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, a bottom attached plume 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 (2004a) 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, $S^2 \sim 0.15\ s^{-2}$. 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, except for the BIS estuarine outflow front.

Keywords: Turbulence; Fronts; Finestructure; Mixing processes; Coastal; Autonomous underwater vehicle; USA, New York, Long Island Sound; USA, Rhode Island, Block Island Sound; USA, Connecticut, Connecticut River.

1. INTRODUCTION

The Mid-Altantic Bight is diluted by four major fresh water sources, with the Connecticut River third in importance (Beardsley and Boicourt, 1985). 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).

Figure 1a.

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, 2008), 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 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 hour 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).

Figure 1b.

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 hours (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 (2006) demonstrated techniques to estimate terms of the TKE balance, solely from small AUV obtained microstructure and finestructure data.

The TKE dissipation rate (see Eq. 1, below) is computed from vertical and transverse, horizontal shear probe data, averaged in the direction of the AUV trajectory. Raw data are processed to remove noise associated with vehicle vibrations. This process is done for each probe using data from all three accelerometers, located in the probe pressure case directly behind the probe mounts (Goodman et al, 2006). The wavenumber response of the shear probes, and the appropriate correction at high frequencies follows Macoun and Lueck (2004). The resulting autospectra compare well to the Nasmyth "universal spectrum" (Oakey, 1982) over the expected range of validity for the occurrence of isotropic turbulence.

For each of the frontal turbulence data sets, the larger scale oceanographic context is provided by ship-based ADCP currents and CTD hydrography from the R/V Connecticut. In addition, for surveys in the regions of the headland site fronts, a towed T/S chain provided detailed stratification data nearly synoptic with the AUV observations. Aside from the river plume study, the larger scale surveys are conducted on the regional scale, i.e., approximately 70 km (north) by 60 km (east) boxes (i.e., Fig. 2,7), as well as on the frontal scale, i.e., over approximately 3-20 km sections (i.e., Figs. 3, 4, 8, 9). For the river plume study, the frontal scale survey was over approximately a 2 km by 1 km study area

2.2 Estimated Turbulent and Finescale Parameters

Under the assumption of local isotropy the shear probes can be used to estimate the TKE dissipation rate from

$$\varepsilon = 15/4\ \nu\ [<(\delta v_m/\delta x)^2> + <(\delta w_m/\delta x)^2>], \qquad (1)$$

where standard notation is employed for the kinematic viscosity (ν), and the microscale athwartships horizontal and vertical velocities (v_m, w_m), with the brackets representing a spatial average.

Using the CTDs and upward and downward ADCPs, the Richardson number is estimated by:

$$Ri = [- g/\rho_o\ (\delta\rho/\delta z)]\ /\ [(\delta u/\delta z)^2 + (\delta v/\delta z)^2], \qquad (2)$$

where standard notation is used, the finescale horizontal velocity components are u, v, respectively, and the z coordinate is directed upwards.

The related Froude number is then given by,

$$Fr = (1/Ri)^{1/2}, \qquad (3)$$

and the buoyancy Reynolds number by

$$Re_b = \varepsilon/\nu\ N^2, \qquad (4)$$

with

$$N^2 = - g/\rho_o (\delta\rho/\delta z) \quad (5)$$

the square of the buoyancy frequency. From Gregg (1987), the eddy viscosity K_v, can be calculated indirectly from the following:

$$K_v = \varepsilon \ / \ [(\delta u/\delta z)^2 + (\delta v/\delta z)^2]. \quad (6)$$

Also, from Simpson and Hunter (1974), the tidally induced mixing parameter can be calculated

$$\phi_{sh} = h \ / \ \{U\}^3 \ \ m^{-2} s^3 \quad (7)$$

where h is the water depth, and $\{U\}$ is the amplitude of the surface tidal velocity. For $\log_{10} \phi_{sh} < 2$, Simpson and Hunter (1974), suggest that tidally induced mixing in the presence of topography is the dominant mechanism responsible for turbulent mixing. Note that (7) can be interpreted as the inverse of a scaled dissipation rate, since it is the inverse of a scaled vertically averaged mean input of power.

In addition, using Garvine (1995), we can characterize an outflow plume, by estimating the Kelvin number, the ratio of the cross-shore length scale, to the baroclinic Rossby radius,

$$K_g = (\gamma L_s) / (c / f), \quad (8)$$

where γ is the ratio of plume cross-shore to longshore scales (the slenderness factor), L_s is the longshore scale, and c is the plume interface internal wave phase speed, f is the Coriolis parameter. For K_g<<1, plume flow is strongly nonlinear, with strong frontal boundaries and internal hydraulic jumps.

3. OBSERVATIONS

In Table 1, transect information is provided for all front datasets. For all cases, as quickly as possible following the frontal scale survey, on the same phase of the tide, the microstructure survey was executed.

3.1 Estuarine Outflow Front

For the estuarine outflow front, an experiment was conducted during the spring maximum in runoff from LIS and BIS, in May 2000. The regional survey (Fig. 2), conducted from 7-9 May, indicated large surface salinity changes, approximately 2 PSU, over approximately 20 km, offshore in the region southeast of the edge of Montauk Point.

Figure 2.

Front Type	Transect Type	Date	Start (local)	End (local)	Water Depth (m)	AUV Depth (m)	Tide	Data Type
estuarine outflow	regional	7-9/05/00	_	_	_	_	flood, ebb	CTD cast
	frontal	11/05/00	1507	1638	20-45	_	ebb	CTD cast, ADCP
	AUV	11/05/00	1746	1812	40-42	8	ebb	ε, CTD, ADCP
headland site, no sand waves	regional	26-27/ 11/01	_	_	_	_	flood, ebb	CTD cast
	frontal	3/12/01	1332	1354	15-20	_	ebb	CTD chain,
	AUV	3/12/01	1502	1533	16-20	3-6	ebb	ε, CTD, ADCP
headland site, no sand waves	regional	26-27/ 11/01	_	_	_	_	flood, ebb	CTD cast
	frontal	3/12/01	0902	0924	13-20	_	flood	CTD chain, ADCP
	AUV	3/12/01	1040	1137	12-20	4-6	flood	ε, CTD, ADCP
Connecticut River Plume	frontal	27/04/00	0933	1017	6-8	_	ebb	bow CTDs, ADCP
	AUV	27/04/00	1215	1220	6-8	2	ebb	ε, CTD, ADCP

Table 1: Frontal Survey Characteristics

For the frontal scale hydrographic survey, conducted on 11 May (Fig 3), the shipboard CTD section above the 10m depth level showed a transition from inshore, less saline, cooler waters to offshore, more saline, warmer waters. At deeper levels, the offshore waters were more saline, and cooler than the inshore waters. Over the 20 km section, changes in salinity of approximately 2.8 PSU, and temperature changes of approximately 3° C, corresponding to density changes of 2.5 kg/m^3, are observed. Bottom attached isohalines, and associated isopycnals, are clustered in the region between 5- 8 km in across-shelf distance. This bottom attachment just inshore of the 30 m isobath has been shown to be typical of the estuarine outflow front. The corresponding shipboard ebb tide ADCP section, Fig. 4, shows mostly southeast flow, but with southwest flow inshore. Currents above the 10m level are large, -0.4 to -0.6 m/s, especially in their northward component.

Figure 3, 4

For hydrographic data acquisition, the AUV performed an approximately 1.5 km transect from SE to NW through the region of the Estuarine Outflow Front (Fig. 2). This trajectory corresponded to the inshore transit from approximately 11.8 – 10.3 km range in the frontal scale CTD and ADCP surveys shown in Figs (3, 4). This was done within the region of intense near-surface salinity and temperature fronts (Fig. 3), with a transit from the warm, salty mid-shelf waters into the fresher, colder inshore waters more influenced by BIS outflow. Here, the currents at the level of the AUV transect were strongly negative in their northerly component (Fig. 4).

For the Estuarine Outflow Front, the AUV-based hydrography, Fig. 5, shows a decrease of approximately 0.2 °C, and 0.05 PSU, along the 1.5 km track, indicated by the AUV label and arrow in Figs 3 and 4. The measurements were obtained later in ebb tide, with local AUV measured currents to the southeast, approximately 0.2 m/s. TKE dissipation rates (Eq. 1) are presented for a 0.24 km section of the front. Within the front, maximum dissipation rate estimates of order 10^{-5} W/kg are obtained, over background within the front values of order 10^{-6}-10^{-9} W/kg (Fig. 6).

Figures 5, 6

3.2 Headland Site Front (no sand waves)

The regional scale survey for the headland site front region, with no sand waves, was conducted during 26-27 November 2001. This headland site front is observed well inshore of the larger scale, strong surface salinity front associated with the Estuarine Outflow Front offshore (Fig. 7, also Fig.2). This inshore frontal scale survey (Fig. 8), conducted just prior to the turbulence survey on 3 December, shows banded finestructure, strongest beyond the range of 3.5 km, with contrasting features of approximately 0.2-0.4 PSU in salinity, 0.2 °C in temperature, and 0.2-0.3 kg m^{-3} in density. Here, the dashed lines are the depths of the actual CTD sensors on the towed chain. A lens of cooler, fresher, low density, water is observed near the front location at 3.0-3.7 km across shelf distance, within the scope of the AUV survey. Also, a lens of cooler, fresher, low density, water is observed near the front location at 1.8-2.3 km across shelf distance. Some of this variability may be associated with internal waves.

The corresponding ship based ADCP currents (Fig. 9) show positive across-shelf current component, and negative along-shelf current component. The across-shelf component has banded structure, often exceeding 0.5 m/s. The along-Shelf component also has banded structure, often from -0.9 to -0.2 m/s. A band of particularly high along-shelf current component corresponds to the lens of cool, fresh, low density, water observed at 1.8-2.3 km across shelf distance.

Figures 7, 8, 9

For this headland site front, the AUV based hydrography time series is shown in Fig. 10. The AUV was yo-yoed between the 3m and 6m depth levels. This corresponds to an offshore transit from approximately 2.6 to 4.4 km range in the frontal scale CTD and ADCP surveys (Figs 8, 9).

Corresponding to the frontal scale survey, the salinity and temperature structure is complex and banded. We observed offshore higher salinity and intermediate temperature, midsection lowest salinity and lowest temperature, and inshore highest temperature and slightly higher salinity,. The AUV based salinities are slightly lower than the ship based at similar range, but were observed higher in the water column. The corresponding density structure mirrored the salinity structure.

Figure 10

In the corresponding low pass filtered turbulence time series (not shown), the vertical and athwartships microscale velocity shear components are consistently turbulent over the record. The corresponding temperature microstructure shows a rise in the final 0.5 km of the transect, associated with the front. The TKE dissipation rate (Eq. 1) transect across the front (Fig. 11) shows consistently high values of order 10^{-5}-10^{-6} W/kg. For this dataset, Goodman et al (2006) found that the mean dissipation rate was in good agreement with the AUV data derived turbulent production estimate. This indicated steady state, homogeneous TKE budget closure, within the statistical uncertainty of the estimates.

Figure 11

3.3 Headland Site Front with Sand Waves

The regional scale survey for the headland site front with sand waves was conducted 26-27 November 2001, the same survey utilized for the other headland site front (Fig. 7). Similarly, the headland site front with sand waves was observed well inshore of the larger scale, strong surface salinity front associated with the estuarine outflow front offshore (Fig. 7, also Fig. 2). This survey was conducted during flood tide. The corresponding frontal scale hydrographic survey (Fig. 12), conducted just prior to the turbulence survey on 3 December, shows, in general, cooler, less saline waters inshore, and warmer, saltier waters offshore. This transition is typical of late fall and early winter. In addition, a band of colder water is observed from –0.8 to –1.1 km range. Over the section, this banded finestructure has contrasting features with changes of approximately 0.4 PSU in salinity, 0.3° C in temperature, and 0.25 kg m^{-3} in density.

Correspondingly, the ship based ADCP currents (Fig. 13) show higher values of across-shelf flow (>-0.35 m/s) in the 0.5 to 1.3 km range. In contrast, the across-shelf flow is reduced (-0.25 m/s<) in –1.5 to –1.0 km range. The along-shelf flow also shows higher values (>.25 m/s) in the 0.5 to 1.3 km range. In contrast, the along-shelf flow is reduced (<0.25 m/s) in the –1.5 to –1.0 km range.

Over the sand wave at 0.5 km across-shelf distance, intense currents are observed throughout the sampled water column (below the 5 m upper limit for the ADCP), with little vertical gradient, and large horizontal gradients (Fig.13). This location corresponds to the offshore edge of a localized salinity and density front (Fig.12). Another correspondence of this type between intense currents throughout the sampled water column, large horizontal current gradients, and the inshore edge of a localized salinity and density front, is observed near –1.0 km.

Figures 12, 13

For this headland site front, the AUV based hydrography time series is shown in Fig. 14. The AUV was yo-yoed between the 4 m and 6 m depth levels. This complete trajectory corresponded to a cross-front transit from approximately 1.3 km to -1.2 km range, in the frontal scale surveys (Figs 12, 13). Consistent with the frontal scale survey, the AUV derived salinity and temperature structure is complex and banded. We observed offshore higher salinity and density, midsection lowest salinity and density, and inshore intermediate salinity and density,.

The corresponding TKE dissipation rate (Eq. 1) transect across the front (Fig. 15) shows extremely strong intermittency (note the log scale) with the highest values of order 10^{-4} W/kg, above a background of 10^{-7}-10^{-6} W/kg. The corresponding sand wave topography is shown in the lower panel.

Figure 14, 15

3.4 Connecticut River Plume Front

The larger scale survey for the plume front was conducted on 27 April 2000, during ebb tide. Six cross-front ship ducted CTDs at 0.8m and 2.8 m, and ADCP sections were obtained (Fig. 16). The subsequent AUV cross-front trajectory is also shown in Fig. 16.

Figure 16

The combined ship-based hydrography and ADCP currents are shown in Fig. 17. In the region of the front, near the origin, the 0.8m, shallower depth salinity contour drops from 26.0 PSU to approximately 10.0 PSU, while the 2.8m, deeper depth, salinity drops from approximately 27.0 PSU to approximately 22.0 PSU.

The shipboard ADCP can only sample at 2m and below. In the immediate region of the plume front, in the observable depth range of 2-4 m, at across-front distances of approximately 5-25 m, the flow is to the southwest, negative in both along-front and cross-front velocity components (Fig. 17). The across-front component peaks at approximately –0.2 m/s at 2m, while the along-front component peaks at approximately –0.6 m/s, in the 2.5-4.0 m depth range. In contrast, the flow in the surrounding waters is mostly positive in across-front component, and weakly negative in along-front component.

Figure 17

For the river plume front, the AUV trajectory was taken subsequent to ship cross-section 1, which is closest to the plume entry point into LIS, but still on the same ebb tide. To place the AUV trajectory, the surface front of the plume was observed by collected foam and color changes across the front. The AUV was deployed near the center of the Connecticut River plume, at 2 m depth. A cross-front microstructure transect was obtained during ebb tide when the plume front is strongest, along a northeasterly track (Fig. 18). Results from this transit show an extreme drop in salinity of approximately 1.8 PSU, a small temperature rise of 0.1 ^{o}C, and a corresponding density drop of 1.2 kg/m^3 over a range of approximately 40-50 m.

Figure 18

For the turbulence survey, low pass filtered time series of the vertical and athwartships turbulent velocity shear, as well as temperature microstructure, clearly indicate high levels of turbulence through the plume (not shown). With the plume salinity minimum set as the 0 m across front distance (see hydrography in Fig 18), the corresponding TKE dissipation rate (Eq. 1) transect across the front, Fig. 19, shows maximum dissipation rates of order 10^{-5} W/kg, against a background of
10^{-6}-10^{-8} W/kg.

Figure 19

4. RESULTS AND DISCUSSION

4.1 Turbulence Characterization

For the four examples of coastal fronts, turbulence can be characterized by estimating a combination of their buoyancy Reynolds numbers (Eq. 4) and Froude numbers (Eq.3). There are a number of issues related to our method of estimating these parameters. As discussed in Goodman et al (2006), the original concept for obtaining stratification along the complete trajectory was to obtain density gradient information from the upper and lower AUV based CTDs. However, drift problems between the AUV mounted upper and lower depth conductivity sensors made this approach unworkable.

Alternatively, near synoptic stratification and fine-scale shear data were obtained from the initial descent and final ascent of the AUV. With this method stratification is obtained using a single CTD (the upper one, with better pressure resolution) with the depth overshoot on the descent exploited. The finescale shear is obtained from the the downward looking ADCP, which is located 1.34 m from the AUV centerline.

Errors associated with the calculation of Fr (Eq. 3) and Re_b (Eq. 4) can be estimated by examining the variability in their respective input parameters, between descent and ascent. For Fr, the magnitude of the stratification and the finescale vertical shear, S, can each typically change by a factor of 2, resulting in variability of 0.4-2.8 Fr. For Re_b, the stratification can typically change also by a factor of 2, , resulting in variability from this effect of 0.5-2.0 Re_b. It should be noted that for the Connecticut River plume case, the shallow AUV depth did not provide the overshoot required for using the new methods – instead stratification and finescale shear were estimated from shipboard data.

These parameter estimates can then be used to evaluate our data sets in relation to three turbulent regimes: the buoyancy dominated regime $Re_b < 20$, where turbulence ceases to exist; the region $20 < Re_b < 200$ in which non-isotropic turbulence occurs and buoyancy is still important; and Re_b

> 200 where isotropy is expected to hold over the dissipative subrange (Gargett et al, 1984) and fully developed turbulence occurs. In addition, for critical Fr>2, shear instability occurs.

4.2 **Comparison of Turbulence Levels**

For the estuarine outflow front, $N^2 \sim 6 \times 10^{-5}\ s^{-2}$, $S^2 \sim 1 \times 10^{-4}\ s^{-2}$, and from Table 2, $\varepsilon_{max} \sim 10^{-5}$ W/kg, which results in Fr ~ 0.4, and $Re_b \sim 9 \times 10^4$. These estimates suggest a less than critical Fr < 2, but with isotropic turbulence at dissipation scales. For the headland site front, without sand waves, $N^2 \sim 2 \times 10^{-5}\ s^{-2}$, $S^2 \sim 1 \times 10^{-4}\ s^{-2}$, and from Table 2, $\varepsilon_{max} \sim 10^{-5}$ W/kg, which results in Fr ~ 2.2, and $Re_b \sim 4.2 \times 10^5$. These results suggest a critical Fr > 2, with isotropic turbulence at dissipation scales. For the headland site front, with sand waves, $N^2 \sim 5 \times 10^{-6}\ s^{-2}$, $S^2 \sim 4 \times 10^{-4}\ s^{-2}$, and from Table 2, $\varepsilon_{max} \sim 10^{-4}$ W/kg, which results in Fr ~ 8.9, and $Re_b \sim 1.6 \times 10^7$. These results suggest a critical Fr > 2, with isotropic turbulence at dissipation scales.
For the river plume front, $N^2 \sim 2 \times 10^{-2}\ s^{-2}$, and $S^2 \sim 1.5 \times 10^{-1} s^{-2}$ (O'Donnell et a., 2008), and from Table 2, $\varepsilon_{max} \sim 10^{-5}$ W/kg, which results in Fr ~ 2.7, and $Re_b \sim 2.8 \times 10^2$. These results suggest a critical Fr > 2, with isotropic turbulence at dissipation scales. Thus, for all four cases, we observe strongly active, isotropic turbulence at dissipation scales. Shear instability is likely to occur in the two headland and the river plume cases.

5. SUMMARY AND CONCLUSIONS

Offshore, the estuarine outflow front (Table 2), located south of the BIS entrance, during spring season, near neap ebb tide, was characterized by an offshore transition to warmer and saltier waters. Turbulence estimates show ε_{max} of order 10^{-5} W/kg with no suggestion of active overturning, but with isotropic turbulence at dissipation scales. This front is offshore of the tidal mixing front predicted by Edwards et al (2004a), with a Simpson-Hunter parameter (Eq. 7), less than 2.0 (Fig. 20). According to Kirincich and Hebert (2005) this is an example of a bottom trapped coastal density front, using the criteria of Yankovsky and Chapman's (1997). In relation to the Edwards et al (2004a) model predictions, this front is located at the boundary of the tidally driven, baroclinically adjusted, outflow from LIS circumscribing the headland eddy (Fig. 1b), with plume outflow constrained by Coriolis accelerations The presence of isotropic turbulence, with reasonably high TKE dissipation rates, is evidence that in the locale studied, the front is not just a sea surface feature, as observed by SST or chlorophyll, or feature of the larger scale coastal circulation. This front is the result of strong tidally induced mixing, modified by advection of low saline, low temperature, BIS waters. In addition, optimum fits of K_ν estimates made by Codiga and Rear (2004) were in the range 0.5 - 3 $\times 10^{-3}$ m^2/s. Utilizing (Eq. 6), we estimate the eddy viscosity, for $S^2 \sim 10^{-4}\ s^{-1}$, and $\varepsilon_{max} \sim 10^{-5}$ W/m^3, $K_{\nu\ max} \sim 10^{-1}$ m^2/s. However, for $\varepsilon_{bg} \sim 10^{-8}$-$10^{-9}$ W/m^3, $K_{\nu\ bg}$ is of order 10^{-4} -10^{-5} m^2/s, overlapping with their tidally averaged estimates.

At the entrance to BIS, northeast of MK, the headland site front, with no sand waves, (Table 2), during winter, on ebb, near spring tide, was characterized by an offshore transition to more saline, and slightly cooler, waters. Turbulence estimates show ε_{max} of order 10^{-6} W/kg, indicating possible active overturning, with isotropic turbulence at dissipation scales. This front is inshore of the tidal mixing front predicted by Edwards et al (2004a), and is characterized by a Simpson-

Hunter parameter less than 2.0 (Fig. 20), along the boundary of the local minimum value suggested by Pingre et al (1977). In relation to the Edwards et al (2004) model, this front is located near the northern end of the anti-cyclonic headland eddy, itself located south and west of Montauk Point (Fig. 1b). Here, the front appears to be related to a strong topographically driven rectified tidal flow forming an eddy south of Montauk Point, with associated large horizontal shears between the eddy and the main outflow from the estuary. These large horizontal shears suggest that, for O'Donnell's (1993) front classification, this may be closest in definition to a shear front, as well as a tidal mixing front.

Also at the entrance to BIS, but further to the northeast of MK, the headland site front with sand waves (Table 2), during winter, on flood, near spring tide, was characterized by an offshore transition to saltier and slightly warmer waters. Turbulence estimates show ε_{max} of order 10^{-4} W/kg, possible active overturning, with isotropic turbulence at dissipation scales. This front is inshore of the tidal mixing front predicted by Edwards et al (2004a), with a Simpson-Hunter parameter less than 2.0 (Fig. 20). In relation to the Edwards et al (2004a) model, this front is located near the northeastern end of the anti-cyclonic headland eddy (Fig. 1b). As in the previous example, this front also appears to be related to a strong topographically driven rectified tidal flow forming an eddy south of Montauk Point, with associated large horizontal shears between the eddy and the main outflow from the estuary. Similarly, these large horizontal shears suggest that, for O'Donnell's (1993) front classification, this may be closest in definition to a shear front, as well as a tidal mixing front. The largest estimated $\boldsymbol{\varepsilon_{max}} \sim 10^{-4}$ W/kg, as well as a critical Fr ~ 8.9, and the largest $Re_b \sim 1.6 \times 10^7$, occurs for this front. It is tempting to attribute the enhanced turbulence to the presence of the sand waves, themselves. A larger data set with observations over sand waves and adjacent bottom areas, over tidal cycles, would be required to test this hypothesis.

Inside LIS, the Connecticut River plume front (Table 2) is located where the river flows into the sound near Lynde Pt., CN. This front is associated with major freshwater input into LIS. During spring season, on ebb, near neap tide, this front was characterized by an intense local reduction in salinity and a temperature increase. Turbulence estimates show ε_{max} of order 10^{-5} W/kg, possible active overturning, with isotropic turbulence at dissipation scales. It is located is inshore of the tidal mixing front predicted by Edwards et al (2004a), but is bottom detached. This front has the largest finescale shear of all four features in the present study. According to the O'Donnell (1993) front classification, and supported by the Fr estimate, this is a classic example of a plume front. Similarly, using the criteria of Yankovsky and Chapman (1997), this front is associated with a surface trapped advecting plume. Also, from Garvine (1995), we can characterize this outflow plume, by estimating the Kelvin number utilizing (Eq. 8). For our case, $\gamma L_s \sim 15$ m, $f \sim 9.3 \times 10^{-3}\ s^{-1}$, h_p is the plume height ~ 5 m, and $c \sim Nh_p \sim 0.7$ m/s, resulting in $K_g \sim 0\ .2$. This low K_g suggests that at times the plume flow may be nonlinear.

In summary, in the series of studies described in this paper, we have traced back some of hot spots of turbulent mixing from the offshore estuarine outflow plume front, back past the mixing at two headland fronts at the mouth of the estuary, and then further back to the mixing associated with the river plume of the major estuarine freshwater source. In future efforts, we hope to study the energetics of these features, over tidal cycles, in conjunction with synoptic modeling efforts.

In particular, an AUV-based turbulence study in the headland eddy fronts would be an appropriate next step.

Coastal Front	Season Date	Tidal Phase	Water Depth	AUV Depth	ε_{max} (W/kg)	ε_{bg} (W/kg)	ϕ_{sh} ($m^{-2} s^{3}$)	Frontal Character: Yankovsky and Chapman(1997) (YC), O'Donnell (1993) (OD), Edwards et al (2004a) (ED)	Probable Primary Mixing Mechanisms
estuarine outflow, offshore of BIS, near 30-40 m isobath, moderate stratification	Spring 11/5/00	Ebb, Near Neap	40 m	8 m	10^{-5}	10^{-6}- 10^{-9}	>2	YC bottom trapped coastal density front*, ED plume outflow constrained by Coriolis accelerations	 Tidally induced mixing
Montauk Pt headland site, east of Montauk Pt, no sand waves, low stratification	Winter 3/12/01	Ebb, Near Spring	16-20 m	3-6 m	10^{-5}- 10^{-6}	n/a	<2	ED tidal mixing front** OD tidal mixing and shear front	Differential bottom mixing due to topography. Lateral shear
Montauk Pt headland site, NE of Montauk Pt, sand waves, low stratification	Winter 3/12/01	Flood Near Spring	12-20 m	4-6 m	10^{-4}	10^{-7}- 10^{-6}	<2	ED Tidal mixing front OD tidal mixing and shear front	Differential bottom mixing due to topography. Lateral shear
Conn. River Plume, in LIS, high stratification	Spring 27/4/00	Ebb, Near Neap	6-8 m	2 m	10^{-5}	10^{-6} - 10^{-8}	<2	YC surface advected plume front O'Donnell plume	 Interfacial shear instability

Table 2: Comparison of Front Characteristics (* from Kirincich and Hebert (2005).

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FIGURE CAPTIONS

Fig. 1a: 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.

Fig. 1b: Observed fronts, from Fig.1a, in relation to the predicted 25-hour 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.

Fig. 2: Regional survey for the estuarine outflow front, showing surface salinity along the R/V Connecticut track, and associated contours, with the plus symbols indicating CTD locations. The frontal scale CTD and ADCP survey track is shown by the red line, and the AUV survey track is shown in black (start indicated by arrow), both crossing this feature.

Fig. 3: Frontal scale survey for the estuarine outflow front, shipboard CTD hydrography. The dashed vertical lines show CTD locations. The AUV survey track is also shown.

Fig. 4: Frontal scale survey for the estuarine outflow front, shipboard ADCP currents, northward (upper), and eastward (lower) components. The positive directions for current components are north and east, respectively. The AUV survey track is also shown.

Fig. 5: AUV hydrography survey for the estuarine outflow front.

Fig .6: TKE dissipation rate versus onshore distance for the estuarine outflow front, with data averaged over approximately 10 m samples, resulting in approximately 50 degrees of freedom.

Fig. 7: Regional survey for the Montauk Pt. headland site front, with no sand waves, showing surface salinity contours, with the plus symbols indicating CTD locations. For the headland site front, no sand waves, the frontal scale CTD and ADCP survey track is shown by the red line, and the AUV survey track is shown by the black line, both closest to MK. For the headland site front, with sand waves, the frontal scale CTD and ADCP survey track is shown by the red line, and the AUV survey track is shown by the black line, further to the northeast.

***Fig. 8*:** Frontal survey for the MK headland site front, for no sand waves. The hydrographic survey shows a complicated banded structure, strongest beyond the range of 3.5 km; here distance is measured offshore along an axis perpendicular to the MK to Block Island gap. Dashed lines indicate depths of towed CTD sensors. The approximate AUV survey track, crossing this track, is also shown.

Fig. 9: Frontal survey for the MK headland site front, for no sand waves. The ADCP survey shows ebb currents, from southeast to southwest. The coordinate system is the same as Fig. 8. The positive direction for across-shelf current is offshore, perpendicular to the MK to Block

Island gap. The positive direction for along-shelf current is from Montauk Pt. towards Block Island. The location of the AUV track, crossing this frontal survey track, is also shown.

***Fig. 10**:* AUV hydrography survey for the headland site front, for no sand waves.

Fig. 11: TKE dissipation rate, ε, versus offshore distance for the headland site front with no sand waves. Estimates of ε were obtained by averaging over 10 m length samples, resulting in approximately 50 degrees of freedom. The dashed line is the mean dissipation rate.

Fig.12: Frontal scale hydrographic survey for the MK headland site front, with sand waves; here distance is measured offshore along an axis perpendicular to the MK to Block Island gap. The AUV survey track is also shown.

Fig. 13: Frontal scale ADCP current survey for the MK headland site front, with sand waves, with the distance scale the same as Fig. 12. The positive direction for across-Shelf current is offshore, perpendicular to the MK to Block Island gap. The positive direction for along-Shelf current is from MK towards Block Island. The AUV survey track is also shown.

Fig.14: AUV hydrography and bottom depth survey for the headland site front, with sand waves. In the range from approximately –1000 to 1000 m, the variability in the water depth, 3-7 m variations, is associated with the sand waves.

Fig. 15: TKE dissipation rate versus offshore distance for survey for the headland site front, with sand waves, with data averaged over approximately 10 m samples, resulting in approximately 50 degrees of freedom. The ordinate is chosen to be logarithmic to show the large range of variability. Bottom topography is shown in the lower panel.

***Fig. 16**:* Ship track (green) and Connecticut River plume front crossings with local frontal coordinates (magenta). The subsequent AUV trajectory through the evolving front is also shown (black).

Fig. 17: Frontal survey for the Connecticut River plume front, ship-based salinity at 0.8 m (blue) and 2.8 m (red), and ADCP along-front and across-front currents (section 1 from Fig. 16). The positive directions for current components are indicated by these axes, as shown by the arrows in Fig. 16.

***Fig. 18**:* AUV hydrography survey for the Connecticut River plume front.

Fig. 19: TKE dissipation rate versus across-front distance for the Connecticut River plume front, with data averaged over approximately 10 m samples, resulting in approximately 50 degrees of freedom.

Fig. 20: Observed fronts in relation to predicted tidal mixing front (Edwards, 2004a).