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Upwelling and convergence in the Middle Atlantic Bight shelfbreak front

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Abstract. Convergent and upwelling circulation within the shelfbreak front in the Middle Atlantic Bight are detected using a dye tracer injected into the bottom boundary layer at the foot of the front. From the three day displacement and dispersion of two dye injections within the front we infer Lagrangian isopycnal (diapycnal) velocities and diffusivities of 2×10^{-2} m/s (4×10^{-6} m/s) and 9 m^2/s (6×10^{-6} m^2/s). These results substantiate model predictions of *Chapman and Lentz* [1994] and previous dye tracer observations by *Houghton* [1997].

Introduction

Model calculations by *Gawarkiewicz and Chapman* [1992] and *Chapman and Lentz* [1994] provide a new paradigm for our understanding of frontogenesis and circulation at the shelfbreak front along the northeast North American continental margin. In their model the density field, altered by offshore buoyancy flux in the bottom boundary layer (BBL), generates convergent cross-shelf flow near the shelfbreak and upwelling along the front.

In a pilot cruise, May 1996, we detected a 0.01 m/s onshore flow within the BBL at the foot of the shelfbreak front on the New England Shelf [*Houghton*, 1997]. The dye tracer technique proved uniquely suited for measuring this weak circulation relative to the front which itself is moving. In this note we report results from a subsequent cruise in May 1997 in which upwelling flow within the front is observed confirming model predictions of *Chapman and Lentz* [1994] and speculations by *Houghton* [1997]. Complementary SeaSoar surveys by *Barth et al.* [1998] detected corroborating patterns of cross-shelf circulation.

Experiment

The experiment was conducted using techniques similar to the pilot cruise [*Houghton*, 1997]. A sled, towed at speeds of 1 to 4 kts (0.5-2 m/s) and equipped with a Sea Cat SBE-19 CTD and a Chelsea MKII Aquatracka fluorometer (both sampled at 2 Hz) and an upward looking RDI 300 kHz workhorse ADCP, was used for both dye injection and detection. The tracer dye, fluorescein, was detectable to dilutions of 1×10^{-11} parts by weight. There were two dye injections each consisting of 86 kg of dye in a 25% water solution mixed with isopropyl alcohol to achieve *in situ* density. This was pumped into the BBL at 5 m above the bottom in 40 minutes to produce a 1 km long streak of dye roughly parallel to the local isobath. Within 12 hours surveys of the dye patch began and continued for three days. During the experiment there was no evidence of warm core rings or frontal eddies that would distort the observations.

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Prior to each dye injection there was a CTD survey of the front (Fig.1). The temperature/salinity correlation is high so temperature can be used to define stratification below depths of 60 m. The foot of the front protrudes onto the shelf while seaward of the shelfbreak the front shoals to the surface (see Fig. 1 in *Barth et al.*, 1998). Where the front intercepts the BBL the stratification associated with the front generates a cross-shelf temperature gradient in the BBL. *Houghton* [1997] hypothesized that the crossfrontal flow reverses direction where the crossfrontal temperature gradient T_y is maximum and T_{yy} changes sign. In the BBL T_y was consistently greatest near 7.5°C and dye was injected 4 km inshore and then 4 km offshore of this point with injection #1 in 6.55°C and injection #2 in 8.58°C water respectively. A thick (10 to 20 m) bottom mixed layer (BML) made it possible to inject all the dye within 0.1°C of the target temperature. The evolution of both dye patches was similar so here we present results from injection #2 for which sampling was more complete.

The lateral displacement and dispersion of the dye patch is illustrated in Fig. 2. Between the first and fourth (46 hours later) surveys the dye patch drifted west with a mean speed of 0.13 m/s. When adjusted for the displacement due to the water column motion relative to the ship track the cross- and along-shelf dimensions of the dye patch in this last survey were both approximately 6 km. As the patch evolved, dye tagged water entered the stratified frontal region above the BML and moved offshore (Fig. 3). The dye was initially injected 5 m above bottom in the BML. Eighteen hours later (Fig. 3A) it had mixed throughout the BML with maximum concentrations at

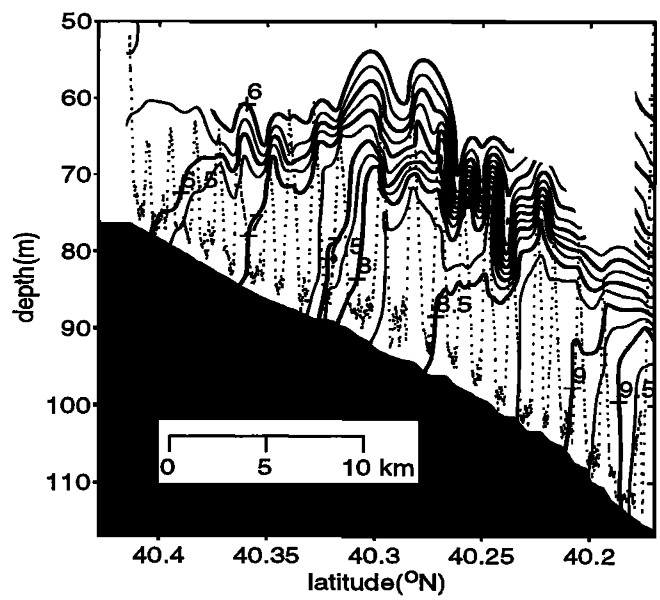

Figure 1. Cross-shelf temperature section, contour interval 0.25°C, through the foot of the shelfbreak front prior to dye injection #2. Sled track, the data source, shown by dotted line.

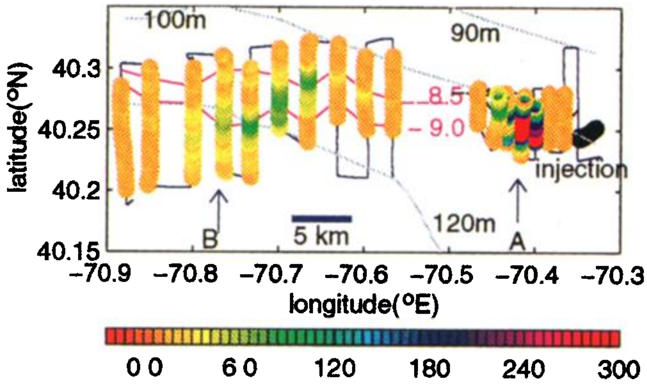

Figure 2. Cruise track during the first and fourth (last) survey of the second dye injection showing the vertically integrated dye in units of 10^{-5} kg/km. Also shown is the injection streak (heavy black line), bathymetry (dotted blue lines), and the BML temperature °C (red line), a 5 km length scale, and the sections A and B presented in Fig. 3.

10 m above bottom. By 68 hours (Fig. 3B) only a trace of dye remained in the BML and the mean height of the dye patch, now fully within the stratified portion of the front, was 36 m above bottom. An inventory of the dye content in the patch during this last survey was equal to 75% of the injected dye so the observed patch is representative of the entire patch of dye tagged water. Dye that moved further offshore within the front and thus shoals most was advected further downstream by the vertical shear of the alongshelf current. Therefore, it was in the downstream (western) end that peak dye concentrations extended further offshore, relative to the position of the front defined by the BML temperature (Fig. 2), and higher in the water column.

Results

The displacement and dispersion of the two dye injections were similar. In both cases the offshore displacement of the center of mass of the dye patch over a three day interval implied an offshore velocity within the front of 0.02 ±.002 m/s relative to the foot of the front. Comparable offshore velocities in the BBL were measured by the Coastal Mixing and Optics experiment current meters moored just inshore of the dye deployments (*S. Lentz, pers. comm.*, 1998). Although the dye concentration in the patch is not strictly normally distributed we estimate the length scale, 2σ, that incorporates 67% of the dye during the first and fourth survey then calculate the diffusivity from $K = .5\, d\sigma^2/dt$ to obtain an isopycnal diffusivity K_{iso}~9 m²/s in both the cross- and alongshelf direction.

Estimates of diathermal (diapycnal) mixing and advection are derived from the temperature distribution of the dye patch (Fig. 4). During the fourth survey the patch had a mean temperature T_{ave}=8.40°C, 0.18°C cooler than the mean injection temperature 8.58°C 64 hours earlier, implying a mean cooling rate T_t=0.79 x10^{-6} °C/s. Assuming that the temperature structure of the front is steady state a mean crossfrontal temperature gradient T_z~0.15°C/m implies a diathermal velocity $v_{dia} = T_t / T_z \approx 5 \times 10^{-6}$ m/s toward the cooler side of the front.

Within the dye patch cooling rates varied. From east to west the mean temperature increased from 8.18°C to 8.50°C as the mean height of the dye increased from 20 to 36 m above bottom. Since the upstream side of the patch was preferentially in or near the BML this suggests that cooling was greater in the BML than in the stratified frontal boundary. To the extent that cooling occurred in the BML the inferred diathermal velocity given above represents an upper bound. However, there was diathermal flow in the front. In regions of highest dye concentration, which were preferentially within the stratified front, T_t=0.6 x10^{-6} °C/s implying a lower but still significant v_{dia}≈4.0 x10^{-6} m/s.

Diapycnal diffusion is inferred from the temperature distribution of the dye patch (Fig. 4) which has a standard deviation of ~0.25°C. Modeling the diffusivity by K=.5 $d\sigma^2/dt$, using T_z = 0.15 °C/m so that σ≈1.7 m, and taking Δt=64 hours we get K_{dia}~6 x10^{-6} m²/s. This is only 43 times larger than the molecular diffusion, K_{mole}≈0.14 x10^{-6} m²/s. If the initial dye temperature distribution is taken to be spread over a 0.2°C interval and not a delta function K_{dia} is only reduced by 10%. The biggest source of error for K_{dia} and v_{dia} is the estimate of T_z which is accurate only to within a factor of two. To the extent that some of the dye dispersion occurs laterally within the

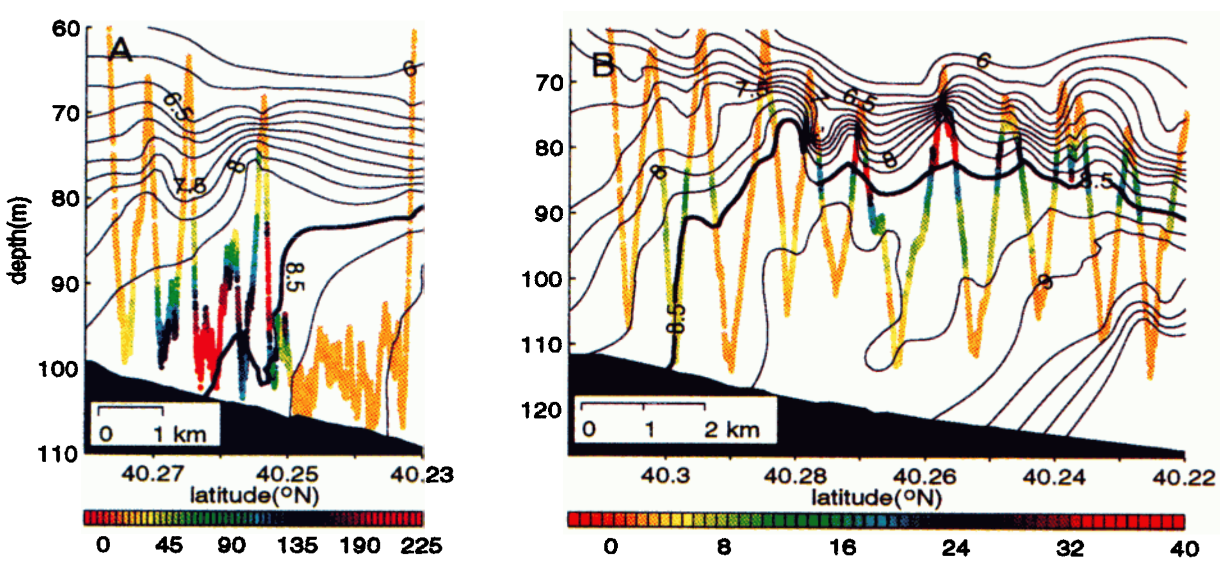

Figure 3. Cross-shelf sections from the first survey (A) and fourth survey (B) showing dye concentration, in units of 10^{-11} by weight, along the sled track and temperature contours, interval 0.25°C, with 8.5°C, the nominal injection temperature, darkened.

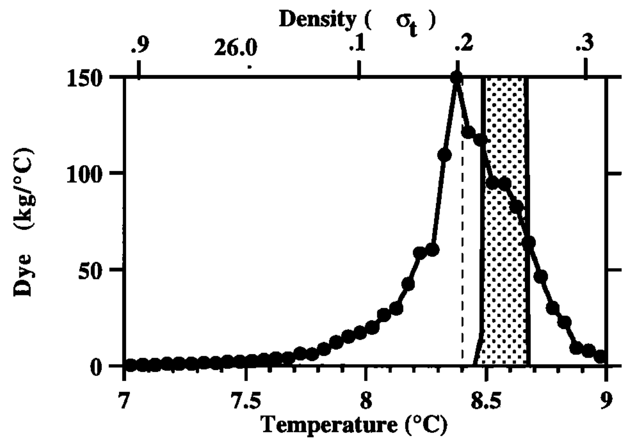

Figure 4. Distribution of dye as a function of temperature and density from the fourth survey with its mean temperature (dashed line) and the temperature interval of the injected dye (stippled band).

BML our calculated K_{dia} is an upper bound for the diffusivity within the stratified front.

Dispersion of dye patch #1 implied a smaller but still comparable diapycnal diffusivity, K_{dia}~4 x10^{-6} m^2/s. But, this dye patch appeared to cool suggesting diathermal flow toward the cold side of the front and not toward a convergence region at 7.5°C as hypothesized [*Houghton*, 1997]. The cooling (T_t = 0.17 x10^{-6} °C/s) was weaker but the temperature gradient (T_z ~ 0.1°C/m) was also less, implying a diathermal velocity of 1.7 x10^{-6} m/s. Since the final dye patch temperature, T_f = 6.51°C is not significantly different from the injection temperature T_i = 6.55°C at the 90% confidence level, and since the patch surveyed contained only 25% of the injected dye, the inference of a non-zero diathermal velocity is not warranted.

Discussion

These estimates of diathermal flow are based on the change in the mean temperature of the dye patch. To investigate whether the spatial structure of diffusion might affect the dye patch temperature distribution, velocity shear data from the ADCP mounted on the sled were used to construct a bulk Richardson number (*Ri*) profile (Fig. 5) across the front. The velocity data was averaged over 2 m vertical and 15 m (10 s) horizontal bins with the lowest bin 5 m above the bottom. The vertical shear, $S=\sqrt{(u_z^2+v_z^2)}$, was calculated between successive bins. The stratification was derived from the CTD profile produced as the sled was lowered at the seaward end of the pre-#2 injection crossfront section (Fig. 1) where the shelf depth is 110 m. At this point the BML was 10°C and approximately 20 m thick so it is equivalent to a profile through the outer portion of the dye patch section shown in Fig. 3B. The profile of vertical shear, an ensemble average (σ~15 % of the mean) of 10 adjacent velocity profiles, and the stratification were smoothed and digitized at 5 m intervals. Profiles of S^2 and the Brunt-Väisälä frequency squared, N^2, are shown in Fig. 5 along with their ratio *Ri*. In the BML *Ri* < 0.25 as expected. In the front it increases to 2.5 then decreases to ~1 in the interior (the cold pool) before increasing at the base of the surface thermocline. The Richardson number profile does not suggest that the vertical variation of the dispersion is sufficiently asymmetric to account for the change in the dye patch temperature.

The Richardson number profile does make clear that dye initially injected into the BML cannot be transferred into the stratified front directly above by mixing. Instead it enters the front along the isotherms (isopycnals) connecting the two regions (Fig. 6). One could envision a transient event whereby the temperature interval in the BML initially containing the dye is suddenly compressed forcing the dye into the same temperature interval within the front. However, the absence of dye in the BML (Fig. 3B) suggests that new fluid has replaced the dye tagged fluid and that there is a mean upwelling circulation at the front. This inference is reinforced by observations of turbidity plumes ascending along the front [*Barth et al.*, 1998].

The estimate of K_{dia}, derived from the dispersion of the patch, can be compared to that derived from the cooling of the patch which in a Lagrangian frame of reference is due to local

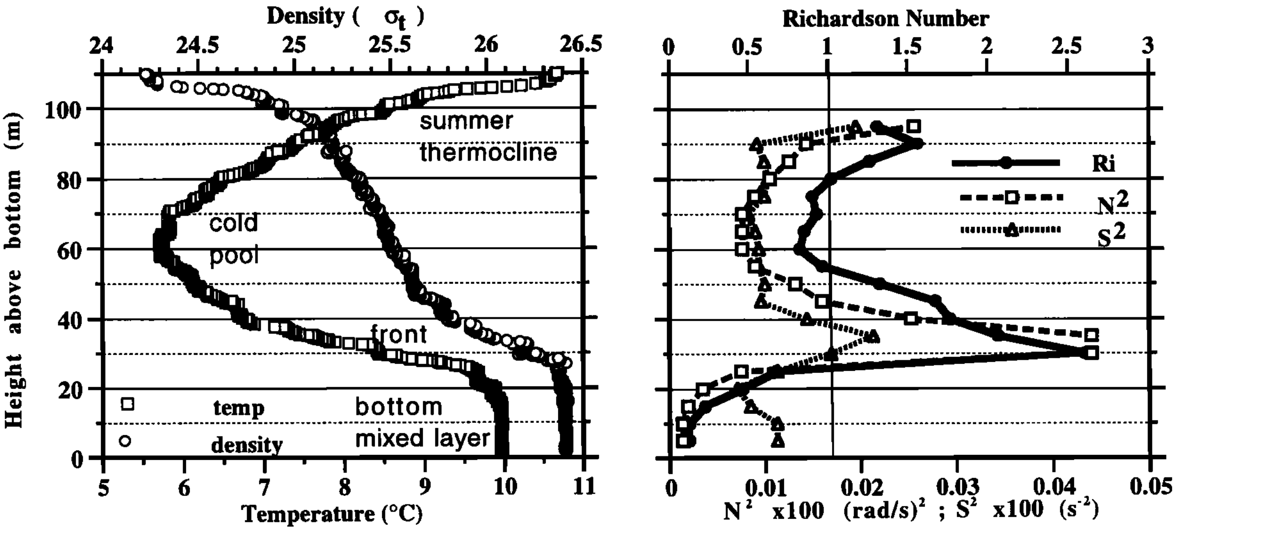

Figure 5. Vertical profile of temperature, density, and stratification at the seaward end of the section in Fig. 1 where bottom depth is 110 m. Also shown are profiles of the total vertical shear, averaged over a region adjacent to the CTD profile, and the corresponding Richardson number. Identified is the bottom mixed layer, the shelfbreak front, the water column interior (cold pool) and the near surface summer thermocline.

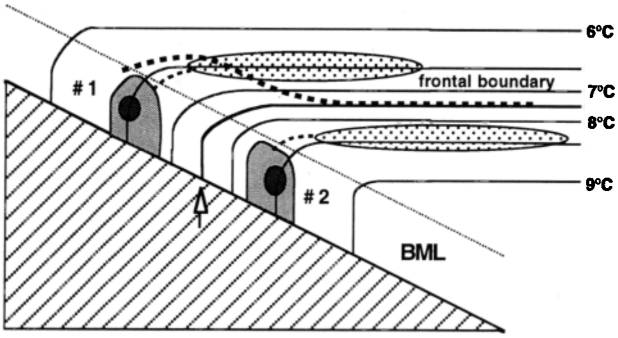

Figure 6. Schematic of the front intercepting the BML showing the location of the two dye injections and the subsequent spreading and trajectory of the dye patch. Arrow inticates where T_{zz}=0 in the BML and heavy dashed line indicates the locus of T_{zz}=0 as inferred from Fig. 1.

mixing, i.e., $T_t=K_z T_{zz}$ where z is the cross-gradient coordinate. For T_t=0.6x10^{-6} °C/s and T_{zz}~0.13°C/m^2 we get K_z=5x10^{-6} m^2/s. Since T_{zz} could be in error by at least a factor of 2 this is consistent with our previous estimate of K_{dia}=6 x10^{-6} m^2/s.

Our observations indicate that the pattern of diathermal flow within the front is more complex than hypothesized by *Houghton* [1997]. This is illustrated in a schematic diagram (Fig. 6). For steady state conditions $v_{dia}T_g=K_{dia}T_{gg}$ where g is the cross-gradient axis, i.e., $g=y$, positive onshore, in the BML and $g=z$, positive upward, in the stratified front. When T_g is at an extremum T_{gg} changes sign and so must v_{dia} and T_t, the dye patch temperature change. The two dye injections were on opposite sides of this convergent point in the BML, i.e., $T_y<0$, $T_{yy}>0$ for #1 and $T_y<0$, $T_{yy}<0$ for #2. Since the stratification increases immediately above the BML we have $T_z<0$, $T_{zz}<0$ for both #1 and #2. Therefore, dye #2 will cool whether it shoals or moves onshore in the BML while dye #1 will cool if it shoals but will warm if it moves offshore toward the convergence region in the BML. A further complication is that for dye #1, moving offshore along the 6.5°C isotherm, T_{zz} changes sign whereas for dye #2, on the 8.5°C isotherm, the sign of T_{zz} remains constant. The locus of T_{zz} = 0, the heavy dashed line in Fig. 6, is derived from the crossfront survey shown in Fig. 1. For this reason the temperature change of dye #1 and hence the inferred v_{dia} will depend on its location and duration within the BML and the stratified region above. Although a hypothetical trajectory of the dye patch #1 is presented in Fig. 6 the surveys did not have sufficient resolution to resolve this complexity.

Conclusions

We now have three realizations of the cross-shelf circulation within a shelfbreak front using a dye tracer. A pattern has emerged which is consistent with model predictions by *Chapman and Lentz* [1994]. During a pilot cruise in 1996 [*Houghton*, 1997] we measured onshore flow of 0.01 m/s in the BML at the foot of the front and in 1997 we observed offshore flow of 0.02 m/s within the stratified front above the BML. The main difference between the two cruises was that in 1996 the BML was 3 to 6 m thick and the dye patch remained within the BML, cooling more rapidly (T_t=4 x10^{-6} °C/s), while in 1997 the BML was 10 to 20 m thick and the dye patch entered the stratified front (Fig. 3) and the cooling rate was less by a factor of six. Initially for dye injection #1 there was evidence of warming to suggest offshore spreading toward the BML convergence region but the patch rapidly entered the stratified front above and subsequent temperature changes where not significantly different from zero.

Within the front the flow was offshore and predominantly isothermal (isopycnal). Isothermal mixing in the cross- and alongshelf direction was comparable with a diffusivity of approximately 9 m^2/s. Diathermal mixing was weak, approximately 6 x10^{-6} m^2/s. This value is close to K_z=10^{-5} m^2/s used by Houghton [1997] to satisfy the heat balance in the BML at the foot of the front. The corresponding Richardson number in the front ranges from 2 to 4. It should be noted that the variation in eddy diffusivity implied by the Richardson number profile (Fig. 5) contrasts the large, K=10^{-3} m^2/s, constant diffusivity used by *Chapman and Lentz* [1994] and suggests that a variable diffusivity is more appropriate in future models.

Besides demonstrating the utility of a dye tracer to measure Lagrangian flow and mixing in a frontal environment we have evidence of upwelling flow at the shelfbreak front. This constitutes a new coastal upwelling mechanism that is forced not by wind stress but from BBL convergence generated by the buoyancy flux in the BBL. The front shoals 100 m from the shelfbreak to the surface 30 to 50 km seaward. Our observed offshore flow of approximately 2 km/day implies a 15 to 25 day transit time to the surface, equivalent to an upwelling velocity of 4 to 7 m/d. This is consistent with the upwelling velocity of 9±2 m/d inferred from shipboard ADCP measurements by *Barth et al.* [1998]. This weak but persistent upwelling could supply nutrient rich water to the euphotic zone and sustain the high biomass accumulation observed in the vicinity of the front [*Marra et al.*, 1990].

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