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Turbulence in coastal fronts near the mouths of Block Island and Long Island Sounds

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ABSTRACT

Measurements of turbulence were performed in four frontal locations near the mouths of Block Island Sound (BIS) and Long Island Sound (LIS). These measurements extend from the offshore front associated with BIS and Mid-Atlantic Bight Shelf water, to the onshore fronts near the Montauk Point (MK) headland, and the Connecticut River plume front. The latter feature is closely associated with the major fresh water input to LIS. Turbulent kinetic energy (TKE) dissipation rate, ε, was obtained using shear probes mounted on an autonomous underwater vehicle. Offshore, the BIS estuarine outflow front showed, during spring season and ebb tide, maximum TKE dissipation rate, ε, estimates of order 10^{-5} W/kg, with background values of order 10^{-6} to 10^{-9} W/kg. Edwards et al. [Edwards, C.A., Fake, T.A., and Bogden, P.S., 2004a. Spring–summer frontogenesis at the mouth of Block Island Sound: 1. A numerical investigation into tidal and buoyancy-forced motion. Journal of Geophysical Research 109 (C12021), doi:10.1029/2003JC002132.] model this front as the boundary of a tidally driven, baroclinically adjusted BIS flow around the MK headland eddy. At the entrance to BIS, near MK, two additional fronts are observed, one of which was over sand waves. For the headland site front east of MK, without sand waves, during ebb tide, ε estimates of 10^{-5} to 10^{-6} W/kg were observed. The model shows that this front is at the northern end of an anti-cyclonic headland eddy, and within a region of strong tidal mixing. For the headland site front further northeast over sand waves, maximum ε estimates were of order 10^{-4} W/kg within a background of order 10^{-7}–10^{-6} W/kg. From the model, this front is at the northeastern edge of the anti-cyclonic headland eddy and within the tidal mixing zone. For the Connecticut River plume front, a surface trapped plume, during ebb tide, maximum ε estimates of 10^{-5} W/kg were obtained, within a background of 10^{-6} to 10^{-8} W/kg. Of all four fronts, the river plume front has the largest finescale mean-square shear, S^2~0.15 s^{-2}. All of the frontal locations had local values of the buoyancy Reynolds number indicating strong isotropic turbulence at the dissipation scales. Local values of the Froude number indicated shear instability in all of the fronts.

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1. Introduction

The Mid-Altantic Bight is diluted by four major fresh water sources, with the Connecticut River third in importance (Beardsley and Boicourt, 1981). At its mouth, this river input passes through an estuarine plume, where it actively mixes with Long Island Sound (LIS) water (O'Donnell, 1997). Also, this river is the major fresh water input to LIS, itself (Gay et al., 2004). Seaward of LIS, offshore flowing estuarine waters encounter Block Island Sound (BIS), with its Montauk Point headland. Offshore, the BIS estuarine outflow front mixes estuarine waters with Mid-Atlantic Bight (MAB) shelf waters (Codiga, 2005). This manuscript describes the turbulence and associated mixing at each of these critical frontal hotspots.

Specifically, turbulence is studied in four coastal fronts near the mouths of BIS and LIS (Fig. 1A). Data are obtained as part of the National Ocean Partnership Program (NOPP) Front Regional Observational Network with Telemetry (FRONT) experiment. The four frontal features studied are: (1) the BIS estuarine outflow front; (2) the headland site front associated with Montauk Point without sand waves, (3) the headland site front associated with Montauk Point with sand waves, and (4) the plume front associated with the Connecticut River outflow (Table 1).

Offshore and SE of Montauk Point, the Estuarine Outflow Front, (E) of Fig. 1A has often been observed in satellite derived sea surface temperature (SST) (Ullman and Cornillon, 1999, 2001) and chlorophyll (Stegmann and Ullman, 2004; Belkin and O'Reilly, 2009-this issue), particularly near the 40 m isobath. It is a plume front, which is bottom trapped inshore of the 30 m isobath (Yankovsky and Chapman, 1997), and then shoals offshore (Kirincich and Hebert, 2005). Garvine (1995) and Edwards et al. (2004a) show that the outflow of the front is in near geostrophic balance. This front is also often associated with a

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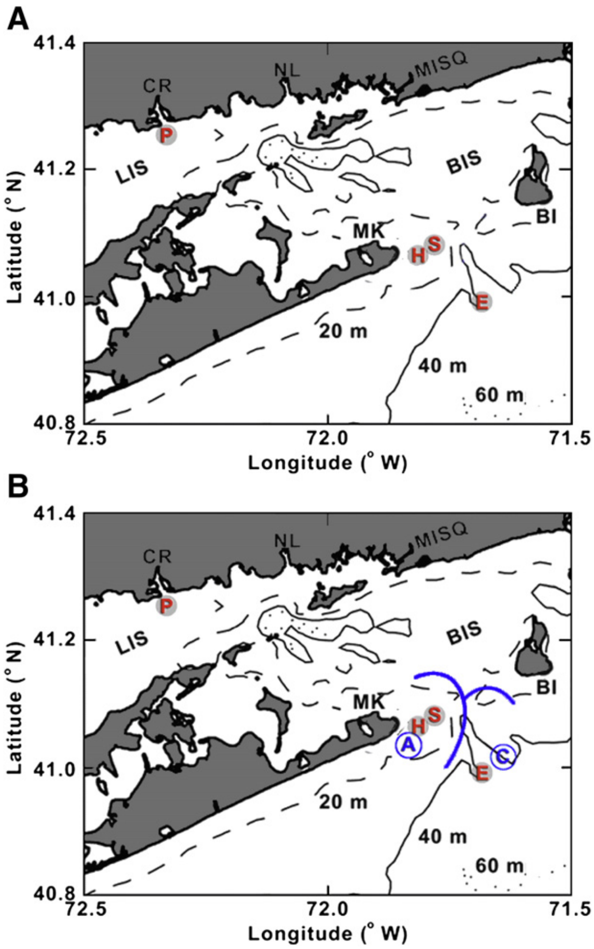

Fig. 1. A. Coastal Front locations near the mouth BIS and LIS, the offshore estuarine outflow front (E), the Montauk Point headland site front, with no sand waves (H), the Montauk Point headland site front, with sand waves (S), and the Connecticut River plume front (P). The base map is from Ullman and Codiga (2004), where the Connecticut River (CR), Block Island (BI), Misquamicut (MISQ), Montauk Point (MK), and New London (NL) are shown. B. Observed fronts, from Fig. 1A, in relation to the predicted 25-h mean surface velocity, showing headland eddy structure near Montauk Point (Edwards, 2004a). A is at the center of the anticyclonic eddy, C is at the center of the cyclonic eddy to the southeast, and the blue lines indicate the eddy boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strong coastal jet, primarily in summer (Ullman and Codiga, 2004). Seasonal changes in flow and frontal characteristics can be explained by the competition between wind and buoyancy forcing (Codiga, 2005).

A general circulation model was run by Edwards et al. (2004a) to examine late spring fronts at the entrance to BIS. The model includes tidal currents, bathymetry, and an estuarine/shelf salinity gradient. The model predicts that residual flows, defined by using 25 h averaging, in the region east of Montauk Point have properties of a headland front, i.e., paired counter-rotating eddies, with an anti-cyclonic eddy closest to Montauk Pt., and a cyclonic eddy further to the east closer to Block Island (Edwards et al., 2004a, Fig. 8). The locations of these features have been superimposed on our front locations in Fig. 1B, and labeled “A” and “C”, respectively. The estuarine outflow front is located southwest and offshore of the cyclonic eddy center. Headland fronts, linked to tidal flows, can generate and dissipate during a tidal cycle, and are often characterized by a local minimum in the Simpson–Hunter parameter. (Pingree et al., 1977). In this headland region, tidal rectification effects typically dominate over that of both wind stress and buoyancy forcing (Edwards et al., 2004b).

East of Montauk Point, the headland site front without sand waves, (H) of Fig. 1A, was observed northeast of the center of the anti-cyclonic gyre predicted by the Edwards et al. (2004a) model (Fig. 1B). Further to the northeast, approximately halfway towards the gyre edge, the headland site front with sand waves, (S) of Fig. 1A, was observed (See Fig. 1B). The bottom sand wave features, themselves, were first reported by Fenster et al. (1990). Mclean and Smith (1979) have argued that mixing over a sand wave field is associated with topographically induced form drag. They observed, in a sand wave region, kinetic energy spectra with a wavenumber dependence of $\kappa^{-5/3}$, but found that local isotropy did not hold.

At the boundary of the Connecticut River in LIS, is the Connecticut River plume front, (P) of Fig. 1A. This front has been modeled by Garvine (1987) and O'Donnell (1987). The Connecticut River plume front was found to be surface attached (bottom-detached). Observations during ebb by O'Donnell (1997) indicate a well defined surface expression with westward propagation and intense horizontal gradients of salinity, velocity and vertical shear. Subsequent ebb observations by O'Donnell et al. (1998) showed convergence and downwelling associated with this front. In addition, this front was the purest example of a surface advected plume, found by Yankovsky and Chapman (1997).

Previous observations of TKE dissipation rate estimates in coastal fronts range from 10^{-6} to 10^{-7} W/kg in Narragansett Bay (Levine and Lueck, 1999), and 10^{-4} W/kg in Haro Strait and Boundary Pass, British Columbia (Gargett and Moum, 1995). Previous observations of neap to spring variability in coastal dissipation rates include the Hudson River estuary, which showed maximum dissipation rates, 10^{-8} to 10^{-4} W/kg, with higher values during spring tide, especially at late ebb. Much lower values were observed during neap (Peters, 1997). Neap to spring variability in a region of fresh water influence, Liverpool Bay, was observed by Sharples and Simpson (1995). Their work suggests a more permanent stratification and frontogenesis near neap, accompanied by inhibition of mixing.

According to O'Donnell (1993), surface estuarine fronts can be classified into three categories, tidal mixing fronts, plume fronts, and shear fronts. For tidal mixing fronts, the dominant mechanism is differential bottom mixing due to topography. For plume fronts, the dominant mechanism is interfacial shear instability between the plume and the estuarine waters. For shear fronts, the dominant mechanism is lateral shear. Some surface fronts may have the features of more than one category.

2. Methodology

2.1. Data acquisition

The observational approach is to measure the horizontal variation of turbulence using an extended REMUS autonomous underwater vehicle (AUV). Our T-REMUS Mod 1, is 2.3 m in length, 56 kg in weight, has an endurance of approximately 2.5 h (5 km). It is instrumented with turbulence and finestructure sensors. The turbulence module, developed by RGL Consulting, is cantilevered off the upper port bow and includes two transverse orthogonally oriented shear probes (Osborn and Crawford, 1982), an FP-07 ultra-fast response thermistor, and 3 orthogonal accelerometers. In addition, the REMUS vehicle measures the vertical gradient of horizontal velocity using an upward and downward looking 1200 kHz RDI acoustic Doppler Current profiler (ADCP), and finescale temperature and salinity using a pair of Falmouth Scientific conductivity-temperature-depth (CTD) instruments. In all cases, the AUV transits through the water at approximately 1 m/s.

Previously, motion and vibration measurements taken aboard a large AUV, LDUUV, in Narragansett Bay (Levine and Lueck, 1999) indicated that an AUV had the stability to be used for dissipation measurements in shallow water. Subsequently, Goodman et al.