R/V OCEANUS Cruise OC342 Cruise Report

We gratefully acknowledge the professional and courteous assistance provided by Captain Lawrence Bearse and crew of the RV OCEANUS. Special thanks to Dave Nelson for the successful operation and maintenance of the Scanfish and to Jay Ardai for overseeing the dye injection and detection systems, both of which made this experiment possible.

This report was prepared by Robert W. Houghton with figure preparation assistance by Cheng Ho. This cruise was sponsored by the National Science Foundation and the National Oceanic and Atmospheric Administration. This work was supported with NSF grant OCE-98-06361.

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Cruise Objectives

The overall objective of the cruise was to measure the mean cross-bank Lagrangian flow in the bottom mixed layer through the tidally-mixed front located along the northeast peak and the south flank of Georges Bank. To do this a fluorescent dye, Fluorescein, was injected into the bottom mixed layers on the off-bank (stratified) side of the front. The subsequent dispersing dye patch was surveyed using a Chealsea Ltd. Aquatraka fluorometer mounted in a Scanfish, a towed vehicle provided by Univ. of Rhode Island. Concurrent CTD measurements were used to map the structure of the front and to determine the location of the patch of dye tagged water with respect to the front. The shipboard ADCP velocity was integrated over depth to produce a real-time progressive vector diagram. This accumulating diagram of water column displacement was used to anticipate the movement of the dye patch and to identify the phase of the tide for optimum dye injection.

This cruise (OC-342) contributed to a coordinated field program with concurrent GLOBEC cruises of the RV Endeavor and RV Edwin Link. Our dye injections were coordinated with surface and pycnocline dye injections by J. Ledwell and drogued drifter deployments by J. Churchill. Circulation and hydrographic data in the vicinity of the front was exchanged and used as input to the onboard modeling activities. Clearly the whole of this activity was greater than the sum of the individual parts.

Cruise Narrative

May 20 Leave Woods Hole 1000 EDT and steam to the Schlitz mooring array (see Fig. 17) on the south flank.

May 21 Arrive near mooring (40 59.95'N, 67 19.86'W) at 1028 UTC (all subsequent times are UTC) to begin a series of cross-bank hydrographic sections. We conducted 4 sections across the southern flank from the 40 to 70 m isobath using a Scanfish to study the hydrographic structure of the tidally-mixed front (Fig.1). Cross-bank displacements of the front, 6-7 km, are comparable to mid-depth (45-25 m depth) water column displacements derived from ADCP data. The bottom temperature is a good indicator of position within the front: 8.0C on the mixed side; 7C on the stratified side (Fig.2).

May 22 After completing the frontal surveys we prepared for the first dye injection. The target temperature was to be 6.9¸C in the bottom mixed layer. We positioned the ship near the anticipated position 1 hour prior to the end of the off-bank tidal flow. A Seabird Seacat CTD attached to a weighted conducting cable was lowered to confirm a suitable bottom temperature. After some final ship maneuvering the Seacat was brought to the surface and a garden hose was attached as the cable was paid out. When the end of the hose, with a diffuser attached next to the Seacat, was 5 m above bottom at the 63 m isobath where the bottom mixed layer was 24 m thick we pumped 153 gal. of a 30% dye solution in water, containing 86 kg of Fluorescein mixed with isopropal alcohol to achieve the approximate *in situ* density of 25 sigma-t.

<u>Dye injection #1:</u> <u>initial</u> <u>final</u>

Time 1545 - 1633

Water temperature 6.74¸C - 6.92¸C

Water salinity 32.38 - 32.37

Latitude 41¸ 4.57'N - 41¸ 4.58'N

Longitude 67¸ 22.05'W - 67¸ 24.29'W

Total pumping time was 46 minutes. Wire angle was minimal. Water speed with respect to ship < 1 kt, so dye streak was less than 1 km long. There was a slight leak in one of the hose connections, not serious enough to stop the injection for repair, but it produced a small surface patch of dye that was subsequently detected during the initial survey.

At 2100 survey of the injected dye patch began using the URI Scanfish. In addition to the Aquatracka the Scanfish contained a SB 911 CTD, a Wet Lab fluorometer to measure chlorophyl, and an altimeter. The Scanfish flew a saw-tooth pattern with surface and bottom turn around at 10 m below surface and 10 m above bottom, both later reduced to 5 m, while being towed at speeds of 6 to 8 kt. Depths of 70 m were readily achievable. Ship speed and cable paid out were increased to get the Scanfish down to 90 m. The maximum bottom depth in the study area on the south flank was 70 m. On the north flank, where bottom depths increased to 200 m on the off-bank end of sections, no attempt was made was made to fly the Scanfish below 90 m. The vertical velocity of the Scanfish was approximately 0.5 m/s. Data was generated at 2 Hz but subsampled for on-board display at 0.5 Hz so the vertical resolution for data shown in this report is 1 m. With a tow speed of approximately 7 kt the horizontal resolution is ~0.55 km at the top and bottom and ~0.26 at mid-depth. Except for one encounter with a loose line in the water, one cable repair, and interference with the ship¸s hf single side band radio transmissions, the Scanfish performed flawlessly throughout the cruise. It was operated continuously for up to 2 days.

May 23 0252: First sighting of dye patch; begin systematic survey of the patch. Example of real-time data display and contoured section through the center of the dye patch are given in Fig. 3 and 4.

1700: Break off survey for rendezvous with RV Edwin Link; transfer glass sample bottles and discuss preliminary dye results with Jim Manning

2308: Stop to re-splice conducting cable to Scanfish.

May 24 0120: Scanfish repair was completed; continued survey, obtained repeated and complete surveys across the dye patch

May 25 0547: Wind blows up to over 30 kts. Towing operation was stopped because of high sea state (waves over bow).

1437: Resume dye patch survey. We see the dye patch temperature increase (Fig. 5 and 6) as it passes through the tidal front moving onto the Bank.

May 26 1539: End of survey of #1 dye patch as the fluorometer signal to noise ratio approaches 2. The patch had drifted west to 67.55¸ W nearly 19 km west of the injection site (see Fig. 18).

1600: prepare for intercomparison of the two CTD¸s by strapping the Seacat onto the Scanfish. This test was only partially successful as the full water column was not sampled.

1923: Steam back to Schlitz mooring region to conduct large scale hydrographic surveys across the front prior to the second dye injection. Conduct repeated cross-bank lines (340¸ heading), perpendicular to the local isobath, crossing 40¸ 5¸N at 3 locations: 67¸ 27¸W, 67¸ 23¸W, and 67¸ 12¸W. The last line was just east of the Schlitz mooring. The line extended from the 45 to 70 m isobath. The inshore edge of the foot of the shelfbreak front is now detected at the off-bank end of the sections (Fig 7 and 8). On the eastern line the shelfbreak front is further on-bank, at 40¸ 6.5¸N, equivalent to the middle of the Schlitz array.

May 27 1430: Repeat CTD intercomparison but this time successfully sample the entire water column. The sensors agree to within 0.002¸C for temperature and 0.005 for salinity. Thus the hydrographic data taken during the dye injection and detection are equivalent.

1959: We complete the pre-injection surveys and position for second dye injection in 7.0¸C bottom mixed layer water. The injection depth was 6 m above the bottom at the 63 m isobath where the bottom mixed layer was greater than 30 m thick. We repeated the procedure used for #1 injection. Start dye pumping at 2127.

Dye injection #2: initial final

Time 2127 - 2230

Water temperature 7.00¸C - 7.015¸C

Water salinity 32.354 - 32.355

Latitude 41¸ 4.14'N - 41¸ 4.86'N

Longitude 67¸ 25.1'W - 67¸ 26.28'W

Total pumping time was 46 minutes during which approximately 86 kg of dye in a 153 gal water and alcohol solution was injected into the bottom mixed layer. At 2135 there was a 3 minute gap to repair the flow gauge. At 2152 the injection hose on deck burst spilling approximately 1 gal of solution requiring 14 minutes to repair. The spilled dye solution was washed off the deck and subsequently detected during the initial dye patch surveys. Water speed with respect to ship was < 0.5 kt and the initial dye streak is estimated to be 0.5 km long.

2348: Start survey to find dye patch #2. Detect surface slicks from spilled dye.

May 28 0200: Pass through dye patch on second try. Initially the dye had been pushed up into the water column (Fig. 9 and 10) where the stratification inhibited vertical mixing and levels of dye concentration remained high. After 24 hours the dye patch was mixed to the bottom.

May 29 Continue dye survey. The Scanfish nearly crashed to the bottom when the "surface park" control malfunctioned. The trouble was traced to electrical interference when the bridge uses its hf single side band radio. Subsequently, when we were notified by the bridge of impending radio use, the Scanfish was first brought to the surface in the parked mode.

May 30 Continue dye survey. The patch does not change temperature significantly, indicating little on bank motion through the tidal front (Fig. 11). The difference from #1 is that now the shelfbreak front remained up on the bank to within 5 km of the dye patch. For #1 it had been greater than 15 km off-bank of the dye patch. Dye patch #2 remained in a temperature minimum, i.e., a small cross-bank temperature gradient and did not move on-bank. This suggests that there is a region of divergence in the cross-bank flow between the two fronts.

Begin daily transmission of ADCP data to RV Endeavor for use in model calculations

May 31 1540: Terminate survey of dye patch #2 when signal to noise is < 2. Steam north to the northeast peak for the 3rd and final dye experiment.

2310: Arrive at 41¸ 59.2N, 66¸ 55.09W to begin hydrographic survey of the tidal front on the northeast peak just west of the moorings (see Fig. 17).

June 1 We begin a series of meridional sections from 42¸ 00¸N (south of the tidal front) to 42¸ 11¸N (~200 m isobath) along 66¸ 55¸, 44¸ and 33¸W. We then repeated sections along 67¸ 00¸ and 66¸ 55¸W for one and a half tidal cycles to predict the position of the front for optimum dye injection.

June 2 0900: Near the end of the pre-injection surveys the conductivity signal went bad. When Scanfish was on deck we discovered that sand had plugged the conductivity pumping tube. Some of the survey sections had passed near shallow regions on the bank where tidal rips were observed. We speculated that in these regions the higher suspended sediment load brought the sand into the pumping tube.

We want to inject dye in 6.8¸C at the end of the off-bank tidal flow. But during the off¸bank phase of the tide this water moves off the bank to 100 m depth. Since dye injection into the bottom mixed layer in water this deep would be difficult with the stronger tidal velocities, it was decided to inject the dye at the end of the on-bank phase of the tidal flow when 6.8¸C water is at 60 m depth (Fig. 12).

1135: We prepare for 3rd dye injection at 6 m above bottom at the 66 m isobath where the bottom mixed layer is 26 m thick. Start pumping at 1159. Inject ~153 gal. in 38 minutes. There were no problems and virtually no current; boat drift to the northwest < .5 km.

<u>Dye injection #3:</u> <u>initial</u> <u>final</u>

Time 1159 - 1237

Water temperature 6.84¸C - 6.85¸C

Latitude 42¸ 6.06'N - 42¸ 6.36'N

Longitude 66¸ 54.72'W - 66¸ 54.9'W

1300: Inspect and clean Scanfish

1546: We begin survey of dye patch #3.

1839: First detection of dye. During the off-bank phase of the tide only the inshore portion of the dye patch is detected as the center of the patch moves off bank to at least 100 m depth.

June 3 Continue survey. Dye tagged water moves rapidly on-bank across the tidal front (Figs. 13, 14, 15). The dye concentration within patch #3 decreased more rapidly than in the previous 2 experiments.

June 4 Dye concentration rapidly approaches the noise level. Near the end, when most of the dye is across the front, i.e., T>8¸C, there is evidence of dye at mid-depth (Fig. 16) now moving off-bank along an isopycnal into the stratified layer. This would be the same layer that Jim Ledwell conducted a dye injection experiment.

June 5 0443: End survey of dye #3 as the signal to noise ratio approaches 2. This is after 2 1/2 days in contrast to 4 days for #1 and #2. The reason for the more rapid decline of dye concentration on the northeast peak is the greater tidal amplitude and the more rapid passage through the tidal front where the dye tagged water is subsequently mixed vertically through the water column.

Because experiment #3 ended 1 1/2 days early we were able to conduct a Scanfish hydrographic survey on the north flank in support of Jim Ledwell¸s dye experiment on the RV Endeavor.

1350: Begin hydrographic survey consisting of 9 sections across the north flank moving westward starting at 66¸ 55.07¸W to 67¸ 25¸W. The sections extended from the 40 to 200 m isobath. The Scanfish cycled from 5 m below the surface to 10 m above the bottom with a maximum depth of 80 m.

June 6 0329: End the "Ledwell" survey. Steam to Woods Hole with a diversion south to conduct an ADCP survey along the PRIMER line for Bob Pickart.

1935: At 39¸ 50.61N, 69¸ 52.99W begin ADCP line steaming at 7 kt.

June 7 Arrive Woods Hole 0900 EDT

Post Cruise ¸ Preliminary results

We present here a few results based on a very preliminary analysis of the data to highlight the differences of the 3 dye injections. The location of the dye injections and the center of the dispersing patch derived from the subsequent surveys are shown in Fig. 17. The patch position is aliassed by tidal excursions shown in Figs.18, 19, and 20. The displacement of the dye patch implies along bank velocities of 4.1 cm/s, 6.3 cm/s, and 11.0 cm/s for #1, 2, and 3 respectively.

Figure 21 shows the time dependence of the maximum dye concentration measured within the dye patch. Prior to 24 hours after injection values for #2 are misleading since the dye that was forced up into the more stratified portion of the water column, where vertical mixing is inhibited, maintained higher concentrations. After 24 hours all data represent bottom mixed layer values.

The time dependence of the dye tagged water temperature where the dye concentration is maximum (Fig. 22) was significantly different for each dye injection. For #1 and #3 the increasing temperature represents the effects of local mixing on water flowing diathermally across the cross-bank temperature gradient associated with the tidal front. From measurements of the mean temperature gradient we infer on-bank Lagrangian velocities of 1.4 cm/s and 3.6 cm/s for #1 and #3 respectively. The higher value on the northest peak is consistent with model calculations. For #2 the absence of any significant temperature change is striking. We suggest that this is due to the fact that the dye patch was located in a divergent region between the tidal and shelfbreak front. Both #1 and #2 were injected in the same location with respect to the tidal front. The difference is that for #1 the shelfbreak front was far to the south (>15 km) while for #2 it was up on the bank (within 5 km of the dye patch) so that the dye patch was equally distant between the two. Satellite SST images suggest that the proximity of an eddy or warm core ring might be the cause of the shelfbreak front displacement.

The time dependence of the cross-bank width, W, of the dye patch, which was approximated by the distance along a section passing through the center of the patch between the location of the peak dye concentration and the point where the concentration is 1/4 of that peak value, is shown in Fig. 23. Toward the end of the experiment this value decreases as peak dye concentration approach the noise level. However estimate of the lateral diffusivity K_h=1/2 $\Delta W^2/\Delta t$ for the first 48 hours yields K_h ~50-75 m^2/s.

Cruise Participants

Scientific Personnel

Robert W. Houghton Columbia University (LDEO) Chief Scientist
Jay Ardai Columbia University (LDEO) Marine Techn.
David Nelson University of Rhode Island Marine Techn.
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Laura Goepfert Woods Hole Oceanographic Inst SSG Techn.

Ship Personnel

Lawrence T. Bearse Master
Anthony D. Mello Ch. Mate
Richard Chase 2nd Mate
Jeffery M. Stolp Boatswain
James La Pierre OS
Horace Medeiros AB
Peter J. Liarikos AB
Glen Loomis Chief Engineer
J. Kevin Kay Jr. Engineer
Alberto Collasius, Jr. Jr. Engineer
Torii Corbett Steward
Raul E. Martinez Mess Attendant

- Chris was to work with Jim Ledwell aboard the R/V ENDEAVOR with a transfer at sea. This was not possible so he stayed on the RV OCEANUS. His presence and participation was most welcomed.

Figure Captions:

Figure 1. Cross-frontal hydrographic section prior to the first dye injection, starting at 41¸ 13.95¸N, 67¸ 25.93¸W along a 160¸ heading (perpendicular to the local isobath), on May 21, 2025-2200.

Figure 2. Bottom mixed layer temperature as a function of cross bank distance, derived from the 4 cross-front temperature sections prior to the first dye injection. North is positive. Curves are shifted to coincide at 7.3¸C.

Figure 3. Real-time Scanfish data of pressure, temperature, salinity, and dye concentration (10^{-11} parts by weight) along 67¸ 26.32¸W on May 24, 0740-0817.

Figure 4. Contours of temperature, salinity, potential density, and dye concentration from Fig. 3.

Figure 5. Real-time Scanfish data of pressure, temperature, salinity, and dye concentration (10^{-11} parts by weight) along 67¸ 30.5¸W on May 26, 0415-0524.

Figure 6. Contours of temperature, salinity, potential density, and dye concentration from Fig. 5.

Figure 7. Cross-frontal hydrographic section prior to the 2nd dye injection, starting at 41¸ 13.86¸N, 67¸ 26.87¸W along a 160¸ heading (perpendicular to the local isobath), on May 26, 1932-2200.

Figure 8. Bottom mixed layer temperature as a function of cross-bank distance, derived from the 5 cross-front temperature sections prior to the 2nd dye injection. Curves are shifted to coincide at 7.3¸C. North is positive. The increasing temperature at the southern end is due to the presence of the shelfbreak front.

Figure 9. Real-time Scanfish data of pressure, temperature, salinity, and dye concentration (10^{-11} parts by weight) along 67¸ 23.0¸W on May 30, 0451-0611.

Figure 10. Contours of temperature, salinity, potential density, and dye concentration from Fig. 9.

Figure 11. Contours of temperature, salinity, potential density, and dye concentration along 67¸ 33.5¸W on May 30, 1449-1661.

Figure 12. Cross-frontal hydrographic section, prior to the 3rd dye injection, starting along 66¸ 50.0¸W on June 1, 1227-1330.

Figure 13. Real-time Scanfish data of pressure, temperature, salinity, and dye concentration (10^{-11} parts by volume) along 66¸ 50.0¸W on June 3, 0020-0058.

Figure 14 Contours of temperature, salinity, potential density, and dye concentration from Fig. 13.

Figure 15. Contours of temperature, salinity, potential density, and dye concentration west along 42¸ 04.5¸N on June 3, 1414-1529.

Figure 16. Contours of temperature, salinity, potential density, and dye concentration south along 66¸ 44.0¸W on June 4, 2033-2130.

Figure 17. Map of the south flank and northeast peak of Georges Bank showing location of current meter moorings and the bottom mixed layer dye injections. Subsequent positions of the center of the dispersing dye patch is given by open circles for the following time lapse (hours) from injection.

#1: 17, 38, 49, 83, 94 #2: 18, 31, 46, 59, 71, 78 #3: 13, 18, 43, 51, 58

Figure 18 Detail of the displacement of #1 dye patch with the corresponding water column displacement. This progressive vector diagram (PVD) is derived by integrating the ship ADCP data between 25 and 45 m depth. The numbered open triangles correspond to the same time on the PVD as the center of the dye patch given by the numbered solid circles.

Figure 19 Same as Fig. 18 except for dye #2.

Figure 20 Same as Fig. 18 except for dye #3. ADCP integration now between 35 and 50 m.

Figure 21. Maximum dye concentration (10^{-11} parts by weight) in dye patch as a function of time lapsed from injection. Noise level is 1×10^{-11}.

Figure 22. Temperature of water in dye patch at the location of the maximum dye concentration as a function of time lapsed from injection.

Figure 23. Cross-bank width of dye patch (distance from dye concentration peak to 1/4 peak value) as a function of time lapsed from injection.

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