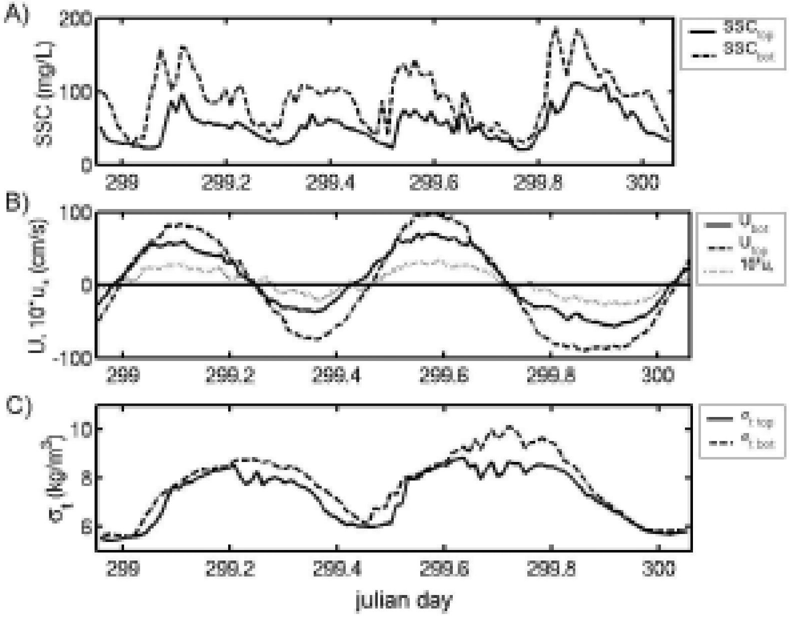

Figure 3: Time series of typical spring day A) suspended sediment concentration; B) streamwise velocity and bed shear stress; and C) density.

TRANSITIONS: None at this time.

RELATED PROJECTS

Observation of physical fluxes between an estuary and the ocean (Sea Grant – Stacey and Powell) – Direct observations of fluxes of water, temperature, salinity, and biological scalars during different seasons to determine which physical mechanisms dominate exchanges.

The role of fronts in estuarine circulation and transport (NSF – Stacey) – Examines the effects of short timescale and small scale features on estuarine circulation, transport and mixing.

Near-shore hydrodynamic conditions and chemical plume tracking (ONR Monismith) - Field experiments looking at plume dispersion and plume source in the near-shore environment as part of the ONR Chemical Sensing in the Marine Environment Program managed by Dr. Keith Ward.

Acquisition of a REMUS AUV for autonomous coastal flow mapping (ONR- Monismith). This DURIP grant will enable us to purchase a REMUS AUV.

PUBLICATIONS

Stacey, M. T. “Estimation of dispersive transport of turbulent kinetic energy from acoustic Doppler current profiler data,” submitted to *J. Atmos. Ocean. Tech.*, 2002.

Lacy, J., Stacey, M. T., Burau, J. R., and Monismith, S. G., “The interaction of lateral baroclinic forcing and turbulence in an estuary,” submitted to *J. Geophys. Res.*, 2002.