SOME PHYSICAL FACTORS THAT MAY AFFECT TURBULENT MIXING IN ALTAMAHA SOUND, GEORGIA

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Abstract. A directed studies research project to understand turbulent mixing processes in Altamaha Sound has been carried out as part of the Georgia Coastal Ecosystems Long Term Ecological Research (GCE-LTER) project. In this study we analyze the flow and salinity characteristics, which has a periodic component of stratification that interacts with turbulent mixing to control water column stability. There is a contrast between the ebb and flood phases of the tides showing that during ebb, the water column is well mixed indicating that shear instabilities give rise to turbulent mixing and that during flood, density gradients stabilize the variations caused by the current shear. These results are contrary to tidal straining theory and are hypothesized to be related to shoaling surrounding the Altamaha channel towards the ocean. Because of shoaling, surface gravity waves may play a key role in enhancing bottom stress variability during flood flow. The physical factors that control turbulence in the coastal ocean are very important for understanding the mixing of water masses and thus the distribution of chemical, biological and physical properties that directly affect water quality.

INTRODUCTION

Coastal tidal channels are sites of enhanced mixing because of the high flow speeds and strong shears that are formed by tide, buoyancy and wind/wave forcing. Turbulence is a very complex fluid motion, which is irregular, random, highly dissipative, three dimensional, and continuous (Tennekes and Lumley, 1999). Its spatial scales are usually small ranging in general from several centimeters to tens of meters. Because of the small scale motion and intermittent spatial and temporal characteristics, it is difficult to measure turbulent flow in the coastal ocean and many researchers have tried to do it since the 1950s (Nihoul, 1977). With recently developed high frequency acoustic techniques it is possible to directly measure many turbulent quantities within the bottom boundary layer and water column of estuarine and coastal environments (see for example Lu and Lueck 1999; Stacey et al. 1999; Rippeth et al., 2001; and Shaw et al, 2001).

One of the difficulties in studying turbulence in the coastal bottom boundary using observational data is that the turbulent flow and hence stresses are often contaminated by surface waves. The coastal surface waves produce velocity variances typically larger than those related to the turbulent flow (Grant and Madsen, 1979) but of the same spatial scale as the energy containing turbulent motions. For measurements in the nearshore Trowbridge (1997) developed a differencing method which removes the bias by surface waves in turbulent shear stresses.

Recently, turbulence in estuarine and coastal regions has become an area of interesting oceanographic phenomena with critical issues related to energy dissipation and friction of surface/bottom boundary layer, erosion and deposition of fine sediments, redistribution of chemical elements and biological nutrients, and even pollutant trapping and releasing. Bottom turbulence is a key factor to understanding many of these processes and for the development of circulation models in these areas. Many observational and numerical studies have been carried out in coastal Georgia regions and Seim et al. (2002) have made some turbulent stress observations.

Turbulent mixing and turbulent flow characteristics are an essential factor in understanding the hydrodynamics of estuaries and in modeling the interaction between intertidal and nearshore systems. The principal objective of this paper is to present turbulent flow characteristics in Altamaha Sound, and show how those characteristics may change over time in terms of tidal, wind, and wave forcings.

EXPERIMENTAL METHOD

The estuarine system of Georgia is characterized by a series of barrier islands, extensive salt marsh complexes, and narrow, shallow channels that connect the estuaries to the open ocean. One of the largest estuarine systems in Georgia is formed from the Altamaha River, which has an annual average river flow of 380 $m^3 s^{-1}$ with peak flow during early spring (Alber and Sheldon 1999). The general circulation is driven by fresh water discharge, tidal-, and to a lesser extent wind- and wave-induced flow. The tidal range can be as much as 1.5 to 3.0 m with corresponding strong currents (>1 m/s) in the main channels.

Figure 1 shows the study area with corresponding instrumentation during a Georgia Coastal Ecosystems Long Term Ecological Research cruise in the Altamaha Sound area over a spring/neap cycle in May 2001. During an 8 day period, we moored an acoustic Doppler velocimeter (ADV) designed to measure turbulent bottom boundary layer dynamics and surface wave heights, an acoustic Doppler current profiler (ADCP) for water column currents and shear, and conductivity-temperature-depth (CTD) profiles were obtained every 30 min for 13 h at an anchor station close to the moorings during spring and neap tide. The oceanic wind and wave forcing parameters are obtained by the National Data Buoy Center station 41008 located at Grays Reef National Marine Sanctuary approximately 30 km offshore Sapelo Island and showed southerly winds typically 8 m/s.

The experiment was carried out with the following questions in mind: 1) Does the surface wave field contribute to the turbulent flow in terms of bottom Reynolds stresses, turbulent kinetic energy dissipation and production? 2) How does the water column stability, hence the stratification, change with tidal period?

RESULTS

Figure 2 summarizes the data collected from the bottom mounted ADCP and ADV instruments. Profiles of the along channel currents show an ebb dominated flow with tidally and depth averaged net flow out of the estuary ranging from 0.06 to 0.1 m/s. The coordinate convention used here is positive currents on ebb (approximately to the east) and negative currents on flood (approximately to the west). The bottom stress is measured in terms of the Reynolds stress: $-<u'w'>$ and shows the expected periodic pattern associated with the tide. During flood, however, the Reynolds stress shows slightly greater magnitudes than during ebb with greater variability. This difference persists over the spring/neap cycle (day of year 149-156) and is contrary to what would be expected for ebb dominated flows. A possible explanation is given in terms of the

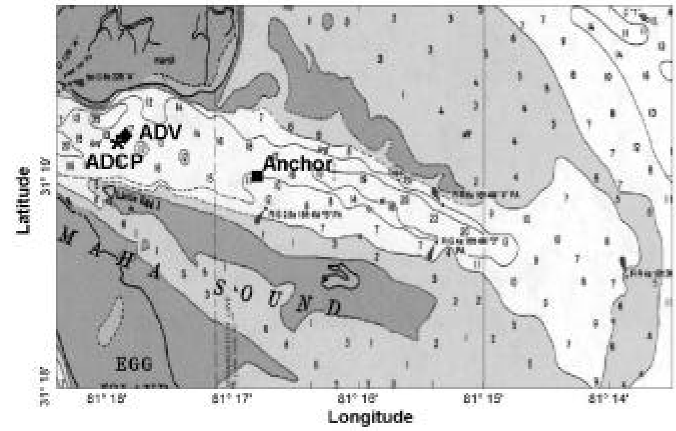

Figure 1. Altamaha Sound showing instrument and anchor locations. Depth is in feet at mean lower low water.

surface waves, which are larger during the flood tide as will be discussed.

Figure 2 also shows the turbulent kinetic energy (TKE), the dissipation rate of TKE which represents a loss of energy to heat due to molecular viscosity, and the production rate of TKE ($P = -<u'w'> dU/dz$) by the working of the mean flow against the Reynolds stresses. The greatest shear occurs during ebb flow and thus the production of energy during ebb flows is greatest despite the slightly greater stresses during flood. This characteristic of increased shear during ebb flow has a marked effect on the stability of the water column and the resulting mixing that takes place.

The final image of Figure 2 is the wave height spectral density determined from the pressure sensor of the ADV specifically sampled at 4 Hz for sea surface wave characteristics. Sea surface waves cause pressure modulations that are attenuated with depth. Spectral analysis of this data shows that there is a modulation of the sea surface with the corresponding tide and that wave-current interactions cause frequency modulations because of the frequency dependence on the current via the dispersion relation. In addition, frequency harmonics of the sea surface waves are shown as three main bands. During flood tide the sea surface waves propagate with the currents and are elongated. During ebb tide the sea surface waves propagate against the current and are steepened. As a result, the waves break over the ebb shoal, dissipating energy so that during ebb very little wave energy enters into the main channel. The fact that the Reynold's stress measurement during flood is more erratic could be directly related to this flood/ebb

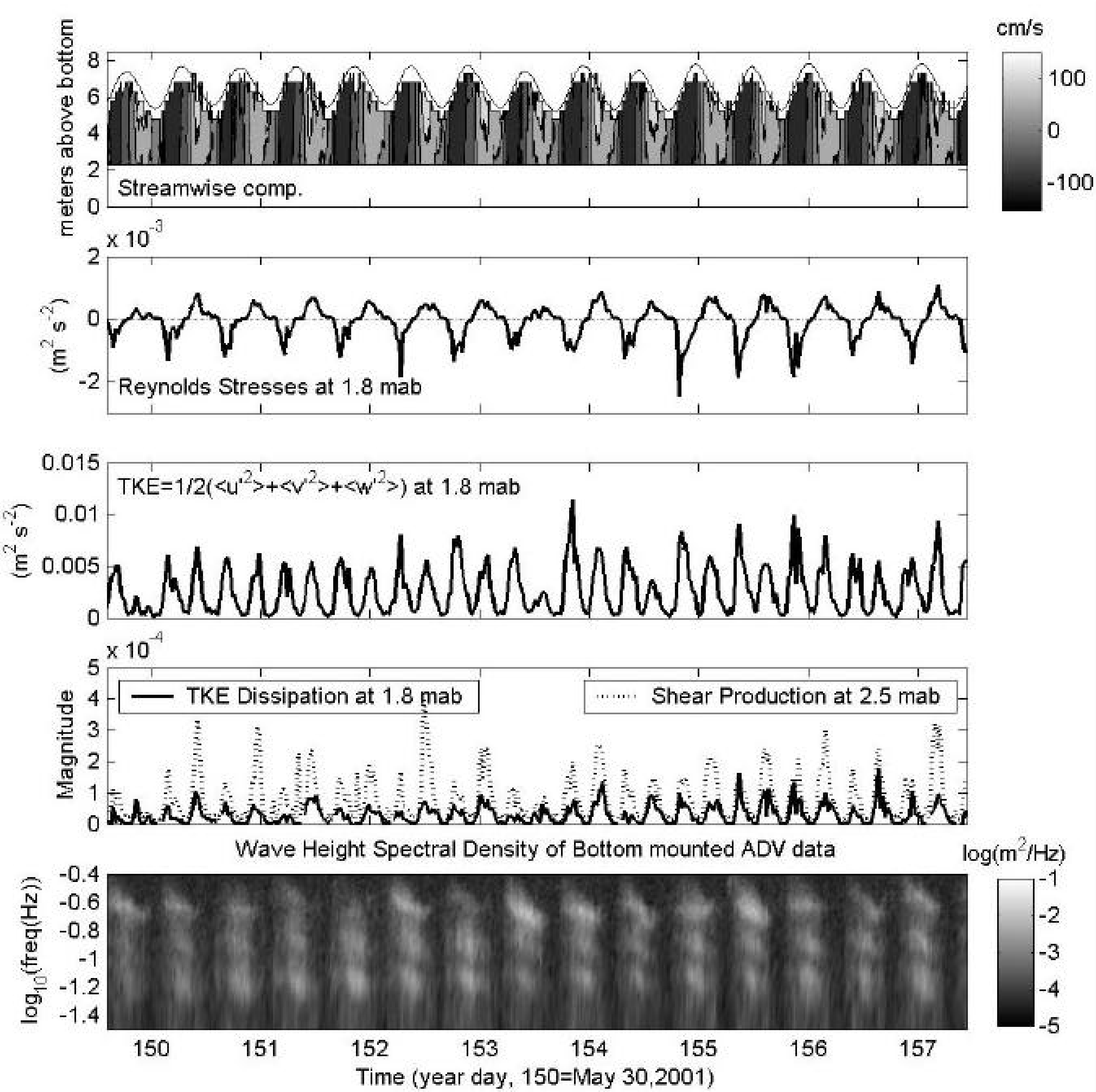

Figure 2. Time series data from moored ADCP and ADV instruments. From top to bottom: current profiles, bottom stress at 1.8 meters above bottom (mab), the turbulent kinetic energy, turbulent kinetic energy dissipation and production rates, the sea surface wave height spectral density.

asymmetry in sea surface waves propagating in the channel.

The water column stability is parameterized in terms of the gradient Richardson number,

$$\mathrm{Ri} = \frac{\frac{-g}{\rho}\frac{\partial \rho}{\partial z}}{[(\frac{\partial U}{\partial z})^2 + (\frac{\partial V}{\partial z})^2]}, \qquad (1)$$

where g is gravity, ρ is the mean density, dρ/dz is the vertical density gradient and the denominator is in terms of the along and cross channel shear. The gradient Richardson number defined by (1) is calculated with 1 m resolution in the vertical and the results are shown in Figure 3 near neap and spring tides. The mean currents show higher shear during spring ebb as a result of the greater mean flow seawards.

The Altamaha River estuary can be classified as a well-mixed estuary and density profiles show that during ebb to slack low water (SLW) the water column is essentially well mixed. But during flood however weak stratification exists. During the flooding current the Ri was consistently >0.25 throughout the water column indicating that the density gradient stabilizes the variations caused by the current shear. As the current starts to ebb the Ri<0.25 indicating that shear instabilities give rise to turbulent mixing and thus the water column becomes well mixed. This is contrary to tidal straining theory of Simpson (1995) in which during the ebb tide the stratification is enhanced thus suppressing vertical mixing and during flood the water column is completely mixed as a result of oceanic water flowing over less dense estuarine water.

CONCLUSIONS

The data presented in this paper shows that bottom generated turbulence in Altamaha Sound dominates the 8 m water column with energetic levels. The flood/ebb asymmetry in the Reynolds stress and surface gravity wave characteristics opens up new questions on how the Reynolds stress may vary as a function of depth over the tidal cycle and the resulting mixing levels in the water column. This kind of measurement may also give insight into the flood/ebb differences in the water column stability. Wave breaking on the ebb shoal at the mouth of the Atlamaha River is hypothesized to be one controlling factors that limits the transmission of wave energy between the estuary and the open ocean.

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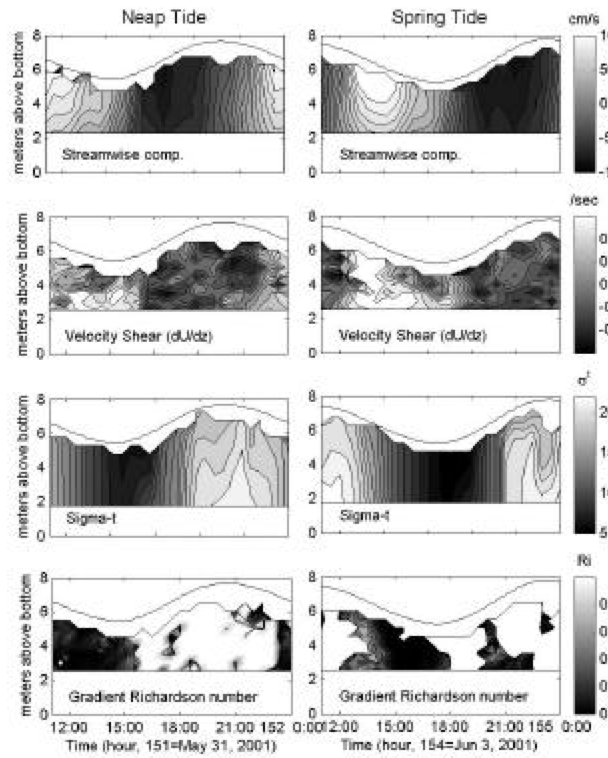

Figure 3. Neap and spring time variations for: profiles of the along channel current speed, the density, the velocity shear and the gradient Richardson number.

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