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1aAO5. Quantification of stratified turbulence using acoustic propagation and broadband scattering techniques
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Narrowband acoustical backscattering techniques have been used for decades as a tool for remote imaging of small-scale physical processes in energetic coastal environments, such as oceanic internal waves and microstructure, on spatial and temporal scales difficult to probe with in situ measurements. However, to date, it has been challenging to infer quantitative information about turbulent intensity from the measured backscatter, in part due to uncertainty in the sources of scattering. In contrast to narrowband techniques, emerging broadband techniques result in increased spectral classification and quantification capabilities. Broadband backscattering collected in the Connecticut River Estuary in 2009 in concert with in situ measurements of turbulence have illustrated the potential of these techniques for quantitative remote-sensing of microstructure intensity over relevant spatial and temporal scales. These measurements have resulted in remote quantification of finescale variability of turbulent mixing as well as examination of the mechanisms and structure of shear instability across a broad range of stratification and shear conditions. Recent measurements of high frequency acoustic propagation have been performed in December 2012 at the same location in the CT River estuary, aimed at using reciprocal transmission acoustic scintillation techniques to infer path-averaged turbulent parameters, and the analysis of these data is ongoing.

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ABSTRACT

Narrowband acoustical backscattering techniques have been used for decades as a tool for remote imaging of small-scale physical processes in energetic coastal environments, such as oceanic internal waves and microstructure, on spatial and temporal scales difficult to probe with in situ measurements. However, to date, it has been challenging to infer quantitative information about turbulent intensity from the measured backscatter, in part due to uncertainty in the sources of scattering. In contrast to narrowband techniques, emerging broadband techniques result in increased spectral classification and quantification capabilities. Broadband backscattering collected in the Connecticut River Estuary in 2009 in concert with in situ measurements of turbulence have illustrated the potential of these techniques for quantitative remote-sensing of microstructure intensity over relevant spatial and temporal scales. These measurements have resulted in remote quantification of finescale variability of turbulent mixing as well as examination of the mechanisms and structure of shear instability across a broad range of stratification and shear conditions. Recent measurements of high frequency acoustic propagation have been performed in December 2012 at the same location in the CT River estuary, aimed at using reciprocal transmission acoustic scintillation techniques to infer path-averaged turbulent parameters, and the analysis of these data is ongoing.

INTRODUCTION

Acoustic backscattering techniques provide a powerful tool to remotely investigate the physical properties of fluids over a large range of spatial and temporal scales. These techniques have been commonly used to obtain images of the physical processes that occur in the ocean interior (Proni & Apel, 1975; Farmer & Smith, 1979; Haury et al., 1979; Sandstrom et al., 1989; Trevorrow, 1998; Farmer & Armi, 1999; Orr et al., 2000; Moum et al., 2003). Significant research effort has been directed at, not just imaging, but quantifying turbulent oceanic microstructure (Seim et al., 1995; Moum et al., 2003; Ross and Lueck, 2003; Warren et al., 2003; Goodman & Sastre-Cordova, 2011) employing high-frequency narrowband acoustic techniques, with moderate success. One of the most egregious problems involves the inversion of the narrowband acoustic scattering returns that are assumed to be due to turbulent microstructure, but are in fact due to one of the many other sources of scattering that have not been correctly classified (e.g., microstructure, bubbles, and suspended sediments, fish, and zooplankton). In situ measurements of the different types of scatterers, obtained with instruments such as microstructure profilers, nets, and optical systems, can help reduce the number of assumptions made in performing inversions, but are typically not collected on spatial and temporal scales that match the acoustic measurements.

The goal of this work is to address some of these challenges by using emerging broadband acoustic scattering techniques (Foote et al., 2005; Lavery et al., 2010a,b; Stanton et al., 2010) in the context of stratified turbulence, providing quantitative information about turbulent intensity, specifically by measuring acoustic spectra continuously over a range of frequencies and by enabling the use of pulse compression signal processing techniques (Chu and Stanton, 1998) to obtain very high-resolution images (Fig. 1). Broadband (160-600 kHz) acoustic scattering techniques have been successfully used previously (Lavery et al., 2010b) to quantify acoustic scattering from stratified turbulence generated by surface-trapped nonlinear internal waves where temperature stratification dominated and salinity stratification played a minor role in determining the scattering.

Results of broadband acoustic scattering measurements of stratified turbulence in the Connecticut (CT) River estuary, an environment dominated by salinity stratification, are presented, together with a suite of in situ measurements. This data set is unique because 1) the broadband acoustic scattering techniques allow the scattering spectra as a function of frequency to be determined, thus providing a powerful tool for discriminating between sources of scattering and for quantifying stratified turbulence, 2) unlike intermittent samples collected with vertically profiling instruments, the in situ measurements in the CT River provide a temporally continuous record of mixing at multiple depths spanning the entire water column (though the vertical spacing of the sensors is too coarse to resolve the details of the structure that is evident in the acoustic images), 3) the in situ and acoustic measurements were performed simultaneously over long time scales (in contrast to profiling instruments), 4) the highly salt-stratified and energetic environment resulted in unprecedented scattering levels at short ranges, resulting in very high quality acoustic data, representing a “natural laboratory”, and 5) a wide range of forcing conditions...
(stratification and mixing intensity) were measured through the tidal cycle, and 6) in contrast to the broadband measurements performed previously by Lavery et al. (2010b), these data were collected in the viscous-convective versus dissipation subrange, allowing the scattering models for turbulent microstructure to be tested in a different scattering regime than is typically encountered in the open ocean.

Finally, recent measurements of high frequency acoustic propagation have been performed in December 2012 at the same location in the CT River estuary. These propagation measurements are aimed at using reciprocal transmission acoustic scintillation techniques to infer path-averaged turbulent parameters, and the analysis of these data is ongoing. This latest experiment also collected broadband acoustic backscattering measurements across a 6 m array orientated first in the along flow directions and subsequently in the across flow direction in order to address questions of the spatial evolution and lateral coherence of shear instabilities observed in the CT River.

**FIGURE 1.** $E_{CP}$ for the MID frequency band (220-320 kHz) at the mouth of the Connecticut River, showing clear shear instabilities and elevated scattering associated to the shear instabilities.

**METHODS**

The measurements described here were conducted in the Connecticut (CT) River estuary on the 16-20 November 2009 on board the RV Tioga. On 18 November 2009, the vessel was anchored throughout an ebb tide in water depths of approximately 6-7 m, depending on the tide.

Details on the high-frequency broadband acoustic scattering system, which spans frequencies from 120 kHz to 600 kHz, and details regarding the calibration of the system, are described in Lavery et al., 2010a. The broadband capabilities of the system are exploited through pulse-compression signal processing techniques (Turin, 1960; Chu and Stanton, 1998; Stanton and Chu, 2008; Stanton et al., 2010). All acoustic images shown involve the envelope of the compressed-pulse output, $E_{CP}$. This type of processing results in significantly increased temporal (and hence range) resolution and increased signal-to-noise ratio. The acoustic system pinged at 10 Hz and the transmit signals consisted of chirps of 500 μs duration. Acoustic scattering spectra, that is, volume scattering strength, $S_v$ versus
frequency (or wavenumber), were calculated by averaging the acoustic returns over 20 cm depth bins and over 30 seconds (to match the analysis of the in situ sensors).

The in situ measurements were collected with the Mobile Array for Sensing Turbulence (MAST), described in Geyer et al., 2008, 2010 and were used to estimates of the dissipation rate of turbulent kinetic energy, $\varepsilon$ (m$^2$/s$^3$), and the dissipation rate of salinity variance, $\chi_S$ (psu$^2$/s) at eight different depths in 30 s bins. Continuous profiles of conductivity, temperature, depth (CTD), and optical backscatter (OBS) measurements were also performed in addition to the collection of water samples. Subsequent analysis has shown that there were essentially no zooplankton present in the samples and the measured abundances cannot account for even a small portion of the observed scattering.

**RESULTS**

**Spectral Classification and Quantification**

In addition to stratified turbulence, swim-bladdered fish and suspended sediments were the most common sources of scattering. For the frequencies employed in this study the scattering from suspended sediments, with grain diameters < 100 $\mu$m, is in the Rayleigh scattering regime with a clear $k^4$ scattering dependence (Medwin and Clay 1998), and the scattering from swim-bladdered fish is generally decreasing over this range of frequencies as a combined result of the resonance frequency occurring well below the lowest frequency available in this study and potential beam-pattern effects (Medwin and Clay, 1998). Thus based on the clear differences in the wavenumber dependence of the observed scatterers, it is possible to perform spectral classification and quantification (Fig. 2).

**Comparison of Acoustic and In situ Spectral Levels**

For times during the ebb tide on 18 November 2009 when there was strong salinity stratification and intense mixing (approximately 1300 to 1500) the spectral levels measured acoustically and by the in situ sensors were in relatively good agreement, particularly at mid-depths (Fig. 3). The acoustic spectral levels were slightly lower than the in-situ measurements throughout the ebb tide. Early in the ebb there was a shallow layer of fresh water near the surface, but the stratification and dissipation rates were low compared to the mid-ebb conditions. Similarly, late in the ebb, the salinity stratification (the in situ sensors are measuring the salinity spectrum) was weaker and there was increased concentrations of suspended sediments, which dominated the scattering, making comparisons of spectral levels due to salinity microstructure measured by the acoustics and in situ sensors unreliable. Though the additional step of
estimating the dissipation rate of turbulent kinetic energy and salinity variance was not performed here, making common assumptions about mixing efficiencies, it is possible to convert the acoustic spectral levels into these parameters.

FIGURE 3. Comparison of spectral levels inferred from the acoustic and in situ measurements during the mid-ebb tide on 18 November 2009.

CONCLUSIONS

When strong salinity stratification and intense mixing was present in the Connecticut River, the spectral levels measured acoustically and by the in situ sensors were in good agreement, illustrating the potential of using acoustic scattering techniques to map turbulent intensities. However, it was necessary to capitalize on emerging broadband acoustic scattering techniques to classify and quantify the observed scattering.
REFERENCES


