# Boundary mixing in Massachusetts Bay

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Summary Report:

# Boundary Mixing in Massachusetts Bay

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**Abstract**

A dye study was conducted in Massachusetts Bay in July, 1995, to determine the intensity of boundary mixing. This study follows a similar investigation of the rate of vertical mixing in western Massachusetts Bay, near the site of the new Boston sewage outfall. The previous investigation revealed weak vertical mixing across the thermocline in the interior of the bay. The present study was designed to test the hypothesis that intensified boundary mixing is quantitatively important as a mechanism of vertical exchange in Massachusetts Bay. A site near Scituate was selected because it is a region where the nutrient-rich effluent from the new outfall is likely to pass in close proximity to the coast, where intensified vertical mixing may provide an important conduit for nutrients to enter the euphotic zone.

The vertical mixing rate was quantified by injecting a known quantity of dye in a thin streak within the thermocline, then mapping its vertical and horizontal distribution using a profiling fluorometer for several days following the injection. Water properties and currents were measured from the vessel while it surveyed the dye patch to determine the forcing conditions for vertical mixing. Drifters were deployed in conjunction with the dye release to aid in tracking the dye and to quantify the Lagrangian water motion.

The vertical diffusion rate was found to be 0.12 to 0.18 $cm^2 s^{-1}$, based on the vertical spreading of the dye patch. The rate of mixing was comparable above and below the thermocline. This rate is several times larger than observed in the interior of Massachusetts Bay (0.06 $cm^2 s^{-1}$) during the 1993 dye study. The mechanism for enhanced mixing in this study was not immediately evident from the measured shear and stratification data—the stability of the flow based on gradient Richardson number calculations was actually higher in the boundary mixing study than in the interior mixing study. There was relatively more high-frequency energy during the boundary mixing study, suggesting greater energy transfer from tidal frequencies to high frequency waves and turbulence due to steepening and dissipation of internal tidal waves.

This study indicates that there is not a dramatic increase in mixing in the near-shore region, but the mixing is enhanced enough that boundary mixing makes a significant contribution to the bay-wide exchange. Generalizing these local observations to the entire perimeter of the Bay, one third to one half of the cross-isopycnal exchange would occur in the 5-km boundary zone. The remainder of the vertical exchange is due to the weaker mixing in the interior and wind-driven upwelling.

# 1 Introduction

The rate of vertical exchange in Massachusetts Bay is a critical parameter for the Bay's ecology, because it determines the rate at which nutrients are replenished to the euphotic zone. From the bloom in the early spring to the fall overturn in early November, nitrate concentrations are extremely low in the euphotic zone (Townsend et al., 1990). However there is a large reservoir of nutrients trapped below the thermocline, and the net primary production rate depends on the vertical flux of nutrients. This vertical flux can occur in the interior of the Bay, due to shears within the thermocline that result in instabilities and turbulence (Thorpe, 1973). At the lateral boundaries where the thermocline intersects the bottom, bottom-generated turbulence also can contribute to vertical flux, and more complex mechanisms of cross-isopycnal exchange can also occur (Garrett, 1991). In addition, internal shears may be intensified near the boundaries due to rough topography and shoaling internal waves, so shear-induced mixing may also be enhanced. Upwelling provides an advective mechanism for vertical transport at the boundaries, which may result in enhanced productivity, as found in many coastal regions around the world.

The interest in vertical mixing has been heightened in recent years due to the construction of the new outfall for Boston's sewage effluent. The nutrient-rich discharge will be trapped beneath the thermocline in western Massachusetts Bay, and thus its impact on the euphotic zone will depend critically on vertical mixing processes. A previous dye study conducted in western Massachusetts Bay (Geyer and Ledwell, 1994) addressed the intensity of vertical mixing in the vicinity of the outfall site. The observed rate of mixing was weak, the estimated diffusivity being 0.06 $cm^2\ s^{-1}$. This rate is not adequate to explain the annual cycle of vertical heat flux in Massachusetts Bay, and it suggested the possibility that there are localized regions of intensified vertical mixing.

One likely candidate for enhanced mixing is the coastal zone near Scituate. Previous measurements indicated significant internal wave activity in this region (Geyer et al., 1992), which might lead to enhanced vertical mixing. A three-dimensional, numerical model of the hydrodynamics of Massachusetts Bay (Blumberg et al., 1993) suggests that there is intensified vertical mixing along the coast near Scituate, due to intensified shears and enhanced turbulence. This region is also important because of the coastal current that produces a net southward transport and may be a major conduit of the effluent from the new outfall.

In order to test the hypothesis that boundary mixing could be a dominant mechanism of vertical exchange in Massachusetts Bay, a dye study was conducted in the coastal zone near Scituate during the summer of 1995. This report summarizes the results of that boundary mixing study and addresses some of the implications for vertical mixing and nutrient transport in Massachusetts Bay.

# 2 Methods

The dye study was performed in southwestern Massachusetts Bay, within approximately 5 km of the shore of Scituate, on-shore of the 20-meter isobath (Figs. 1a and 1b). The dye injection took place on July 11, 1995, and the dye was surveyed the day of the release (Day 1), the day after the release (Day 2), and 3 days after the release (Day 4).

### *2.1 Dye Injection*

Rhodamine WT was released in a 2.8 km long path in the along-shore direction, approximately 1 km off-shore (Fig. 1b). The total depth varied between 14 and 18 meters along the injection track. The dye was released on the 10.0 °C isothermal surface, with a root mean square (rms) error of 0.1 °C (Fig. 2). This isotherm was below the region of maximum stratification, at depths of 4.5 to 7.5 m, and 8 to 12 meters off the bottom. The mean potential density during the injection was 24.41, and the rms error in density was less than 0.02, equivalent to less than 0.3 meters in the mean density gradient.

The dye was introduced by pumping from a set of four 200-liter drums on the deck of the R/V Asterias through a garden hose terminated in a perforated T-shaped disperser. Two gear pumps in parallel were used on deck, to give a flow rate of 10 L/min. The injection took 70 minutes, with the ship moving at 0.7 m/s. The total amount of Rhodamine-WT released was 100 kg. This dye was purchased as a 20% aqueous solution and was mixed with isopropyl alcohol to bring the mixture to a specific gravity of 1.0248 at 10 °C. Hence the dye mixture was within 0.5 parts per thousand of the target density. Mixing by the disperser and by the wake of the sled would have reduced the density anomaly of the plume by a factor of 100 at least, equivalent to less than 5 cm of displacement in the mean density gradient.

Satellite tracked "ARGOS" drifters were deployed at even intervals during the dye injection for tracking purposes. The drifters had 5-m long holey-sock drogues, 1 m in diameter, centered at 6-m depth.

### *2.2 Dye Sampling*

The dye was sampled with a system built around a SeaBird 9/11 CTD on a sampling "sled" which was heavily weighted for towing and robustly built for occasional encounters with the bottom. This sled was tow-yo'd at speeds of 1 to 2 m $s^{-1}$, with winch speeds of approximately 0.5 m $s^{-1}$. Several instruments were mounted on the sled which sent analog data to the CTD system for incorporation in the data stream, including a fluorometer (Chelsea Instruments) tuned for Rhodamine and an altimeter (Datasonics) with a range of 30 meters to help avoid the bottom. A second optical instrument was included to help correct for background fluorescence. In some cases this was an absorption meter tuned for Rhodamine (WetLabs); in others it was a second fluorometer (Chelsea) tuned for chlorophyll. Both could not be run at the same time because of limitations in the power handled by the CTD.

The minimum detectable level of Rhodamine by the fluorometer in clear water is approximately 0.01 ppb (parts per billion by weight). However, variability in background fluorescence in coastal waters raises the noise level to at least 0.02 ppb. In the present case, corrections were derived by determining the dependence of the background on temperature for profiles that were taken outside the dye patch on the surveys on Day 1 and Day 2 (Fig. 3). The rms variability of the background fluorescence reached a maximum at 9 °C of 0.05 ppb. Above the target surface of 10 °C, this variability is approximately 0.03 ppb. These variabilities set the practical rms error of the measurements.

There is an electronic filter with a time constant of 1 second in the fluorometer circuitry, which introduces a time lag of the fluorometer data relative to the CTD data, recorded at 6 Hz. Also, it has been found that there may be a lag on the order of 1 second in all sensors due to the finite time to flush the sled with new water. The total lag was accounted for empirically by finding the offset in the data records which gave the best agreement between adjacent up and down casts for each crossing of the dye patch, i.e., for data segments about 30 minutes long.

## 3. Results

### *3.1 Horizontal Advection and Dispersion*

The dye patch was advected and stretched along-shore, as it spread in the cross-shore direction (Figs. 4-6). Its movement along-shore was arrested at a point at 42° 13' N, where it spread mostly off-shore, following the drogues (Fig. 7). During most of the experiment, the dye remained on-shore of the 20-meter isobath, and the in-shore edge of the patch remained in close contact with the bottom. Hence, the height above the bottom of the dye patch started at 10 meters, and continued to probe the bottom 10 meters of the water column throughout the experiment.

The center of mass of the dye patch moved at about 2 cm $s^{-1}$ in both the along-shore and off-shore directions. The rms dispersion of the dye patch in the along-shore and cross-shore directions indicate an effective lateral diffusivity on the order of 10 $m^2$ $s^{-1}$ acting at length scales of 1 to 5 km.

### *3.2 Diapycnal Mixing*

The dye spread across isopycnals faster than for the dye experiment performed in the interior. The increase in the second moment of the vertical distribution between Day 1 and Day 4, estimated from Fig. 8, implies a vertical diffusivity of 0.12 to 0.18 $cm^2$ $s^{-1}$ (see Fisher et al., 1979). By contrast, the value estimated for the 1993 experiment was 0.04 to 0.08 $cm^2$ $s^{-1}$. Penetration upward into the pycnocline was as rapid as penetration downward, indicating that the enhancement of turbulence in this near-shore region was distributed throughout the water column. Judging from the uniformity in the diapycnal distribution of the dye across the patch, the diffusivity seems to be on the order of 0.15 $cm^2$ $s^{-1}$ everywhere within the 20-meter isobath, i.e., within 5 km or so of the shore.

### *3.3 Forcing Conditions*

Tidal range reached 3.9 m during the dye experiment (indicative of spring tide conditions), compared to its monthly mean of 2.9 m. The night-time tides were about 30% larger than the daytime tides during this period, so the measured velocities (which were only obtained during daylight) are underestimates of the 24-hour average conditions.

Winds were variable during the first two days of the dye release (Fig. 9), and southerly winds became dominant during the last two days. Southerly winds had dominated for the week prior to the dye release, which produced strong upwelling conditions, as evidenced by cold, near-surface water in western Massachusetts Bay (Fig. 10). The upwelling produced colder surface waters than average at the release site and caused the thermocline to be shallower than average for this time of year.

Currents observed by the shipboard ADCP during the dye experiment showed a complex mixture of tides, mean flow, and other high- and low-frequency variations. The time-mean currents were dominated by the along-shore component, which was nearly 6 cm $s^{-1}$ to the north near the surface and linearly decreased to zero by 20-m depth. The mean cross-shore flow over the period was less than 1 cm $s^{-1}$, although it fluctuated from day to day.

Semidiurnal tidal currents were around 7 cm $s^{-1}$ and oriented approximately 60 degrees north of the on-off-shore direction at the surface, and 30 degrees north of the on-off-shore direction at 20-m depth. The near-bottom tidal currents lead the near-surface currents by 80 minutes. Internal tidal variations were evident both in the variations in shear and the variations in pycnocline level (Fig. 11). Tidal analysis of the shear indicated that the semidiurnal frequency had more energy than the mean, but a noteworthy result was that the combined energy in the quarterdiurnal and sexdiurnal frequencies was nearly equal to the semidiurnal energy, indicating highly nonlinear internal tidal waves.

## 4 Analysis

### *4.1 Water-Column Stability: Richardson Number Analysis*

The local stability of stratified fluid depends on the gradient Richardson number, which is defined by

$$Ri = \frac{-\frac{g}{\rho}\frac{\partial \rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} = \frac{N^2}{S^2}$$

where g is the acceleration of gravity, ρ is the density, z is the vertical coordinate, and u and v are horizontal velocity components. N is the buoyancy frequency, and S is the magnitude of the vertical shear. Miles (1963) showed that Ri>0.25 ensures stability for parallel shear flow, and generally it is found that mixing occurs for Ri<0.25 (Thorpe, 1973; Geyer and Smith, 1987).

The magnitudes of the buoyancy frequency and shear were calculated for all of the observations at the target level of the dye (9-11 °C), and from these estimates the Richardson number was calculated. The velocity was averaged over 90 seconds for these estimates, corresponding to a horizontal distance of approximately 200 m, to reduce the noise in the shear.

This smoothing process inadvertently removes the influence of high frequency, high wavenumber motions, but the narrow-band ADCP was not capable of resolving these motions.

The daily average magnitude of the buoyancy frequency was nearly constant at 0.026-0.028 $s^{-1}$. The mean shear varied somewhat from day to day, from 0.019 $s^{-1}$ on July 12 to 0.024 $s^{-1}$ on July 13. The gradient Richardson number based on these means was always larger than 1, indicating that the flow on average was quite stable. Fluctuations in shear and stratification produced instantaneous occurrences of Ri<0.25, leading to intermittent turbulence production. Table 1 shows the occurrence of low Ri for each of the days of the dye study.

**TABLE 1**

| | **Ri<1.0** (%) | **Ri<0.5** (%) | **Ri<0.25** (%) |
|---|---|---|---|
| **July 11** | 26 | 10 | 4 |
| **July 12** | 28 | 13 | 7 |
| **July 13** | 29 | 11 | 4 |
| **July 14** | 32 | 16 | 8 |
| **Average** | 29 | 13 | 6 |

The average occurrence of Ri<0.25 of 6% compares to a value of 10% for the 1993 dye study. According to this measure, the intensity of mixing should have been substantially higher in 1993, yet it was almost a factor of 3 lower.

A partial explanation for this apparent discrepancy is that the tides were 35% stronger at night than day during the 1995 observations, while the Richardson number estimates were made during the day. If the shears were proportionately affected, then the incidence of low Richardson number would be augmented to 10-11%, similar to the value in 1993. Another partial explanation for the discrepancy is that the ADCP could not resolve shears at scales less than 1-2 m. It is conceivable that as the internal waves steepened in the shoaling water, a significant amount of mixing occurred due to high-frequency, small-scale fluctuations in shear. The frequency content of the internal waves was shifted to higher frequencies in the 1995 observations relative to those in 1993, suggesting more nonlinearity and presumably smaller vertical scales.

### *4.2 The Influence of Internal Tides*

The source of energy for mixing in the boundary zone is most likely the internal tide. The surface tide is not particularly energetic at this location, and surface tides are very inefficient at converting their energy to vertical mixing (Simpson and Hunter, 1974). Although not much is known about the dissipation of internal tides, they would be expected to be more efficient at producing vertical mixing due to the strong shears across the pycnocline. As the internal tide propagates into the boundary zone, most of its energy is lost due to dissipation rather than reflecting energy back out. This loss of energy provides the driving force for mixing. A crude estimate of the convergence of energy flux of the internal tide is 1 x $10^{-7}$ watts/kg (assuming a velocity amplitude of 3 cm $s^{-1}$, a group velocity of 40 cm $s^{-1}$ and a convergence scale of 4 km). This is close to the estimated dissipation rate within the pycnocline based on the observed vertical mixing rate, using Osborn's (1980) relation

$$\epsilon = 5\,K\,N^2$$

where the ratio of buoyancy flux to dissipation is assumed to be 0.2. This relation also yields an estimate of $\epsilon$ of 1 x $10^{-7}$ watts $kg^{-1}$. If the efficiency of mixing by the internal tide is as high as 0.2, then incident internal tides could provide the energy for mixing.

Returning to the comparison of the 1993 and 1995 mixing rates, an important difference between the two sites may be that whereas there was more internal tidal energy at the 1993 site in western Massachusetts Bay, there was less convergence of flux. The convergence of flux causes steepening of the internal waves and transfers energy to higher frequencies and smaller vertical scales. This is consistent with the high energy level observed in the quarterdiurnal and sexdiurnal frequencies in the 1995 observations. Unfortunately, the data were not adequate to discern whether there was higher energy at smaller vertical scales.

### *4.3 Influence of Upwelling on Cross-Isopycnal Transport*

Upwelling is an advective process, so by itself it does not result in transport of dye or nutrients across the pycnocline. Instead, it transports the pycnocline itself. This may be enough to have an important impact on productivity, as long as the pycnocline gets shallow enough that nutrient-rich waters reach the euphotic zone. For short-lived upwelling events, the advective transport may not be important, however, because the nutrient-rich water can return to deep water as the upwelling relaxes.

Upwelling can, however, contribute to irreversible, cross-isopycnal flux, by carrying the cold, nutrient-rich water close to the surface where it can be warmed by incoming sunlight and atmospheric heat exchange. Relatively cold, upwelled water will gain heat more rapidly than ambient surface waters due to differences in long-wave radiation as well as sensible heat transfer. As the upwelled water gains heat, it crosses isopycnals not by mixing but by an internal change in density due to heating. When the upwelling relaxes, the warmed water will have decreased its density relative to the average distribution in Massachusetts Bay, because of the enhanced heat flux into the cold, upwelled waters.

Because upwelling conditions occurred during the dye deployment, the data were analyzed to identify the potential influence of near-surface heating contributing to cross-isopycnal transport of dye. The signature of this process would be the warming of water in the upper part of the dye patch. This could be distinguished from mixing by comparing the temperature to salinity in the upper water column on successive days. The temperature in the upper part of the patch did not increase relative to salinity in the dyed water (Fig. 12); in fact it cooled slightly. This suggests that heating of the upper water column did not contribute significantly to the cross-isopycnal transport of dye.

### *4.4 Implications of Boundary Mixing on Overall Mixing in Massachusetts Bay*

The entire fringe of Massachusetts Bay is likely to be the site of enhanced vertical mixing, due to the energy dissipation of incident internal waves. The intensity of that energy input varies from place to place, but it is not obvious that Scituate has unusually high internal wave energy. The internal wave energy observed during the 1993 study in western Massachusetts Bay was actually 35% higher than the 1995 observations. Notwithstanding the uncertainty of the intensity of the internal wave field, the significance of boundary mixing can be estimated by extrapolating the results at Scituate to the entire boundary of the bay. The 5-km wide fringe of the bay represents approximately 25% of its area. If the mixing rate is enhanced in this boundary zone by a factor of 3 relative to the interior, then the boundary zone will contribute the same amount of vertical flux as the interior. The 50% deficit in the heat balance from the 1993 interior mixing study can thus be accounted for by the additional mixing contributed by the boundaries.

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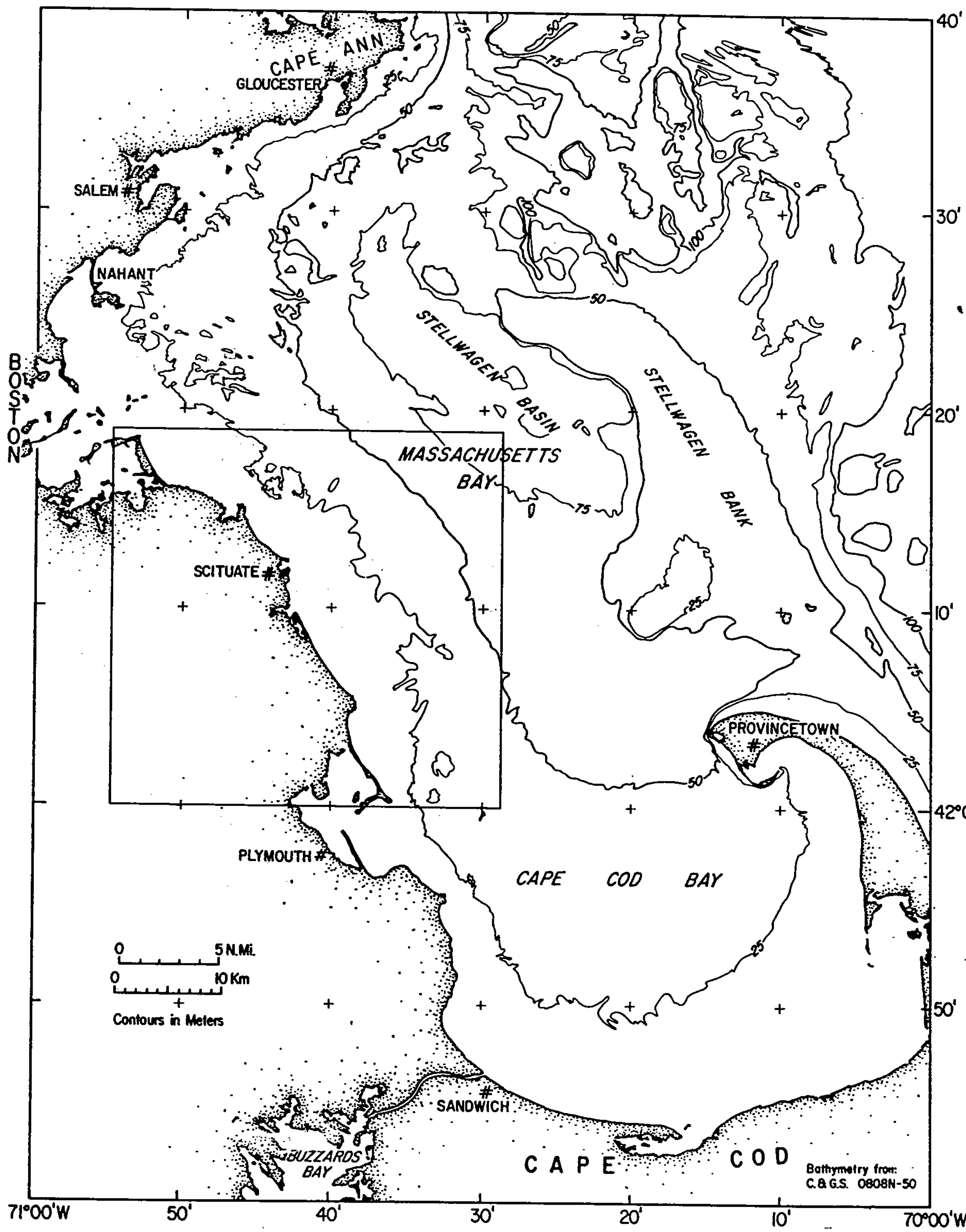


Fig. 1a. Massachusetts Bay. The box outlines the region of the dye experiment, shown in Fig. 1b.

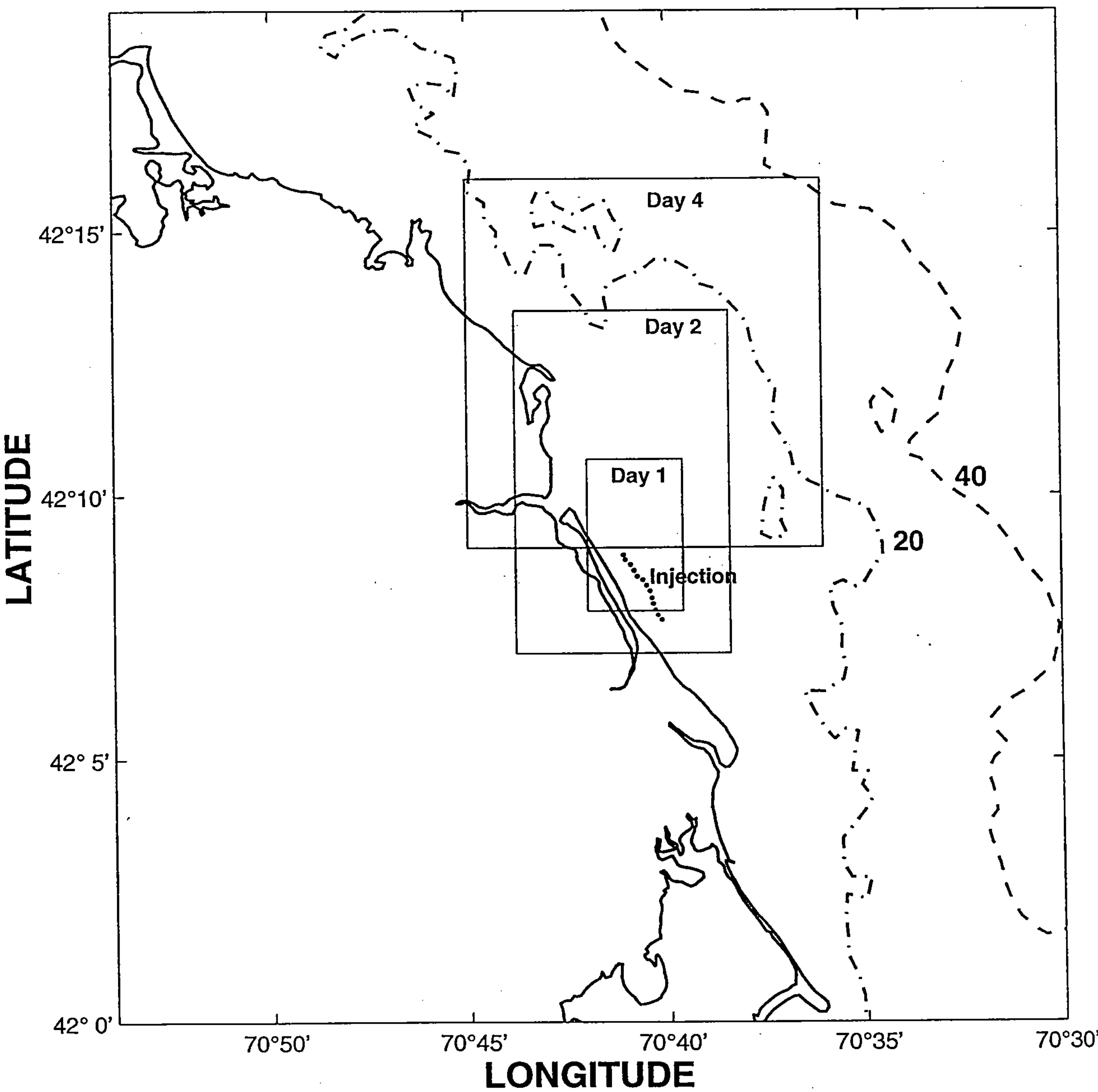


Fig. 1b. Experimental site. The dotted track shows the injection, parallel to the shore at Humarock in Scituate. The rectangles locate the frames of the dye survey maps in Figs. 4, 5 and 6. The 20-meter and 40-meter isobaths are also shown.

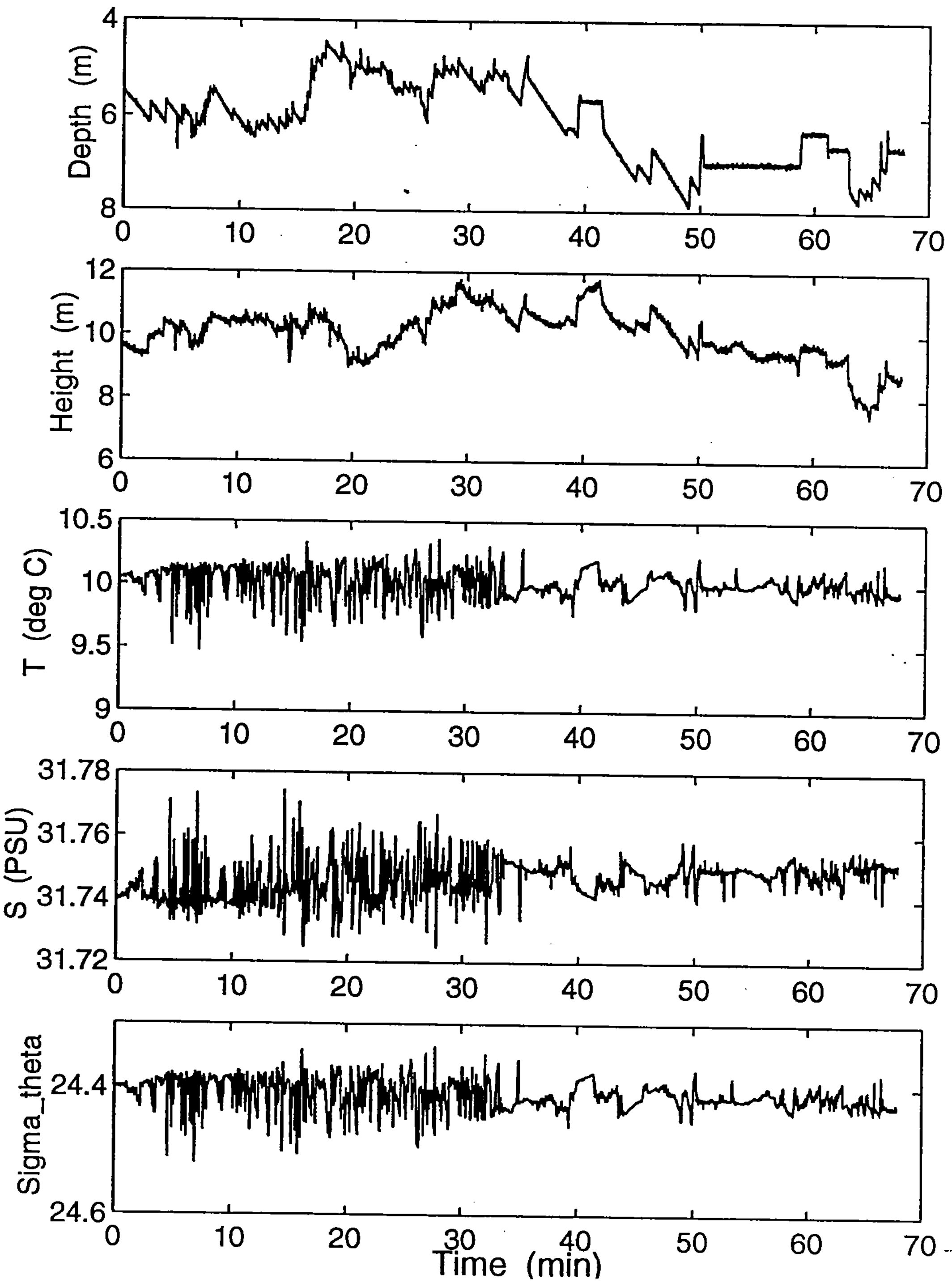


Fig. 2. Hydrographic parameters measured at the injection sled during the dye release. Height is the height above the bottom. Time is the time since the start of the injection.

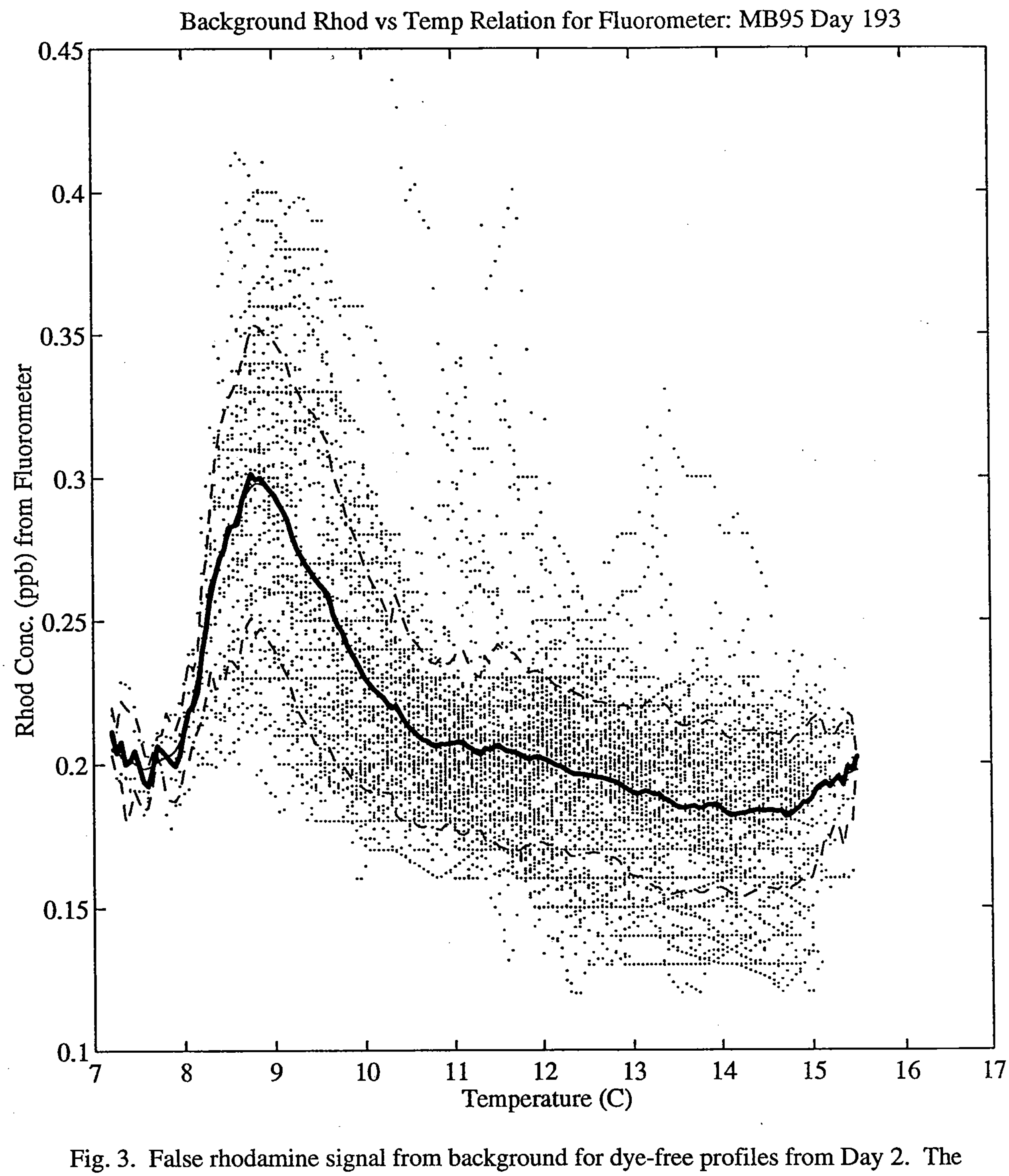


Fig. 3. False rhodamine signal from background for dye-free profiles from Day 2. The heavy line is a running mean used for the background correction. The dashed lines indicate the rms spread of the data about this mean, and indicate the size of the random error introduced by the background correction.

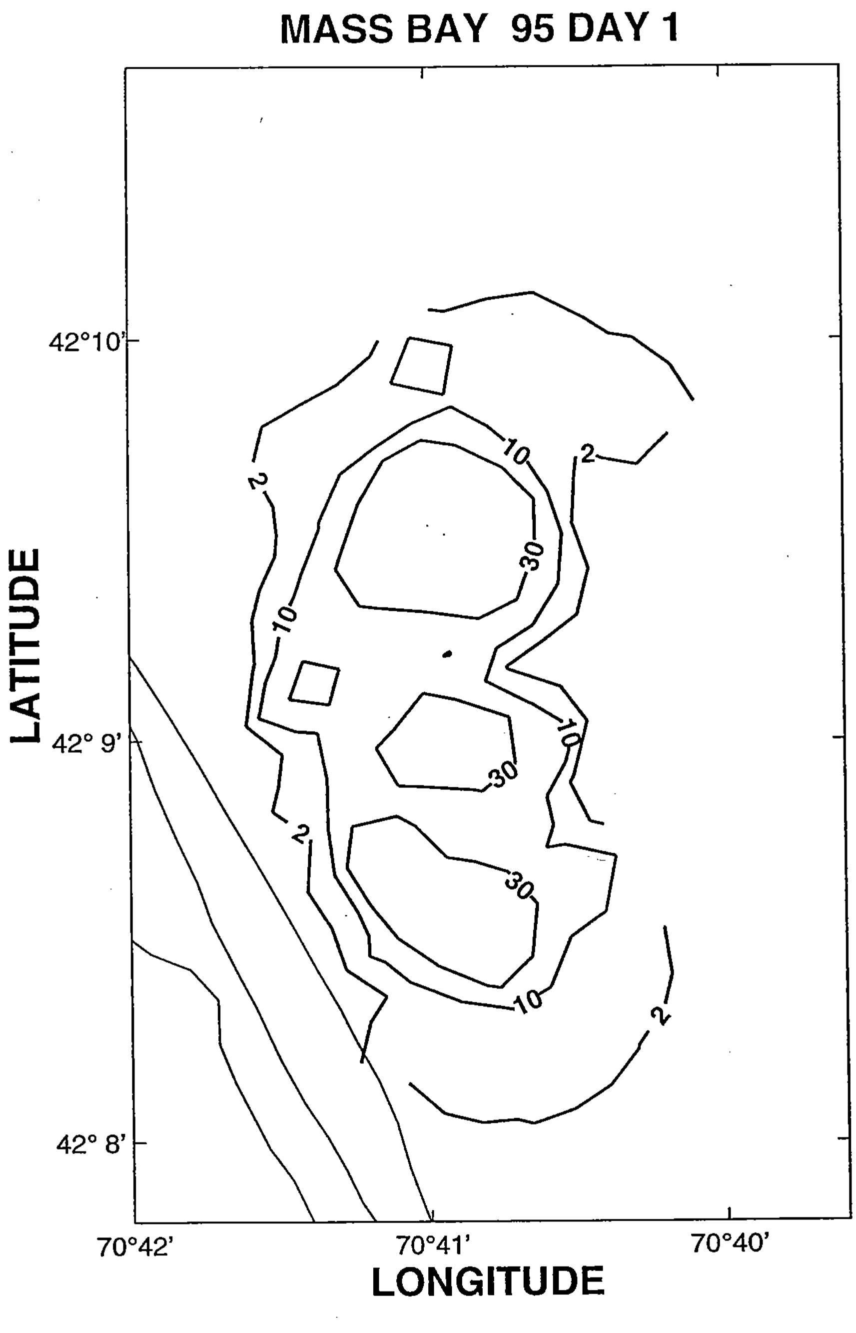


Fig. 4. Map of the dye patch on Day 1. The shore is shown with light lines. The contours are denoted in mg $m^{-2}$.

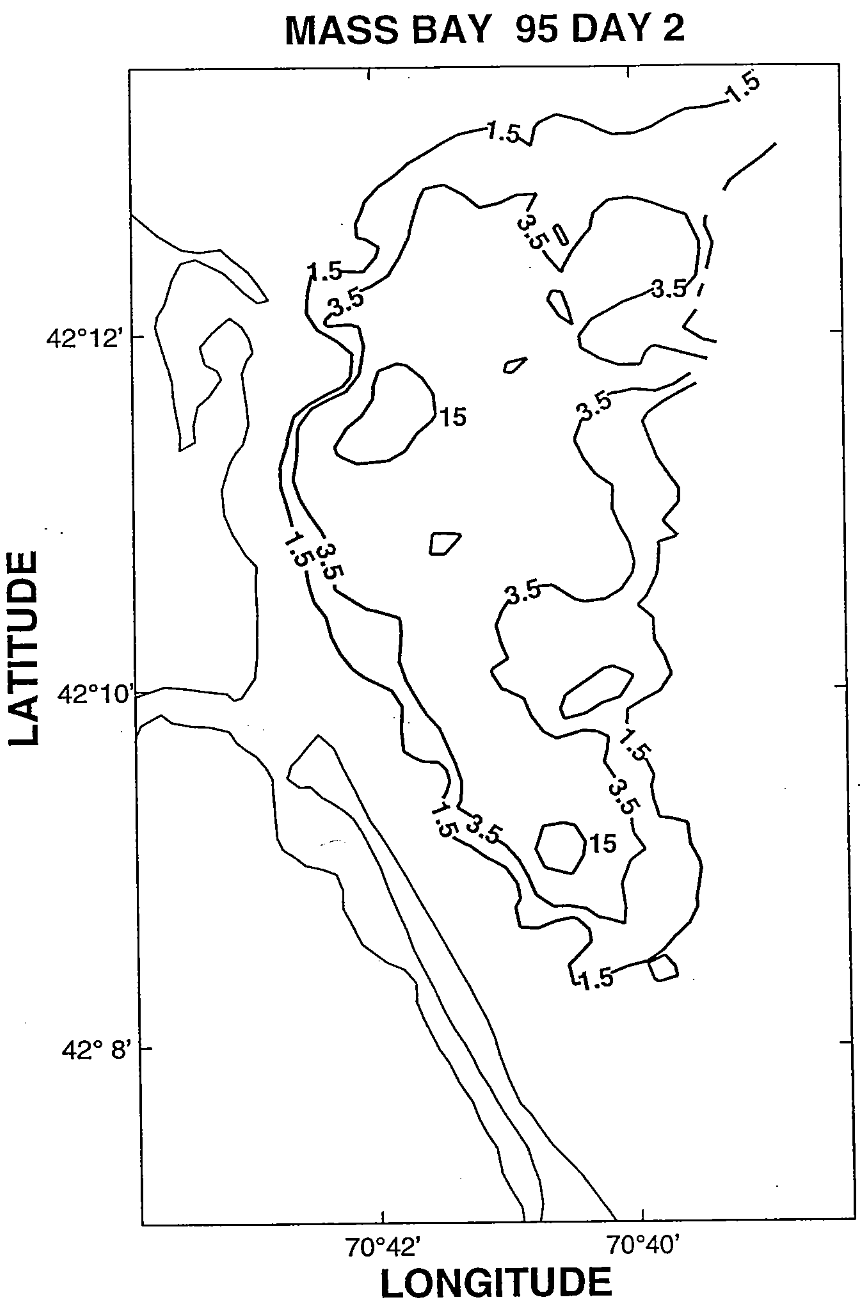


Fig. 5. Map of the dye patch on Day 2. The shore is shown with light lines. The contours are denoted in mg $m^{-2}$.

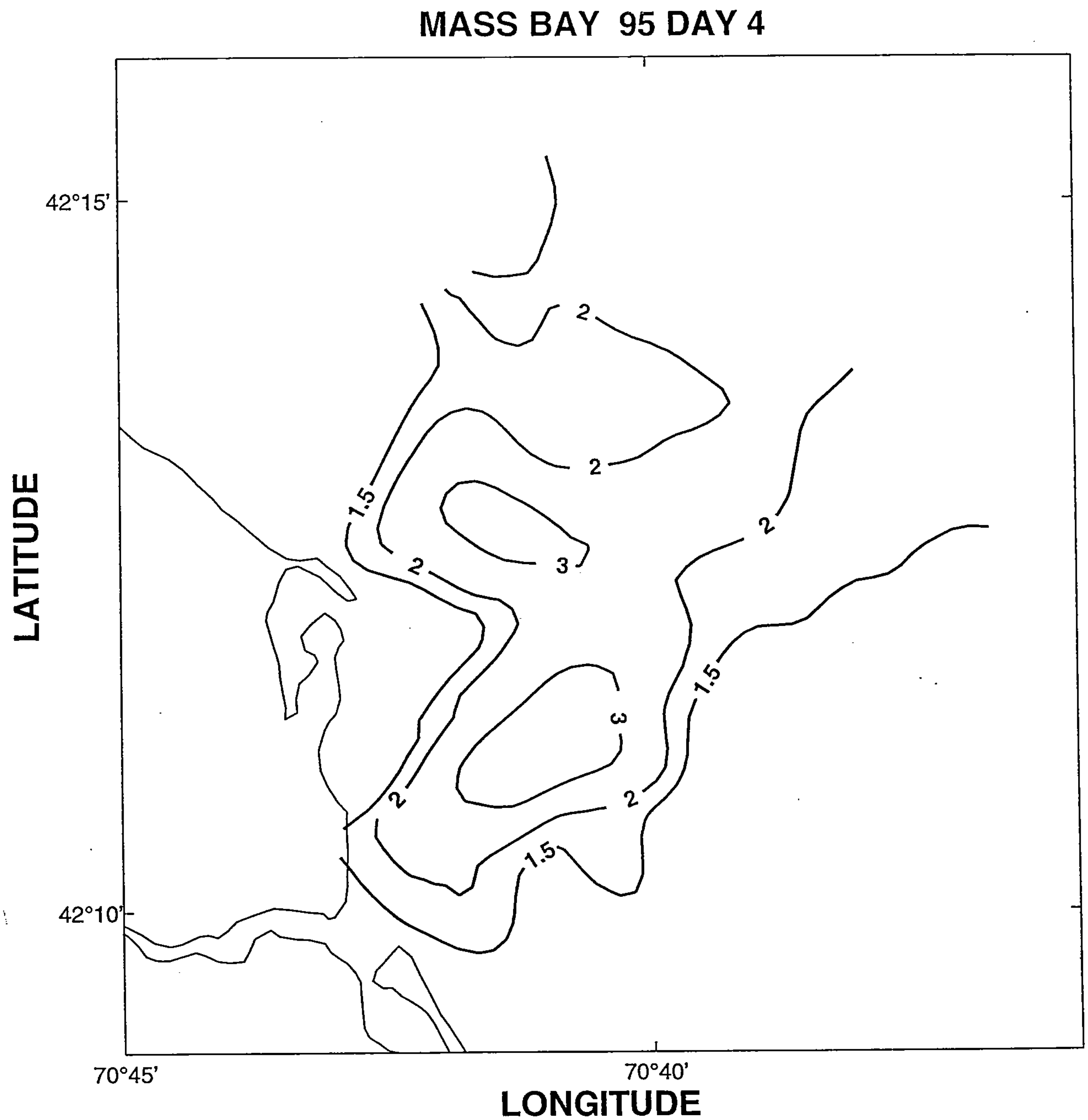


Fig. 6. Map of the dye patch on Day 4. The shore is shown with light lines. The contours are denoted in mg $m^{-2}$.

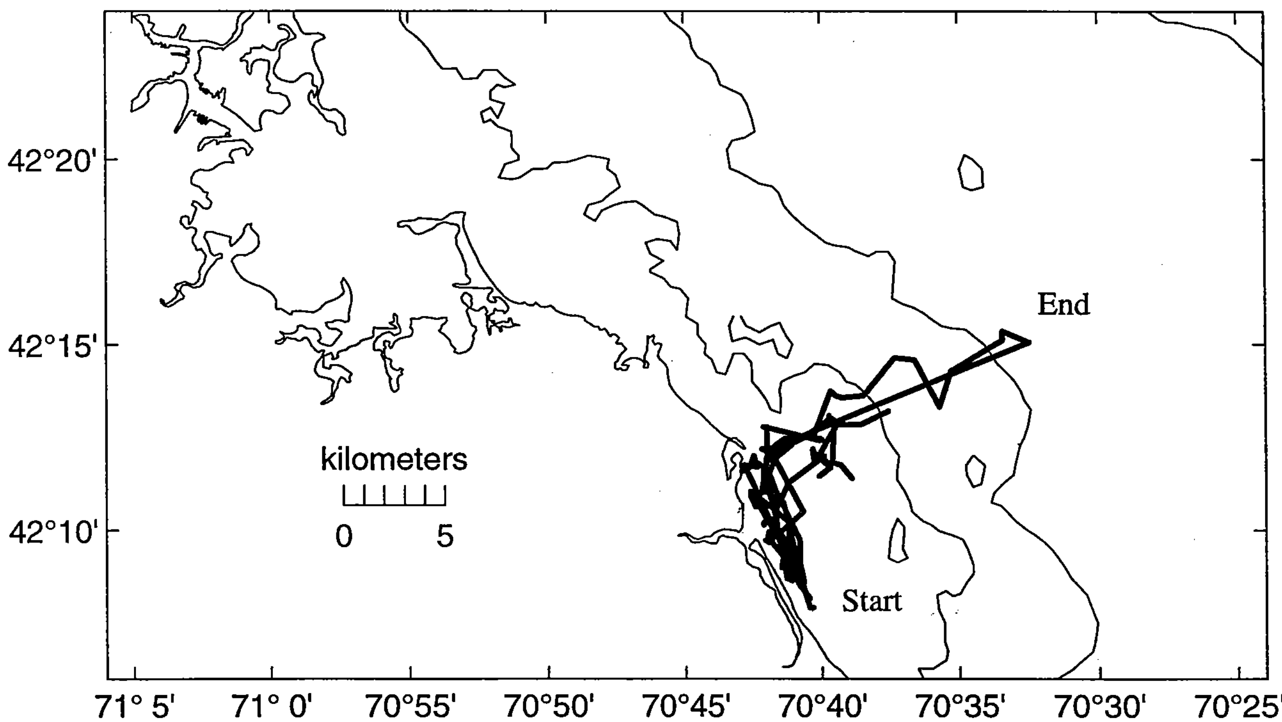


Fig. 7. Drifter trajectories during the dye experiment. The drifters moved northward along the coast at roughly 3 cm $s^{-1}$, then turned eastward and moved offshore at an average speed of 4.5 cm $s^{-1}$.

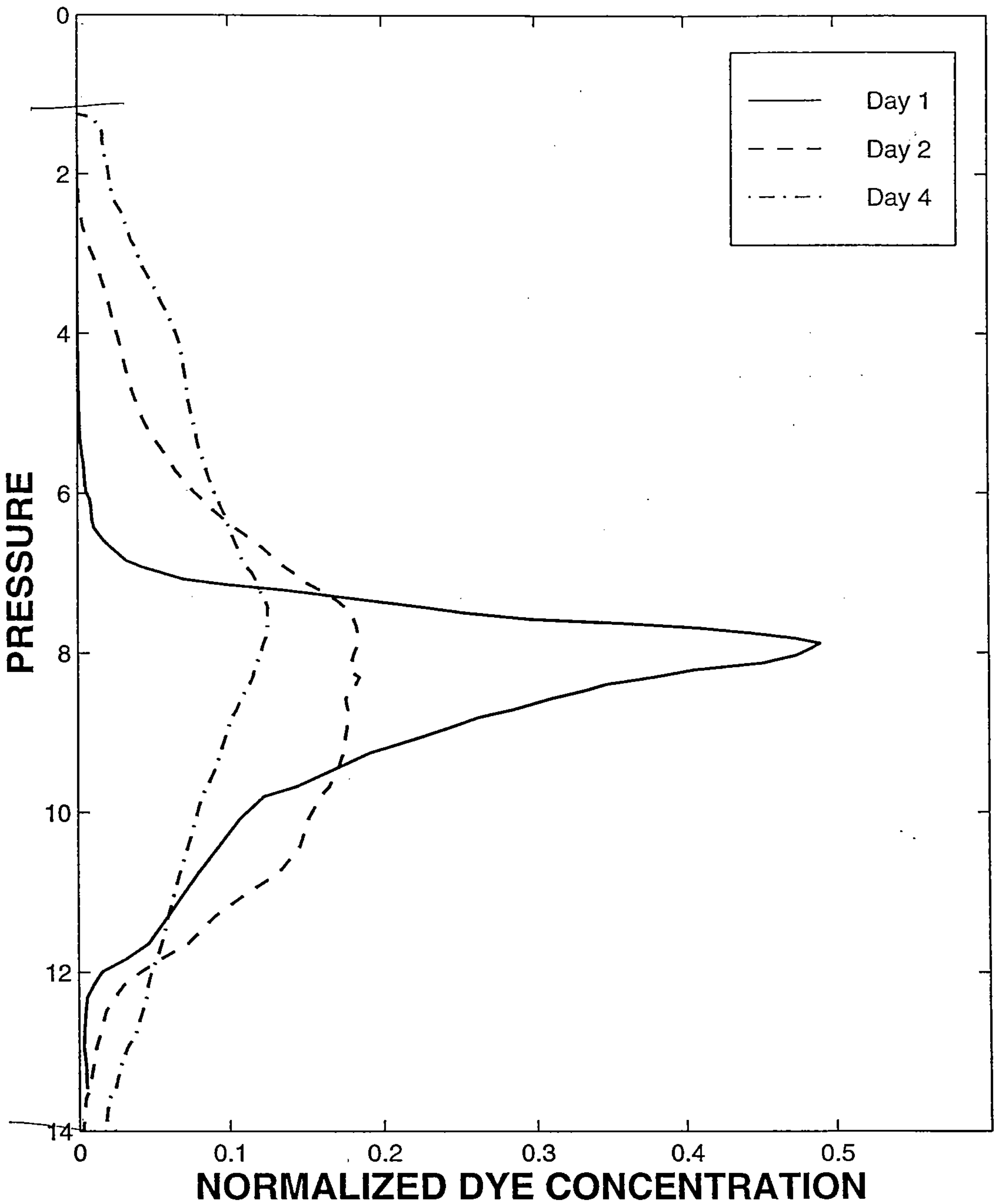


Fig. 8. Evolution of the mean vertical dye profile. From the spreading of the dye with time a diffusivity of 0.12 to 0.18 $cm^2\ s^{-1}$ is estimated for the boundary region of Massachusetts Bay.

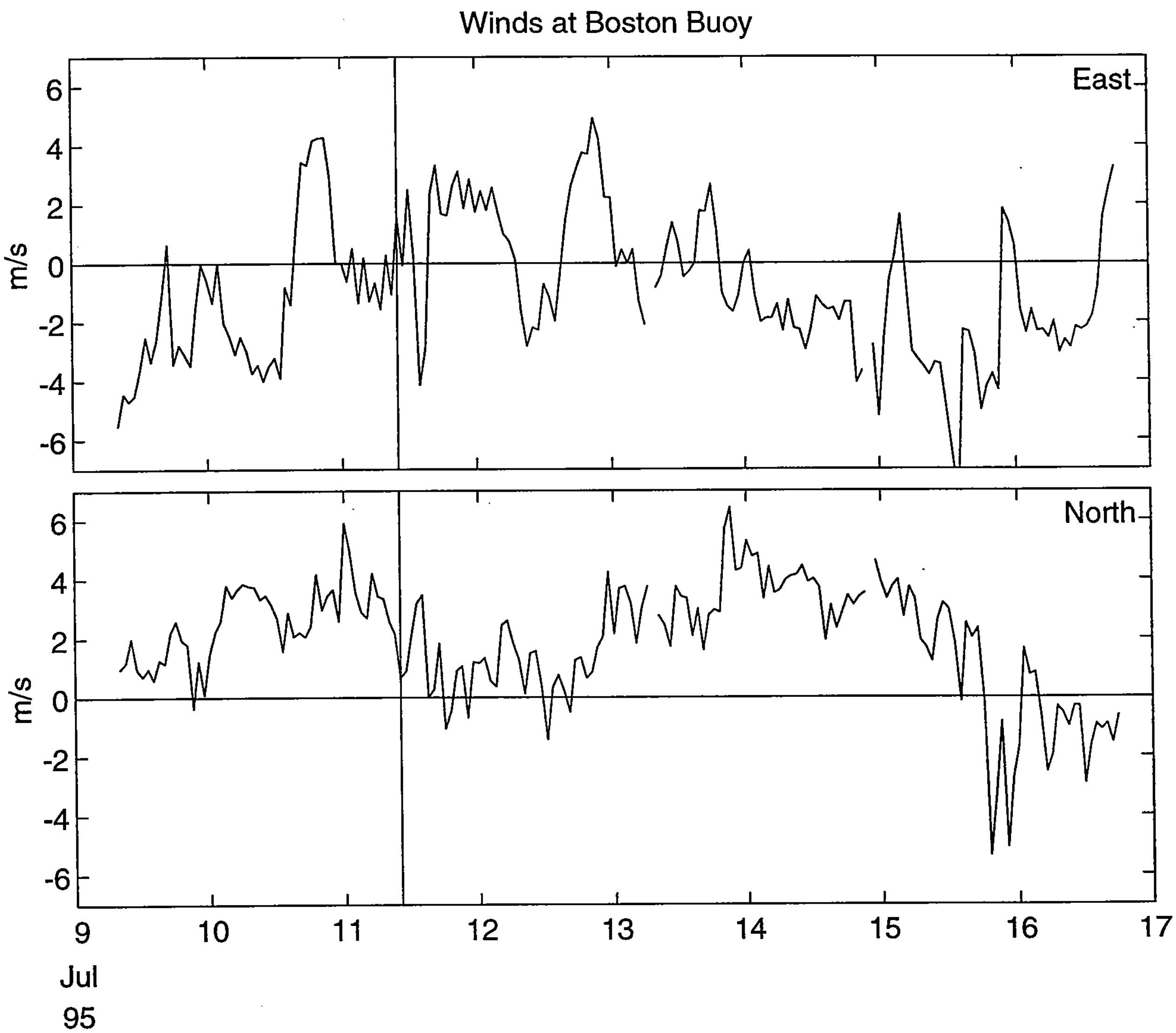


Fig. 9. Winds at Boston buoy during dye experiment. Positive values indicate eastward and northward winds, respectively. The vertical line corresponds to the dye release.

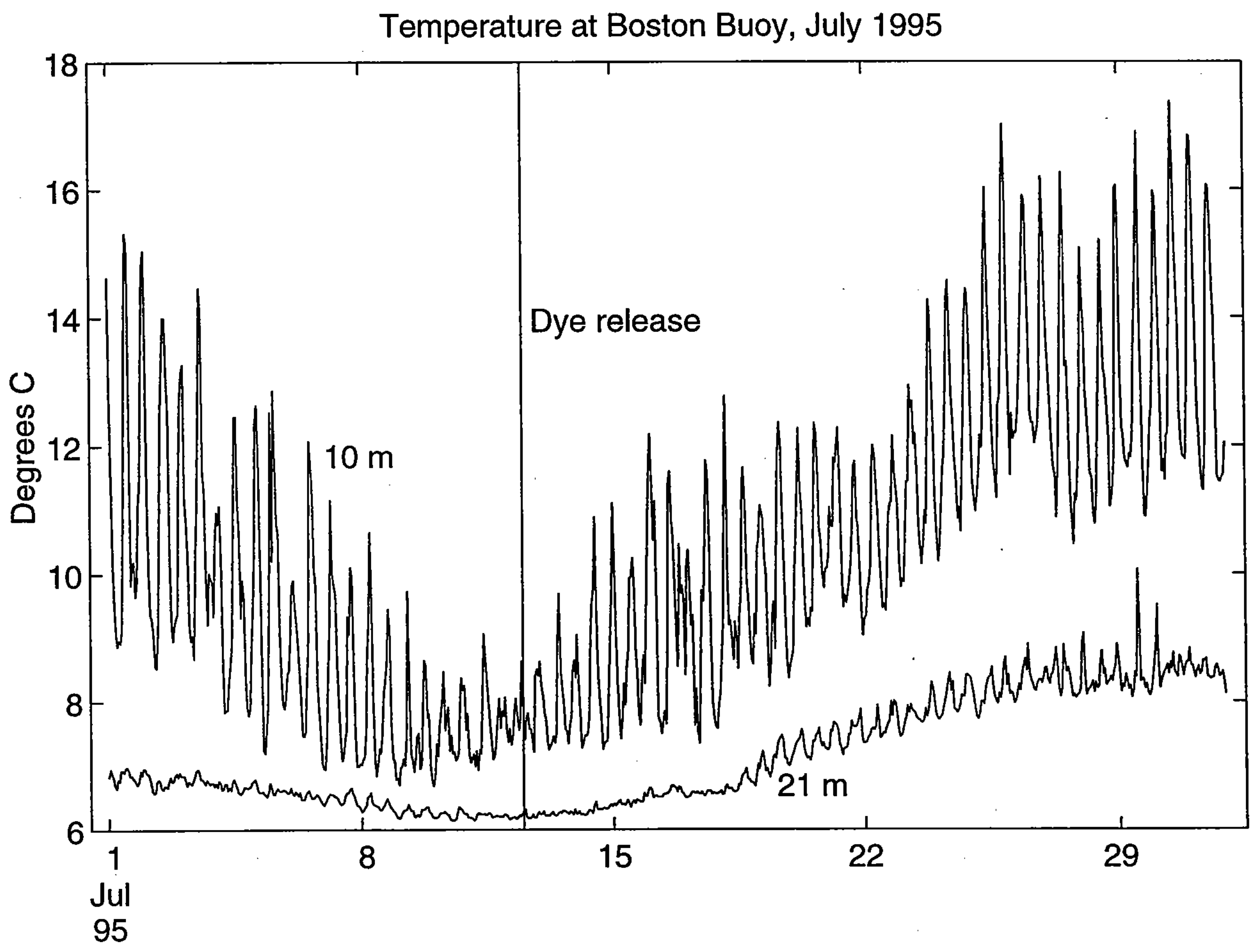


Fig. 10. Temperature data at 10- and 21-m depth at the Boston Buoy during the dye experiment.

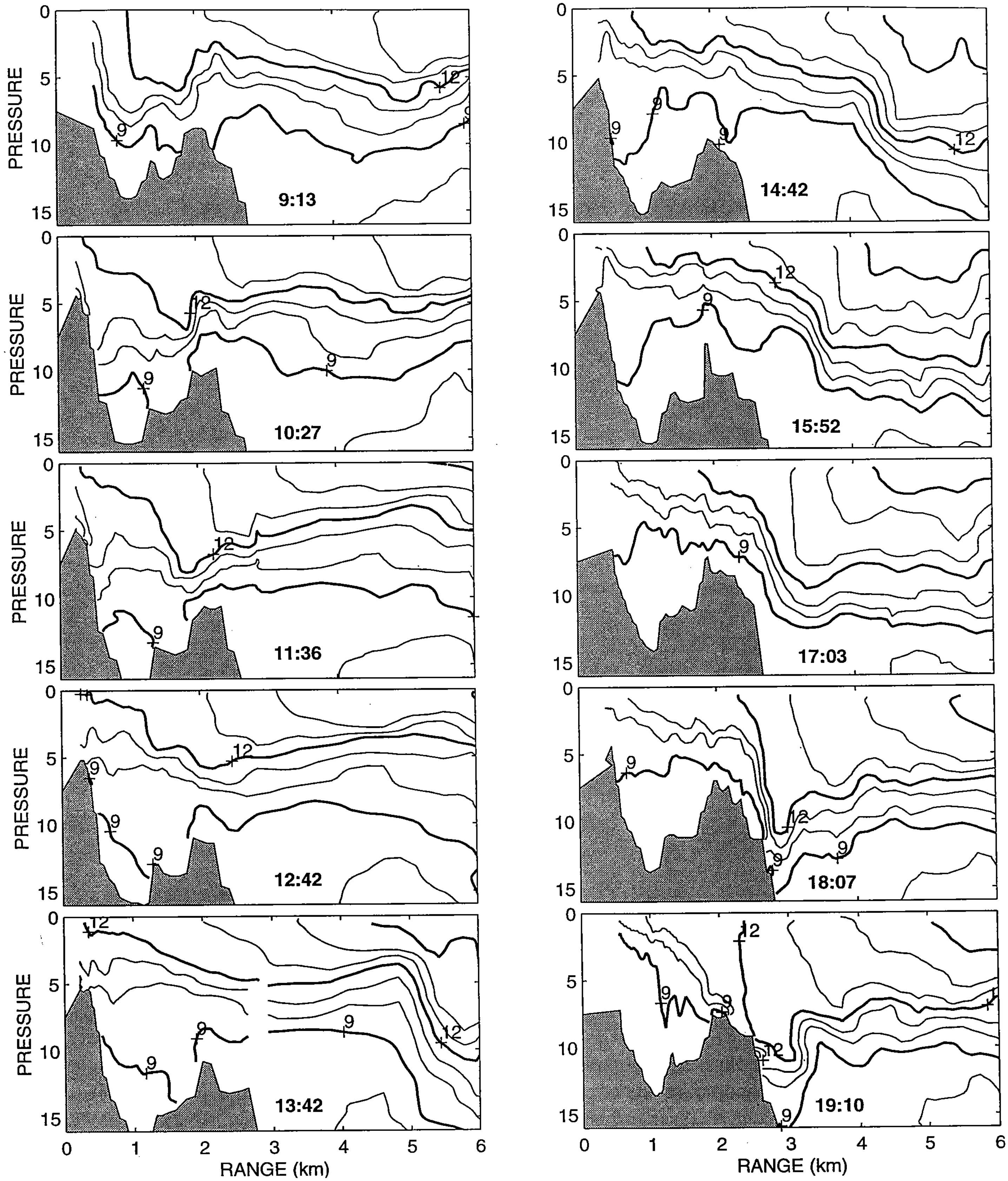


Fig. 11. Time series of temperature on Day 3 (July 13) on a cross-shore track through the dye patch. Local time is shown for the midpoint of each section. The contour interval is 1 °C. Fluctuations in the depth of the thermocline are dramatic. The sequence from 13:42 to 19:10 shows a wave front propagating toward shore.

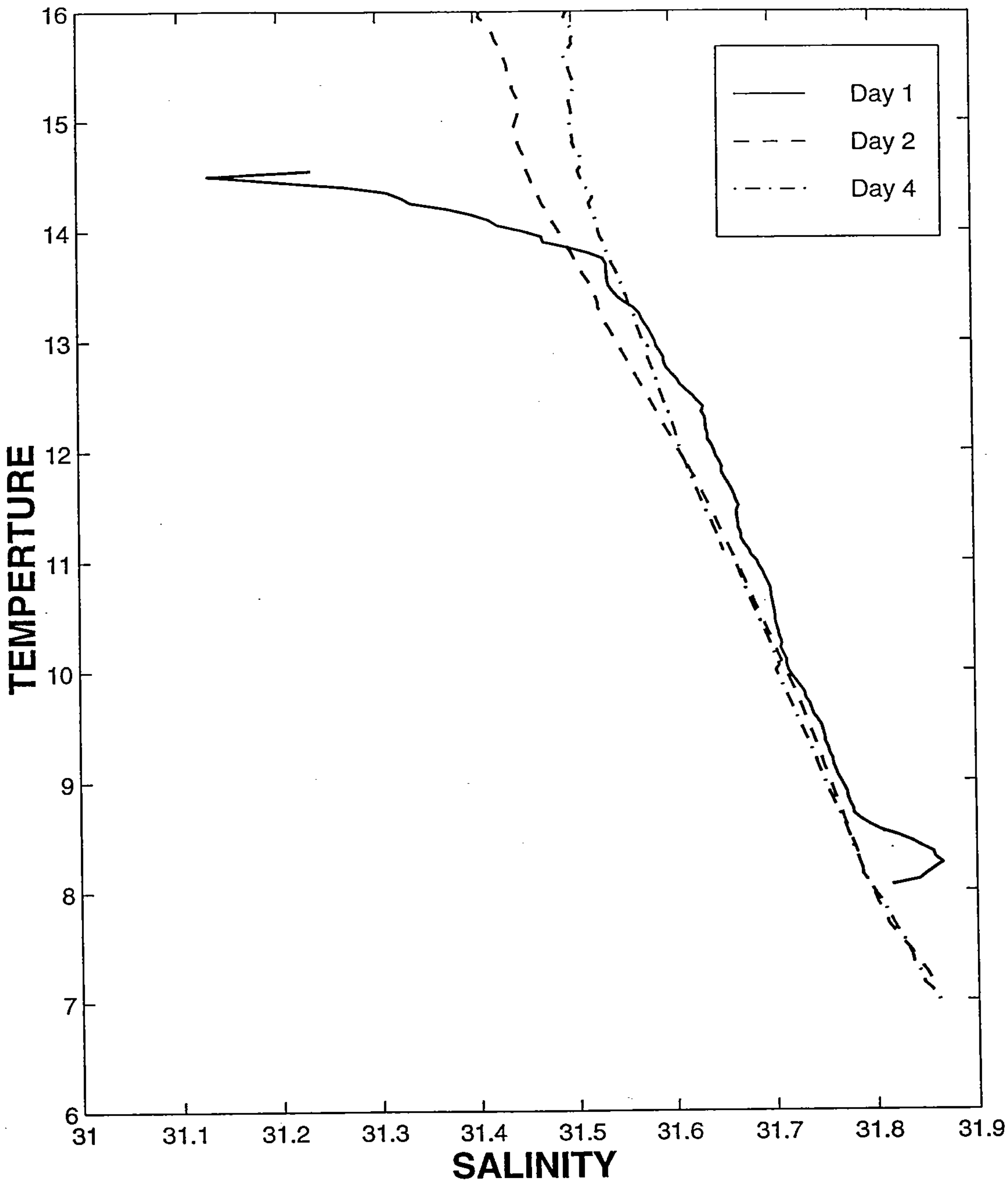


Fig. 12. Mean temperature versus salinity for Days 1, 2, and 4. The changes in temperature at fixed salinity are small, indicating negligible solar heating of the dyed water during the experiment below 14 °C. The large change that occurs between Day 1 and Day 2 above 14 °C does not involve dyed water. The water cooled at deeper levels between Day 1 and 2, no doubt due to along-isopycnal mixing. These changes, and the changes between Days 2 and 4 do not affect the estimate of the vertical diffusivity strongly.

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