Remote Sensing of Temperature and Salinity Microstructure in Rivers and Estuaries Using Broadband Acoustic Scattering Techniques

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Abstract

The long-term goals of this research are to 1) measure and understand high-frequency broadband acoustic scattering in rivers and estuaries characterized by strong temperature and salinity gradients and intermittent, high dissipation rates of turbulent kinetic energy, and 2) use these measurements and understanding to develop a remote sensing tool for quantifying the structure of stratified turbulence.

The specific objectives are to:
1. Measure high-frequency broadband acoustic backscattering in highly stratified, energetic, estuarine environments, where there is significant salinity stratification, high shear, and high dissipation rates of turbulent kinetic energy.
2. Validate these measurements, and support their interpretation, by performing coincident, direct measurements of turbulence parameters at similar scales to the acoustic measurements. Estuaries provide an excellent environment to quantify stratified turbulence and its influence on acoustic backscattering, as these environments provide a broad range of stratification and turbulence intensities within a single tidal cycle.
3. Test the validity of existing microstructure scattering models, determining the range of conditions under which these scattering models are valid, and quantifying the contribution to scattering from salinity versus temperature variance over a broad frequency range.

Background

Significant improvements in both the visualization and quantification of acoustic scattering from stratified turbulence can be achieved through the use of broadband acoustic scattering techniques, spanning multiple octaves of bandwidth (Lavery et al., 2009; Lavery et al., submitted). The goal of these high-frequency broadband acoustic scattering techniques is to capitalize on the different characteristic frequency-dependent spectra associated with different scattering sources, which may in principle lead to decreases in the ambiguities associated with interpretation of acoustic scattering measurements. Furthermore, once a scattering source has been identified, broadband acoustic scattering measurements may lead to more robust inversion of the acoustic spectra for pertinent parameters, such as the dissipation rate of turbulent kinetic energy. The most robust method for inverting measurements of acoustic scattering from microstructure, as well as for classifying particular scattering features as being dominated by scalar microstructure, involves measuring acoustic spectra over sufficient bandwidth that both the temperature and salinity dissipative roll-offs are resolved (Lavery et al., 2009). To invert measurements of acoustic scattering from turbulence-induced microstructure, it is necessary to use an accurate acoustic scattering model that describes the scattering of sound from microstructure (Lavery et al., 2003), as well as to use a turbulence model that adequately describes the spectra associated to scalar variances of heat and salt in stratified turbulence (Ross et al., 2004). For well-developed turbulence, acoustic scattering from turbulence-induced microstructure is related to the three-dimensional spectra of temperature and salinity fluctuations and their co-spectra. Testing of these models was one of the goals of this research. To date, however, there is no scattering model that includes anisotropy or scattering from turbulence that is not fully developed. An additional benefit of broadband acoustic techniques is the ability to perform matched-filter-based signal processing, resulting in greatly increased resolution in range (Turin, 1960; Chu and Stanton, 1998; Stanton and Chu, 2008).

The approach taken here to understanding acoustic scattering in highly stratified, energetic environments involves the combination of field measurements performed using emerging broadband acoustic techniques, simultaneous characterization of as many sources of scattering as possible, and interpretation of the data within the framework of existing physics-based acoustic scattering models. The Mobile Array for Sensing Turbulence (MAST) provides an ideal platform for simultaneously measuring in-situ turbulence "directly" and acoustic scattering in highly-stratified estuarine environments. In previous studies, co-located measurements of acoustic backscatter and turbulence (e.g., Seim et al., 1995; Moum et al., 2003; Ross and Lueck, 2003) have provided far greater spatial-temporal resolution of turbulent structures than could have been accomplished with turbulence sensors alone. However these prior studies relied on microstructure profiles, which are not well matched to the measurement volumes of acoustic backscatter systems, and as a result the actual coincidence of acoustic and turbulence measurements is too limited to provide a rigorous examination of the turbulent structure. The MAST, in contrast, provides continuous measurements of turbulence quantities at multiple levels within the field of view of the acoustics, allowing detailed comparison between the structures revealed by acoustic backscatter and the continuous turbulence measurements.

The work performed here to better quantify acoustic scattering by turbulence has provided an unparalleled opportunity to quantify the structure of stratified turbulence, due to the synergy between the imaging capability of the acoustics and the in-situ measurement capability of the MAST. This combination of measurements has lead to new insights about the structure of stratified turbulence at high Reynolds number. These results underscore the importance of refining these techniques for quantifying the spatial structure of turbulence.

Work Completed

Two field experiments in the Connecticut (CT) River (Figure 1) were performed in November 2008 and November 2009. The CT River was chosen as a desirable location for the field work as strong acoustic backscatter (measured with an ADCP) had been seen previously associated with intense shear instabilities, with classic Kelvin-Helmholtz appearance, formed when fresh surface water ebbed over a relatively stationary saltier lower layer.

The primary platform for the measurements was the MAST (Figure 2) which was deployed from the R/V Tioga (WHOI's 60' coastal research vessel). The MAST is 8" in diameter, 5 m long, with 8 sensor locations with adjustable depths, and is designed to make measurements in 0.3-2 m/s flow. The MAST provides a unique means of measuring turbulent velocities and scalar fluxes in shallow, stratified environments. The turbulence sensor suite at each depth includes acoustic Doppler velocimeters (ADVs- sampling at 25 Hz), micro-conductivity sensors (SBE-7 sampling at 200 Hz), CTD measurements (RBR sampling at 6 Hz), in addition to an altimeter and an inertial measurement system for supporting measurements of platform motion. This instrument platform provides continuous measurements at multiple vertical locations through the water column, producing continuous temporal resolution of the turbulent processes. This advanced turbulence-resolving platform provides critical support for the acoustics measurements as well as providing unprecedented measurements of turbulent stress, buoyancy flux, mixing efficiency and turbulence length scales in stratified, estuarine flows. In addition to the MAST, a profiling microstructure instrument was deployed in November 2008, ADCP measurements were performed, and continuous CTD profiles were performed from the R/V Mytilus (WHOI's 24' coastal research vessel) in Novmber 2008. Two broadband acoustic backscattering systems were deployed (Figure 2): 1) a compact, low-power system developed at WHOI with three broadband transducers with center frequencies at 200 kHz, 500 kHz, and 1 MHz, and mounted on the MAST, and 2) a pole-mounted system developed by Edgetech with 4 octave-bandwidth broadband transducers with center frequencies at 200, 270, 380, and 500 kHz. Unfortunately, the 1 MHz BB transducer on the WHOI broadband system suffered from high noise levels and did not result in usable data in 2008. A direct consequence of this was that the dissipative roll-off in the salinity spectrum could not be resolved acoustically. This was rectified during the 2009 field trip, in addition to increasing the acoustic frequency range by adding a 2 MHz broadband transducer to the WHOI system.

Analysis of the data collected during the 2008 experiment indicated that deployment of the Edgetech broadband system from a pole mount on the opposite side of the vessel to the MAST resulted in significant phase ambiguities in aligning the observed fluid structures acoustically and with the MAST data. As a consequence the Edgetech system was moved to the same side of the vessel as the MAST for part of the November 2009 experiment. In addition, due to concerns that a significant portion of the scattering might be due to either sediment or zooplankton, the MAST was "plumbed" for the 2009 experiment, with water samples collected at multiple depth to allow the suspended sediment load to be assessed. The zooplankton samples indicated that there was very little biomass of zooplankton present during this experiment.

Two types of measurements were performed: anchor-station and along-river transects. The advantage of the anchored measurements is that the velocities relative to the MAST are relatively low, allowing higher effective spatial resolution of eddies (based on Taylor's "frozen turbulence" hypothesis). This is not an issue for the quantification of conductivity variance due to the rapid sampling rate of the micro-conductivity sensors, but the direct estimation of stress via direct eddy correlation is more effective with a stationary vessel. The advantage of a moving vessel is the ability to resolve the spatial evolution of instabilities, which is typically more pronounced than the local, temporal evolution. In this mode the dissipation of TKE and scalar variance are readily measured; however the Reynolds stress cannot be precisely quantified due to relatively high relative velocities (typically 1.5-2 m/s).

Results

The CT River field experiments have generated high-resolution acoustic images of the turbulent field (Figures 3 and 4), using pulse compression techniques. These images have revealed a highly inhomogeneous regime, with localized patches of turbulence (based on intensified backscattering and confirmed by microstructure data) separated by quiescent zones. Most significantly, the acoustic scattering indicates that the vertical structure of the stratified shear flow is highly variable, suggesting patchiness and anisotropy of the turbulence, as well as indicating the importance of 3D effects.

Using the direct turbulence measurements it has been possible to predict acoustic scattering over the range of frequencies used to perform the broadband measurements, and the predictions and measurements are in general agreement over the available frequency band (Figure 5). In addition, the MAST has allowed the first field measurements of velocity, temperature, salinity, and scalar variance at approximately the same scales as the acoustics, showing co-located zones of intense acoustic scattering and intense stratified turbulence. The measurements have also confirmed that intense acoustic scattering is correlated with scalar variance generated by turbulence (Figure 6).

The measurements of stratified turbulence provide compelling evidence for the effectiveness of this combination of broadband acoustics and turbulence measurements for revealing new phenomena related to stratified turbulence. The measurements were obtained in a stratified shear layer, in which a topographic transition produced a persistent zone of energetic shear instabilities. The turbulence measurements revealed elevated rates of dissipation of turbulent kinetic energy in the unstable regions, as have been documented in earlier studies. What was unique about these measurements was the ability to determine *where within the developing instabilities the turbulence occurred*, based on the continuous measurements of conductivity microstructure at multiple levels within the Kelvin-Helmholtz billow. With this ability to localize the distribution of turbulent mixing, we found that the maximum turbulent intensities did not occur in the statically unstable cores of the billows, as indicated in Direct Numerical Simulation (DNS) studies of shear instability as well as laboratory studies, but rather these measurements clearly indicate that the intense turbulence and mixing occur along the strongly sheared braids that extend diagonally between the cores. This result was hypothesized by Corcos and Shearman (1976) for high Re number, but the idea received little further attention, in large part because DNS is incapable of attaining the Re numbers required to develop turbulence in the braid. Smyth (2003) recently re-examined the Corcos and Shearman hypothesis and confirmed the occurrence of secondary instability within the braids for Re>2000, although his simulations did not produce fully developed turbulence in the braids. However our new observations greatly exceed the Re number (and Prandtl number) that can be achieved with the most advanced DNS calculations, bringing us into a regime that is structurally different, in fundamental ways, from the low to moderate Re regime that has been well characterized in DNS and laboratory measurements.

This new finding (which is described in a manuscript to be submitted to *Geophysical Research Letters*) has potentially important implications for mixing efficiency, as noted by Smyth (2003) in his analysis, as well as in the phenomenology of the growth and breakdown of instabilities. Perhaps more importantly, the marked difference between these field measurements at high Re and "conventional wisdom" based on low-Re analysis emphasizes the great value of highly resolved "experiments" at the scales relevant to ocean mixing processes.

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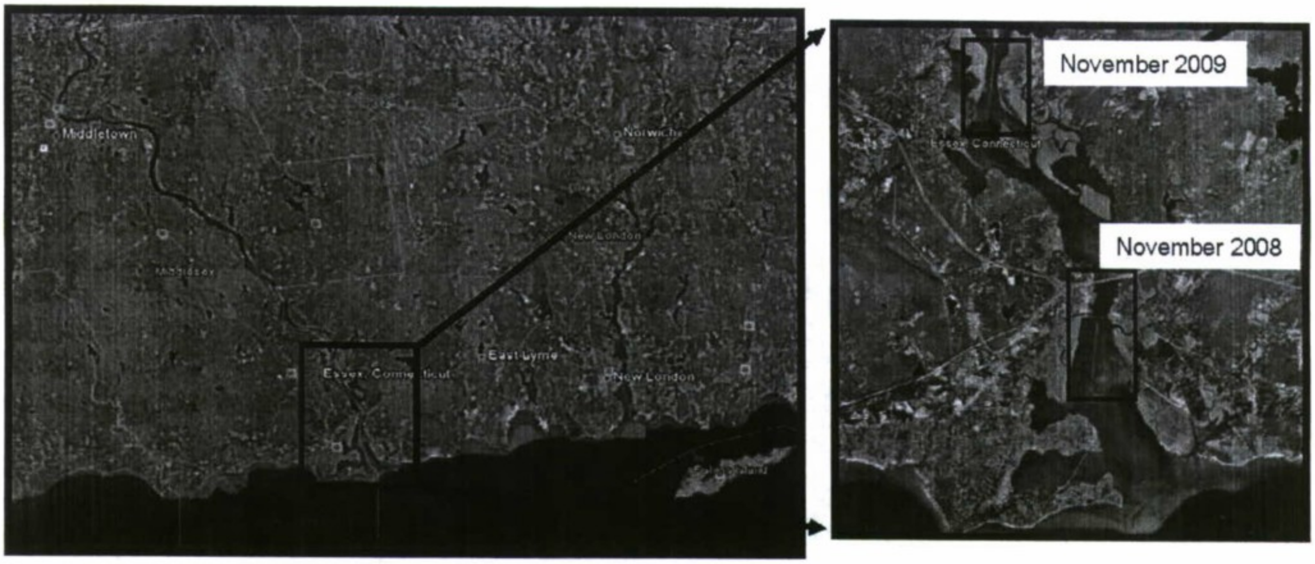

Figure 1. The Connecticut River,, showing the location of the November 2008 experiment, and the anticipated location of the upcoming November 2009 experiment.

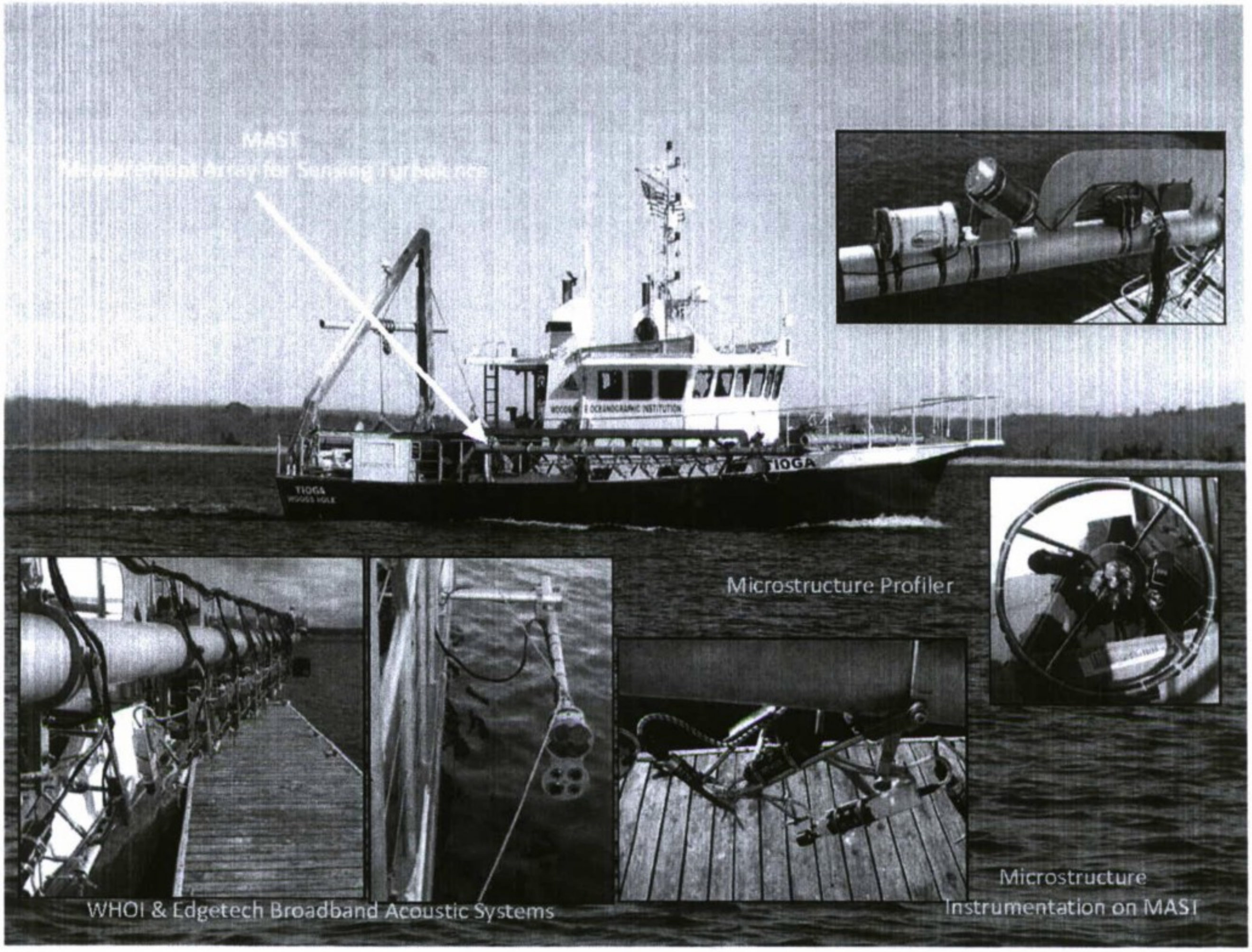

Figure 2. The WHOI coastal research vessel, R/V Tioga, in the Connecticut River showing the MAST, the instrumentation on the MAST, and the suite of acoustic instrumentation.

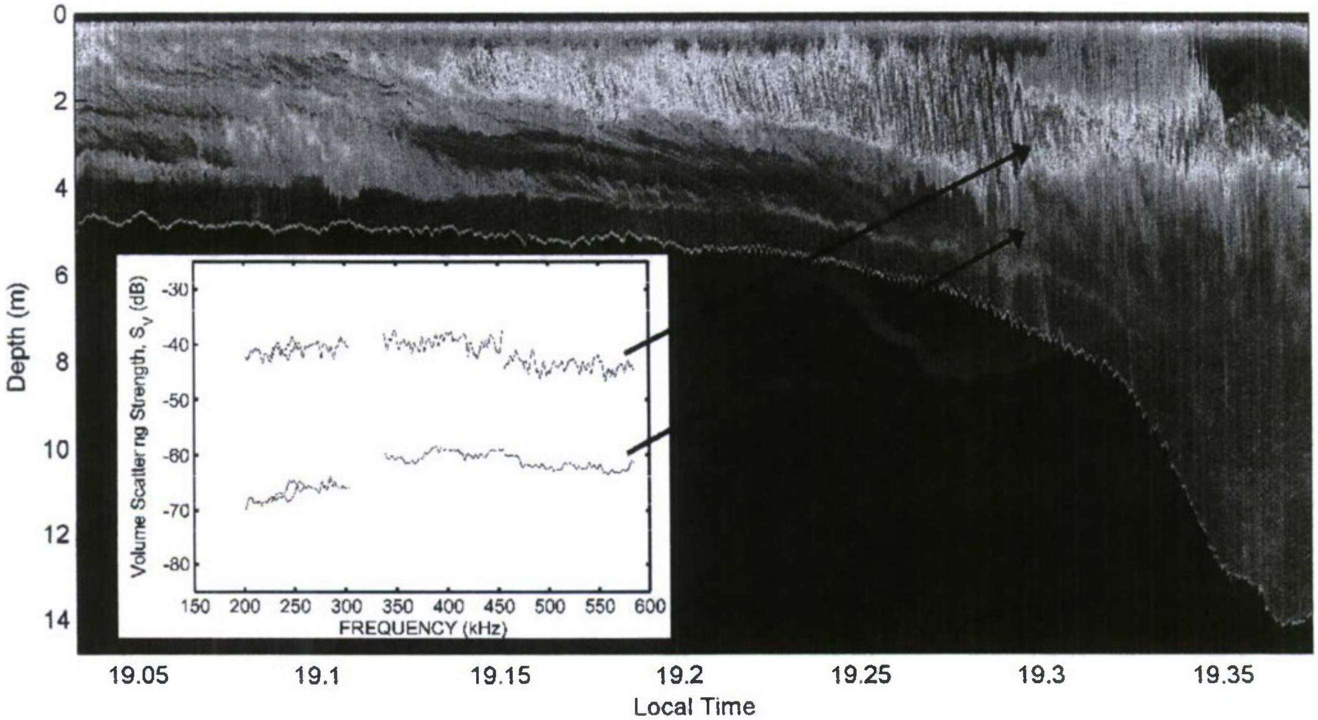

Figure 3. High-resolution acoustic image from the Connecticut River in November 2008, indicating the presence of highly inhomogeneous and apparently anisotropic turbulence. Inset shows acoustic scattering as a function of frequency at the locations marked by the arrows. The measured levels are in good general agreement with predictions (Figure 5).

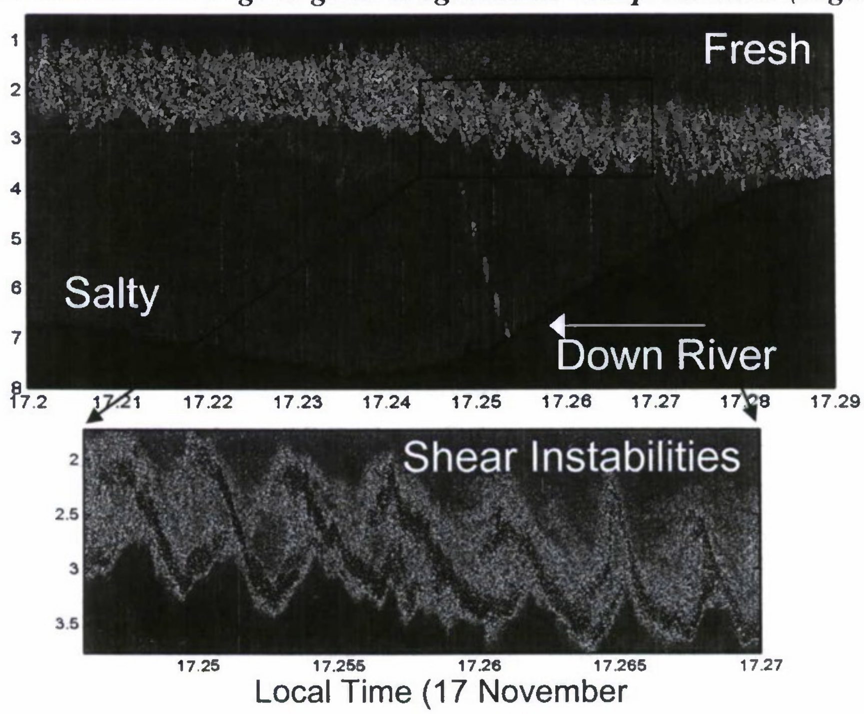

Figure 4. High-resolution acoustic image from the Connecticut River in November 2009, indicating the presence of highly inhomogeneous and apparently anisotropic turbulence.

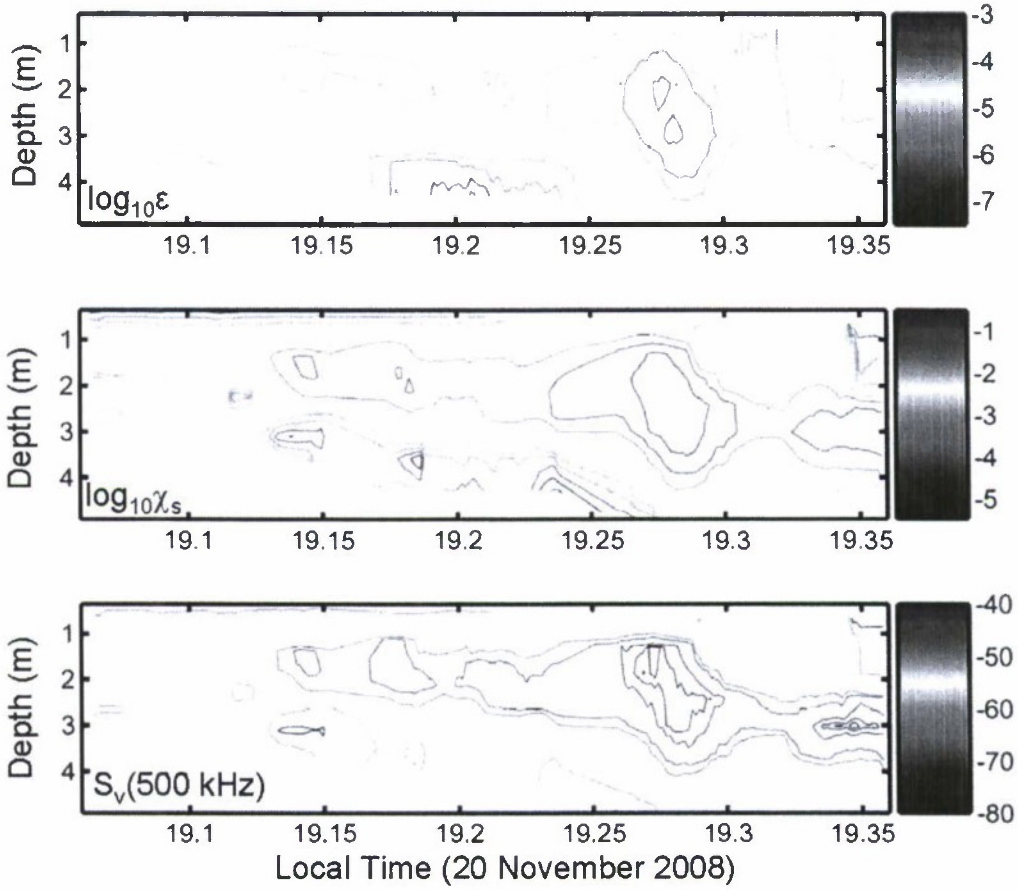

Figure 5. Measured dissipation rates and scalar variance in CT River in November 2008. Predictions of acoustic scattering at 500 kHz based on these measurements.

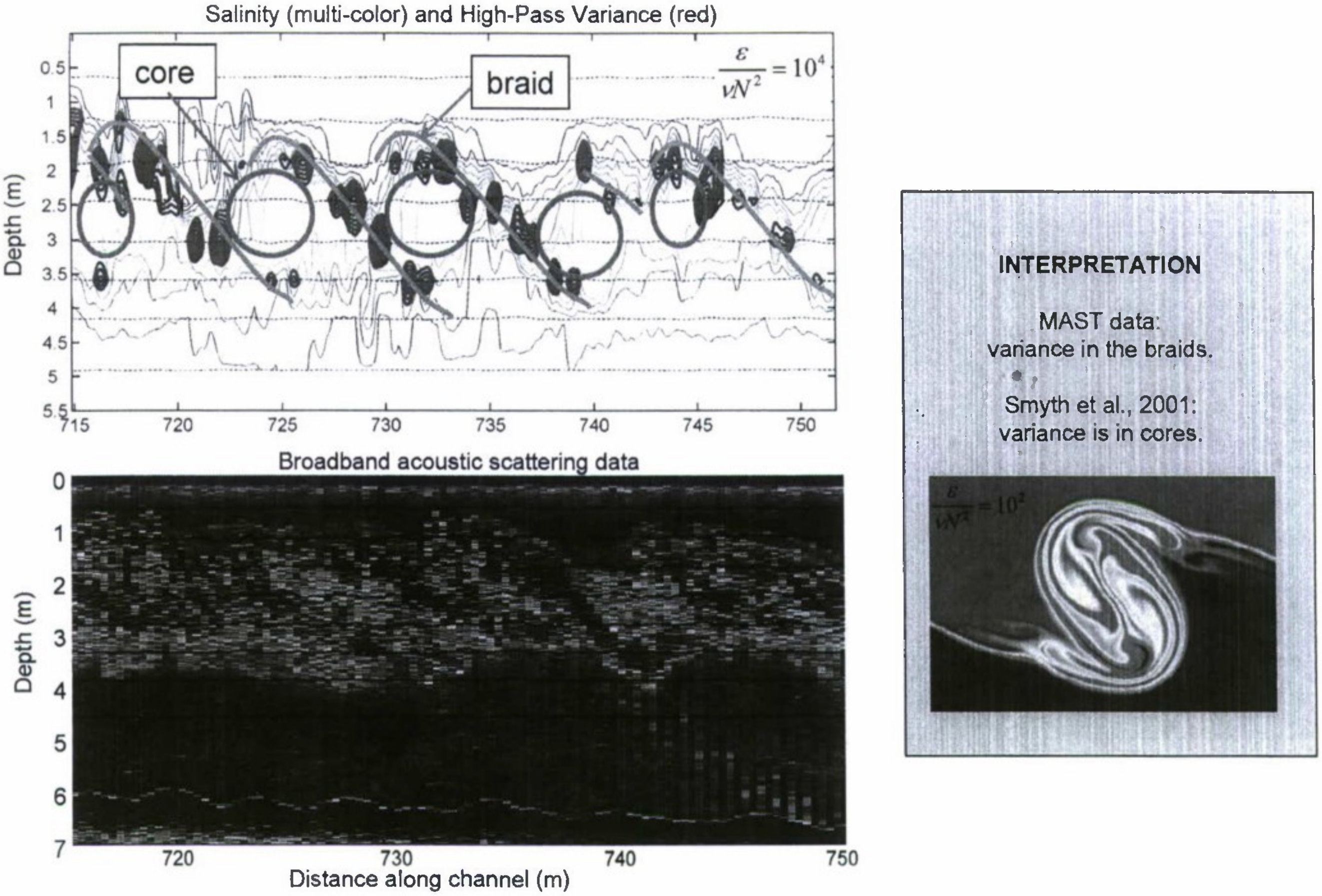

Figure 6. Coincident measurements of broadband acoustic scattering and salinity variance on similar scales, and the interpretation of these measurements.

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