Report to the

MASSACHUSETTS BAYS PROGRAM

PHYSICAL OCEANOGRAPHIC INVESTIGATION OF MASSACHUSETTS AND CAPE COD BAYS

Prepared by

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October 1992

MBP-92-03

Printed and distributed by the Massachusetts Bays Program, a cooperative venture of
Massachusetts Coastal Zone Management Office and the U.S. Environmental Protection Agency.
Funded under U.S. Environmental Protection Agency Cooperative Agreement CE001534-01

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FOREWORD

The roots of the Massachusetts Bays Program extend back to 1982, when the City of Quincy filed suit against the Metropolitan District Commission and the Boston Water and Sewer Commission over the chronic pollution of Boston Harbor, Quincy Bay, and adjacent waters. Outdated and poorly maintained sewage treatment plants on Deer Island and Nut Island were being overwhelmed daily by sewage from the forty-three communities in the Metropolitan Boston area. Untreated and partially treated sewage were spilling into Boston Harbor.

Litigation over the pollution of Boston Harbor culminated in 1985 when the United States Attorney filed suit on behalf of the Environmental Protection Agency against the Commonwealth of Massachusetts for violations of the Federal Clean Water Act. The settlement of this suit resulted, in 1988, in the creation of the Massachusetts Water Resources Authority, the agency currently overseeing a multi-billion dollar project to repair and upgrade Metropolitan Boston's sewage treatment system. In addition, the settlement resulted in the establishment of the Massachusetts Environmental Trust - an environmental philanthropy dedicated to improving the Commonwealth's coastal and marine resources. $2 millon in settlement proceeds are administered by the Trust to support projects dedicated to the restoration and protection of Boston Harbor and Massachusetts Bay.

The Trust provided $1.6 million to establish the Massachusetts Bays Program, a collaborative effort of public officials, civic organizations, business leaders, and environmental groups to work towards improved coastal water quality. The funding was used to support both a program of public education and a scientific research program focussing on the sources, fate, transport and effects of contaminants in the Massachusetts and Cape Cod Bays ecosystem. To maximize the efficiency of limited research funding, the sponsored research program was developed in coordination with research funded by the MWRA, the United States Geological Survey, and the Massachusetts Institute of Technology Sea Grant Program. The study described in this report provides the first bay-wide description of the circulation and mixing processes on a seasonal basis.

In April, 1990, following a formal process of nomination, the Massachusetts Bays Program became part of the National Estuary Program. The additional funding provided as part of this joint program of the Environmental Protection Agency and the Commonwealth of Massachusetts is being used to continue a coordinated program of research in the Massachusetts Bays ecosystem, as well as supporting the development of a comprehensive conservation and management plan for the coastal and marine resources of Massachusetts and Cape Cod Bays.

The information in this document has been subject to Massachusetts Bays Program peer and administrative review and has been accepted for publication as a Massachusetts Bays Program document. The contents of this document do not necessarily reflect the views and policies of the Management Conference.

The Massachusetts Bays Program is sponsored by the Massachusetts Executive Office of Environmental Affairs through the Coastal Zone Management Office and the U.S. Environmental Protection Agency, Region I, John F. Kennedy Federal Building, Boston, MA 02203.

$1\ Sv = 1*10^6\ m^3\ s^{-1}$

This research was made possible in part by funding from The Massachusetts Environmental Trust - an environmental philanthropy focussing on the Commonwealth's coastal resources.

Additional funding was provided by the United States Environmental Protection Agency under assistance agreement CE001532-01 to the University of New Hampshire. The contents of this document do not necessarily reflect the view of the agency and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Publication No. 17268-504- 200 - 1/93 - 11.44 C.R.
Approved by: Philmore Anderson III, State Purchasing Agent

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OCTOBER, 1992

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Acknowledgements

The authors would like to thank Susan Becker, Francesca Giancristofaro, Matt Gould, Fran Hotchkiss, Woody Lee, Craig Marquette, Neil Pettigrew, Bill Strahle, and and Marinna Martini for their help in the field program and data analysis. Many thanks to Susan Oliver for compiling and editing the final report.

Additional copies of this document are available through the Massachusetts Bays Program, Room 2006, 100 Cambridge Street, Boston, MA 02202.

Contents

Executive Summary

This physical oceanographic study of the Massachusetts Bays was designed to provide for the first time a bay-wide description of the circulation and mixing processes on a seasonal basis. Most of the measurements were conducted between April 1990 and June 1991 and consisted of moored observations to study the current flow patterns, hydrographic surveys to document the changes in water properties, high-resolution surveys of velocity and water properties to provide information on the spatial variability of the flow, drifter deployments to measure the currents, and acquisition of satellite images to provide a bay-wide picture of the surface temperature and its spatial variability. A long-term objective of the Massachusetts Bays program is to develop an understanding of the transport of water, dissolved substances and particles throughout the bays. Because horizontal and vertical transport is important to biological, chemical, and geological processes in Massachusetts and Cape Cod Bays, this physical oceanographic study will have broad application and will improve the ability to manage and monitor the water and sediment quality of the Bays.

Key results are:

- There is a marked seasonal variation in stratification in the bays, from well mixed conditions during the winter to strong stratification in the summertime. The stratification acts as a partial barrier to exchange between the surface waters and the deeper waters and causes the motion of the surface waters to be decoupled from the more sluggish flow of the deep waters.

- During much of the year, there is weak but persistent counterclockwise flow around the bays, made up of southwesterly flow past Cape Ann, southward flow along the western shore, and outflow north of Race Point. The data suggest that this residual flow pattern reverses in fall. Fluctuations caused by wind and density variations are typically larger than the long-term mean.

- With the exception of western Massachusetts Bay, flushing of the Bays is largely the result of the mean throughflow. Residence time estimates of the surface waters range from 20–45 days. The deeper water has a longer residence time, but its value is difficult to estimate. There is evidence that the deep waters in Stellwagen Basin are not renewed between the onset of stratification and the fall cooling period.

- Current measurements made near the new outfall site in western Massachusetts Bay suggest that water and material discharged there are not swept away in a consistent direction by a well-defined steady current but are mixed and transported by a variety of processes, including the action of tides, winds, and river inflow. One-day particle excursions are typically less than 10 km. The outfall is apparently located in a region to the west of the basin-wide residual flow pattern.

- Observations in western Massachusetts Bay, near the location of the future Boston sewage outfall, show that the surficial sediments are episodically resuspended from the seafloor during storms. The observations suggest onshore transport of suspended material during tranquil periods and episodic offshore and southerly alongshore transport of resuspended sediments during storms.

- The spatial complexity of the flow in the Massachusetts Bays is typical of nearshore areas that have irregular coastal shorelines and topography and currents that are forced locally by wind and river runoff as well as by the flow in adjacent regions. Numerical models are providing a mechanism to interpret the complex spatial flow patterns that cannot be completely resolved by field observations and to investigate key physical processes that control the physics of water and particle transport.

Overall Findings

Water Properties

The water properties in the Bays showed a marked seasonal cycle, varying from cold, well-mixed waters during the winter to strongly stratified conditions during the summer months. Stratification was dominated by salinity variation during the spring, when run-off from the Maine rivers contributed to a reduction of near-surface salinity due to local and regional river discharge. During the summer and fall, temperature variations were the most important contributors to stratification. Variations in water properties were found to be the result of several factors, including internal tides, upwelling and downwelling, and run-off events. Internal tides cause tidal period fluctuations in the height of the thermocline throughout the Bays, most notably in Stellwagen Basin. Upwelling by southwesterly winds causes cold, sub-thermocline water to reach the surface along the western portions of the Bays, with the most intense upwelling occurring in Broad Sound. Downwelling, resulting from northerly or northeasterly winds, causes a weakening of the stratification in the coastal regions.

Circulation

The study indicated that there are several circulation regimes that apparently result from distinct forcing agents. First there is a persistent counterclockwise flow through the Bays that is apparently driven by the large scale circulation of the Gulf of Maine. Second, there are episodic intrusions of relatively fresh, low-density fluid resulting from run-off events in the rivers of the Gulf of Maine, with a lesser contribution from the Charles River and the Massachusetts Water Resources Authority (MWRA) outfalls. Third, there is a wind-driven regime associated with winds from the northwest that reinforced the mean counterclockwise circulation pattern, and finally there is a wind-driven regime associated with southwest–northeast winds that produces significant upwelling or downwelling in the coastal regions and a variable response in the rest of the Bays. Deep currents tend to be weak, particularly during the stratified seasons.

The study confirmed earlier observations that the dominant circulation regime in the Bays is a counterclockwise flow that enters south of Cape Ann, flows south through most of Massachusetts Bay, and exits north of Race Point. This flow regime was found to persist through most of the observation period, the only significant disruption occurring during the fall of 1990, when the circulation pattern appeared to reverse itself. The counterclockwise circulation pattern is most evident in the coastal flow (measured offshore of Scituate and Manomet) and in the outflow north of Race Point. Based on drifter observations, the southward flow appears to extend across Massachusetts Bay as far as Stellwagen Bank, with no obvious intensification in the coastal region. However the mooring in Stellwagen Basin show little evidence of a mean southward flow. This may be the result of tidal rectification of the flow around Stellwagen Bank that resulted in a local current anomaly. Contrary to the overall tendency of the Bays circulation, the region offshore of Boston Harbor does not indicate a significant net southward flow. Cape Cod Bay appears to have a fairly weak net throughflow except during periods of run-off events.

Run-off events were identifiable by decreased near-surface salinity, typically 10–20 days following a peak in run-off in the Maine rivers. The circulation pattern is quite complex during run-off events in the northern portion of Massachusetts Bay, but in the southern portion of the bay and Cape Cod Bay there is a distinct coastal current, which reinforces the mean counterclockwise circulation regime. This pattern of flow through Cape Cod Bay was most clearly evident in drifter trajectories following periods of high run-off. Interestingly, there were no major run-off events in the Bays during the winter months, in spite of some major freshwater flows in the Maine rivers. Apparently the vertical mixing in the western Gulf of Maine is adequate to prevent the development of a coastal current during the winter months.

Wind-driven motions were discerned by statistical analysis of the moored current meter records. The strongest response of the currents is to along-bay winds, most often being northwesterlies, which drive a southward flow through the middle of the Bays and outflow past Race Point, thus reinforcing the mean circulation. The strongest response to the winds was observed along the coast off Scituate. Southwesterly winds result in upwelling along the coast, causing near-surface temperatures to drop markedly as deep water was carried to the surface. Occasional northeasterly storms cause strong downwelling, which results in weakening of the stratification in the coastal regions.

Deep circulation is weak, and the deep throughflow was not well quantified. Evidence from Stellwagen Basin suggests that there is little horizontal exchange during the spring and summer months, with horizontal transport only becoming important during the fall. This is also suggested by moored data at Race Point.

Exchange Rates

The residence times for the near-surface waters were estimated at 20–40 days, based on the drifters and the moored and drifting velocity data. Lower values were derived from the drifters than the moorings, and the discrepancies may relate on the one hand to the small number of drifters deployed and on the other hand to the sparse spacing of the moored instruments.

The residence time of the deep water was found to vary seasonally. During the unstratified periods, coupling of the deep motion with the surface waters probably results in residence times approaching values of the surface waters. However, the decoupling of the upper and lower portions of the water column during stratified periods causes the deep regions to become much more sluggish during the summertime. There was evidence in Stellwagen Basin that there was essentially no horizontal exchange of deep water between April and October, suggesting that the only deep water exchange was due to vertical mixing. The timescale of vertical mixing was estimated to be approximately 300 days, based on the variations of water properties during the stratified period. Since this timescale exceeds the duration of stratification, the residence time of the deep water during the summer is comparable to the length of time of stratification, or roughly 6 months.

The motion in western Massachusetts Bay, near the future sewage outfall, is qualitatively different than most of the Bays in the sense that it does not exhibit a significant mean circulation. The exchange of water from this portion of the Bays occurs as a result of episodic processes, either by run-off events, winds, or some combination, which causes the fluid to be carried far enough that it is incorporated into the mean counterclockwise circulation.

Perhaps the longest residence times of the surface waters occur in Cape Cod Bay, based on drifter trajectories as well as water properties. There were not adequate data to actually quantify the residence time; in fact it may not be a well-defined quantity in Cape Cod Bay due to the episodic variation in the circulation regime there. It appears that during periods of freshwater inflow, there is a significant non-tidal flow around the perimeter of Cape Cod Bay. This buoyancy driven flow appears to be impeded by the shallow water in western Cape Cod Bay, resulting in the accumulation of low salinity water in that region. During periods when there is no freshwater inflow, the motions in Cape Cod Bay are weak. One drifter remained in Cape Cod Bay for more than one month during the summer of 1990 before being carried out past Race Point.

Nutrient Distributions

The distribution of nutrients in Massachusetts Bays is controlled by a combination of both physical and biological processes. There are wide variations in nutrient concentrations especially during the seasons when Massachusetts Bays is relatively well stratified (i.e., spring, summer and fall). Areas of low nutrient concentrations are almost always those where biological processes, mainly phytoplankton nutrient uptake, have occurred. These processes are most prominent during the spring months, so that by late spring (April, May) all nutrients are very low in the surface waters throughout the Bays. It is during this period that even waters in the deeper parts of the Bays (Stellwagen Basin) have reduced nutrient concentrations.

During the stratified seasons, certain areas of the Massachusetts Bays system almost always have relatively higher nutrients than other areas. Different areas are enriched for a variety of both physical and biological reasons including:

- Cape Ann area: input of Gulf of Maine water and river-sourced coastal plume nutrients;

- Boston Harbor and Broad Sound area: input of nutrients from the MWRA outfall;
- Western Cape Cod Bay area: nearshore upwelling caused by SW winds;
- Southeastern Cape Cod Bay area: vertical mixing in shallow waters;
- Stellwagen Basin and Central Cape Cod Bay areas: nutrient regeneration in the bottom waters.

Recommendations

This study provides a solid observational foundation for understanding the physical oceanographic regime of the Massachusetts Bays. Some analysis was undertaken in this study, but by no means does it do justice to the wealth of information contained in these data. All aspects of the physics deserve closer scrutiny than was possible in the timescale of this report. The tidal processes, the density driven flow, and wind-driven processes all should be examined in much greater detail. Only with an understanding of the processes can the results of observations from one particular period be used to draw inferences about the circulation processes occurring at other times.

Numerical modeling is an important means by which to use the knowledge gained about the Bays from this program in a predictive sense. Some early comparisons of the data to model results obtained from the USGS modeling effort suggest that considerable insight into the dynamics and transport processes will come from a combination of three-dimensional modeling and data analysis. Questions will arise in the implementation of the numerical model regarding boundary and initial conditions that may call for additional field measurements.

The need for models is argued in terms of what the present study could never provide. Given the limited resources available, it will not be possible to determine the complex temporal and spatial structure of the exchange between the Bays and the Gulf well enough for quantitative prediction of contamination fluxes. Our observations provide a crude qualitative picture of the flow structures. Models, which represent the physics reasonably well, will be used to provide the essential detailed description. The validity of the model must be tested using observations. The Bays Program observations will be used for that purpose. The model can only work if the conditions along its open boundary are accurately specified. That specification could be provided by very expensive observations and/or results from a "correct" model of the Gulf. In either case, models and observations will have to be integrated — in ways like those used by meteorologists — in order to (1) accurately describe the details of the flow and water property structure at a particular time and (2) make predictions about the future.

Additional field measurements are also warranted to address important questions that did not receive adequate attention in this study. Vertical mixing and exchange mechanisms are very important to the ecology of the Bays, since they determine the rate at which nutrients can be supplied from the deep waters to the euphotic zone. Additional field work is necessary to provide more quantitative information about rates of vertical exchange by vertical mixing and coastal upwelling.

The impact of the new sewage outfall for Boston obviously provides a major driving force for future studies. Since the outfall plume will be trapped in the lower portion of the thermocline, additional measurements should focus on the circulation of the waters between 15 and 25 m depth. Subsurface drifters would probably be very valuable for describing the general characteristics of the flow at the depths that the plume will be trapped.

We need a better understanding of how and when water enters the Bays. A major forcing agent of the flow in the Bays is freshwater inflow from the Gulf of Maine, yet we still cannot quantify the fraction of that water that enters the Bays. A better understanding of this problem will come from a combination of modeling, additional field measurements and more satellite data analysis.

Finally, we need more interdisciplinary studies, to address the relationship between the physical processes and the ecology of the Bays. Many of the water quality concerns of the Bays are related to impacts on the living resources. We need to be able to quantify the response of the Bays ecosystem to changes in anthropogenic inputs, yet we have little understanding of how the natural forcing agents influence the ecosystem. The physical transport processes play key roles in the ecological response of the Bays; that is why the Massachusetts Bays Program made this large investment in physical oceanographic research. Future ecological research should be cognizant of the physical factors that are influencing distributions of nutrients and organisms, and likewise these ecological studies should provide insights to gain a better understanding of the physical regime.

1 Introduction

This report describes a study of the physical oceanography of Massachusetts and Cape Cod Bays (the Bays). The study was conducted by scientists at the Woods Hole Oceanographic Institution (WHOI), the University of Massachusetts at Boston (UMB), the University of New Hampshire (UNH) and the U.S. Geological Survey (USGS). This study was designed to provide for the first time a bay-wide description of the circulation and mixing processes on a seasonal basis. A long-term objective of the Massachusetts Bays program is to develop an understanding of the transport of water, dissolved substances and particles throughout the bays. Because horizontal and vertical transport is important to biological, chemical, and geological processes in Massachusetts and Cape Cod Bays, this physical oceanographic study will have broad application and will improve the ability to manage and monitor the water and sediment quality of the bays. It should be made clear that this measurement program was not specifically designed to predict the effects of the new ocean outfall that will begin operation in 1995 in western Massachusetts Bay, an issue of considerable public concern, but to provide an overall framework of the seasonal variability of transport processes in the Massachusetts Bays. The results of this program should have direct input to the strategies for monitoring the new outfall however, and will provide important information for site specific studies.

The goals of this study were:

- to characterize the water properties and transport processes in the Bays through one annual cycle;
- to determine the relative importance of the tidal, wind-driven and density-induced motions during the different seasons;
- and to determine how these motions influence the transport and exchange of water and waterborne substances.

The study consisted of field measurements between November 1989 and June 1991, with the most intensive activity between April 1990 and June 1991. The field effort consisted of a series of detailed water property surveys of the Bays during different seasons, an array of moored water property, bottom pressure and velocity measurements, and a series of surface drifter deployments. Additional data from other sources included satellite sea-surface temperature, meteorology, coastal sea level and river discharge.

This report contains the results of measurement conducted as part of the Massachusetts Bays Program study as well as measurements conducted by the USGS. The remainder of this section includes the scientific background relevant to the study and a description of the field program. Section 2 includes a detailed description of the observations, organized in terms of the different data types. Section 3 includes analysis and discussion of the physical processes responsible for the observed circulation and water properties variations, as well as estimates of rates of exchange and residence times. Section 4 includes a summary and recommendations, with some discussion of the implications of the study on water quality issues.

1.1 Background

1.1.1 Physical Setting

Massachusetts and Cape Code Bays (the Bays) are situated in the western Gulf of Maine (fig. 1-1), but are partially isolated from the rest of the Gulf by Stellwagen Bank, which rises to within 30 m of the surface (fig. 1-2). There are silled channels on either side of Stellwagen Bank. North Passage (our nomenclature), the channel between Cape Ann and Stellwagen Bank has a sill depth of 60 m, while South Passage, the channel between Race Point and Stellwagen Bank, has a sill depth of 50 m. The deepest portion of the Bays is Stellwagen Basin, with typical depths of 80 m. The western portion of Massachusetts Bay has rough, irregular topography, while Cape Cod Bay is relatively smooth. There are no major rivers entering directly into Massachusetts Bay. The largest is the Charles, with an annual average discharge rate of about 10 $m^3\ s^{-1}$. The major freshwater sources to the north have much larger transports; including the Merrimack (320 $m^3\ s^{-1}$), Androscoggin (320 $m^3\ s^{-1}$), Kennebec (320 $m^3\ s^{-1}$) and Penobscot (475 $m^3\ s^{-1}$) Rivers.

1.1.2 Prior Physical Oceanographic Study

Bigelow (1927), Bumpus and Lauzier (1965), Bumpus (1973) and Bumpus (1974) studied the physical oceanography of Massachusetts Bay, providing descriptions of the circulation and water properties. Based on a limited number of surface and bottom drifter observations, Bumpus (1973) suggested a weak residual circulation regime with inflow through North Channel, counterclockwise flow through the Bays, and outflow in South Channel. He noted a marked seasonal variation of temperature, with strong thermal stratification occurring during the summer and well-mixed conditions occurring during the winter months. Butman (1975) reported on near-bottom moored measurements in Massachusetts Bay, describing the response of the Bays to wind forcing and freshwater inflow. While he could resolve the baywide sea-level variations in response to wind forcing, the current measurements were not sufficient to provide a clear indication of the baywide circulation and its variability. Butman (1976) clearly showed the important influence of the Merrimack River in spring on the hydrography and circulation in northern Massachusetts Bay. A variety of moored measurements have been performed as part of engineering studies. Generally the duration of these deployments has been inadequate to characterize the seasonal variations of the circulation.

Several oceanographic studies of the Gulf of Maine have addressed aspects of the oceanography of the Bays. For example, Mountain and Jensen (1987) showed the important influence of winter cooling in Massachusetts Bay on the formation of dense water that flows out of Massachusetts Bay and becomes deep water in the Gulf of Maine. Wright et al. (1986) modeled the response of the Gulf of Maine to winds, using a vertically integrated model. Their model indicated large sea-level variations in the Bays as a result of SW–NE (across-bay) winds, and large along-bay currents in response to NW–SE (along-bay) winds. Of special interest was the 2-gyre circulation, with downwind flow along the coastal portion of the Bays and upwind flow in the deeper interior. It was not known whether the vertically integrated nature of the model compromised its ability to represent the major features of the circulation. Tidal models of the Gulf of Maine and Massachusetts Bay have been implemented by Greenberg (1983) and Isaji and Spaulding (1984). These simulations indicate significant tidal residuals, especially in the vicinity of Race Point.

One aspect of the physical oceanography of the Bays that has received considerable attention is the generation and propagation of large amplitude internal waves in Stellwagen Basin (Halpern, 1971; Haury et al., 1979; Chereskin, 1983). The influence of these waves on the mean circulation and vertical mixing rate in the Bays was not determined in these studies.

These previous studies indicated some of the general characteristics of the water properties and circulation of the Bays, but the resolution of the circulation was inadequate to quantify the mean transport through the Bays, and very little was known about the seasonal variations of circulation, nor the response to wind and runoff events. The existing physical oceanographic data did not provide an adequate basis for assessing the fate and transport of waterborne substances in the Bays; for this reason the Massachusetts Bays Program chose to focus their initial research on a characterization of the physical oceanographic processes in the Bays.

1.2 Field Program Description

The field measurement program was designed to resolve the general characteristics of the circulation and water properties through the annual cycle as well as to provide estimates of the scales of variability of currents and water properties. Because of the complexity of the physical regime in the Bays, it was recognized that the measurements by themselves would not be capable of resolving completely the temporal and spatial structure, and that an effective research strategy would be to couple the measurement program with a numerical modeling study. A modeling study is presently underway by USGS, and as the modeling and data are synthesized, the fruits of this observational program will be fully realized.

The measurement program included five principal components (see Table 1.1), namely:

- moored observations of current, temperature, conductivity (salinity), and pressure at various locations in the Bays (fig. 1-3), with an emphasis on the period April 1990 – June 1991;
- six baywide hydrographic surveys and several abbreviated surveys: April 1990 – June 1991;
- high resolution surveys of the velocity and water properties at selected coastal transects (fig. 1-5);
- drifter deployments at five times during the interval of moored measurements;
- satellite sea surface temperature imagery; summer 1990.

Table 1.1: Summary of the Massachusetts Bays Program Cruises

Date(s)		Funding Agency
13 April 1990	Hydrography (Northern Bay)	MBP
23–27 April 1990	Instrument Deployment	MBP
27–28 April 1990	Hydrography	MBP
30 April 1990	Coastal Survey: Scituate	
1 May 1990	Drifter Deployment	
2 May 1990	Coastal Survey: Broad Sound	
15 May 1990	Drifter Deployment	
29 June 1990	Hydrography (Northern Bay)	MBP
16–17 July 1990	Instrument Deployment	MBP
24–26 July 1990	Hydrography	MBP
23–28 July 1990	Instrument Recovery Redeployment	MBP
25 July 1990	Drifter Deployment	
31 July 1990	Coastal Survey: Broad Sound	
2 August 1990	Coastal Survey: Scituate	
11–13 September 1990	Instrument Recovery Redeployment	MBP & USGS
20 September 1990	Coastal Survey: Manomet	
28 September 1990	Hydrography (Northern Bay)	MBP
15 October 1990	WHOI Mooring Turnaround	
15 October 1990	Drifter Deployment	
16–18 October 1990	Hydrography	MBP
15–16 January 1991	Instrument Recovery	MBP & USGS
30 January–1 February 1991	Instrument Deployment	EPA
3 February 1991	Drifter Deployment	
4–7 February 1991	Hydrography	MBP
7–8 February 1991	Instrument Deployment	EPA
21–23 March 1991	Hydrography	MWRA
25 March 1991	Hydrography	USGS "Followup"
25 April 1991	Hydrography (Boston Only)	MBP
25 May 1991	Coastal Survey: Scituate	
29 April–1 May 1991	Hydrography	EPA
3 May 1991	Hydrography	USGS "Followup"
8 May 1991	Drifter Deployment	
23 May 1991	Coastal Survey: Broad Sound	
23 May 1991	Drifter Deployment	
13 June 1991	Hydrography	MBP
16–20 June 1991	Instrument Recovery	EPA

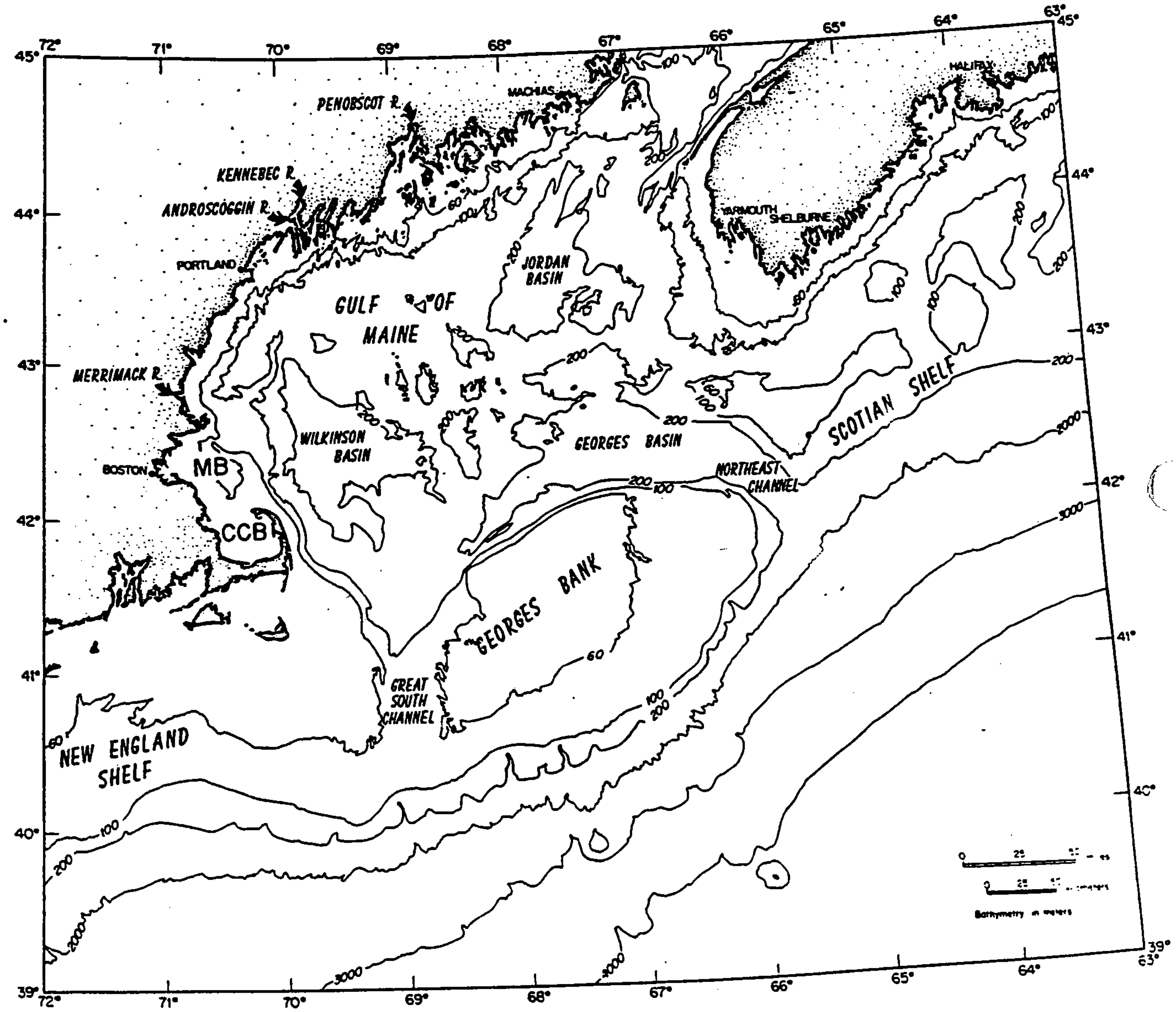


Figure 1.1 The Massachusetts Bay (MB)/Cape Cod Bay (CCB) system is a semi-isolated embayment in the western Gulf of Maine.

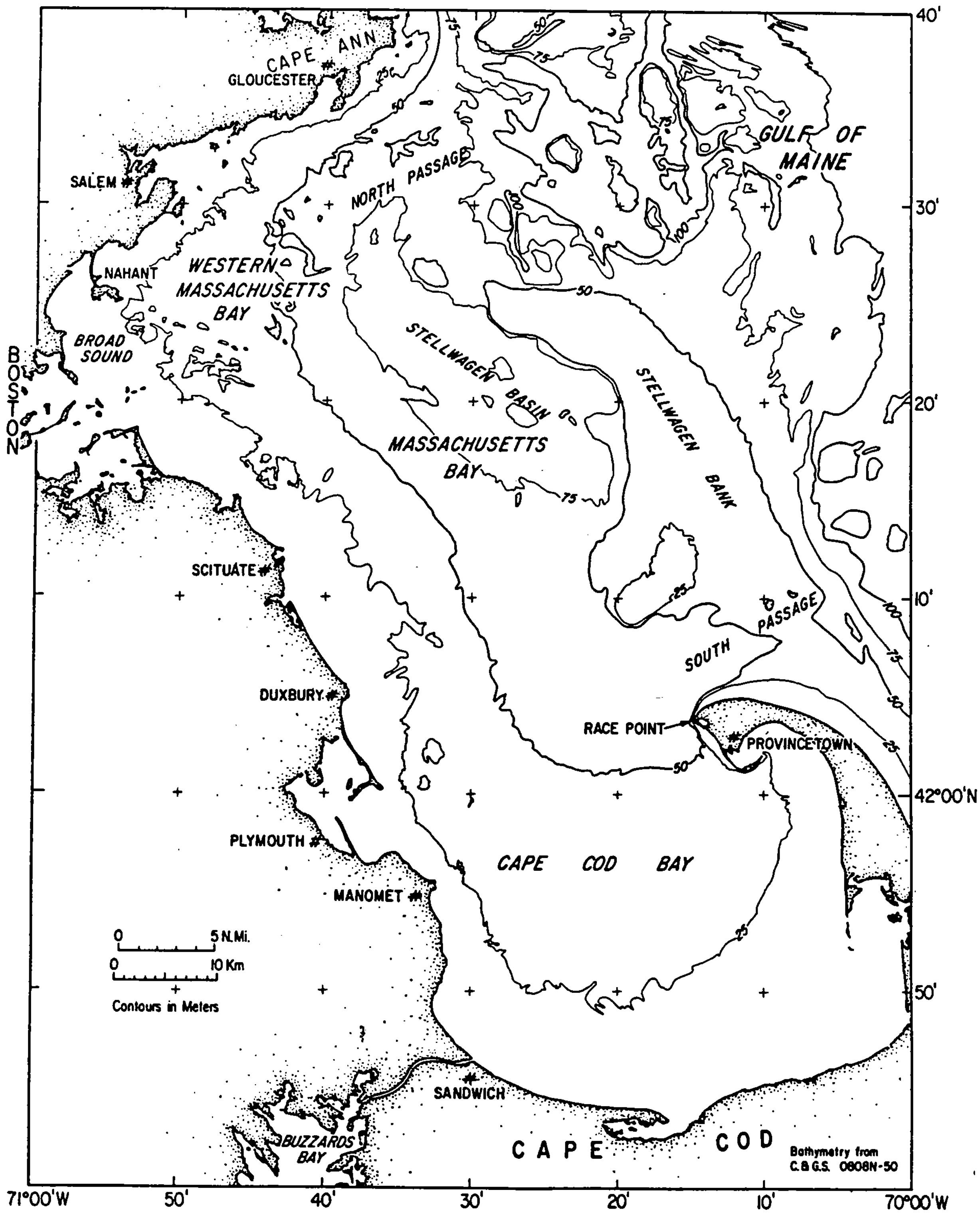


Figure 1.2 Bathymetry of Massachusetts/Cape Cod Bay system, indicating the major bathymetric features.

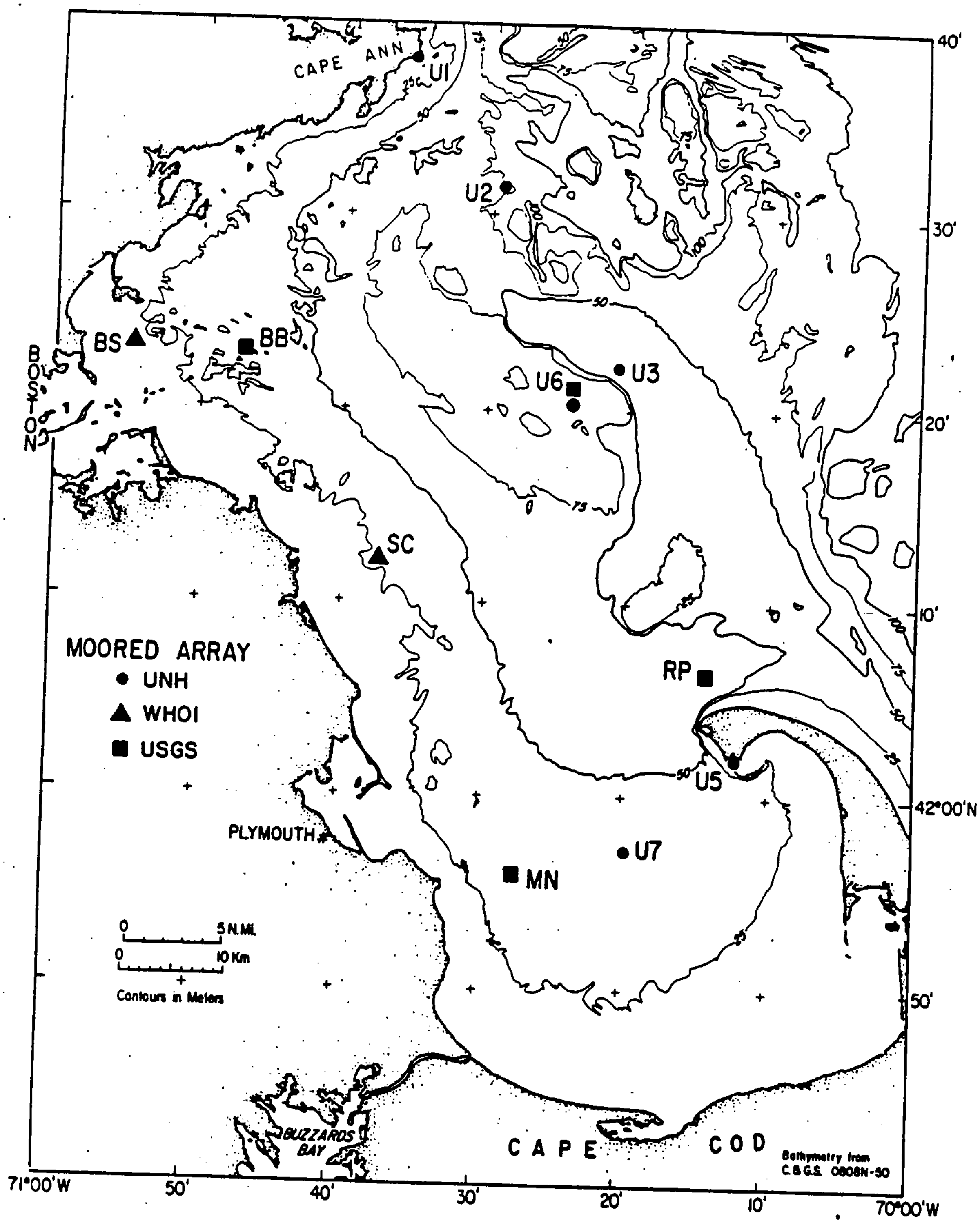


Figure 1.3 The combined Massachusetts Bays Program–USGS moored array.

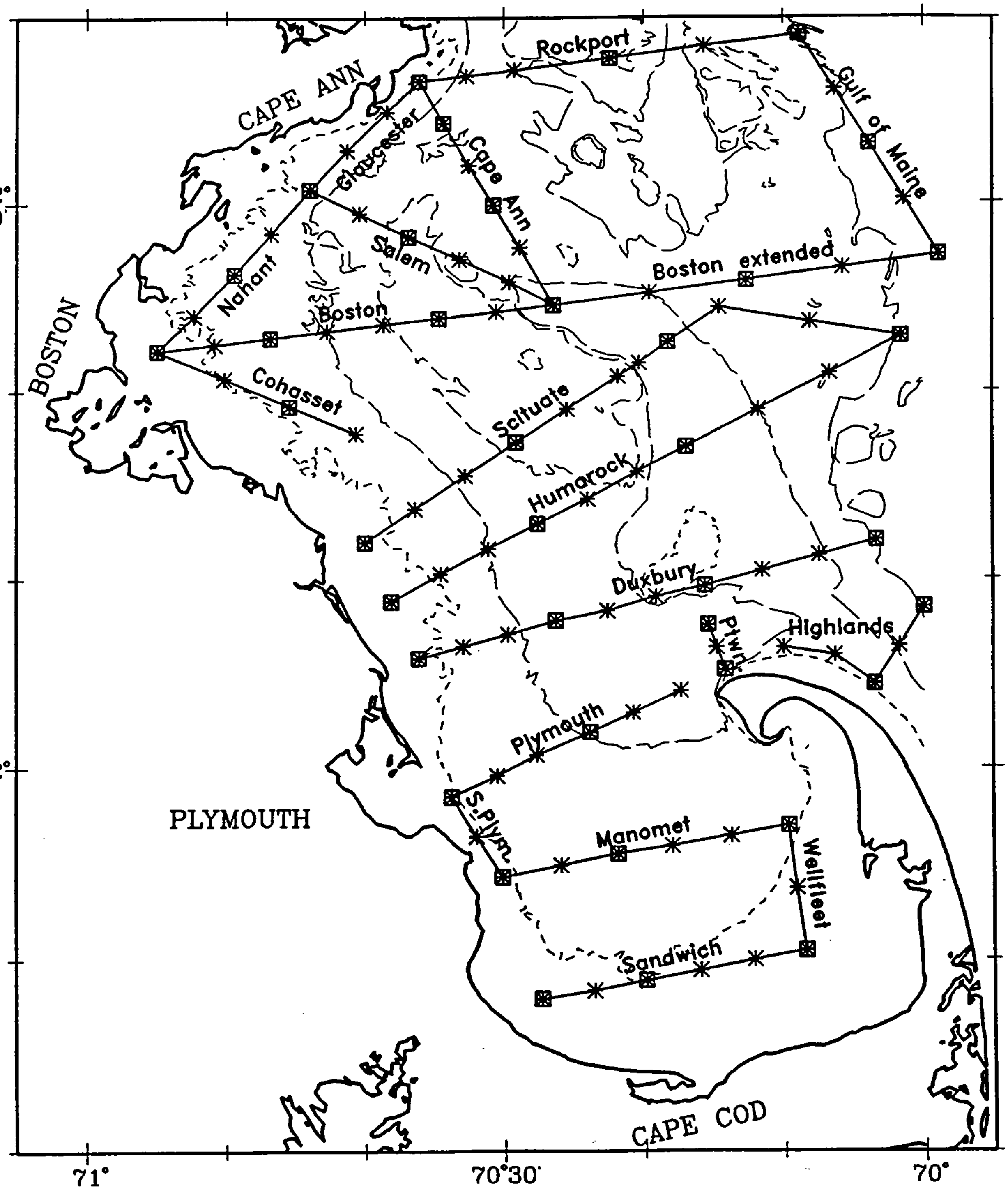


Figure 1.4 The extended hydrographic station array for the Massachusetts Bay Program during the 1991 surveys. (The 1990 surveys had limited coverage outside the Bays; see Section 2.4). The squares indicate where nutrients were obtained.

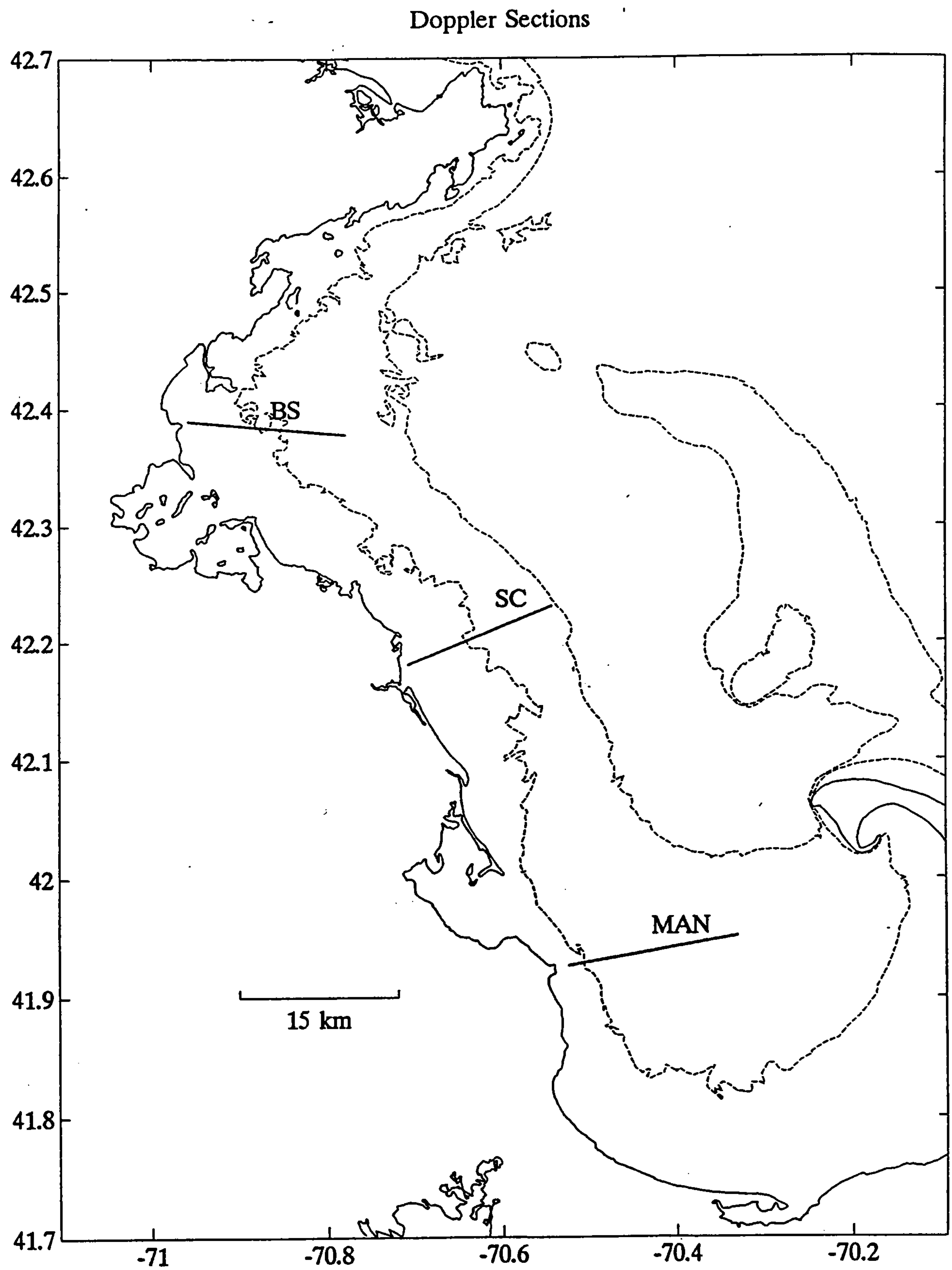


Figure 1.5 Coastal survey tracks for the Massachusetts Bays Program.

2 Data Description

This section includes the observations obtained during the field program. Each subsection refers to a particular type of data. Within each subsection the methods by which the data were obtained are discussed and the data are presented. While there is some interpretation of the data included in this section, the overall synthesis of the program results appears in Section 3.

2.1 Meteorological and Run-off Data

2.1.1 Wind Stress

Local wind stress is known to cause shallow water current and sea level fluctuations. Remote winds can also generate coastal trapped waves, which travel along the coast to the right (in the northern hemisphere), causing variability as they go. To assess the effects of winds on Bays variability we have obtained 3-hourly wind records from the National Climatic Center for Logan Airport and the National Ocean Data Center (NODC) for one site within the Bays: Boston Buoy (BB; see fig. 1-3), from sites "upcoast" from the Bays (Isles of Shoals, Portland, Matinicus Rock, and Mt. Desert Island), from ocean sites (Gulf of Maine, Georges Bank and Nantucket). Hourly wind stresses have been derived from observed winds using the method of Large and Pond (1981) and spline interpolation.

The wind records most relevant to the local forcing of the Bays are the records at Logan Airport in Boston and the Boston Buoy. The magnitude of the wind stress and its seasonal variation are evident in the upper panel of fig. 2.1-1, in which the short-term fluctuations are averaged out by a 15-day filter. Higher wind stress occurred between October and March, with peaks occurring in November and March. Minimum wind stress occurred during the months of July and August. The wind direction varied on timescales of 1–3 days (lower panel of fig. 2.1-1), but there were seasonal variations that can be detected from a plot of 15-day average stress (middle panel of fig. 2.1-1). During the summer months the wind stress tends to be northward, due to the prevailing "southwesterlies", while during the winter it is more variable, with strong wind events coming from the southwest, northwest and occasionally the northeast. When these events are averaged, the mean stress is from the northwest.

The correlation timescale of the wind stress was estimated by integrating the autocorrelation function out to its first zero crossing. This timescale represents the time over which a typical wind event acts on the currents before the wind direction or strength changes considerably. During the summer of 1990, the autocorrelation timescale was 1.1 days, with the zero crossing occurring at 3.8 days. During the winter of 1990–1991, the timescale was 0.76 days, with the zero crossing occurring at 1.2 days. These short timescales mean that even if there is an energetic response to wind forcing, the duration is so short that it may not represent large displacements of water before the winds shift to another direction.

2.1.2 Heat Flux

The large annual variation of solar insolation and latent heat flux at the latitude of the Bays result in large variations in heat flux. The net heat flux at the water surface is the sum of the incoming solar short-wave radiation (SWR), the longwave radiation (LWR), the sensible (SHF) and latent (LHF) heat fluxes. We have used observations from Logan Airport and Boston Buoy in conjunction with bulk formulae (see Appendix B) to estimate the heat flux and evaporative transport through the period of the deployment. Incoming radiation was estimated from climatology (Hopkins and Raman, 1987).

The results of these estimates are shown in fig. 2.1-2. The net heat flux is positive from the beginning of the deployment period until the end of August, due to the dominance of incoming radiation. Net cooling occurs becomes pronounced in November and continues through the winter until mid-March, due principally to latent heat losses.

2.1.3 Freshwater Inputs

The freshwater discharge from the coastal Maine rivers in spring has been shown by Franks (1990) to collect in a coastal plume and flow southwestward toward Massachusetts Bays. The principal river systems that contribute to this freshwater inflow are the Merrimack, the Androscoggin, the Kennebec and the Penobscot. The Saint Johns River, which empties into the Bay of Fundy, is the largest riverine input to the Gulf of Maine, however it is far enough from Massachusetts Bay that its influence is less distinct than that of the rivers of the western Gulf of Maine.

The April 1990–June 1992 time series of average daily discharge rates of the western Gulf of Maine rivers (obtained from the U.S. Geologic Survey) are presented in Fig. 2.1-3. The large peaks in the discharge records are related to major storm or melting events. There was a period of high discharge in the spring of 1990, several peaks during the summer, and another period of high discharge between mid- October 1990 and January, 1991. High discharge again occurred during the months of April and May, 1991, related to the spring freshet. The contribution of the Merrimack was typically one fifth of the total discharge of these rivers. Comparing the discharge of the Merrimack River during the deployment period to the averages over the last 6 years, the discharge was approximately 30% higher than average, with the biggest anomaly being the high discharge during the October–January period.

The major direct inputs of fresh water into the Bays enter via Boston Harbor. They include the Charles River and the Massachusetts Water Resources Authority (MWRA) discharges (fig. 2.1-4). Their contribution is only a few percent of the discharge of the Gulf of Maine rivers, however it does have an influence on the salinity of the western portion of Massachusetts Bay. The percentage of the discharge from the other rivers that actually enters Massachusetts Bays appears to be highly variable and has not been well quantified.

There are other small rivers that enter the Bays as well as groundwater discharge, which dominates the runoff from Cape Cod (Menzie and Cura, (1991)). None of these sources is significant except with respect to near-shore variations of salinity.

Another direct source of freshwater to the Bays is the direct precipitation onto the surface of the Bays. This is compensated for by evaporation from the sea surface, so the net freshwater input at the surface is the difference between precipitation and evaporation, or P-E (fig. 2.1-5). Precipitation observations were obtained at Logan Airport. The evaporation time series was estimated from observations and bulk formulae as discussed in Appendix B. Based on the area of the Bays of 3.7×10^9 m^2, 1 cm/day of P-E is equivalent to roughly 400 $m^3\ s^{-1}$, so the contribution of surface freshwater flux to the Bays freshwater budget is larger than the Boston Harbor sources and typically smaller than the Gulf of Maine river discharge volumes.

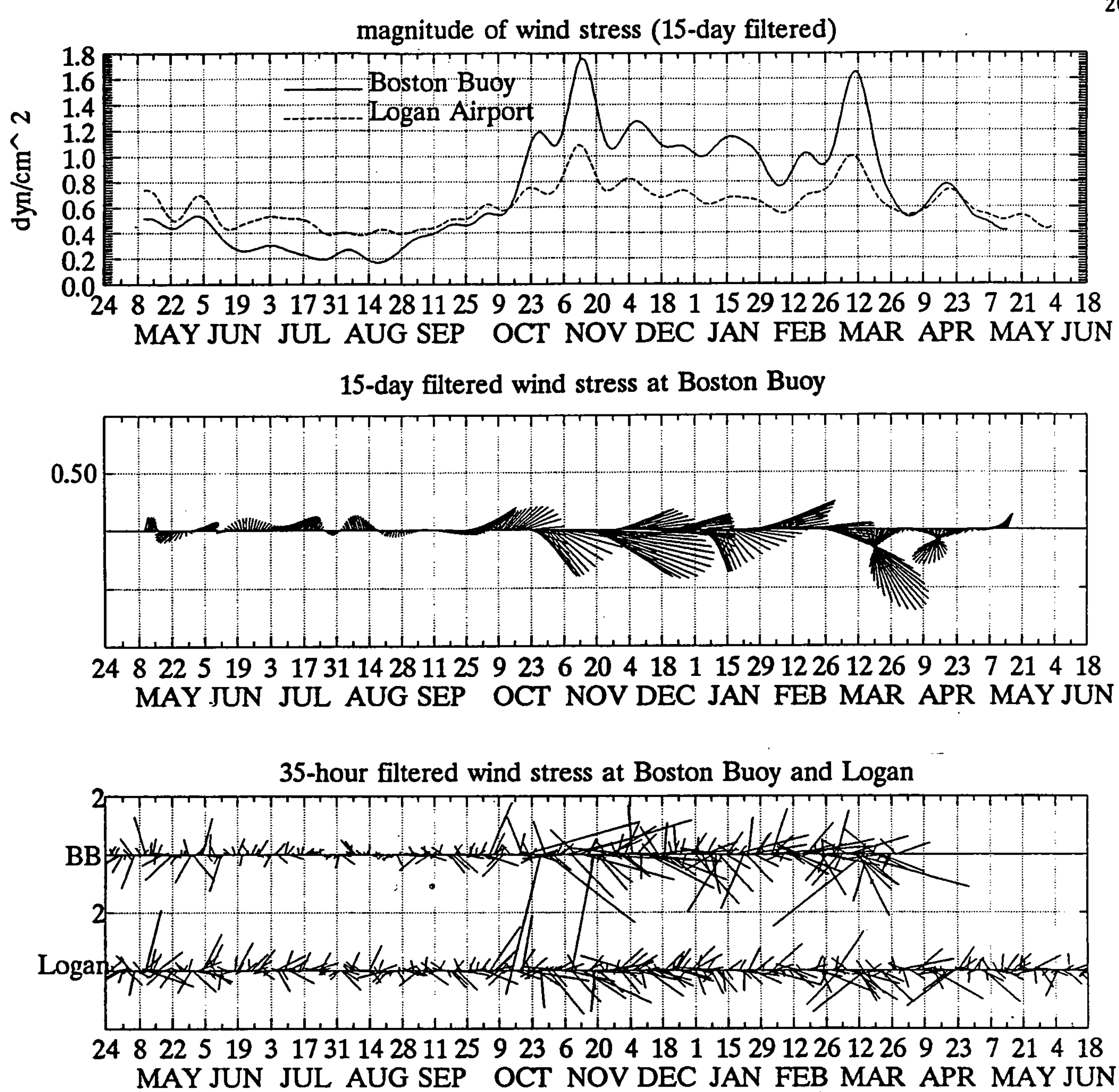


Figure 2.1-1. Wind stress variations at Logan Airport (Boston) and the Boston Buoy during the deployment period, April 1990 – June, 1991. Upper panel: 15-day averaged stress magnitude, showing an increase in wind stress during the fall and winter months and a minimum during the summer. Middle panel: 15-day average wind stress vectors. (The direction of the vectors indicates the downwind direction, and the length indicates the magnitude. Northward is straight up.) Relatively weak winds from the southwest (SW) are found during the summer months and stronger, WSW to NW winds occur during the winter months. Lower panel: daily, 35-hour filtered wind stress vectors, showing the short timescale of variability of the winds.

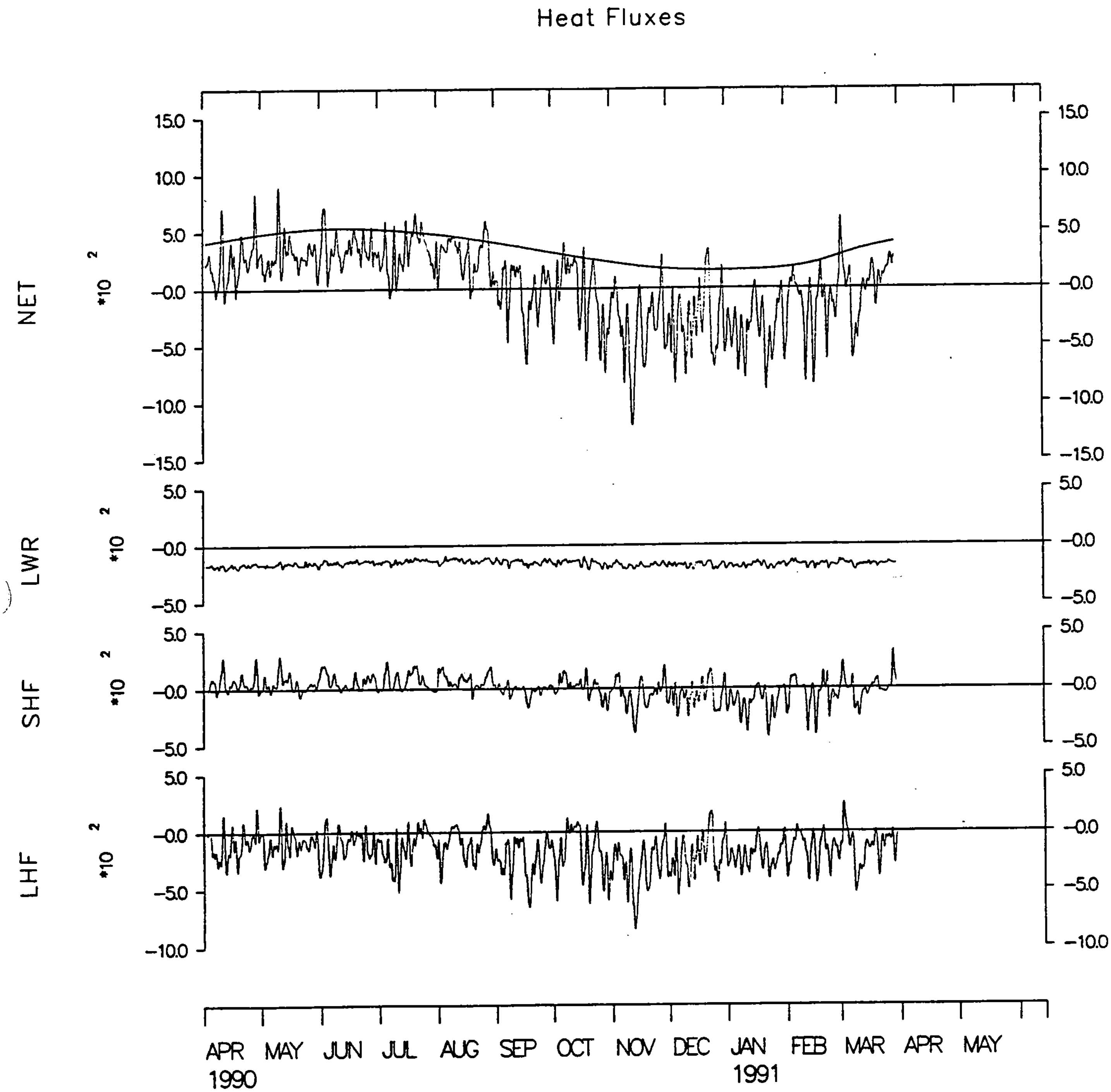


Figure 2.1-2. Heat flux timeseries for northern Massachusetts Bay, based on observations at Logan Airport and the Boston Buoy, using bulk heat flux fomulae for long-wave radiation (LWR), sensible heat flux (SHF) and latent heat flux (LHF), and climatological data for incoming solar radiation. The upper panel includes the incoming solar radiation (smooth line) and net heat flux (jagged line). The lower panels indicate the other contributors to heat flux. Units are cal cm^{-2} day^{-1}. Positive values indicate net heating.

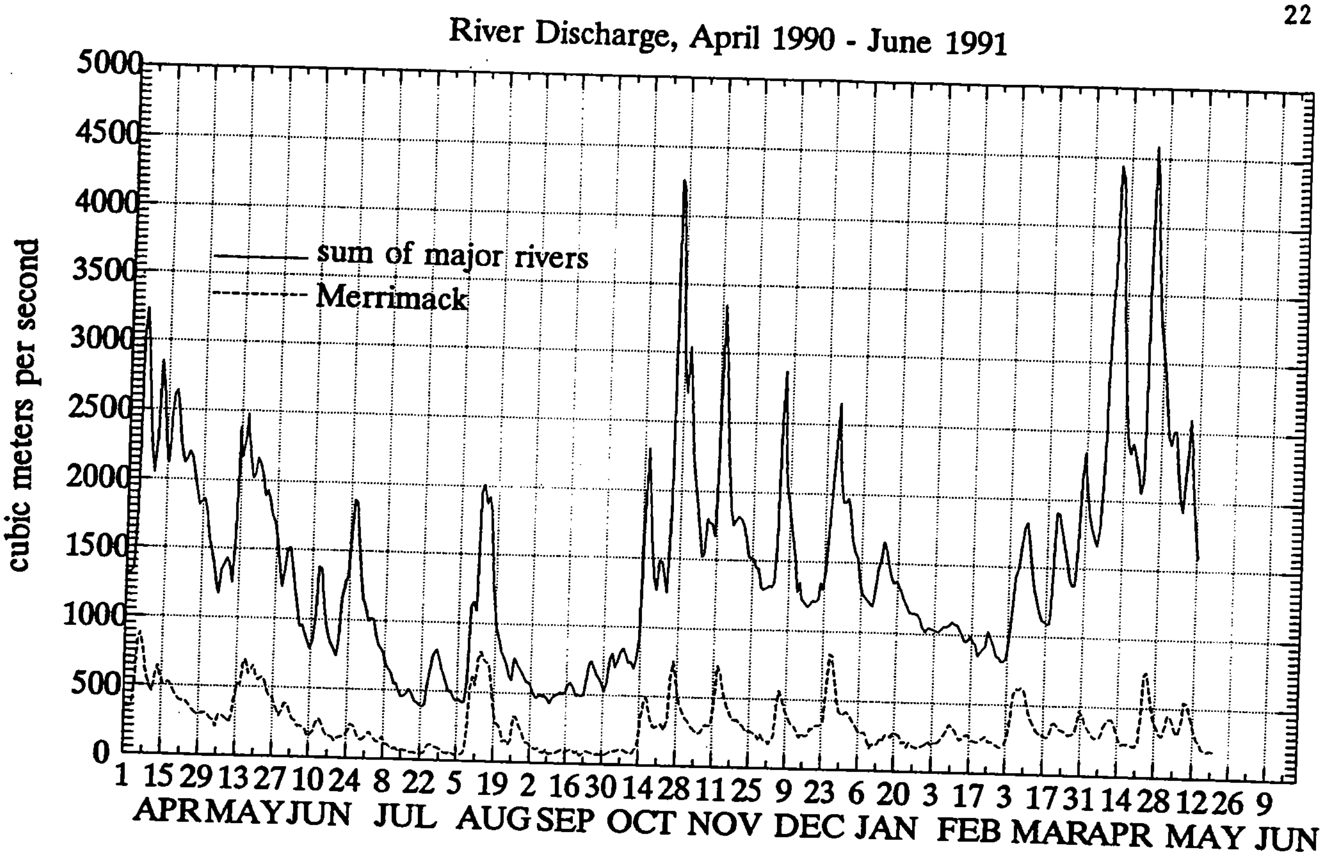


Figure 2.1-3. USGS Daily river discharges from the four principal river systems feeding the western Gulf of Maine: the Penobscot, the Kennebec, the Androscoggin and the Merrimack. The contributions to the river discharge below the gauging stations are believed to be less than 5%.

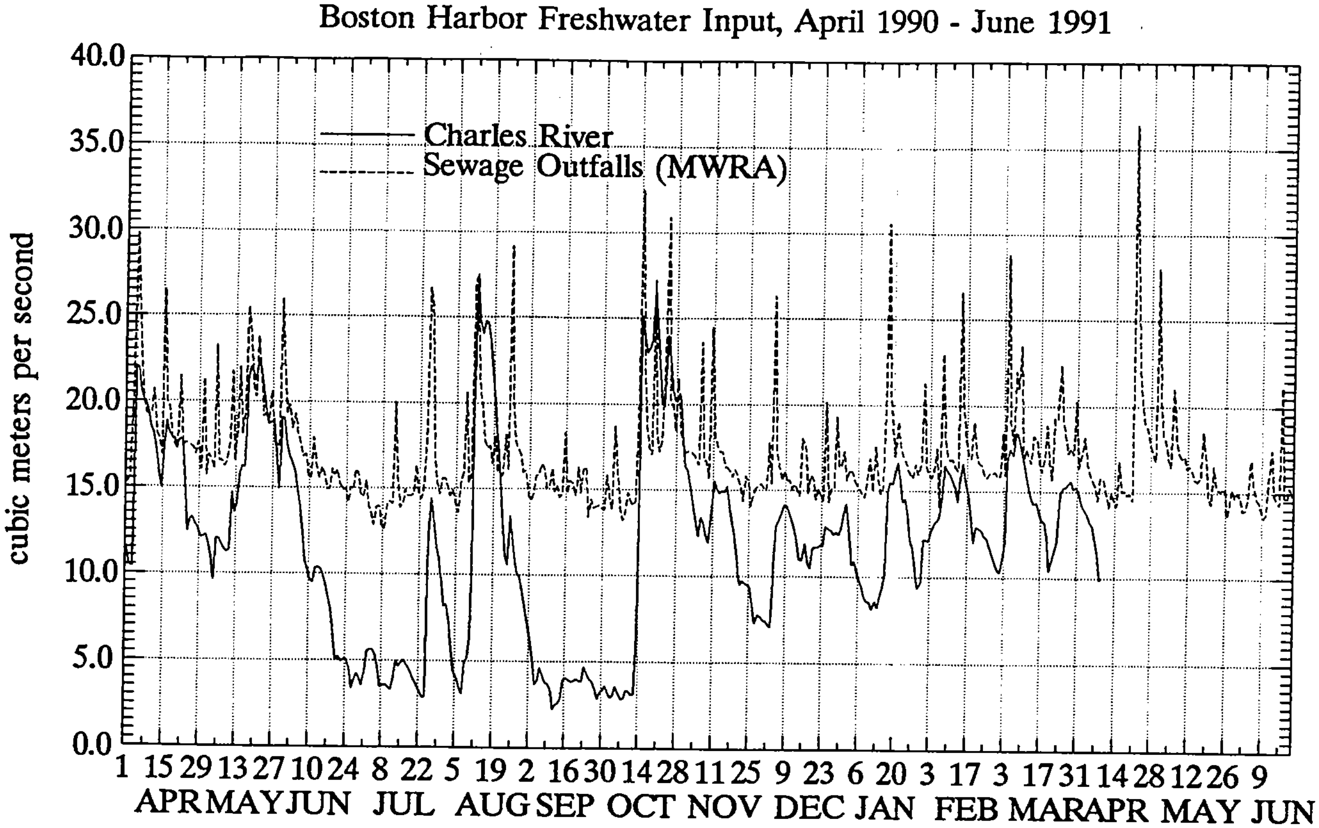


Figure 2.1-4. Daily discharge from the Charles River and the combined Nut Island and Deer Island sewage discharges in Boston Harbor (Nut Island values were assumed to be 50% of the values at Deer Island). Note that the contributions from combined sewer overflows and storm drains are not included.

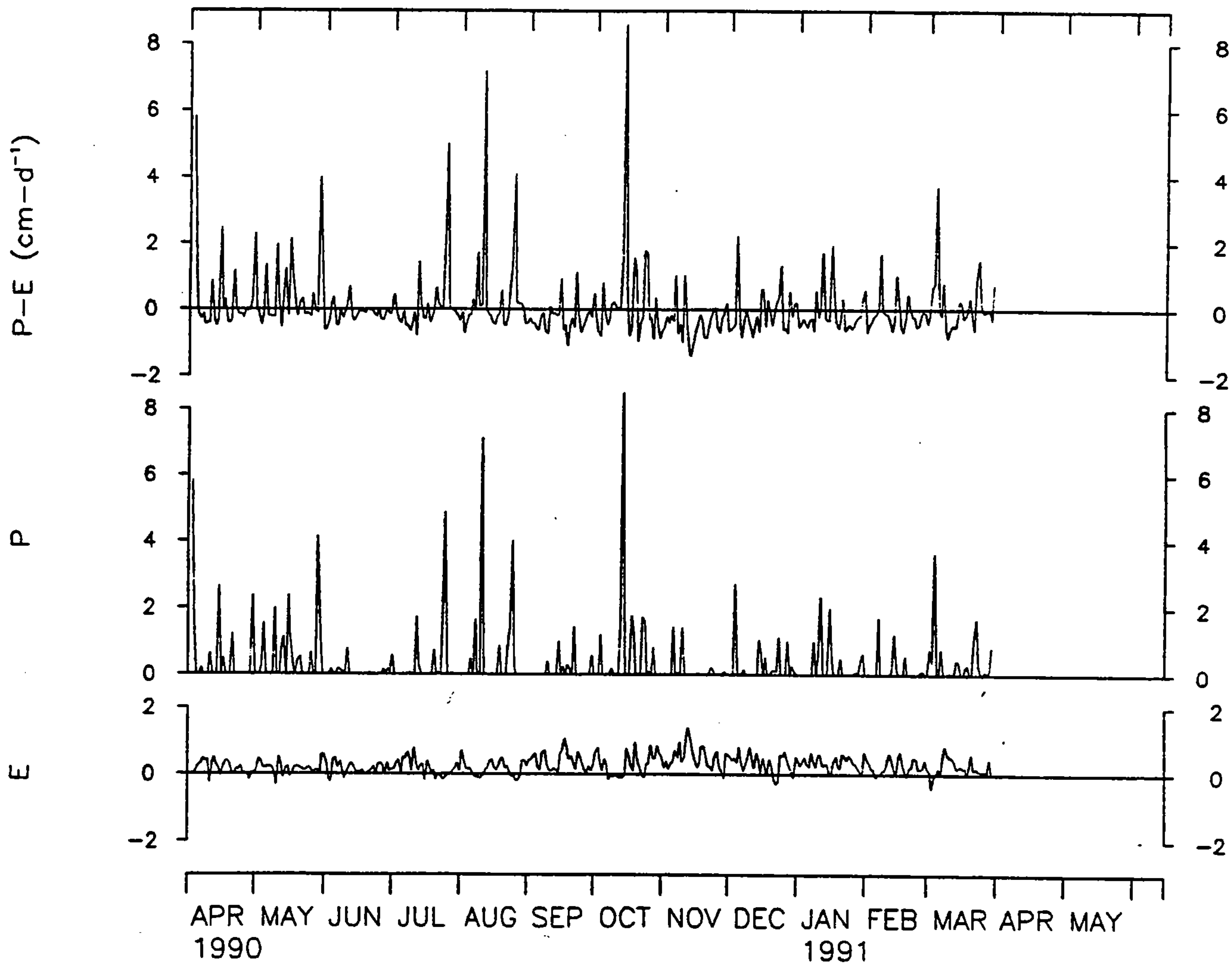


Figure 2.1-5. Precipitation and evaporation time series for northern Massachusetts Bay, based on observations at Deer Island, Logan Airport and the Boston Buoy (see text for calculations). The top panel shows the net, i.e., P–E, while the lower panels show precipitation and evaporation, respectively. Note the high evaporation rates during the wintertime. This is due to the low relative humidity during the winter months.

2.2 Moored Measurements

2.2.1 Moored Array Design and Instrumentation

Recognizing that the moored measurement program would not be able to resolve all of the spatial variability of the currents in the Bays, the moored array focussed on the coastal region and the open boundary between the Bays and the Gulf of Maine (fig. 2.2-1). The focus on the coastal region was motivated by model results of Wright et al., (1976) and Csanady (1974) that suggested an intensification of the wind-driven response in coastal regions. The boundary moorings provide an indication of the exchange between the Bays and the Gulf of Maine.

The configuration of the moorings is indicated in fig. 2.2-2. Measurements of currents and water properties were made at near-surface, mid-depth and near-bottom depths at selected stations. Near-surface instruments were at a nominal depth of 5-m, placing them above the seasonal thermocline during the summer months.

The types of measurements obtained at each site are indicated in Table 2.2-1. Currents, temperature and salinity were measured at most locations, and light transmission was measured at several locations to document resuspension of bottom sediments. The moored water properties measurements complement the shipboard hydrographic measurements by resolving the temporal variability of the system.

Measurements of bottom pressure provided information on tides as well as pressure differences which are related to Bay-scale non-tidal flow. The bottom pressure (BP) array (fig. 2.2-1) consisted of four UNH stations (U1, U2, U3, U5) along the open boundary between Massachusetts Bay and the Gulf of Maine. USGS stations at BB and U6 provided information on bottom pressure in the central Bays. Coastal sea level at Boston and elsewhere around the Gulf augmented the Bays/USGS Program observations. This array provided pressure difference information across the North and South Passages located north and south of Stellwagen Bank, respectively.

The periods of deployments of the various instruments are indicated in fig. 2.2-3. The USGS measurements at the Boston Buoy (BB) commenced in November, 1989, and the Massachusetts Bays Program array was first deployed in April, 1990. Additional instruments were deployed by USGS in September, 1990. All of the moorings except for the Boston Buoy instruments were recovered in June, 1991.

Table 2.2-1 Moored Instrumentation

SITE	POSITIONS	SITE DEPTH (m)	INST. DEPTH (m)	PRESSURE	VELOCITY	TEMPERATURE	CONDUCTIVITY TRANSMISSION	BASIC SAMPLING INTERVAL (minutes)
UNH								
U1	42 36.7'N x 70 39.8'W	5	3	Paros	—	Sea Data Thermistor	—	7.5
U2	42 32.0'N x 70 29.0'W	70	4	—	VMCM	VMCM Thermistor	—	4
			25	—	VACM	VACM Thermistor	Sea Bird SBE-4	15
			60	—	VACM	VACM Thermistor	Sea Bird SBE-4	15
U3	42 22.2'N x 70 20.5'W	29	4	—	VMCM	VMCM Thermistor	—	4
			25	Paros	VACM	VACM Thermistor	Sea Bird SBE-4	15
U5	42 03.7'N x 70 14.6'W	5	3	Paros	—	Sea Data Thermistor		7.5
U6	42 21.2'N x 70 24.3'W	87	4	—	DAPCM	Sea Bird SBE-3	Sea Bird SBE-4	60
			10	—	—	Sea Bird SBE-3	Sea Bird SBE-4	60
			25	—	—	Sea Bird SBE-3	Sea Bird SBE-4	60
			45	—	—	Sea Bird SBE-3	Sea Bird SBE-4	60
			60	—	—	Sea Bird SBE-3	Sea Bird SBE-4	60
U7	41 58.0'N x 70 20.0'W	39	4	—	VMCM	VMCM Thermistor	—	4
			25	—	VACM	VACM Thermistor	Sea Bird SBE-4	15
WHOI								
BS	42 23.2'N x 70 54.5'W	20	5	—	S4	SBE Seacat	SBE Seacat	10
			18	—	S4	SBE Seacat	SBE Seacat/LT	10
SC	42 12.2'N x 70 31.5'W	25	5	—	S4	SBE Seacat	SBE Seacat	10
			23	—	S4	SBE Seacat	SBE Seacat/LT	10
USGS								
BB	42 22.6'N x 70 46.9'W	34	5	—	VMCM	SBE Seacat	SBE Seacat/LT	3.75
			25	—	VMCM	SBE Seacat	SBE Seacat/LT	3.75
			33	Paros	DLCM	YSI Thermistor	Sea Bird SBE-4/LT	3.75
RP	42 6.4'N x 70 14.8'W	60	5	—	VMCM	VMCM Thermistor	—	3.75
			25	—	VACM	VACM Thermistor	—	3.75
			50	—	VACM	VACM Thermistor	Sea Bird SBE-4/LT	3.75
			59	—	VACM	VACM Thermistor	—	3.75
U6	42 21.3'N x 70 23.9'W	87	75	—	VACM	VACM Thermistor	—	3.75
			85	Paros	DLCM	YSI Thermistor	Sea Bird SBE-4/LT	3.75
MAN	41 55.9'N x 70 27.6'W	36	5	—	VMCM	VMCM Thermistor	—	3.75
			26	—	VACM	Sea Bird SBE-3	Sea Bird SBE-4/LT	3.75

VMCM = Vector Measuring Current Meter
VACM = Vector Averaging Current Meter
DAPCM = Doppler Acoustic Profiling Current Meter
Resolves velocities in 4 meter bins from 10m to 74m
DLCM = Data Logging Current Meter (VACM Sensors)
LT = Sea Tech Transmissometer

UNH Moorings

A downward-looking Doppler Acoustic Profiling Current Meter (DAPCM) at U6 in Stellwagen Basin (300 kHz) provided velocity measurements at 4 m depth intervals between 8 and 65 m depth. Temperature and conductivity were measured with Sea Bird sensor pairs at 2, 10, 25, 45 and 65 meters depths. Hourly-averaged data were telemetered via the GOES satellite to UNH using technology employed successfully in the Gulf of Maine for 13 months (Wood and Irish, 1987; Irish et al., 1987). All of the station U6 observations were also recorded internally for later retrieval.

In the passage north of Stellwagen Bank (U2) currents were measured at three depths. Vector Measuring Current Meters (VMCMs), which are designed for more accurate current measurement in the presence of surface waves, were used to measure near-surface currents. The UNH moorings employed elastic tethers to minimize mooring motion effects on the deeper Vector Averaging Current Meter (VACM) measurements below surface buoys.

The North Passage mooring at station U2, consisted of a surface VMCM with temperature sensor at 4 meters depth, and two VACMs, each with temperature and a Sea Bird conductivity sensor, located at 25 and 60 meters depth, respectively. The Stellwagen Bank station U3 consisted of a bottom-mounted instrument frame with a VACM with temperature, Sea Bird conductivity and Paroscientific pressure sensors and a separate mooring with a VMCM with temperature deployed at 4 meters depth. The Cape Cod Bay mooring at station U7 consisted of a VMCM with temperature at 4 meters depth and a VACM/temperature/Sea Bird conductivity sensor at 25 meters.

The UNH bottom pressure instrumentation at stations U2 and U3 consisted of a Sea Data recorder with a temperature sensor and a Paroscientific pressure sensor (Brown, 1976 and Irish, 1989). The same pressure instrumentation with temperature was mounted at a depth of about 3 m on U.S. Coast Guard dock pilings in Gloucester Harbor (U1) and Provincetown (U5). The USGS bottom tripods at stations BB and U6 also had Paroscientific pressure sensors with temperature.

WHOI Moorings

The moorings at Scituate and Broad Sound consisted of surface slack-line moorings for the near-surface sensors and sub-surface taut-line moorings for the near-bottom sensors. Electromagnetic S4 current meters and SeaCat temperature — conductivity sensors were used at the near-surface and near-bottom locations. S4 current meters measure current components directly and thus do not need to be isolated from surface wave motion. The near-bottom SeaCats also had Seatech transmissometers (25-cm pathlength) for measuring turbidity. The near-surface sensors were approximately 5-m below the water surface, and the near-bottom sensors were approximately

1.5-m above the bottom.

USGS Moorings and Tripods

The long-term mooring at station BB maintained by the USGS in cooperation with the MWRA includes measurements of current, temperature, salinity and light transmission by means of vector measuring current meters (VMCM) and SeaCat sensors at 5 and 23 m from the surface. The instrumentation at 5 m is suspended from the Large Navigational Buoy and the instrumentation at 23 m is deployed on a taut subsurface current mooring. A tripod system on the seafloor also measures current, temperature, salinity, light transmission and bottom pressure (Butman and Folger, 1979). Instrumentation on the tripod also photographs the sea floor and collects samples of suspended matter during selected events. A time series sediment trap at 24 m from the surface collects sediments at 9-day intervals. This objective of this mooring is document long-term changes in currents, hydrography, and suspended-matter concentration in western Massachusetts Bay and the importance of infrequent catastrophic events, such as major storms or hurricanes, in sediment resuspension and transport (see Butman et al., 1992). The mooring was first deployed in December 1989 and will be maintained at least through 1995.

The USGS moorings at RP, MN and U6 were designed to augment the original UNH/WHOI moored array design, providing additional information about flow across the open boundary of Massachusetts Bay in the channel north of Race Point and into Cape Cod Bay in the nearshore zone. In addition, all of the USGS moorings measured light transmission at selected depths to document sediment resuspension and transport. At stations MN and RP measurements of currents and temperature were made at 5 m by means of VMCMs, and measurements of current, temperature, salinity and light transmission by means of VACMs at 25 m (RP) and 10 m above the bottom (RP and MN). The surface moorings employed elastic tethers, similar to the UNH moorings, to minimize mooring motion effects on the Vector Averaging Current Meters. At U6b, current, temperature, salinity and light transmission were measured at 10 meters above the bottom (mab). A bottom tripod, similar to the instrument at the long-term station, was also deployed at U6b. The USGS moorings were deployed in September 1990, recovered in January 1991, redeployed in February 1991, and retrieved in June, 1991.

2.2.2 Moored Array Data Quality

UNH Moorings

A detailed discussion of the data quality and error analysis of the UNH moorings is included in Appendix A. A summary of the precision of each of the sensors is included in Table 2.2-2.

Table 2.2-2. Nominal Sensor Accuracy and Precision

Sensor	Manufacturer	Method	Accuracy	Precision
Pressure	Paroscientific	Quartz	0.1 dbar*	0.01 dbar
Temperature	Sea Data Inc.	Thermistor	0.05 deg	0.005 deg
	Sea Bird	Thermistor	0.005 deg	0.001 deg
	EG&G VACM	Thermistor	0.1 deg	0.001 deg
	EG&G VMCM	Thermistor	0.1 deg	0.002 deg
Conductivity	Sea Bird	Electrode	0.01 S/m*	0.0005 S/m
Velocity	EG&G VACM	Rotor/Vane	5 cm/sec	3 cm/sec
	EG&G VMCM	Two Fans	5 cm/sec	3 cm/sec
	UNH SSVACM	Rotor/Vane	5 cm/sec	3 cm/sec
	RDI ADCP	Acoustic	5 cm/sec	5 cm/sec

* After removal of drift due to sensor creep or fouling.

Comparisons between ADCP and VACM currents show an RMS difference of 3.5 cm/sec. Without fouling, this contains some effects of mooring motion on the ADCP. Normally an accuracy of 3 cm/sec would be expected but was increased to 5 because of limited turnarounds to remove fouling. The increase in uncertainty is due to fouling, particularly in the Nov. 1989 – Jan. 1990 period.

WHOI Moorings

The velocity data from the S4 current meters at Scituate and Broad Sound appeared to be good when the instruments were functioning properly; unfortunately there were catastrophic failures in several instruments that resulted in data loss at both mooring locations during a significant fraction of the deployment period (fig. 2.2-3). Due to a shortage of properly functioning current meters, no deep instruments were deployed at Scituate between January and April, 1991.

The S4 instruments were internally calibrated at Interocean before the deployment, and zero tests were performed on each instrument at WHOI. Based on extensive testing of S4s (Bottero and Pillsbury, 1987), the accuracy of S4 current meters is ± 2 cm s^{-1}, with possible zero offsets of ± 2 cm s^{-1}, even after doing zero tests. Adding these errors and increasing for possible fouling effects with time, an accuracy of 4 to 5 cm/sec is again obtained and is consistent with the other current meters.

Fouling of the S4s tended to be fairly slight, and there was no indication from the velocity records of a reduced response with time that could be attributed to fouling. In all but one case, the time base of the instruments checked out to within 2 minutes over a 3-month period. The deep instrument at the Scituate mooring had a 4-hour time-base error during the Spring, 1990 deployment. This error is only significant with respect to tidal analysis for that record. There were no data spikes in any of the velocity records that required editing.

The SeaCat temperature and conductivity sensors were calibrated before the deployments at SeaBird Inc., Bellevue, WA. Accuracy of the temperature measurements was ±0.05°, and accuracy of the salinity was ±0.1 psu, based on prior experience and comparison with shipboard measurements.

The temperature and conductivity sensors on the Scituate and Broad Sound moorings generally worked well, based on comparisons with nearby hydrographic data on various cruises. Conductivity sensor failed on two occasions; the Broad Sound deep sensor failed between September and January, and there were no good deep salinity measurements at Scituate between November and the end of April. The near-surface and deep conductivity sensors at Broad Sound showed significant drift between December, 1990 and the end of the deployment, amounting to an error of 1 psu (the instruments reading too low) by the end of the deployment. These records were corrected with a linear correction to the trend, providing a consistent fit with respect to shipboard measurements during the period and consistent values with nearby moored instruments.

<u>USGS Moorings</u>

The experiment's time frame, April 1990 to June 1991, spanned 5 deployments at the USGS long-term mooring. SeaCats recorded good quality temperature and conductivity at both 5 m and 23 m for the entire interval. Light transmission records at these levels were truncated by fouling of the transmissometer optics after about one to three months on station. VMCMs deployed at 5 m produced good data for the entire period, except from August 19 to October 23, 1990, when biological fouling severely impeded the propellers. The only gap in the 23 m VMCM record is for the interval October 23, 1990 to February 12, 1991, when the VMCM did not record.

The tripod current records at the long-term mooring are complete except for the period from May 17 to July 10, 1990 and from August 30 to October 24, 1990. Tripod temperature and salinity records are complete except for these two recording gaps, and in addition hardware failures caused the temperature data to end early, on June 7, 1991 and the conductivity to end on April 25, 1990. All the tripod conductivity cells progressively fouled, resulting in salinities erroneously low by as much as one psu by the end of the 4-month deployments. Tripod light transmission was not truncated by biological fouling as were the shallower transmissometers, but the record ends on April 25, 1991.

USGS instruments at Race Point, Manomet Point, and U6b were deployed twice, September 1990 to January 1991 and February to June 1991. For the first deployment all the current meters produced good current and temperature data. The conductivity cell failed at Race Point, 55 m, and transmissometers failed both at this location and at 75 m at U6b. During the second deployment all the instruments produced good data, with the exception of the 5 m VMCM at Race Point that stopped on May 17 when its propellers became wrapped by a fishing line, the 75 m VACM at U6b was caught by a fishing boat, ending its data on April 28, and the tripod at U6b stopped recording data on April 9.

2.2.3 Moored Water Properties

There is a pronounced seasonal cycle to the variations in water properties in the Bays, with strong stratification occurring during the summer and well-mixed conditions occurring between November and April. Strong spatial and temporal variations were observed in temperature as well as salinity, both of which significantly influence the density structure of the Bays. Twenty-nine temperature time series and 20 salinity time series were obtained during the deployment. For the purpose of describing the variability, 4 near-surface instruments (Scituate 4-m, Boston Buoy 5-m, U6 4-m, U7 4-m) and 2 deep instruments (Boston Buoy 23-m and U6 45-m) were selected. These provide representative values of water properties in coastal and offshore portions of Massachusetts Bay and central Cape Cod Bay location. These time series were low-pass filtered (35-hours) to remove the fluctuations due to tidal and other high frequency effects.

Temperature Variations

Near-surface temperatures increased from 6° C to 20° between April and August, while deep water temperatures increased from 4° to only 6-8° over the same period (fig. 2.2-4). During this warming period, there were several pronounced drops in the near-surface temperatures at the Scituate and Boston Buoy locations (sc4 and bb5), the most pronounced drop occurring between July 17 and 31. These temperature drops were due to wind-forced upwelling (see Section 3.3). Generally the warmest water was in Cape Cod Bay during this period, while the coldest near-surface water was found in Broad Sound, due to upwelling.

Between August and November, surface waters cooled rapidly to 10°, while the deep temperatures continued to increase. The cooling occurred in a steplike fashion, with sudden drops occurring during cold air outbreaks, the strong northerly winds and cold air temperatures causing rapid heat loss of the surface waters (figs. 2.1-1, 2.1-2). Interestingly, the deep waters tended to increase in temperature during these surface cooling events, apparently due to enhanced vertical mixing.

Enough cooling had taken place by early November that the water column became vertically mixed , and from then on through the winter there was negligible vertical variation in temperature. The water continued to cool until January, and from then until the end of March it maintained a nearly uniform temperature of 3–4.5°. The inshore waters were about 1° colder than the waters of Stellwagen Basin.

Surface temperatures began to warm around the first of April, with warming continuing at a rapid rate through early June, when temperatures reached 16°. Bottom temperatures warmed slightly in April, then remained nearly constant once the stratification was well established. A major event in early June caused a drop in near-surface temperatures and a large increase in bottom temperature. This event appeared to be forced by moderate northeast winds and unseasonably cool air temperatures, that apparently lead to mixing of the nearshore waters.

Salinity Variations

Salinities were found in the range of 29–33 psu during the period (fig. 2.2-5). This range is typical of the coastal waters of the Gulf of Maine. Near-surface salinity showed large fluctuations throughout the period from April through August, due apparently to freshwater input from the rivers of the Gulf of Maine. Around May 5, May 20, and August 14, the salinity records at Scituate, Boston Buoy and U6 all showed sharp drops of 0.5 to 1 psu, indicating the intrusion of low-salinity surface water into Massachusetts Bay. (These run-off events are discussed in detail in Section 3.2). Smaller amplitude and localized fluctuations were observed throughout the period from April through August. The deep waters also showed significant fluctuations during the major run-off events, although the amplitude was diminished relative to the surface waters.

During the period from mid-August to early November, there was a marked increase in the salinity of the surface waters, reaching the salinity of the deep waters (32.2 psu) by early November. This period of increasing salinity corresponds to the period of surface cooling. The deep salinity at the Boston Buoy increased during this period, while the deep salinity at U6 fluctuated but showed no trend. Apparently the increase in salinity of the near-surface waters was the result of horizontal advection from offshore, rather than vertical mixing, since vertical mixing would have reduced the salinity of the deep waters while increasing the salinity of the surface waters. There were vertical mixing events during the period, but they cannot account for the overall trend of increasing salinity.

After well-mixed conditions were reached in early November, the salinity remained nearly uniform at around 32.2–32.5 psu for the entire winter, with minor, short-lived fluctuations in salinity at various locations. (The jump in salinity at the U6 45-m sensor was probably related to a calibration offset between two different sensors, rather than an actual jump in the deep salinity). Interestingly, there were major run-off events during this period (fig. 2.1-3), but they did not appear to influence the salinity of the Bays. Apparently the run-off from the Gulf of Maine did not enter the Bays during the well-mixed conditions of the wintertime (see Section 3.2).

Starting in March, 1991, again the salinity started to decrease, apparently as a result of the spring run-off from the Gulf of Maine. Again there were some pronounced run-off events, the most notable ones occurring around April 24, May 8 and May 13 (see Section 3.2).

Density Variations

Density variations in the Bays show the combined influence of temperature and salinity, with salinity effects being more important during the spring run-off period, and temperature effects being dominant in the summer, when the thermocline is most strongly developed. The density of the near-surface waters decreased until early August, with some fluctuations associated with run-off and upwelling events (fig 2.2-6). The density of the deep waters only decreased slightly during the period. Maximum stratification of 5–6 kg m^{-3} occurred in early August. From mid-August until early November the near-surface density increased rapidly, owing to both cooling and increased salinity. Well mixed conditions were observed from early November until mid-March. From March to June, the near-surface density decreased, due initially to decreased salinity and then to the combined effects of warming and freshening.

Water Properties Variation in Stellwagen Basin

The annual cycle in both the Stellwagen Basin temperature and vertical temperature variation is clearly revealed in the composite of the hourly measurements at station U6 (fig. 2.2-7). Internal tidal motions, generated on or near Stellwagen Bank, cause the pronounced, high frequency temperature and salinity fluctuations. The temporal displacement of isotherms (fig. 2.2-8) define the internal tide structure over a few day period in July 1990. This internal tidal motion — seen at a number locations in the Bays besides Stellwagen — is strongest during the periods of strong density stratification.

Despite the internal tides the envelopes are revealing in themselves. They show for example, the maximum temperatures are reached in mid-August 1990 at the surface (approx. 22°C) and in late October near the bottom (approx. 10°C). In early November 1990, the water column became well-mixed in temperature. The well-mixed water column cools from October 1990 through March 1991. The minimum water column temperatures in 1990 and 1991 were comparable at about 3°C. Warming and temperature restratification of the 1991 central Bays in Stellwagen Basin (station U6) began in early April and increased until the end of the observations in mid-June.

While the temporal characteristics of the salinities and vertical differences in salinity at station U6 in 1990 looked similar, combined Bays salinity observations show that the spring 1991 Bays were fresher than the 1990 Bays (fig. 2.2-7). This observation is qualitatively consistent with the relatively larger 1991 river discharges (fig. 2.1-3). During spring 1990 and 1991, both the surface and deep salinities generally decrease, with the minimum surface salinities (approx. 29.5 psu) and maximum salinity differences (approx. 2 psu) occurring in May. Another pulse of fresher surface water was seen at station U6 in mid-August 1990. Thereafter, the surface salinity generally increased until reaching a maximum in mid-December. The near-bottom salinity, which had decreased since April, reached its minimum values (32.25 psu) in September. The Stellwagen Basin (U6) water column became nearly well-mixed in early December 1990. Then the water column began to gradually restratify in salt, reaching a winter steady state top to bottom difference of about 0.25 psu, bracketing a salinity of about 32.4 psu. In late March, the water column salt restratification began to increase rapidly, accompanied by decreasing salinity (and increasing temperatures) throughout the water column. The 1991 salinities never reached the April 1990 levels. While the near-surface salinities reached a minimum in May, the deeper salinities continued to decrease until the end of the observations in June.

2.2.4 Moored Pressures

The Bays pressure program consists of bottom pressure observations and the coastal synthetic subsurface pressure (SSP = atmospheric + sea level pressures) from Boston and other coastal stations around the Gulf, pressure observations reflect a seasonally varying blend of tidal, wind, and buoyancy-forced motions in the Bays. The Bays pressures and currents (e.g., fig. 2.2-9) were dominated by the semidiurnal tides which are part of a Gulf of Maine scale response to deep ocean tidal forcing. The large tides in the Gulf of Maine result from the near-resonance of the system with the Atlantic Ocean tidal forcing at semidiurnal frequencies. The energy spectra of the pressure variability (fig. 2.2-10) also show this strong semidiurnal tidal response. The predicted tides were subtracted from each of the pressure records before smoothing with a lowpass filter. At subtidal fluctuation periods (longer than 2 days) there is also significant energy in the pressure and pressure difference fields as shown in a representative energy density spectra (fig. 2.2-10).

Tidal sea level in Massachusetts and Cape Cod Bays rises and falls in nearly in unison with that in the western Gulf of Maine. The tidal currents, associated with the Bays surface tide, interact with Stellwagen Bank bathymetry to produce internal tides. The tidal elevation results were derived from an array of bottom pressure and Boston coastal sea level measurements (fig. 2.2-1). These records clearly show that semidiurnal tidal energy dominate both sea level and current variability in the Bays. Three different tidal analysis techniques were used to analyze for the Bays pressure (and current) measurements for tides. One was the classic harmonic method, using a modified version of the Dennis and Long (1971) approach (Irish and Brown, 1986). A second was the response method devised by Munk and Cartwright (1966) The third was the least squares method of Foreman (1977). Each method was used on the pressure records from Stellwagen Bank for comparison. Table 2.2-3 shows that the results of the three tidal analyses for the four largest diurnal and semidiurnal lines are in good agreement except at the solar semidiurnal S_2 frequency. The response method separated the S_2 energy into that part forced by the astronomy and/or deep ocean tides and other causes like meteorology. The response analysis suggests the gravitational S_2 constituent should be larger, and uses a radiational component that is nearly 180° out of phase to reduce the total energy at the S_2 frequency to that observed. Thus the response method S_2 results help our understanding the response of the region to tidal forcing, but this constituent is still small compared to M_2.

A harmonic analysis of the observed pressure and sea level records from the Bays program was performed. Pressures were converted to elevation by multiplying by 100.45 cm/dbar. Most of the energy in the Bays pressure (sea level) fluctuation energy (92.1%) is at the principal lunar frequency, M_2. Only 2% of the energy is in the diurnal tidal band. Thus the ratio of the principal diurnal (K_1 + O_1) to the principal semidiurnal (M_2 + S_2) amplitudes is 0.17. According to Defant (1961) tides with this ratio are classified as semidiurnal tides — not surprisingly.

The results for the principal lunar tide (M_2) are presented in terms of the amplitude and Greenwich epoch distribution (fig. 2.2-11) Charts for the other semidiurnal constituents show similar patterns (see Table 2.2-4). The similarity in these results document a Bays-scale tidal sea level which rises and falls nearly uniformly throughout the Bays, with a slight amplification and phase lag in Boston harbor.

Table 2.2-3. A comparison of tidal constituent amplitudes (H) and Greenwich epoch (G) phases determined for the Stellwagen Bank bottom pressure by three different methods (see text).

Tide Line	Harmonic	Response	Least Squares
Darwin Symbol Freq.(cpd)	H(cm) G(degrees)	H(cm) G(degrees)	H(cm) G(degrees)
Q1 0.893244	2.10 359.8	2.07 171.2	2.0 164.0
O1 0.929536	10.82 186.7	10.71 185.3	10.9 186.0
P1 0.997262	4.57 175.2	4.62 203.3	4.2 201.7
K1 1.002738	13.80 203.5	13.73 204.0	13.5 204.4
N2 1.895982	27.15 72.5	26.80 77.0	28.0 74.1
M2 1.932274	122.75 108.3	122.70 108.2	122.8 108.4
S2 2.000000	18.94 141.9	30.50 145.6	18.9 142.3
K2 2.000000	5.15 144.7	6.40 148.9	5.2 142.0

The Bays Program subtidal pressure records (fig. 2.2-12) are highly correlated as expected. The greatest fluctuation amplitudes are during the fall/winter months when wind-forcing is strongest. Experience suggests that the visual correlation is significant and in many cases related to the response of the Gulf of Maine to along-Gulf (i.e., across-Bays) wind stress forcing. However, we know that buoyancy-driven flows could also leave a pressure signature. The great visual similarity of the pressure records is a reflection of the very large spatial scales characteristic of the pressure field variability. The pressures, particularly the coastal pressures are important proxies for the large-scale response of the Gulf and Bays. The measureable differences between pairs of pressure records are related to geostrophic flow between the stations and thus are also of that are of particular interest in describing the Bays-scale flow variability. These points are discussed in greater detail in section 3.

Table 2.2-4. Tidal harmonic constants for the Mass/Cape Cod Bays system.

Station	Deployment or Segment	Latitude Longitude	Record days	M_2 H(cm) G(deg)	N_2 H(cm) G(deg)	S_2 H(cm) G(deg)	K_1 H(cm) G(deg)	O_1 H(cm) G(deg)
Provincetown	1	41.9667	60	134.1	27.5	21.9	13.0	11.9
(U5)		70.6633		112.2	75.4	146.3	201.7	192.7
	2		243	133.5	30.0	20.3	13.8	11.4
				106.6	72.3	141.9	204.8	185.6
	3		186	132.4	30.5	21.4	14.5	11.4
				111.9	75.9	146.7	208.6	189.7
	YR1		365	133.3	29.9	21.0	13.8	11.4
				106.5	72.3	142.6	204.6	185.6
	YR2		365	131.9	30.4	20.3	13.6	11.1
				109.0	75.8	144.6	205.9	186.0
Stellwagen	1	42.3718	10	131.6	23.0	13.7	12.0	10.7
Bank (U3)		70.3483		108.1	81.9	148.3	217.0	163.1
	2		171	122.4	27.9	17.0	13.8	10.8
				108.5	76.0	138.4	203.6	185.1
	3		102	122.8	27.4	19.4	14.7	10.9
				107.6	71.3	141.9	204.1	190.9
	Sum		300	122.8	27.2	18.9	13.8	10.8
				108.3	72.5	141.9	203.5	186.7
Stellwagen	1	42.3552	123	122.1	27.9	19.8	13.3	10.4
Basin (U6)		70.4002		105.8	72.9	137.2	202.0	183.1
	2		67	123.1	27.2	19.7	14.9	11.6
				106.6	70.3	141.0	202.3	188.2
	Sum		207	122.2	27.9	21.9	13.4	10.7
				104.4	71.7	156.3	202.7	182.4
North		42.5223	138	122.8	28.6	18.6	13.2	11.3
Channel (U2)		70.4877		113.0	71.2	148.4	206.7	191.2
Gloucester	1	42.0617	47	129.0	27.6	21.6	13.5	12.0
(U1)		70.2433		107.0	66.8	139.5	200.9	191.8
	2		83	126.9	27.7	17.4	14.6	10.9
				108.2	74.2	150.4	210.0	183.5
	3		204	126.1	28.3	18.1	13.9	11.1
				106.4	72.0	147.4	205.6	185.1
	2&3		288	126.5	28.6	19.7	13.5	10.9
				106.8	72.8	142.6	204.8	183.7

Table 2.2-4 Continued.

Station	Deploy-ment or Segment	Latitude Longitude	Record days	M_2 H(cm) G(deg)	N_2 H(cm) G(deg)	S_2 H(cm) G(deg)	K_1 H(cm) G(deg)	O_1 H(cm) G(deg)
Boston Light	1	42.3767	50	129.6	28.6	18.9	13.8	11.5
Buoy		70.7817		108.4	85.5	144.6	207.1	188.2
	2		109	127.0	28.5	20.0	14.1	11.2
				105.6	72.1	140.1	207.8	184.1
Boston		42.35	365	135.4	30.3	20.8	14.0	11.1
		70.05		109.8	76.6	147.8	206.8	184.9

2.2.5 Moored Currents

The Bays Program current observations reflect a seasonally varying blend of tidal, wind, and buoyancy-forced motions in the Bays. A representative time series of near-surface currents at the Boston Buoy (fig. 2.2-13) shows the relative strengths of the tidal fluctuations and the low-frequency variations resulting from wind- and freshwater-forcing. The variations at high frequencies (≥1 cycle/day) are dominated by tidal fluctuations with semi-daily (or semidiurnal) periods. The separation of tidal currents can be removed from the current record by filtering the data with a "low-pass" filter (1.5 day cut-off period). Figure 2.2-13 indicates tidal velocities at the Boston Buoy are typically 10 cm s^{-1}, with occasional maxima near 20 cm s^{-1}. Low-frequency motions during this time period range from 5 to 15 cm s^{-1}. The large variations in tidal amplitude observed during this period are due in part to astronomical effects (e.g., the spring–neap cycle), but also to variations in the internal tide, whose amplitude depends on variations in stratification and other effects. A detailed discussion of the tides is found in Section 3.1. The remainder of this subsection describes the observed low-frequency motions.

<u>Mean Baywide Flow</u>

Timeseries of the velocities at all of the mooring locations are shown in figures 2.2-14, 2.2-15 and 2.2-16 in the form of stick vector plots. Figure 2.2-14 includes the moorings along the coast and in Cape Cod Bay, figure 2.2-15 includes the instruments along the open boundary, and figure 2.2-16 includes measurements at various depths at the Stellwagen Basin site. The gaps in the timeseries indicate periods when instruments were not deployed or when data were not usable.

A general characterization of the non-tidal flow in the Bays is obtained by a record-length average of the moored data, shown in figures 2.2-17, 2.2-18 and 2.2-19. The vectors at each location indicate the mean currents and the ellipses indicate one standard deviation of the fluctuations. These data are also summarized in Table 2.2-

5. Note that not all of the records include the same time periods (see fig. 2.2-3 for a timeline), so there are seasonal biases reflected in some of the means.

Table 2.2-5. Summary statistics of moored current meter data. Mooring locations correspond to figure 2.2-1. Instrument depths in meters are as noted. The averages correspond to the total record for each instrument, which represents different periods for the different instruments. All of the data are low-pass filtered to remove the tides. Speed is the absolute value of the velocity; velocity is the vector average with direction in compass coordinates; s.d. denotes standard deviation of the speed; variance ellipses are major and minor axes of variation, in units of cm/s, with orientation of the major axis noted. The percentage of the total deployment period (April 1990 - June 1991) represented by each record is indicated in the last column.

	Inst. depth	speed cm/s	velocity mag.	velocity dir.	s.d. cm/s	variance ellipse major	variance ellipse minor	variance ellipse dir.	fraction of total
bs	5	3.57	0.89	351.9	3.96	3.32	2.16	22.6	0.33
bs	18	2.66	1.23	167.2	2.85	2.34	1.63	99.1	0.65
bb	5	5.97	0.51	153.9	7.23	5.73	4.41	176.9	0.82
bb	23	3.46	0.49	115.6	4.34	3.88	1.94	139.9	0.71
bb	33	2.78	0.82	280.3	3.47	3.17	1.43	110.8	0.70
sc	5	8.62	3.03	135.2	9.58	8.68	4.04	160.6	0.71
sc	23	1.72	0.87	266.4	1.76	1.46	0.98	114.4	0.36
mn	5	7.73	3.69	113.9	8.61	7.78	3.70	156.0	0.60
mn	29	4.04	1.91	133.7	4.67	4.16	2.13	128.3	0.60
u7	4	8.43	4.14	88.6	9.02	6.93	5.77	169.5	0.61
u7	25	4.19	2.42	41.5	4.48	3.91	2.17	36.0	0.38
u2	4	13.94	10.13	165.9	12.72	10.71	6.86	6.3	0.40
u2	25	13.92	13.29	185.9	7.31	6.21	3.86	177.9	0.28
u2	60	6.19	4.41	175.4	5.80	4.62	3.51	166.4	0.58
u3	4	11.72	6.00	153.0	12.15	9.24	7.89	8.0	0.53
u3	25	4.48	1.90	187.4	5.11	4.39	2.62	15.2	0.66
u6	8	6.14	1.53	210.3	7.08	5.54	4.41	111.7	0.85
u6	28	6.36	2.72	245.1	6.81	5.72	3.70	112.0	0.85
u6	80	2.34	1.00	175.9	2.98	2.17	2.05	39.9	0.85
u6b	75	4.33	0.14	103.8	5.24	4.25	3.06	112.3	0.49
u6b	84	2.81	0.27	180.9	3.44	2.82	1.98	105.1	0.44
rp	5	12.07	8.18	77.8	11.07	9.89	4.96	49.9	0.53
rp	23	6.86	1.84	158.9	7.96	7.49	2.70	56.1	0.29
rp	55	7.28	3.07	160.7	7.87	7.27	3.02	56.3	0.61
rp	60	4.37	2.63	154.3	4.29	3.94	1.69	62.3	0.32

Near-surface Currents

Figure 2.2-17 shows southeastward flow along the open boundary of 6–10 cm s^{-1}, with some suggestion of inflow at U2. There is strong outflow (8 cm s^{-1}) at Race Point. A consistent pattern of counterclockwise flow is observed at the Scituate (SC), Manomet (MN) and Cape Cod Bay (U7) moorings, with speeds of 3–4 cm s^{-1}. The mean flow is weak in western Massachusetts Bay (BS and BB). Variability about the mean tends to be larger than the mean, with magnitudes of fluctuations of 7–12 cm s^{-1}, except in Broad Sound (BS) where magnitudes of fluctuations are only 4 cm s^{-1}.

Intermediate-depth Currents

Intermediate-depth currents (fig. 2.2-18) are weaker, both in terms of means and standard deviations, and they show a less consistent pattern of throughflow than the surface currents. Currents are much weaker at Broad Sound and Scituate than elsewhere because these instruments were located in the bottom boundary layer, while at the deeper stations the data reflect mid-depth conditions. The intermediate-depth currents at U2, Manomet and Cape Cod Bay indicate a similar pattern of circulation as the near-surface flow, but the Race Point data do not show persistent outflow.

Near-bottom Currents

Near-bottom currents (fig. 2.2-19) are weaker still, and they show little evidence of a baywide circulation. There is some evidence from the seasonal variations in water properties that there is little horizontal exchange of deep water (>40-m depth) except during a brief period of deep inflow during the fall (see Section 3.4).

Seasonal Description of the Currents

Because of the marked seasonal variation of the hydrographic structure of the Bays as well as variability of the forcing variables, one would expect to find marked seasonal variations in the circulation of the Bays as well. Interestingly, the seasonal variability of the currents was not particularly striking; only during the fall did the seasonally averaged circulation differ markedly from the 14-month average flow described above.

The 14-month deployment period was divided into five segments in order to provide more stationary statistics and better elucidate the nature of the response to the forcing. The time periods of these divisions were based largely on variations in stratification.

Spring 1990	March 1 - June 1	salt stratification
Summer 1990	June 1 - September 1	thermal stratification
Fall 1990	September 1 - November 1	decreasing stratification
Winter 1990 - 1991	November 1 - March 1	well-mixed
Spring 1991	March 1 - June 20	salt stratification

The breakdown is also appropriate for wind and buoyancy forcing. Wind stress tends to be weaker during the late spring–summer period, with dominance of southwesterlies, while during the fall and winter the winds increase in strength, with dominance of northwesterlies. Runoff typically peaks in the spring, but 1990 was an anomalous year, with a large peak in river discharge in the fall (fig. 2.1-3).

April – May, 1990

The only location with a significant mean flow was U2, which showed a strong southward flow (16.6 cm s^{-1}; see Table 2.2-6a and fig. 2.2-20). The other locations indicated weak and variable mean currents. Current fluctuations tended to be more energetic in the near-surface waters, with standard deviations of 6–9 cm s^{-1} compared to values of 1.5–5 cm s^{-1} for the deep waters. The weakest currents were found in the deep water near the coast.

Table 2.2-6a. Summary statistics for moored data: Spring 1990

		speed	velocity		s.d.	variance ellipse			fraction
		cm/s	mag.	dir.	cm/s	major	minor	dir.	of total
bs	18	2.63	0.94	103.1	3.15	2.60	1.78	92.1	0.99
bb	5	8.04	3.15	277.6	9.09	7.44	5.22	156.6	1.00
bb	23	4.50	0.35	206.3	5.53	5.27	1.69	140.0	1.00
bb	33	3.80	0.71	302.0	4.66	4.53	1.09	113.4	0.55
sc	23	1.65	0.78	300.9	1.72	1.44	0.93	112.4	0.99
u7	4	7.84	3.16	47.2	8.51	7.12	4.66	134.9	0.97
u7	25	4.97	2.78	41.2	4.74	4.13	2.32	10.9	0.88
u2	25	17.05	16.58	178.9	8.53	7.69	3.70	8.8	0.95
u6	8	6.07	2.94	188.2	6.71	5.60	3.70	55.7	0.93
u6	28	6.09	4.02	221.5	5.94	4.99	3.22	98.1	0.93
u6	80	2.38	1.58	181.5	2.46	1.97	1.48	21.9	0.93

Timeseries data (figs. 2.2-21 and 2.2-22) show persistent southward flow at U2, with two periods of stronger flow that were apparently related to freshwater inflow. The currents elsewhere in the Bays show considerable variability, due to the combined influence of winds and freshwater inflow. The lack of correlation between the various records is apparently due to the complexity of the interaction between the wind-driven and density-driven flows.

June – August, 1990

A more coherent pattern of mean flow was evident in the summer of 1990, again with strong southward flow at U2 (12 cm s^{-1}; Table 2.2-6b and fig. 2.2-23), but now with counterclockwise throughflow evident at the Scituate and Cape Cod Bay near-surface instruments. The waters at the Boston Buoy apparently did not participate in this mean counterclockwise flow, based on the negligible mean currents at that location. Again the fluctuations in the deep waters tended to be much weaker than the near-surface motions, particularly in the coastal locations. Although the coherences were low between the different instruments, one event occurred during the period August 1–5 (fig. 2.2-24) which was manifested in the near-surface currents at Boston Buoy (BB5), Scituate (SC5) and Cape Cod Bay (U7-4). This event coincided with a 0.5 psu drop of salinity at BB and SC, hence it appears to be a run-off pulse. The winds were from the north during the period, reinforcing the southward motion. (See Section 2.5 for shipboard measurements obtained during this period, and Section 3.2 for a more in-depth discussion of the freshwater-driven flow).

Table 2.2-6b. Summary statistics for moored data: Summer 1990

		speed	velocity		s.d.	variance ellipse			fraction
		cm/s	mag.	dir.	cm/s	major	minor	dir.	of total
bs	18	2.36	1.61	127.0	2.23	1.83	1.29	100.3	0.97
bb	5	6.37	0.43	16.9	7.61	6.48	3.99	1.5	0.82
bb	23	2.44	0.41	85.9	3.04	2.59	1.60	146.5	0.96
bb	33	1.69	0.80	303.3	1.84	1.69	0.72	115.7	0.51
sc	5	10.74	8.29	173.2	9.27	8.33	4.07	135.7	0.41
sc	23	1.94	1.53	275.9	1.60	1.29	0.94	119.0	0.66
u7	4	11.38	6.91	64.7	10.44	7.69	7.06	168.5	0.93
u2	4	20.61	17.81	171.0	13.74	11.88	6.91	27.5	0.38
u2	25	12.55	11.94	190.2	6.01	4.79	3.63	176.3	0.88
u2	60	4.62	4.15	183.0	2.77	2.16	1.74	36.9	0.38
u3	4	8.20	2.37	188.8	9.18	7.30	5.57	87.0	0.38
u3	25	4.45	3.98	172.8	3.17	2.70	1.66	5.9	0.46
u6	8	4.89	1.84	251.5	5.18	3.82	3.50	177.4	1.00
u6	28	5.45	4.43	269.6	4.13	3.32	2.45	113.2	1.00
u6	80	1.45	0.52	192.9	1.65	1.35	0.95	6.6	1.00

September – October, 1990

The addition of USGS moorings at Manomet and Race Point provided better resolution of the currents from this period until the end of the deployment. Significant mean currents were observed throughout the Bays (Table 2.2-6c, fig. 2.2-26), but the circulation pattern differed markedly from the counterclockwise throughflow of the other seasons. There was strong southeasterly flow at U2 and U3, roughly parallel to the mouth of the bay, as opposed to earlier periods, when it was directed slightly inward. The most pronounced difference from the typical circulation regime was a northward flow along the coast at the Scituate and Manomet moorings. The flow at U7, only 10-km from the Manomet mooring, was oriented almost 180° to the coastal flow. The flow at Race Point was directed into the Bays, in contrast to other periods.

Table 2.2-6c. Summary statistics for moored data: Fall 1990

		speed	velocity		s.d.	variance ellipse			fraction
		cm/s	mag.	dir.	cm/s	major	minor	dir.	of total
bs	18	3.18	2.54	155.2	2.64	2.32	1.25	122.8	0.95
bb	5	8.21	6.87	179.7	8.04	7.85	1.73	11.9	0.12
bb	23	3.63	1.24	69.3	4.16	3.73	1.85	123.6	0.83
bb	33	4.90	2.40	150.5	5.63	4.96	2.66	101.8	0.10
sc	5	10.52	5.47	357.3	10.61	9.47	4.78	172.0	0.95
mn	5	10.41	7.53	8.8	8.73	7.11	5.07	158.2	0.79
mn	29	3.48	0.29	39.4	4.77	3.89	2.75	131.6	0.79
u7	4	9.59	6.55	138.0	8.52	6.83	5.09	172.2	1.00
u2	4	13.91	8.10	154.7	13.54	11.22	7.58	8.3	1.00
u2	60	4.86	2.74	204.3	4.73	3.70	2.95	88.2	1.00
u3	4	12.22	7.94	146.7	11.32	9.25	6.52	20.0	0.98
u3	25	6.09	5.58	195.9	4.77	4.29	2.08	29.4	1.00
u6	8	4.84	1.83	136.5	5.17	4.45	2.63	155.3	0.93
u6	28	5.66	2.45	251.9	6.07	5.40	2.77	128.8	0.93
u6	80	2.43	0.99	138.8	2.84	2.17	1.84	10.9	0.93
u6b	75	3.97	2.33	121.0	4.29	4.10	1.24	125.5	0.77
u6b	84	2.26	0.93	119.9	2.58	2.39	0.98	116.7	0.77
rp	5	11.12	5.47	166.6	11.10	9.67	5.43	50.3	0.79
rp	23	8.52	4.25	204.4	8.52	7.89	3.21	53.1	0.79
rp	55	8.54	3.15	162.8	9.78	9.55	2.12	53.9	0.79

Timeseries data from the fall period (figs. 2.2-27 and 2.2-28) show coherent variations between the Scituate and Manomet records of the coastal flow, but they do not show coherence with any of the other moored records. The flow at U2 was more variable than during the other seasons; the fall was the only season in which there were sustained northerly currents at that location. Likewise the Race Point record was anomalous in the persistence of inflow events observed during the period.

The anomalous currents during the fall period appear to be related to changes in the density structure of the Bays, which may result from seasonal cooling, upwelling, and variations in freshwater input. Some or all of these factors lead to higher density waters occurring along the coast, which drove a northward geostrophic flow in the coastal region.

November, 1990 – February, 1991

The wintertime period showed a stronger mean wind-stress than the other periods, and this mean wind stress appeared to influence the mean near-surface currents, with a relatively uniform southeastward tendency exhibited by the near-surface flow (fig. 2.2-29). There was again strong southeastward flow at U2, and strong outflow at Race Point. The near-surface currents at Scituate and the Boston Buoy were highly correlated with the winds, (r=0.7 and 0.6, respectively). The mean flow is likely to result largely from the influence of the mean wind-stress, which had a significant component from the northwest during the period. Northwesterly winds were found to drive a strong along-bay flow, based on covariance analysis (see Section 3.3).

Currents were found to have shorter correlation time scales during the winter than the other seasons, apparently due to the dominance of the wind forcing, which had a correlation timescale of only 0.8 days during the winter period. The lack of significant salinity fluctuations during the winter period (cf. Section 2.2.4) indicates the absence of freshwater-driven motions, which would be expected to have longer correlation time scales.

Timeseries data during the period (figs. 2.2-30 and 31) show the influence of the wind-driven fluctuations at the coastal locations. The records at U2 and U6 show longer-period fluctuations that are not correlated with the winds, but which presumably result from variations in the flow of the Gulf of Maine.

March – June, 1991

The mean currents during the spring of 1991 (fig. 2.2-32) were similar to those during the summer of 1990. Unlike the summer of 1990, the instruments at Race Point allows the strong outflow at that location to be observed during this period. Significant downcoast flow was observed at Scituate and Manomet, but the flow was weak at the Boston Buoy and Broad Sound, as in the summer of 1990. Several run-off events were observed in the time series data (fig. 2.2-33 and 2.2-34), although the strong wind forcing during the early part of the record makes it difficult to distinguish run-off and wind events (see Section 3.2 and 3.3).

Table 2.2-6d. Summary statistics for moored data: Winter 1990 - 1991

		speed	velocity		s.d.	variance ellipse			fraction
		cm/s	mag.	dir.	cm/s	major	minor	dir.	of total
bs	5	3.46	1.48	65.8	3.62	2.87	2.20	18.8	0.24
bs	18	2.61	1.92	234.3	2.25	1.72	1.45	63.2	0.73
bb	5	4.20	1.18	104.4	4.65	3.92	2.50	12.3	0.98
bb	23	3.21	1.29	320.0	3.57	3.18	1.63	174.7	0.12
bb	33	2.34	1.10	293.7	2.52	2.15	1.32	140.0	0.96
sc	5	7.65	4.59	129.1	7.45	6.98	2.60	158.9	0.98
mn	5	5.00	3.37	132.8	5.16	4.85	1.77	150.7	0.78
mn	29	3.54	1.28	148.6	4.29	3.89	1.80	129.8	0.78
u7	4	4.29	2.39	92.8	4.28	3.38	2.62	129.0	0.61
u7	25	3.16	0.78	42.9	3.56	3.18	1.59	35.0	0.17
u2	4	10.80	8.36	169.6	9.67	8.19	5.14	167.0	0.61
u2	60	5.25	2.10	190.0	6.02	5.21	3.01	2.8	0.35
u3	4	11.55	8.12	119.1	9.67	8.29	4.97	155.1	0.17
u3	25	3.88	0.83	32.7	4.66	3.76	2.75	174.5	0.84
u6	8	7.03	4.08	128.9	6.99	5.16	4.72	131.0	0.54
u6	28	7.83	4.53	134.8	7.72	5.85	5.03	116.9	0.54
u6	80	3.37	1.35	149.5	3.89	2.94	2.54	119.0	0.54
u6b	75	4.99	1.68	278.2	5.80	4.37	3.82	101.5	0.83
u6b	84	3.20	0.87	256.5	3.86	3.04	2.39	100.7	0.84
rp	5	11.40	9.26	76.6	8.78	7.31	4.86	63.5	0.84
rp	23	5.78	2.26	97.7	6.80	6.43	2.20	61.1	0.62
rp	55	7.20	3.46	199.6	7.60	6.80	3.39	58.4	0.83
rp	60	4.70	3.27	180.4	4.22	3.93	1.55	56.1	0.22

Table 2.2-6e. Summary statistics for moored data: Spring 1991

		speed	velocity		s.d.	variance ellipse			fraction
		cm/s	mag.	dir.	cm/s	major	minor	dir.	of total
bs	5	3.50	1.01	341.8	3.88	3.34	1.97	19.6	1.00
bb	5	6.45	1.42	143.7	7.31	5.91	4.31	2.7	1.00
bb	23	3.75	0.87	159.1	4.72	4.28	1.99	142.5	1.00
bb	33	3.45	0.95	253.8	4.35	4.16	1.29	104.4	1.00
sc	5	7.70	4.31	147.4	7.97	7.18	3.47	152.1	0.93
sc	23	1.56	0.79	188.5	1.53	1.27	0.85	79.3	0.38
mn	5	8.32	6.47	131.8	7.21	6.20	3.68	140.8	1.00
mn	29	4.75	3.52	129.2	4.50	4.05	1.96	123.9	1.00
u7	25	4.14	2.53	42.4	4.42	3.97	1.95	42.8	1.00
u2	60	8.16	7.09	164.6	6.07	4.88	3.60	1.4	1.00
u3	4	12.04	5.18	150.6	12.95	9.70	8.58	172.9	1.00
u3	25	3.94	1.44	202.4	4.44	3.56	2.65	27.2	0.78
u6	8	7.55	3.55	263.5	8.20	6.80	4.57	109.7	1.00
u6	28	6.74	4.01	261.3	6.71	5.39	3.99	100.1	1.00
u6	80	2.52	1.37	198.1	3.39	2.57	2.22	50.0	1.00
u6b	75	3.45	1.78	75.3	3.40	2.72	2.04	124.1	0.62
u6b	84	2.44	1.24	100.9	2.46	1.94	1.50	119.3	0.42
rp	5	13.54	12.31	62.6	9.79	8.81	4.27	52.1	0.83
rp	55	6.58	3.94	124.9	6.22	5.61	2.69	53.3	1.00
rp	60	4.55	2.70	146.8	4.48	4.11	1.79	64.9	1.00

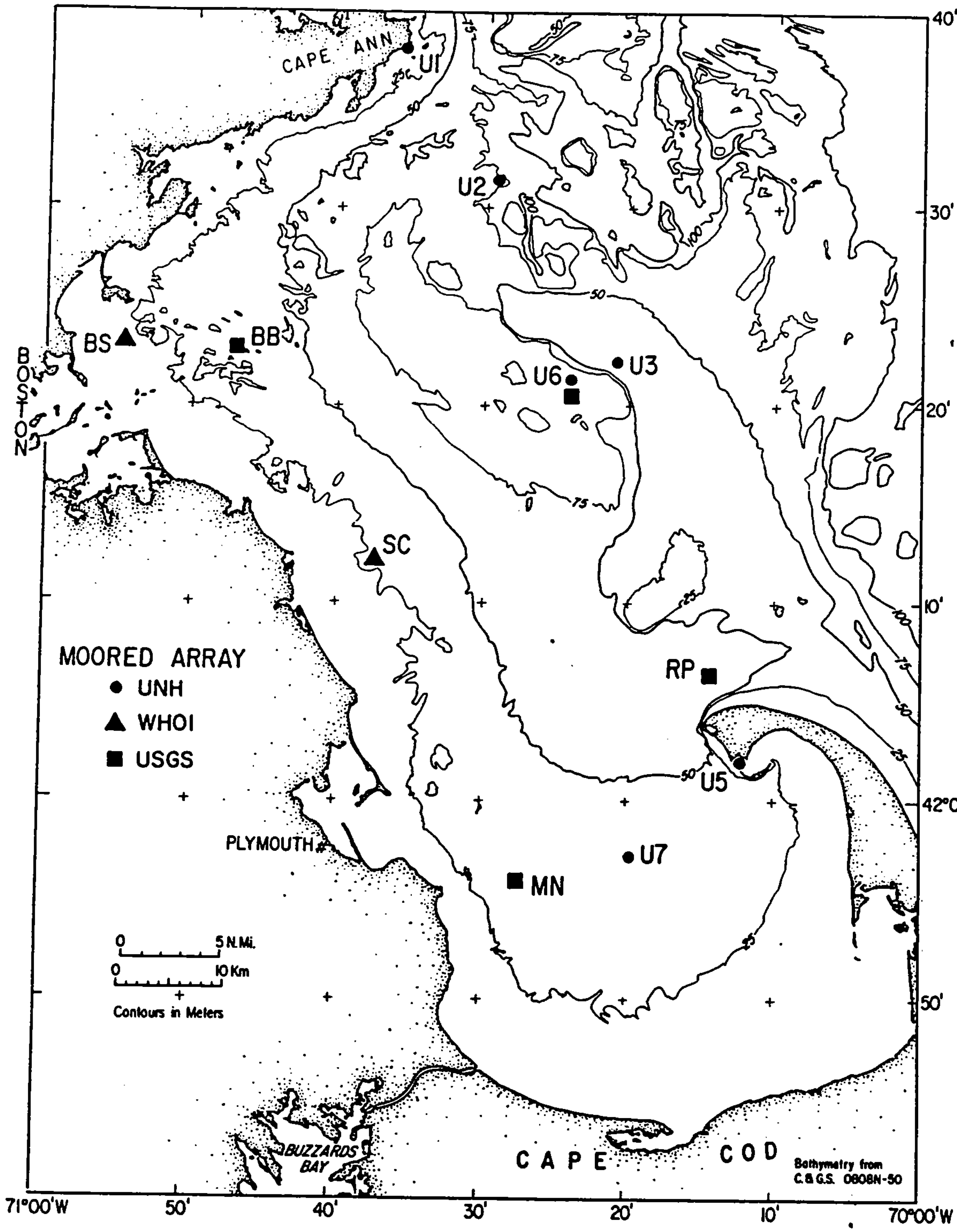


Figure 2.2-1 Massachusetts Bays Program/USGS moored array.

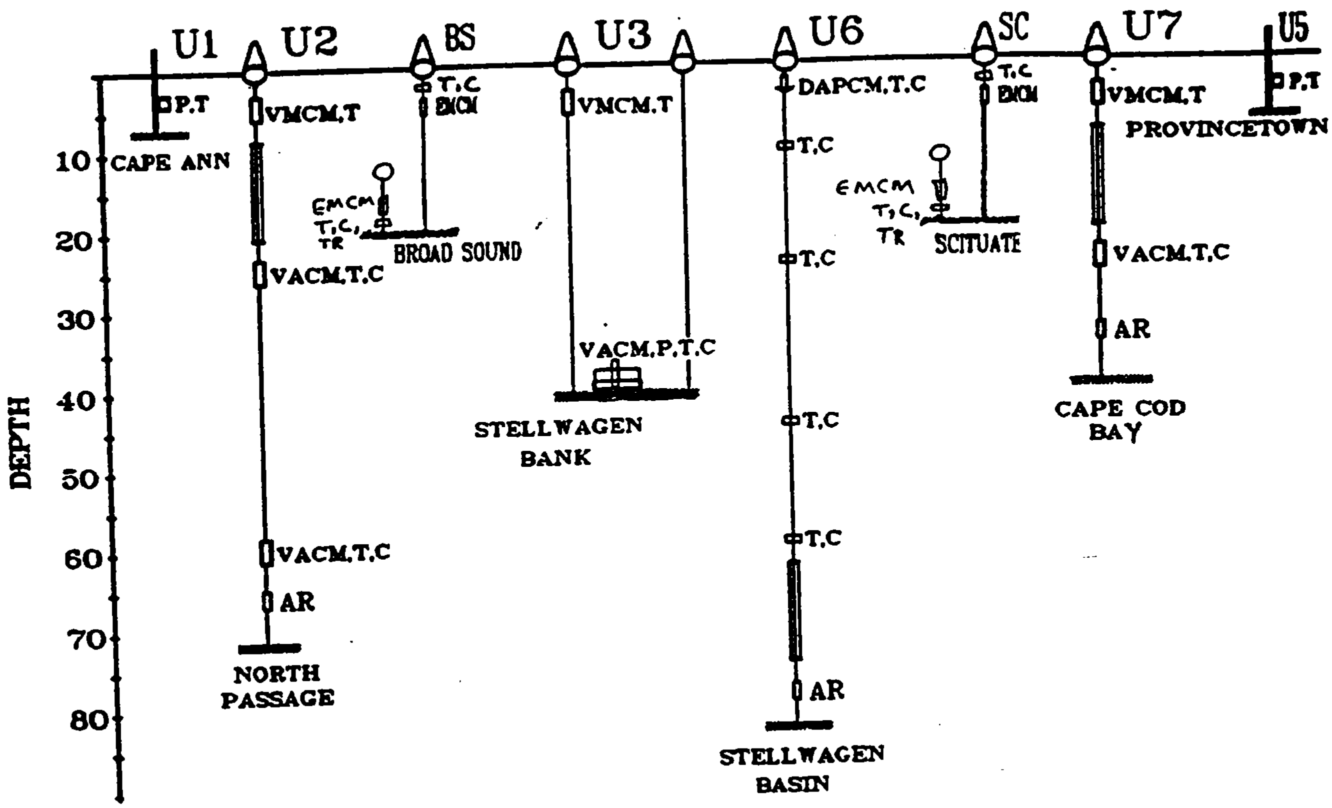


Figure 2.2-2a Massachusetts Bays Program moored array configuration. Legend: pressure/temperature (P,T); Vector Measuring Current Meter (VMCM); Vector Averaging Current Meter (VACM); Electromagnetic Current Meter (EMCM); Doppler Acoustic Profiling Current Meter (DAPCM); Temperature/Conductivity (T,C); Acoustic Release (AR); Light Transmission (LT); Savonius Rotor Current Meter (CM).

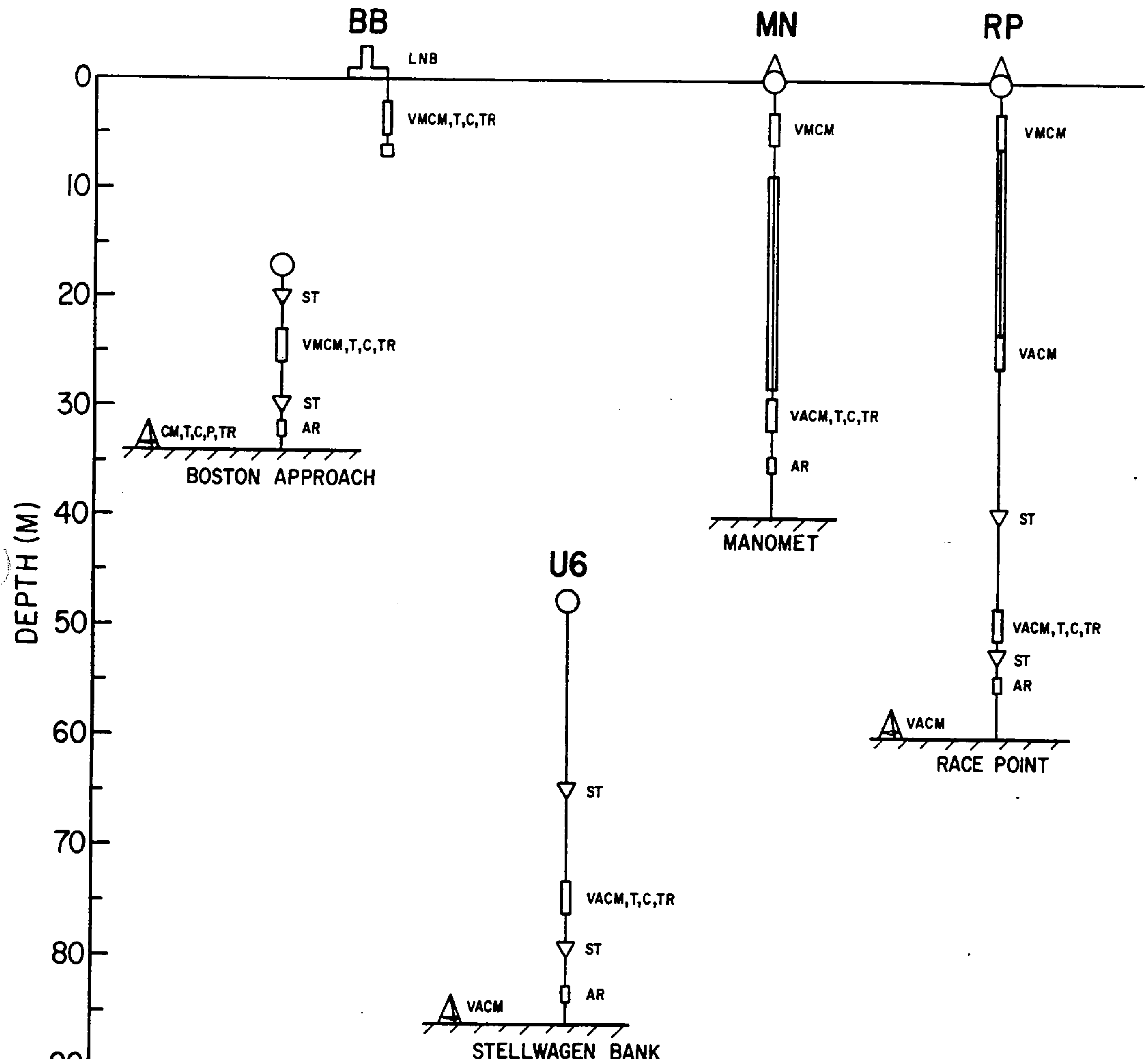


Figure 2.2-2b USGS moored array configuration.

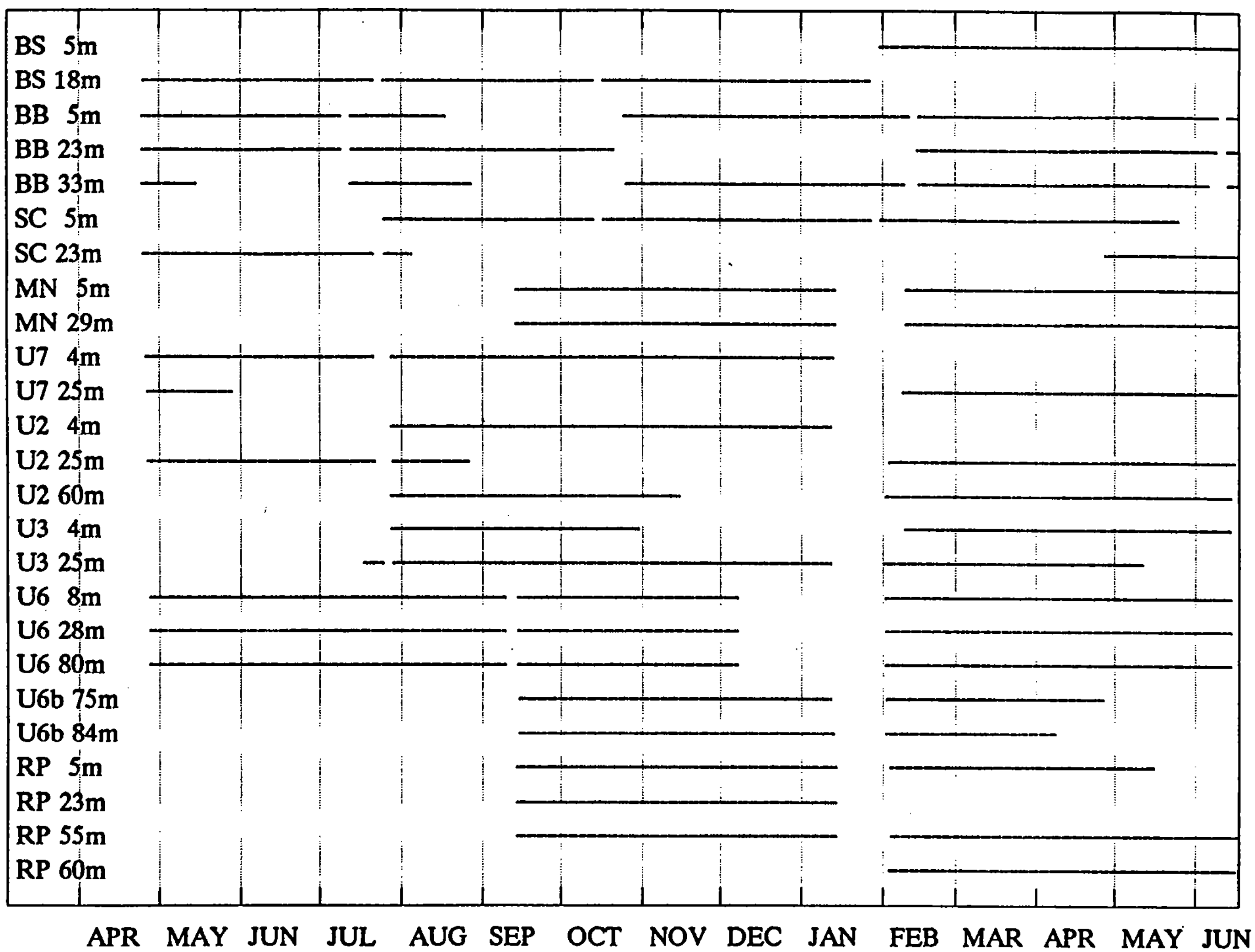


Figure 2.2-3 Time-line of moored current meter data, showing periods of good velocity data at each of the mooring locations. Note that most of the USGS moorings were first deployed in September, 1990. Measurements at the Boston Buoy were started in the fall of 1989. Gaps in the data in some cases are related to servicing the instruments; in other cases they result from instrument malfunction.

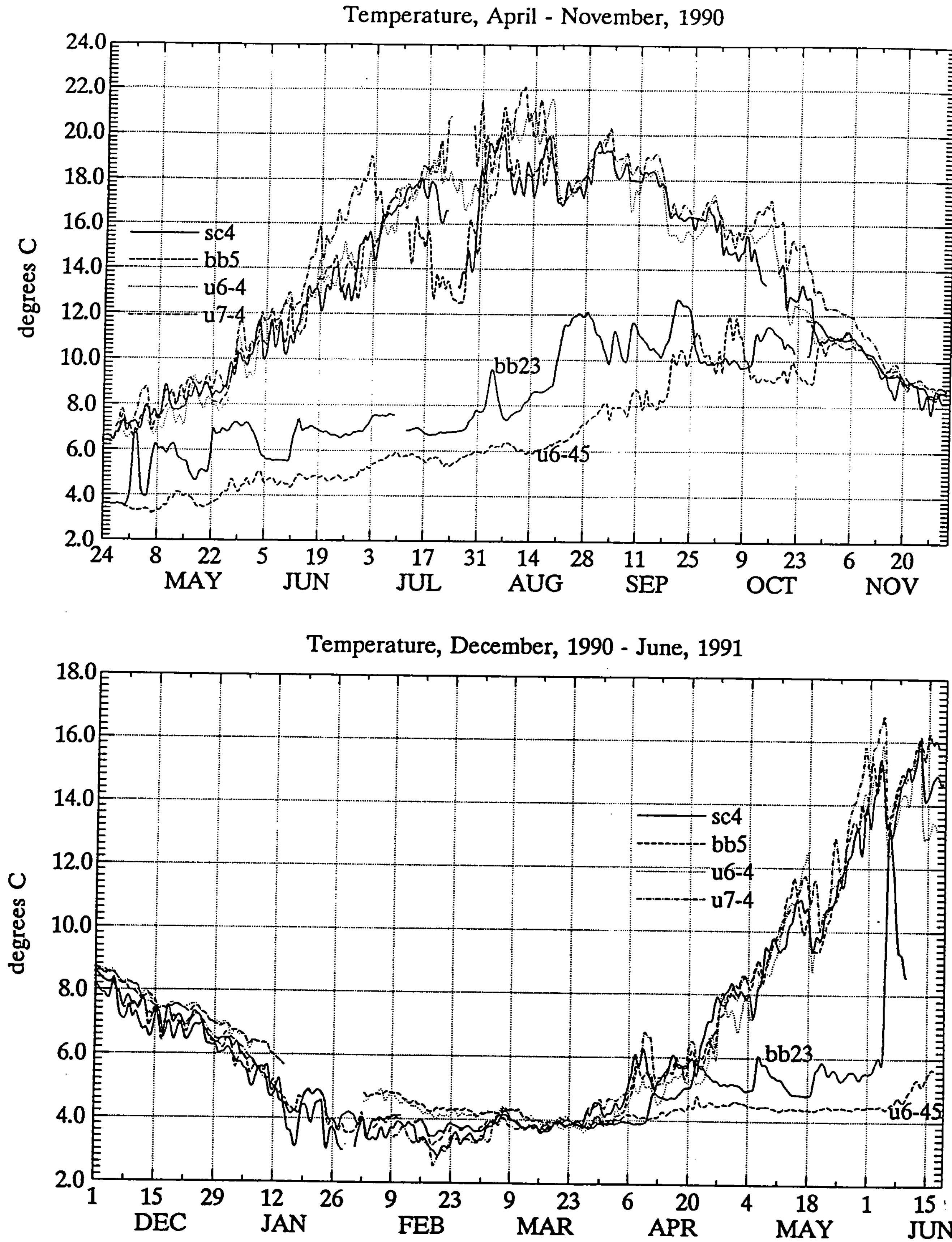


Figure 2.2-4 Timeseries of temperature at various locations in Massachusetts and Cape Cod Bays. The stations (sc, bb, u6 and u7) are as indicated in fig. 2.2-1. The numbers following the station designation indicate depths of the instruments in meters. The near-surface instruments show a strong seasonal signal, while there is relatively modest seasonal variation in the deep instruments. Upwelling causes large variations in the near-surface temperatures at timescales of weeks.

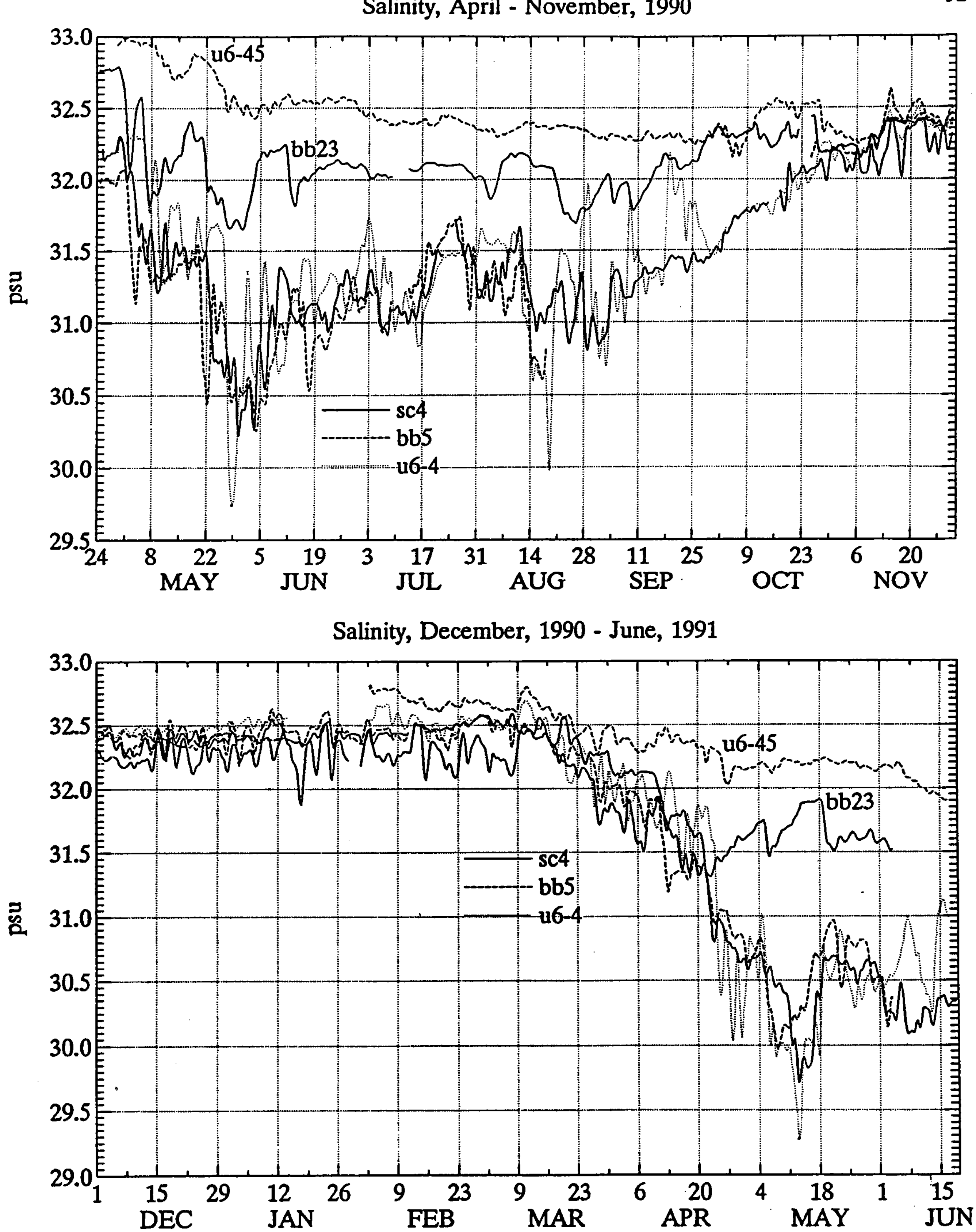
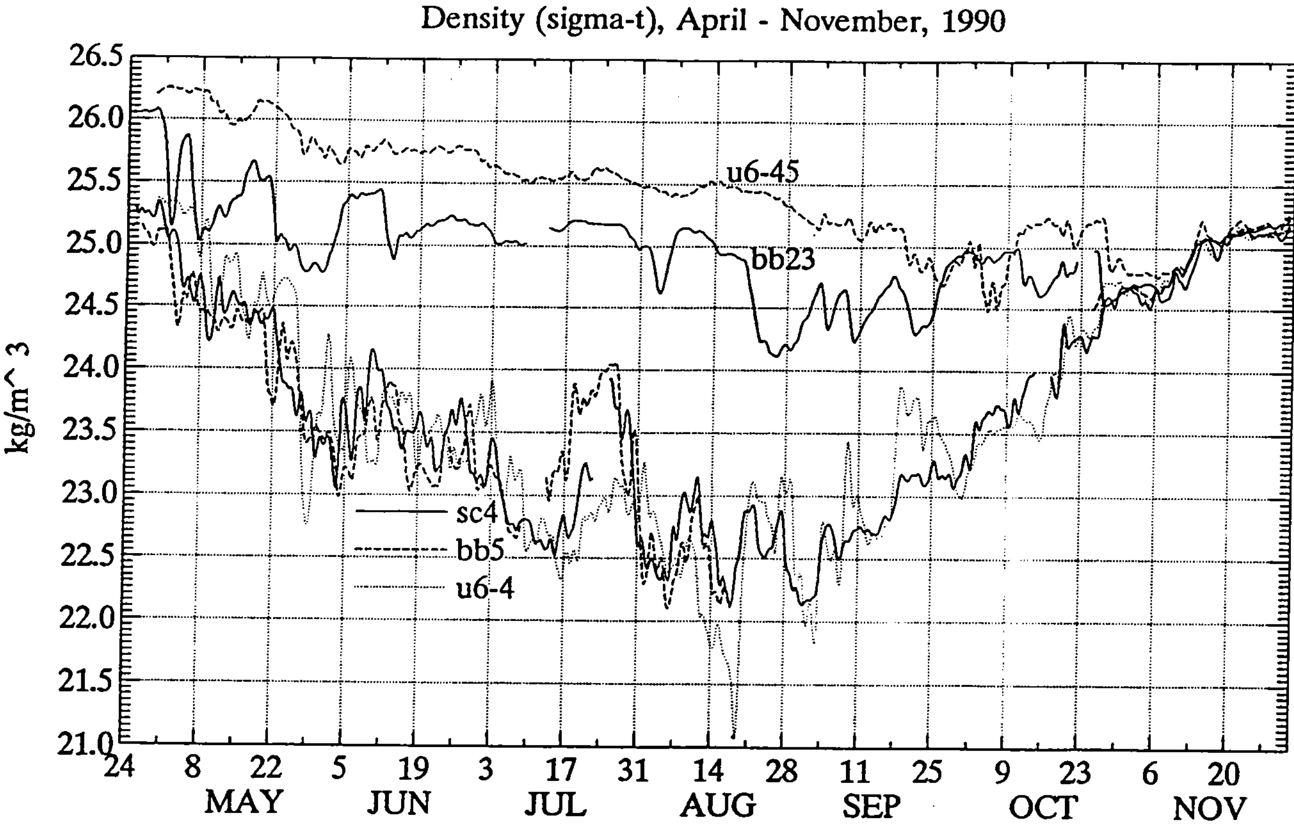


Figure 2.2-5 Timeseries of salinity at various locations in Massachusetts Bay during the deployment period. The salinity of the near-surface waters drops during the spring in a stepwise fashion, due to freshwater inflow. During the winter the salinity is nearly uniform throughout Massachusetts Bay.



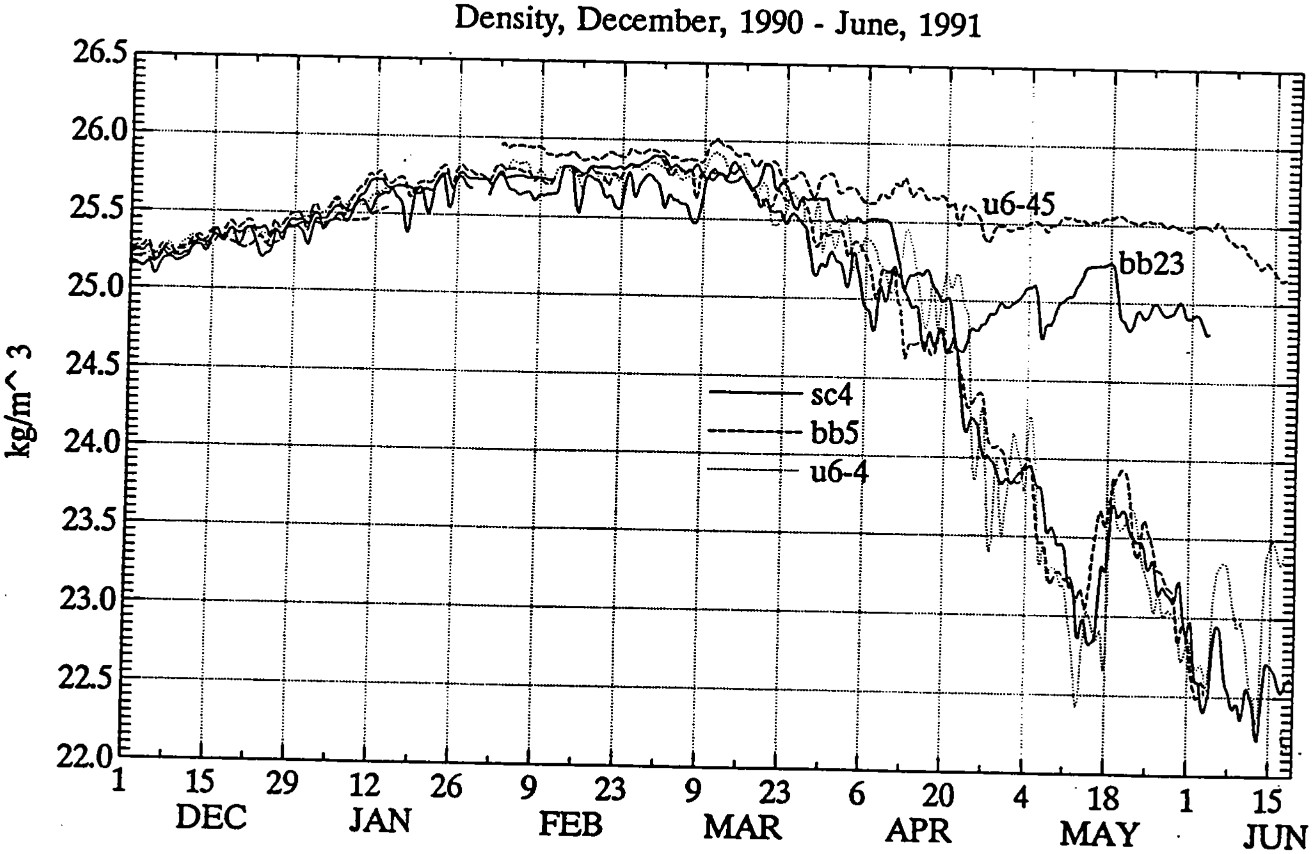


Figure 2.2-6 Timeseries of density in Massachusetts Bay. The density depends both on temperature and salinity, with relatively more influence of salinity in the spring, and more influence of temperature in the summer and fall. The stratification is indicated by the separation between the near-surface and near-bottom density records.

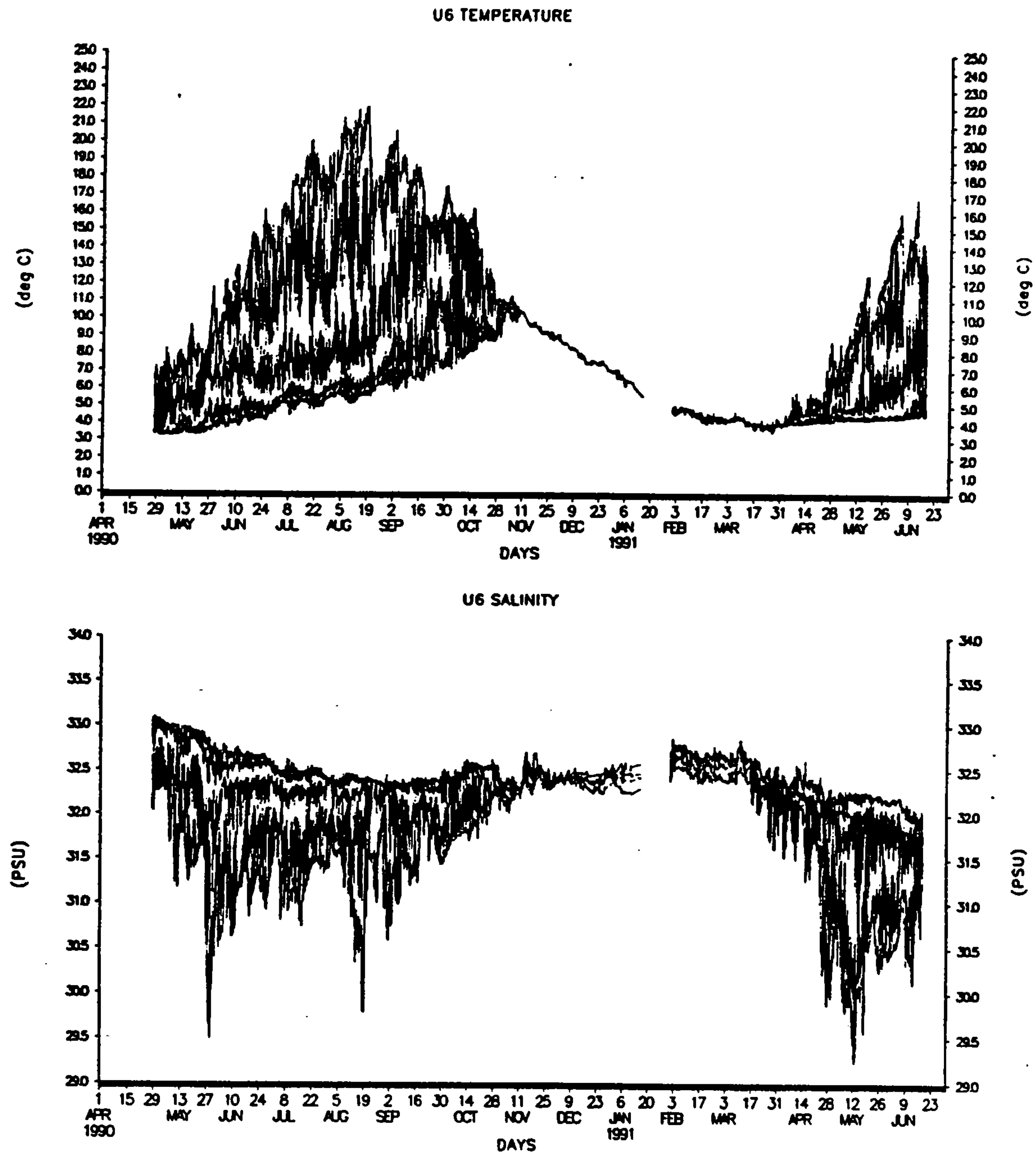


Figure 2.2-7 Composite presentation of the station U6 hourly temperature (above) and salinity (below) time series. The envelope of records is an indication of the stratification strength over the 4 m to 60 m portion of the water column.

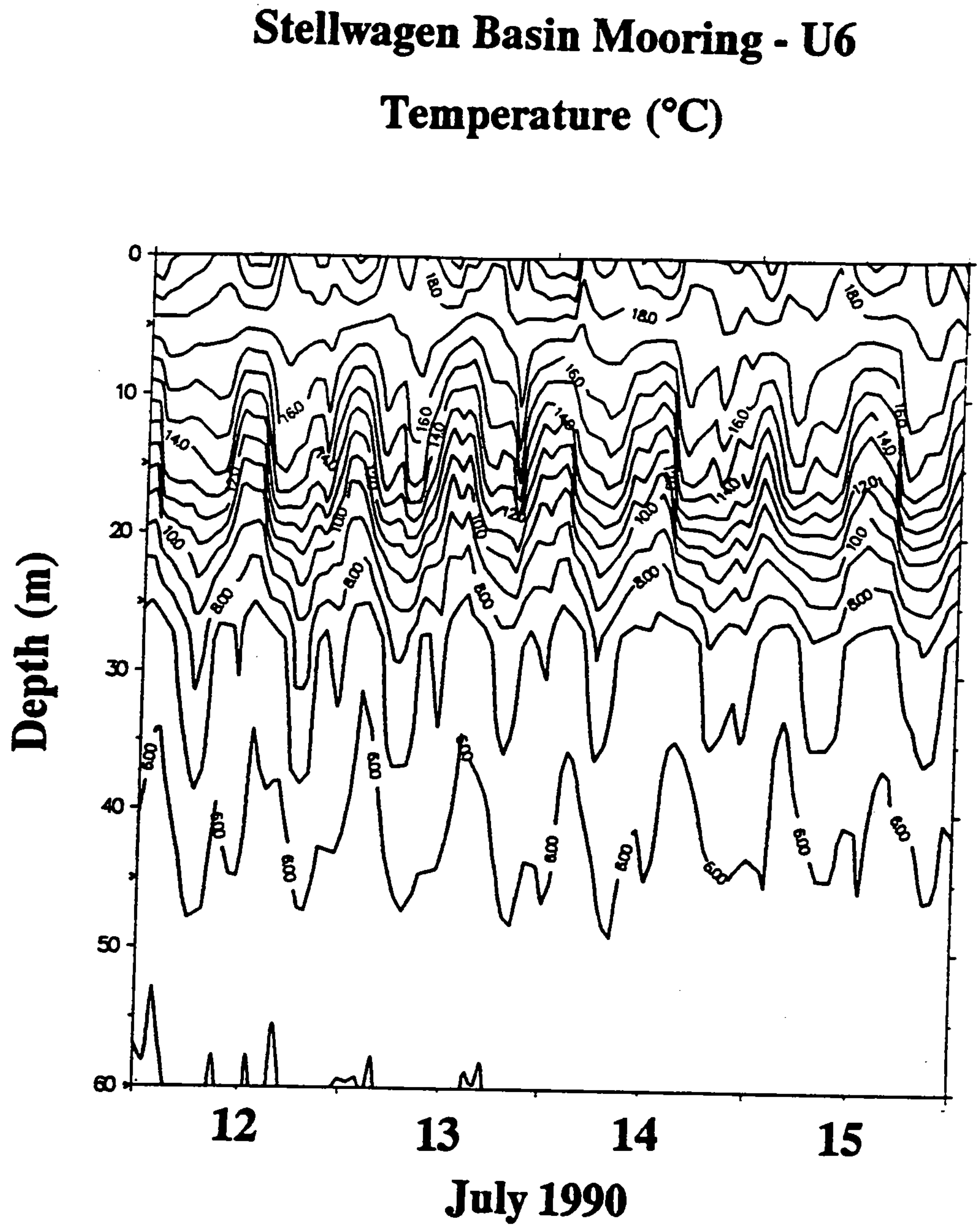


Figure 2.2-8 Contour plot of isotherms at the U-6 mooring for a 4-day period in July, 1990, showing the presence of large internal tidal oscillations.

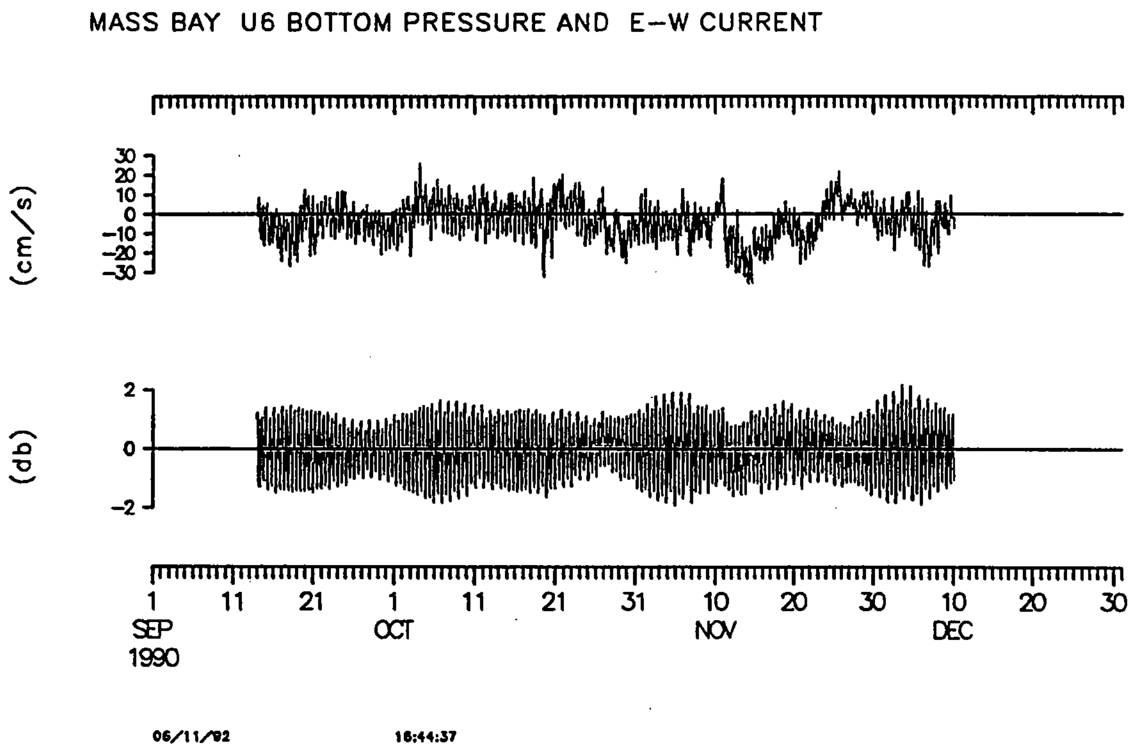


Figure 2.2-9 The comparison of an hourly bottom pressure record showing the tidal sealevel response and a 14m eastward current record at Stellwagen Basin site U6.

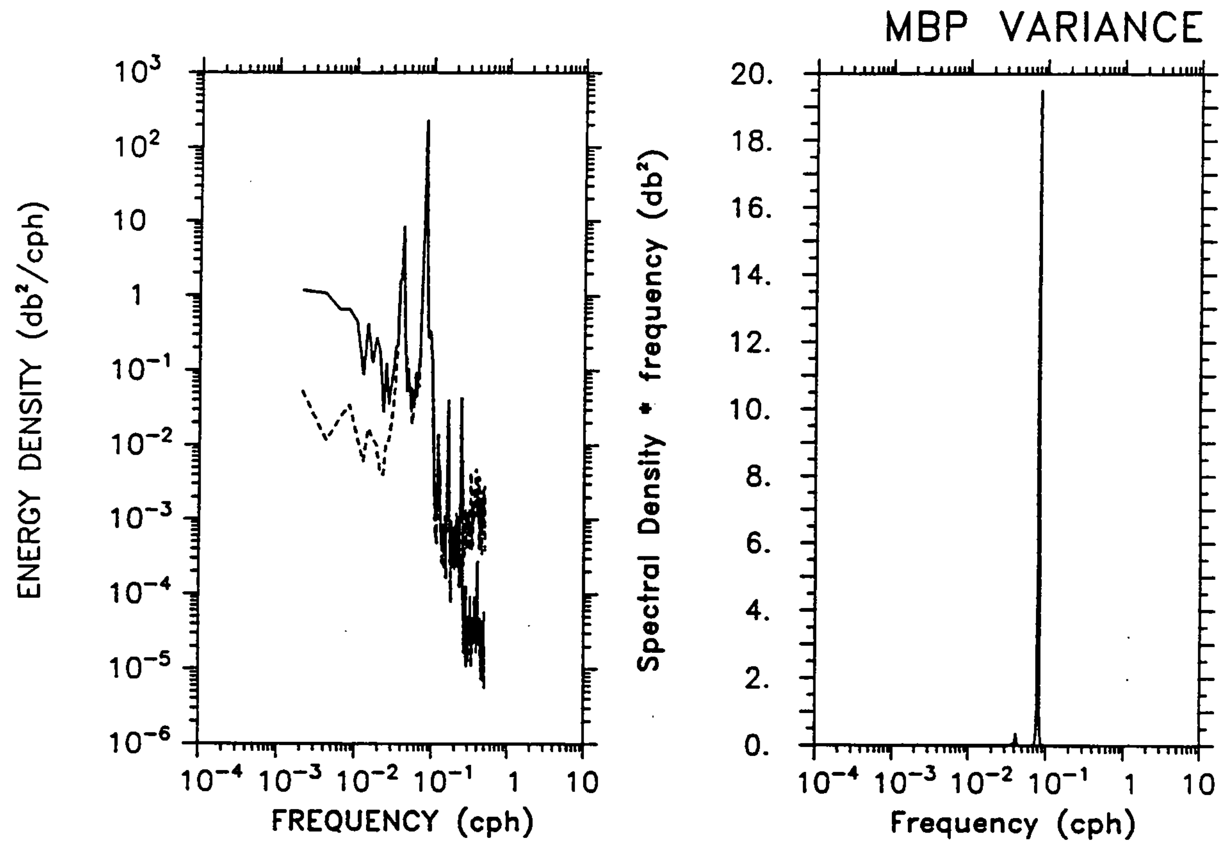


Figure 2.2-10 An energy density spectrum of the pressure (solid) and pressure difference (dashed) records respectively (left). The spectral energy presentation on the right, in which the energy is proportional to the area under the curve, clearly shows the dominance of the semidaily tidal pressure variability.

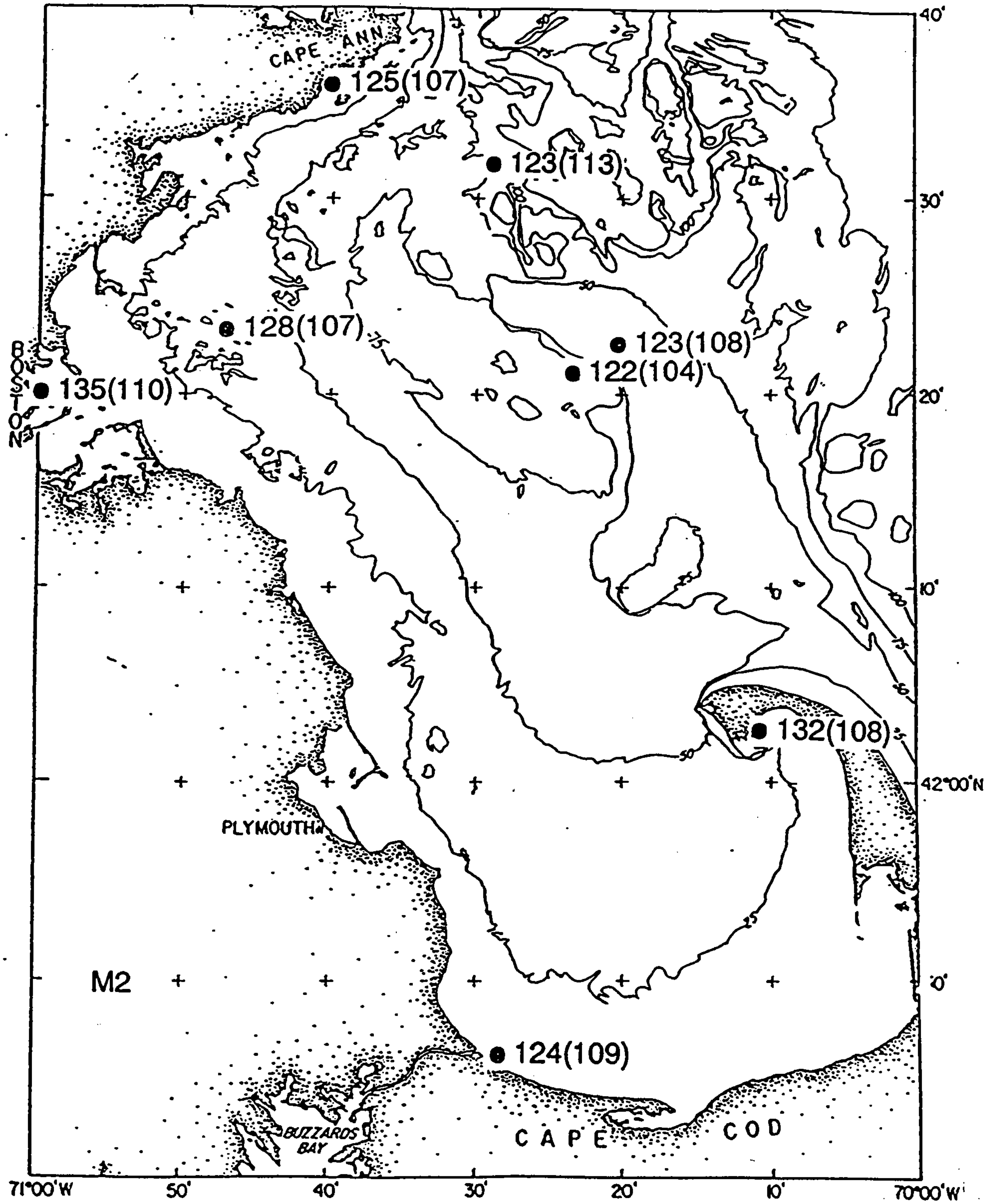


Figure 2.2-11 A chart of the M_2 constituent tidal elevation (in cm) and phase (in Greenwich epoch, in parentheses). Typical uncertainties in the amplitude and phase estimates range from 0.1 to 1.0 cm and 0.2 to 1.0°, respectively.

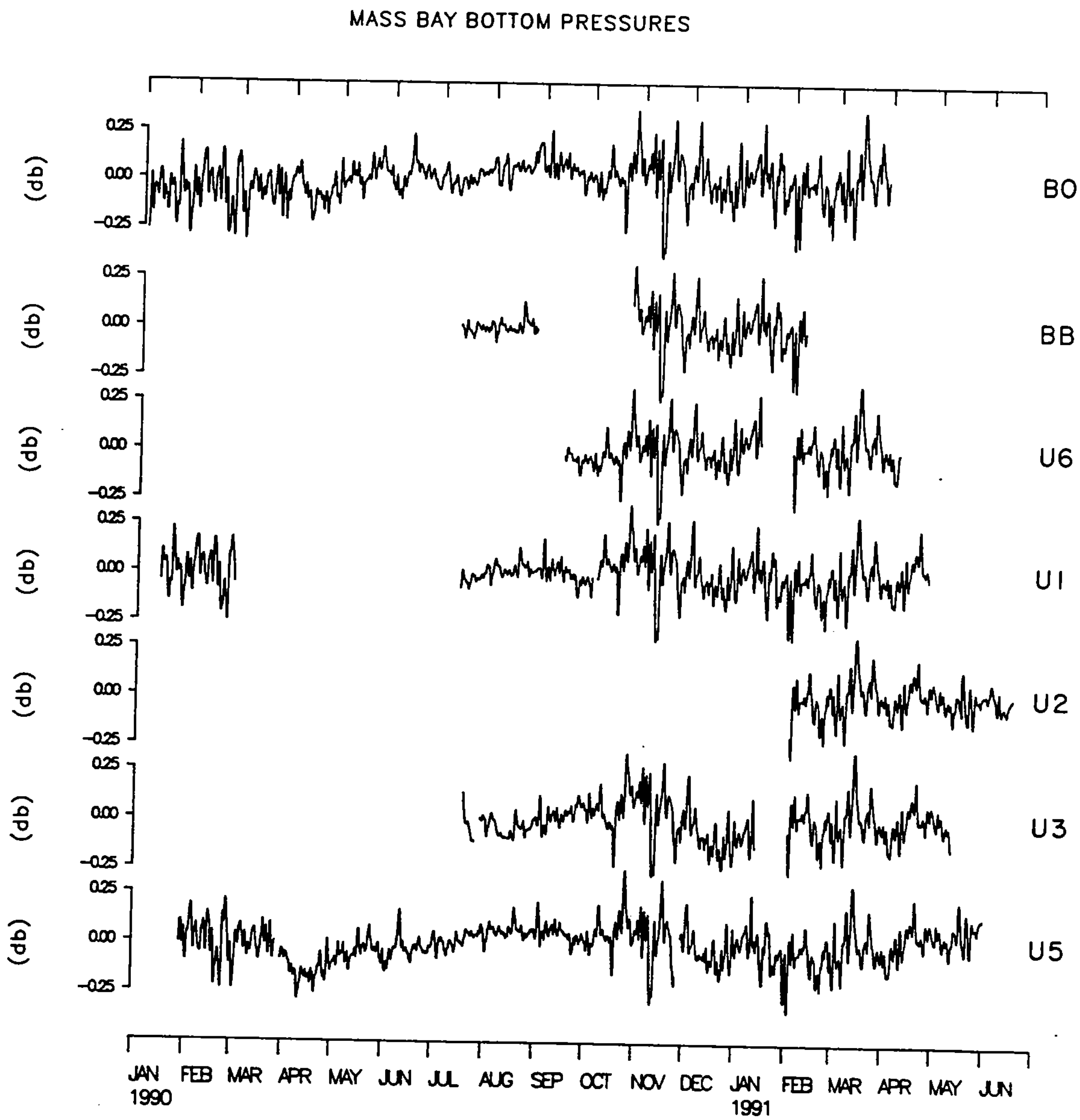


Figure 2.2-12 Subtidal coastal SSP records (sea level plus atmospheric pressure) from Boston (BO) and Bays program bottom pressures.

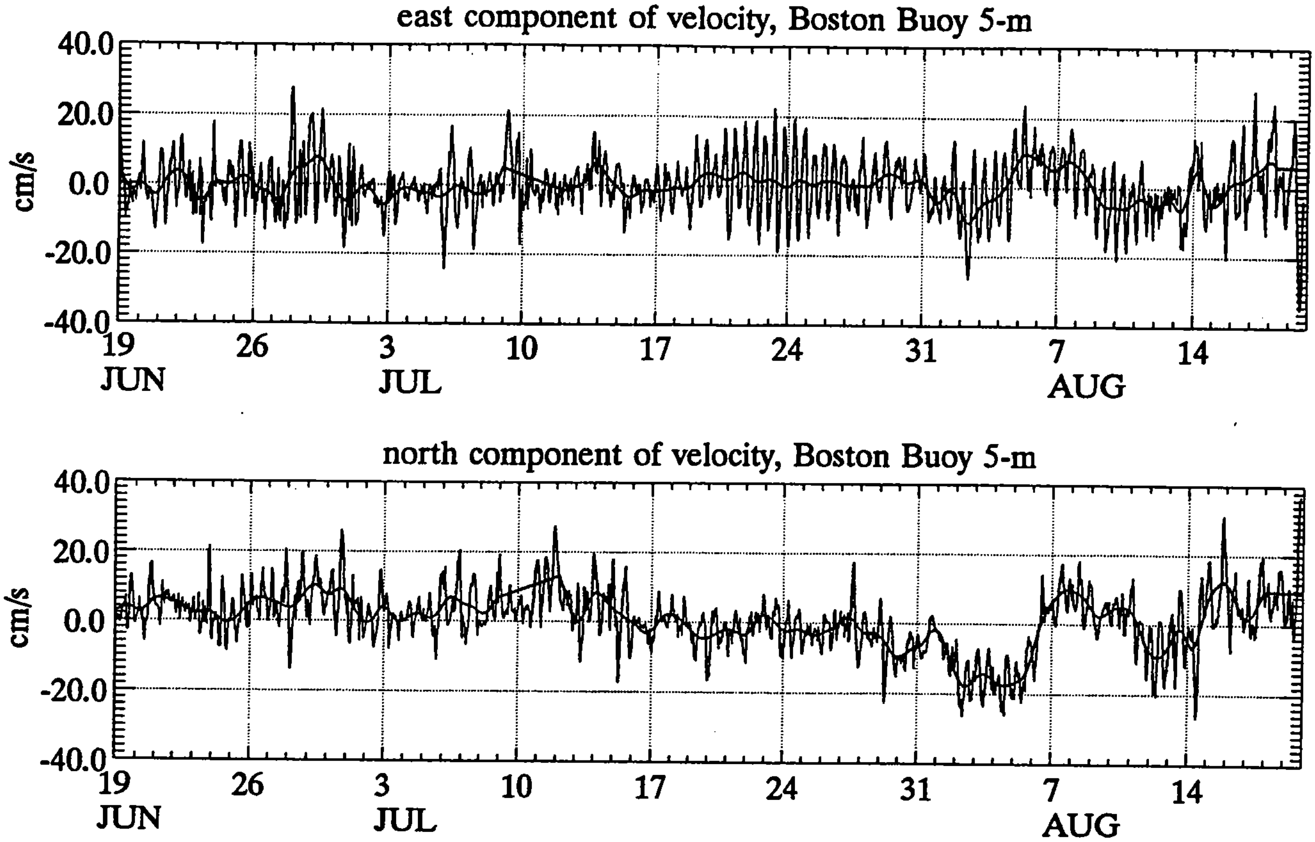


Figure 2.2-13 One-hourly velocity data from the 5-m depth current meter at the Boston Buoy, with 1.5 day filtered data superimposed. The magnitudes of the tidal and low-frequency motions are comparable. Large variations in tidal amplitude are related to internal tidal effects.

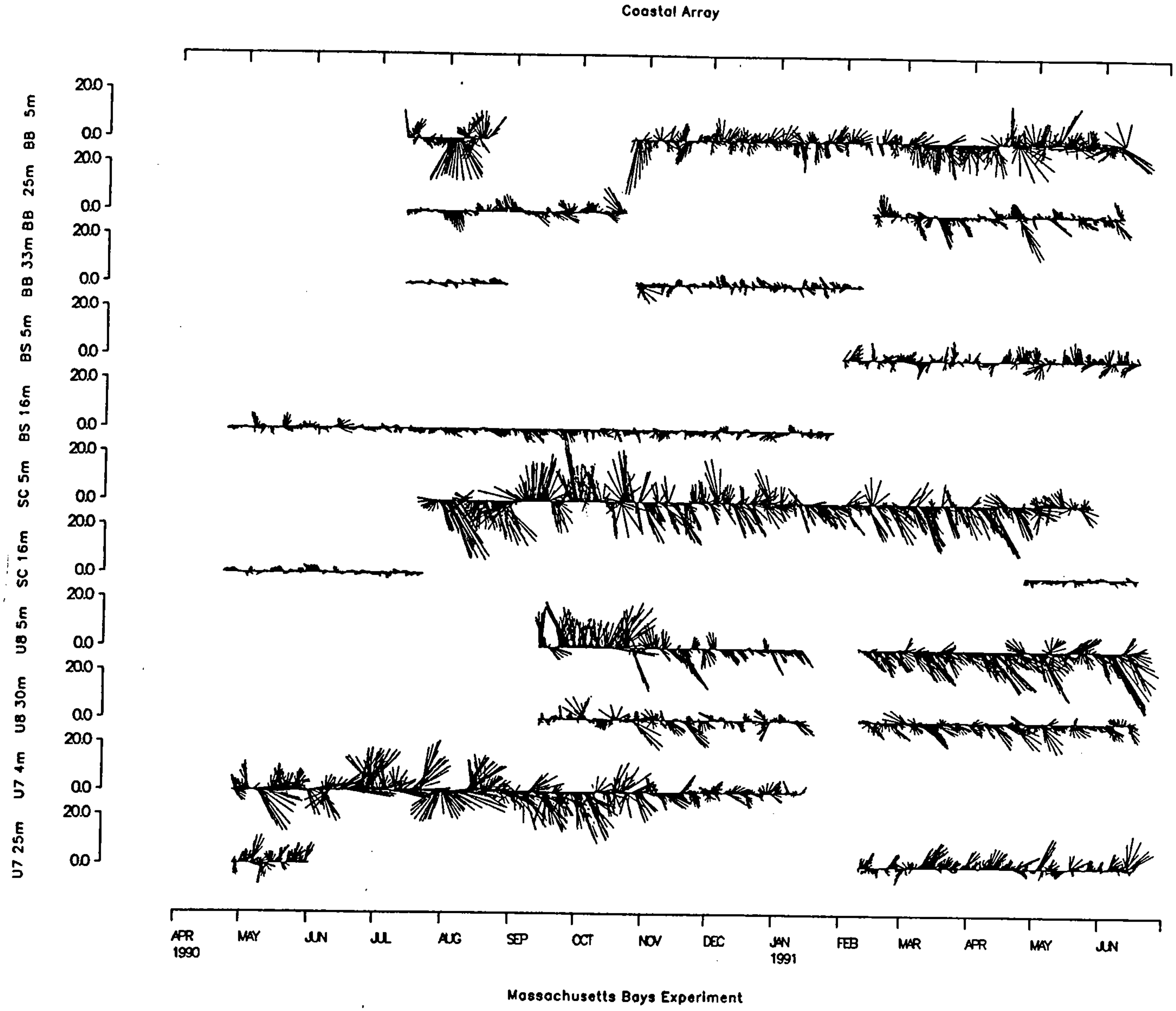


Figure 2.2-14 Six-hourly subtidal current vectors from the coastal array of moorings at the indicated depths (cm/s; northward is up).

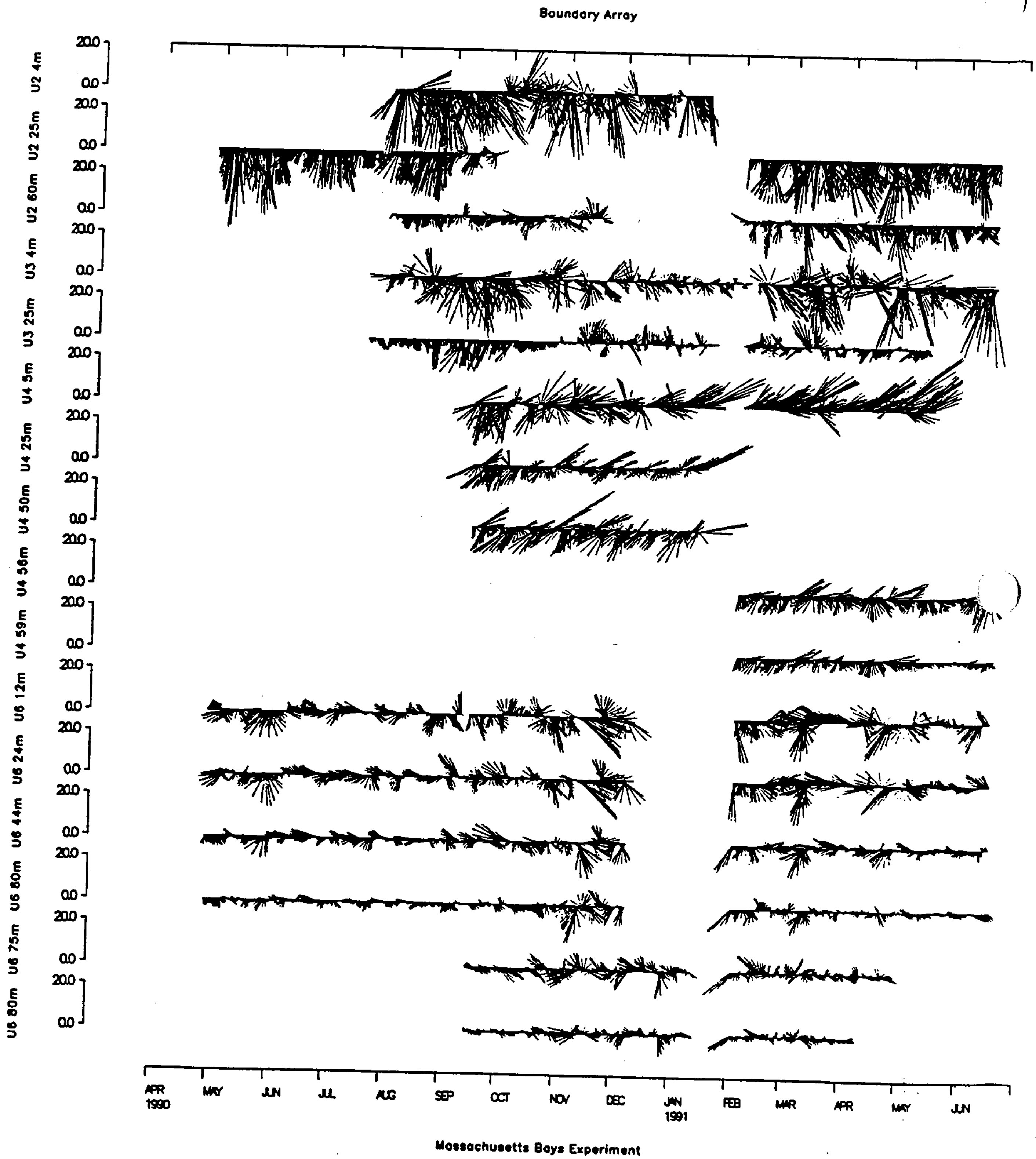


Figure 2.2-15 Six-hourly subtidal current vectors from the open boundary array of moorings at the indicated depths. The station U6 records are a subset of the full set of the full set of DAPCM measurements (cm/s; northward is up).

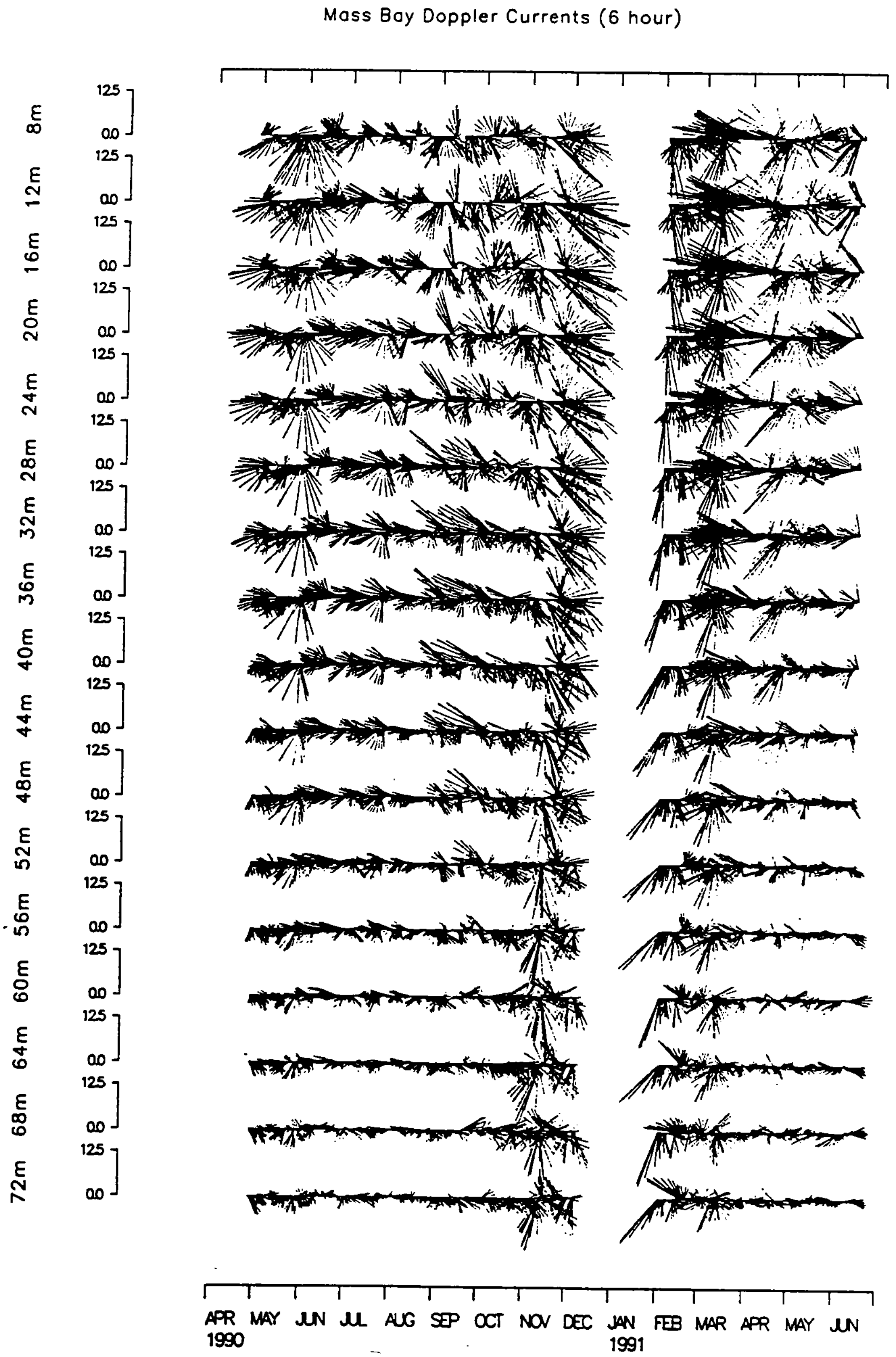


Figure 2.2-16 Six-hourly subtidal current vectors for the DAPCM at station U6 (cm/s; northward is up).

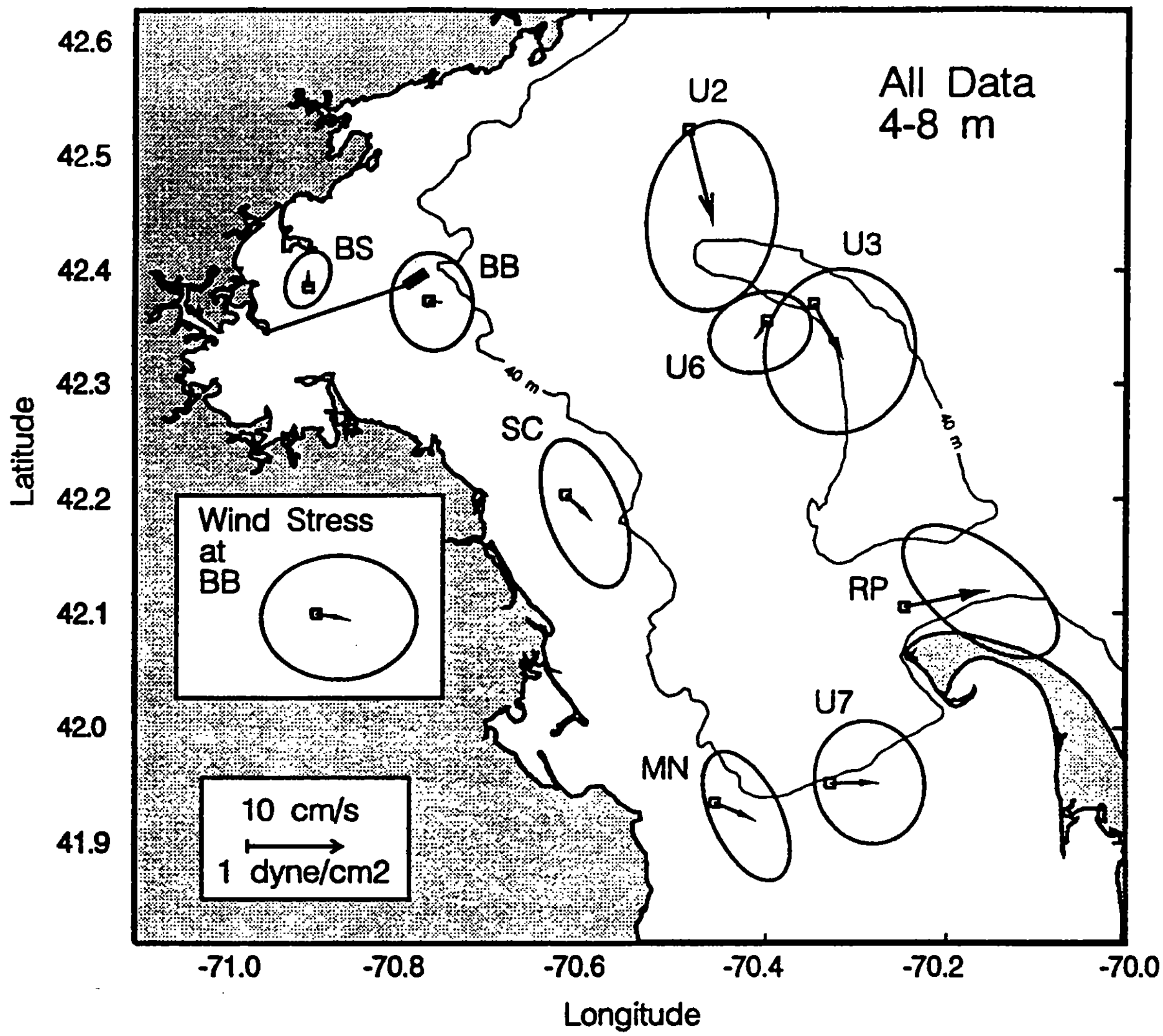


Figure 2.2-17 Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) for all near-surface (4–8 m depth) current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. With the exception of station U2 and RP, the fluctuations are larger than the mean. The mean-flow pattern suggests weak flow into Massachusetts Bay from the north and across Stellwagen Bank, southeastward along-shore flow near Scituate and Plymouth, easterly flow in Cape Cod Bay, and outflow in the channel north of Race Point. Note that the area of the new ocean outfall in western Massachusetts Bay is an area of weak flow compared to the outer bay and there is no strong preferred direction of flow; it is apparently located to the west of the stronger residual coastal current system. This means that water and material here are mixed and transported by a variety of processes rather than being swept in a consistent direction by well-defined steady currents.

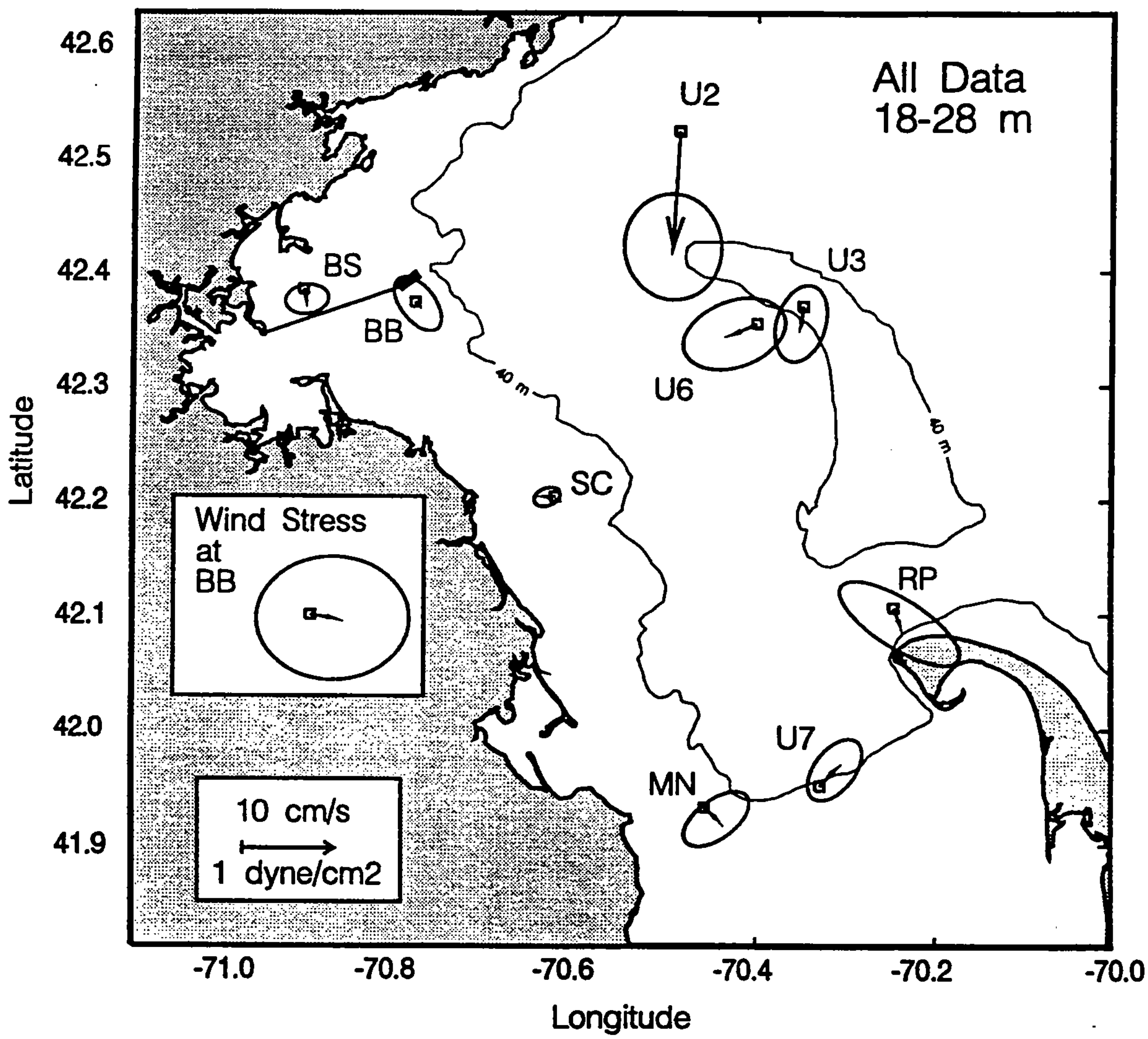


Figure 2.2-18 Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) at depths between 18 and 28 m from the surface for all current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. At 18–28 m, the fluctuations are weaker than at 4–8 m from the surface (fig. 2.2-17). Note that the strong flow to the east out of Massachusetts Bay at station RP at 4-8 m (fig. 2.2-17) does not occur at 18–28 m.

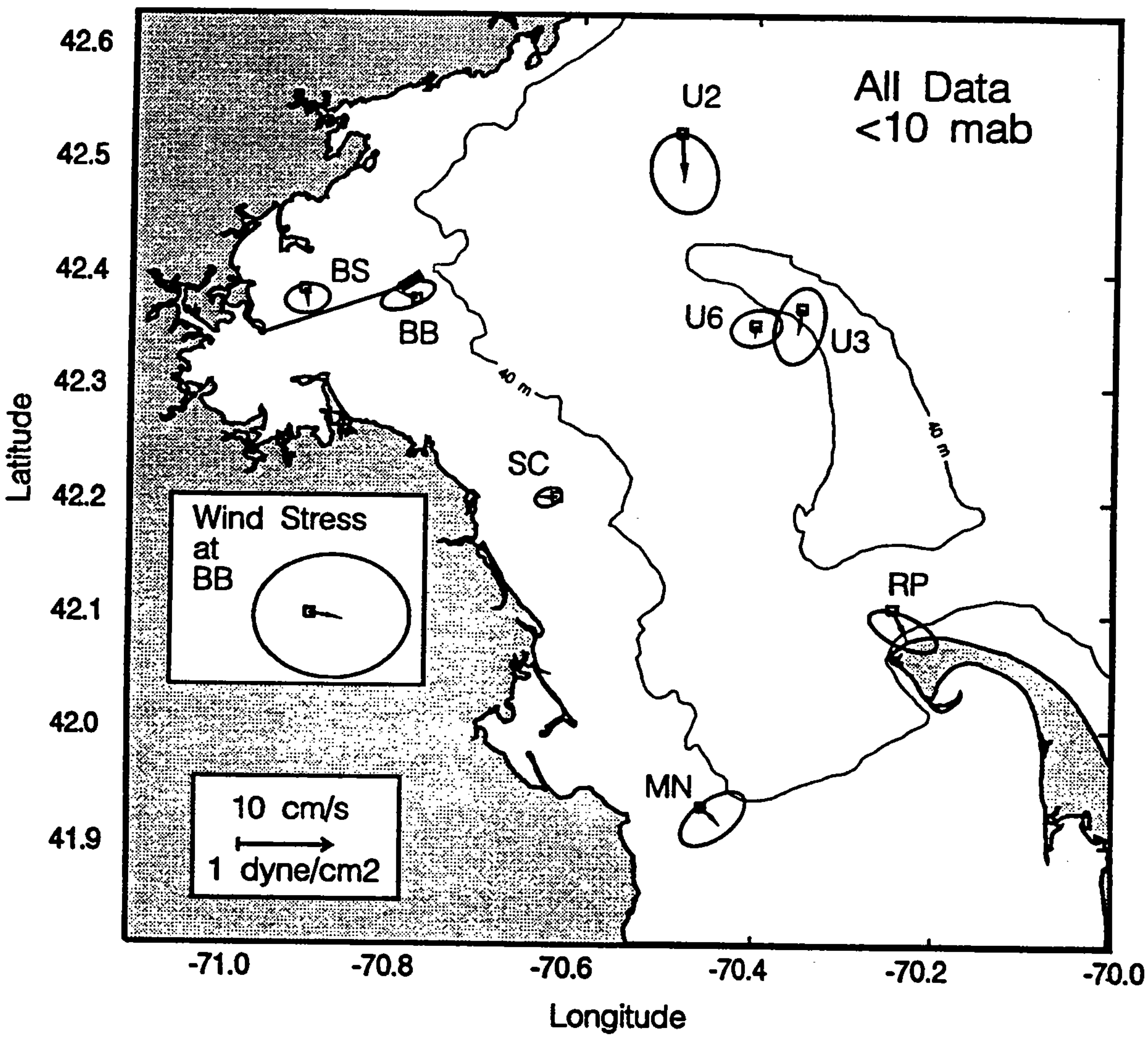


Figure 2.2-19 Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) at depths within 10 m of the bottom for all current measurements made from December 1989 to September 1991. Typically, the daily- averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. Note the very weak onshore flow near the bottom at Station BB and SC, suggesting coastal upwelling in the bottom layers.

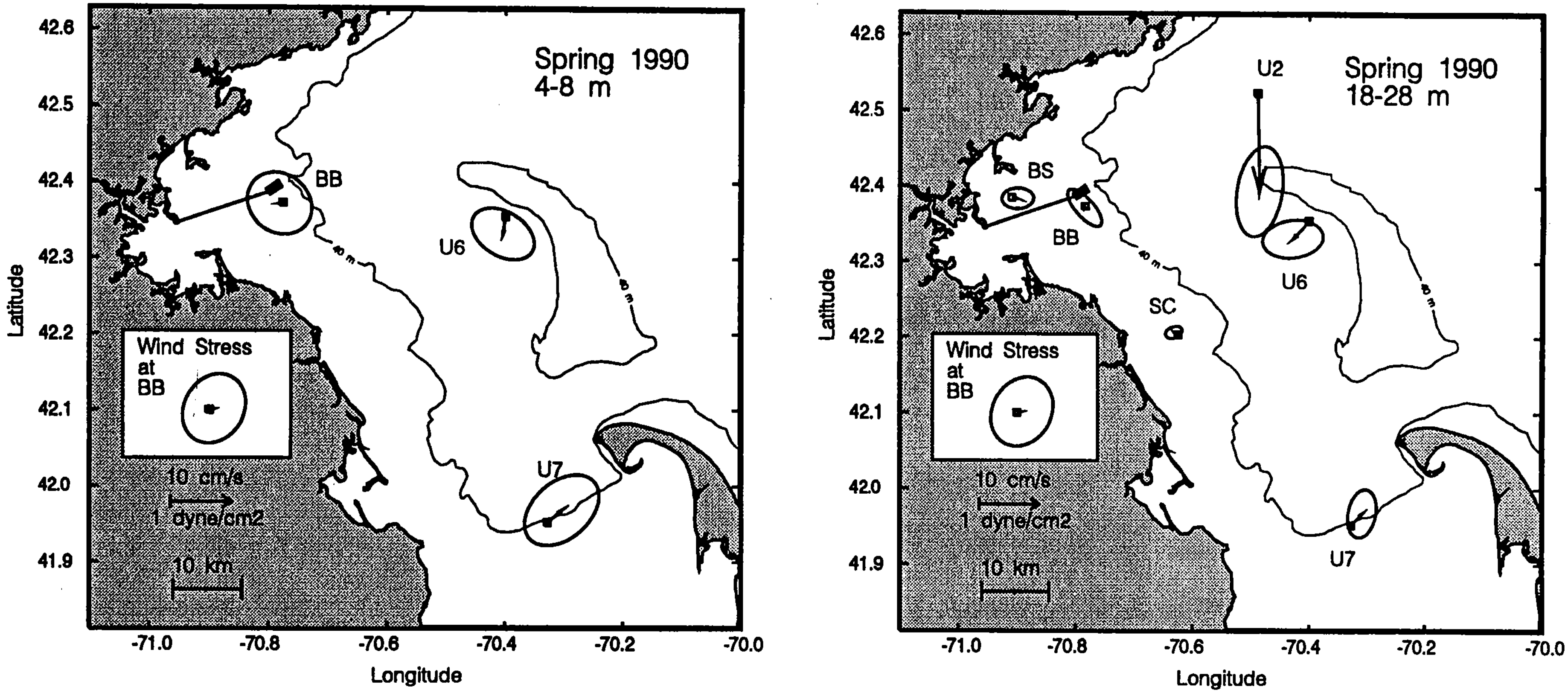


Figure 2.2-20 Means and standard deviations of near-surface and subsurface (18–28 m) currents for the spring of 1990.

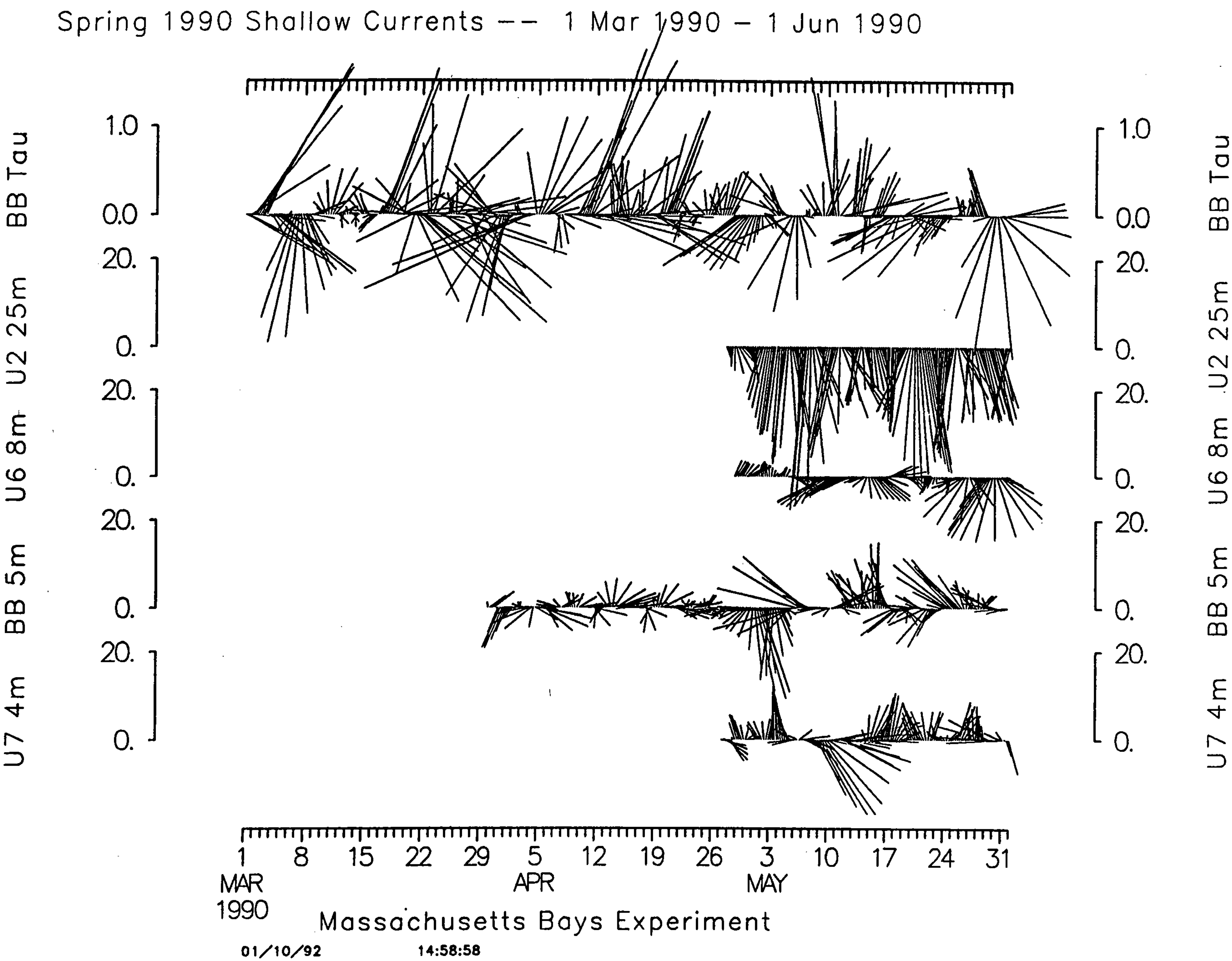


Figure 2.2-21 Stick plot of wind stress at the Boston Buoy (oceanographic convention) and near-surface currents at selected moorings during the spring of 1990 (see Figure 2.2-1 for locations)

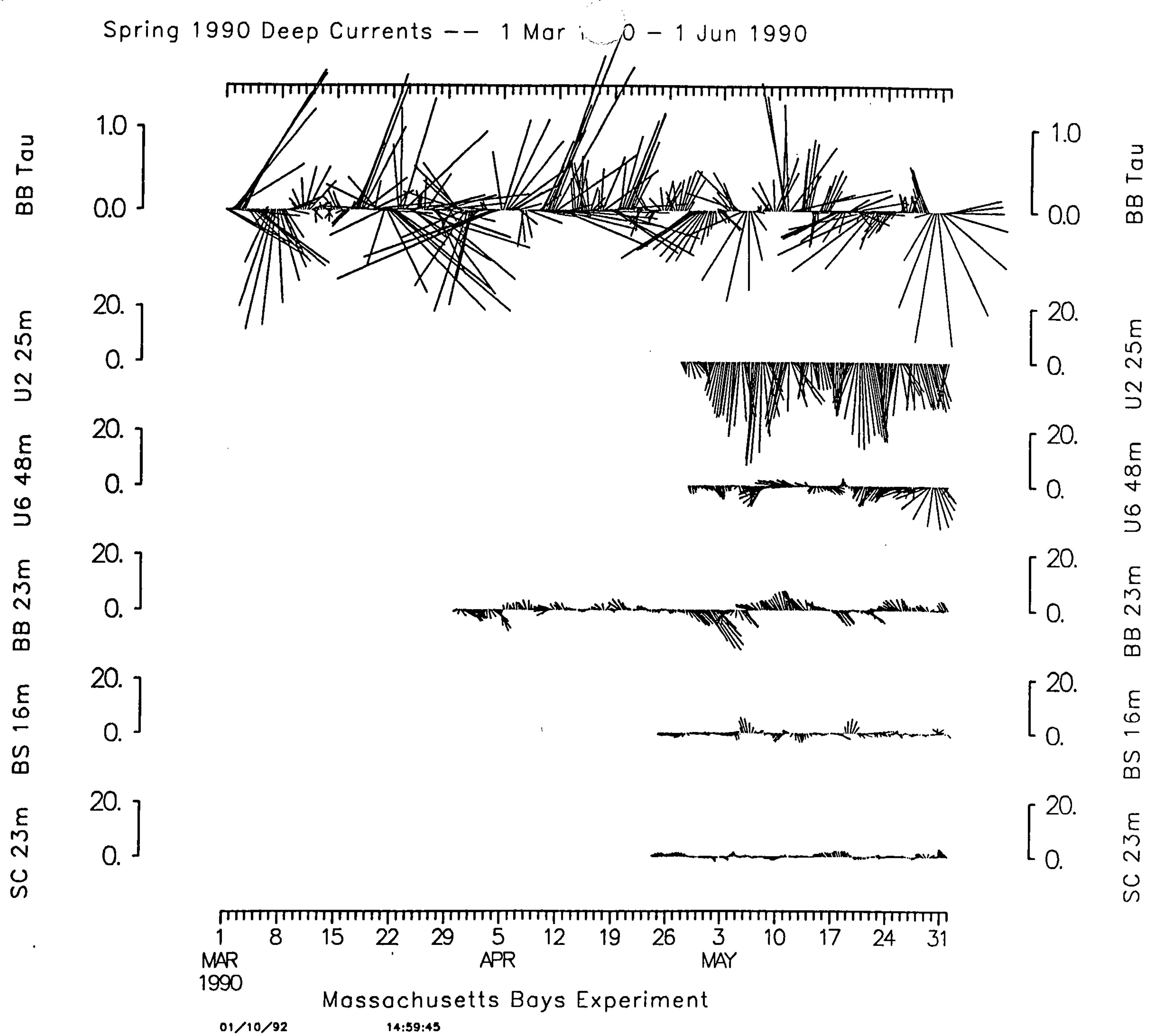


Figure 2.2-22 Stick plot of wind stress at the Boston Buoy and subsurface currents at selected moorings during the spring of 1990.

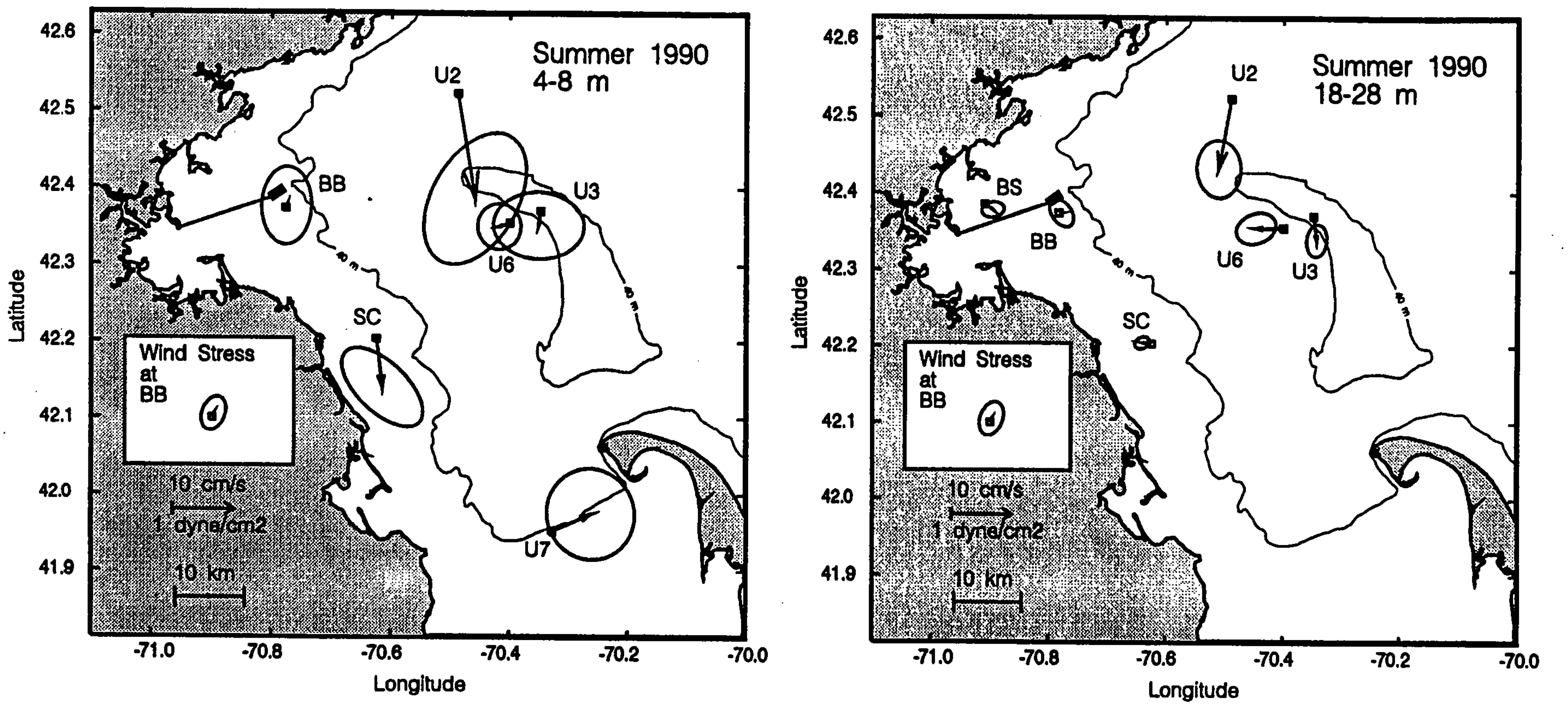


Figure 2.2-23 Means and standard deviations of near-surface and subsurface (18–28 m) currents for the summer of 1990.

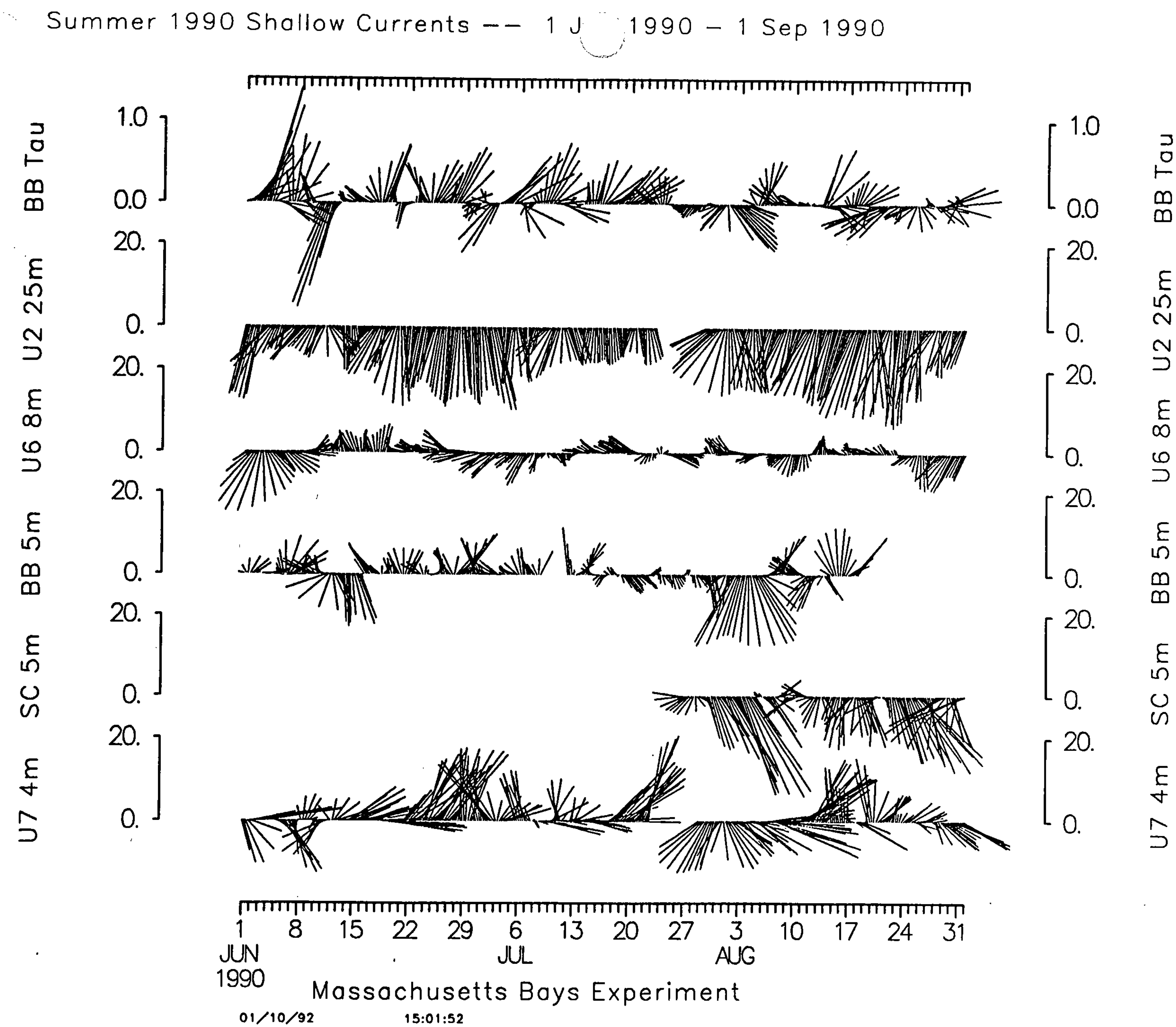


Figure 2.2-24 Stick plot of wind stress at the Boston Buoy (oceanographic convention) and near-surface currents at selected moorings during the summer of 1990.

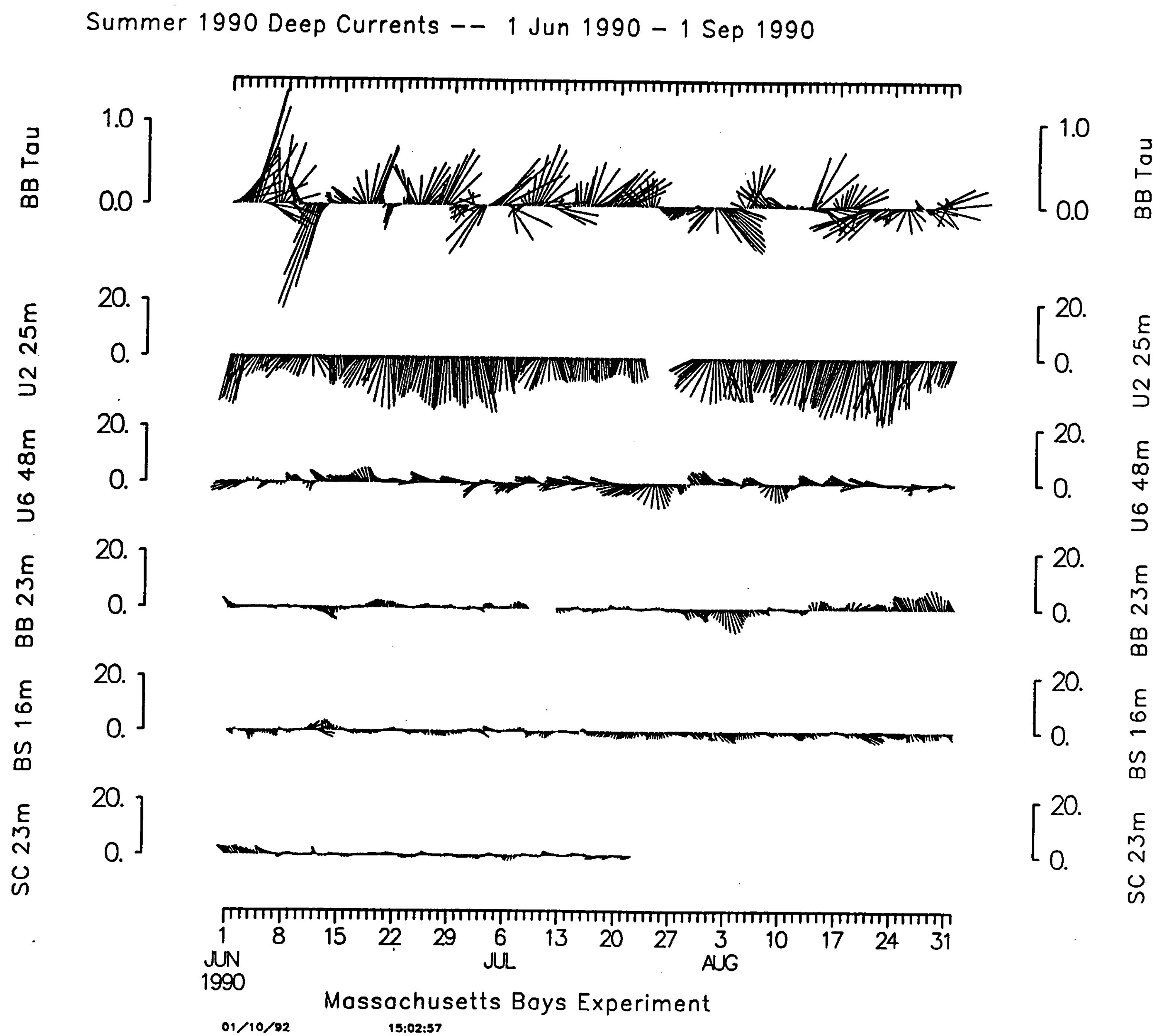


Figure 2.2-25 Stick plot of wind stress at the Boston Buoy and subsurface currents at selected moorings during the summer of 1990.

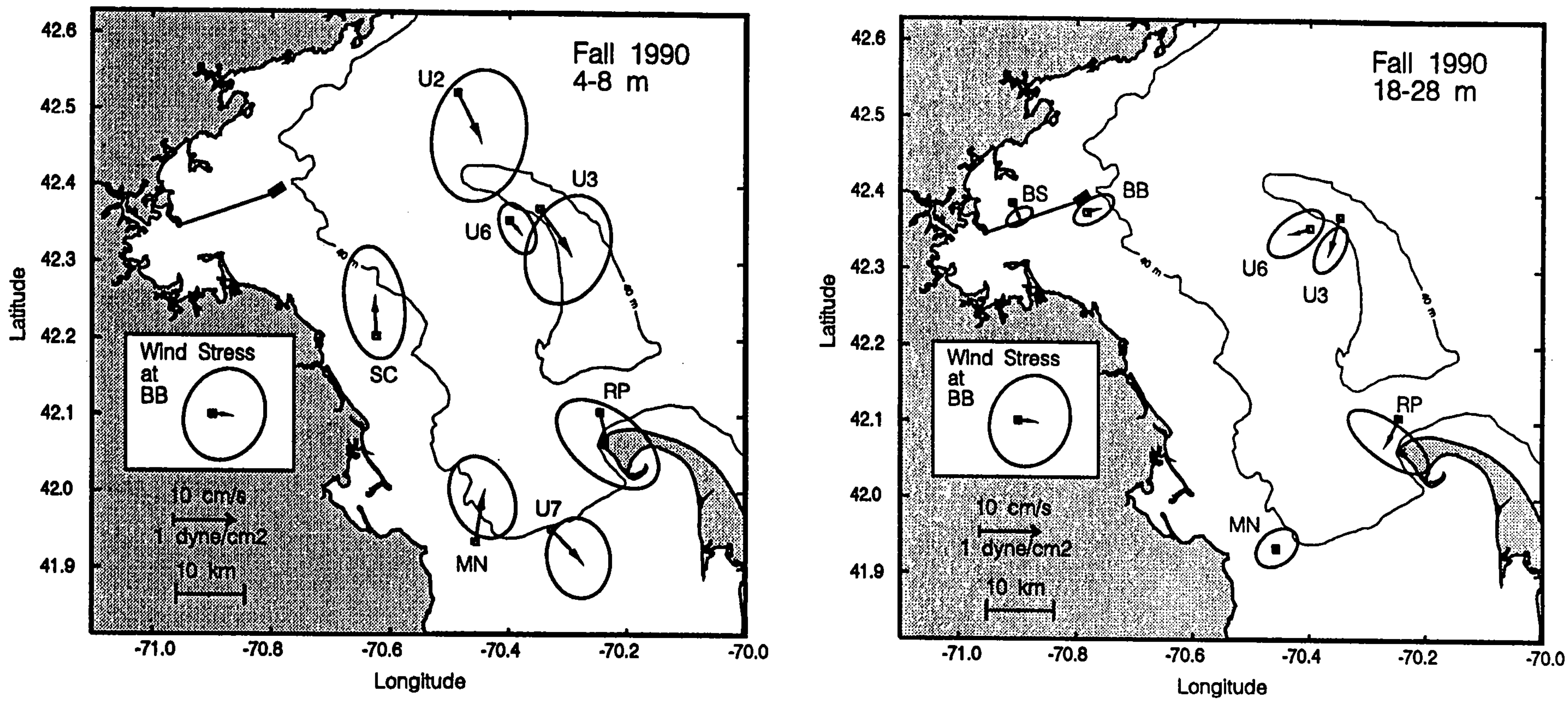


Figure 2.2-26 Means and standard deviations of near-surface and subsurface (18–28 m) currents for the fall of 1990.

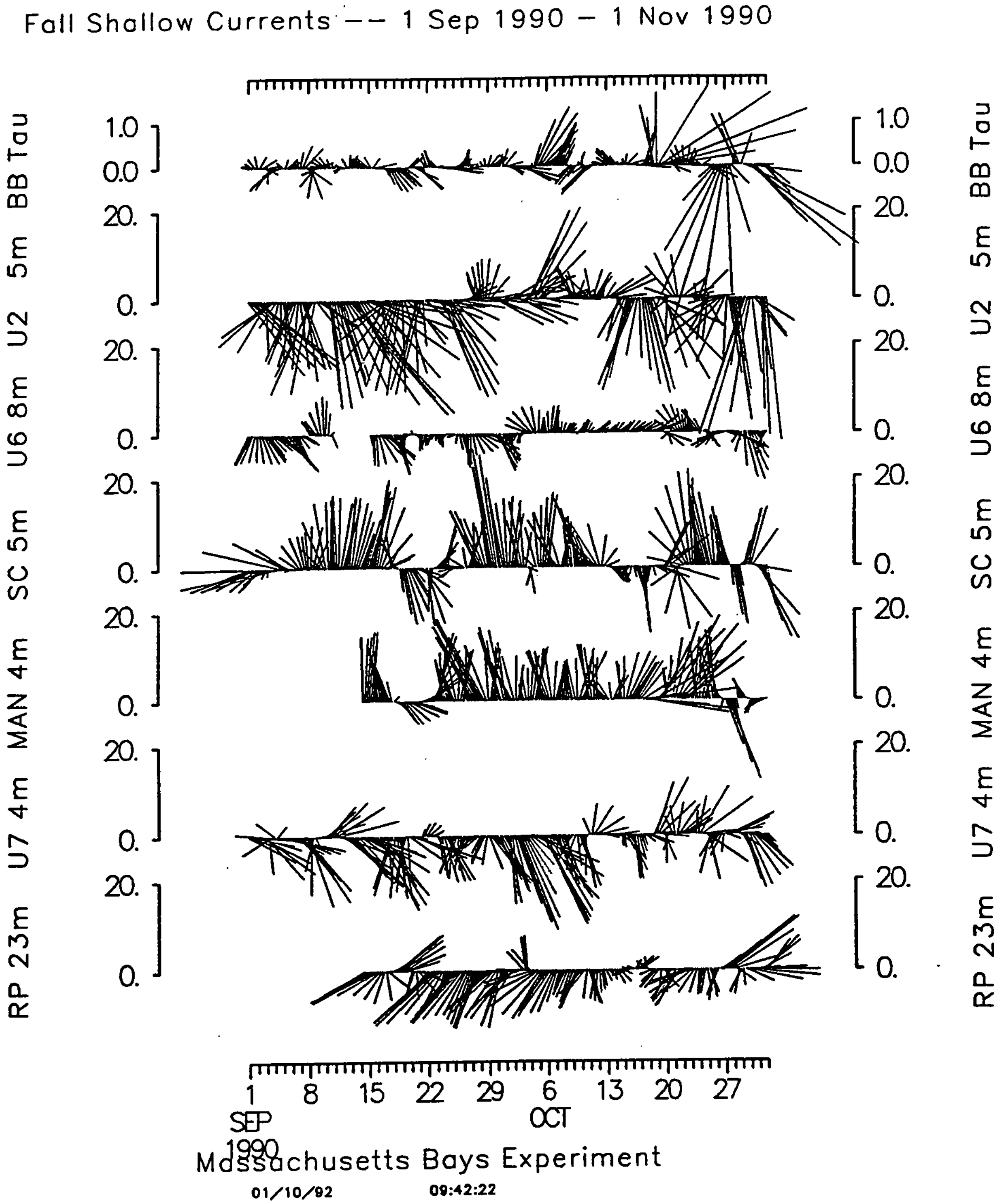


Figure 2.2-27 Stick plot of wind stress at the Boston Buoy (oceanographic convention) and near-surface currents at selected moorings during the fall of 1990.

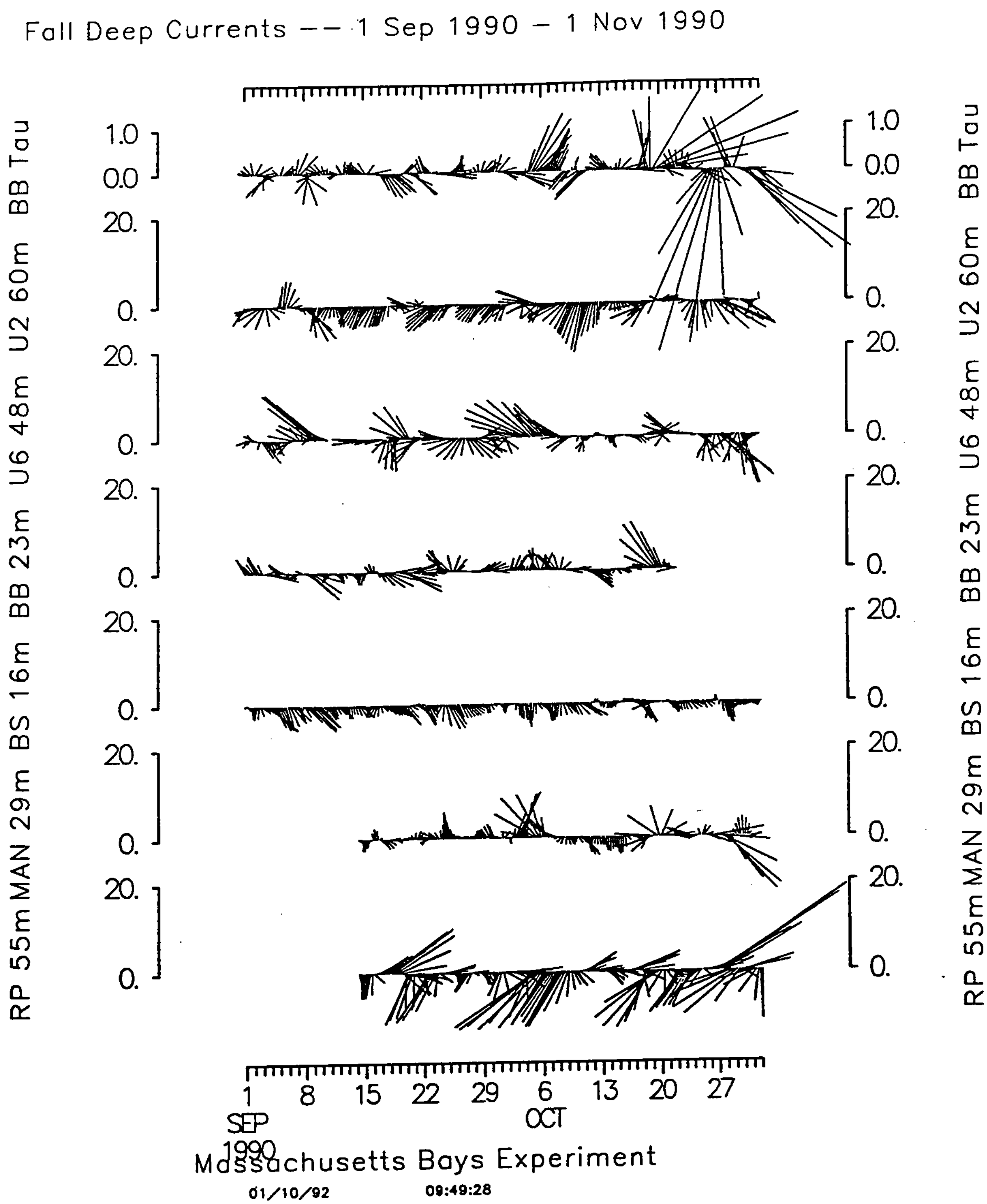


Figure 2.2-28 Stick plot of wind stress at the Boston Buoy and subsurface currents at selected moorings during the fall of 1990.

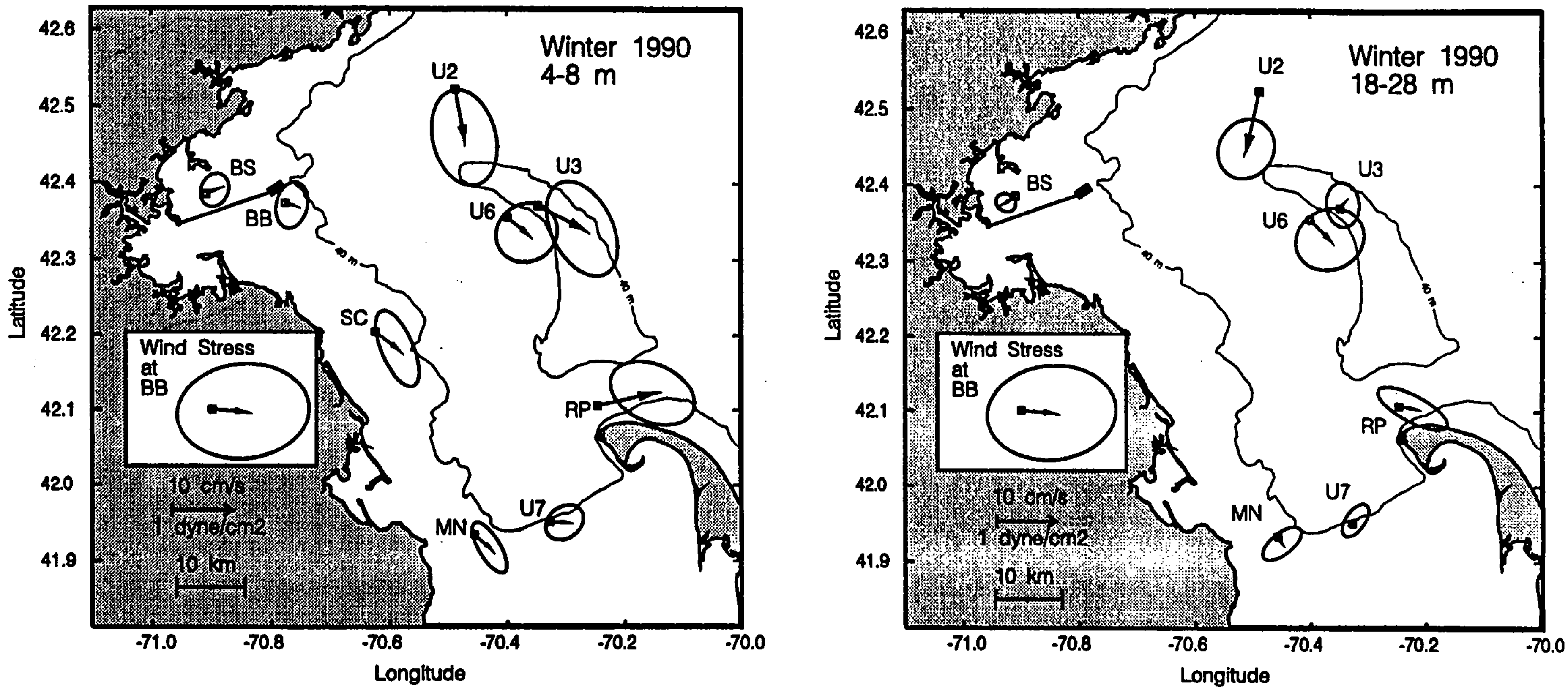


Figure 2.2-29 Means and standard deviations of near-surface and subsurface (18–28 m) currents for the winter of 1990–1991.

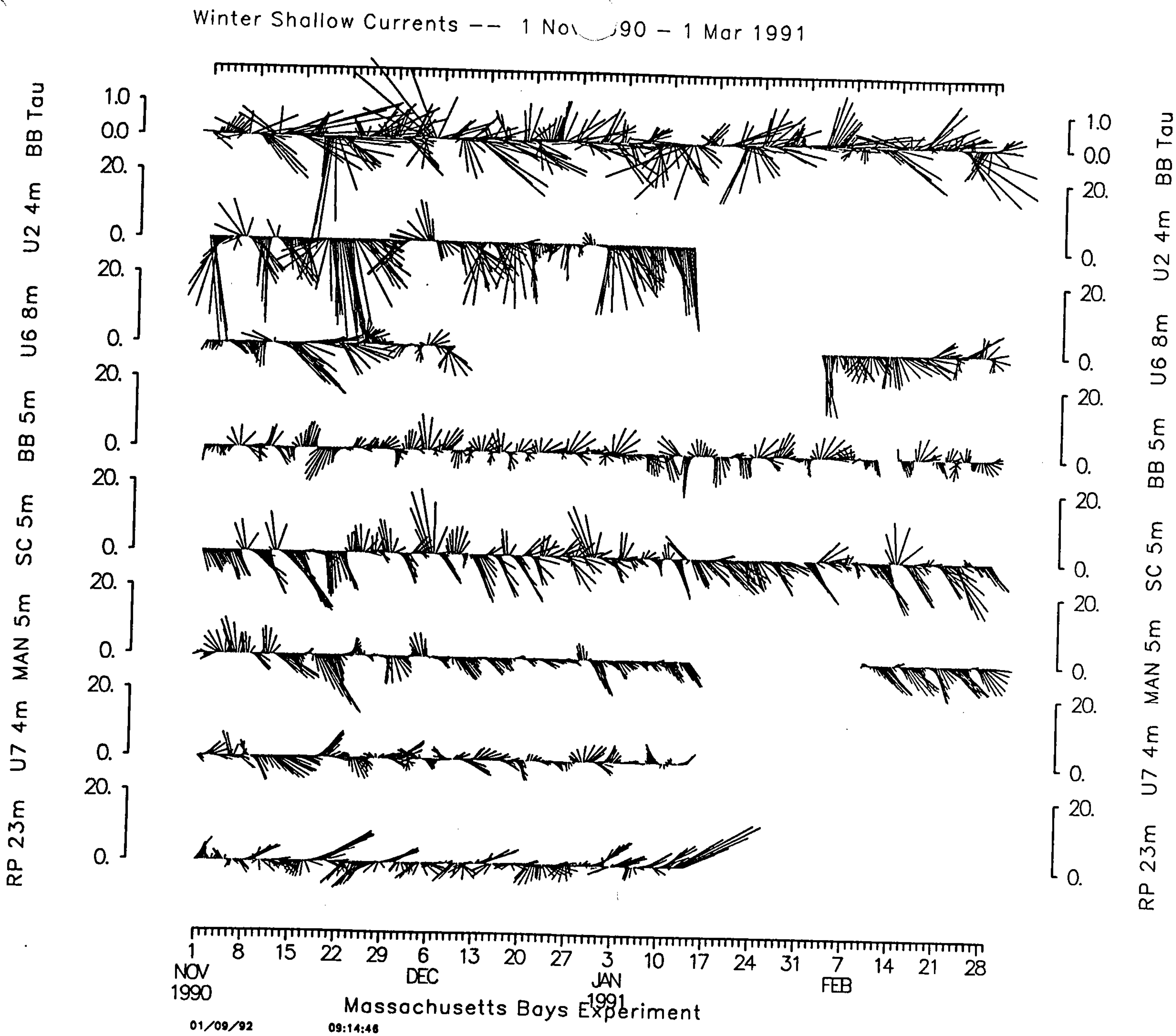


Figure 2.2-30 Stick plot of wind stress at the Boston Buoy (oceanographic convention) and near-surface currents at selected moorings during the winter of 1990–1991.

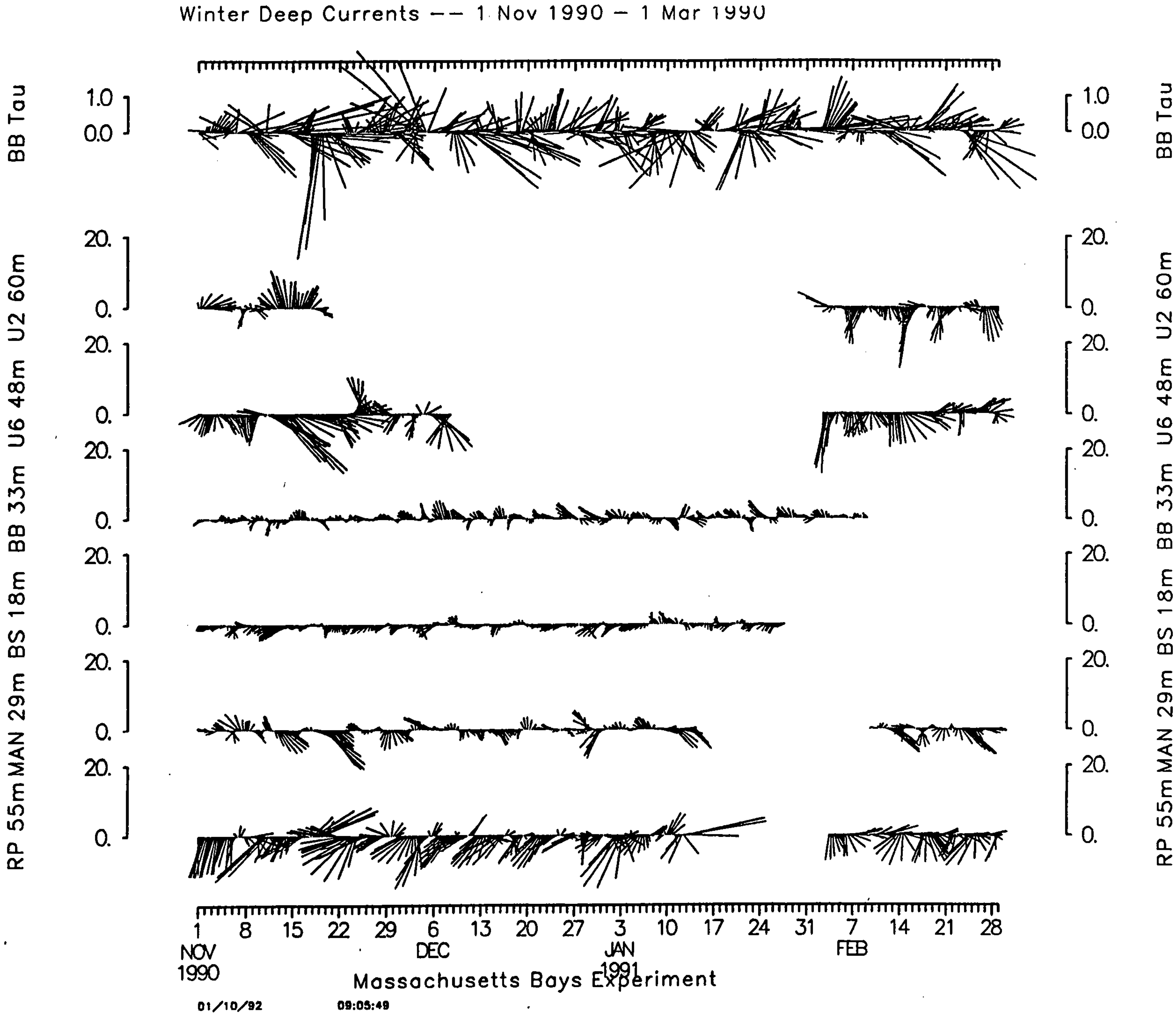
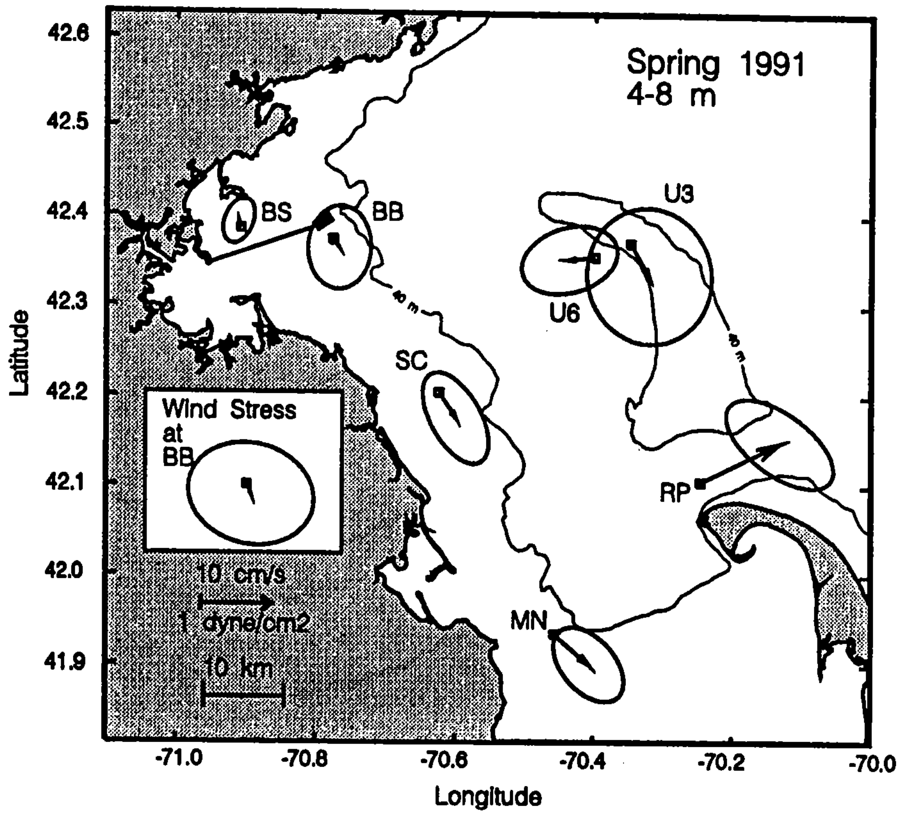


Figure 2.2-31 Stick plot of wind stress at the Boston Buoy and subsurface currents at selected moorings during the winter of 1990–1991.



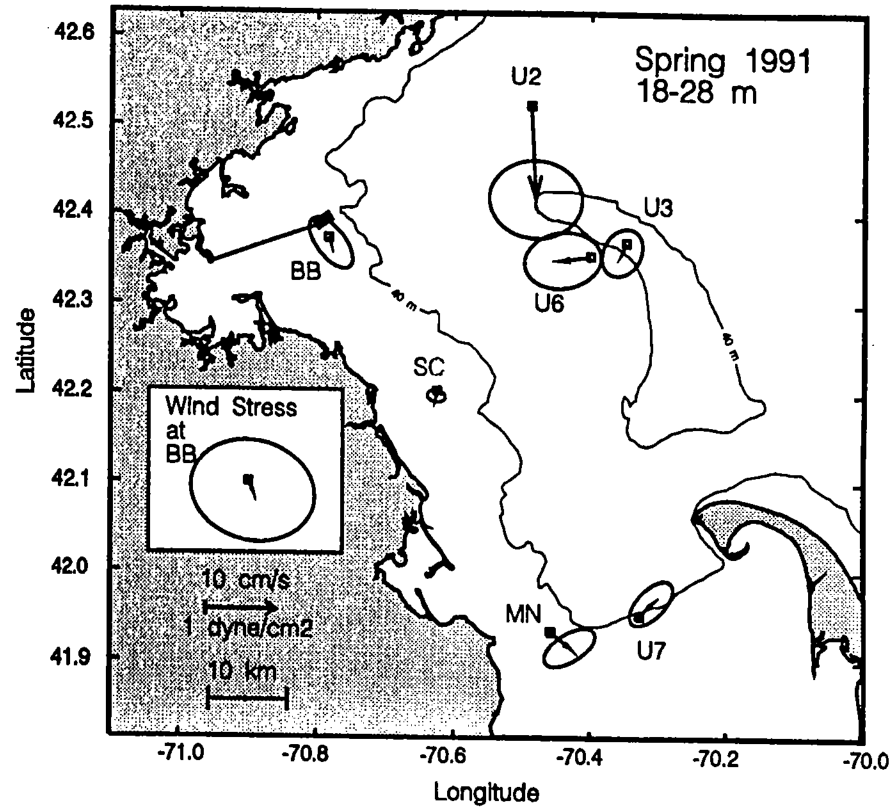


Figure 2.2-32 Means and standard deviations of near-surface and subsurface (18–28 m) currents for the spring of 1991.

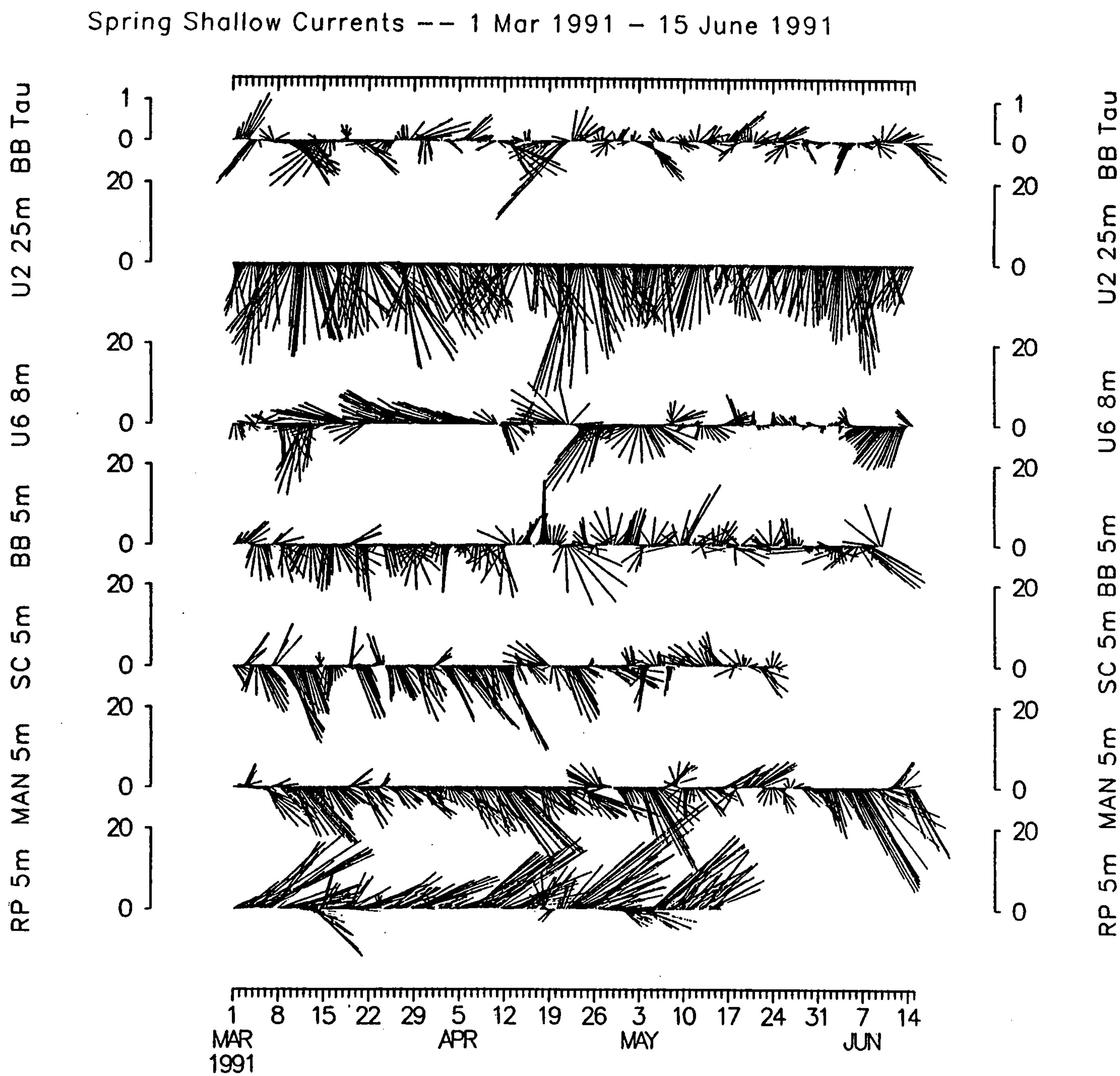


Figure 2.2-33 Stick plot of wind stress at the Boston Buoy (oceanographic convention) and near-surface currents at selected moorings during the spring of 1991.

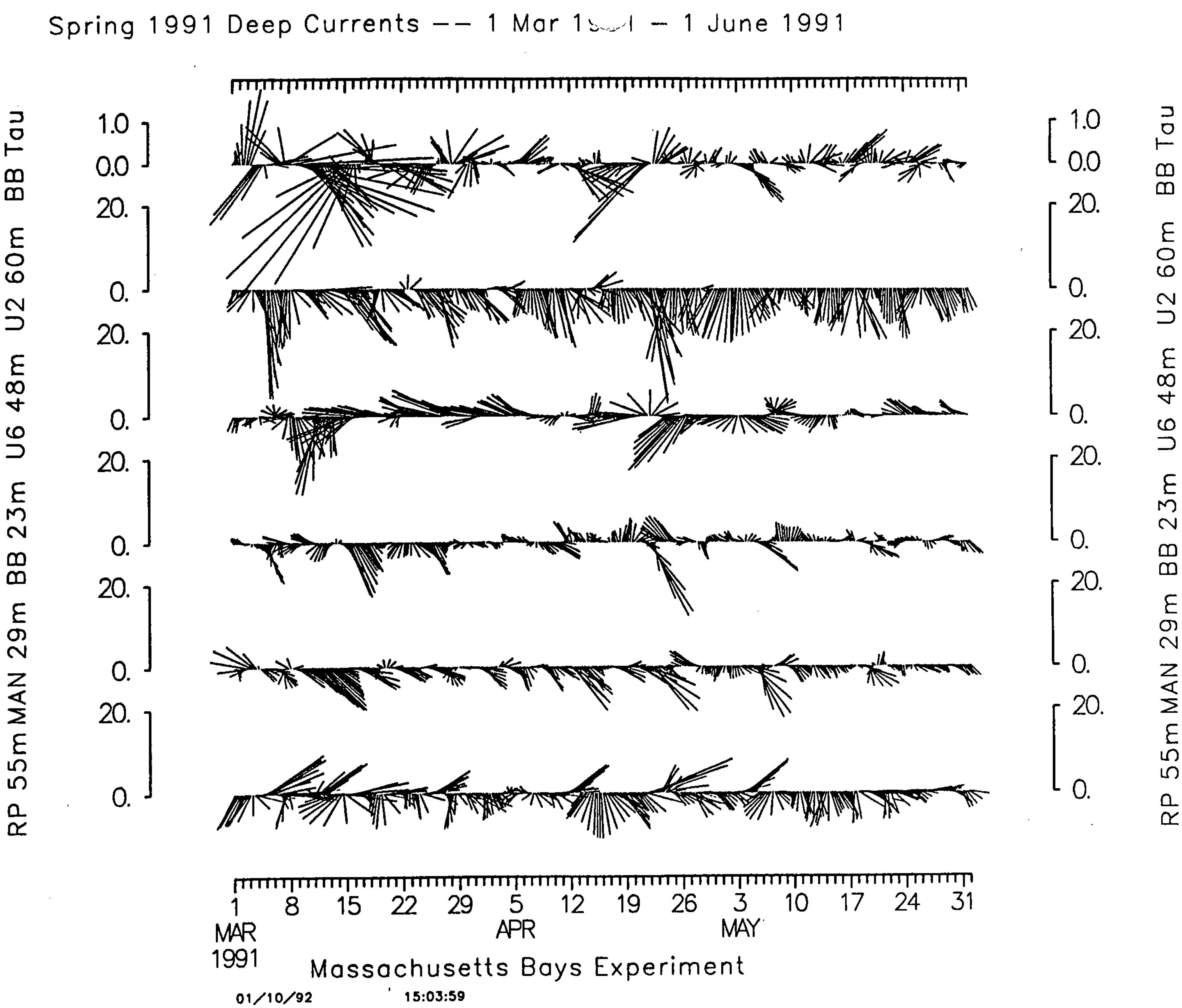


Figure 2.2-34 Stick plot of wind stress at the Boston Buoy and subsurface currents at selected moorings during the spring of 1991.

2.3 Drifter Measurements

2.3.1 Drifter Instrumentation

Mixed-layer drifters were deployed as part of the Massachusetts Bays physical oceanography program to determine the Lagrangian transport in the waters above the thermocline. Drifters were deployed around the times of the baywide hydrographic cruises, and were tracked for a two-month period (or until they grounded).

The drifters, called Low-Cost Drifters or LCD's, were designed and manufactured by John Dahlen of Draper Laboratory (Dahlen, 1986). They consist of a pill-shaped surface buoy, 0.4 m in diameter and 0.15 m in height, to which is attached a 1 m tether and 10 m long drogue. The drogue is a "holey-sock", which consists of a 0.4-m diameter cylinder made of dacron, with holes spaced at 0.4-m intervals to improve its stability. An ARGOS satellite transmitter inside the surface buoy, sends signals to the polar-orbiting NOAA satellites in order to provide 5–8 fixes per day. The accuracy of each fix is approximately 300 m. Due to the small size of the surface buoy and the large drogue, the water-following characteristics of the drifter system are excellent. "Slippage" of the drifter relative to the average water velocity across the drogue depth (1–11 m depth) is on the order of 1 cm/s (Geyer, 1989) which is similar to the accuracy of moored current meters.

The drifters move at approximately the average velocity of the top 10 m of the water column. If there is stronger shear near the surface, the drift will be biased toward the near-surface velocity. Since wind-driven currents tend to be more strongly sheared near the surface, the drifters may tend to over-estimate the wind-driven motions relative to the moored measurements obtained at 5 m depth.

Drifters were deployed in five different periods, designated MB-1 through MB-5. The dates of the deployments are indicated in Table 2.3-1. The drifters were generally deployed in western Massachusetts Bay, in the vicinity of the Boston Buoy (BB). The exceptions were MB-3 (January 1991) when two drifters were deployed in Stellwagen Basin, and MB-5 (May 1991), when one of the drifters was deployed off the mouth of the Merrimack River.

2.3.2 Drifter Results

First deployment: spring, 1990

Three drifters were deployed in western Massachusetts Bay on May 1, 1990, from the R/V ARGO Maine. Their initial locations were 5 km to the NW, NE and S of the Boston Buoy respectively (fig. 2.3-1). Drifter 1 headed directly into Boston Harbor, taking 1.5 days to enter the Harbor, with an average westward speed of

10 cm s^{-1}. The other two drifters headed SSE at speeds of 15 to 20 cm s^{-1}. Drifter 3 washed ashore in Marshfield two days after deployment, while drifter 2, which started further offshore, continued along the west coast and entered Cape Cod Bay 5 days after deployment. It continued around the perimeter of Cape Cod Bay, approximately following the 25-m isobath, to a point about 10 km south of Provincetown, where it stopped for 5 days, then continued around the tip of Cape Cod, passing within 1 km of Race Point and following the shoreline of the Outer Cape to the southeast.

Table 2.3-1: Deployment dates and locations of the drifters

Deployment	Date	Comments
MB-1 (initial deployment)	5/1/90	Western Massachusetts Bay (3 drifters)
MB-1 (second deployment)	5/14/90	Western Massachusetts Bay (2 drifters)
MB-2	7/25/90	Western Massachusetts Bay (2 drifters)
MB-3	10/15/90	Western Massachusetts Bay (3 drifters)
MB-4	2/1/91	Western Massachusetts Bay (3 drifters)
MB-5 (first deployment)	5/8/91	Merrimack River Mouth (1 drifter)
MB-5 (second deployment)	5/24/91	Western Massachusetts Bay (1 drifter)
MB-5 (third deployment)	5/29/91	Western Massachusetts Bay

Drifters 1 and 3 were recovered and redeployed as drifters 4 and 5 on May 15, 1990 to the NE and NW of the Boston Buoy (fig. 2.3-2) from the R/V Neritic. These drifters both headed ENE, then curved eastward and southeastward through Stellwagen Basin. Drifter 4 continued southward until May 20, whereupon it turned westward, then turned sharply southward and followed the coastline into Cape Cod Bay. It stayed close to shore, probably with the drogue touching bottom, passed Barnstable and across Billingsgate Shoal as it headed north toward Provincetown. This drifter, like drifter 2, spent about a week milling around just south of Provincetown before drifting toward the middle of Cape Cod Bay. It remained in Cape Cod Bay for a total of 43 days before exiting north of Provincetown. It was apparently trapped in a clockwise eddy for much of this period. Drifter 5, which had been approximately 20 km ahead of drifter 4 in Stellwagen Basin, curved southwestward toward Marshfield, then hooked back to the east, looped to the north, then headed rapidly eastward, heading out of the Bay at 30 cm s^{-1}.

Second Deployment: Summer, 1990

Three drifters were deployed in western Massachusetts Bay on July 25, 1990, from the R/V ARGO Maine (fig. 2.3-3). One of the drifters failed to transmit, but it was recovered 1 week after deployment in Marshfield. The other two drifters also headed southsoutheast, approximately following the shore. Drifter 1 remained about 5 km offshore, at speeds of 10–20 cm s^{-1}, until July 31, when it grounded at the tip of the spit at the entrance to Plymouth Harbor. Drifter 2, which had been deployed further offshore, roughly paralleled the track of Drifter 1 but at speeds of 5–10 cm s^{-1} until August 1, when it increased its southward speed to 20 cm s^{-1} and quickly circuited the perimeter of Cape Cod Bay, passing Race Point on August 5.

Third Deployment: Fall, 1990

Three drifters were deployed in western Massachusetts Bay on October 15, 1990 from the R/V ARGO Maine (fig. 2.3-4). Drifter 1 headed southeast along the coast for 1 day, then headed sharply northward. It looped back to the southeast along the 50-m isobath, then continued southwest and grounded at the spit at the entrance to Plymouth Harbor on October 21. Its highest speeds were 20 cm s^{-1} while it was following the 50-m isobath. Drifter 2 headed straight south, almost going ashore in Cohasset before turning sharply northward, then making a clockwise loop through western Massachusetts Bay with a speed of 20 cm s^{-1}. It then continued southeastward, also along the 50-m isobath, until Oct. 21, whereupon it turned sharply eastward, It went as far as the edge of Stellwagen Bank, then looped back to the southwest almost to Plymouth. Finally it zig-zagged back eastward and grounded in Provincetown on November 11. Drifter 3 travelled due south for one day before being hauled up by a Cohasset lobsterman.

Fourth Deployment: Winter, 1991

One drifter was deployed near the Boston Buoy on January 29 from the R/V ARGO Maine, and two were deployed in Stellwagen Basin on Feb. 1 from the R/V Oceanus (fig. 2.3-5). Drifter 1, which was deployed 5 km inshore of Stellwagen Bank near the U-6 mooring, crossed the bank into the Gulf of Maine, then curved back to the 50-m isobath, which it followed to the southeast past the Outer Cape. Drifter 2 was deployed just to the northwest of the tip of Stellwagen Bank. it looped around within 10 km of its release point for two weeks, then heading southeastward, across Stellwagen Bank, to the 50-m isobath. It also followed the 50-m isobath past the Outer Cape. Drifter 3, which started in Western Massachusetts Bay, zig-zagged into Stellwagen Basin, in which it slowly drifted southward. On February 15 it started moving rapidly to the southeast, around the corner of Stellwagen Bank and out of the Bay past Race Point at greater than 20 cm s^{-1}.

Fifth Deployment: Spring, 1991

One drifter was deployed just offshore of the mouth of the Merrimack River on May 8 by the charter vessel Unity. It washed ashore a week later just to the north of the Merrimack River, and it was redeployed 10 km southeast of the Merrimack outflow on May 24. It rapidly headed southward around Cape Ann, (fig. 2.3-6) curving around into western Massachusetts Bay. It grounded in Nahant on May 30, and was recovered and redeployed just south of Nahant on June 7. From there it retraced its path toward Cape Ann, then rapidly looped southeastward past the tip of Stellwagen Bank and into Stellwagen Basin. By June 14 it made it just to the entrance to Cape Cod Bay before turning back to the northeast and exiting the Bay. The second drifter was deployed on May 24 near the Boston Buoy. It slowly moved southeastward along the 50-m isobath, then turned northeastward on June 7 and exited the bay. The third drifter was deployed on May 30 in the northern portion of Stellwagen Basin. It also followed the 50-m isobath for several days, but on May 5 it turned inshore and looped rapidly (15–25 cm s^{-1}) around Cape Cod Bay, leaving to the north of Race Point on June 9th.

Far-field Trajectories

Figures 2.3-7, 2.3-8, and 2.3-9 indicate the trajectories of the drifters that were tracked for significant periods once they left Massachusetts Bay. Drifter 5 from the May, 1990 deployment continued south along the Outer Cape (fig. 2.3-7), then looped southwestward around Nantucket Shoals. Drifter 2 from the July, 1990 deployment crossed Great South Channel and stopped transmitting to the north of Georges Bank.

None of the drifters from the October deployment were tracked beyond Massachusetts Bay.

In the January, 1991 deployment (fig. 2.3-8), all of the drifters headed southeastward, past the tip of Cape Cod, across Great South Channel.

In the May, 1991 deployment (fig. 2.3-9), all of the drifters followed the outer Cape southward. Drifter 3 turned slightly eastward as it approached the southeastern tip of the Cape, after which it paralleled the other drifters in a roughly southerly track. All of the drifters turned westward around Nantucket Shoals.

Table 2.3-2: Fate of the drifters

Drifter #	Date	Deployment 1
1	5/1-5/4/90	Grounded in Boston Harbor after 2 days.
2	5/1-5/21/90	Grounded on Outer Cape (Truro) after 3 weeks. Reached CC in 4 days; left Bays after 18 days.
3	5/1-5/4/90	Grounded in Marshfield after 2 days.
4	5/14-6/15/90	Entered CC Bay in 7 days. Left Bays in 50 days.
5	5/14-6/14/90	Nantucket Shoals, 1 month. Did not enter CC Bay. Left Bays in 10 days.
		Deployment 2
	7/26-7/29/90	No transmit. Grounded in Marshfield after 2 days.
1	7/26-8/1/90	Grounded in Duxbury after 6 days.
2	7/26-9/20/90	Georges Bank in 5 weeks. Entered CC Bay in 7 days. Left Bays after 12 days.
		Deployment 3
1	10/16-10/21/90	Grounded in Duxbury after 5 days.
2	10/16-11/10/90	Grounded to S of Race Pt in Provincetown after 25 days. Did not enter CC Bay.
3	10/16-10/17/90	Intercepted by Lobster boat off Cohasset.
		Deployment 4
1	2/1-2/27/91	Deployed in Stellwagen Basin; Great South Channel, 12 days. Did not enter CC Bay. Left Bays in 6 days.
2	2/1-2/27/91	Deployed in Stellwagen Basin; Great South Channel, 21 days. Did not enter CC Bay. Left Bays in 15 days.
3	1/31-2/27/91	Deployed near B Buoy; Great South Channel, 25 days. Did not enter CC Bay. Left Bays in 16 days.
		Deployment 5
1	5/8-7/8/91	Deployed off Merrimack River; redeployed at Merrimack River 5/24; western Mass Bay 5/29; grounded, redeployed 6/7; Nantucket Shoals; 30 days. Did not enter CC Bay; left Bays in 7 days.
2	5/24-7/8/91	Deployed off B buoy; Nantucket Shoals, 30 days; Did not enter CC Bay; left Bays in 15 days.
3	5/29-7/8/91	Deployed off B buoy; Nantucket Shoals, 30 days; Entered CC Bay in 6 days; left Bays in 10 days.

Summary statistics of drifters:

Total number of drifters: 17

Deployed in western Mass Bay 15
Deployed in Stellwagen Basin 2

Number that left Mass Bay: 10

via Race Point channel 8
across Stellwagen Bank 2 (both had been deployed in Stellwagen Basin)

Number retained in Mass Bay: 7

Grounded or snagged, Cohasset to Duxbury 5
Grounded, Boston Harbor 1
Grounded, Provincetown 1

Residence or Transit times:

1. Western Mass. Bay to Race Point: 7 10 10 12 15 16 18 25+ 50 days
2. Within Cape Cod Bay: 4 5 14 43 days
3. Western Mass. Bay to Cape Cod Bay: 4 6 7 7 days

Drift direction:

16 out of 17 had a net southward or southeastward component of drift.

Table 2.3-3: Average Speeds, Drifters (Data for drifters within Bays)

Spring 1990

Drifter No.	Mean Speed cm/s	Net Drift cm/s	Direction	Days	Fate
1	2.05	1.14	206	6	grounded in Boston Harbor
2	8.56	3.70	123	19	exited
3	7.31	5.14	164	4	grounded near Marshfield
4	8.61	1.67	127	50	exited
5	11.95	6.72	120	11	exited

Summer 1990

Drifter No.	Mean Speed	Net Drift	Direction	Days	Fate
1	10.44	9.98	156	5	grounded near Plymouth
2	13.11	5.24	121	11	exited

Fall 1990

Drifter No.	Mean Speed	Net Drift	Direction	Days	Fate
1	8.19	3.81	165	13	grounded near Plymouth
2	8.70	2.77	129	26	grounded at Race Point
3	13.57	13.56	183	1	snagged near Cohasset

Winter 1991

Drifter No.	Mean Speed	Net Drift	Direction	Days	Fate
1	10.69	5.32	127	7	exited
2	6.08	2.78	124	19	exited
3	6.91	3.87	120	18	exited

Spring 1991

Drifter No.	Mean Speed	Net Drift	Direction	Days	Fate
1	9.75	3.57	148	21	exited
2	7.12	4.55	119	16	exited
3	12.87	5.57	127	11	exited

Composite Representation of Drifter Data

The drifter data provide observations of velocity in regions that were not occupied by moored instruments, thus providing more insight into the spatial structure of the flow. The limited temporal coverage of the drifters in any given portion of the Bays does not permit the estimation of reliable mean velocities, and the estimation of an Eulerian current field from Lagrangian drifters yields a biased estimate of the flow (Davis, 1985). In spite of these limitations, a map was constructed of the spatial distribution of near-surface currents in the Bays based on a composite of all of the drifters released during the project (fig. 2.3-10). A map of the currents was generated by interpolating the low-pass filtered velocity data (6 hour subsamples) onto a uniform grid, then smoothing the data with a 3×3 box-car filter. The number of velocity estimates in each grid cell is indicated in fig. 2.3-11 (upper panel). Note that there are few velocity observation in the seaward part of the Bays with which to base a velocity estimate, but there are quite a few points in the central portions of the Bays.

The result of this analysis is shown in fig. 2.3-11 (lower panel). Not surprisingly, the drifters indicate a mean throughflow, although the inflow is not well resolved. This is due to the fact that all but one of the drifters was deployed within the Bays. Along-bay currents of 5–10 cm s^{-1} are found through the middle portion of the Bays, and there is no evidence of intensification of the flow along the coast. The strong outflow at Race Point is clearly indicated. The drifter data show stronger southward flows at the locations of the Scituate and Stellwagen Basin moorings than were observed in the moored records. These differences probably reflect the uncertainty of the mean velocity estimate from the drifter data due to the very small sample size. An attempt was made to compare drifter velocities directly to moored current measurements, but the large spatial variability of the flow likely explains most of the difference.

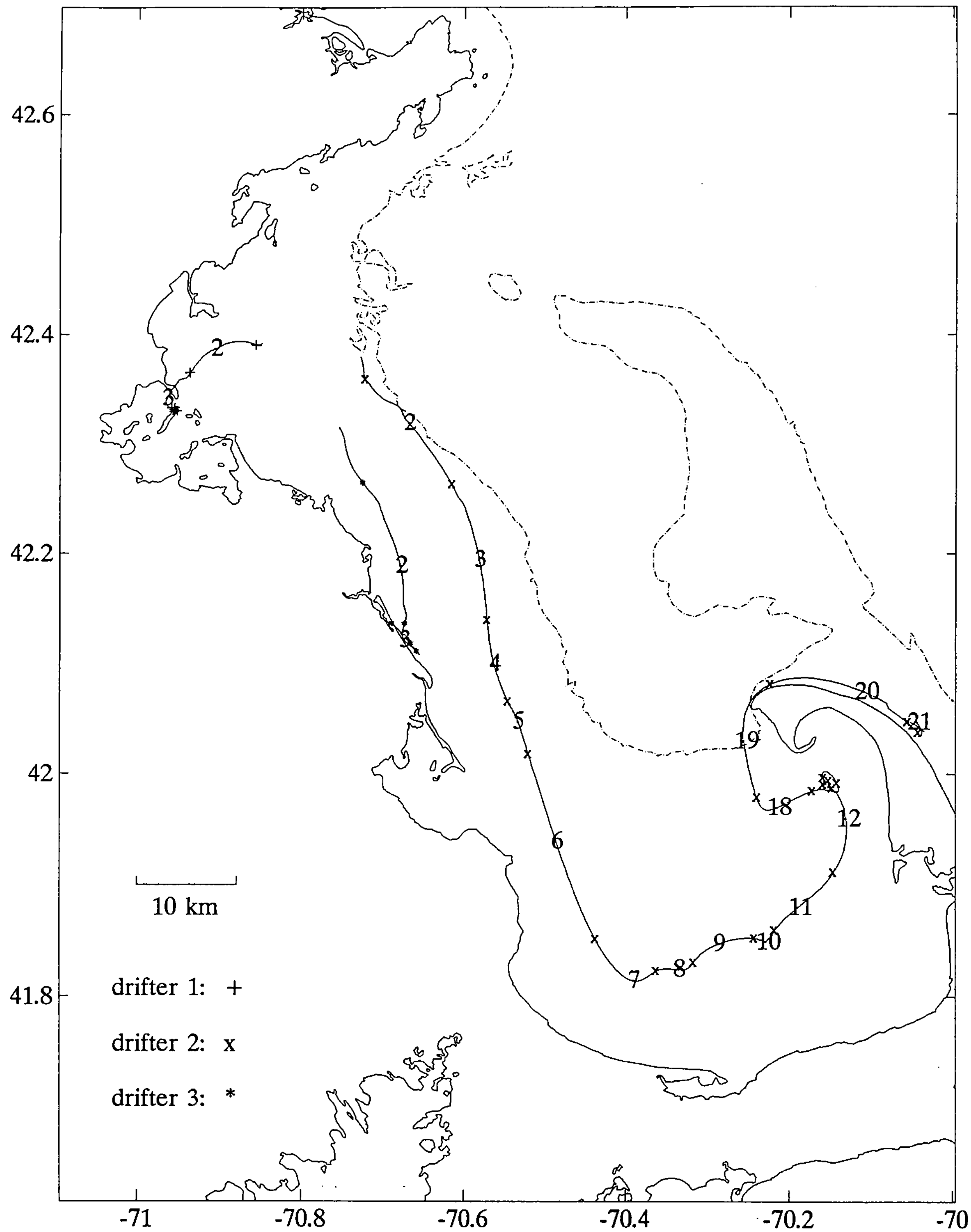


Figure 2.3-1 Drifter trajectories, first release, May, 1990. Three drifters were released to the east of Boston Harbor on May 1, 1990. The numbers on the drifter tracks indicate the calendar day in May, at 1200 GMT. The symbols denote 0000 GMT. The data have been smoothed with a 35-hour filter to remove tidal motions, except at the beginning and end of each trajectory.

MB-1B, May - July, 1990

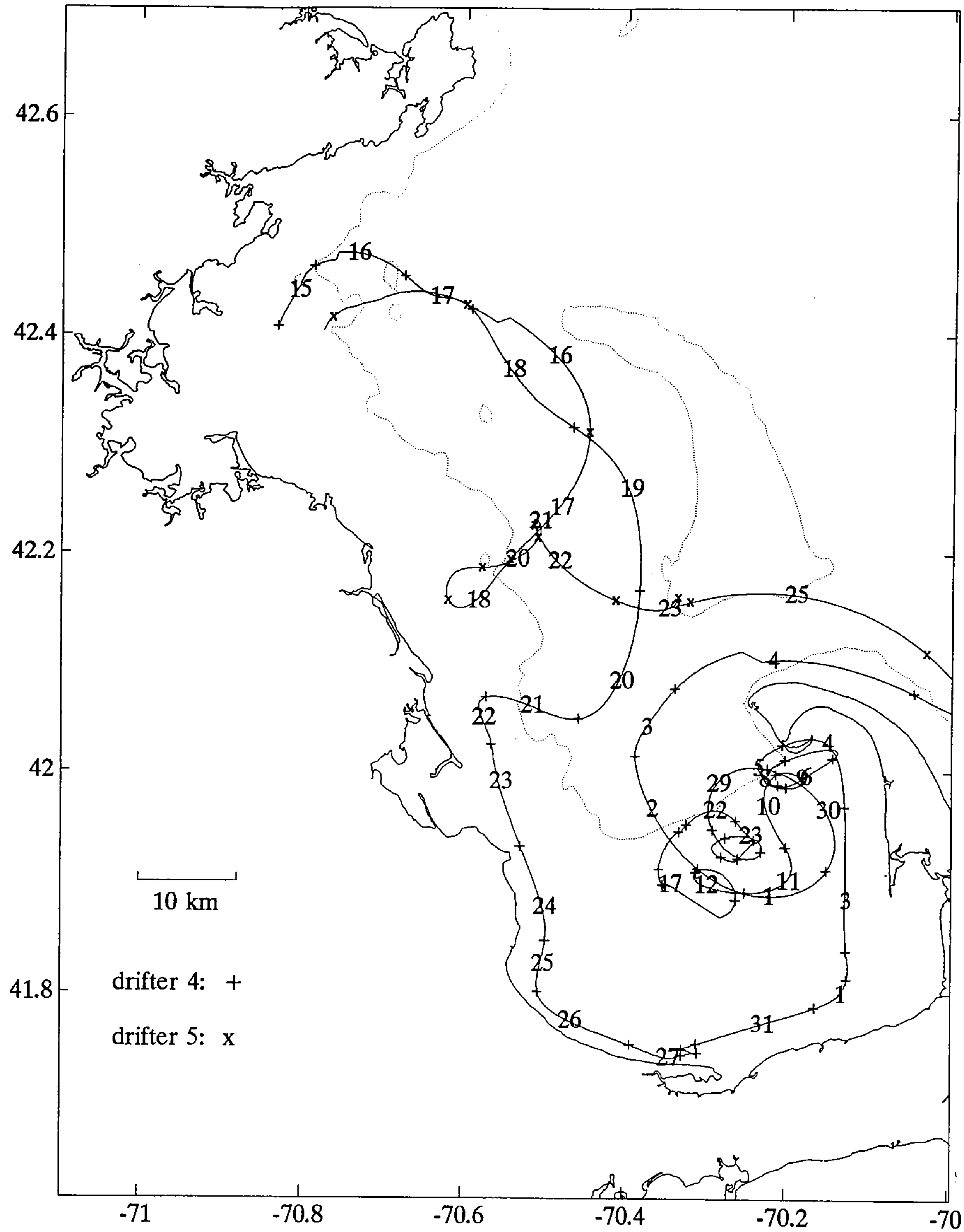


Figure 2.3-2 Drifter trajectories, second release, May–June, 1990. Two drifters were released to the east of Boston Harbor on May 16, 1990.

MB-2: July - August, 1990

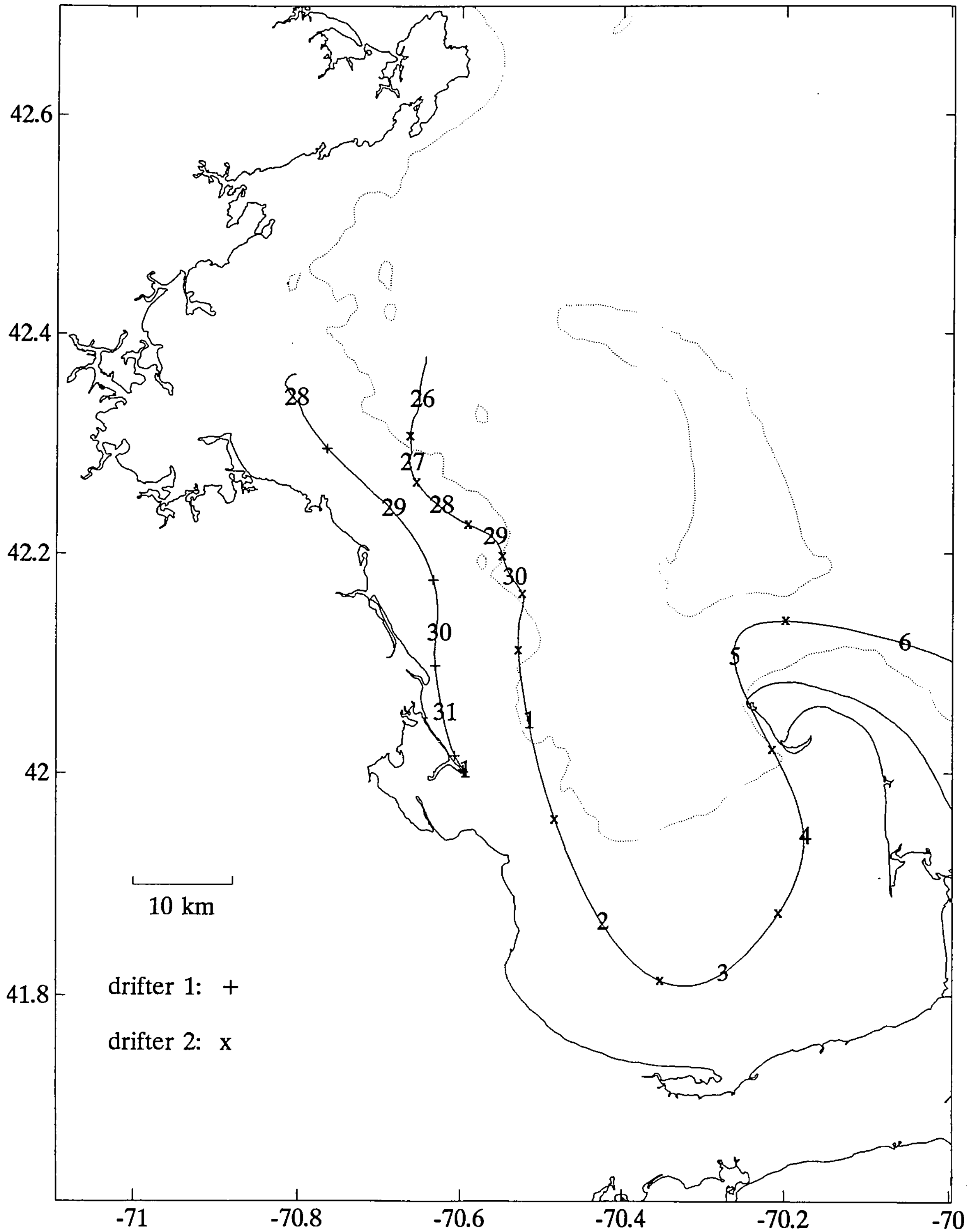


Figure 2.3-3 Drifter trajectories, July–August, 1990. Three drifters were released to the east of Boston Harbor on July 27, 1990. One drifter's tracking system failed.

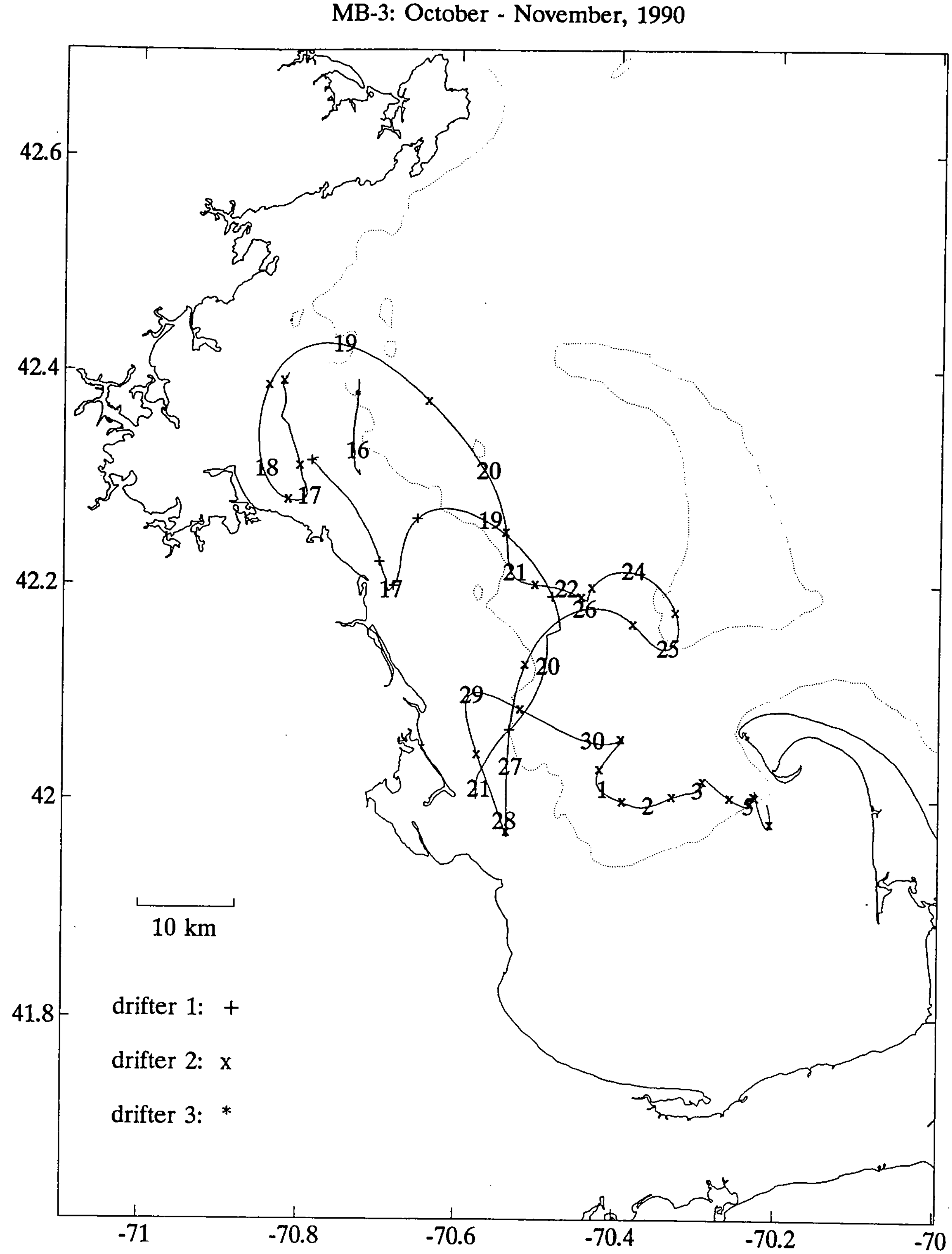


Figure 2.3-4 Drifter trajectories, October–November, 1990. Three drifters were released to the east of Boston Harbor on October 15, 1990. One drifter was intercepted by a fishing boat one day after release.

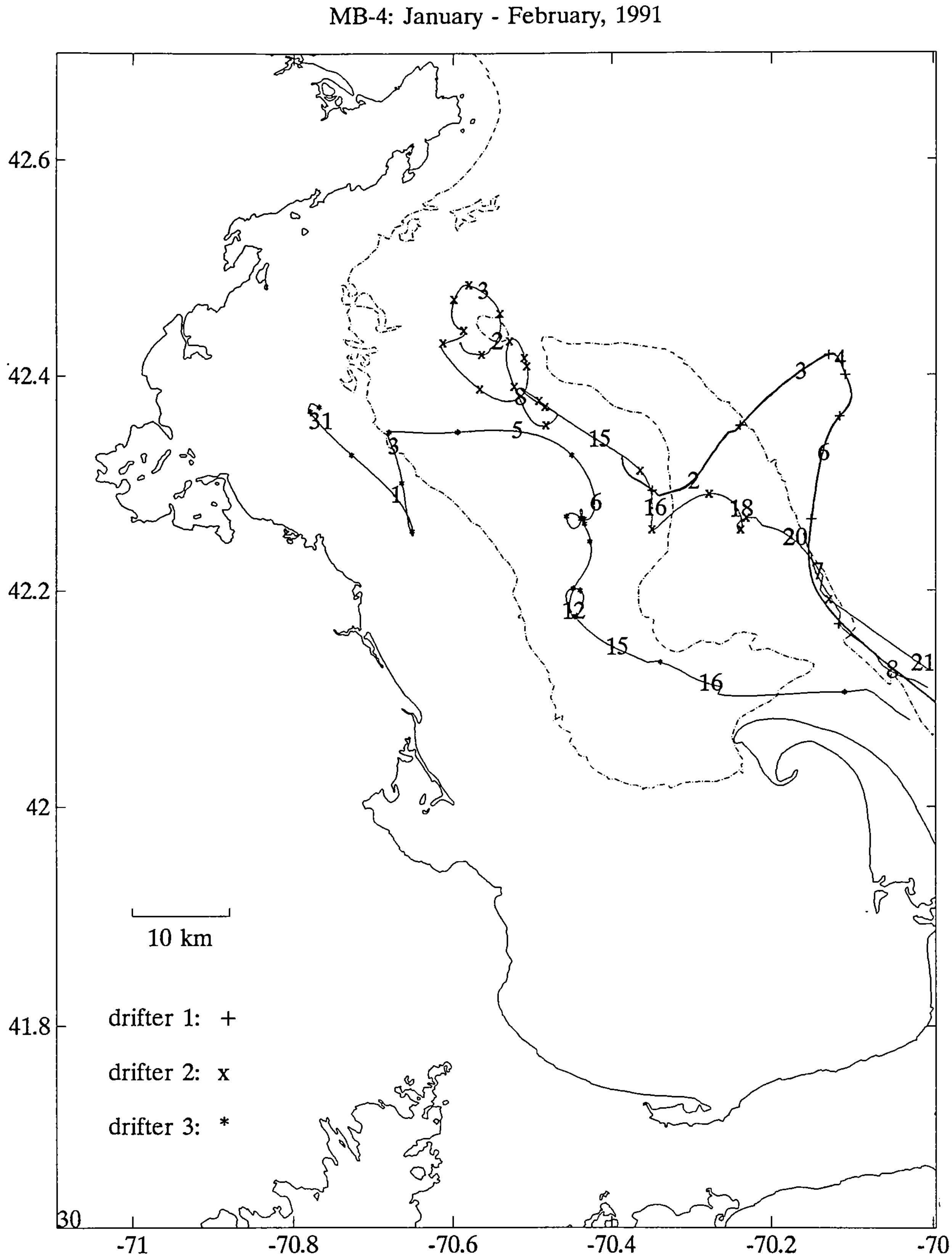


Figure 2.3-5 Drifter trajectories, January–February, 1990. Three drifters were released in northern Massachusetts Bay between January 30 and February 1, 1991.

MB-5: May - June, 1991

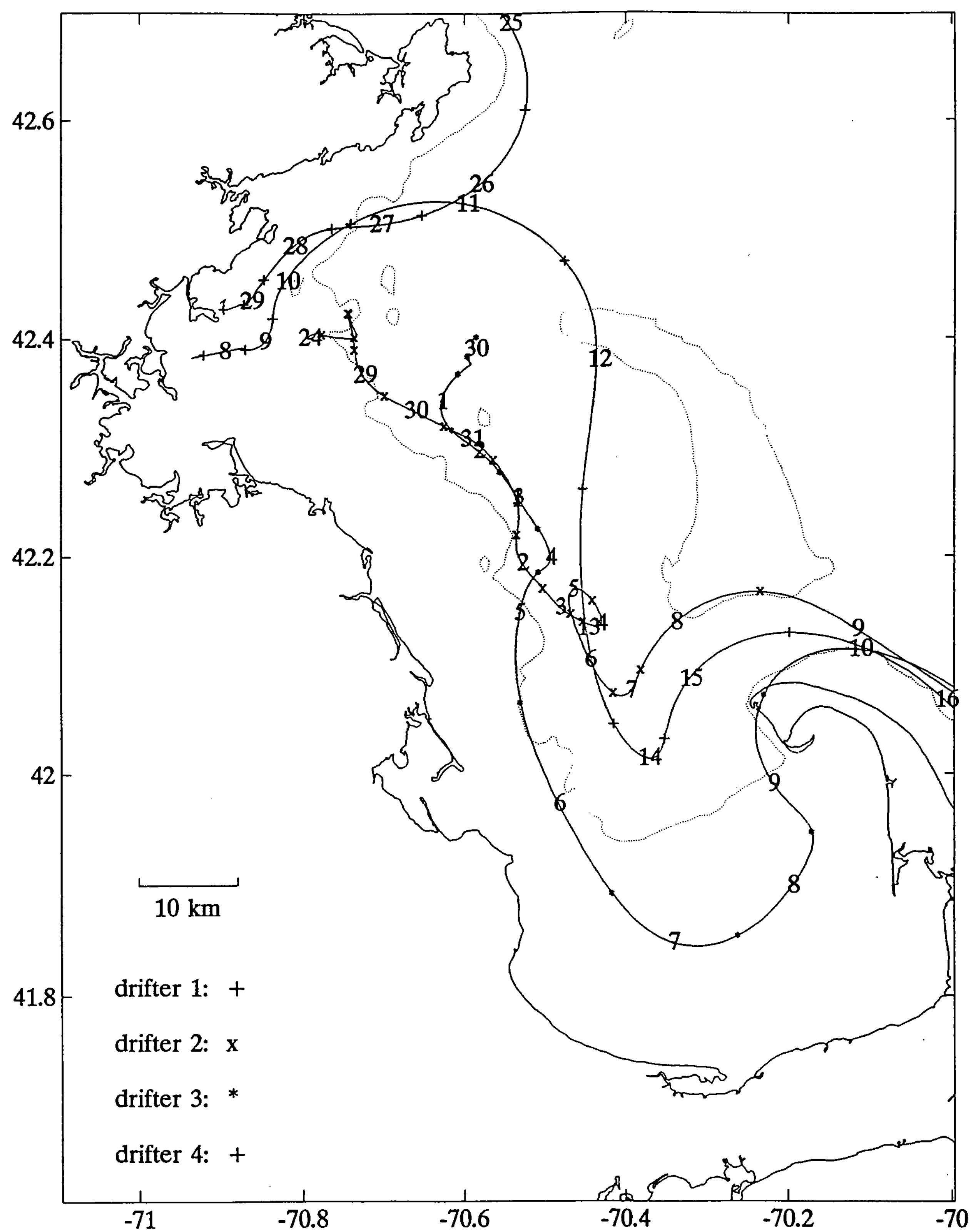


Figure 2.3-6 Drifter trajectories, May–June, 1991. One drifter was released offshore of the Merrimack River, and two drifters were released in northern Massachusetts Bay. Drifter 1 was recovered at Nahant and redeployed on June 7, 1991.

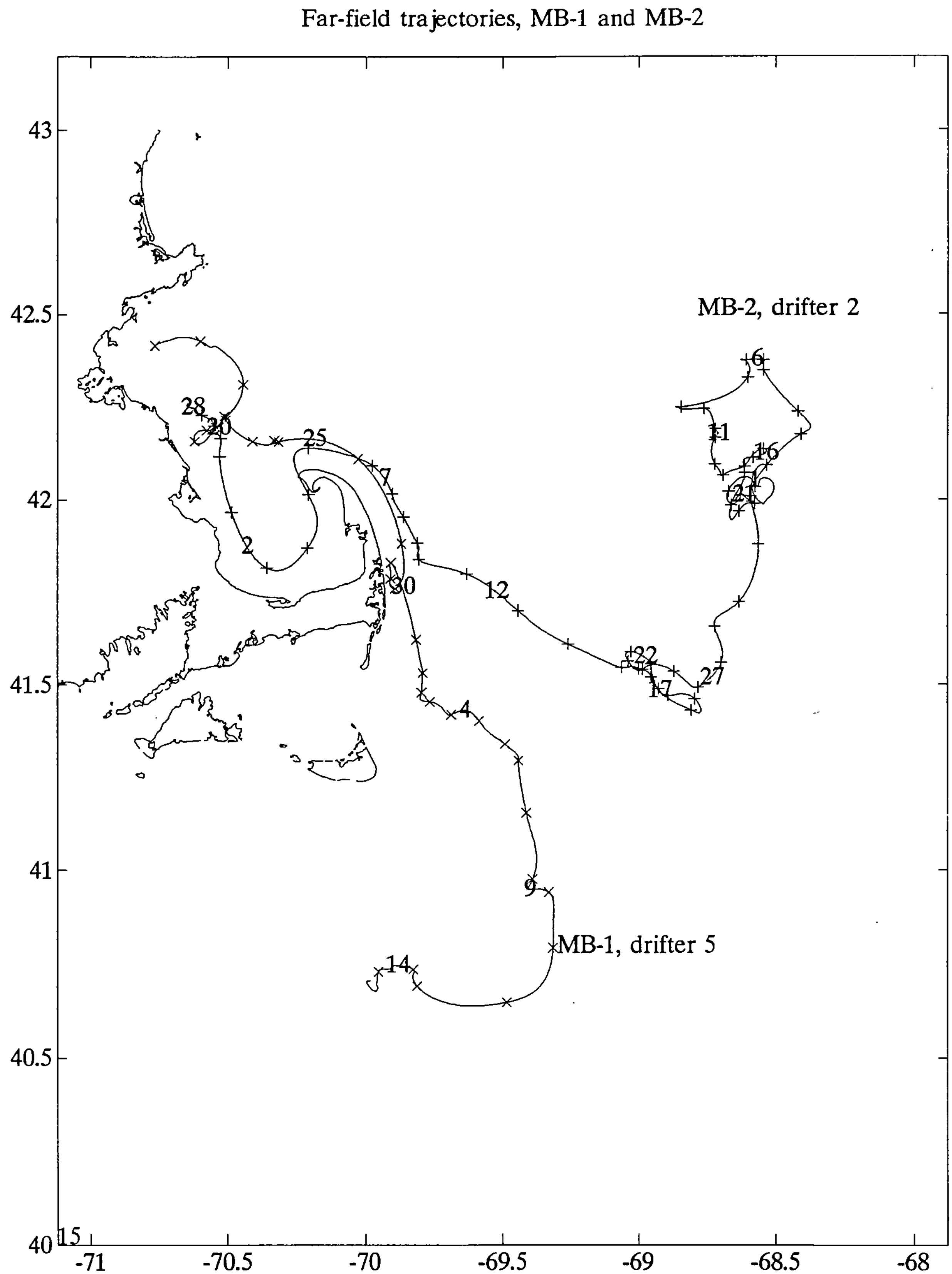


Figure 2.3-7 Far-field trajectories of spring and summer releases, 1990. Two drifters continued beyond Massachusetts Bay. The drifter released in May continued southward around Nantucket Shoals, while the drifter deployed in July headed east, to a position west of Georges Bank.

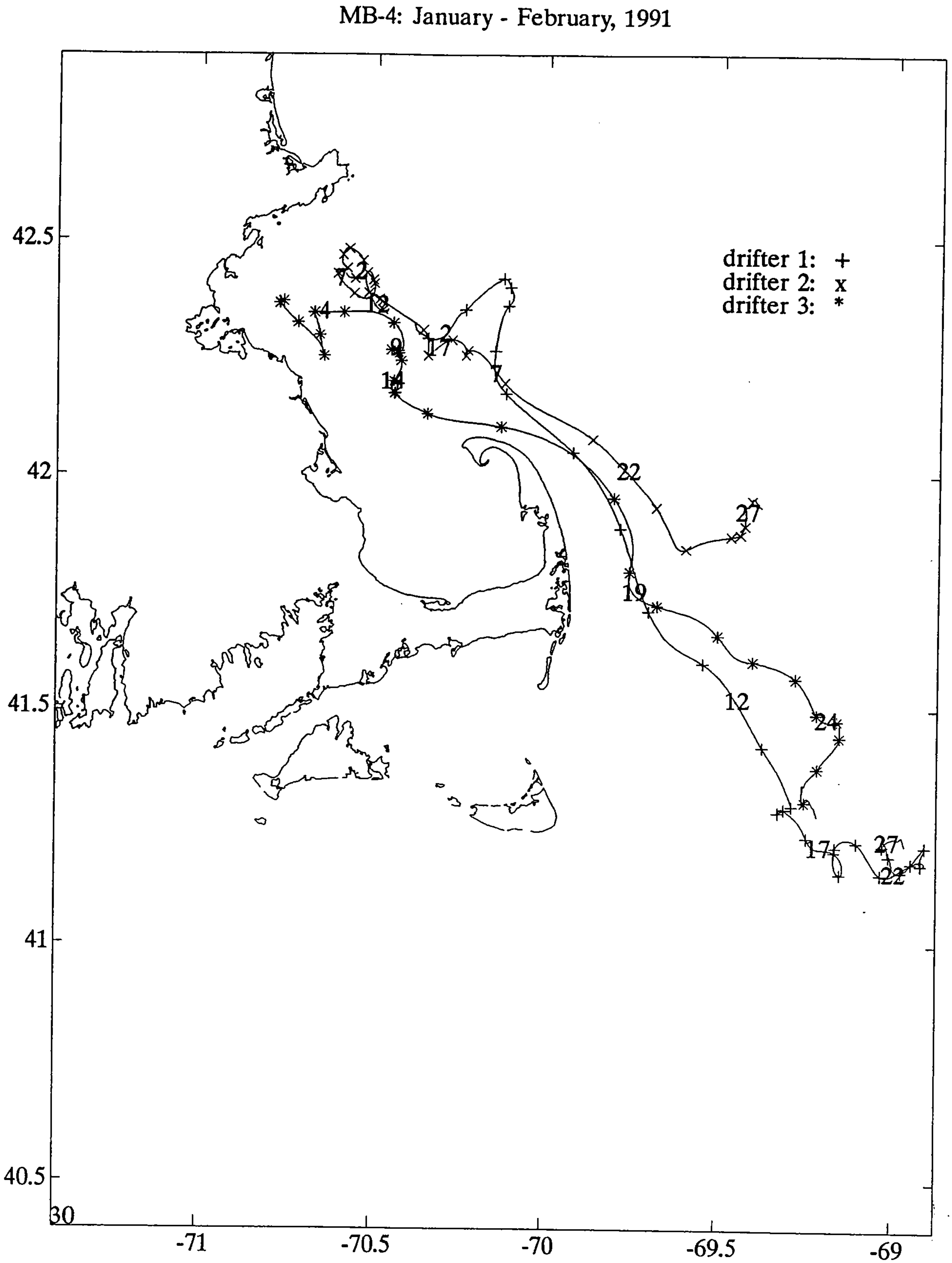


Figure 2.3-8 Far-field trajectories, winter release, 1991.

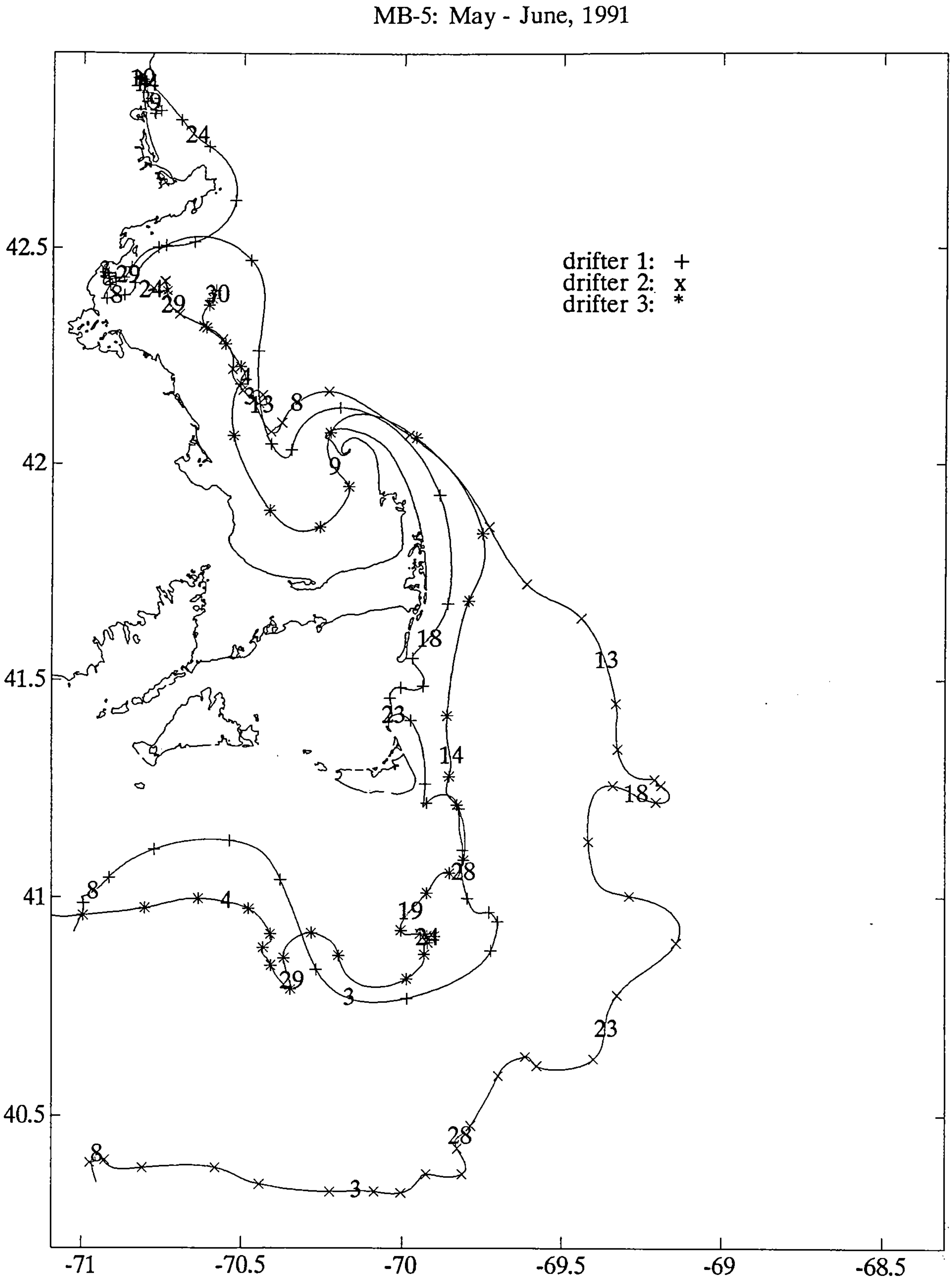


Figure 2.3-9 Far-field trajectories, spring release, 1991.

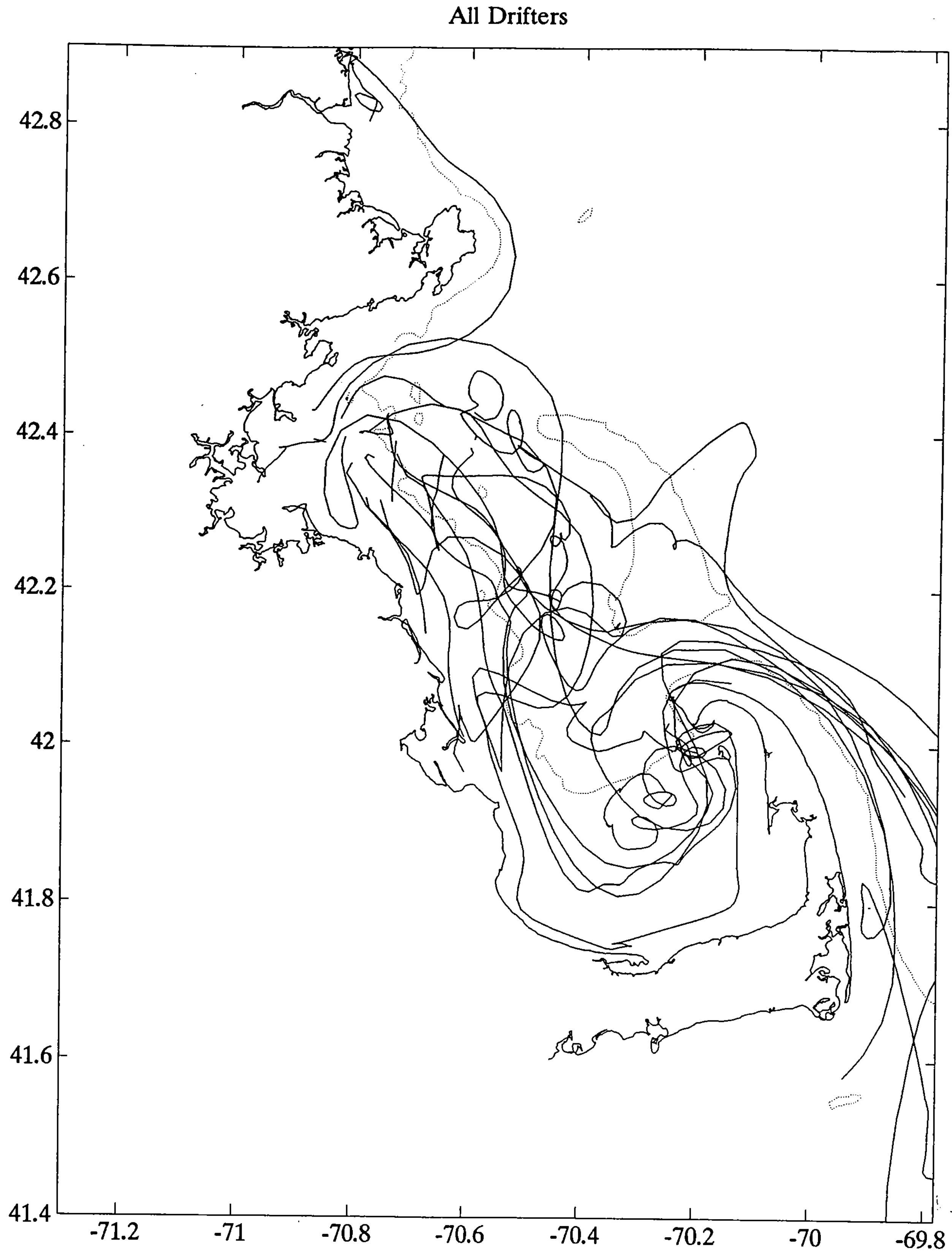


Figure 2.3-10 Composite of trajectories of all of the drifters released during the Massachusetts Bays Program.

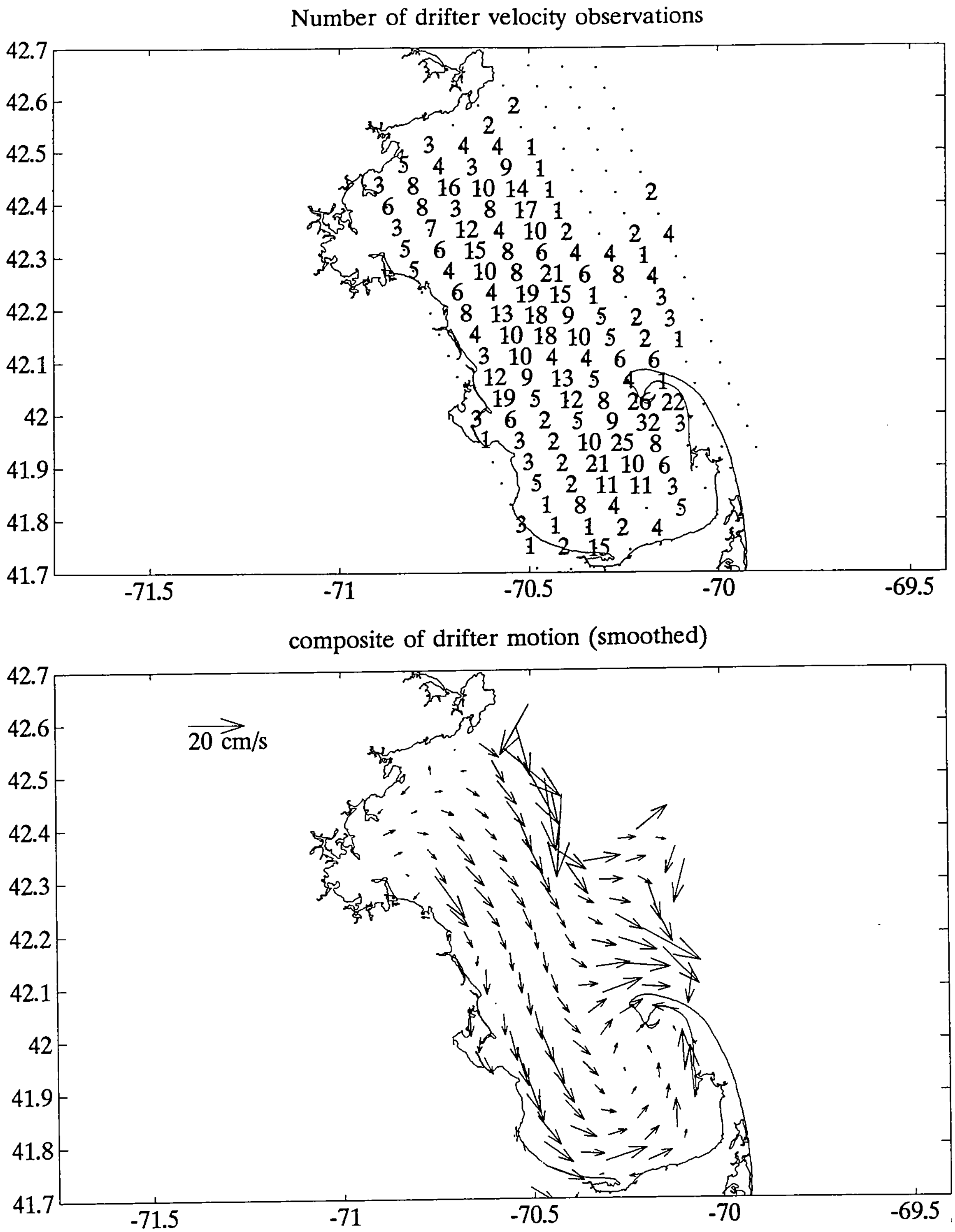


Figure 2.3-11 Spatial rendition of drifter velocity field, using composite of all of the drifter data. Upper panel: number of drifter velocity estimates in each spatial bin. Lower panel: velocity vectors, based on composite of drifter velocity data. Although many of the velocity estimates are not statistically significant due to the small number of samples, the overall flow pattern is consistent with the moored data.

2.4 Hydrographic Surveys

2.4.1 Methods: Hydrographic Surveys

Twelve hydrographic surveys were conducted during the period from April, 1990 through June, 1991. Three types of survey cruises were performed. Six baywide surveys provided detailed coverage of the Bays during different seasons. The first two of these were conducted jointly by UMB and WHOI. Later cruises were conducted entirely by UMB. Baywide cruises in April, July and October, 1991 surveyed approximately 75 stations, largely within Massachusetts and Cape Cod Bays. The last three cruises were extended to provide information concerning the oceanographic conditions in the adjacent portion of the Gulf of Maine. The cruise in March, 1991 was funded by the Massachusetts Water Resources Authority. This cruise, which followed the same cruise track as the Bays Program cruises, was added to obtain additional data during the spring bloom.

Four one-day cruises were conducted using the R/V Neritic, a 25 ft. boat owned and operated by UMB. These cruises surveyed the northern portion of Massachusetts Bay (from Boston to Cape Ann), and provided enhanced temporal resolution of conditions in that portion of the Bay.

Following the March and April, 1991 seasonal surveys, follow-up surveys were conducted which essentially covered the boundary of the main study. These were funded by the USGS, primarily to provide information on short-term variations for use in the development of a numerical model of the circulation of Massachusetts and Cape Cod Bays. Cruise dates are summarized in figure 2.4-1.

Measurements made on all cruises include temperature, salinity, fluorescence (as an indication of Chlorophyll-a concentration), light transmission (with 0.25m path length transmissometer), dissolved oxygen, and relative velocity, measured with a Seabird Electronics CTD system and associated instruments. During the April and June, 1990 cruises, the measurements in Cape Cod Bay were obtained with a Neil Brown MK III CTD. In addition to these parameters, bottle samples were obtained at selected stations and analyzed for dissolved oxygen and chlorophyll-a for calibration purposes. Nutrients and total suspended solids were determined for the bottle samples by Dr. Ted Loder and Susan Becker of the University of New Hampshire (see Section 2.7).

Station locations for the surveys are indicated in figures 2.4-2, 2.4-3 and 2.4-4. For convenience in locating the stations they have been grouped into sections, with names based on geographic locations near the inshore end of each section. Note that there was a change in the Cohasset section associated with the addition of offshore stations for the last three cruises. Station lists, including actual time and location are included in appendix H for each cruise.

The CTD data were processed using software supplied by Seabird Electronics with modifications made at UMB. Measurements were averaged to 0.5 meter bins. The averages are stored in ASCII flat files in a format designed to facilitate access by plotting and analysis programs. Two auxiliary files are used for each cruise to allow individual stations or sections to be examined. Station locations, depths and times as well as data file names are stored in a header file. To allow for the plotting of vertical sections, lists of stations and section names are stored in a section file.

2.4.2 Hydrographic Data Quality Control

The conductivity and temperature sensors on the CTD were returned to the factory regularly for recalibration and for replatinizing the conductivity sensor. The temperature sensor is extremely stable, with a drift between calibrations of less than 0.01°C per year. The conductivity sensor is less stable, and the recalibrations are necessary to maintain optimum accuracy. As a check on the conductivity sensor, water samples obtained at a subset of the nutrient sampling stations were analyzed by UNH to determine the salinity. Comparison of CTD determined salinity with the UNH values showed that the CTD was accurate to better than 0.03 psu. This accuracy is more than adequate for the estuarine and coastal work reported here.

Comparison of laboratory determined chlorophyll with the fluorometer signal indicated that the response of the fluorometer is modified by factors not measured as well as the chlorophyll concentration. An attempt was made to fit calibration curves for each cruise, but the variation was too large for this to be acceptable. As an alternative, all data from all cruises was combined to obtain a single calibration. This was used to correct the fluorescence data to provide the best estimate of chlorophyll-a. The data reported here represent that estimate (in μg/l). However the data are labeled as "fluorescence" to stress the fact that the calibration is uncertain. The data is adequate to judge trends and patterns in the data, but individual values may be in error by a factor of two or more. For future field studies, if more accurate determination of chlorophyll-a is required a much larger number of samples should be taken, preferably using a rosette sampler rather than attaching bottles to the hydro-wire as was done on the Bays program cruises.

The oxygen data from the CTD and laboratory were used to derive calibrations for each cruise. For some cruises there was not a sufficiently wide variation to fit a linear curve, and for these a multiplicative correction was derived instead.

2.4.3 Hydrographic Observations

Overview

The spring conditions were characterized by significant salinity stratification, particularly in the northern portion of the study region, associated with freshwater input from rivers entering the Gulf of Maine to the north of Massachusetts Bay. There was considerable horizontal heterogeneity in the surface salinity which is best explained as indicating episodic intrusions of relatively fresh water due to variations in river flows or in the effect of wind on the path of the coastal current.

Compared with spring measurements, the thermal stratification was found to be more important in the summer and fall. The horizontal variability of temperature and salinity was generally lower than in the spring except in the nearshore region where upwelling resulted in relatively cold surface water.

Nearly well mixed conditions existed in the vertical during the February 1991 cruise. The temperature was lowest nearshore, indicating that cooling was most effective there. This evidence of enhanced cooling was particularly striking in Cape Cod Bay. A cold, relatively fresh surface current was identified flowing from Cape Cod Bay around the outer shore of Cape Cod. While the cooling occurring near the coast clearly influenced the water properties in Stellwagen Basin, no evidence was found of this cold water penetrating into the deep water of the Gulf of Maine as was suggested by Mountain and Jessen (1987). The winter of 1990–1991 was, however, relatively mild.

Chlorophyll-a concentrations were generally highest in the vicinity of the pycnocline during the spring, summer and fall surveys. The concentration was very low in February except in Cape Cod Bay, where a significant phytoplankton bloom was in progress.

Contour Plots: Baywide Cruises

The hydrographic measurements from the baywide cruises are presented in this section in a series of figures showing contours of temperature, salinity, density and fluorescence along cross bay sections and on horizontal surfaces. The vertical distributions are represented by the Boston (northern), Humarock (mid-bay) and Plymouth (southern) sections. The horizontal fields are shown on contour plots of properties averaged from one to three meters. Station locations are indicated by t's on the horizontal plots. The vertical and horizontal plots are combined on a single page for each property/cruise to facilitate the three-dimensional interpretation of the data. In addition to the cross bay/horizontal contour figures, vertical contour plots along the center of the bay are also presented. These use the same stations as the mid-Bays nutrients sections in section 2.7.

April 27-28, 1990

Vertical stratification was found in both temperature and salinity in the spring, 1990 data, as seen on figures 2.4-5 and 2.4-6. The temperature was relatively uniform horizontally through most of Massachusetts Bay, with slightly higher temperatures in Cape Cod Bay, consistent with more effective warming in the shallower water there. A layer of relatively fresh water was found in northern Massachusetts Bay, indicating the intrusion of a coastal current containing water from the Merrimack River as well as the Androscoggin, Kennebec and Penobscot Rivers in Maine. This water is seen most clearly near Cape Ann. The fresh water layer near Boston may have come from Boston Harbor, although there is evidence that freshwater pulses from the Gulf of Maine sometimes follow the north shore into western Massachusetts Bay (see Section 3.2). The southern portion of Massachusetts Bay and Cape Cod Bay show a higher salinity, with a boundary between the two regions near the Humarock section. There was also slightly lower salinity in the southeastern corner of Cape Cod Bay, which may be due to local freshwater sources (principally groundwater) or trapping of water that had entered Cape Cod Bay from the north. The density field (fig. 2.4-7) reflects the temperature and salinity, with considerably stronger stratification at Boston than at the other two sections.

Figure 2.4-8 shows the fluorescence (chlorophyll-a) signal. Data are available only at the northern two thirds of the Bays, because the instrument package used by WHOI to survey the southern third did not include a fluorometer. The highest surface values are seen near Boston, possibly reflecting the effect of nutrient enrichment from the MWRA treatment plants (see Section 2.7). The vertical distribution shows a chlorophyll maximum in the vicinity of the pycnocline. Nitrogen levels were relatively low in the upper mixed layer (see Section 2.7), suggesting that the phytoplankton were concentrated near the pycnocline due to an optimal combination of light and nutrients.

The distribution of temperature, salinity and fluorescence along a north-south section in mid-bay are shown in figures 2.4-9, 2.4-10 and 2.4-11. Note that the fluorescence section ends at Humarock. The pycnocline is slightly deeper and broader in the southern portion of the Bays than the northern. The maximum of the fluorescence signal near the pycnocline is clearly seen in figure 2.4-11, with highest concentration at the Scituate section.

July 24-25, 1990

Thermal stratification was considerably greater in July, 1990 than found during the April, 1990 cruise, with surface to bottom differences of 12°C to 15°C, compared to 3°C in the spring (fig. 2.4-12). The rapid increase in surface temperature of more than 10°C between April and July is due to the high rate of solar insolation during this season. The temperature of the deep waters increased by only 2°C. There was no identifiable surface mixed layer, the gradients extending virtually to the water surface. The salinity (fig. 2.4-13) was 0.5 psu to 1.0 psu lower than in the spring, with the largest change occurring in Cape Cod Bay. The salinity of the deep water in Massachusetts Bay increased by approximately 0.3 psu. The implications of these changes for mixing processes in the pycnocline and for the associated time scale of renewal of the deep water is discussed in section 3.4.2.

There was a clearly defined front, evident in the temperature, salinity and density (fig. 2.4-14) surfaces extending northeast from Plymouth. Cape Cod Bay is considerably shallower than Massachusetts Bay, and the front may be attributed in part to greater warming within Cape Cod Bay. The reduced salinity there, however is harder to explain. It may be a remnant of an earlier intrusion of fresh water from the rivers of the Gulf of Maine, though the flow from the Merrimack and other Gulf of Maine rivers was relatively low during the period preceding the cruise. An alternative source for the fresh water in Cape Cod Bay is the relatively modest discharge of ground water from Cape Cod, as mentioned above. If there was relatively little exchange with adjacent waters, this flow could account for the reduced salinity. Superimposed on the generally warm, fresh water of Cape Cod Bay was a colder, saltier region at the extreme southern edge of the bay. This dense water along the coast indicates upwelling, which was found to occur during periods of southerly or southwesterly winds (see Section 3.3).

The fluorescence levels (fig. 2.4-15) were highest near the surface, with particularly high levels near Boston. The nutrient data showed depletion in the near-surface waters, presumably stripped by the phytoplankton associated with the fluorescence signals.

Figures 2.4-16, 2.4-17 and 2.4-18 display the mid-bay longitudinal sections of temperature, salinity and fluorescence. It is evident from figures 2.4-16 and 2.4-17 that the front between Massachusetts and Cape Cod Bays was a relatively near surface phenomenon with the deeper isoclines deflecting relatively little. The warm, fresh region in Cape Cod Bay is seen as a shallow lens of water with a maximum depth of approximately 10 m. The moderately high, uniform fluorescence is seen above 25 m, with measurable amounts to the bottom. Growth of phytoplankton below 20-30 m is unlikely due to light limitation, so the deeper chlorophyll signal may be the result of the sinking of dead cells.

October 16–18, 1990

Temperature (fig. 2.4-19), salinity (fig. 2.4-20) and density (fig. 2.4-21) were characterized by upper and lower mixed layers with a strong pycnocline between. Surface temperature was lower, and deep temperature higher than in July, suggesting continued mixing between the two layers. However, the salinity of the deep water actually increased from July to October, which can only be explained by an advection of water from the Gulf of Maine. (See Section 3.4.4 for a discussion of the implications in term of water mass exchange). The warmest surface water extended from Cape Cod Bay to the Humarock section, though there was not a well defined front between the northern and southern regions as found in July.

A patch of cold, high salinity water was found near Plymouth. Based on the transverse and vertical structure of the isotherms, this anomaly appears to be due to both upwelling and seasonal cooling. Higher density of the water along the coast compared to the middle of Cape Cod Bay during the fall resulted in the northward flow observed at the coastal moorings during this period (section 2.2).

Pronounced salinity anomalies were observed offshore of Boston Harbor and near Cape Ann. These are apparently explained by a period of rain prior to the cruise, resulting in increased flow in the Merrimac River, north of Cape Ann, and in the rivers entering Boston Harbor.

Fluorescence levels (fig. 2.4-22) were highest above the pycnocline, with slight evidence of a subsurface maximum. High levels existed near Plymouth, corresponding to the upwelling mentioned above. Slightly elevated NO_3 concentration in this area (Section 2.7, fig. 2.7-14) supports the conclusion that upwelling of deeper water provided increased nutrients, contributing to phytoplankton production.

Variations of temperature, salinity and fluorescence along the mid-bay longitudinal section are shown in figures 2.4-23, 2.4-24 and 2.4-25 respectively. All three are dominated by a depression of the isoclines at the Scituate section, slightly less than half way from north to south. This feature was caused by the presence of an internal wave at station SC4 at the time of the profile. These large amplitude waves have been reported by several investigators (e.g. Halpern, 1971; Haury et al., 1979) in Massachusetts Bay (see also Section 3.1). The sampling was too coarse in both space and time on the Bays Program cruises to resolve the waves, particularly in the north–south direction. Hence the structure represented by these figures does not represent the actual wave structure. The figures do provide an indication of the amplitude of the internal waves, which in this case are on the order of 20 m.

February 4–6, 1991

During the winter, the water column was well mixed (figs. 2.4-26, 2.4-27 and 2.4-28). There was a strong horizontal gradient of temperature (colder near shore) due to the increased effectiveness of cooling in the shallower areas. Also, the salinity was lowest nearshore, suggesting a contribution to the coastal, surface waters from Boston Harbor and other sources within the Bay. Moored observations (Section 2.2) suggest that little advective exchange occurred between the Bays and the Gulf of Maine during the winter period, increasing the importance of local sources of fresh water. Note particularly the cold, fresh region in the eastern side of Cape Cod Bay. This appears to be isolated from other areas of the Bays. Cooling in this very shallow region explains the temperature. Again, the reduced salinity may result from local groundwater input from Cape Cod or from trapping of fresh water from an earlier run-off event originating in Boston Harbor.

Very low fluorescence levels characterized most of the study area in February (fig. 2.4-29), except in Cape Cod Bay, where high levels of fluorescence were found in the shallow portion of the Bay near Billingsgate Shoal. Although light limitation usually prevents blooms this early in the year, the shallow water in eastern Cape Cod Bay may permit phytoplankton growth in the winter, since the attenuation of light with depth is not a major factor in water depths of less than 10 m.

The cold, relatively fresh water in Cape Cod Bay is clearly seen in figures 2.4-30 and 2.4-31, which display the mid-bay longitudinal sections of temperature and salinity. Figure 2.4-32 clearly indicates the difference in the fluorescence level between Cape Cod and Massachusetts Bay.

March 20–23, 1991

The temperature of the Bays had increased slightly by March 20, but the water was still well mixed vertically, with very little horizontal variation within the Bays (fig 2.4-33). The temperature in the Gulf of Maine was approximately 0.75°C higher than that within the Bays, but colder than it had been in February. Apparently the Bays warmed more rapidly than the deeper Gulf, due most likely to the depth difference.

The salinity field (fig. 2.4-34) was characterized by three regions of relatively fresh water. A large plume of low salinity ($\leq$ 31.6 psu) water entered the Bays at Cape Ann, and was identifiable as far as the Humarock section as a lens of approximately 32.3 psu water near the outer boundary of Massachusetts Bay. This plume was separated from Cape Cod Bay by a region of higher salinity surface water, while Cape Cod Bay itself had a minimum surface salinity of 32.1 psu. Finally, a region of water with salinity less than 32.2 psu extended southward along the coast from the mouth of Boston Harbor to the Duxbury section. The different pools of low-salinity water may reflect different sources, but they also may reflect differences in the flushing of the different parts of the Bays. Certainly the dominant source of fresh water is from north of Cape Ann; whether the local sources from Boston Harbor and Cape Cod are adequate to produce the observed salinity anomalies is still an open question (see Section 3.4 for further discussion). Density showed patterns (fig. 2.4-35) similar to salinity due to the small temperature variation and the reduced influence of temperature on density below 5°C.

Fluorescence was moderately high throughout the Bays, indicating the presence of a spring bloom, as seen in figure 2.4-36. Highest concentrations were found in Cape Cod Bay and in a patch in northern Massachusetts Bay between the Boston Harbor and Cape Ann fresh water plumes. Nutrient levels were uniformly low within the Bays at this time so the fluorescence variation must be related to other limiting factors on phytoplankton growth.

The cold, uniform temperature is reflected in the mid-bay longitudinal section (fig. 2.4-37), with variations only between 3.8°C and 4.0°C. The low salinity regions near Cape Ann and in Cape Cod Bay are evident in figure 2.4-38, the longitudinal salinity section. Also the high fluorescence level in Cape Cod Bay and moderate levels elsewhere are reflected in the longitudinal section of fluorescence in figure 2.4-39.

April 29–May 2, 1991

By the end of April, the temperature of surface waters had increased from the 4.0°C of March 20–23 to 8.0°C, and both temperature and salinity stratification were established (figs. 2.4-40 and 2.4-41). More rapid warming in shallow coastal areas again resulted in higher temperatures near shore, particularly in Cape Cod Bay. A plume of very low salinity water (< 30.0 psu) at Cape Ann indicated a strong coastal current just entering the Bays during this period. However, this plume did not penetrate significantly into the Bays. In contrast to the previous two cruises, the salinity in Cape Cod Bay was slightly higher than that in Massachusetts Bay. Comparison of figure 2.4-42 with figures 2.4-40 and 2.4-41 shows that the density field is still dominated by the salinity variations.

The fluorescence data (fig. 2.4-43) shows a continuing high level of chlorophyll in the water. The most notable feature is the region of extremely high fluorescence near Boston and extending to the Duxbury transect. This appears to be related to nutrient supply from Boston Harbor. Little or no subsurface maximum in chlorophyll was observed within the Bays, but one was seen outside the Bays in the Humarock section. This pronounced difference in the plankton distribution between the Bays and the Gulf of Maine suggests that there are distinct differences in the phytoplankton dynamics between the two areas.

Figure 2.4-44 shows the mid-bay longitudinal temperature section. The increased stratification relative to the March cruise is again seen. The higher temperatures in Cape Cod Bay appear to be largely a surface feature. The salinity along the mid-bay transect (fig. 2.4-45) shows lower mid-depth and surface salinity in the northern portion of the Bays, with slightly higher surface salinities in Cape Cod Bay. The longitudinal section passed through the end of the high fluorescence patch described above, as seen in figure 2.4-46. The only other significant feature on figure 2.4-46 is the region of high fluorescence near the bottom in Cape Cod Bay. This may reflect growth of phytoplankton at or near the bottom in the relatively shallow depth.

Temperature-Salinity Diagrams

The seasonal evolution of the water properties of the Bays can be represented by the temperature-salinity relationships on a Bay-wide basis. Figures 2.4-47, 2.4-48 and 2.4-49 display three-dimensional histograms of the temperature and salinity distributions for the ten cruises (including baywide and one-day cruises). The raw data are averaged into 0.5 M bins as part of the data processing procedure. Each 0.5 M sample was examined to determine the appropriate 0.5°C by 0.1 psu T-S bin. Counters for that bin, and for the total number of samples in the cruise were then incremented. After all stations for the cruise were examined, the percentage for each bin was determined from the number of samples in that bin, and in the entire cruise. This is similar to a temperature-salinity-volume (T-S-V) diagram, except the area represented by each station is not considered. The sample grid was relatively uniform in coverage, and it is not expected that the results would be greatly different for T-S-V diagrams.

Beginning with April 13, 1990, (fig. 2.4-47), the bay was generally cold (below 5°C) with a salinity of 32-33 psu. A small amount of fresher water was present. Two weeks later, April 27–28, 1990, the maximum temperature had increased to 8°C. By June 25 the maximum temperature increased to over 15°C, though most of the water was below 10°C. No well defined surface mixed layer existed at this time, consistent with the low percentages for the warmer bins. Similar conditions existed in July. Maximum temperatures exceeded 20°C, but the largest volume was still well below 10°C.

A bimodal distribution was found on September 28 (fig. 2.4-48), with a well defined surface mixed layer at about 16°C and 31.5 psu, and the deep water at 8.5°C and 32.3 psu. By October 16, these two water types had mixed considerably as the pycnocline began to break down. As noted above, the maximum salinity increased between July and October, and careful examination of figure 2.4-48 shows that this change occurred in fact between September 28 and October 16. The low salinity water observed at Boston and Cape Ann, described in the previous section, is seen as a low ridge to the left of the main water mass at 14°C.

Cold, relatively salty water was found in February, 1991 as expected during winter. The coldest water was also the freshest, due to the inshore cooling and fresh water sources. Note that while for spring through fall conditions the variation seen in these diagrams is due primarily to vertical temperature and salinity gradients, horizontal gradients are more important in the winter. Conditions did not change dramatically between February and March 21–23. The minimum temperature was somewhat higher, and a small amount of fresher water was also present. Considerably more fresh water had entered the system by April 29 (fig. 2.4-49), and this water had warmed to 8°C. On June 18, 1991 a surface mixed layer was found at 14°C, 30.8 psu.

Dynamic Height

The dynamic height is an indication of the vertically integrated density field used to calculate geostrophic velocities. The conditions required for geostrophic calculations to be accurate (steady state, no frictional effects, no advective acceleration) are met less well in coastal areas than in the open ocean. Still, the dynamic height provides a useful indication of surface current patterns, as long as these competing physical effects are considered. Contours of dynamic height are described in this section for the six bay-wide cruises. A reference depth of 30 m was used, with a contour interval of 0.2 cm. The dynamic height represents the difference between the height of the water column and a reference water column with water of 35 psu and 0°C having the same mass per unit area. Since the water in the Bays is generally lighter than the reference water, the dynamic height is positive, ranging from about 6 cm to 10 cm. If there were no motion at 30 m depth, the dynamic height variations would closely approximate the actual variations in sea level. The contour charts include a velocity scale based on a geostrophic calculation. The closer the contours are spaced, the greater the pressure gradient, and corresponding geostrophic velocity. The horizontal axis on the velocity scale represents the spacing between adjacent contours (solid to dashed), and the vertical scale represents the corresponding velocity.

Figure 2.4-50 shows the dynamic height for the April 27–28, 1990 cruise. The low salinity intrusion at Cape Ann shows up as a topographic high, and the gradient between the northern and southern regions of the Bays near the Humarock section is also clearly evident. The significant high (to 7.8 cm) near the outer boundary of Massachusetts Bay was associated with an internal wave which was profiled on the Scituate section. This is definitely not geostrophic, since the passage of the wave is highly time dependent, and water velocities should not be inferred from this feature.

The front between northern and southern portions of the bays is also clearly seen in figure 2.4-51, which shows the dynamic height contours for July 24–25, 1990. The warm, fresh water in Cape Cod Bay created high dynamic height values (up to 11.6 cm). Geostrophic flows of 40–50 cm s^{-1} are indicated around the high west of the tip of Cape Cod. (The flow would be such that the high dynamic height is to the right facing in the direction of the flow, i.e. clockwise around a high and counterclockwise around a low.) Flows along the front are on the order of 10 cm s^{-1}. It is important to note that these velocities may vary considerably from actual values due to violations of the assumptions required for geostrophy, but the variations in dynamic height do tend to produce velocities of this magnitude. Other processes (tides, wind, internal waves) are superimposed on the geostrophic flow, which may be a reasonable measure of medium term (few days) conditions. The low nearshore north of Boston is probably too nearshore and too shallow for the geostrophic calculation to have much validity.

The dynamic height field for the October 16–18, 1990 cruise (fig. 2.4-52) again shows a frontal region, though at this time the front was more north–south than east–west. Velocities of 10 cm s^{-1} to 20 cm s^{-1} are suggested along the front. The high in mid-bay is caused by the internal wave described above from the longitudinal section.

Little pattern appears in the February 4–6, 1991 dynamic height plot (fig. 2.4-53), due to the nearly uniform water properties. The offshore water was slightly more saline, resulting in a dynamic height difference of 0.4 cm s^{-1}. The offshore gradient in dynamic height is consistent with a southward flow offshore, which appears to be persistent through most or all of the year, based on the moored data at U2 (Section 2.2). This gradient was not well resolved in the earlier cruises, due to the limited offshore stations.

Conditions during the March 20–23, 1991 cruise (fig. 2.4-54) were generally similar to those in February except for the effects low salinity plume near Cape Ann. There is an indication of a flow east of Cape Cod to the southeast of approximately 15 cm s^{-1}, though this region is on the edge of the available data, and the contours may not be very accurate. Again the offshore slope of dynamic height indicates southward flow in the offshore region, consistent with the current meter data.

Dynamic height gradients were larger in the final baywide cruise in the spring of 1991 (fig. 2.4-55), due to the pronounced salinity anomalies resulting from fresh-water inflow. Most of the geostrophic flow at this time skirts the Bays, passing over Stellwagen Bank and then passing seaward of Race Point. This southward flow has a geostrophic velocity of up to 20 cm s^{-1}. A large gyre-like feature east of Boston indicates velocities on the order of 5 cm s^{-1}, with northward flow near the proposed MWRA outfall.

Boston Transect Time Sequence

In order to gain a better picture of the seasonal variation of water properties, composite figures were made showing temperature, salinity, density and fluorescence along the Boston transect for all 12 surveys (bay-wide, northern bay and follow-up cruises). This provides 12 samples covering the period from April, 1990 through June, 1991 with a minimum spacing of five days (between last two bay-wide cruises and corresponding follow-up cruises) to three and one half months between the October, 1990 and February, 1991 cruises.

The temperature sequence is shown on figures 2.4-56 and 2.4-57. On April 13, 1990 the water column was nearly isothermal. Significant stratification had developed two weeks later (April 27–28), and the thermal stratification intensified through June and July. Note that through this period there was no well defined upper mixed layer, with the thermocline extending essentially to the surface. On September 28, 1990 a surface mixed layer did exist, at least in the central portion of the transect, and the thermocline had become much more diffuse. The thermocline was further eroded on October 16, partially due to mixing, but as indicated previously, there is evidence for an intrusion of Gulf of Maine water which shifted the water properties in the basin. In February, 1992 (fig. 2.4-57) the water was largely vertically mixed, though some vertical variation persisted in the deepest waters. A strong lateral temperature gradient is seen between the shallow area nearshore and the deeper water. On March 21 and March 25, the nearly isothermal condition is again seen, slightly colder than that seen on April 13, 1990. The water had become stratified again by April 30, 1991, with a shallow surface mixed layer over most of the section. Similar conditions prevailed five days later. Finally, on June 18, 1991 the stratification was stronger, with a more well defined mixed layer than in the 1990 data.

In contrast to the temperature, the salinity field was significantly stratified on April 13, 1990 (fig. 2.4-58). This suggests that the initial stratification comes from the inflow of relatively fresh water from the northern rivers, rather than from seasonal warming. After this stratification becomes established solar heating is more effective in warming the surface waters due to the reduced vertical mixing in the more stable water column. The salinity pattern on April 13 suggests two sources of fresh water, Boston Harbor and the coastal current carrying the flow from the northern rivers. By April 27, the lenses of low salinity water at the ends of the transect had largely disappeared, leaving a moderate, nearly horizontal halocline. In June and July, 1990, the salinity showed no surface mixed layer, similar to the temperature field. Some freshening of the deep water may indicate cross-pycnocline mixing. A mixed layer is apparent in September and October, as is the influence of Boston Harbor as a fresh water source.

As with the temperature, the water column was well mixed over most of the section in February, 1991 (fig. 2.4-59). Fresh water from Boston Harbor is again evident nearshore. The two March, 1991 cruises show a remarkable change over a period of four days. While the deep water remained similar at 32.5-32.7 psu, a 30 m thick layer of water below 32.2 psu extended over the outer half of the section on March 21, but was almost completely absent on March 25. This most likely resulted from the shifting position of the coastal current. Salt stratification was well established by April 29, and remained on May 5, 1991. However, there was again a significant change in the salinity field, with a much greater stratification over the outer half of the section on the later cruise. The varying position of the coastal current again provides the best explanation. A shallow mixed layer existed on June 18 except at the outer end of the section, where the water over Stellwagen Bank appeared was mixed.

The density sequence is presented in figures 2.4-60 and 2.4-61. In the winter and early spring, the density field is dominated by salinity, and the density contours are similar to those of salinity. In late spring through fall, temperature salinity and density show similar patterns.

Fluorescence (chlorophyll-a) shows a somewhat more complex sequence (figs. 2.4-62 and 2.4-63) than the physical properties because it depends not only on those properties, but also on light, nutrients, and other ecological factors. This report is not intended to address these complex biological interactions, but some comments about fluorescence sequence may prove useful. The fluorescence levels were extremely low on April 13, at which time there was significant stratification, and evidence of fresh water intrusion from both Boston Harbor and from the northern coastal current. The nutrient levels seemed adequate to support some phytoplankton growth (see section 2.7). The explanation for the low levels at this time is not apparent. For the other stratified periods, there was generally a strong subsurface fluorescence maximum associated with the pycnocline. In the winter there was again very little chlorophyll, presumably due to light limitation. Note that the plot for February 5 has contour intervals of 0.1 μgm/l rather than 0.5 μgm/l or 1 μgm/l for the other dates. On seven of the twelve dates, (April 27, June 29, July 24, and September 28, 1990, February 3, April 30, May 4, and June 18, 1991) the highest levels were observed near the inshore end of the section. This may be due in part to a flux of nutrients from Boston Harbor, and in part to fact that the shallower water there can provide a higher effective light availability during well mixed conditions. Peaks were observed near the break in bottom slope at the western edge of Stellwagen Basin on March 21 and 25, 1991. This may have been associated with the inshore edge of the fresh water layer mentioned above. On March 20, there was a bulge of the isopycnals near the fluorescence maximum, possibly enhancing nutrient availability in the euphotic zone.

Dissolved Oxygen in Stellwagen Basin

The temporal response of the dissolved oxygen sensor on the CTD is too slow to allow good contour charts of oxygen. However, the calibrations based on Winkler titrations indicated that values in the deeper portions of Stellwagen Basin, where the vertical variation is small, are accurate to within approximately 0.5 mg/l. Oxygen values were compiled from the deepest sample at station BO7 (approximately 90 m) for all bay-wide and northern cruises. The results are plotted in figure 2.4-64, both as concentration, and as percent saturation. The minimum values occur in October, at the end of the stratified period. This is best explained as resulting from the biochemical utilization of oxygen during a period when the deep layer is effectively isolated from exchange with the surface by the pycnocline. Levels rise during the winter as vertical mixing increases the exchange between surface and deep water. The value in June, 1991 is essentially 100% saturated, rather surprising for a time approximately two months after the water column became stratified. Relatively low fluorescence values in the upper waters of Stellwagen basin at this time (figure 2.4-63) suggest productivity was relatively low. Even if production were in the vicinity of the pycnocline, it would probably not increase O_2 in the bottom water. No immediate explanation is available for the high O_2 level, and the value should be regarded with caution.

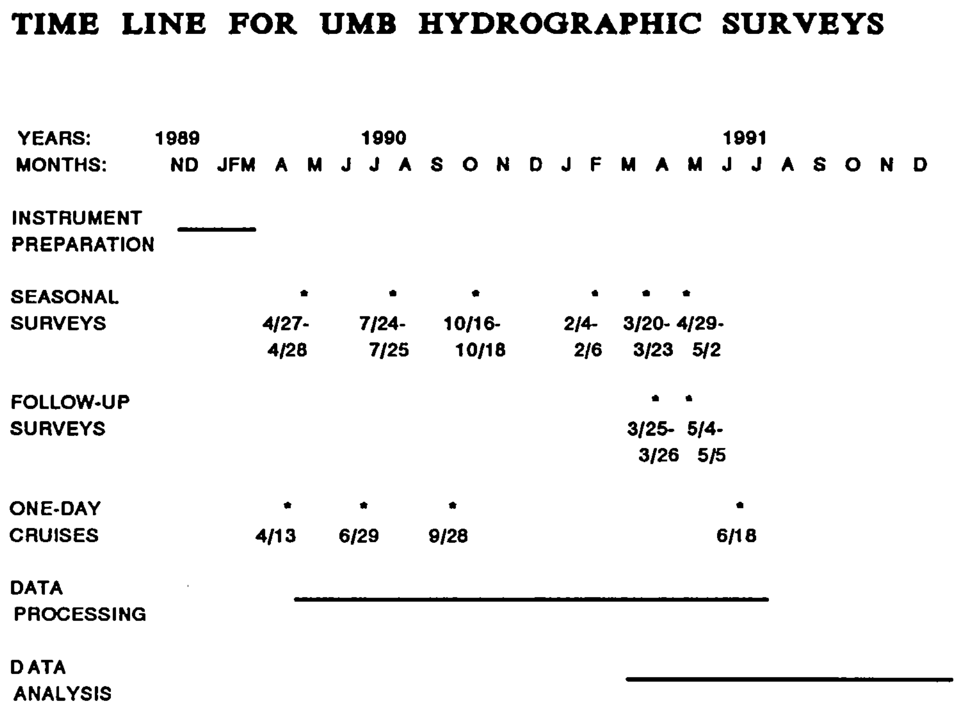


Figure 2.4-1 Time line for the hydrographic surveys conducted by UMB, UNH and WHOI. WHOI participated in the first two seasonal surveys. UNH collected samples for nutrient and TSS analysis on all seasonal and one-day cruises.

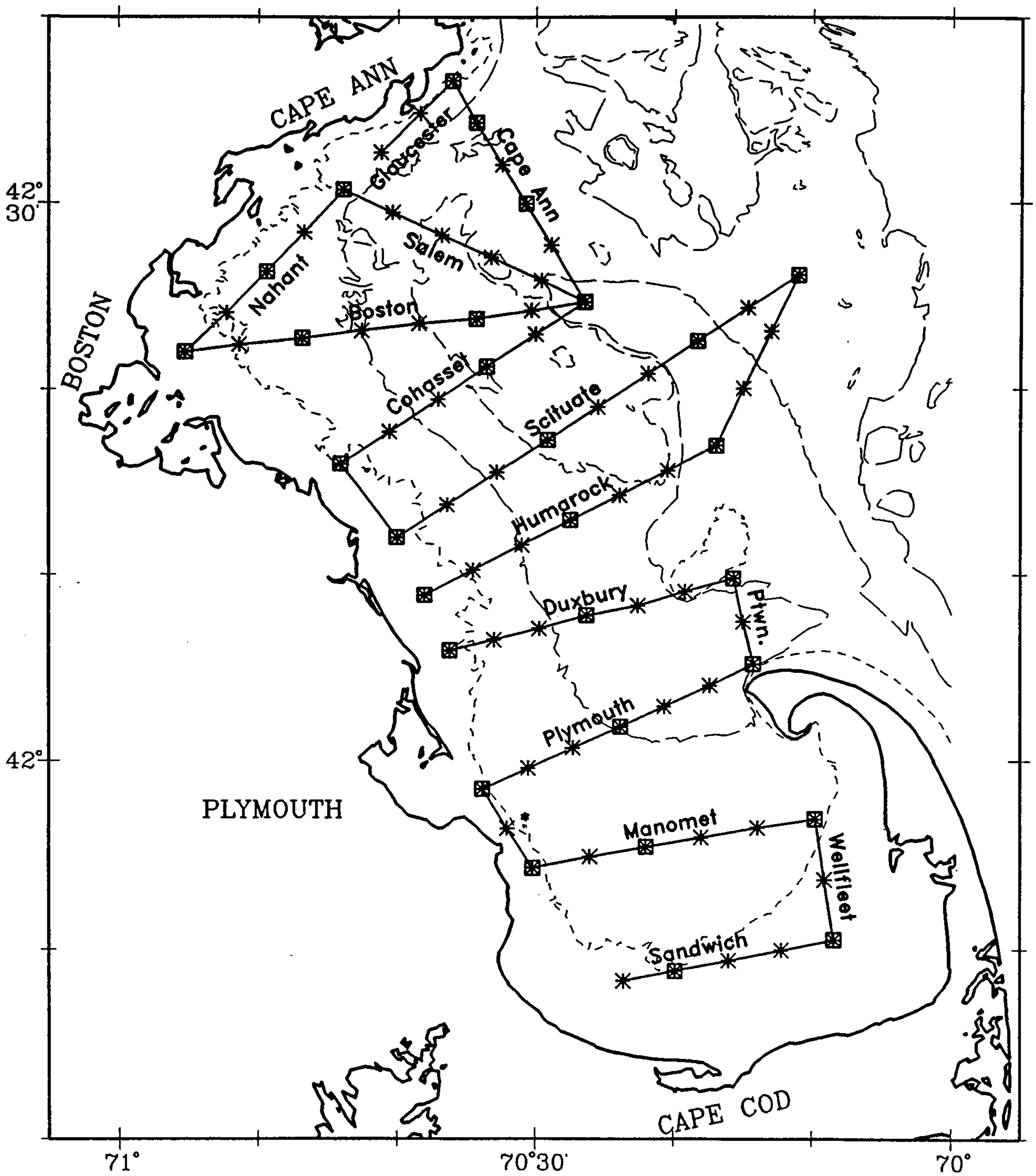


Figure 2.4-2 Cruise track for the first three seasonal cruises and the one day cruises. Water samples were obtained for nutrient and TSS analysis at stations marked by squares. On the first two seasonal cruises, WHOI occupied sections from Duxbury south, inclusive, while UMB covered the sections from Humarock north. The one-day cruises included the Boston and Cape Ann sections, and the inner 3 or 4 stations of the Salem section.

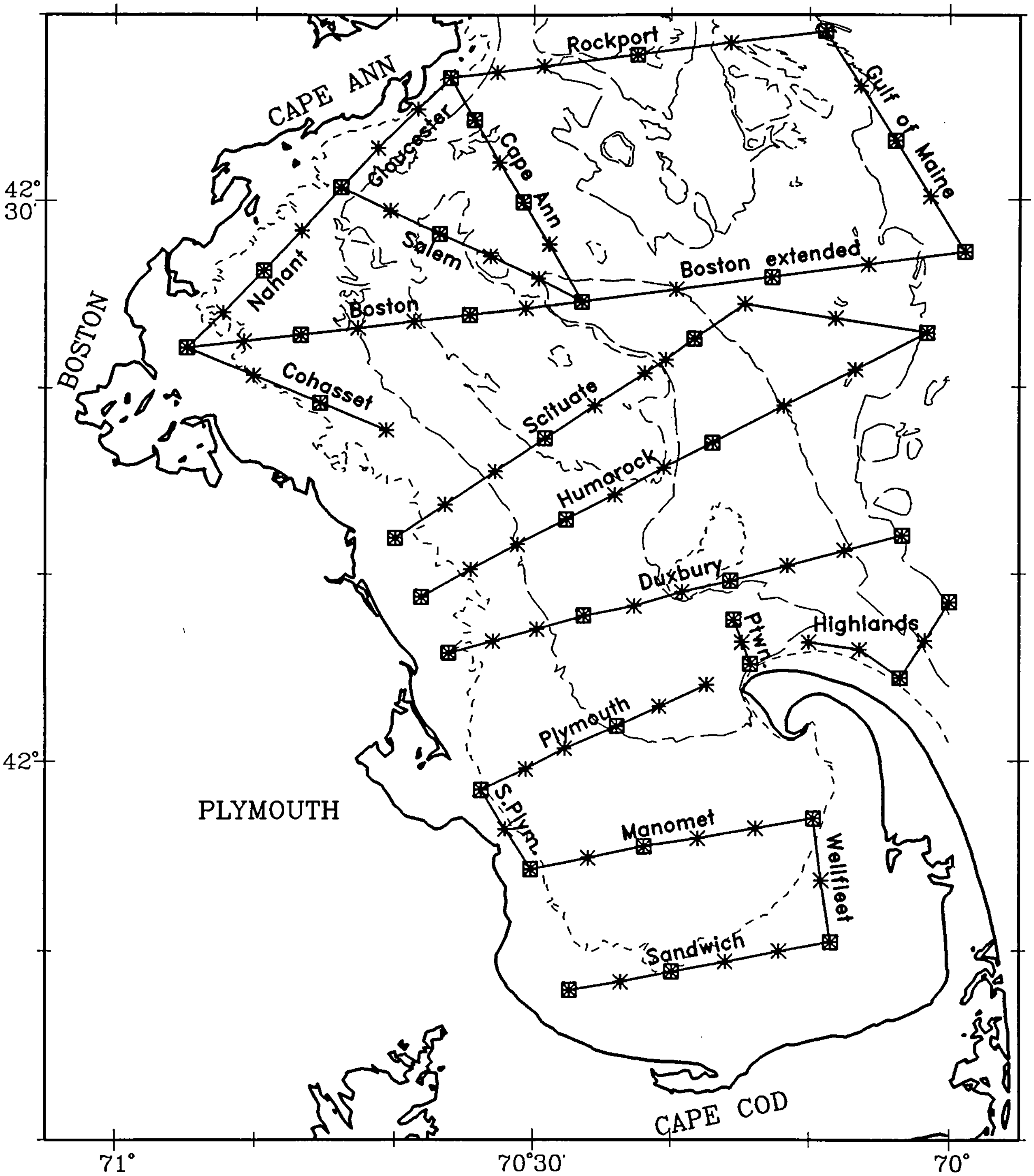


Figure 2.4-3 Cruise track for the final three seasonal cruises. Additional stations were added in the Gulf of Maine to better define the boundary conditions for processes within the Bays. Note that the Cohasset section was changed from the original cruise track.

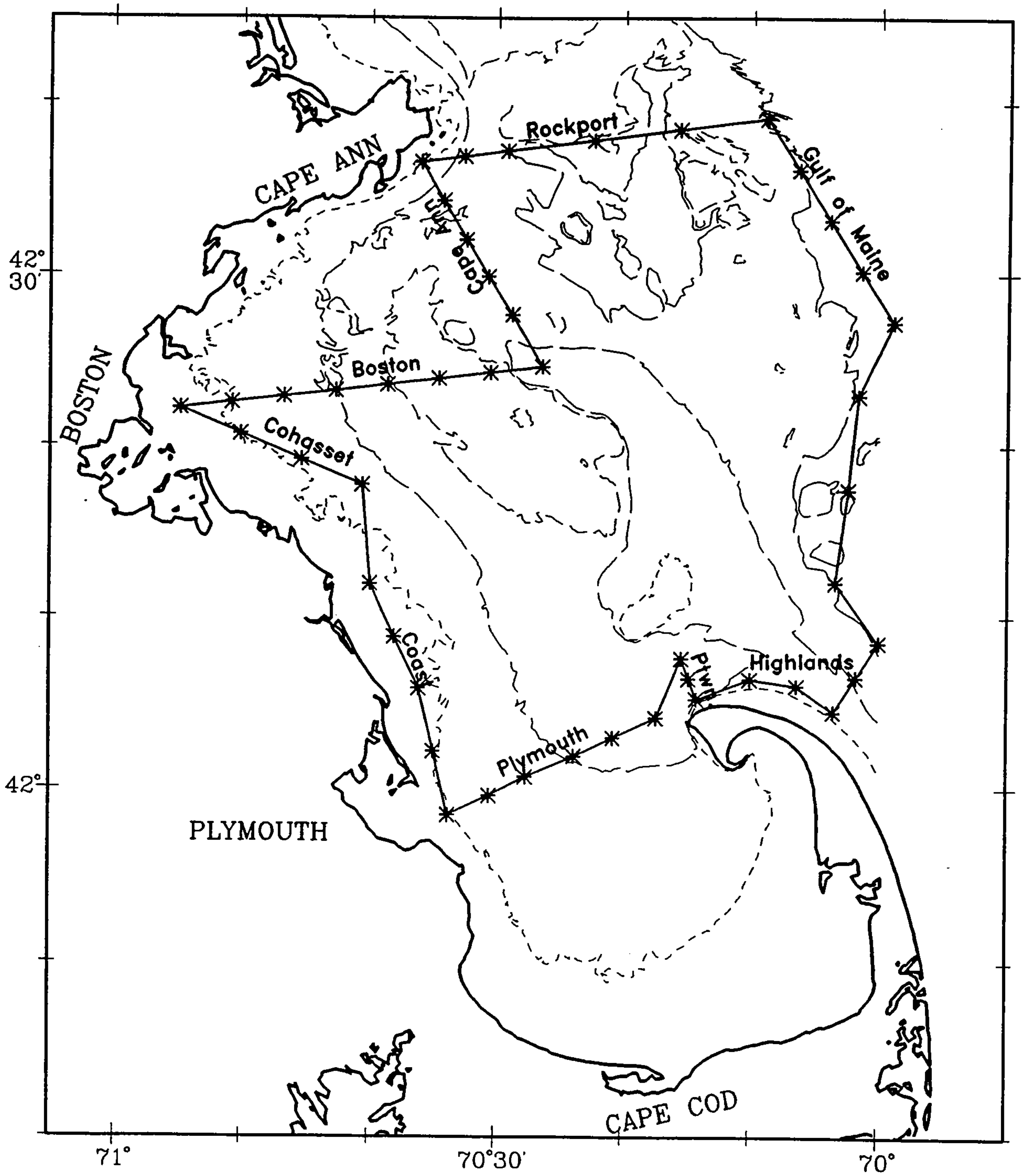


Figure 2.4-4 Cruise track for the follow-up cruises conducted after the final two seasonal cruises.

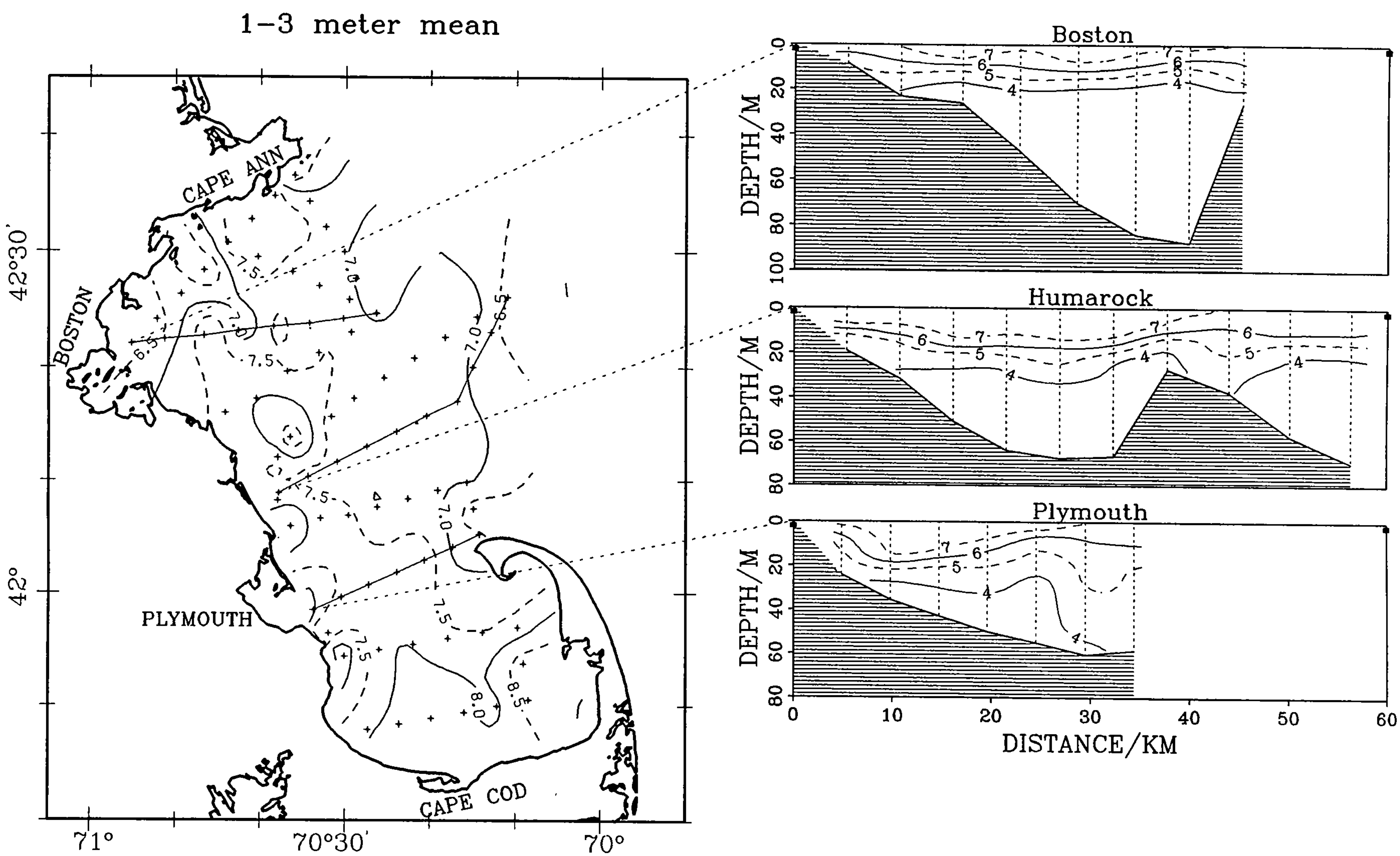


Figure 2.4-5 Surface and vertical section contour plots of temperature (°C) for the April 27–28, 1990 cruise. The contour intervals are 1.0°C for the vertical sections and 0.5°C for the surface plot. Note that locations of the vertical sections are marked on the surface plot.

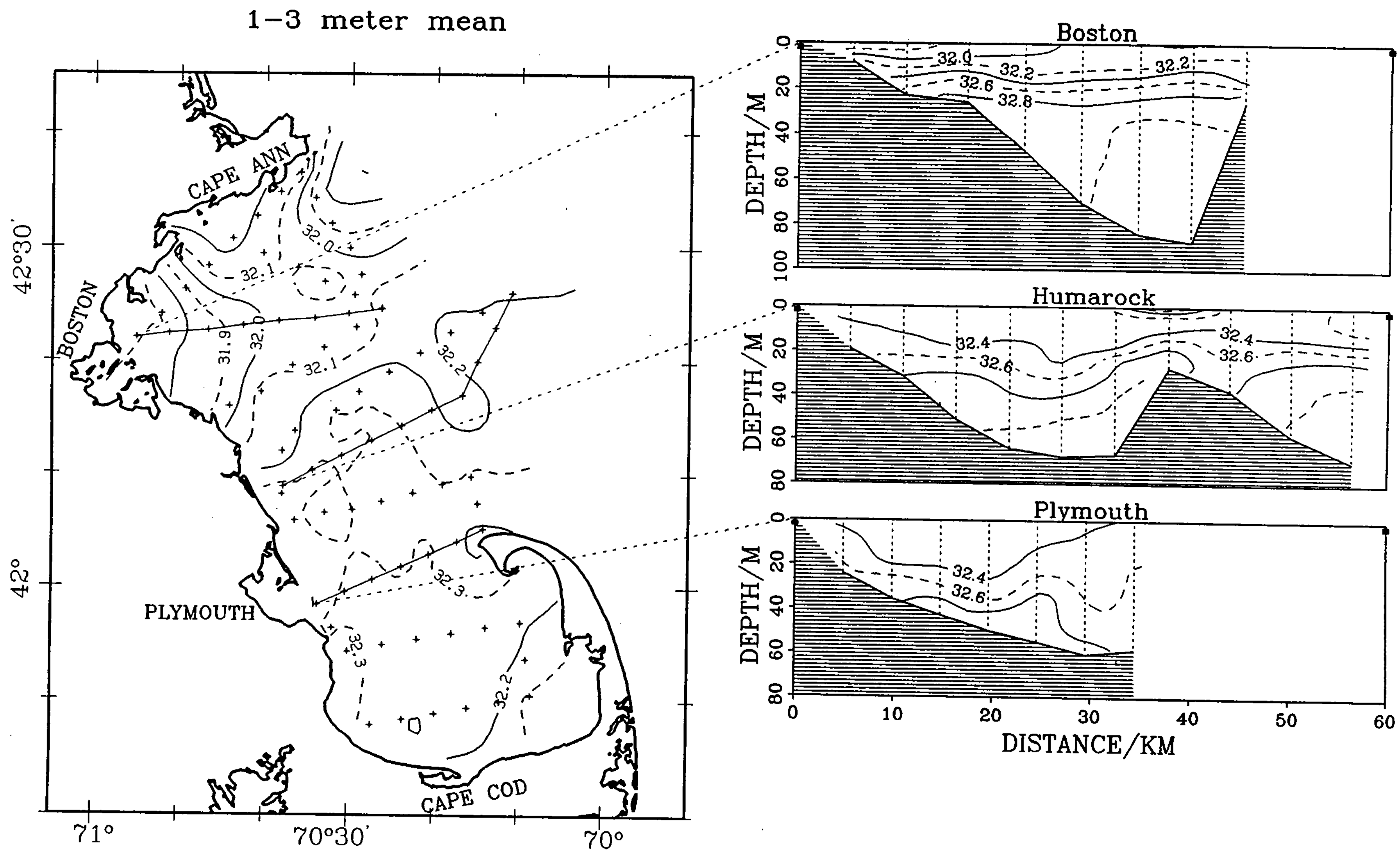


Figure 2.4-6 Surface and vertical section contour plots of salinity (PSU) for the April 27-28, 1990 cruise. The contour intervals are 0.2 PSU for the vertical sections and 0.1 PSU for the surface plot. Note the low salinity patches near Cape Ann and Boston, and the slightly higher surface salinities in Cape Cod Bay.

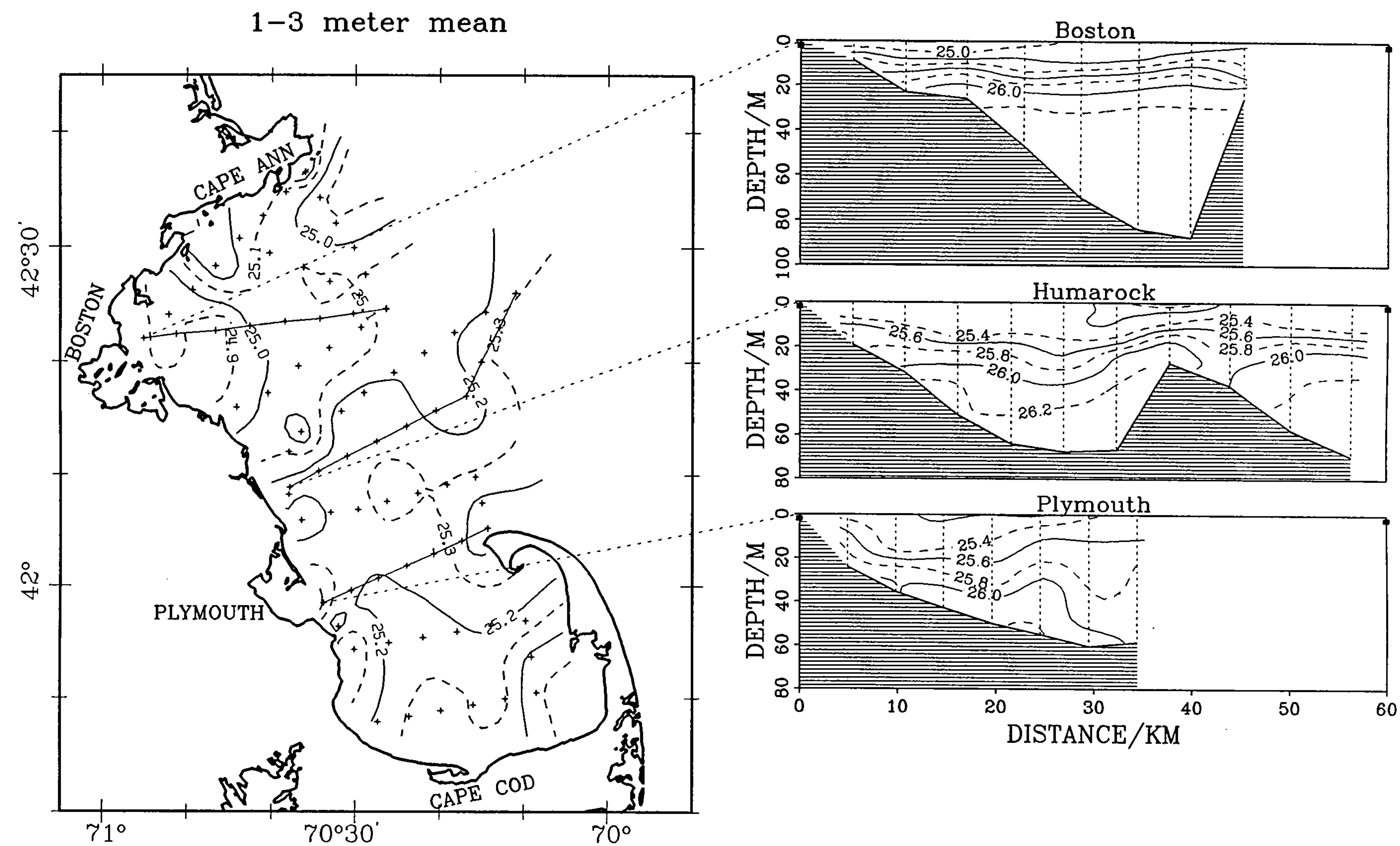


Figure 2.4-7 Surface and vertical section contour plots of σ_θ (kg m^{-3}) for the April 27–28, 1990 cruise. The contour intervals are 0.2 kg m^{-3} for the vertical sections and 0.1 kg m^{-3} for the surface plot. The density pattern closely follows the salinity pattern (fig. 2.4-6).

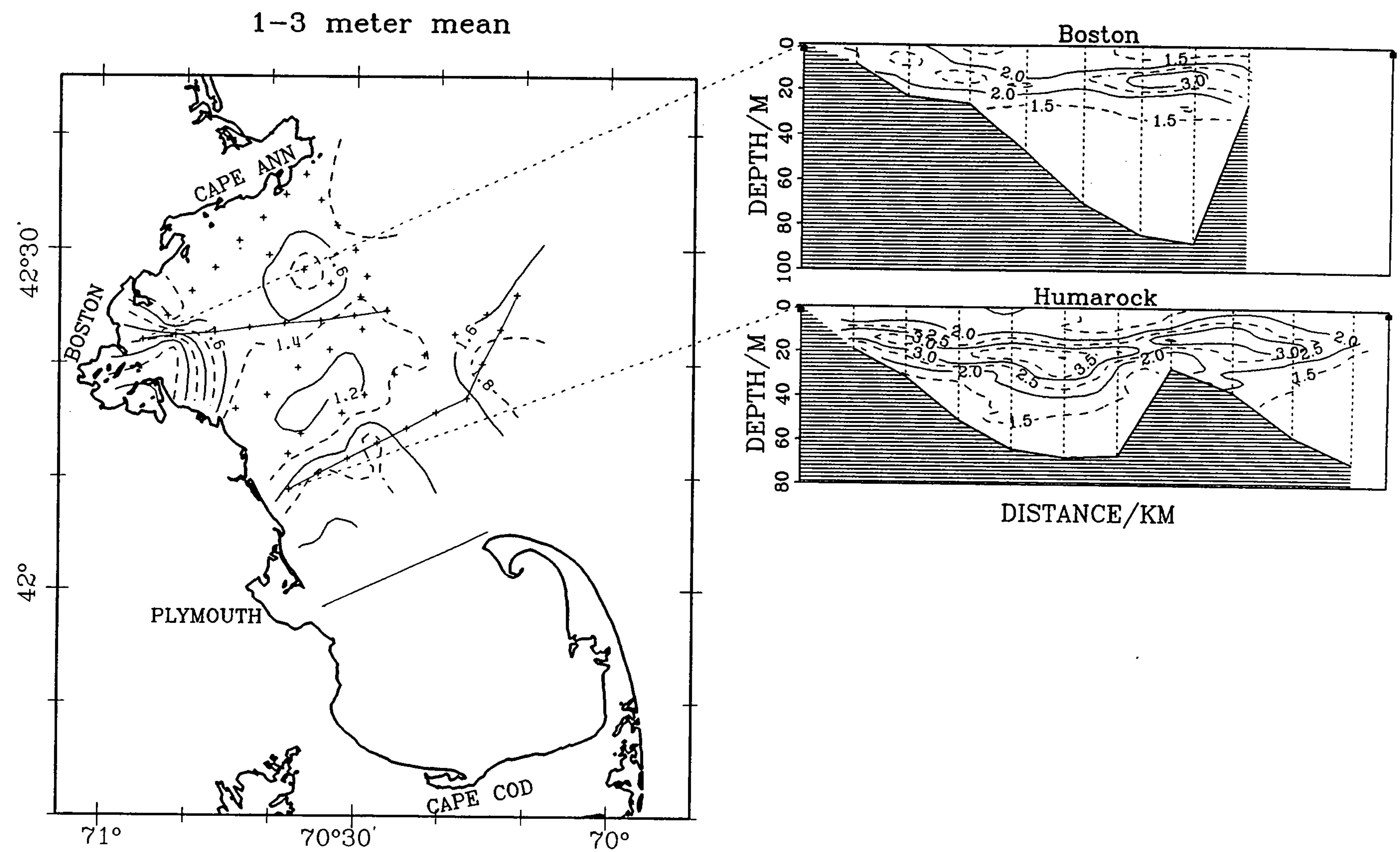


Figure 2.4-8 Surface and vertical section contour plots of fluorescence (approximately chlorophyll-a in $\mu g\ l^{-1}$) for the April 27–28, 1990 cruise. The contour intervals are 0.5 $\mu g\ l^{-1}$ for the vertical sections and 0.2 $\mu g\ l^{-1}$ for the surface plots. Fluorescence data is only available from the region sampled by UMB. Chlorophyll was concentrated along the pycnocline and in the region near Boston Harbor.

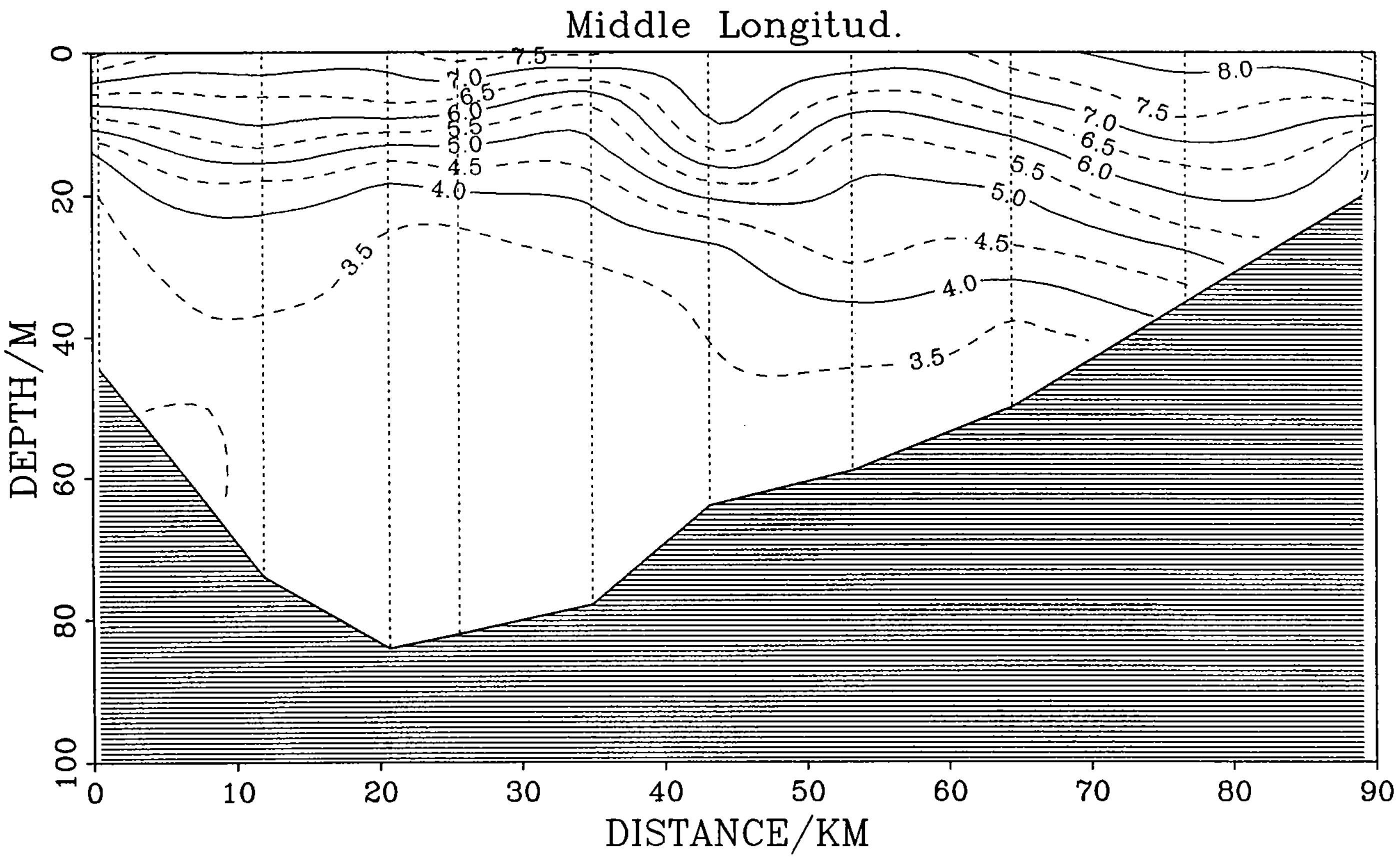


Figure 2.4-9 Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature (°C) for the April 27–28, 1990 cruise. The contour interval is 0.5°C. North is to the left. Total temperature variation is 4.5 to 5.0°C, with little surface mixed layer.

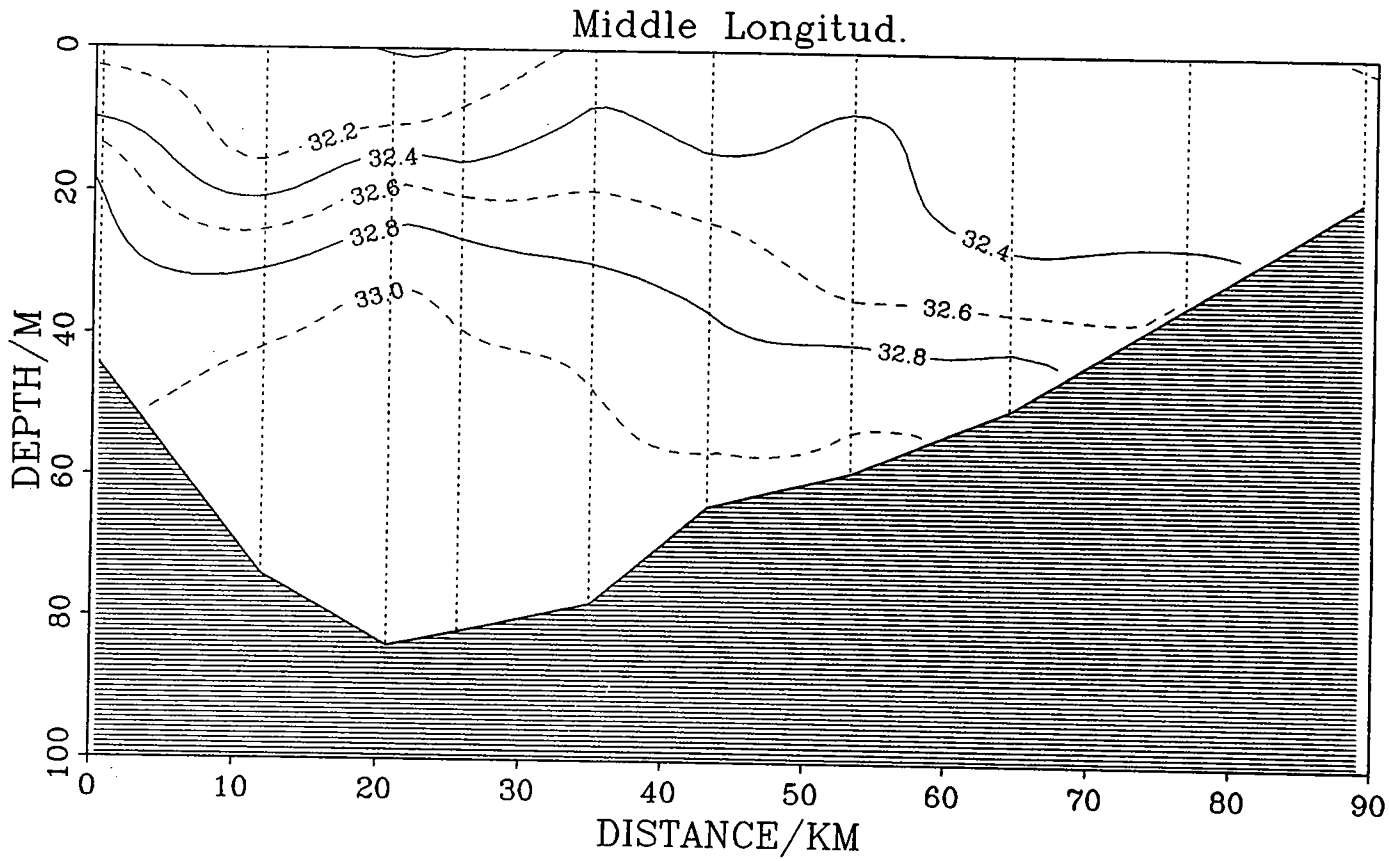


Figure 2.4-10 Mid-bay longitudinal section contour plot of salinity (PSU) for the April 27–28, 1990 cruise. The contour interval is 0.2 PSU. Salinity was lower at the north end of the section.

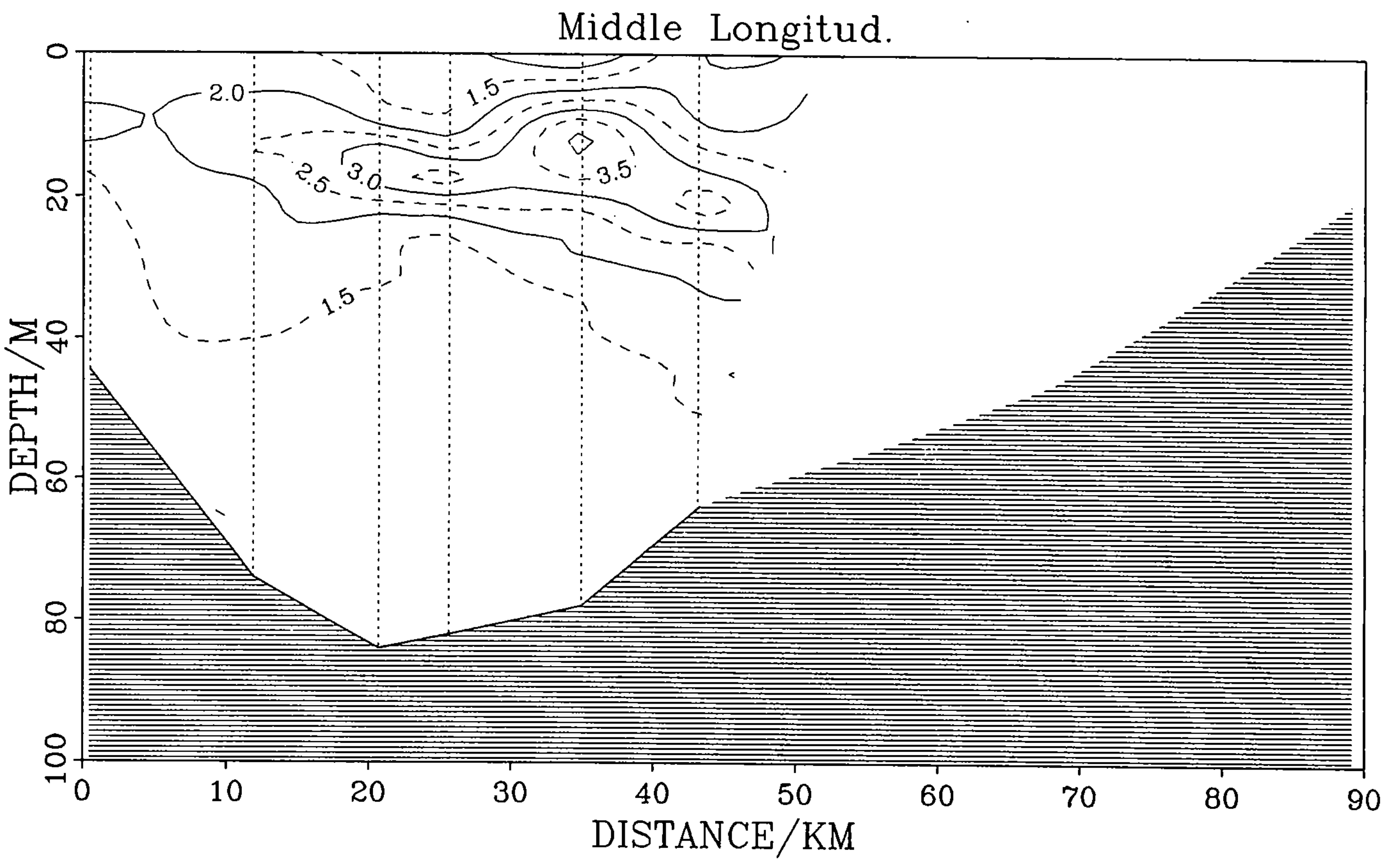


Figure 2.4-11 Mid-bay longitudinal section contour plot of fluorescence (approximately $\mu g\ l^{-1}$ of chlorophyll-a) for the April 27–28, 1990 cruise. The contour interval is 0.5 $\mu g\ l^{-1}$. Note the maximum in the pycnocline.

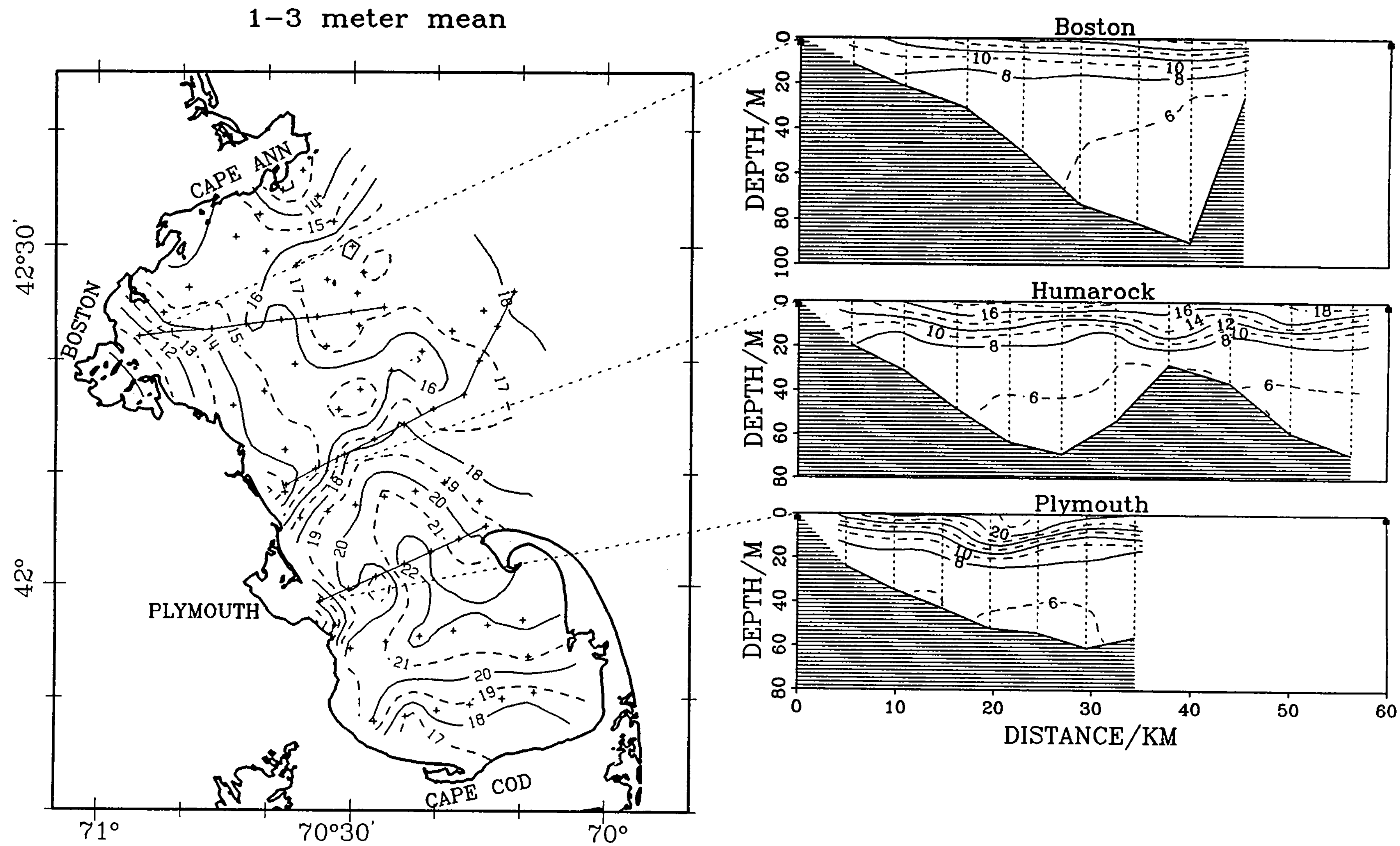


Figure 2.4-12 Surface and vertical section contour plots of temperature (°C) for the July 24–25, 1990 cruise. The contour intervals are 1.0°C for all plots. Note the distinct front between the colder region in the north and the warmer region to the south. The thermocline extends to the surface with no clear surface mixed layer.

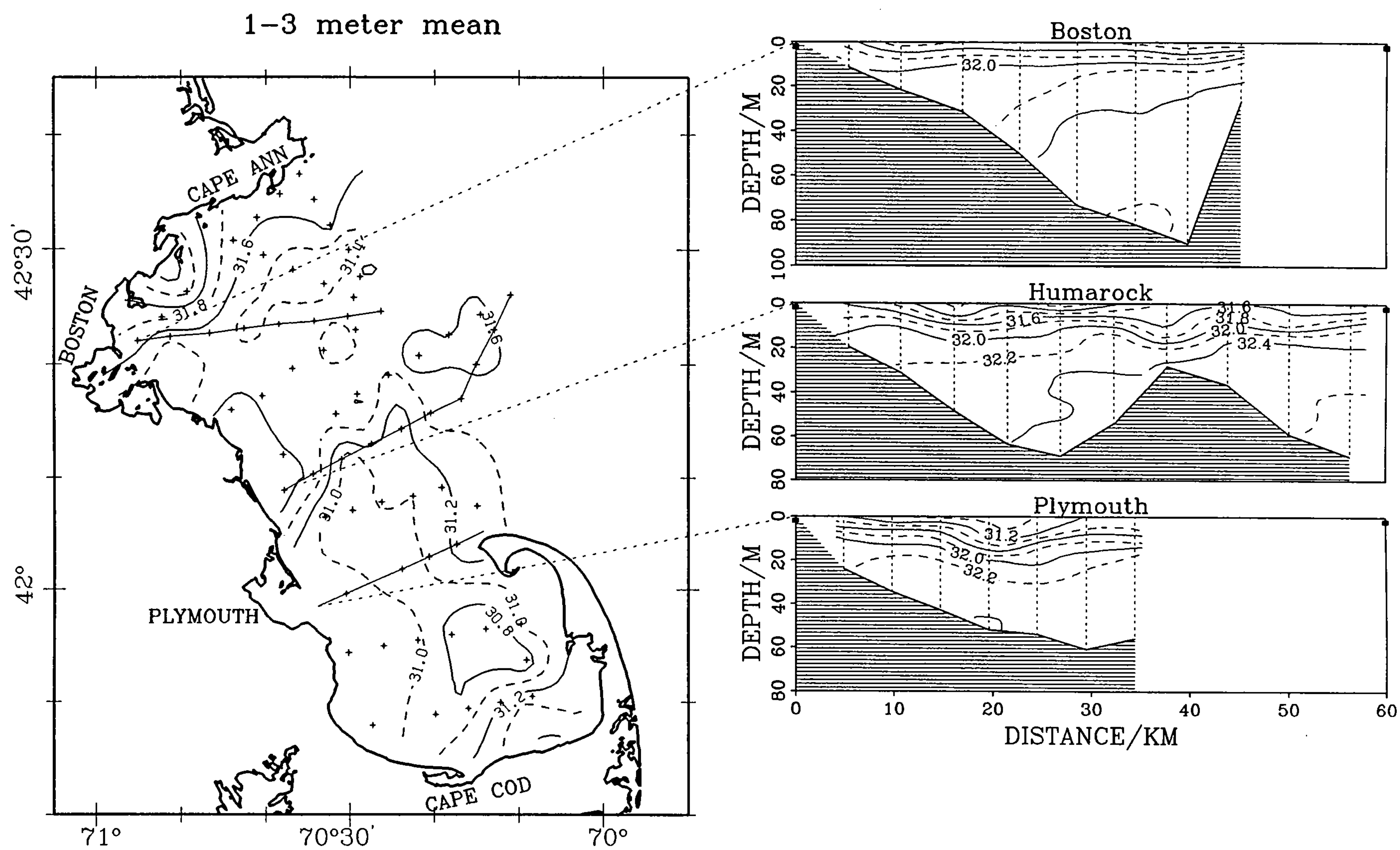


Figure 2.4-13 Surface and vertical section contour plots of salinity (PSU) for the July 24–25, 1990 cruise. The contour intervals are 0.2 PSU for all plots. The front in mid-bay seen in the temperature plot is also evident in the salinity. The region of high salinity north of Boston may indicate upwelling.

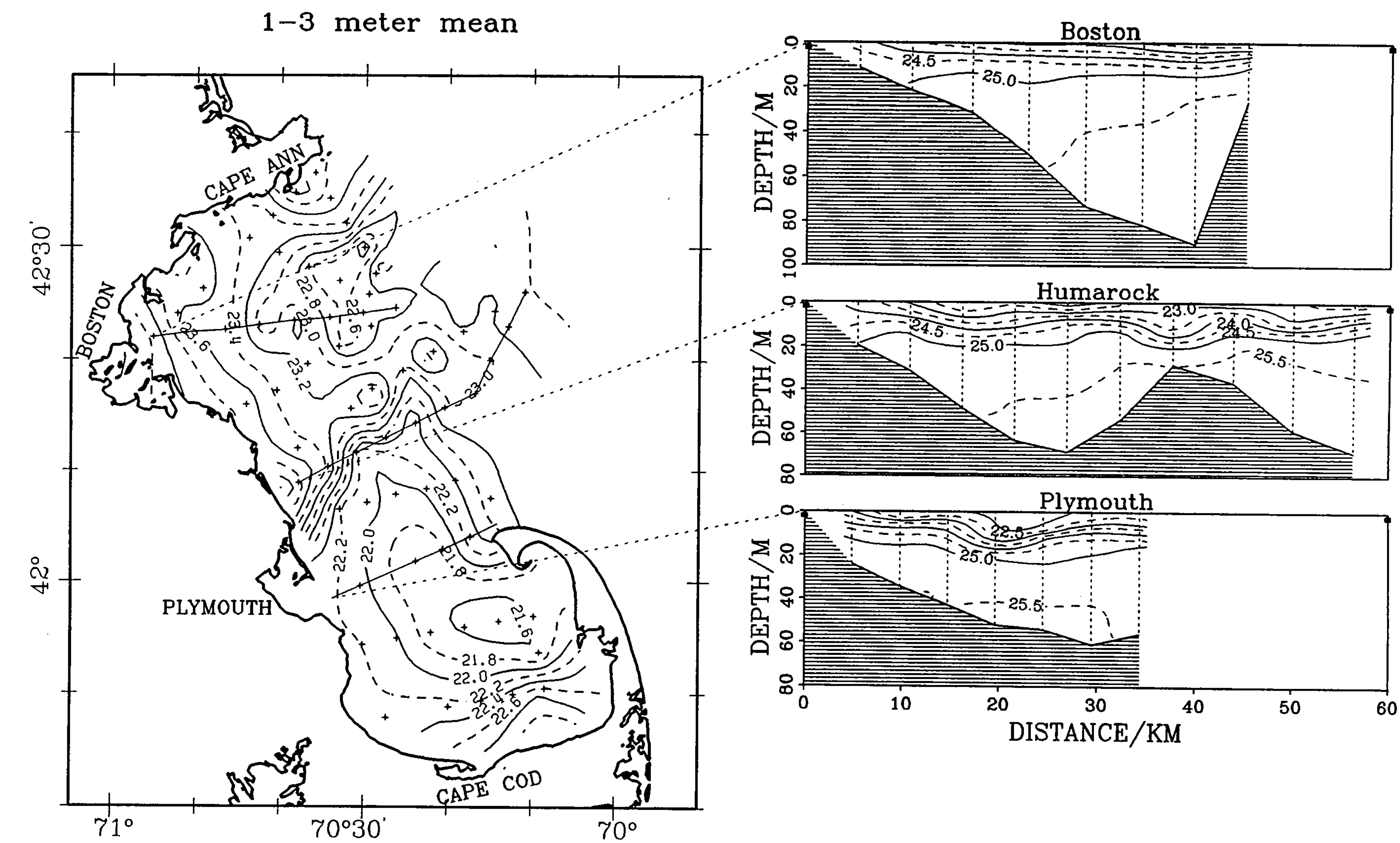


Figure 2.4-14 Surface and vertical section contour plots of σ_θ (kg m^{-3}) for the July 24–25, 1990 cruise. The contour intervals are 0.2 kg m^{-3} for the vertical sections and 0.1 kg m^{-3} for the surface plot.

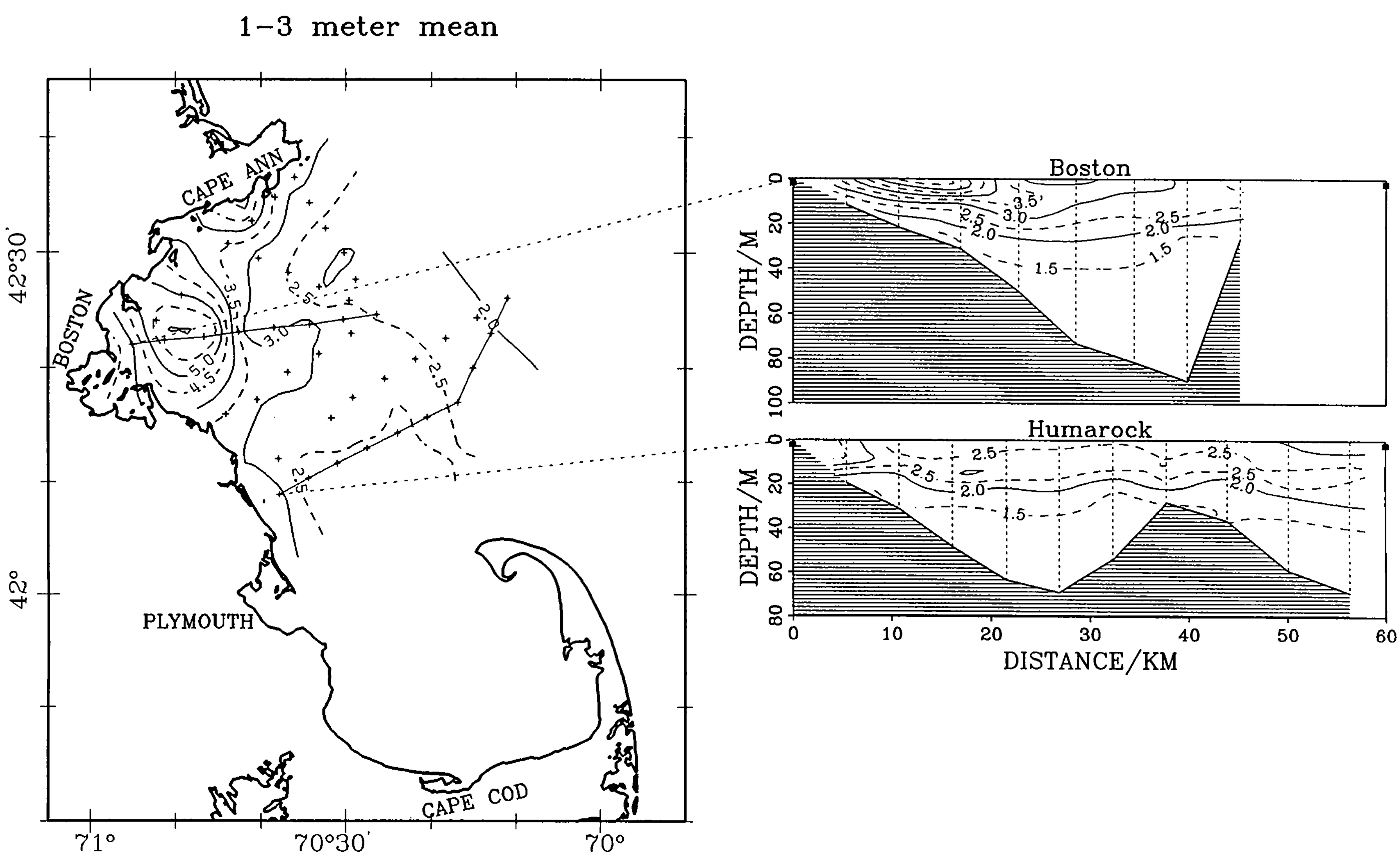


Figure 2.4-15 Surface and vertical section contour plots of fluorescence (approximately chlorophyll-a in $\mu g\ l^{-1}$) for the July 24–25, 1990 cruise. The contour intervals are 0.5 $\mu g\ l^{-1}$ for all plots. Fluorescence data is only available from the region sampled by UMB. Chlorophyll was concentrated along the pycnocline and in the region near Boston Harbor.

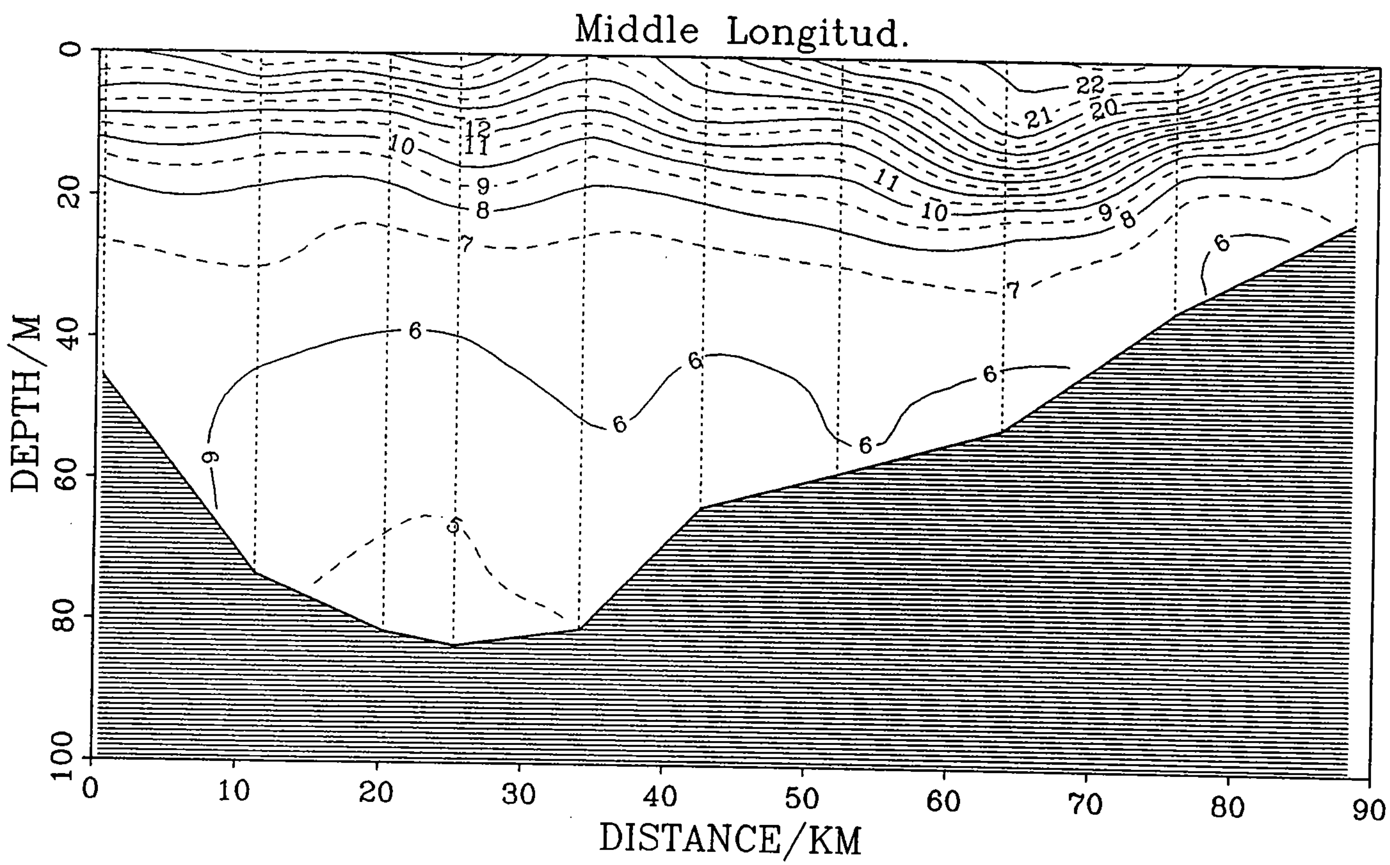


Figure 2.4-16 Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature (°C) for the July 24–25, 1990 cruise. The contour interval is 1.0°C for all plots. Total temperature variation is 16.0°C, with little surface mixed layer.

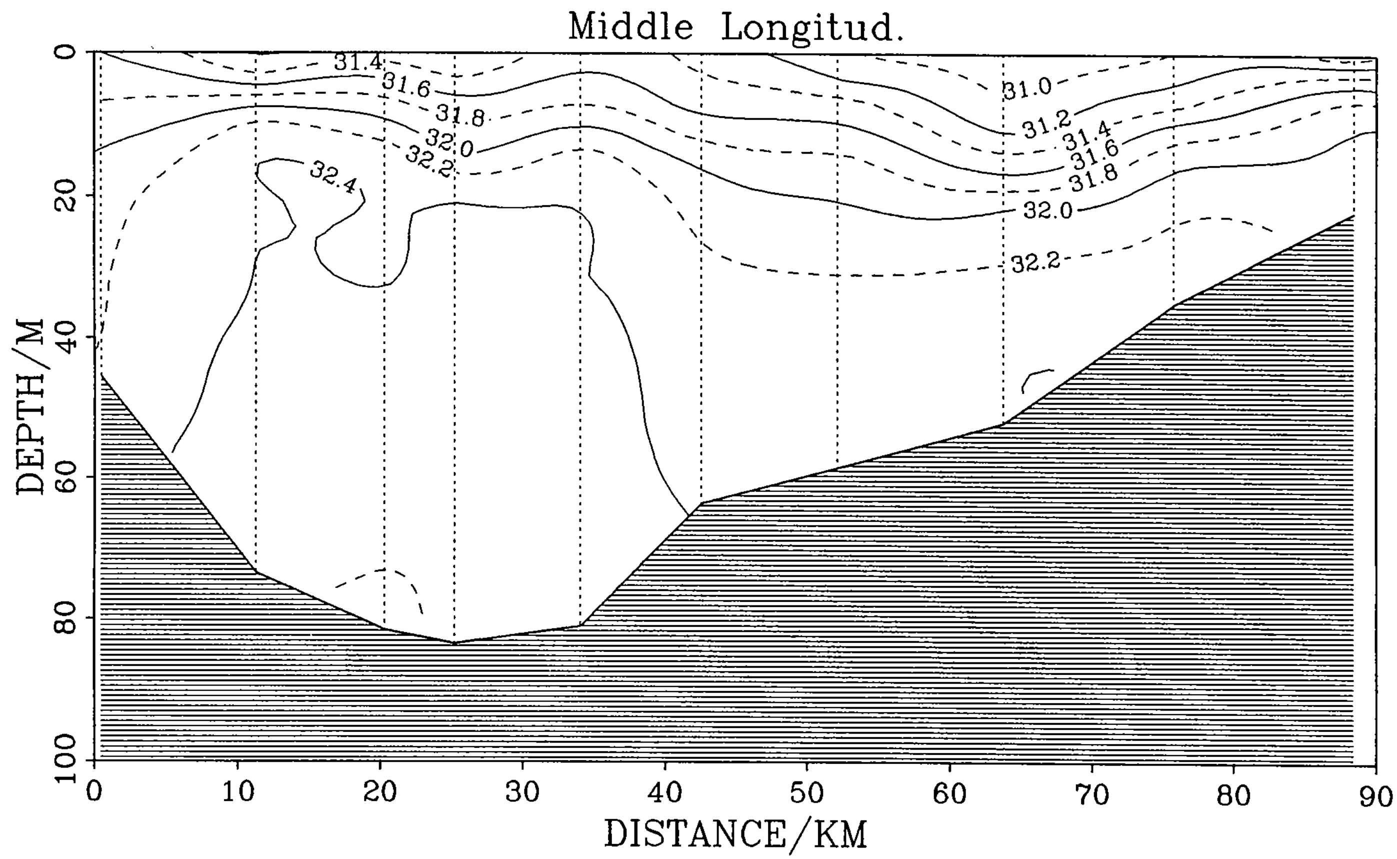


Figure 2.4-17 Mid-bay longitudinal section contour plot of salinity (PSU) for the July 24–25, 1990 cruise. The contour interval is 0.2 PSU for all plots. Salinity was higher at the north end of the section with a low salinity lens in Cape Cod Bay.

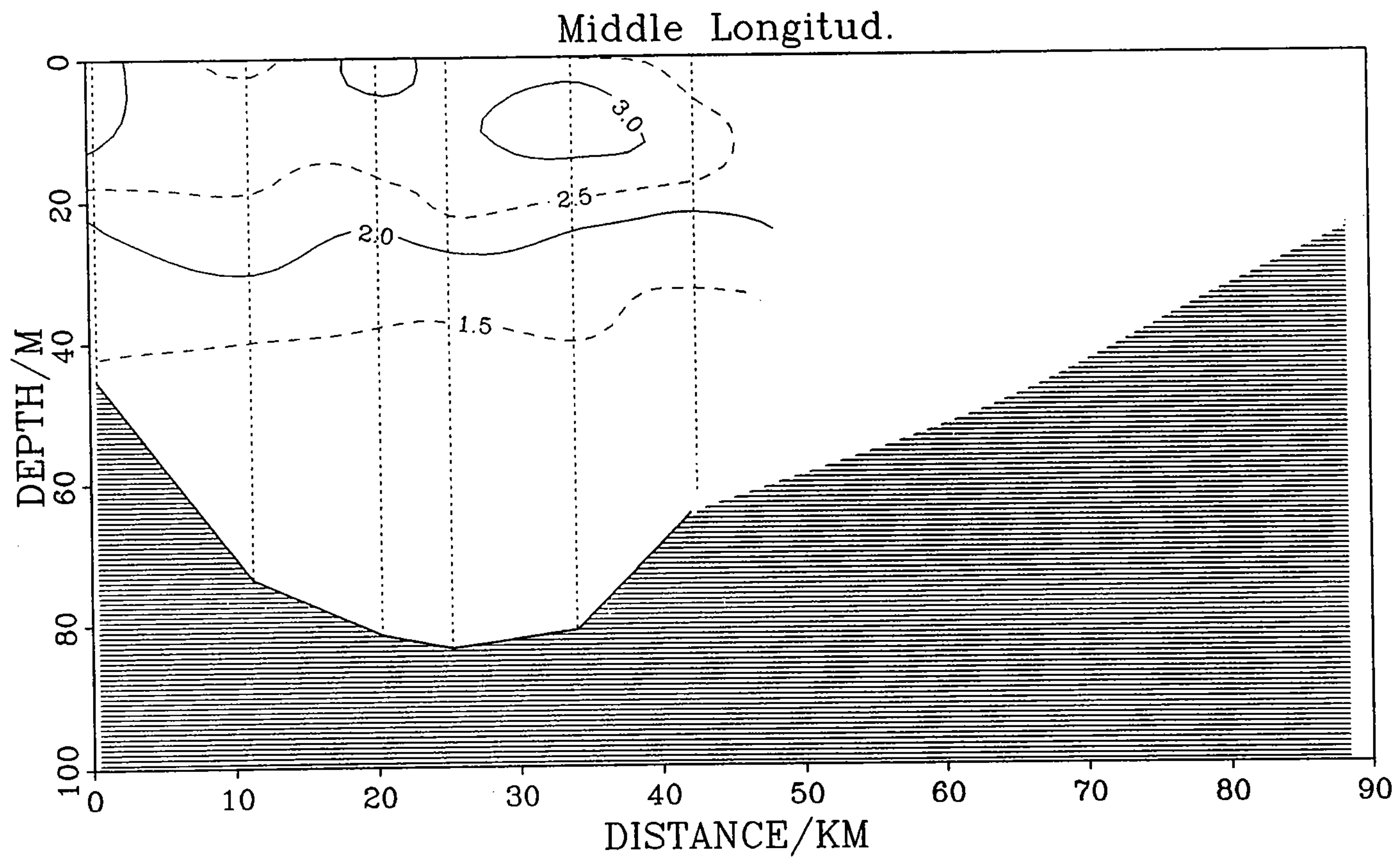


Figure 2.4-18 Mid-bay longitudinal section contour plot of fluorescence (approximately $\mu g\ l^{-1}$ of chlorophyll-a) for the July 24–25, 1990 cruise. The contour interval is 0.5 $\mu g\ l^{-1}$ for all plots. Note the maximum in the pycnocline.

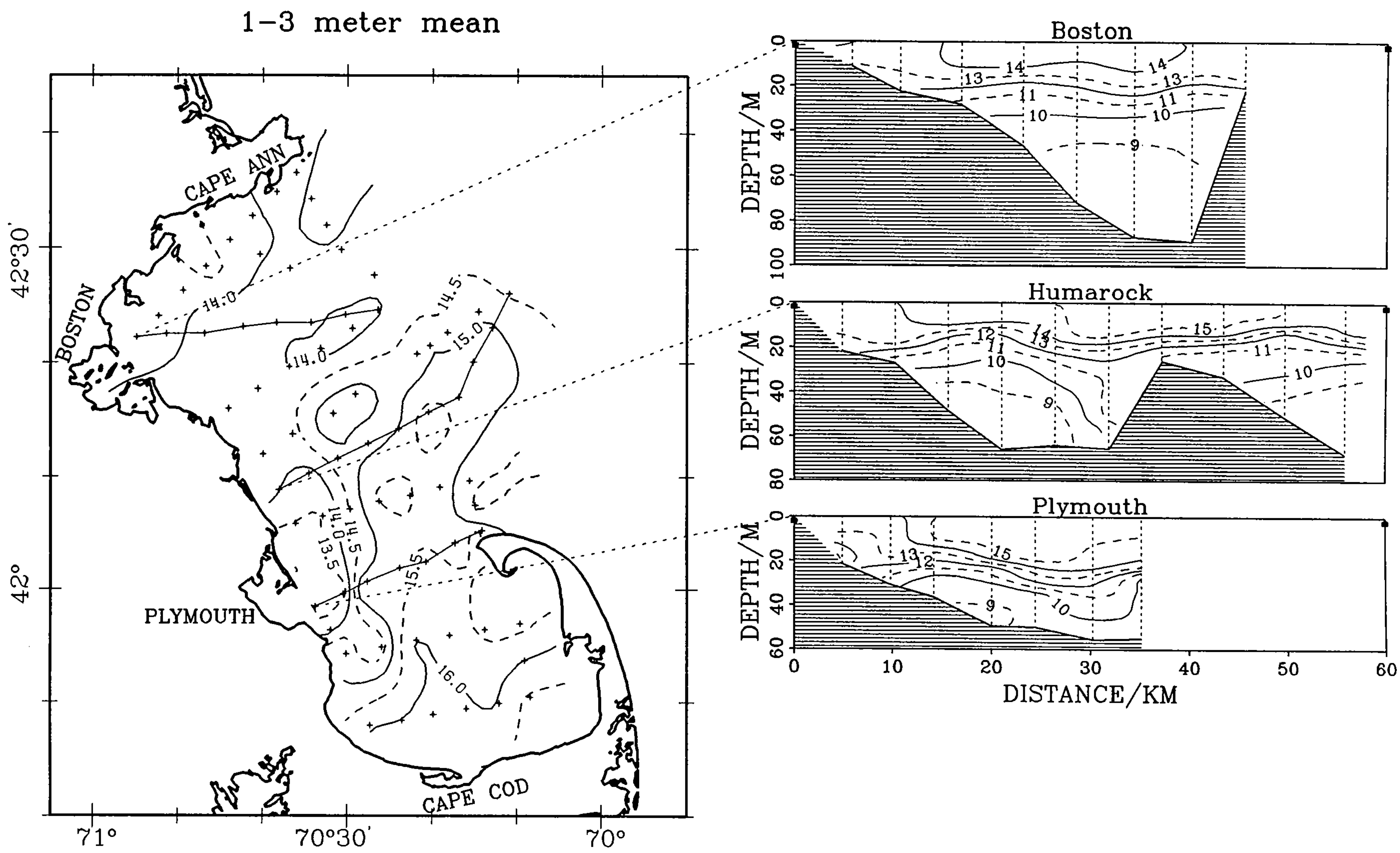


Figure 2.4-19 Surface and vertical section contour plots of temperature (°C) for the October 16–18, 1990 cruise. The contour intervals are 1.0°C for the vertical sections and 0.5°C for the surface plot. The water is warmer in Cape Cod Bay, with a tongue of warm water extending northeast across Stellwagen Bank. Note the colder region near Plymouth, possibly indicative of upwelling. A distinct surface mixed layer exists in contrast to the previous two cruises.

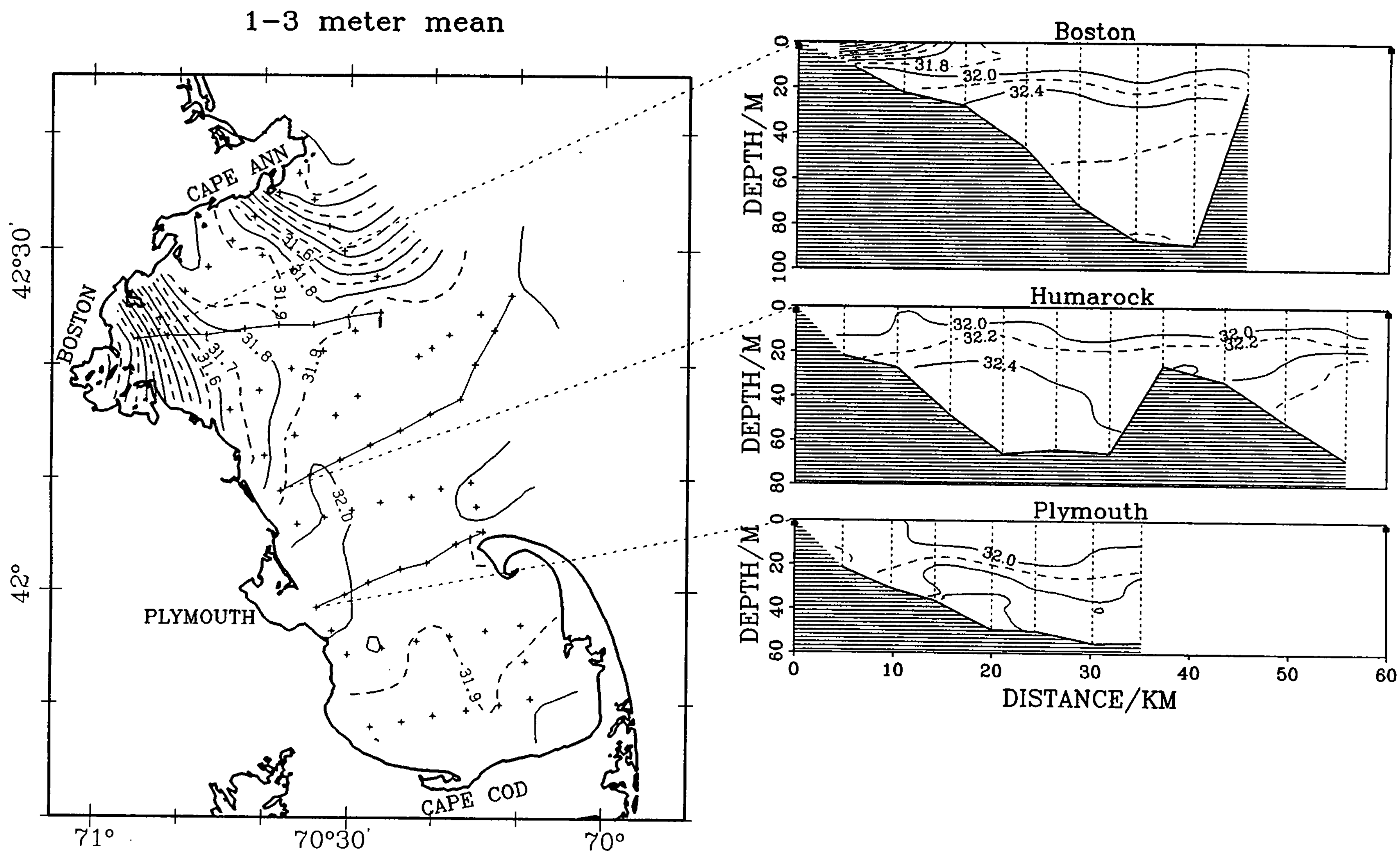


Figure 2.4-20 Surface and vertical section contour plots of salinity (PSU) for the October 16–18, 1990 cruise. The contour intervals are 0.2 PSU for the vertical sections and 0.1 PSU for the surface plot. The salinity field is dominated by low salinity areas near Boston and Cape Ann. Note also the high salinity area near Plymouth, corresponding to the cold area seen on figure 2.4-19.

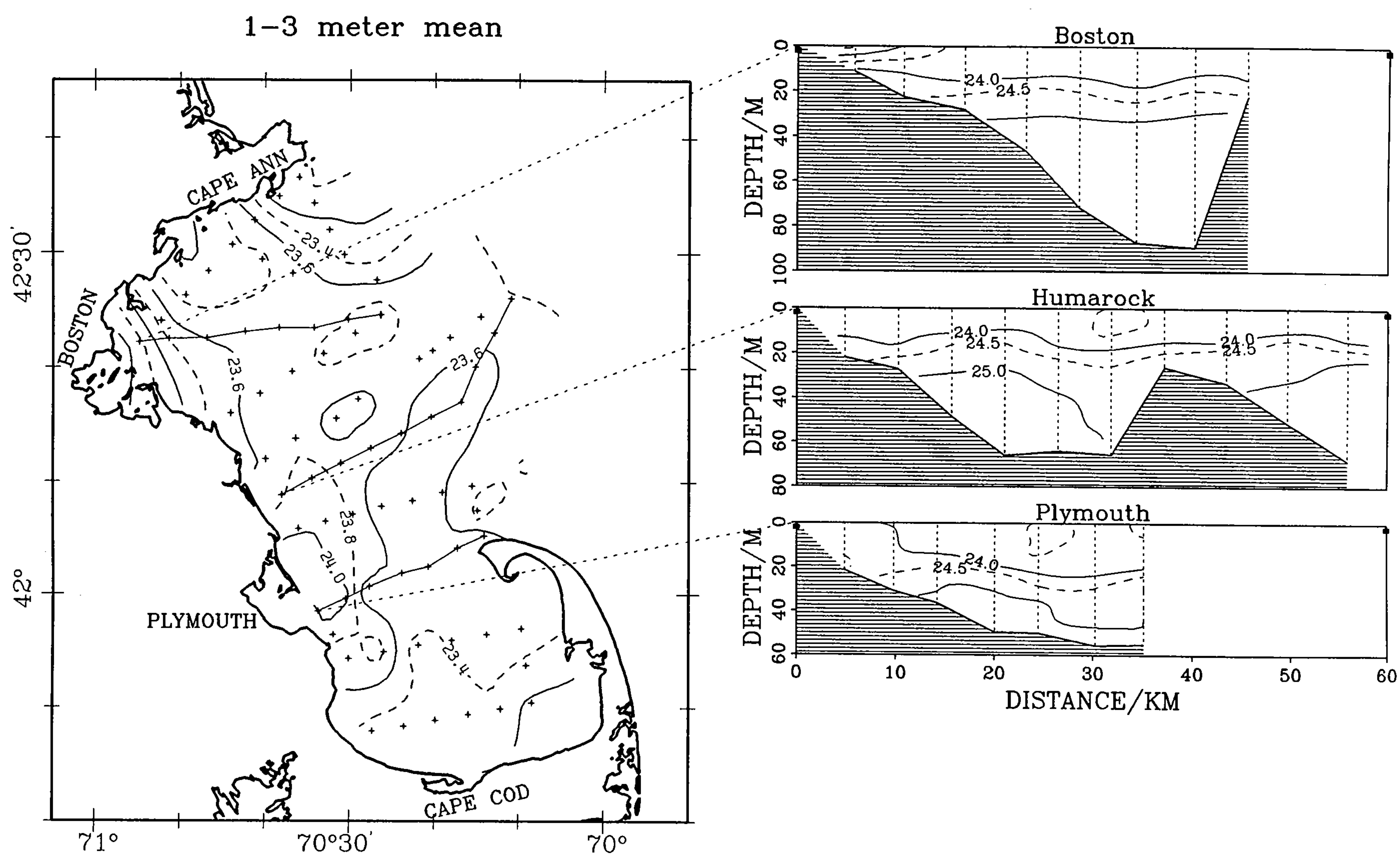


Figure 2.4-21 Surface and vertical section contour plots of σ_θ (kg m^{-3}) for the October 16–18, 1990 cruise. The contour intervals are 0.5 kg m^{-3} for the vertical sections and 0.2 kg m^{-3} for the surface plot.

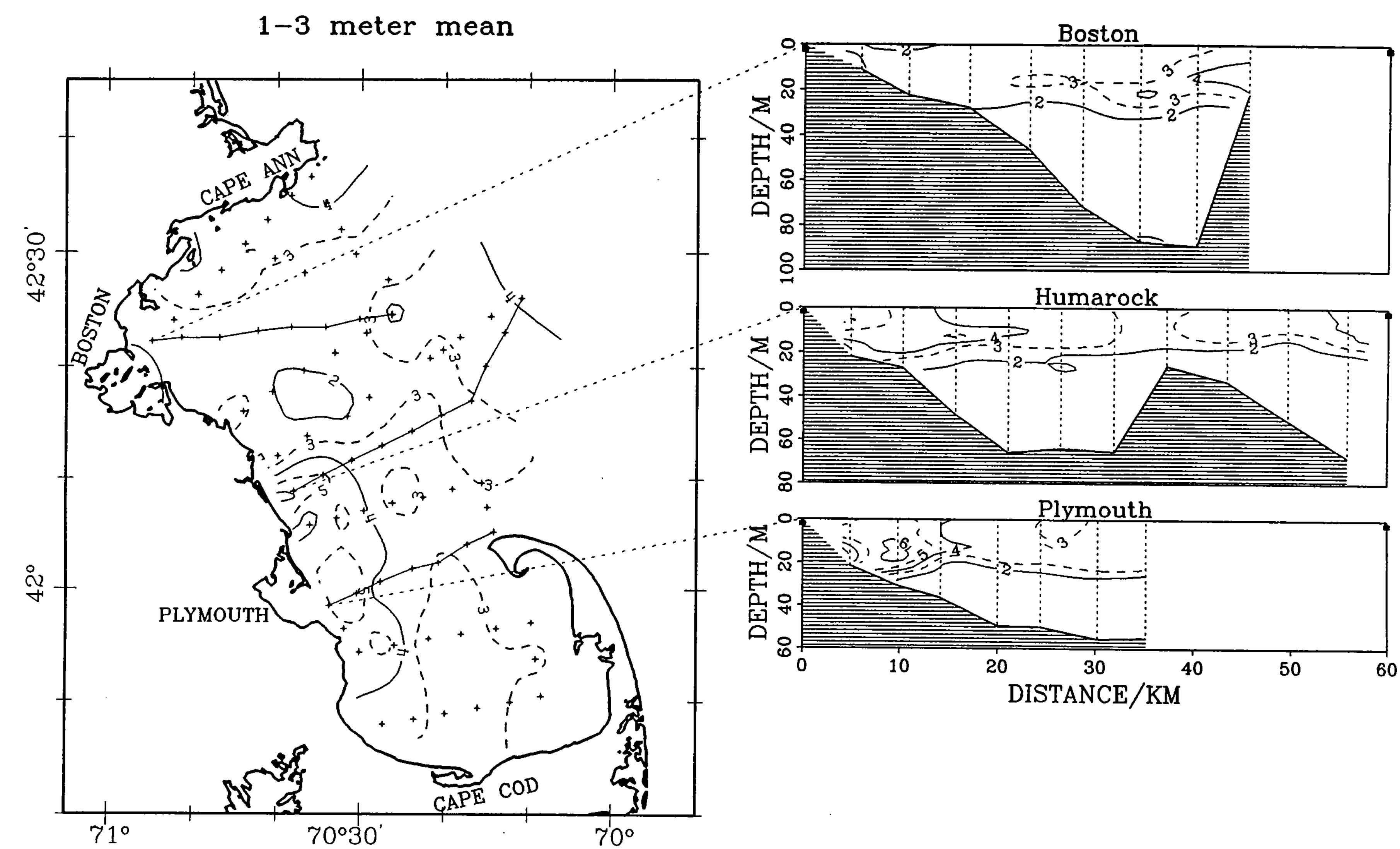


Figure 2.4-22 Surface and vertical section contour plots of fluorescence (approximately chlorophyll-a in $\mu g\ l^{-1}$) for the October 16–18, 1990 cruise. The contour intervals are 1.0 $\mu g\ l^{-1}$ for all plots. Chlorophyll was relatively low over much of the Bays, but a region of high concentration existed in the apparent upwelling region near Plymouth.

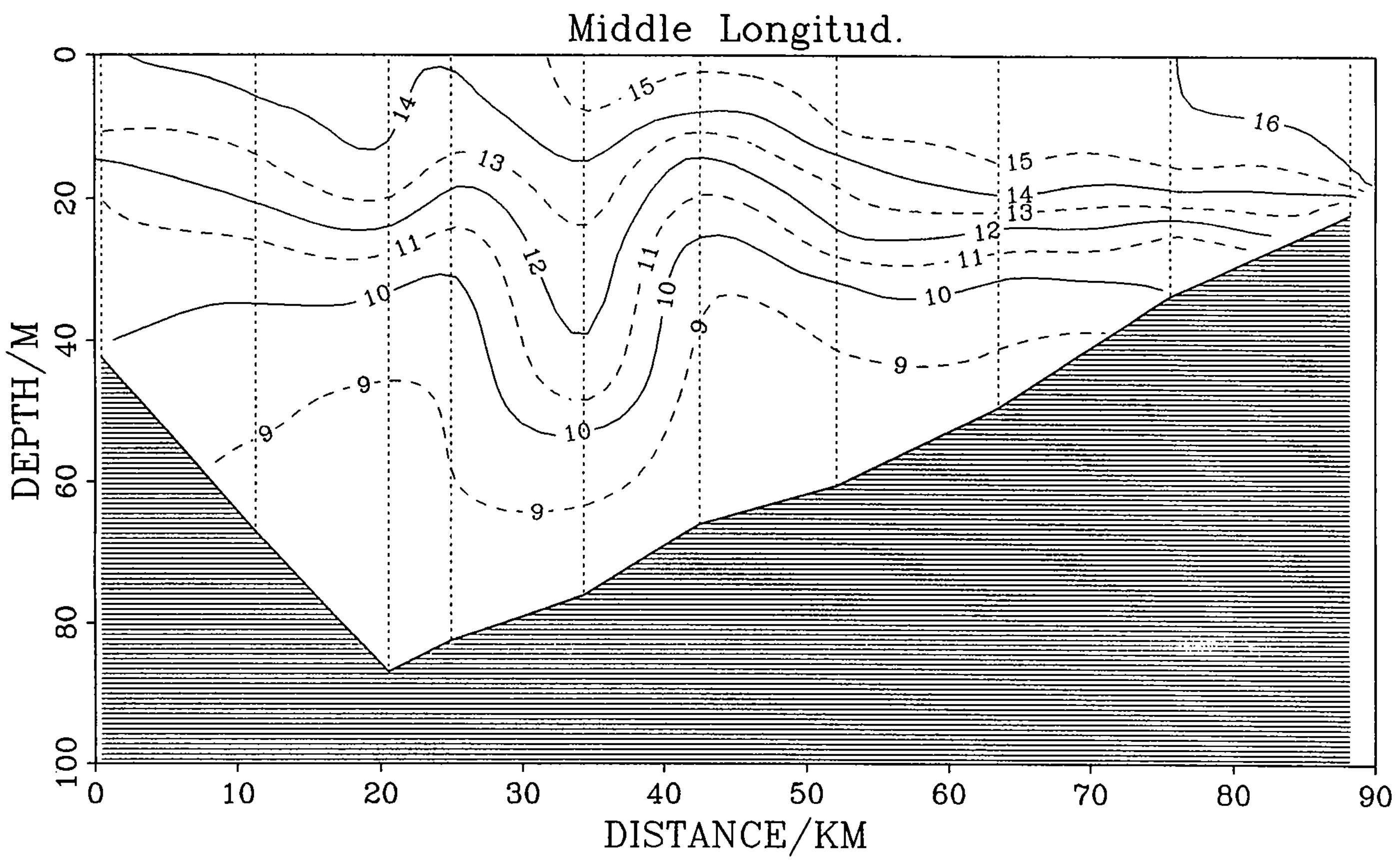


Figure 2.4-23 Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature (°C) for the October 16–18, 1990 cruise. The contour interval is 1.0°C. The isotherm depression near the middle of the section was associated with an internal wave through which the SC4 station was sampled.

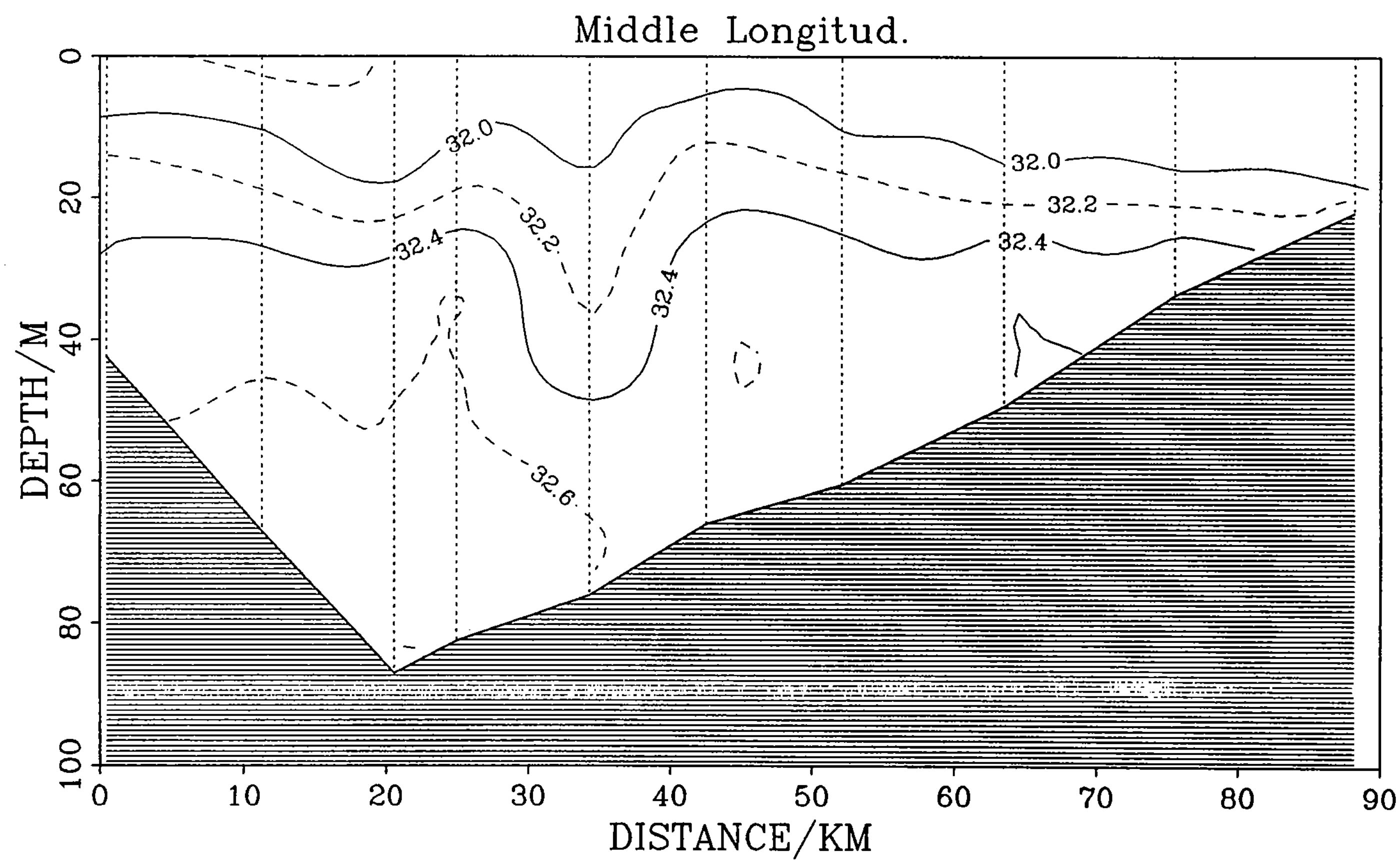


Figure 2.4-24 Mid-bay longitudinal section contour plot of salinity (PSU) for the October 16–18, 1990 cruise. The contour interval is 0.2 PSU. The effect of the internal wave noted in figure 2.4-23 is also seen here.

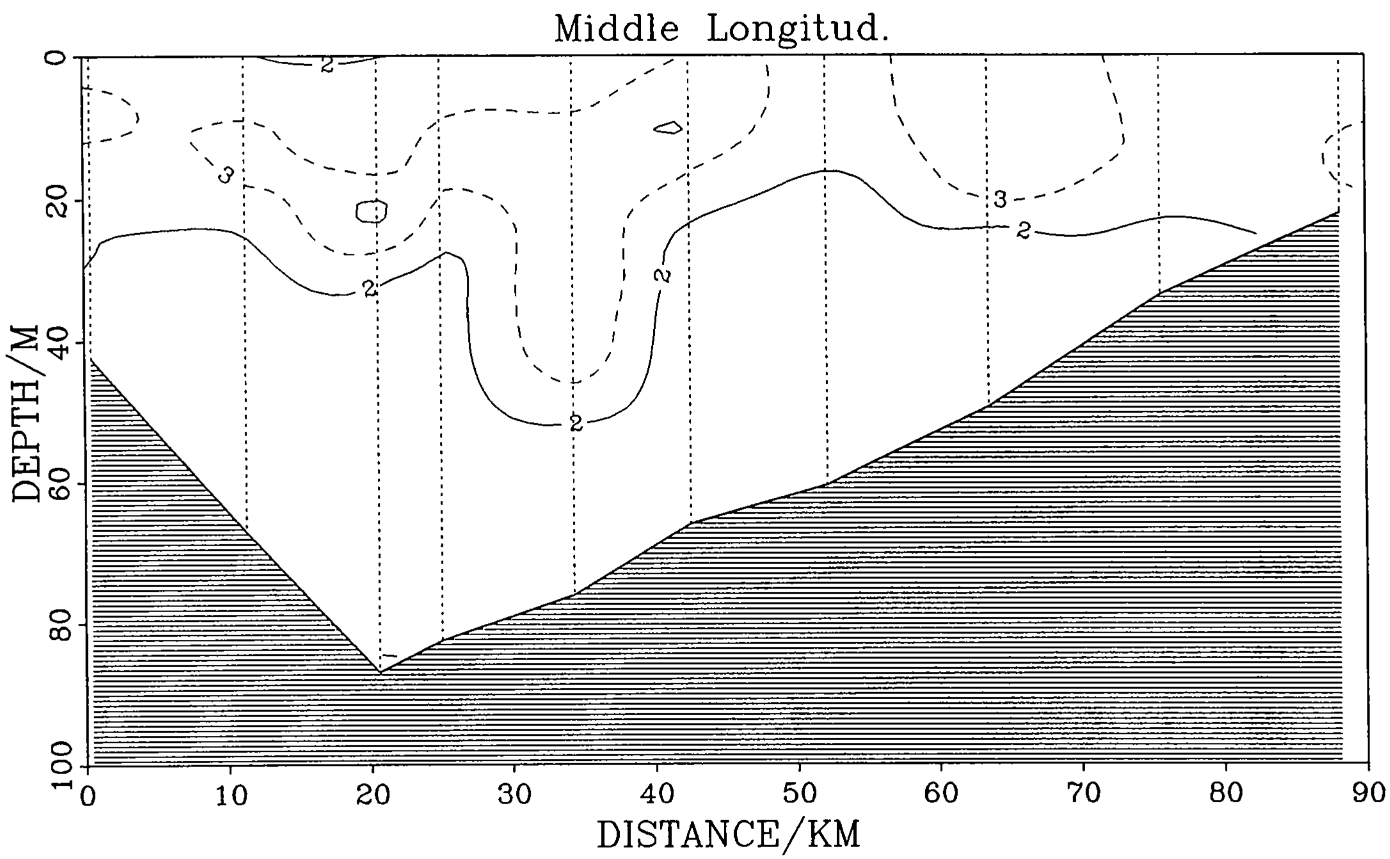


Figure 2.4-25 Mid-bay longitudinal section contour plot of fluorescence (approximately $\mu g\ l^{-1}$ of chlorophyll-a) for the October 16–18, 1990 cruise. The contour interval is 1.0 $\mu g\ l^{-1}$. The fluorescence is relatively uniform in and above the pycnocline.

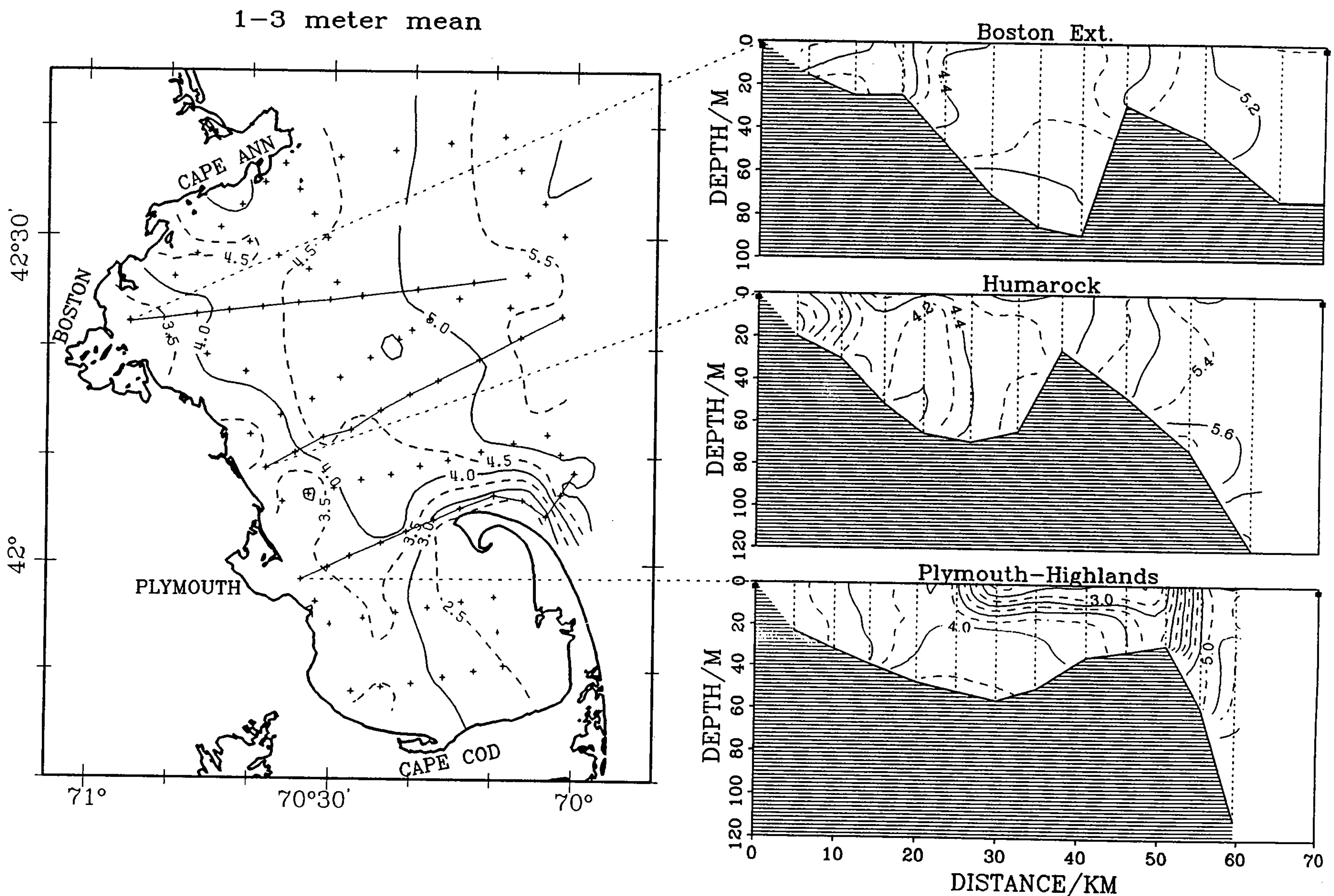


Figure 2.4-26 Surface and vertical section contour plots of temperature (°C) for the February 4–6, 1991 cruise. The contour intervals are 0.2°C for the vertical sections and 0.5°C for the surface plot. Surface water was coldest nearshore, particularly in Cape Cod Bay. The layer of very cold water in the Plymouth-Highlands section appears to originate in the eastern side of Cape Cod Bay.

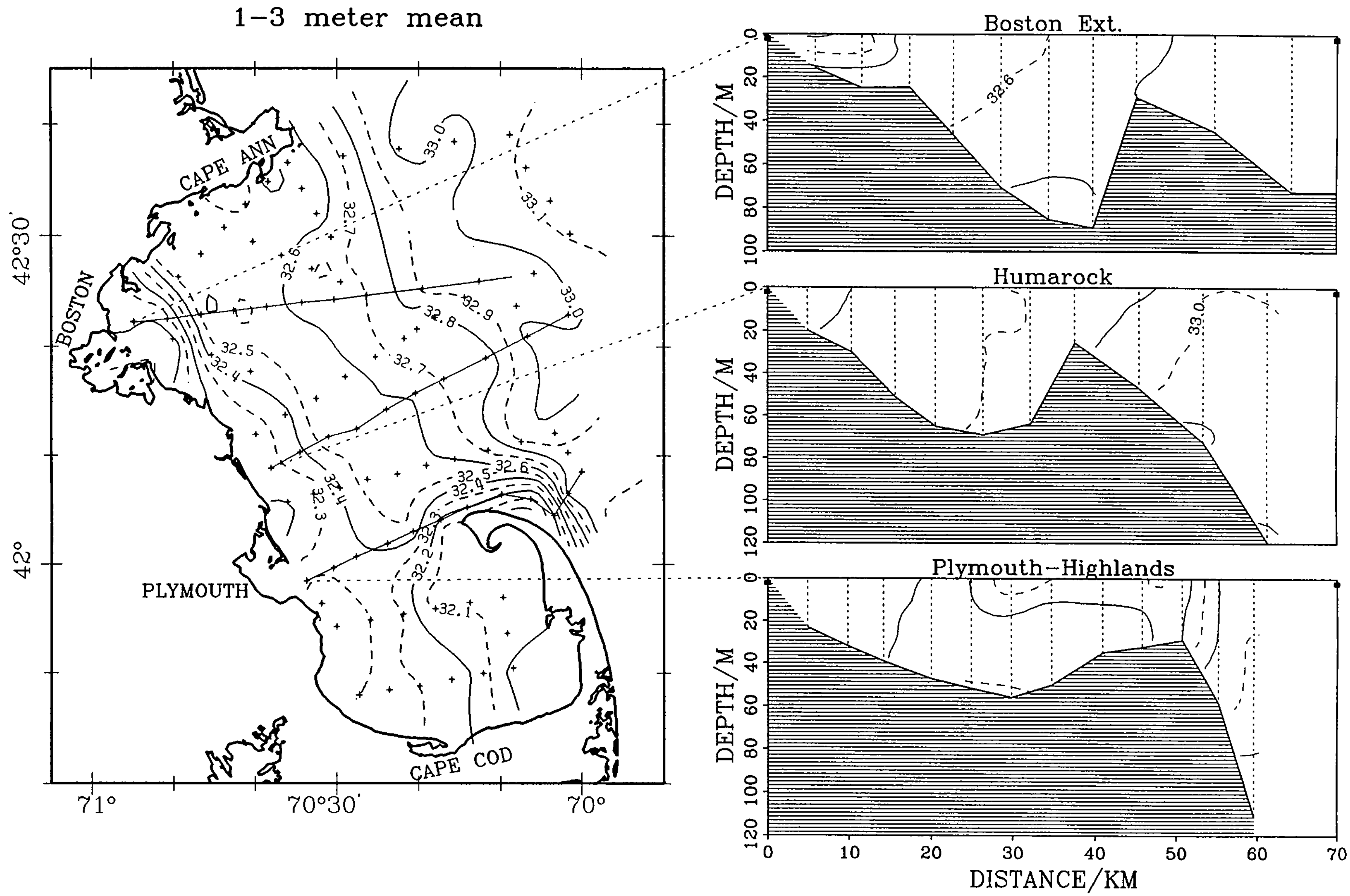


Figure 2.4-27 Surface and vertical section contour plots of salinity (PSU) for the February 4-6, 1991 cruise. The contour intervals are 0.2 PSU for the vertical sections and 0.1 PSU for the surface plot. Relatively fresh water was found along the coast, corresponding to the lowest temperature water (fig. 2.4-26).

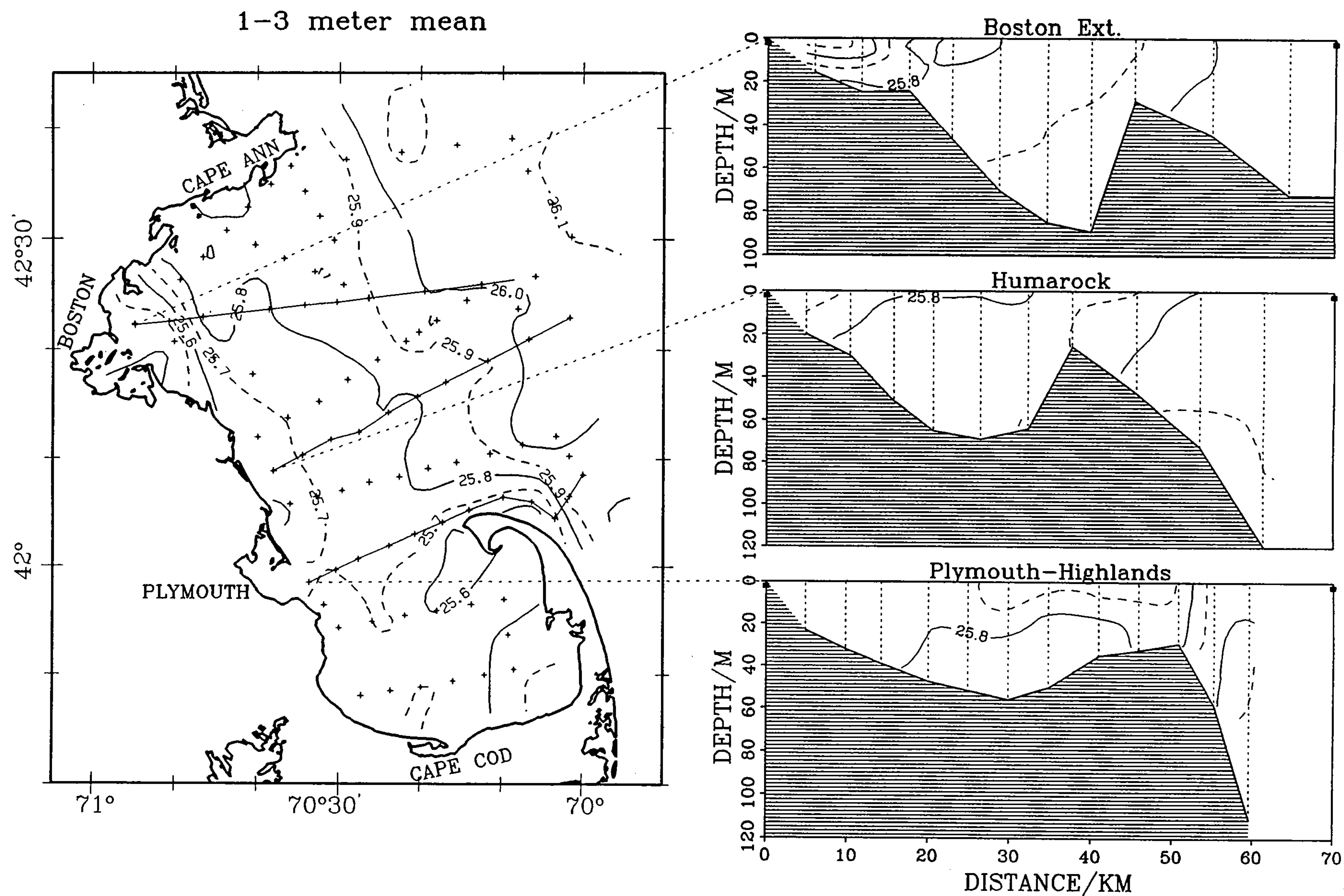


Figure 2.4-28 Surface and vertical section contour plots of σ_θ (kg m^{-3}) for the February 4–6, 1991 cruise. The contour intervals are 0.2 kg m^{-3} for the vertical sections and 0.1 kg m^{-3} for the surface plot. Note that the temperature and salinity variations partially compensate, so that σ_θ varies less.

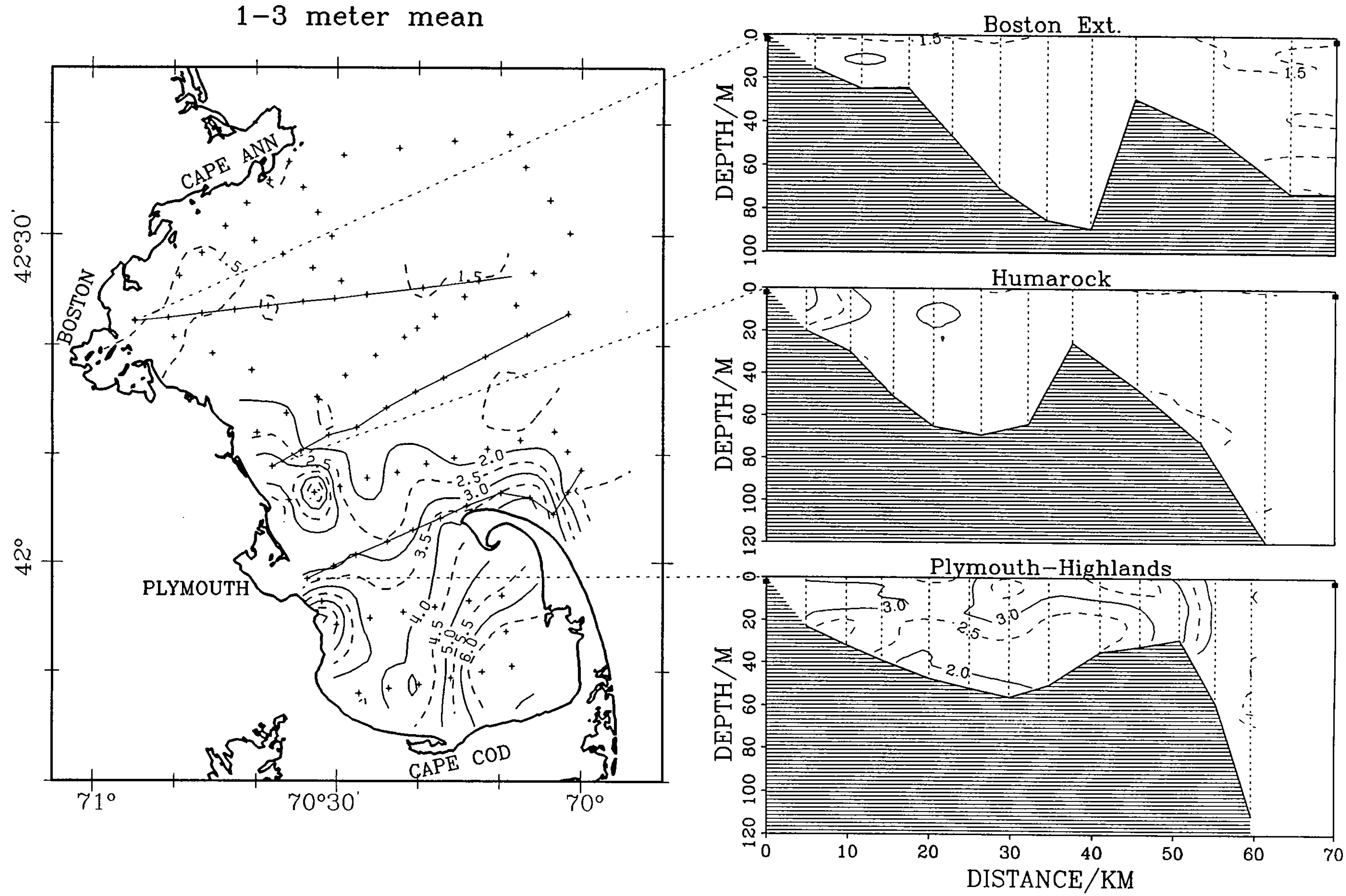


Figure 2.4-29 Surface and vertical section contour plots of fluorescence (approximately chlorophyll-a in $\mu g\, l^{-1}$) for the February 4–6, 1991 cruise. The contour intervals are 0.5 $\mu g\, l^{-1}$ for all plots. Chlorophyll concentration was very low over most of the Massachusetts Bay, but high levels existed in Cape Cod Bay.

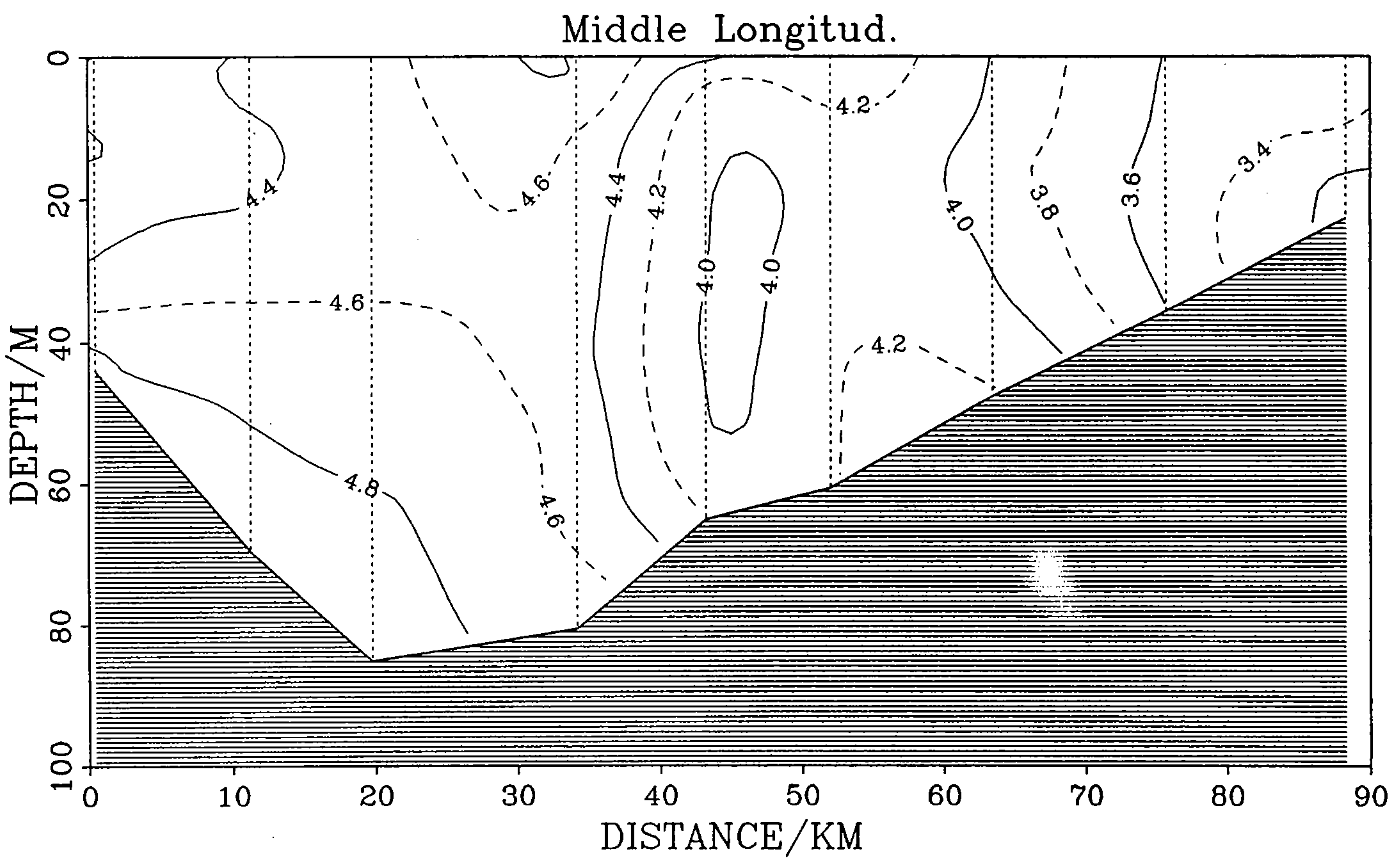


Figure 2.4-30 Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature (°C) for the February 4–6, 1991 cruise. The contour interval is 0.2°C. Cold water in Cape Cod Bay extended northward into the southern portion of Massachusetts Bay.

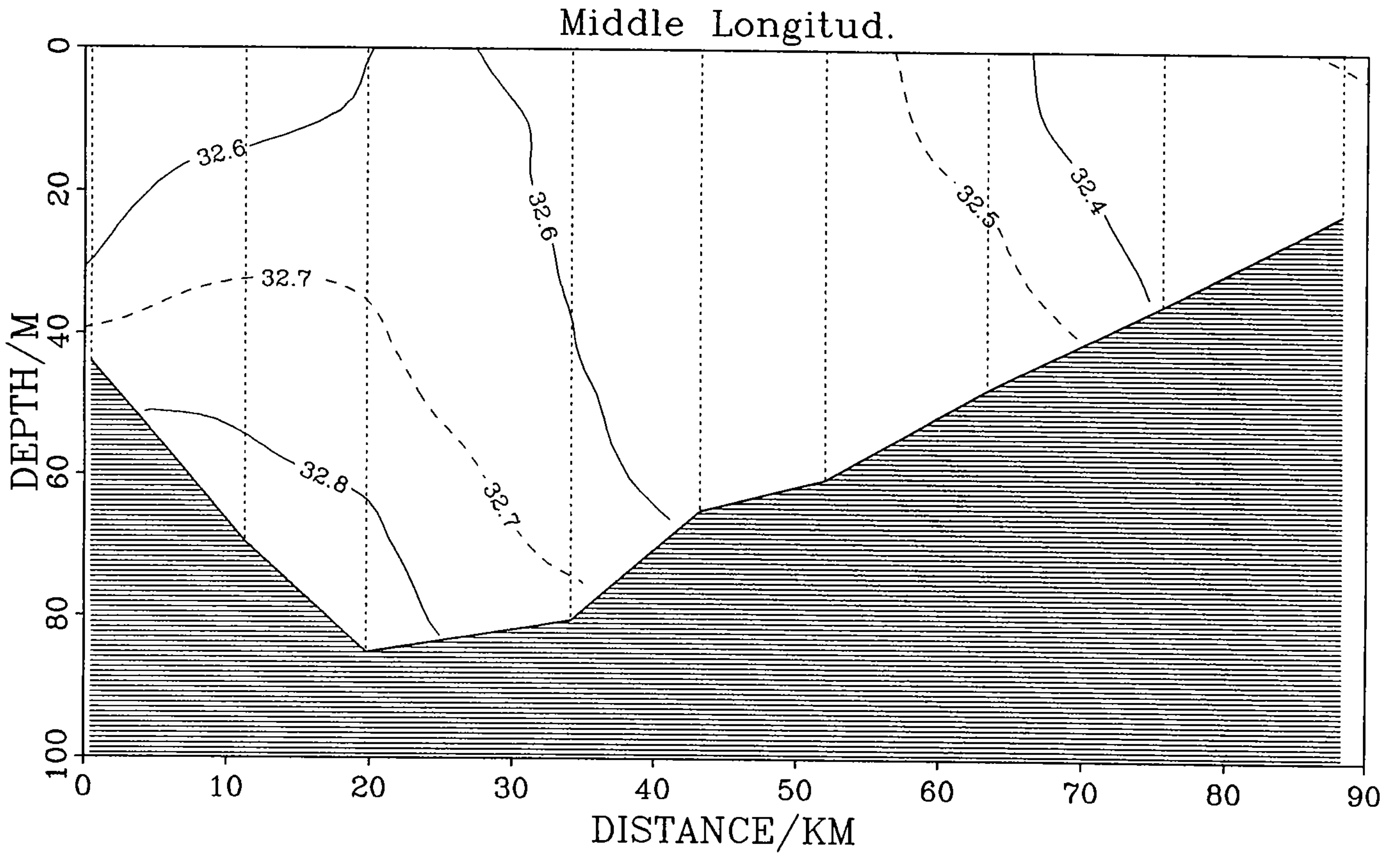


Figure 2.4-31 Mid-bay longitudinal section contour plot of salinity (PSU) for the February 4–6, 1991 cruise. The contour interval is 0.1 PSU. Note that there is a slight stratification in the deep water of Massachusetts Bay.

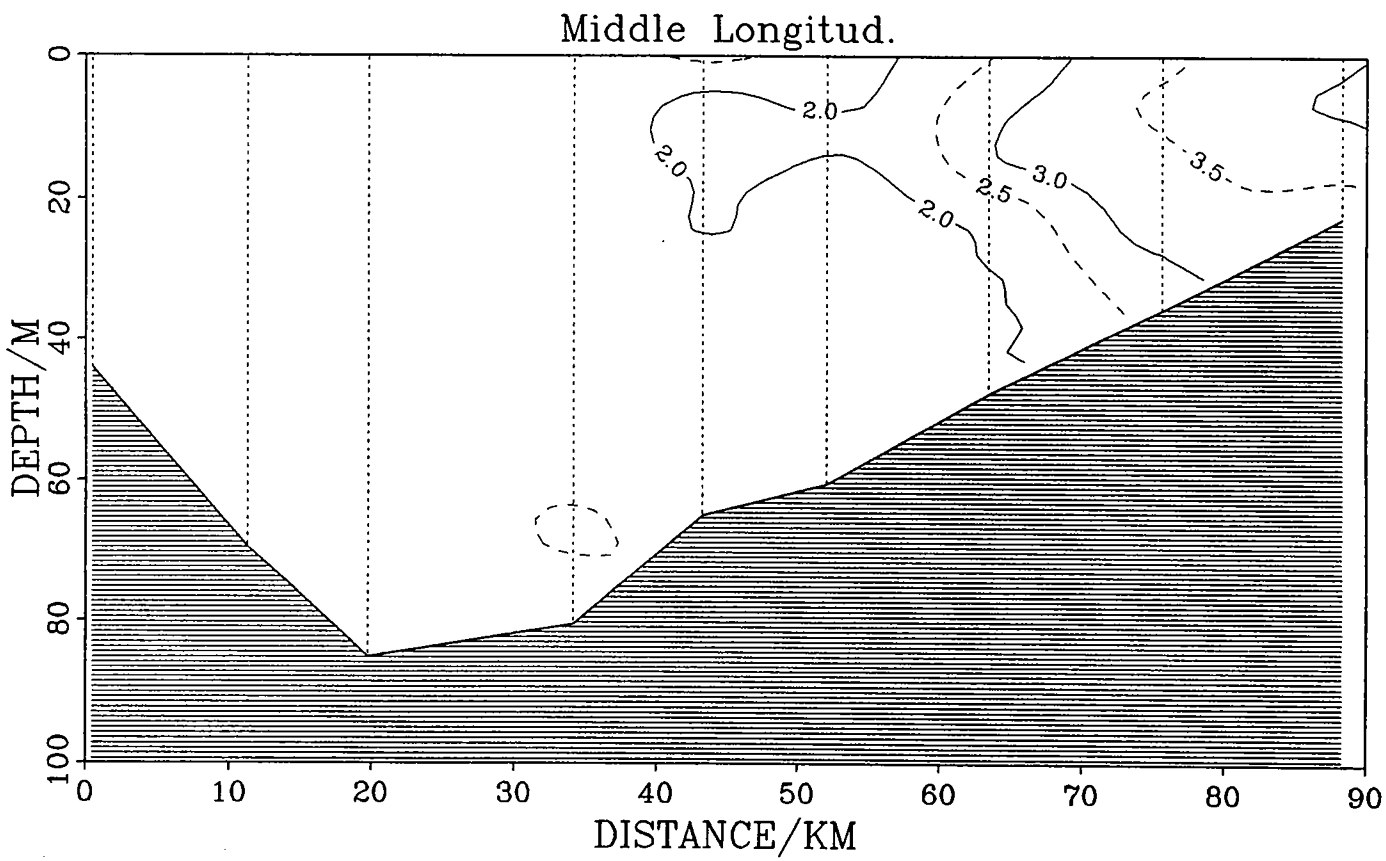


Figure 2.4-32 Mid-bay longitudinal section contour plot of fluorescence (approximately $\mu g\, l^{-1}$ of chlorophyll-a) for the February 4–6, 1991 cruise. The contour interval is 0.5 $\mu g\, l^{-1}$. High fluorescence levels were confined to Cape Cod Bay and southern Massachusetts Bay.

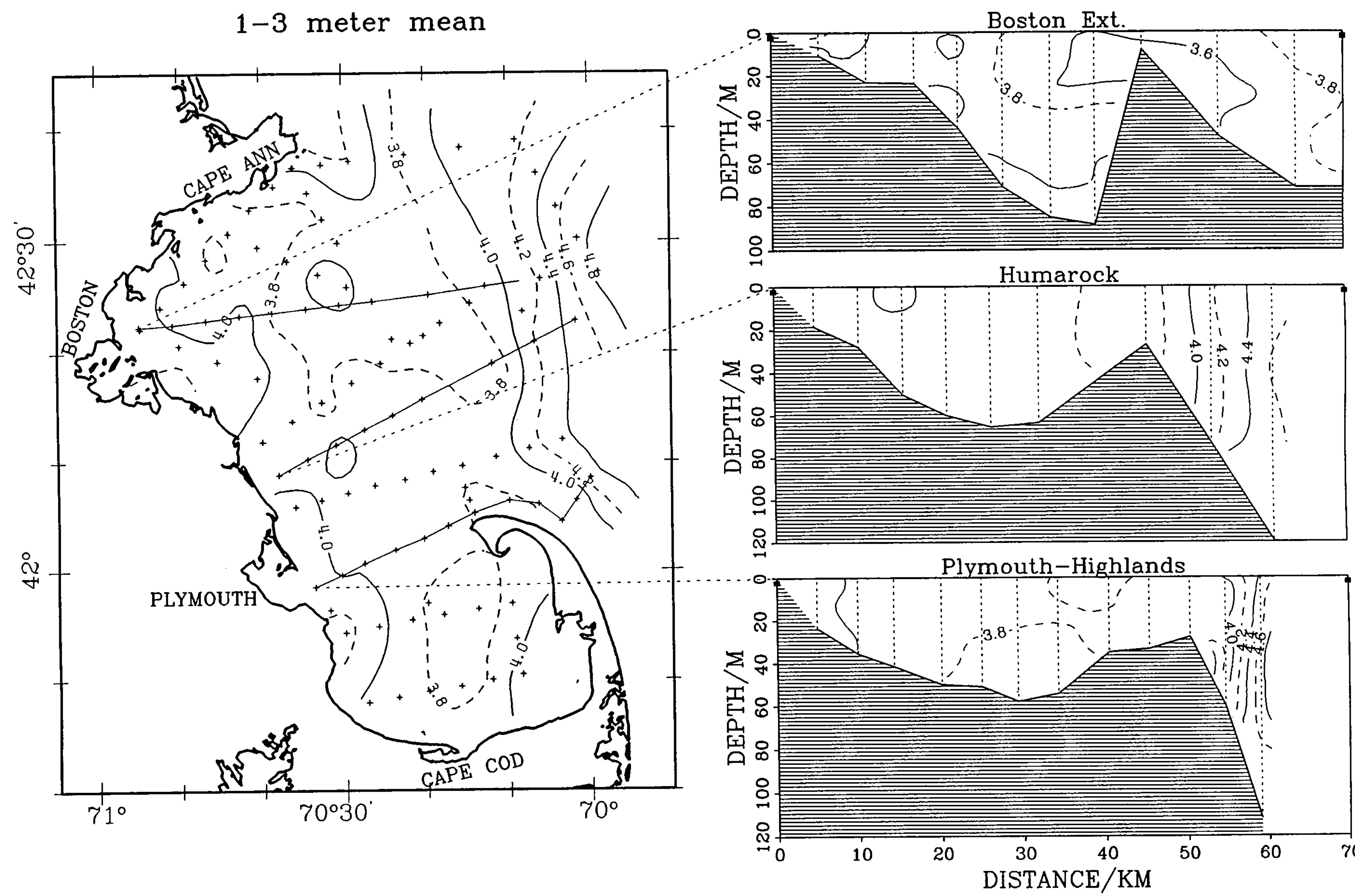


Figure 2.4-33 Surface and vertical section contour plots of temperature (°C) for the March 20–23, 1991 cruise. The contour intervals are 0.2°C all plots. The Bays are nearly isothermal, with slightly warmer water offshore.

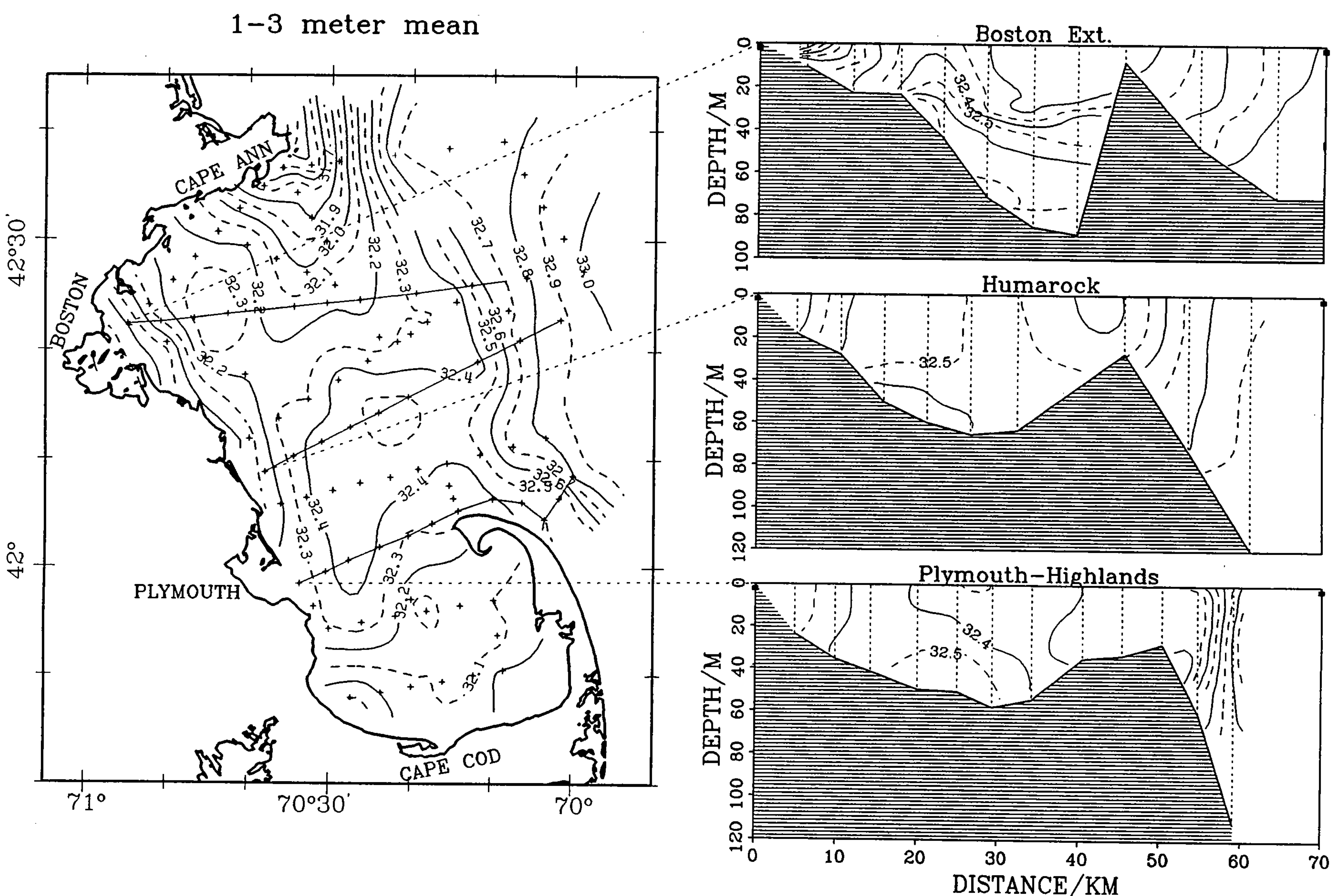


Figure 2.4-34 Surface and vertical section contour plots of salinity (PSU) for the March 20–23, 1991 cruise. The contour interval is 0.1 PSU for all plots. A low salinity plume extended from Cape Ann across northern Massachusetts Bay and coastal regions near Boston and in Cape Cod Bay were relatively fresh.

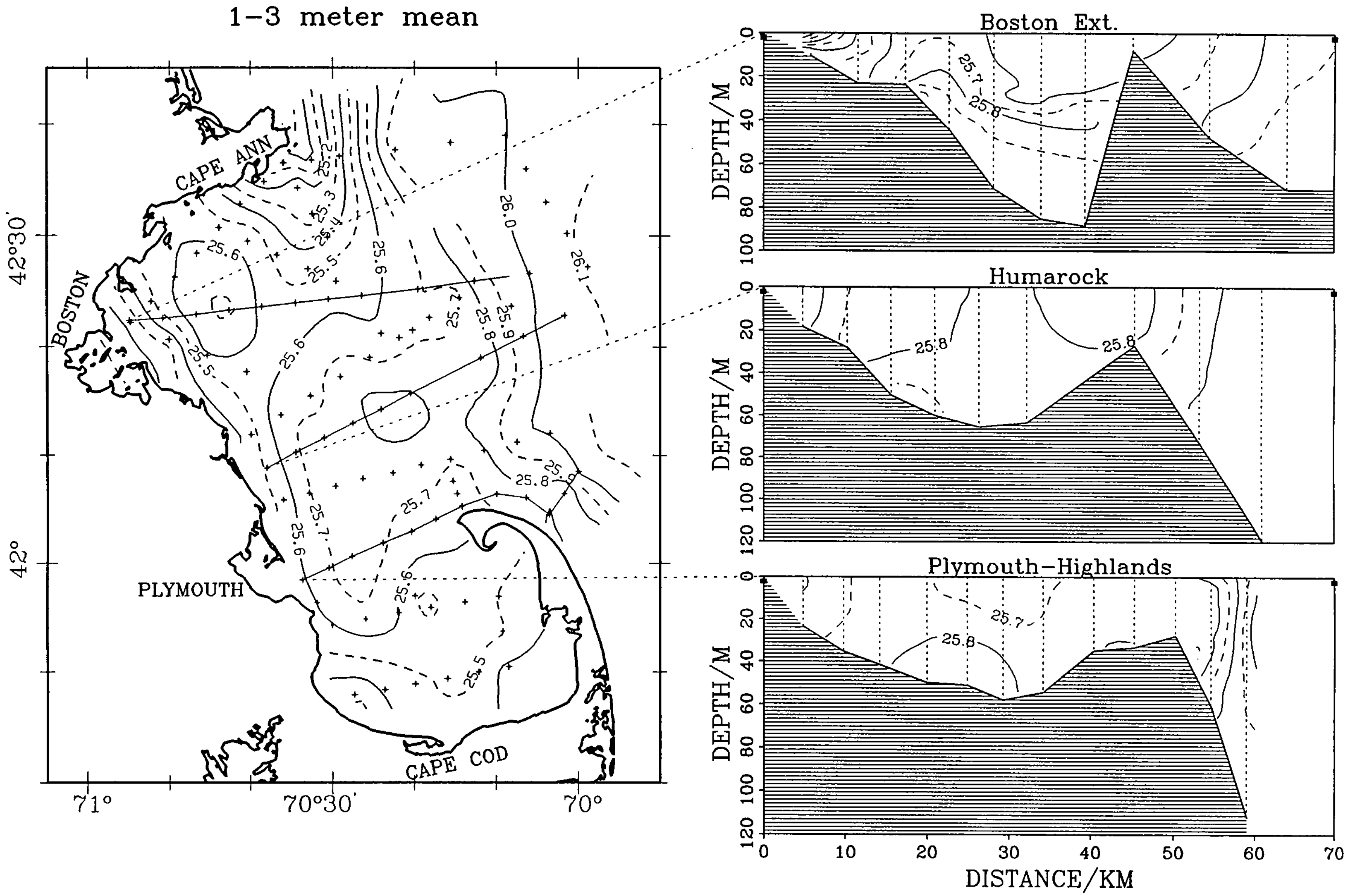


Figure 2.4-35 Surface and vertical section contour plots of σ_θ (kg m^{-3}) for the March 20–23, 1991 cruise. The contour intervals are 0.2 kg m^{-3} for the vertical sections and 0.1 kg m^{-3} for the surface plot. Density was largely determined by salinity.

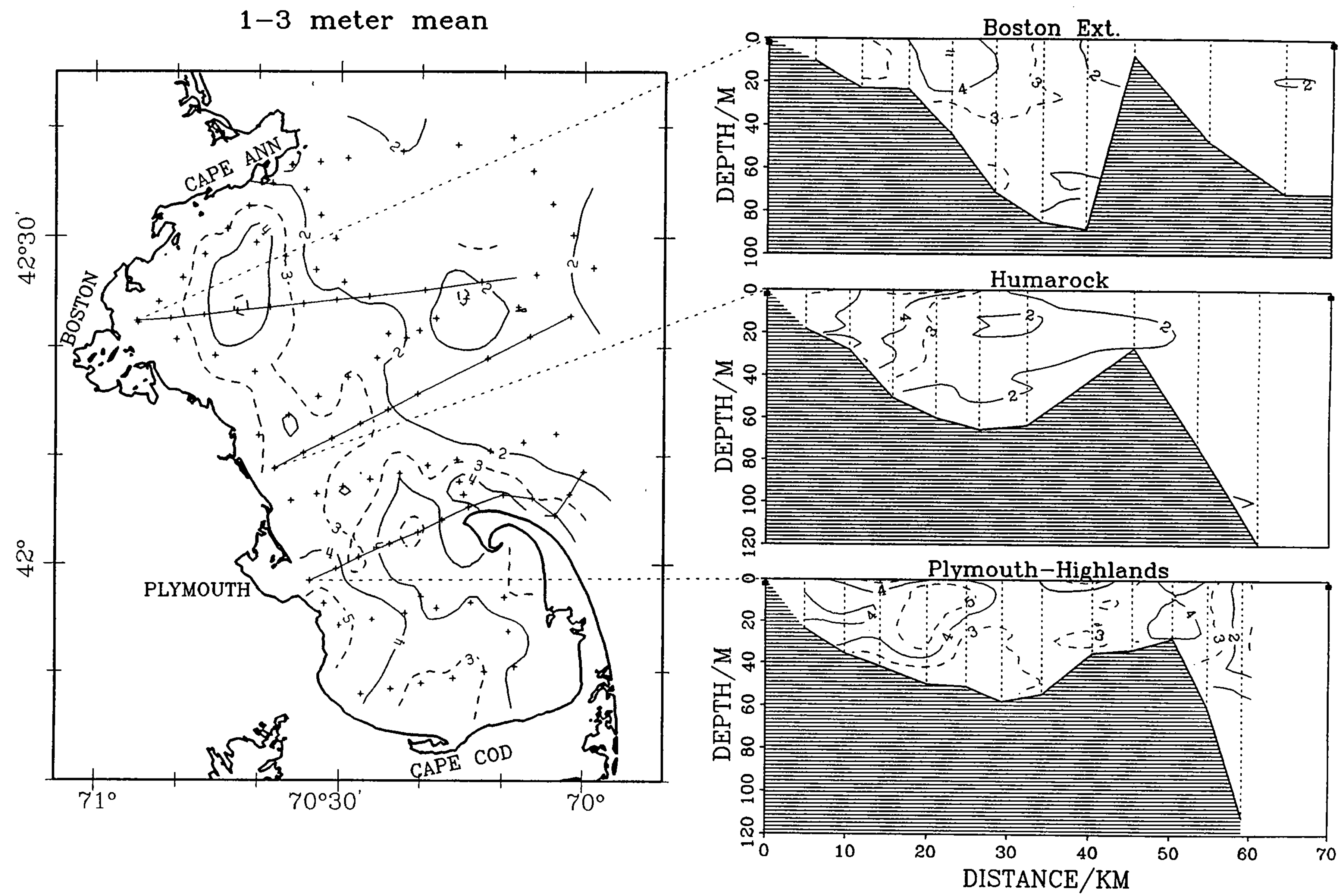


Figure 2.4-36 Surface and vertical section contour plots of fluorescence (approximately chlorophyll-a in $\mu g\ l^{-1}$) for the March 20-23, 1991 cruise. The contour intervals are 1.0 $\mu g\ l^{-1}$ for all plots. Fluorescence levels were generally high, indicating presence of a spring bloom.

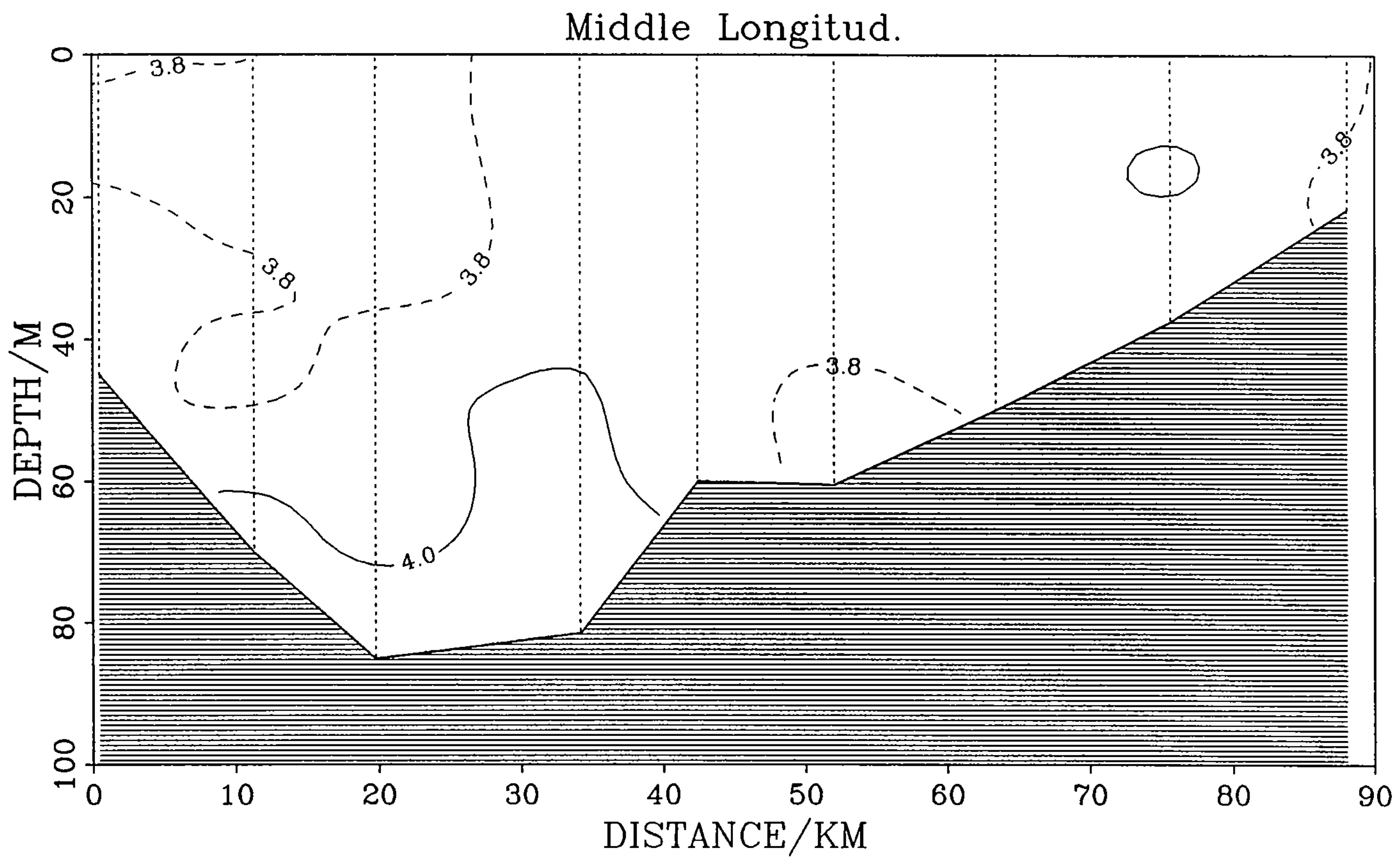


Figure 2.4-37 Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature (°C) for the March 20–23, 1991 cruise. The contour interval is 0.2°C.

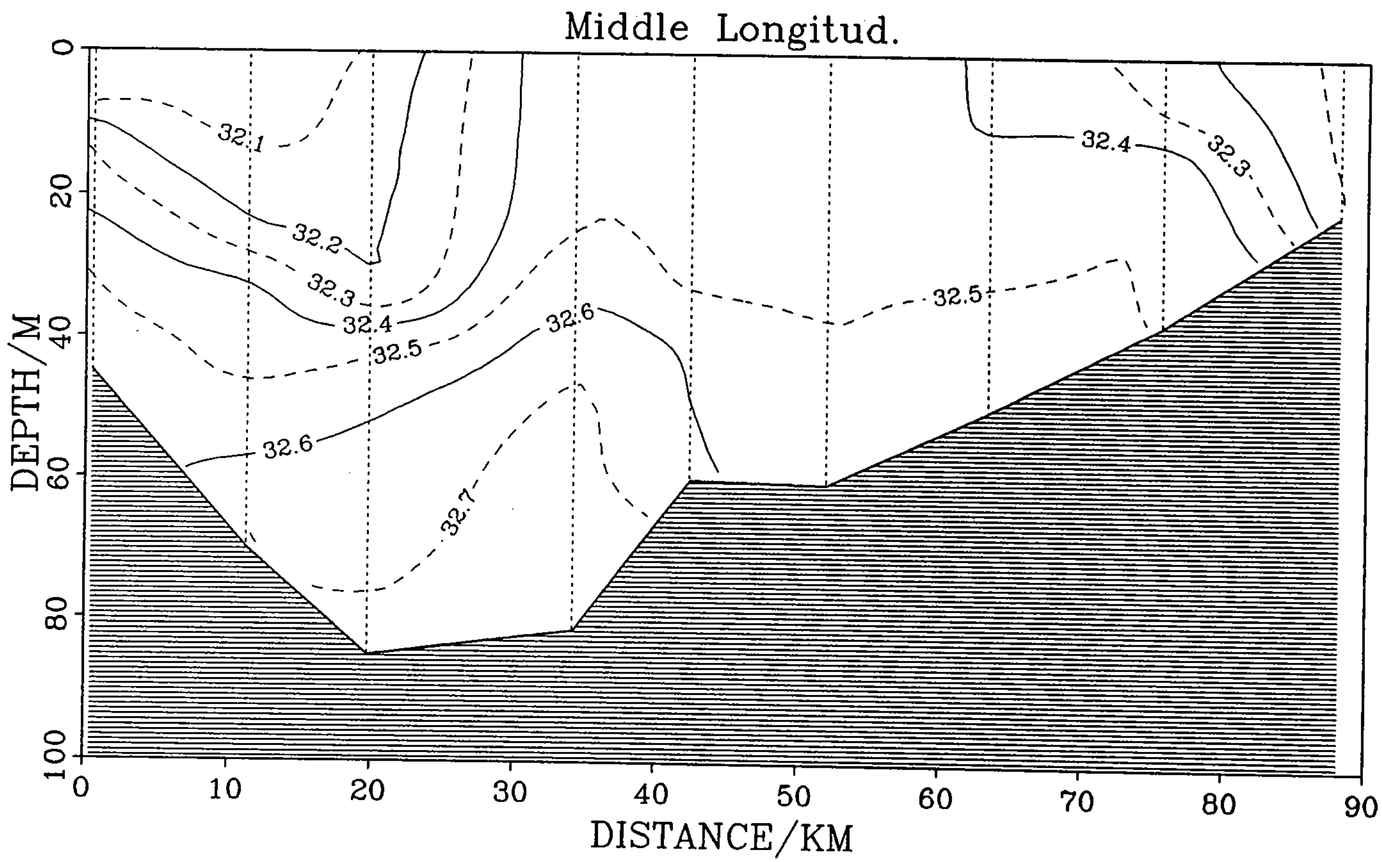


Figure 2.4-38 Mid-bay longitudinal section contour plot of salinity (PSU) for the March 20–23, 1991 cruise. The contour interval is 0.1 PSU. Low surface salinity existed in Cape Cod Bay and northern Massachusetts Bay.

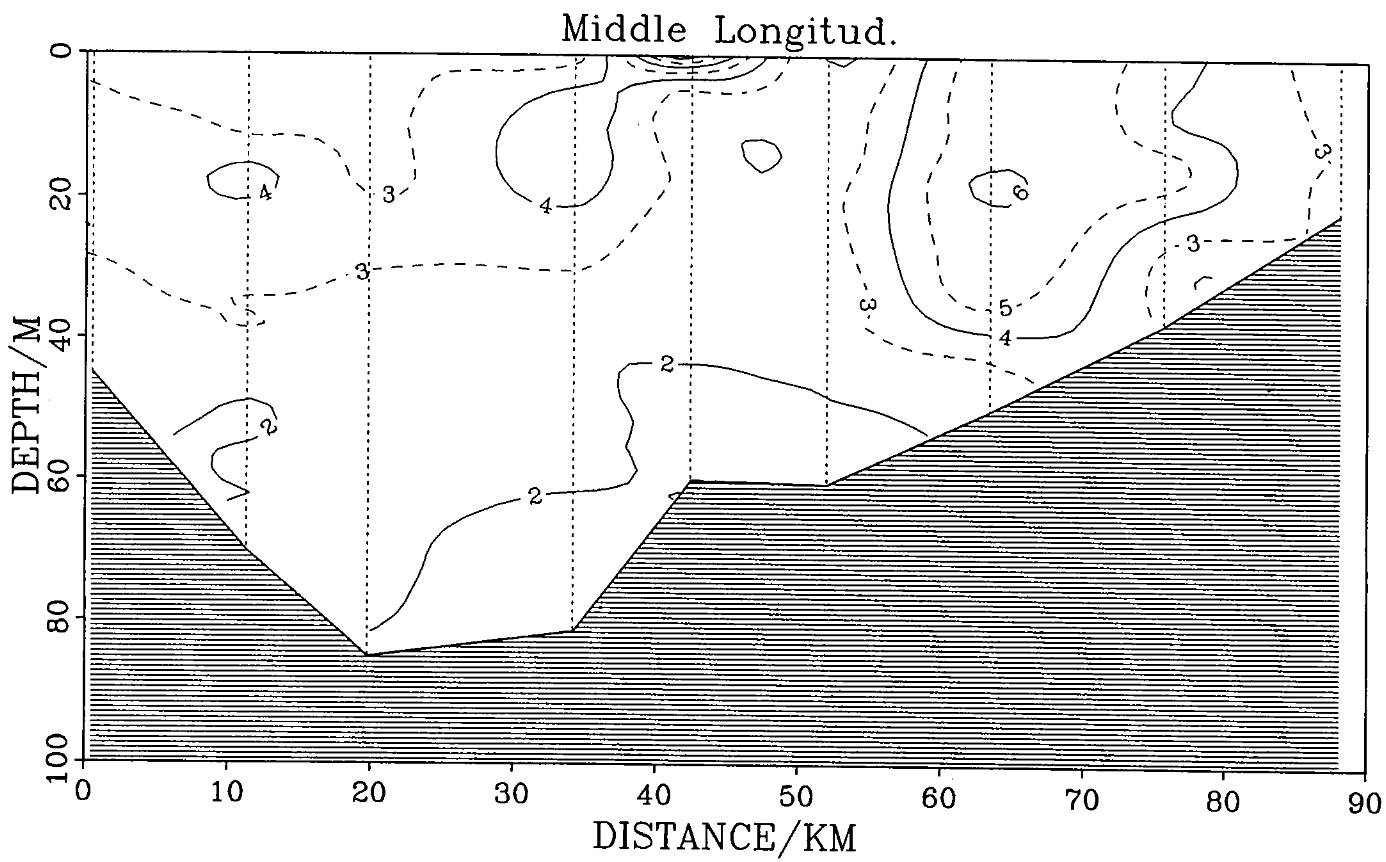


Figure 2.4-39 Mid-bay longitudinal section contour plot of fluorescence (approximately $\mu g\ l^{-1}$ of chlorophyll-a) for the March 20–23, 1991 cruise. The contour interval is 1.0 $\mu g\ l^{-1}$. Highest fluorescence levels were in northern Cape Cod Bay.

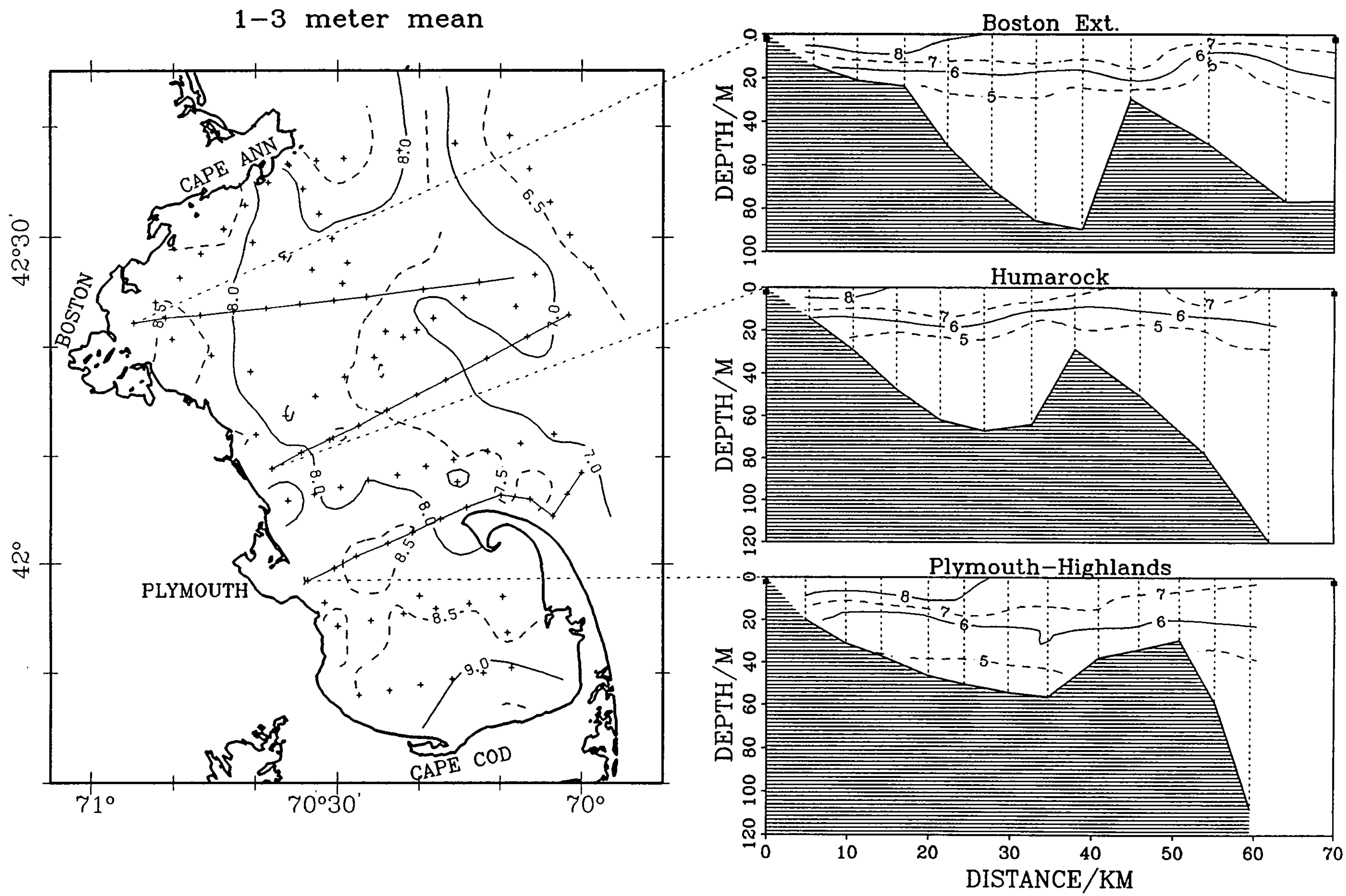


Figure 2.4-40 Surface and vertical section contour plots of temperature (°C) for the April 29–May 2, 1991, 1991 cruise. The contour intervals are 1.0°C for the vertical sections and 0.5°C for the surface plot. Warmest temperatures are along the shore and in Cape Cod Bay.

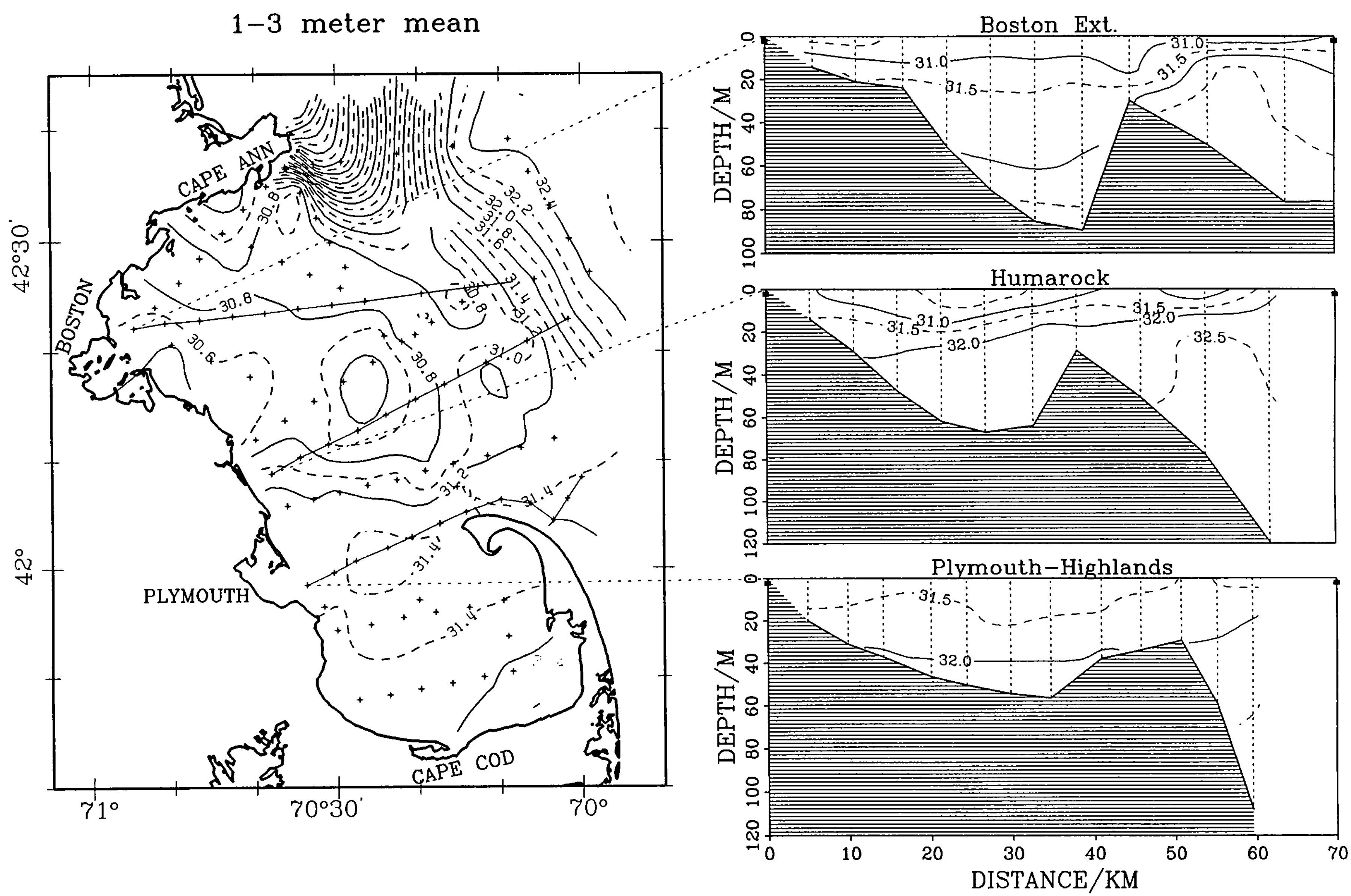


Figure 2.4-41 Surface and vertical section contour plots of salinity (PSU) for the April 29–May 2, 1991 cruise. The contour interval is 0.5 PSU for the vertical sections and 0.2 PSU for the surface plot. Note the patch of low salinity water in the middle of Massachusetts Bay.

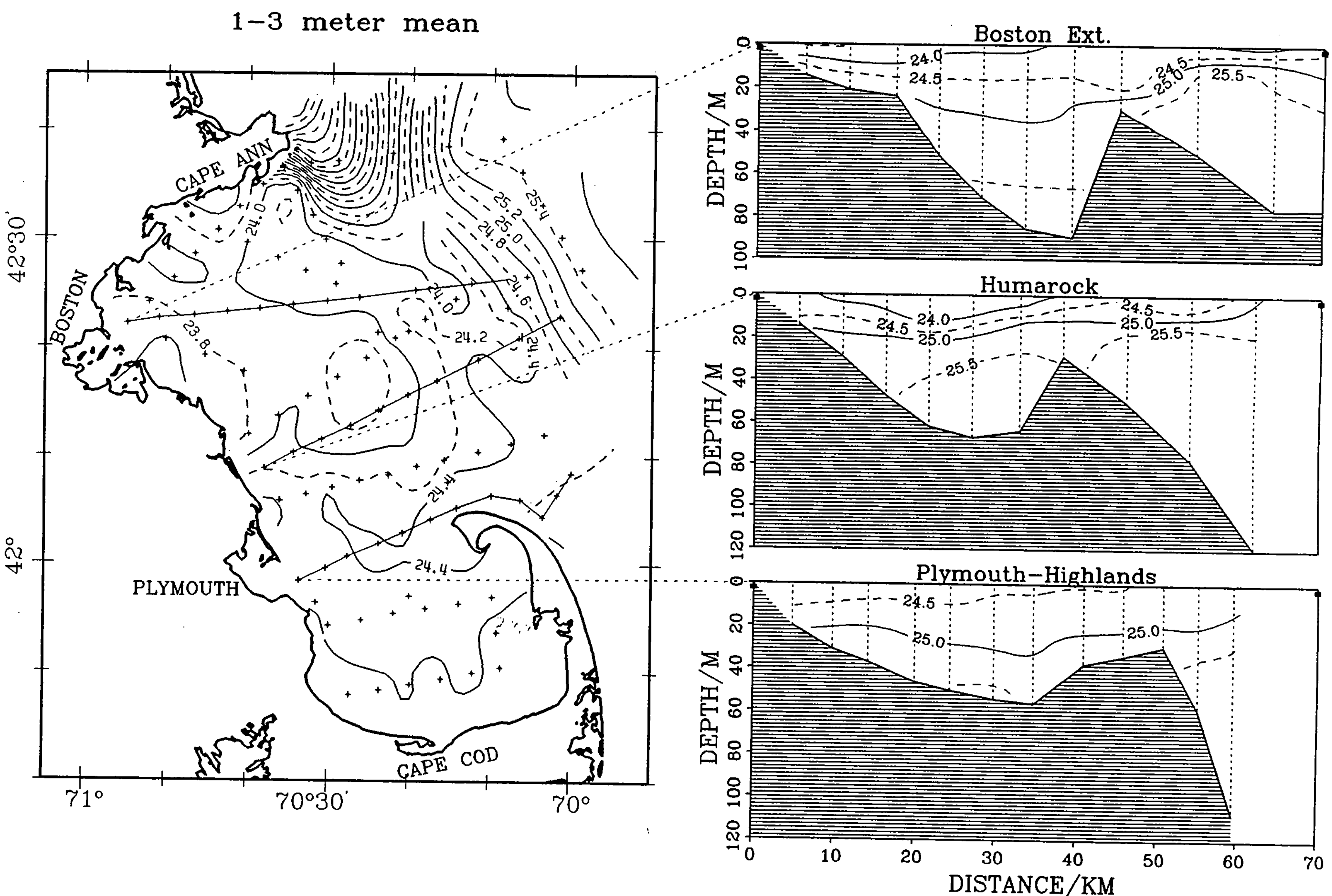


Figure 2.4-42 Surface and vertical section contour plots of σ_θ (kg m^{-3}) for the April 29–May 2, 1991 cruise. The contour intervals are 0.5 kg m^{-3} for the vertical sections and 0.2 kg m^{-3} for the surface plot. The density field is similar to the salinity field (fig. 2.4-41).

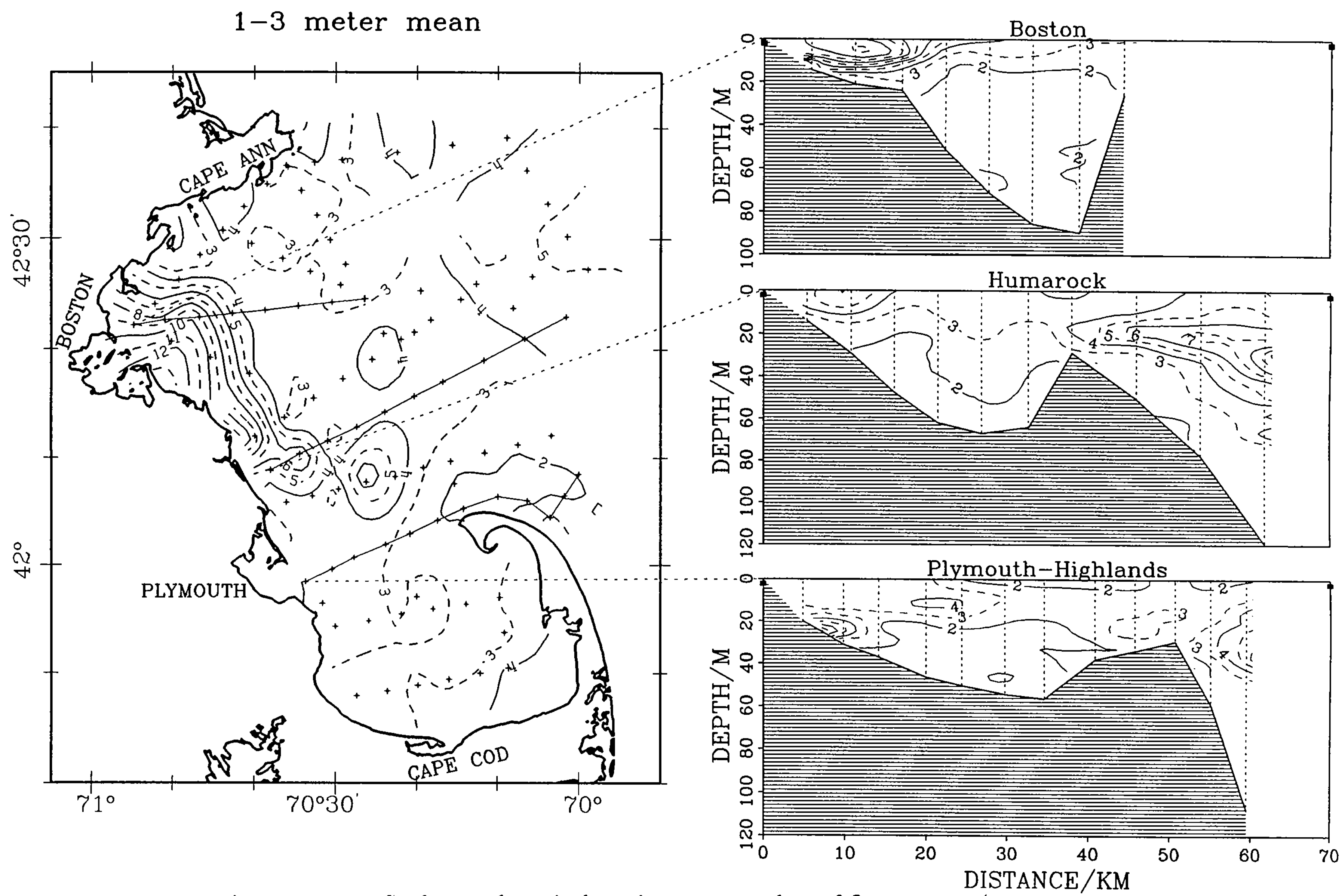


Figure 2.4-43 Surface and vertical section contour plots of fluorescence (approximately chlorophyll-a in $\mu g\ l^{-1}$) for the April 29–May 2, 1991 cruise. The contour intervals are 1.0 $\mu g\ l^{-1}$ for all plots. Fluorescence levels were generally high, with a region of extremely high fluorescence extending along the coast from Boston.

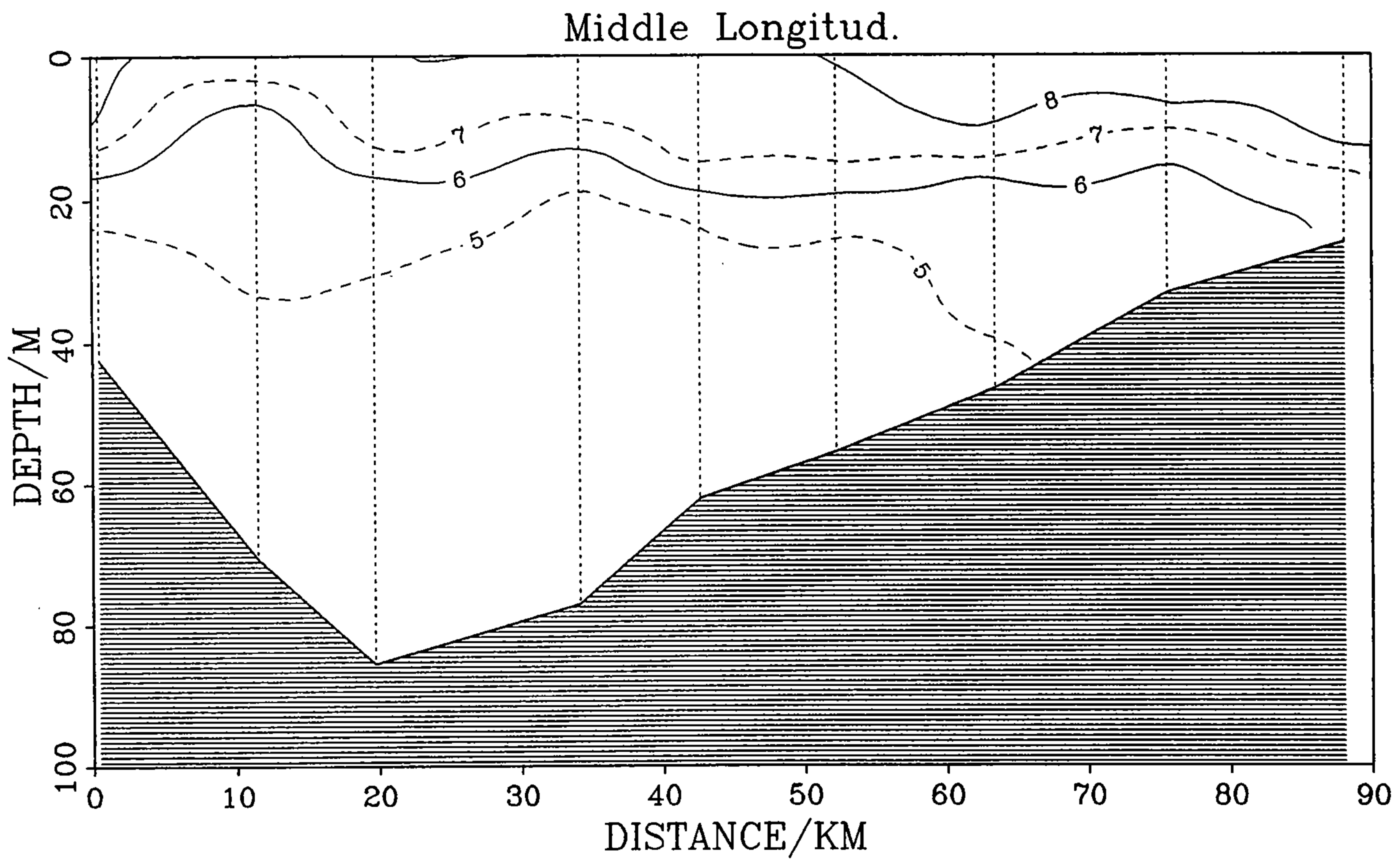


Figure 2.4-44 Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature (°C) for the April 29–May 2, 1991 cruise. The contour interval is 0.2°C. Moderate thermal stratification was found with warmest water in Cape Cod Bay.

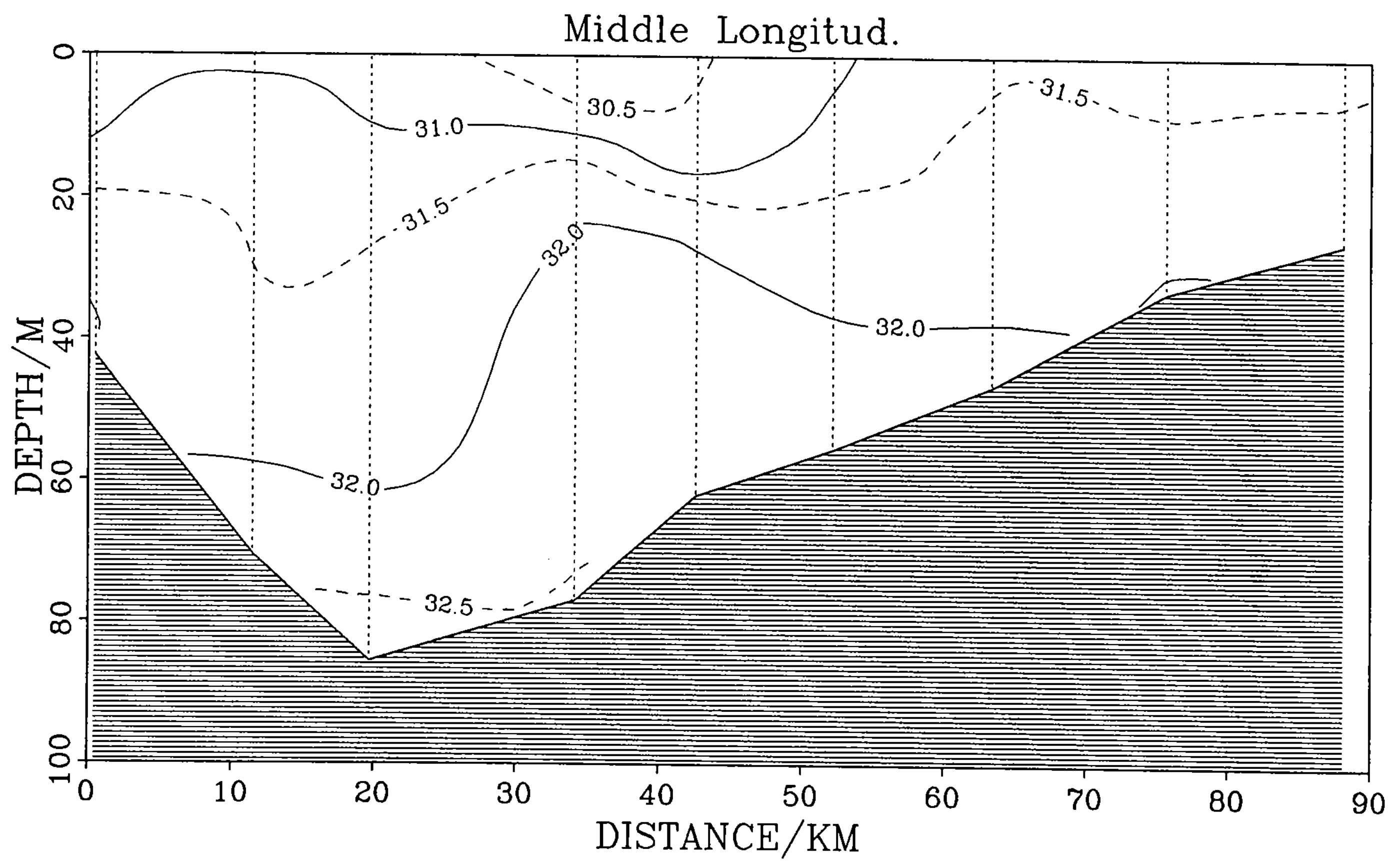


Figure 2.4-45 Mid-bay longitudinal section contour plot of salinity (PSU) for the April 29–May 2, 1991 cruise. The contour interval is 0.5 PSU.

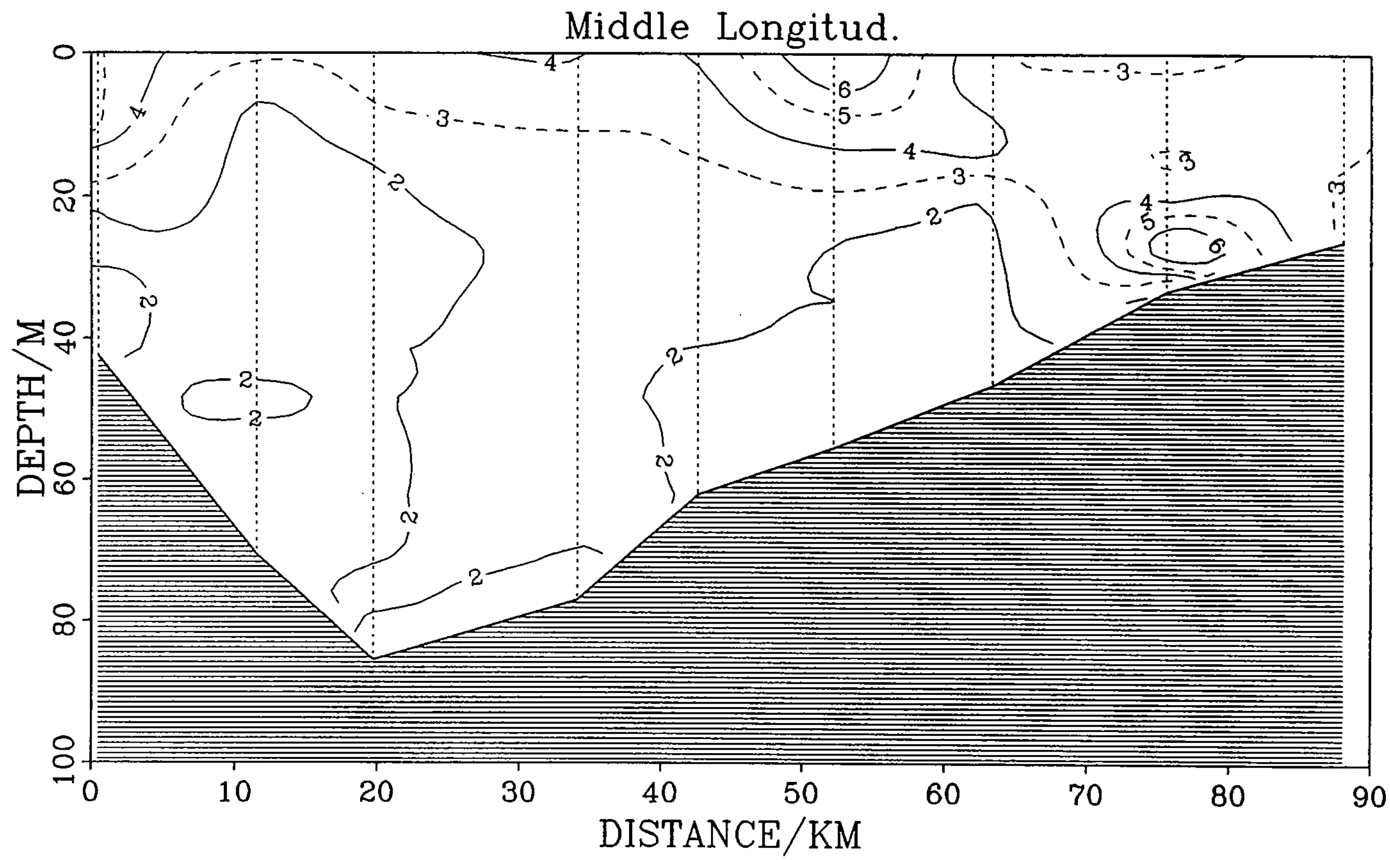


Figure 2.4-46 Mid-bay longitudinal section contour plot of fluorescence (approximately $\mu g\ l^{-1}$ of chlorophyll-a) for the April 29–May 2, 1991 cruise. The contour interval is 1.0 $\mu g\ l^{-1}$. Highest fluorescence levels were in northern Cape Cod Bay.

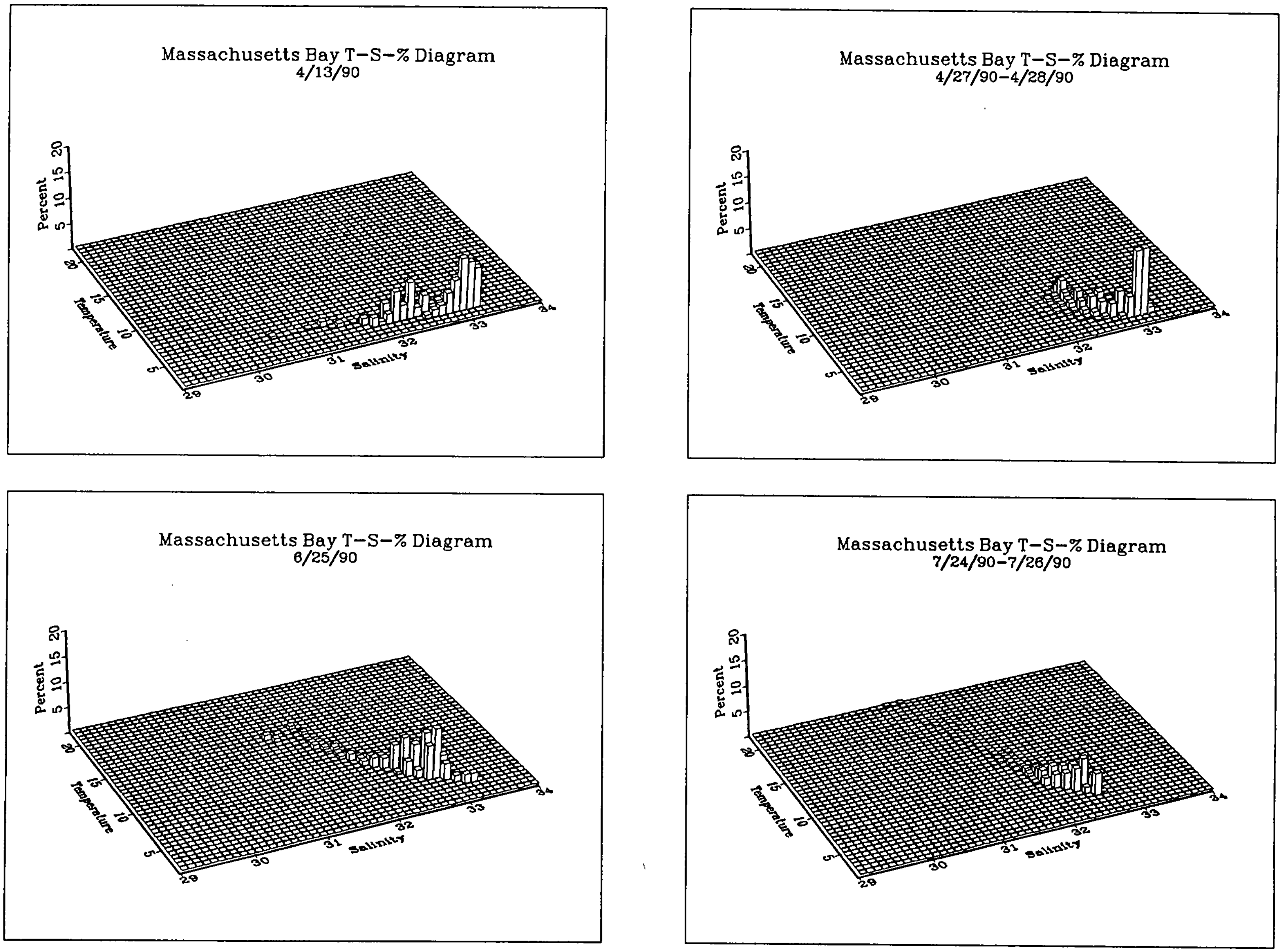


Figure 2.4-47 Three-dimensional bar charts showing percent of Bays water in 0.5°C by 0.1 PSU temperature-salinity bins for April through July, 1990.

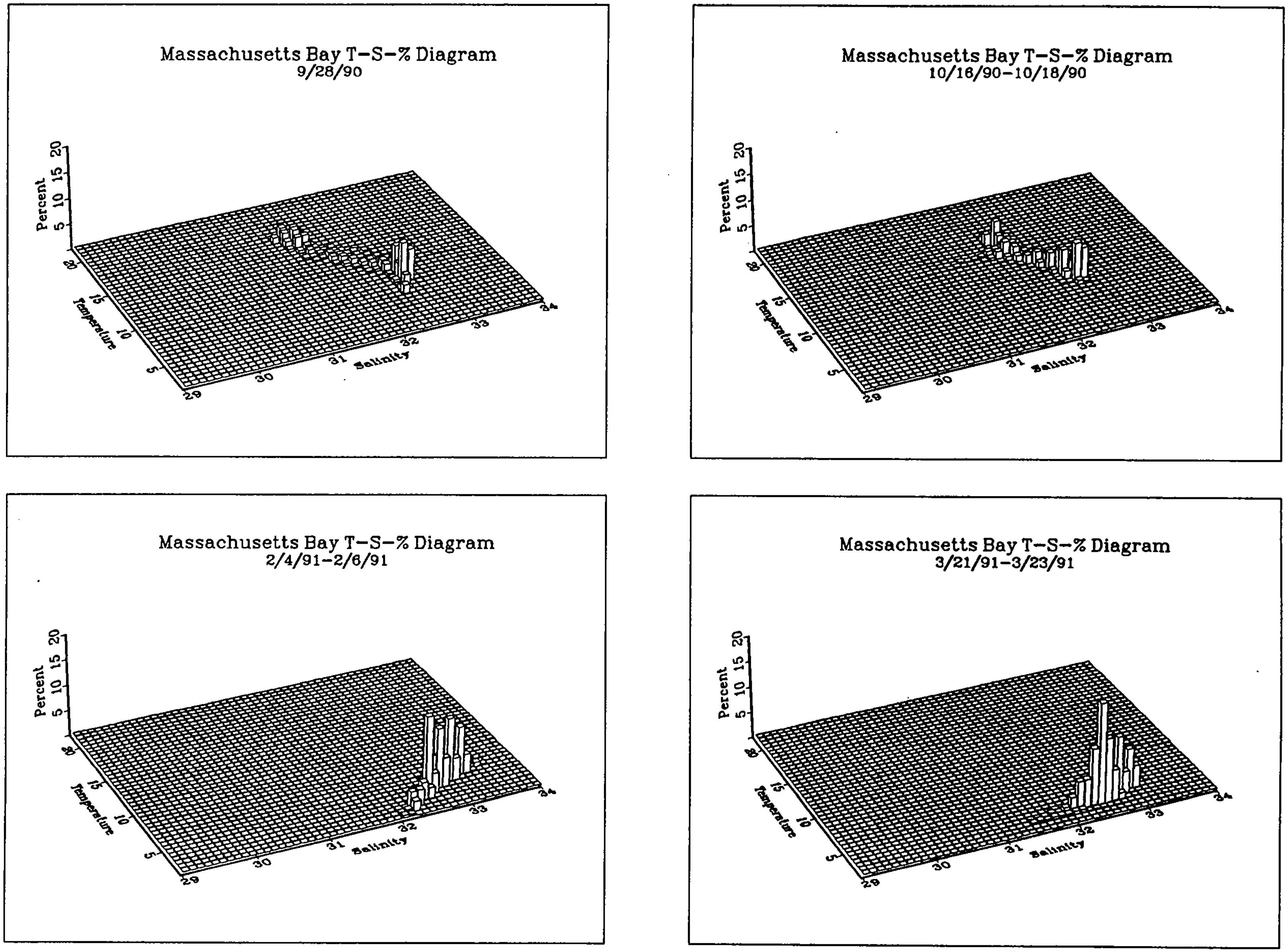


Figure 2.4-48 Three-dimensional bar charts showing percent of Bays water in 0.5°C by 0.1 PSU temperature-salinity bins for September, 1990 through March, 1991.

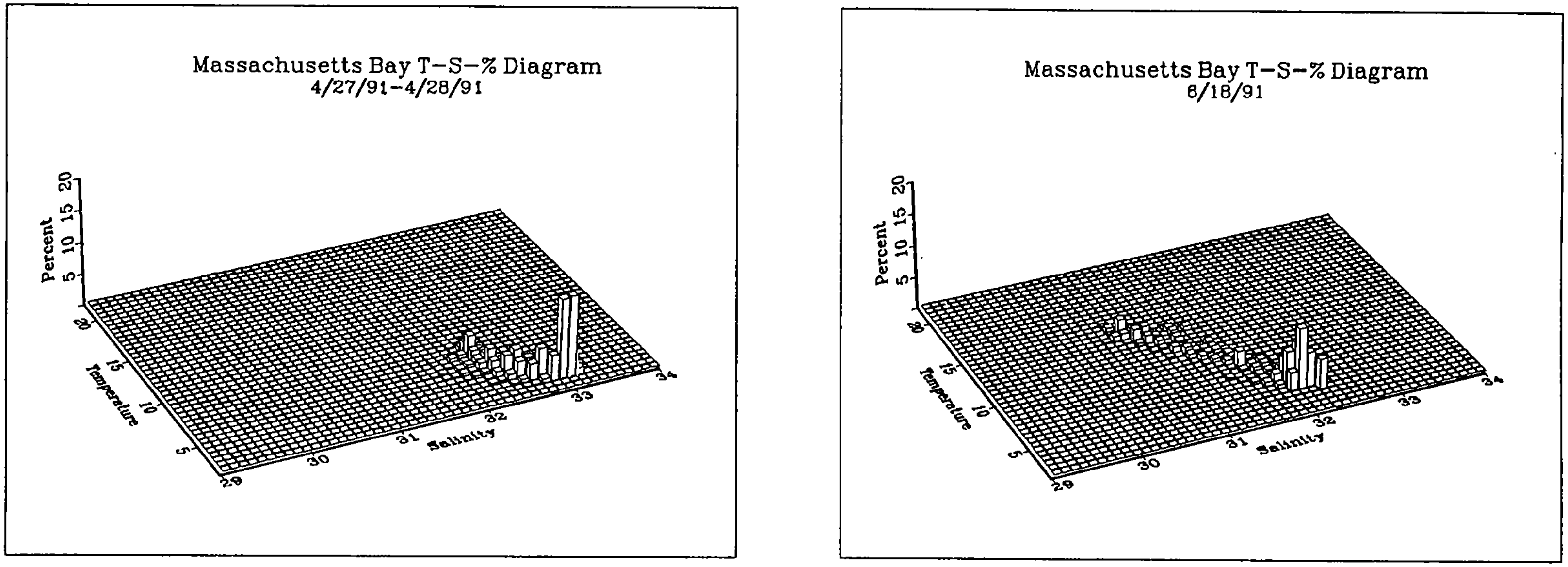


Figure 2.4-49 Three-dimensional bar charts showing percent of Bays water in 0.5°C by 0.1 PSU temperature-salinity bins for April through June, 1991.

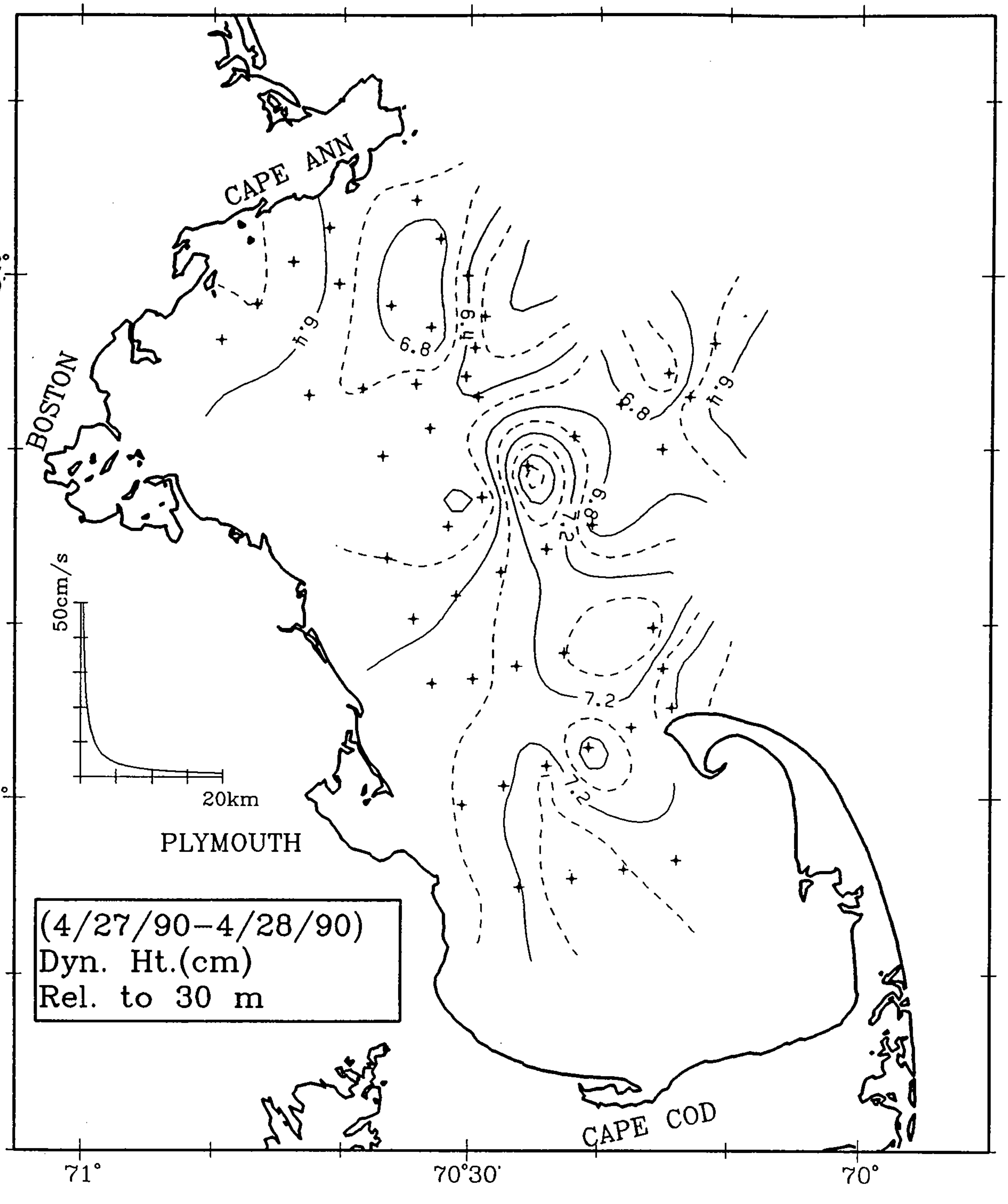


Figure 2.4-50 Dynamic height relative to 30 m for the April 27–28, 1990 cruise. The contour interval is 0.2 cm. The high located mid-way between Cape Cod and Cape Ann was caused by sampling through an internal wave, and does not represent the undisturbed state of that area.

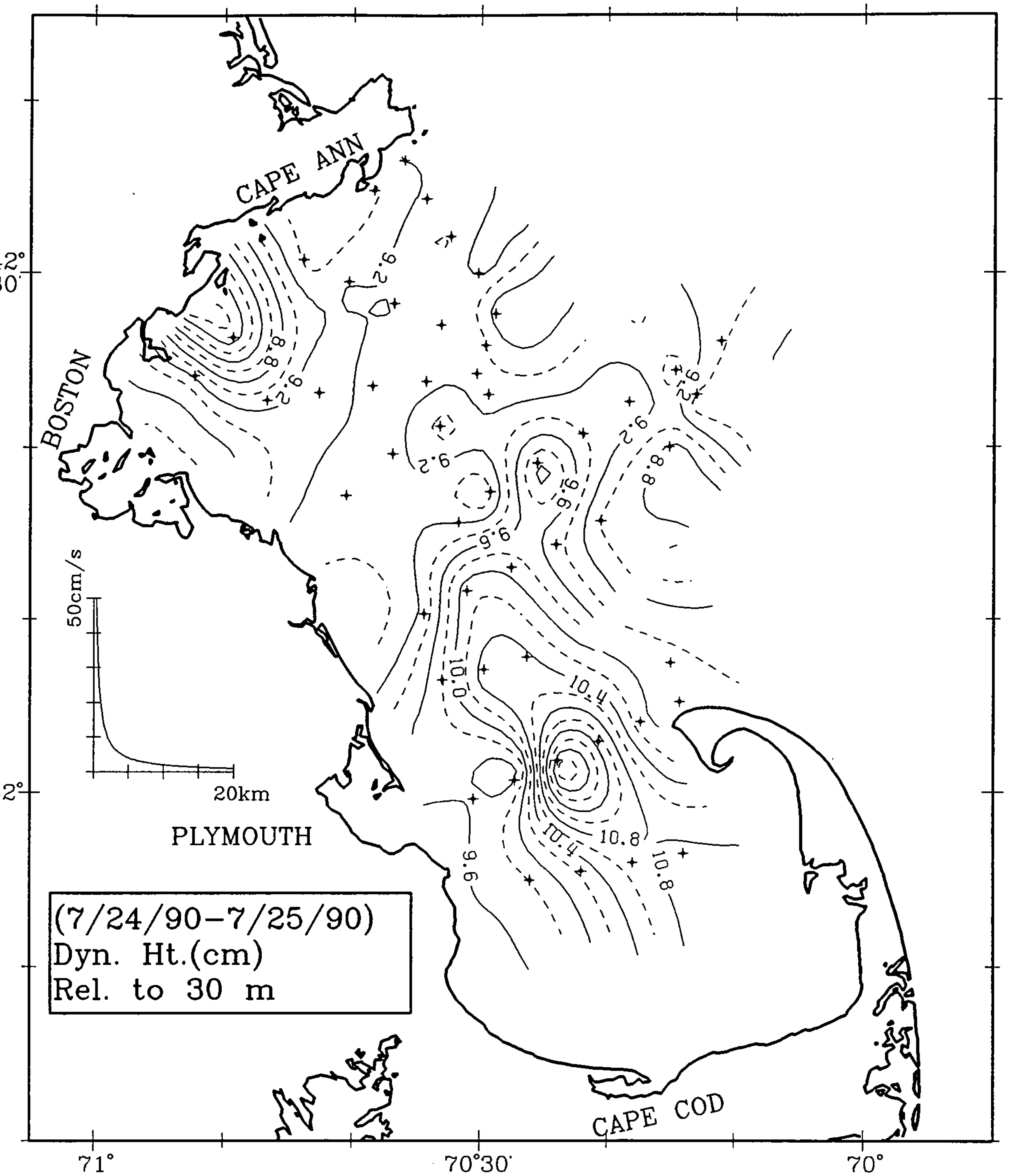


Figure 2.4-51 Dynamic height relative to 30 m for the July 24–25, 1990 cruise. The contour interval is 0.2 cm.

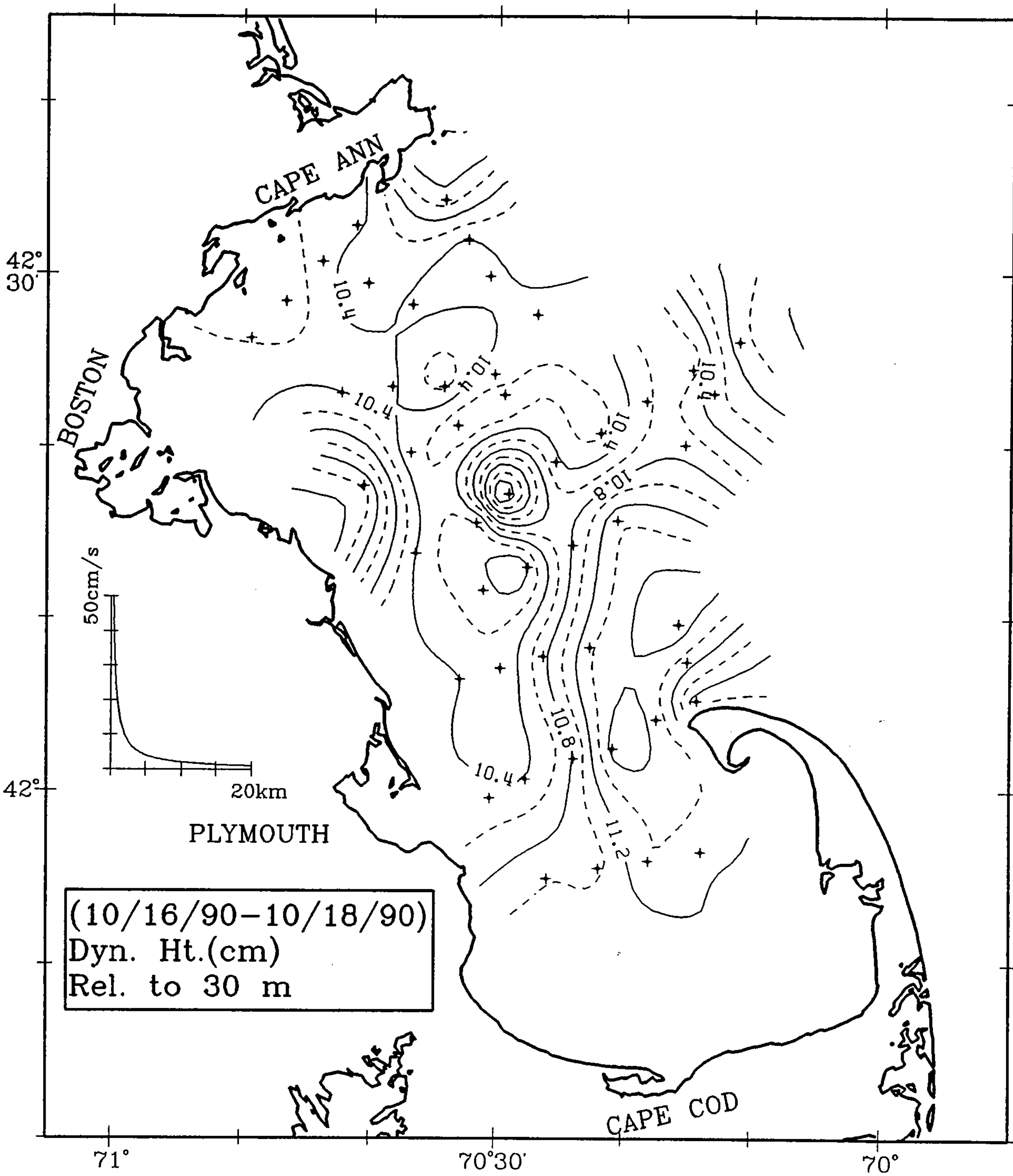


Figure 2.4-52 Dynamic height relative to 30 m for the October 16–18, 1990 cruise. The contour interval is 0.2 cm.

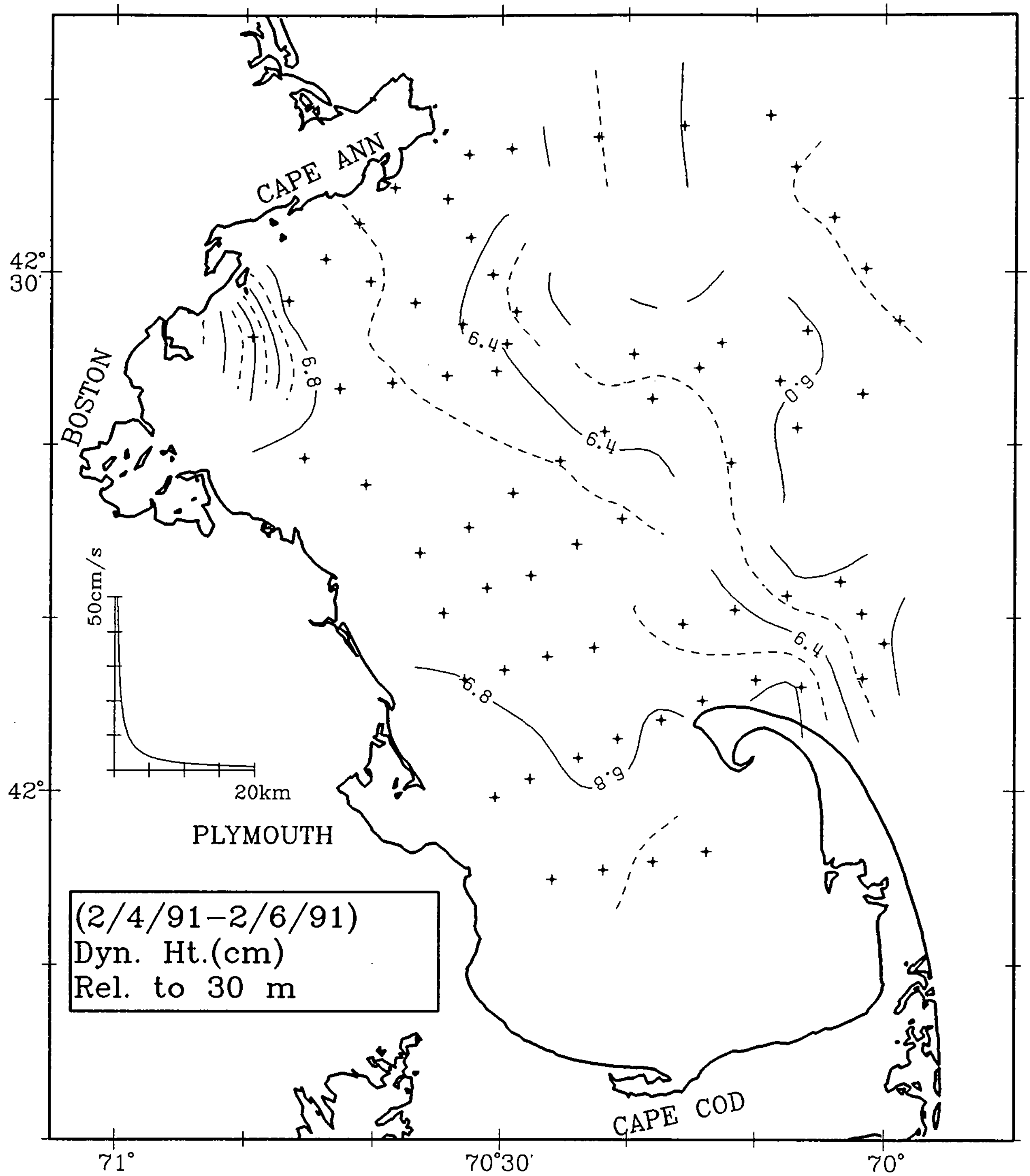


Figure 2.4-53 Dynamic height relative to 30 m for the February 4–6, 1991 cruise. The contour interval is 0.2 cm.

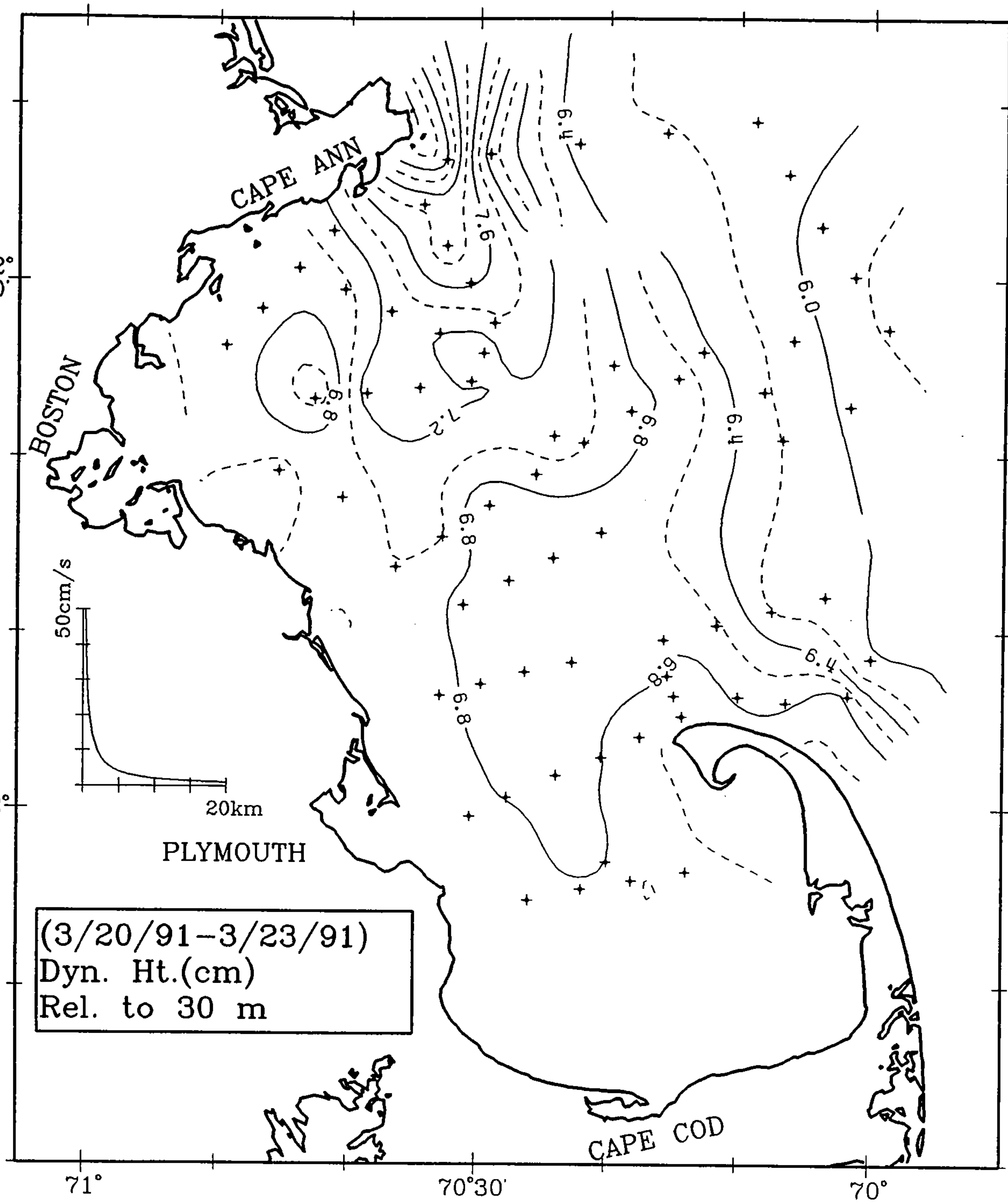


Figure 2.4-54 Dynamic height relative to 30 m for the March 20–23, 1991 cruise. The contour interval is 0.2 cm.

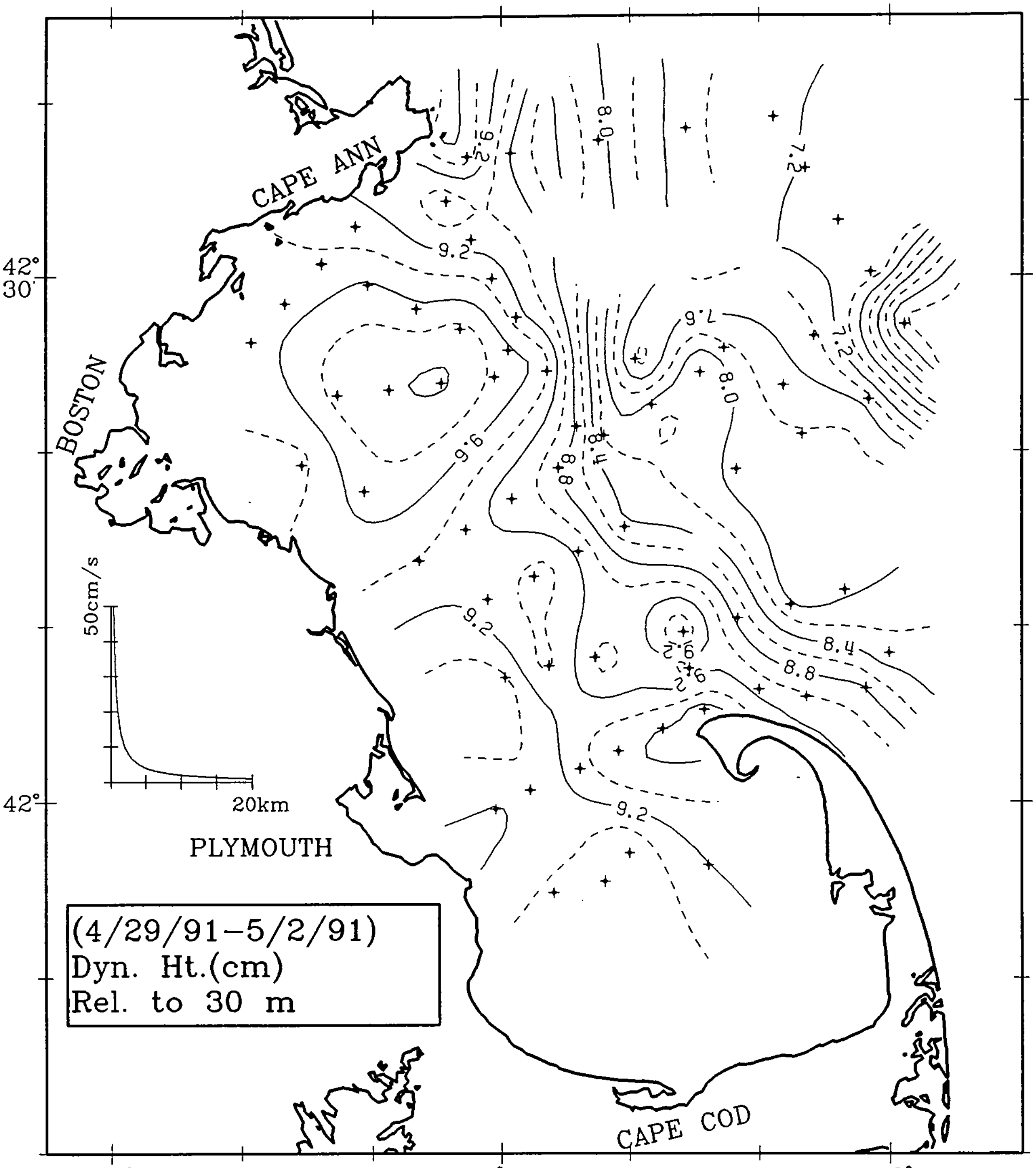


Figure 2.4-55 Dynamic height relative to 30 m for the April 29–May 2, 1991 cruise. The contour interval is 0.2 cm.

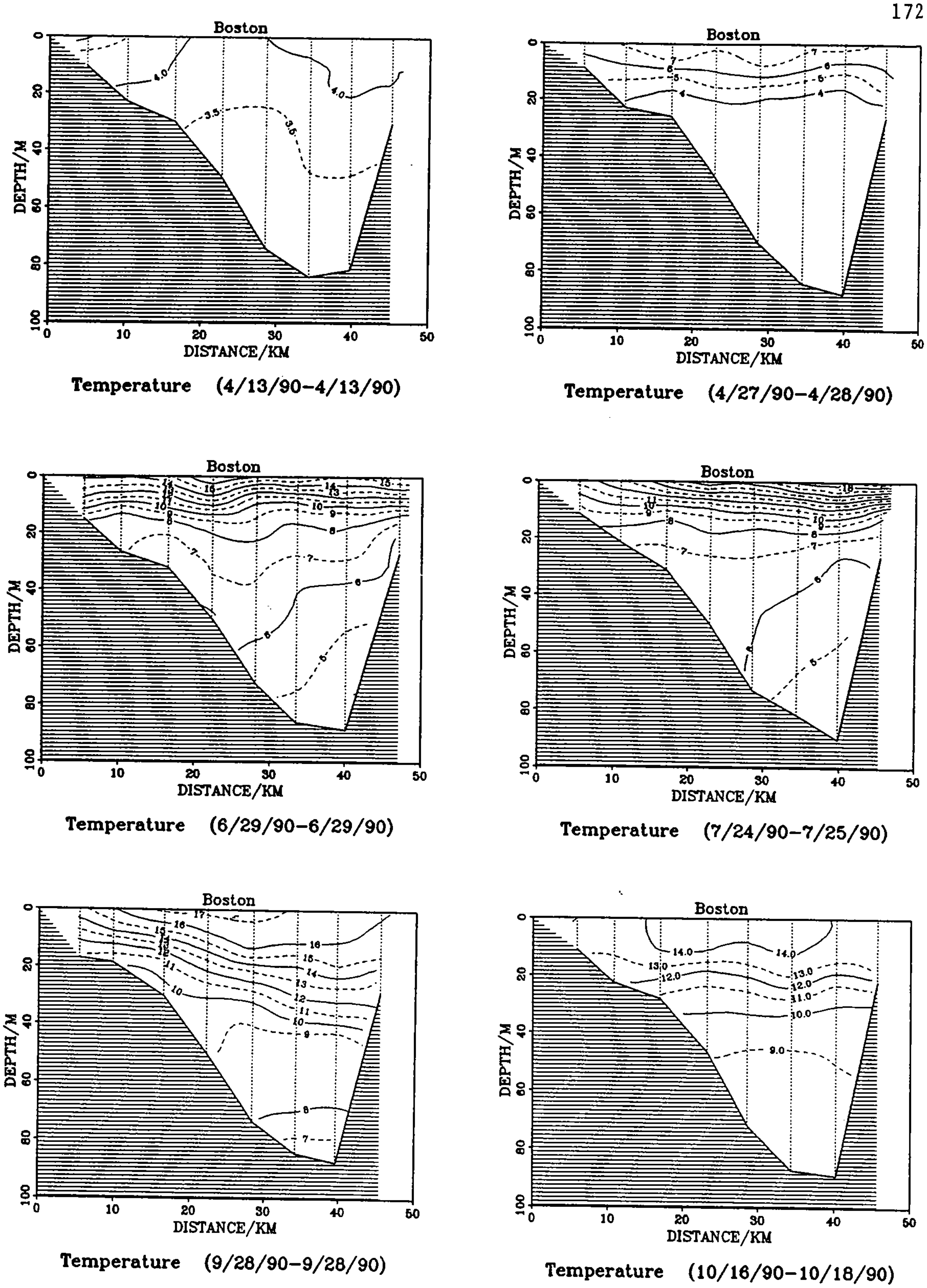


Figure 2.4-56 Sequence of vertical temperature (°C) sections for the Boston transect for April through October, 1990.

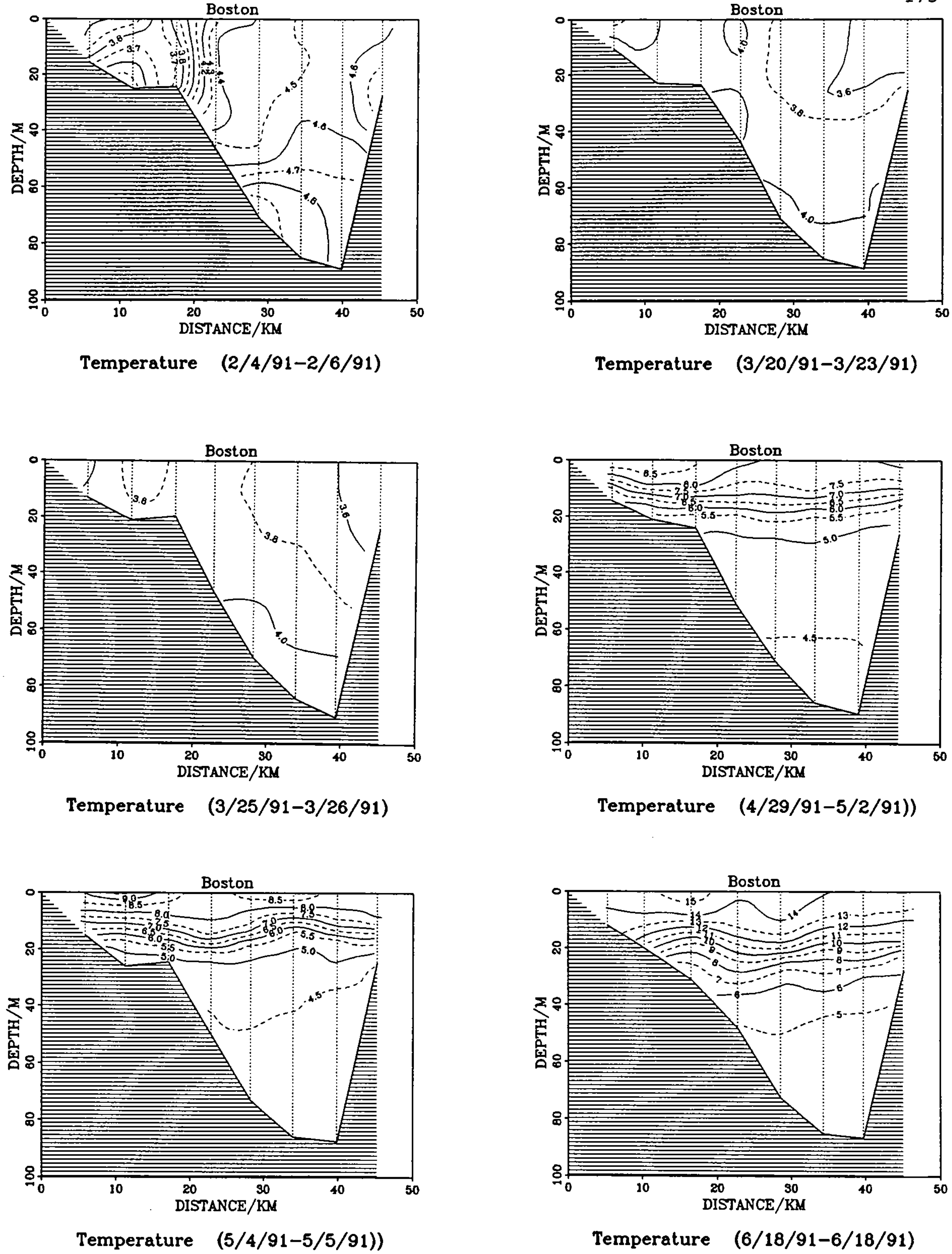


Figure 2.4-57 Sequence of vertical temperature (°C) sections for the Boston transect for February through June, 1991.

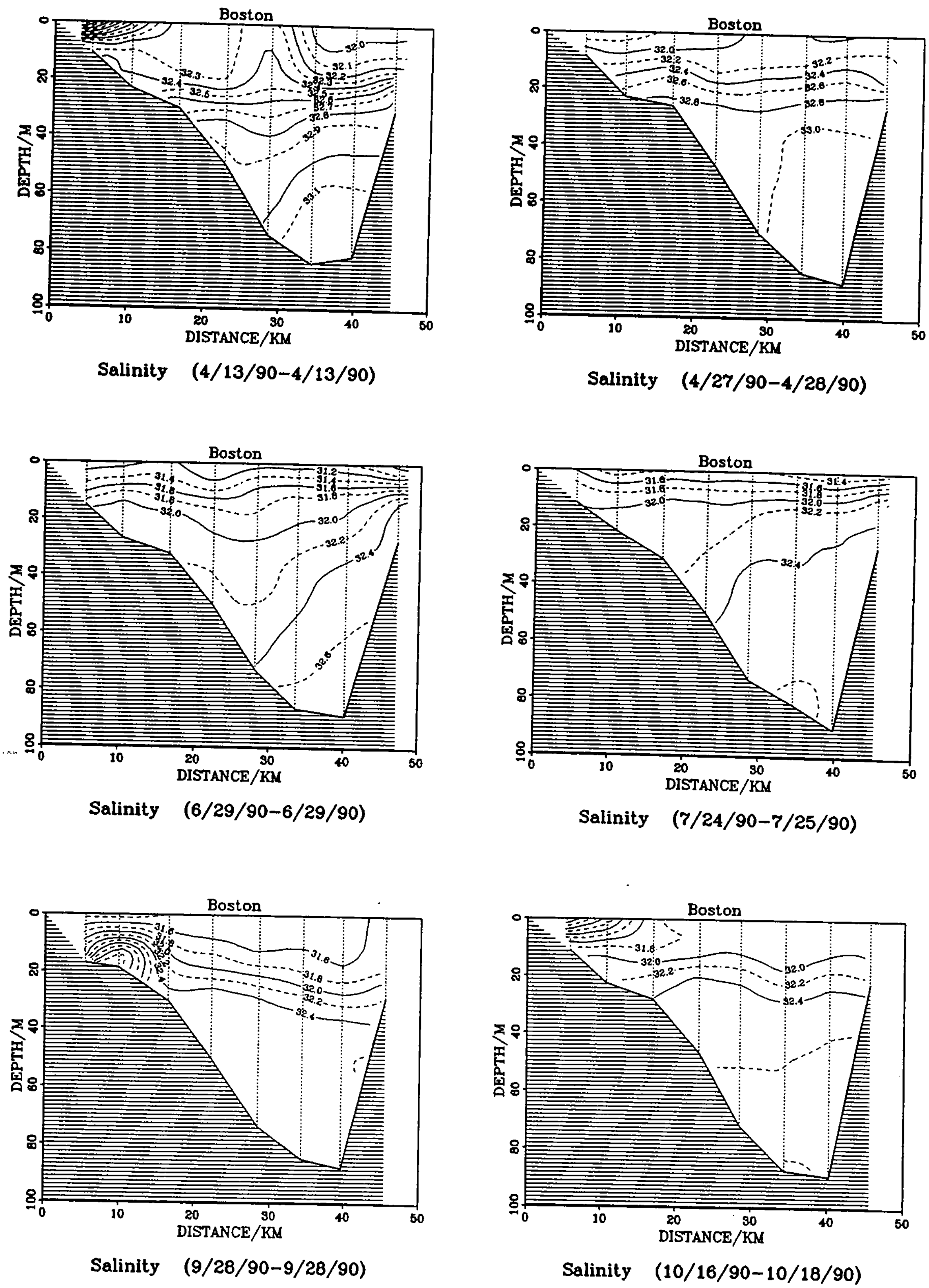
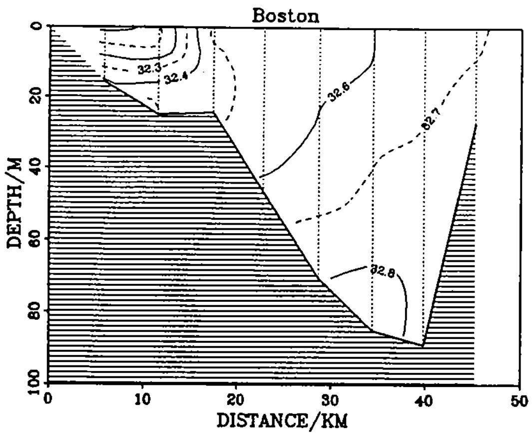
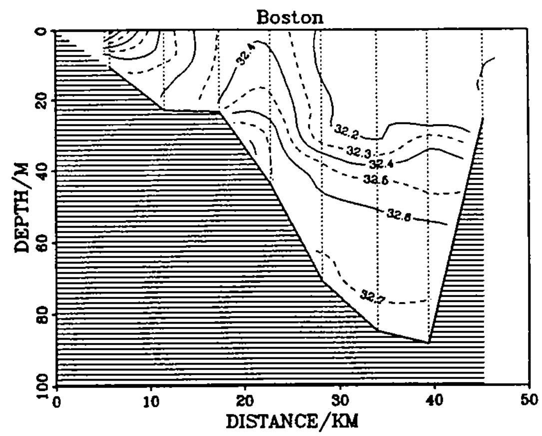


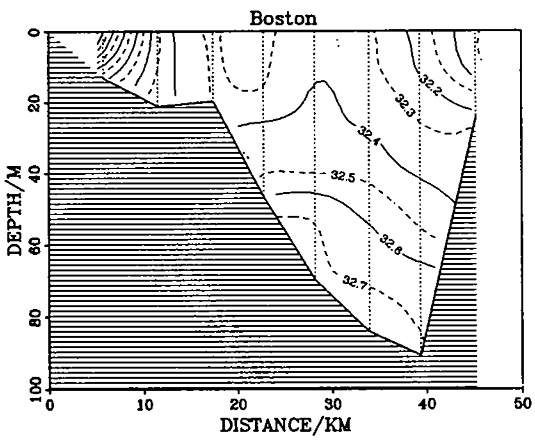
Figure 2.4-58 Sequence of vertical salinity (PSU) sections for the Boston transect for April through October, 1990.



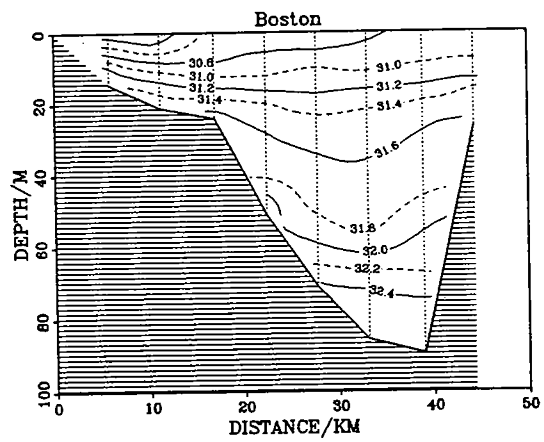
Salinity (2/4/91–2/6/91)



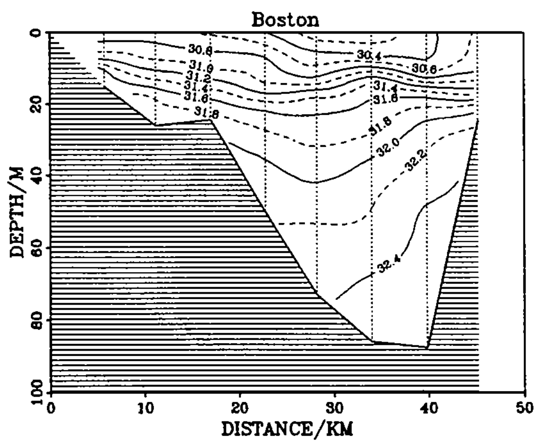
Salinity (3/20/91–3/23/91)



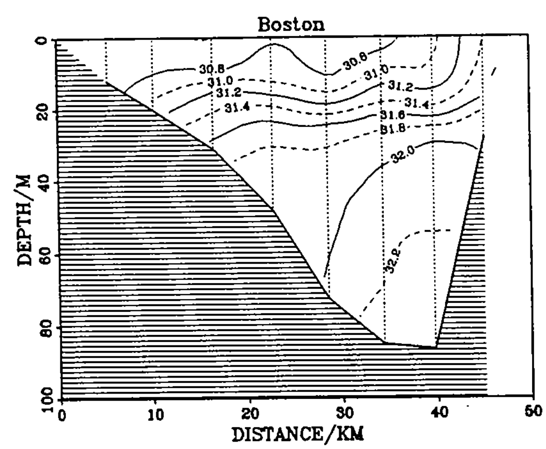
Salinity (3/25/91–3/26/91)



Salinity (4/29/91–5/2/91))



Salinity (5/4/91–5/5/91))



Salinity (6/18/91–6/18/91)

Figure 2.4-59 Sequence of vertical salinity (PSU) sections for the Boston transect for February through June, 1991.

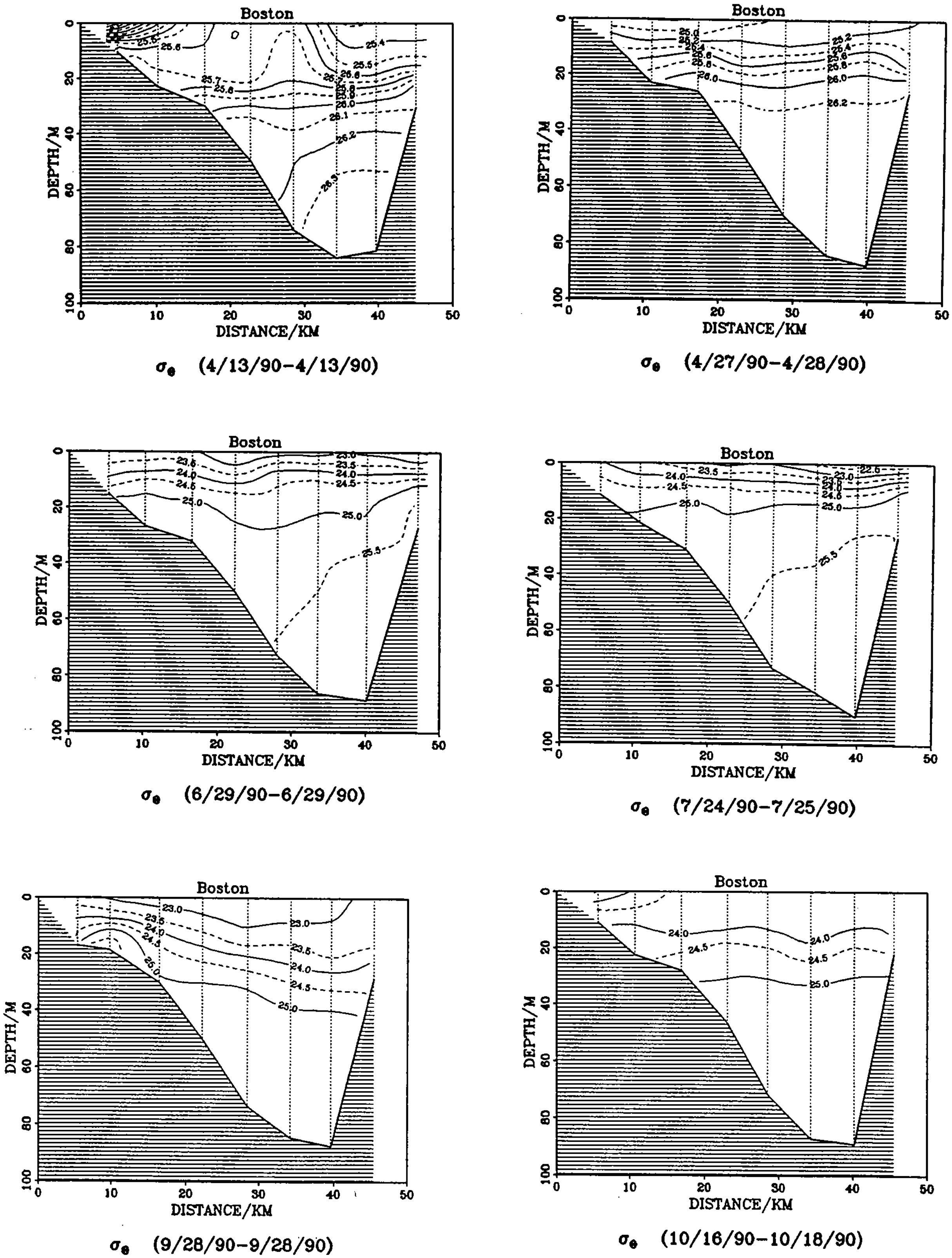


Figure 2.4-60 Sequence of vertical σ_θ (kg m^{-3}) sections for the Boston transect for April through October, 1990.

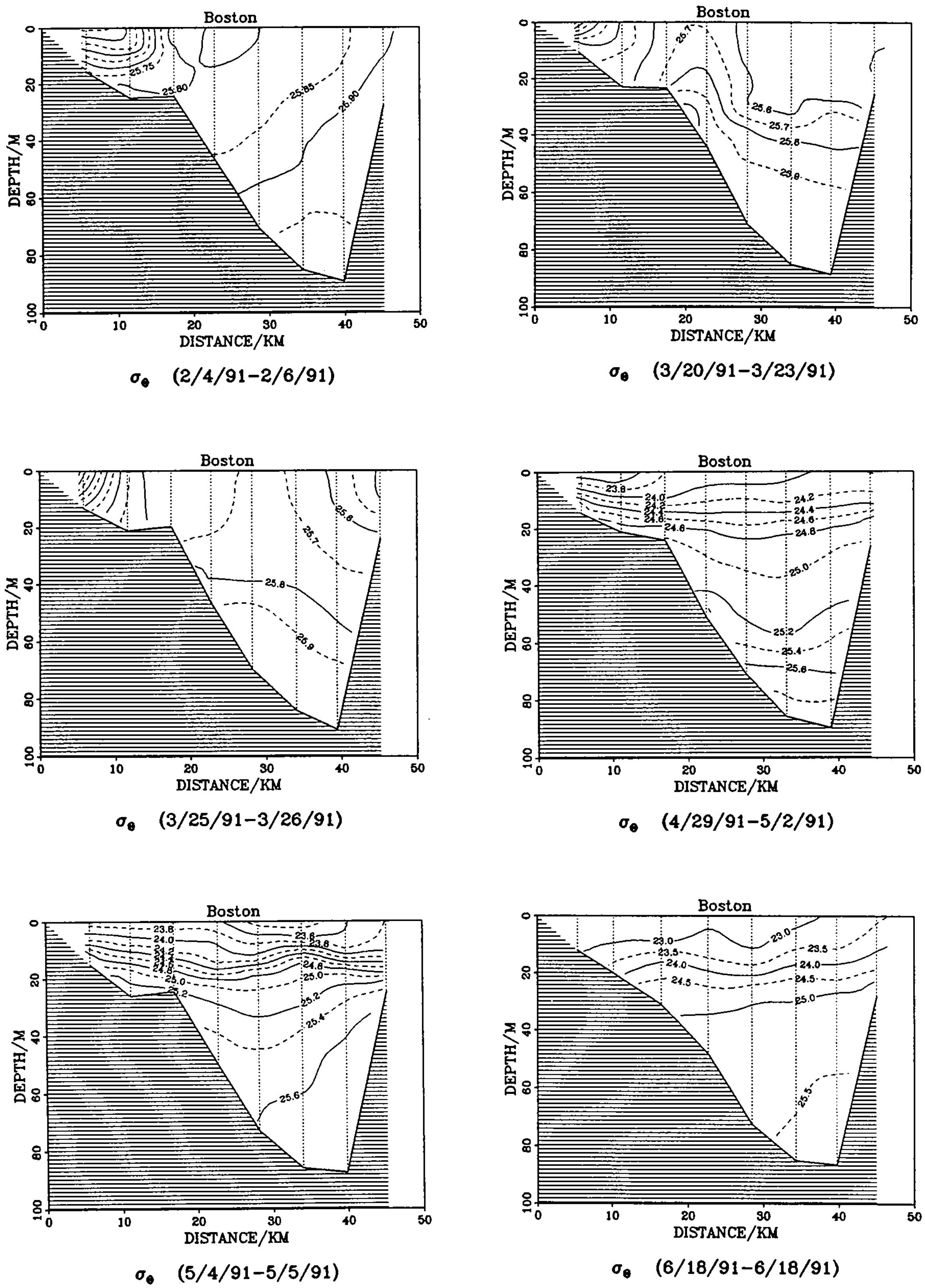


Figure 2.4-61 Sequence of vertical σ_θ (kg m^{-3}) sections for the Boston transect for February through June, 1991.

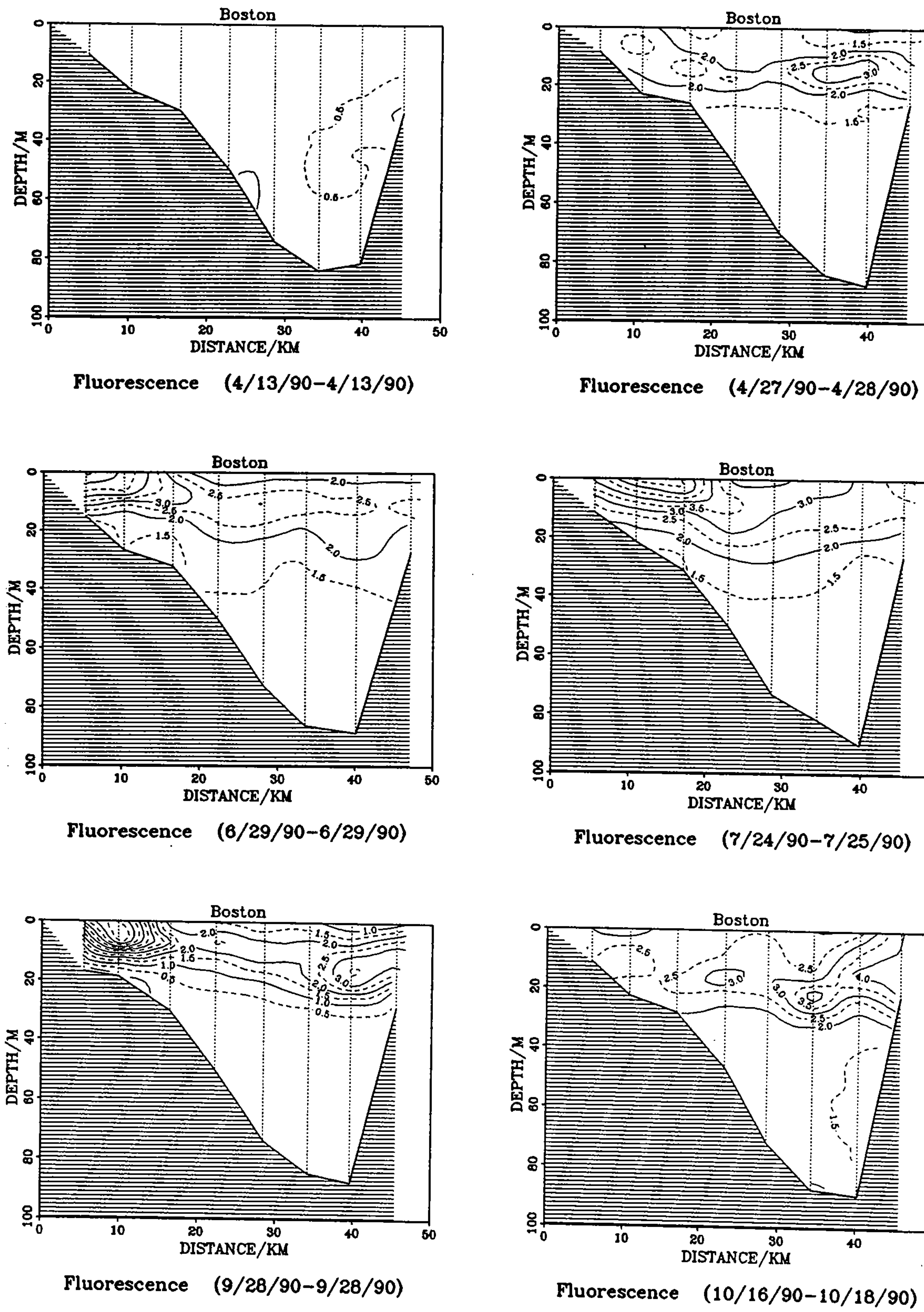


Figure 2.4-62 Sequence of vertical fluorescence (approximately chlorophyll-a in $\mu g\ l^{-1}$) sections for the Boston transect for April through October, 1990.

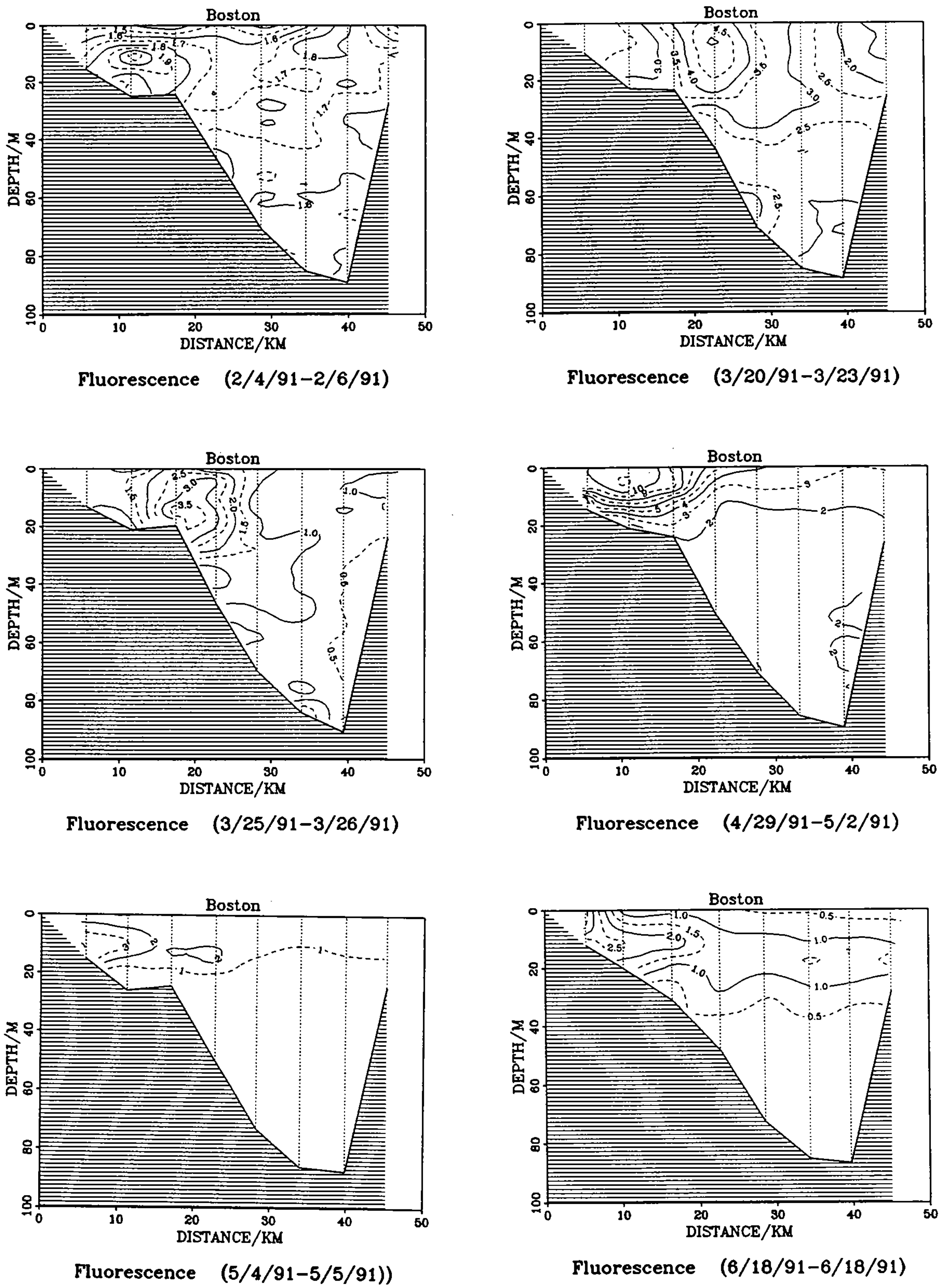


Figure 2.4-63 Sequence of vertical fluorescence (approximately chlorophyll-a in μg l^{-1}) sections for the Boston transect for February through June, 1991.

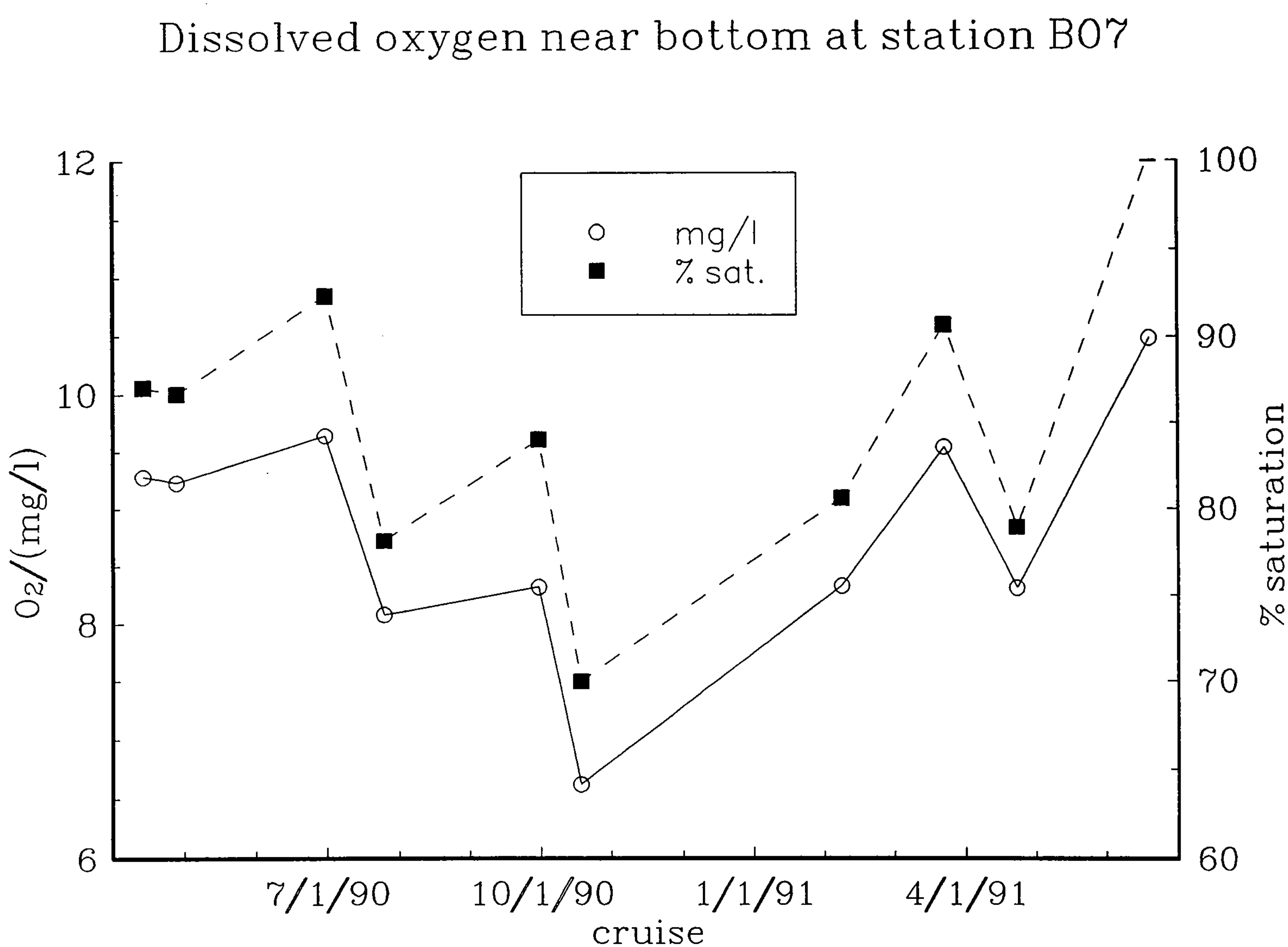


Figure 2.4-64 Dissolved oxygen in Stellwagen Basin. The minimum oxygen concentration was found during the October, 1990 cruise at the end of the stratified period in the Bays.

2.5 Coastal Doppler Velocity Surveys

2.5.1 Methods: Doppler Surveys

Surveys were performed in western Massachusetts Bay with an acoustic Doppler current profiler (ADCP) to determine the spatial structure of the currents in the region within 10–15 km of the coast. The surveys each had a duration of approximately 12 hours, repeating a single transect 8 times over the period. This provided adequate temporal resolution to provide some information about the tidal currents and to be able to average out the tides over the sampling period. CTD profiles were obtained during alternate transects, at horizontal spacing of approximately 2.5 km. Figure 2.5-1 shows the locations of the surveys, and Table 2.5-1 indicates the dates. Seven surveys were performed in all, 5 in 1990 and 2 in 1991.

Table 2.5-1: ADCP Surveys

DATE	SURVEY	WIND
4/30/90	Scituate (SC1)	NE, 7 - 9 m/s
5/ 2/90	Broad Sound (BS1)	NW, 3 - 4 m/s
7/31/90	Broad Sound (BS2)	N-NE, 6 - 7 m/s
8/ 2/90	Scituate (SC2)	W-NW, 4 - 7 m/s
9/20/90	Manomet (MAN)	WNW, 6 - 11 m/s
4/25/91	Scituate (SC4)	NNW, 3 - 4 m/s
4/26/91	Scituate (SC4)	SW-SE, 0 - 6 m/s
5/23/91	Broad Sound (BS4)	NE-E, 6 - m/s

A 1.2 mHz ADCP manufactured by RD Instruments, Inc., was mounted on the R/V Asterias. The transducer was fixed to the keel, approximately 1.8 m below the water surface. The instrument provides horizontal velocity measurements at 1-m depth intervals between 3 and 30 m depth, with an accuracy of 1–5 cm s^{-1} depending on the sea conditions (see Geyer and Signell, 1990, for a detailed discussion of the measurement technique). The ship steamed at 3.5 m s^{-1}, and the ADCP sampled at 1-min intervals, providing spatial resolution of 200 m. The data were resampled at even spatial intervals, providing 12-hour timeseries at approximately 75 horizontal positions along each transect.

2.5.2 Coastal Survey Data Quality

Based on previous applications of the shipboard velocity measurement technique, the accuracy of the velocity estimates was expected to be ±2–5 cm s^{-1} (Geyer and Signell, 1990), depending on the sea conditions. The velocity observations were compared directly against moored measurements for the same time periods to check for consistency between the two methods of estimating velocity. Typical deviations between the moored and shipboard techniques was 2–3 cm s^{-1}, with no apparent bias.

The weather during the surveys was generally favorable for high-quality measurements, but rough conditions during the SC1, BS2 and MAN surveys required additional data processing to eliminate noise in the velocity data, particularly in the along-ship-track direction, i.e., the east–west component. This additional processing required the assumption that the vertical average of the east–west component of velocity varied on spatial scales of several kilometers or more. This is a reasonable assumption, although it was not experimentally verified, so the east–west velocities obtained during those cruises must be treated with some degree of caution.

2.5.3 Coastal Survey Observations

Averaging the data over the 12-hour interval of observations provided an adequate means of removing the tidal velocity, the magnitude of which was roughly 10 cm s^{-1}. This technique could not be applied in the case of the Manomet, Scituate 1991 and Broad Sound 1991 surveys, since the duration of the surveys did not include a complete tidal cycle. Following is a description of the observed currents, presented in chronological order, presenting tidally averaged data for cases when it is available.

Scituate Spring Survey, 1990

The tidally averaged data from Scituate on 4/30/90 (SC1) indicate southward flow throughout the water column at speeds of 2–10 cm s^{-1} (fig. 2.5-2). The flows were slightly stronger near the bottom and at the inshore end of the transect. A vertical section (fig. 2.5-3) indicates the normal component of velocity (roughly N-S) as contours, and the transverse component (roughly E-W) as vectors. The transverse velocity indicates downwelling.

Water properties at the beginning and end of the SC1 survey are indicated in fig. 2.5-4. The water column was stratified by both temperature and salt, although the thermal stratification was still weak relative to summertime conditions. The pycnocline sloped downward toward shore, consistent with a geostrophic balance of the southward flow. Changes in the water properties through the day indicate both the influence of downwelling and other variations, probably related to internal tidal fluctuations. The light transmission data indicate seaward advection of turbid water at approximately 20 m depth.

Broad Sound Spring Survey, 1990

Conditions at the Broad Sound section, obtained two days later, were similar to Scituate, although the southward currents were stronger, reaching more than 15 cm s^{-1} at the seaward end of the section (fig. 2.5-5). The southward-directed, near-surface currents were considerably stronger than the deep currents. Strong downwelling was observed, with transverse velocities of up to 15 cm s^{-1} (fig. 2.5-6).

The BS1 water properties data (fig. 2.5-7) indicate weak thermal stratification at the beginning of the survey except in the deep water, where a temperature front was evident at the seaward end of the line. By the end of the survey, warm water had advected in at the surface, augmenting the stratification. The salinity stratification was fairly uniform throughout the survey. The isohalines deepened by 5-m through the course of the day due to downwelling. Light transmission shows fairly uniformly clear water. One patch of slightly turbid water (73% transmission) was advected landward and downward between the first and last transect.

Broad Sound Summer Survey, 1990

The Broad Sound survey on 7/31/90 again showed southward flow (fig. 2.5-8), this time with speeds of greater than 20 cm s^{-1} in the near-surface waters and weak flow in the deep water. The strongest southward currents were about two thirds of the way to the seaward end of the transect. The transverse velocity (fig. 2.5-9) indicates a complex structure, with shoreward flow at the surface, seaward flow at mid-depth, and variable flow in the deep water.

Strong thermal stratification was evident during this survey (fig. 2.5-10), with more than 10° temperature contrast between the surface and deep waters. The thermocline was nearly level at the beginning of the survey, but it tilted downward in the landward direction at the end of the survey. The deep water had a landward increasing temperature gradient throughout the survey. The surface salinity had a local minimum of 30.6 psu which persisted through the day approximately 5 km from the landward end of the line. Light transmission indicated a slightly turbid plume advecting seaward at 8-m depth. This corresponds to the level that offshore flow was observed with the ADCP.

Scituate Summer Survey, 1990

The Scituate Survey on 8/2/90 shows very strong southward velocities in the near-surface waters, with speeds in excess of 30 cm s^{-1} in the shoreward third of the section (fig. 2.5-11). The velocity rapidly decreased and reversed at the shoreward end of the section. Deep currents were much weaker, with speeds of a few cm s^{-1}. Figure 2.5-12 indicates the very strong vertical shears, the velocity changing by 25 cm s^{-1}

over approximately 10 m. Transverse velocities were weak and variable. The complex structure of the transverse velocities reflects the energetic internal tidal motions that were not completely averaged out in obtaining the mean.

Water properties show strong thermal stratification, as in the BS2 survey. (fig. 2.5-13). A marked isotherm slope was evident during the first CTD transect, but the isotherms became a lot flatter by the last transect. Salinity showed similar structure to temperature, except that significant freshening occurred toward the coast. The light transmission data indicate two turbid zones, one in the near-surface waters close to the coast, and the other in the near-bottom waters close to the 20-m isobath. The near-surface turbid zone became more intense and moved seaward during the day, while the deep zone of turbidity was advected offshore at approximately 18-m depth.

Manomet Fall Survey, 1990

The first transect of the Manomet survey (fig. 2.5-14a) indicates strong southward currents in the near-surface waters, reaching as much as 30 cm s^{-1} and indicating considerable transverse variability. The near-bottom currents were weak and variable. Four hours later (fig. 2.5-14b) the surface currents were redirected to the northwest at around 10 cm s^{-1}, while the near-bottom currents were northeasterly. This change in the current structure is partly due to the tides, but there may also be some influence of relaxation of wind stress.

A malfunction of the CTD caused data to be lost across most of the first CTD transect. The remainder of the transect indicate a deep thermocline (fig. 2.5-15), centered at approximately 30-m. The second transect, 4-hours later, shows a deep thermocline across the entire transect. The water was nearly uniform above 20-m depth. No light transmission data were obtained for this or subsequent surveys.

Scituate Spring Survey, 1991

The first transect of Scituate survey on 4/26/91 (fig. 2.5-16a) indicates divergent flow in the surface waters, with southwestward flow at the west end of the transect and southeastward flow at the east end, with magnitudes of up to 20 cm s^{-1}. The near-bottom flow was variable, with speeds of around 5 cm s^{-1}. Six hours later (fig 2.5-16b), the flow was directed offshore, except for a the westwardmost portion of the line, in which the surface currents were directed northward. Again bottom currents were weak. The variations in the currents are largely attributable to tidal motions, both barotropic and internal. It is conceivable that the divergence observed in fig. 2.5-16a is due to internal tidal motion.

Water properties data (fig. 2.5-17) indicate moderate thermal stratification and significant salt stratification. Some variations in water properties in time and across the section are probably evidence of internal tidal motions.

Broad Sound Spring Survey, 1991

The Broad Sound survey on 5/23/91 provides the only Doppler survey with significant northward velocities. Near-surface, northward directed velocities ranged from 10 to 15 cm s^{-1}, while the near-bottom velocities were directed eastward at 5–10 cm s^{-1} (fig. 2.5-18). The transverse velocity shows a substantial offshore flow at all depths, with speeds of 5–15 cm s^{-1}. The cross-section (fig. 2.5-19) shows that the offshore flow extends over most of the water column. This is likely due in large part to the tidal flow, which has not been averaged out in this survey, since its duration was only 8 hours.

Water properties (fig. 2.5-20) indicate continued spring warming, with a 6° temperature difference between surface and deep waters. The thermocline was broad, extending from 5 to 20-m depth. The surface salinity decreased to a minimum of 30.5 psu at the seaward end of the line. Variations in water properties again most likely reflect the influence of internal tides.

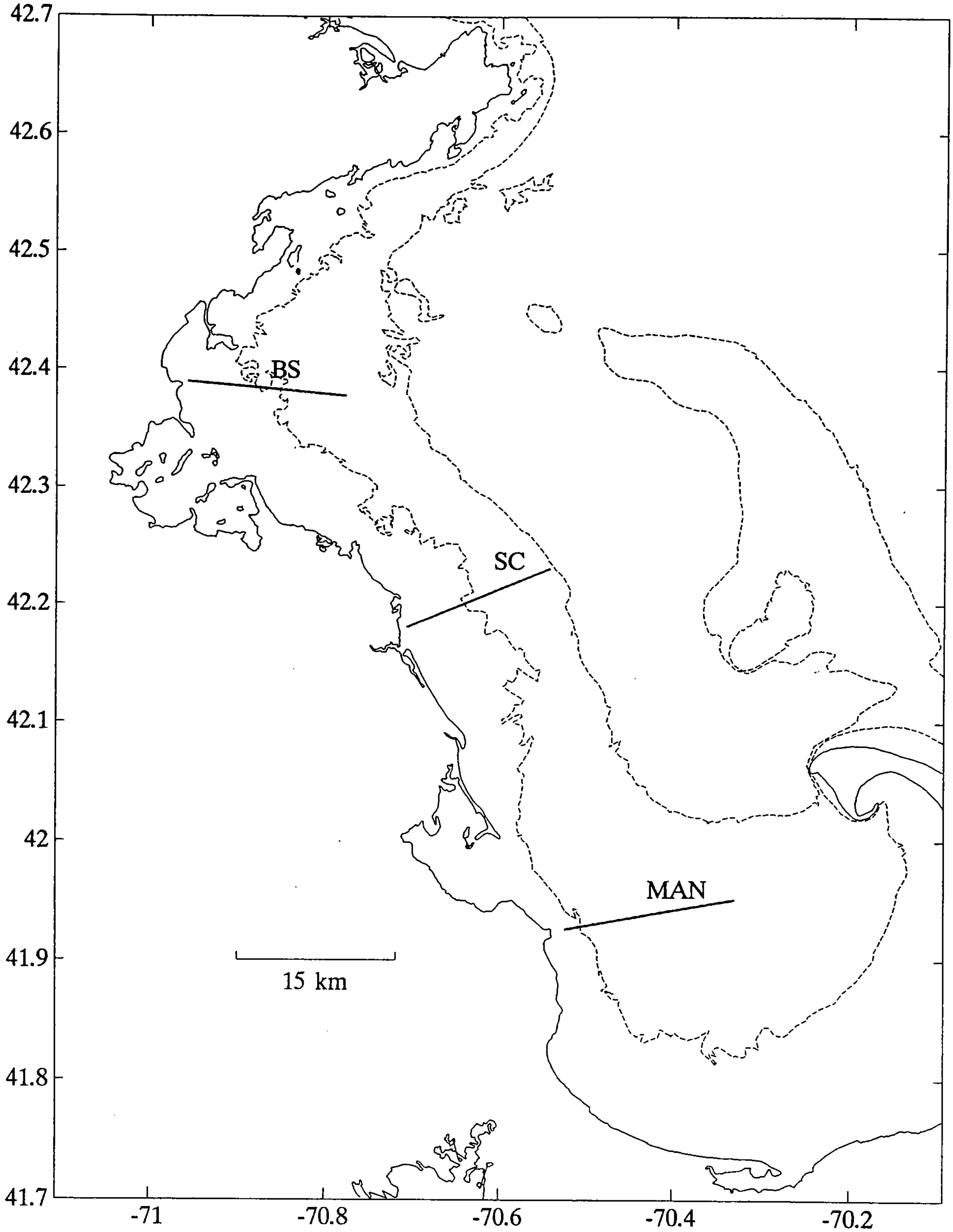


Figure 2.5-1 Location map of ADCP surveys.

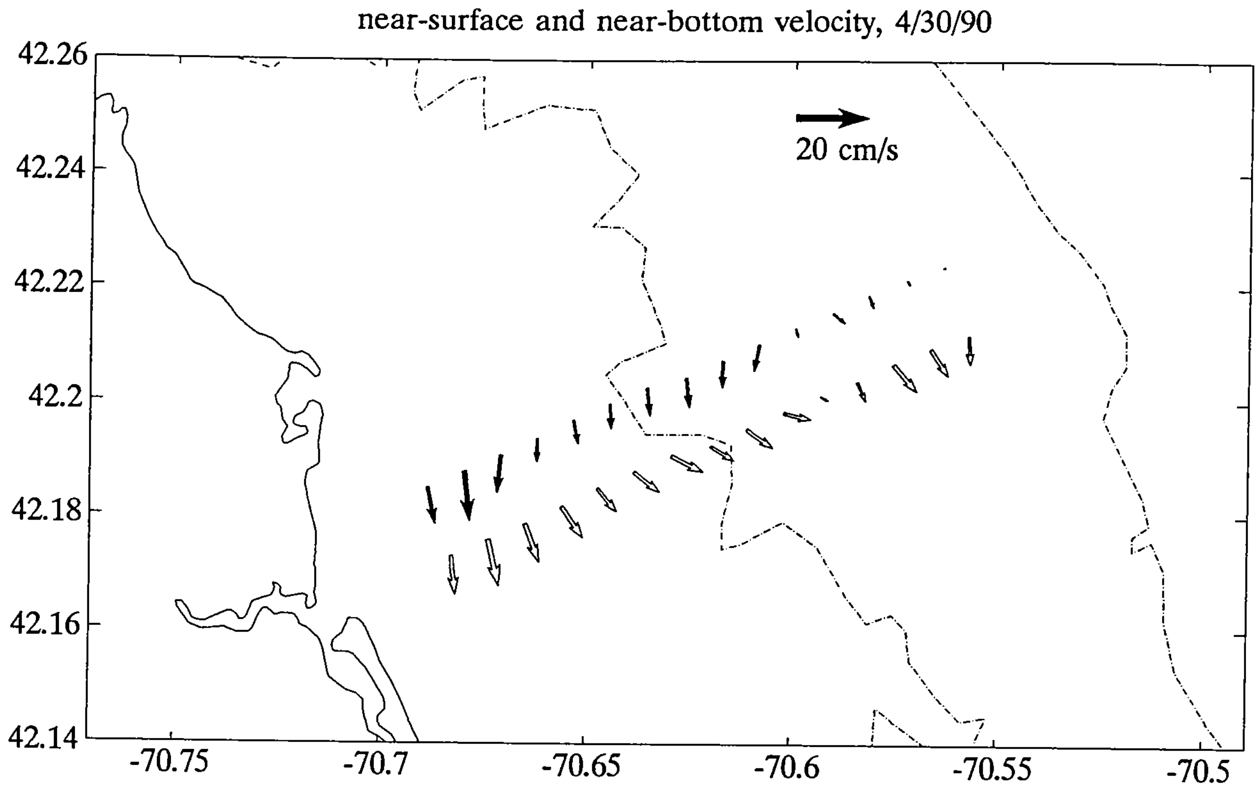


Figure 2.5-2 Near-surface (solid arrows) and near-bottom velocity (hollow arrows) at Scituate, 4/30/90. Data are averaged over the 12-hour survey period, removing most of the tidal motion.

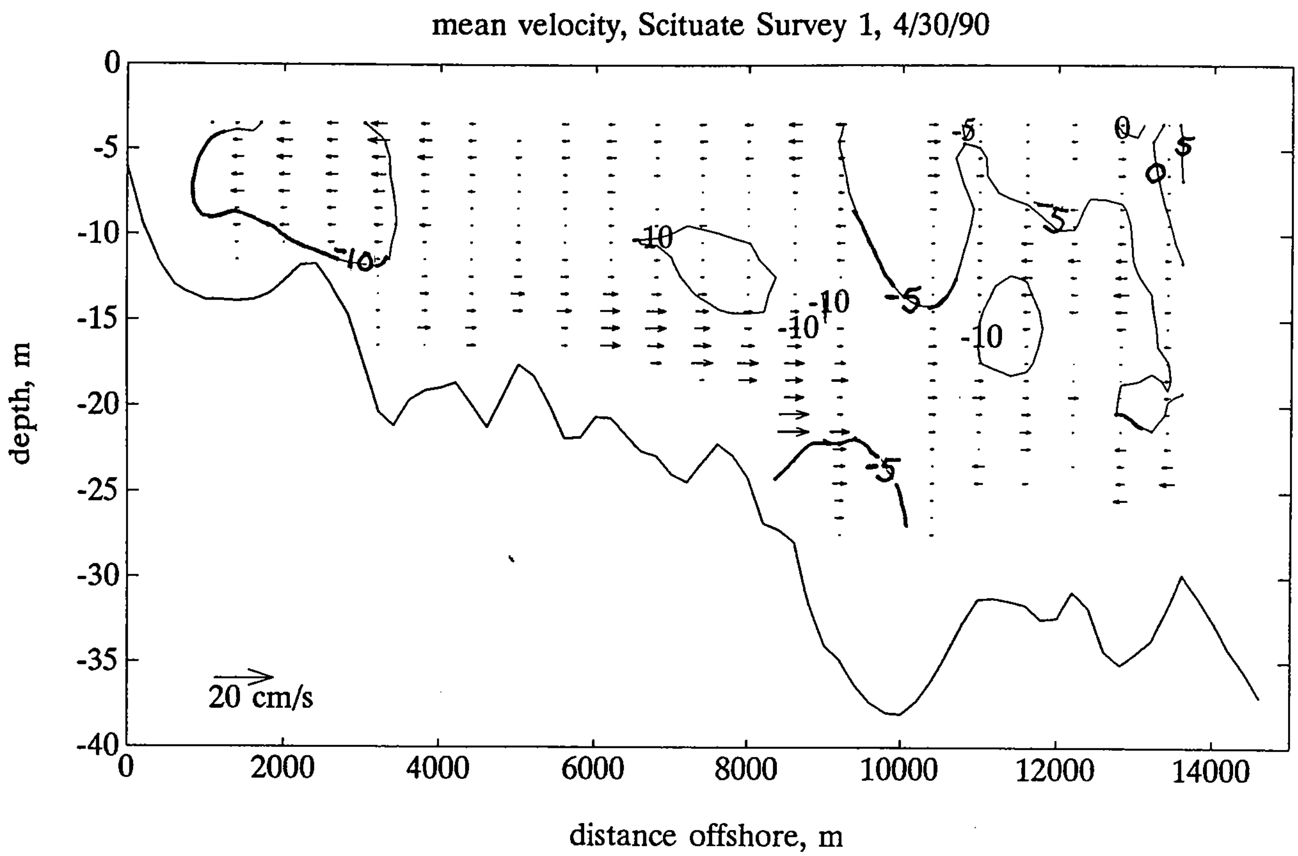


Figure 2.5-3 Cross section of currents at Scituate, 4/30/90. Data are averaged as in fig. 2.5-2. Alongshore currents (oriented approximately N-S) are indicated by contours, while the cross-shore currents are indicated by vectors. The alongshore currents can be thought of as going into or out of the page, while the cross-shore currents are in the plane of the page.

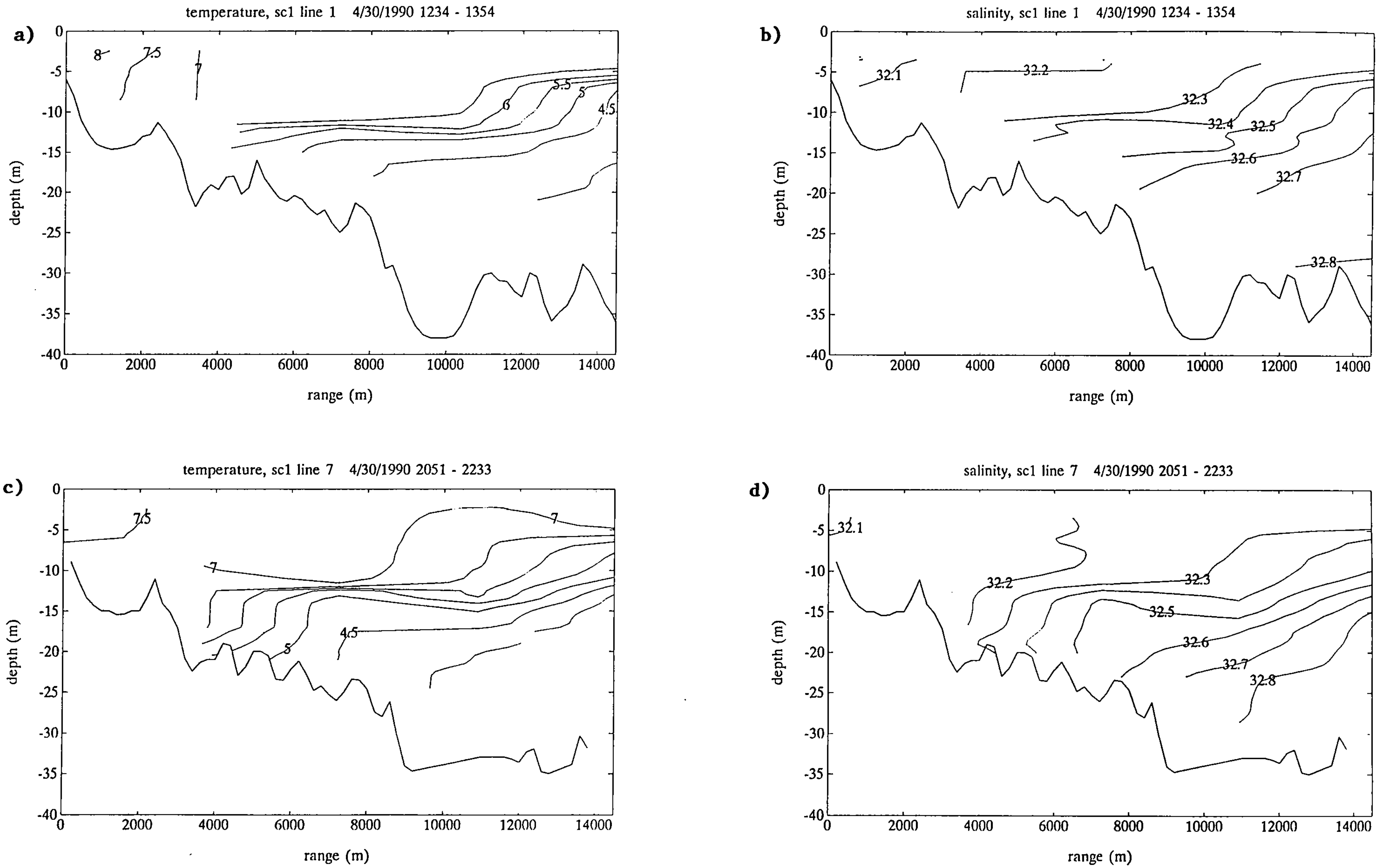


Figure 2.5-4 Water properties at Scituate, 4/30/90. a) temperature, first CTD line; b) temperature, last CTD line; c) salinity, first CTD line; d) salinity, last CTD line. Times are GMT.

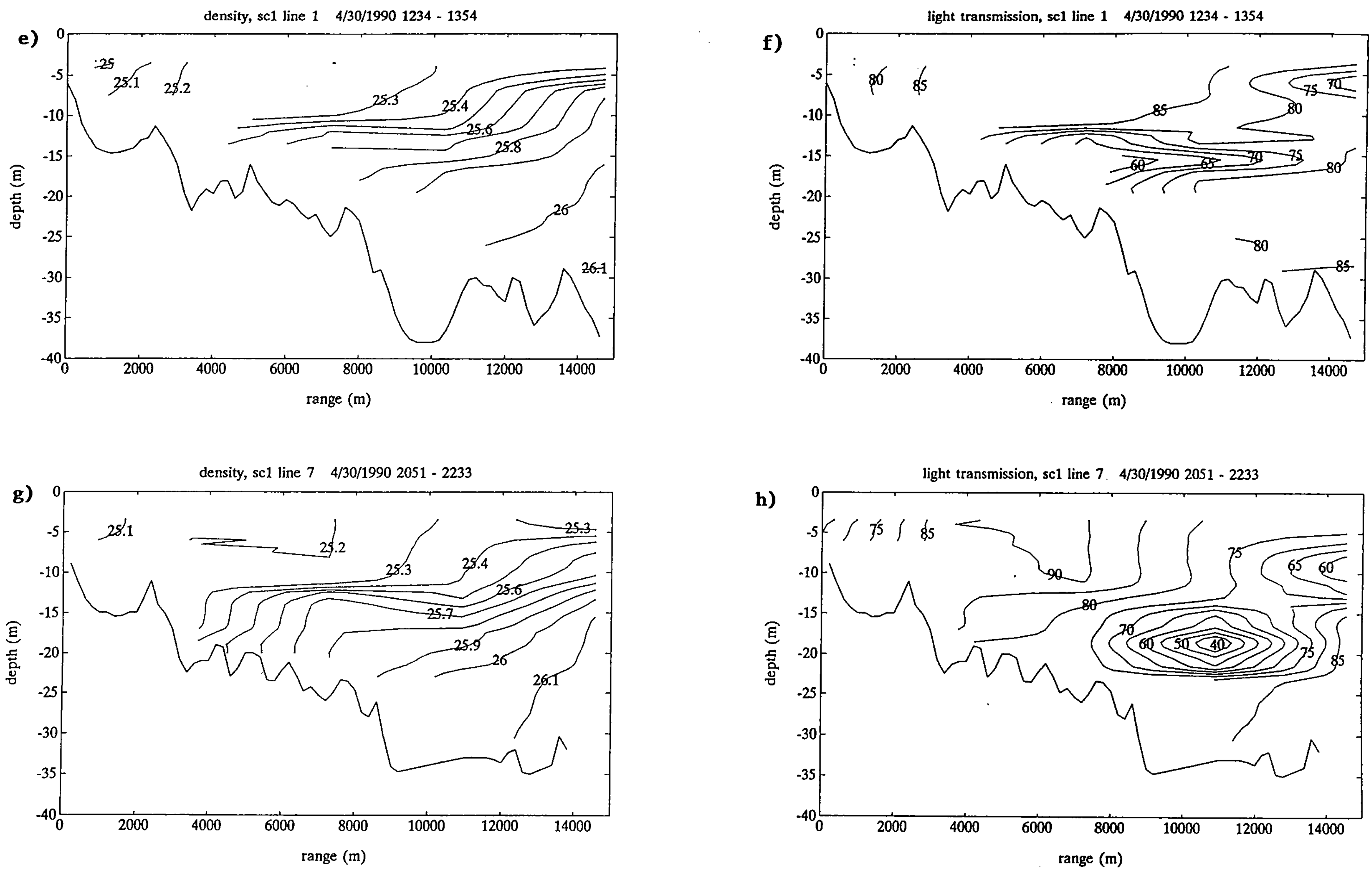


Figure 2.5-4 (Con't) Water properties at Scituate, 4/30/90. e) density, first CTD line; f) density, last CTD line; g) light transmission (25-cm pathlength), first CTD line; h) light transmission, last CTD line. Times are GMT.

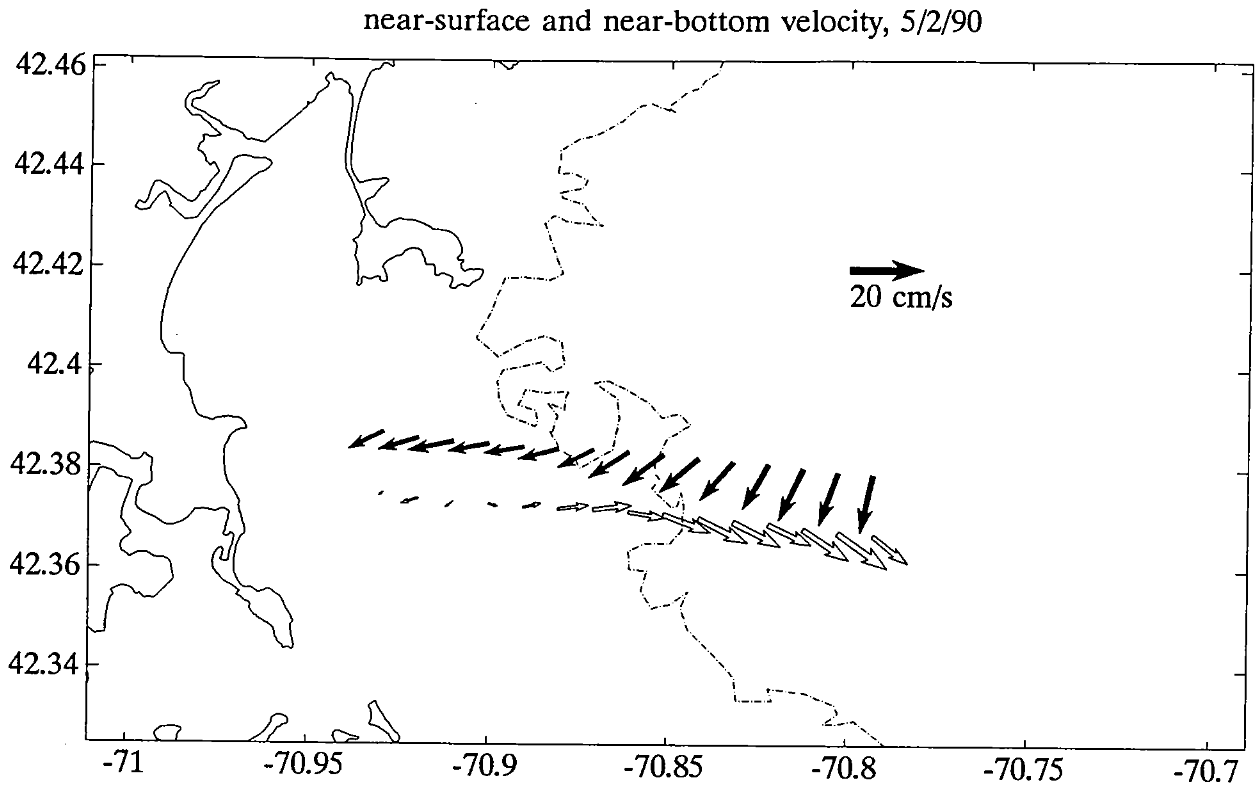


Figure 2.5-5 Near-surface and near-bottom velocity at Broad Sound section, 5/2/90, as in fig. 2.5-2.

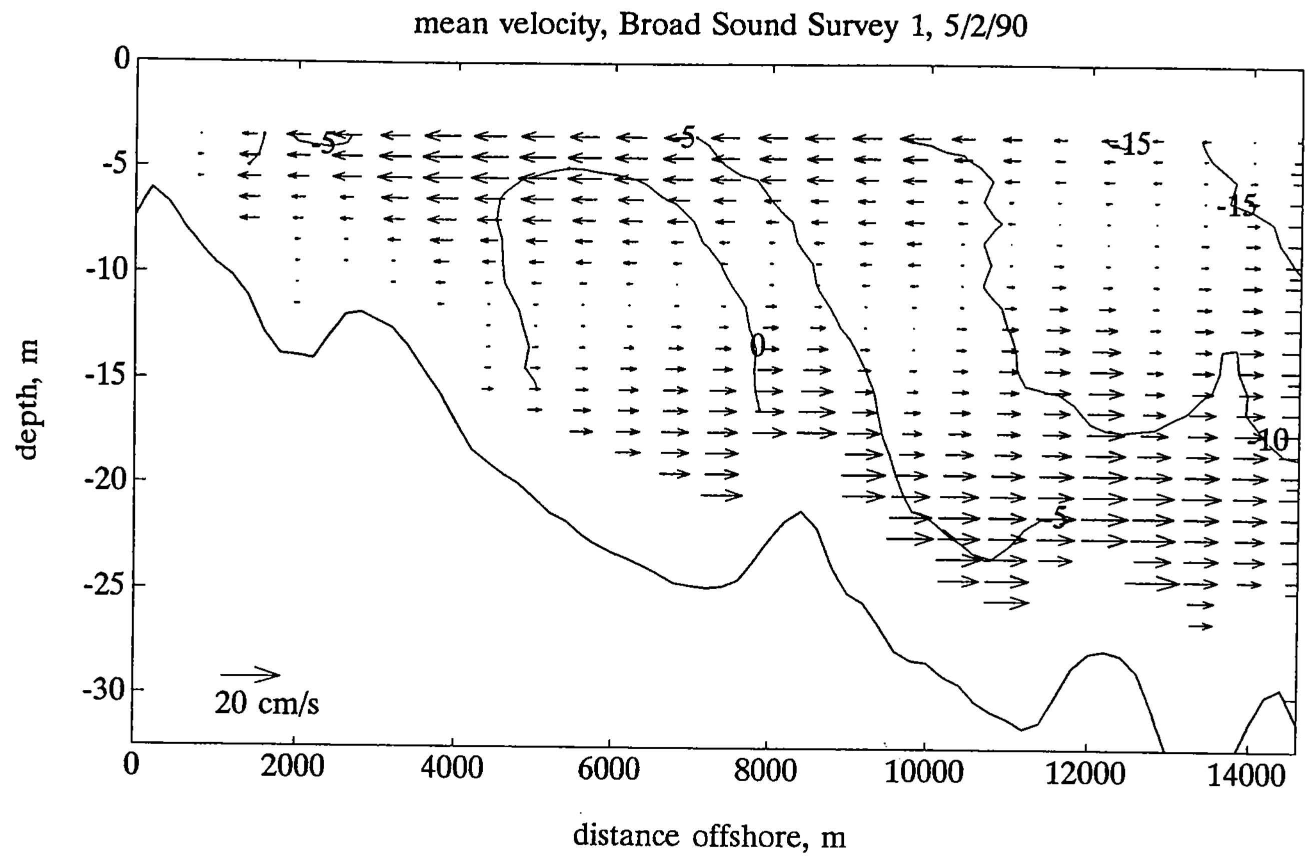


Figure 2.5-6 Cross section of currents at Broad Sound section, 5/2/90, as in fig. 2.5-3.

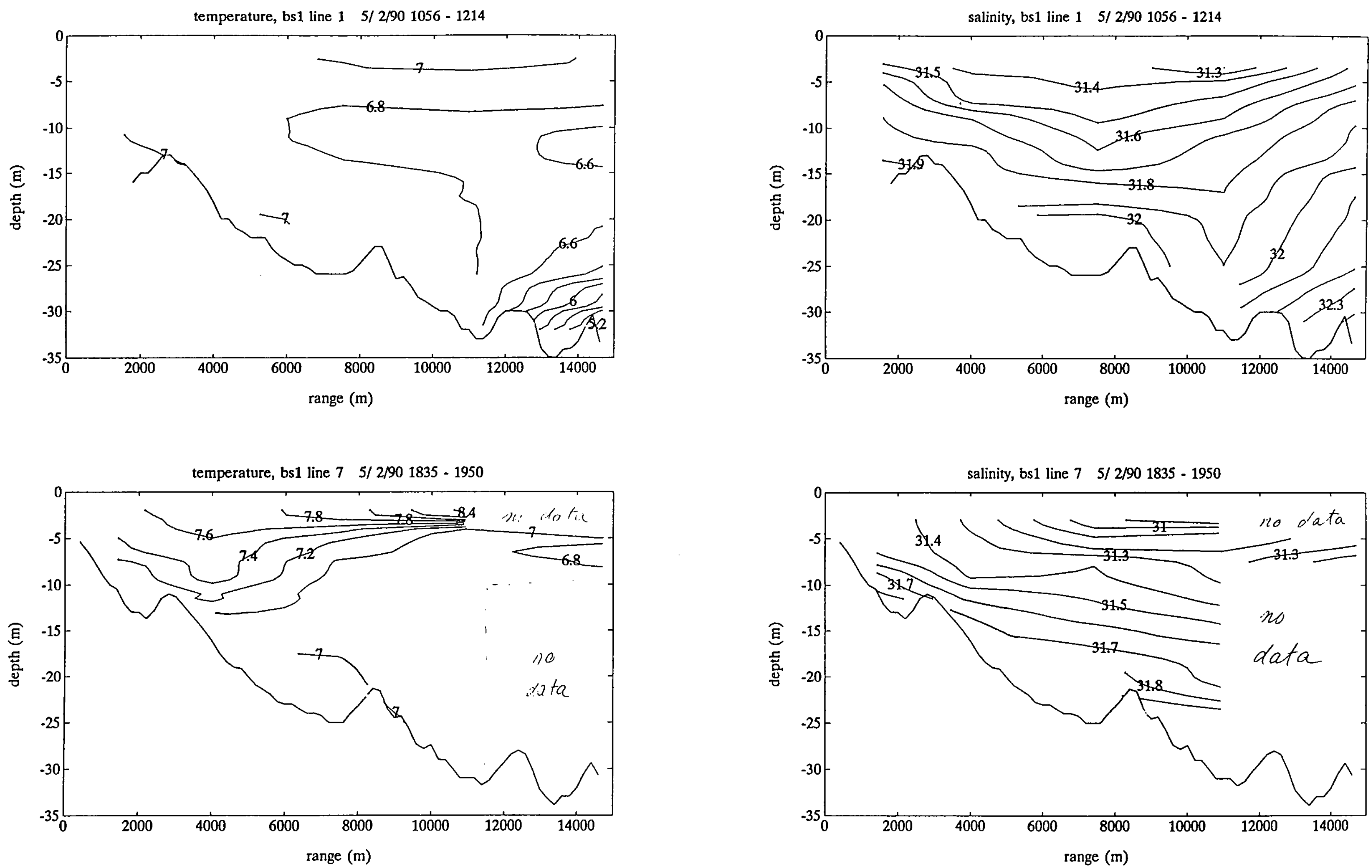


Figure 2.5-7 Water properties at Broad Sound section, 5/2/90.

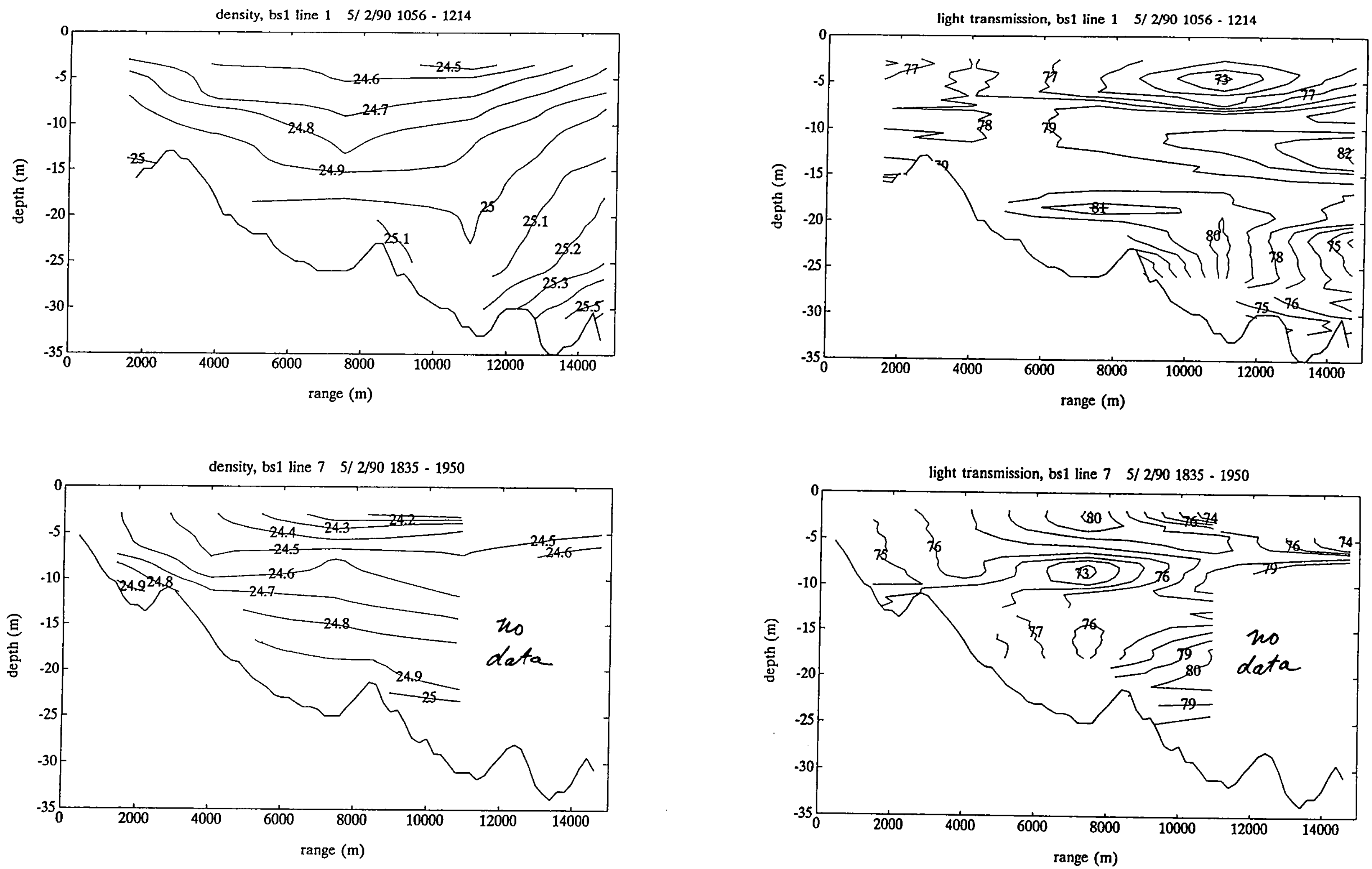


Figure 2.5-7 (Con't) Water properties at Broad Sound section, 5/2/90.

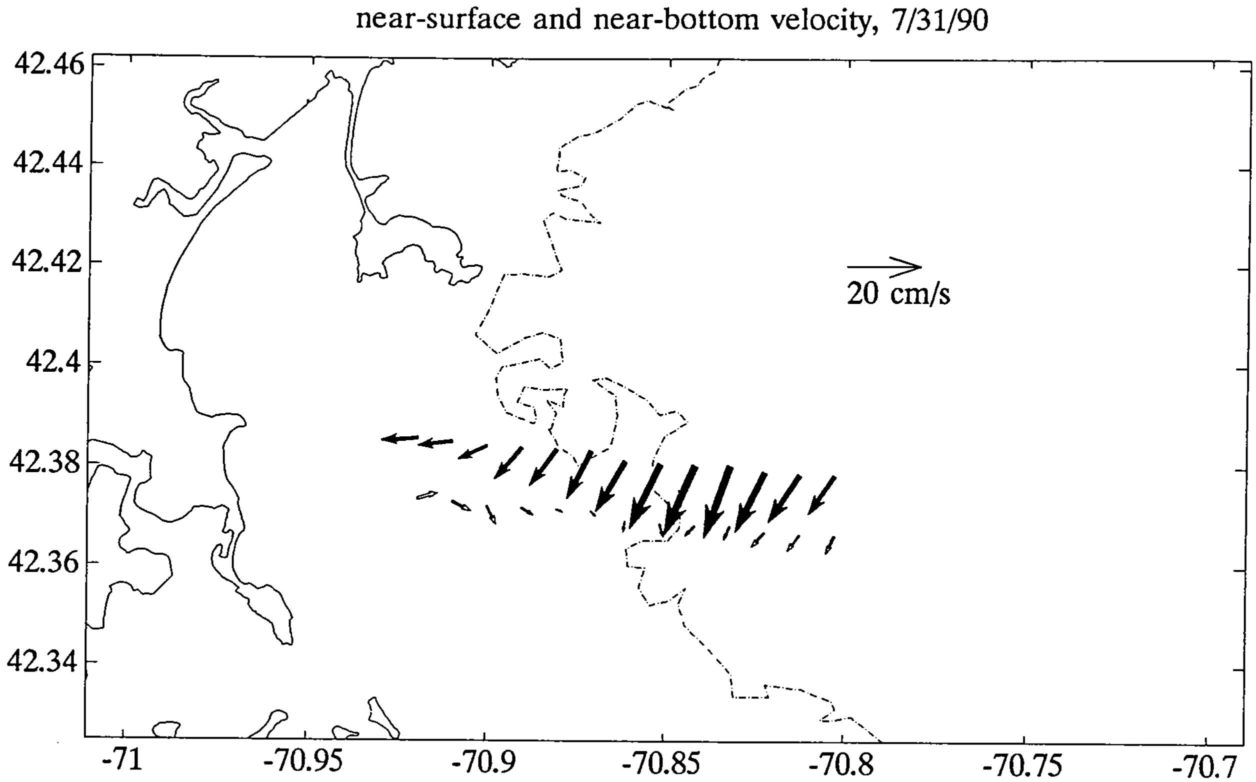


Figure 2.5-8 Near-surface and near-bottom velocity at Broad Sound section, 7/31/90, as in fig. 2.5-2.

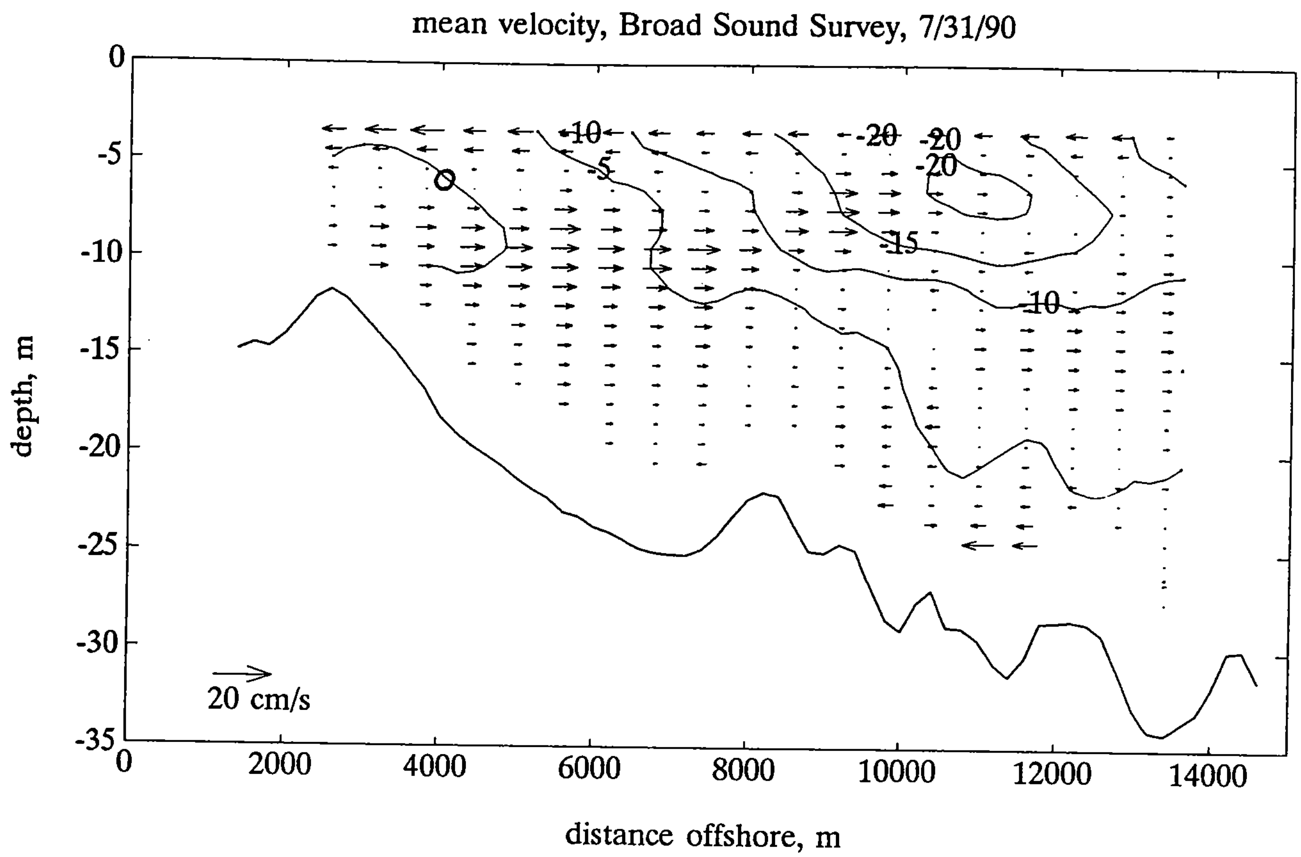


Figure 2.5-9 Cross section of currents at Broad Sound section, 7/31/90, as in fig. 2.5-3.

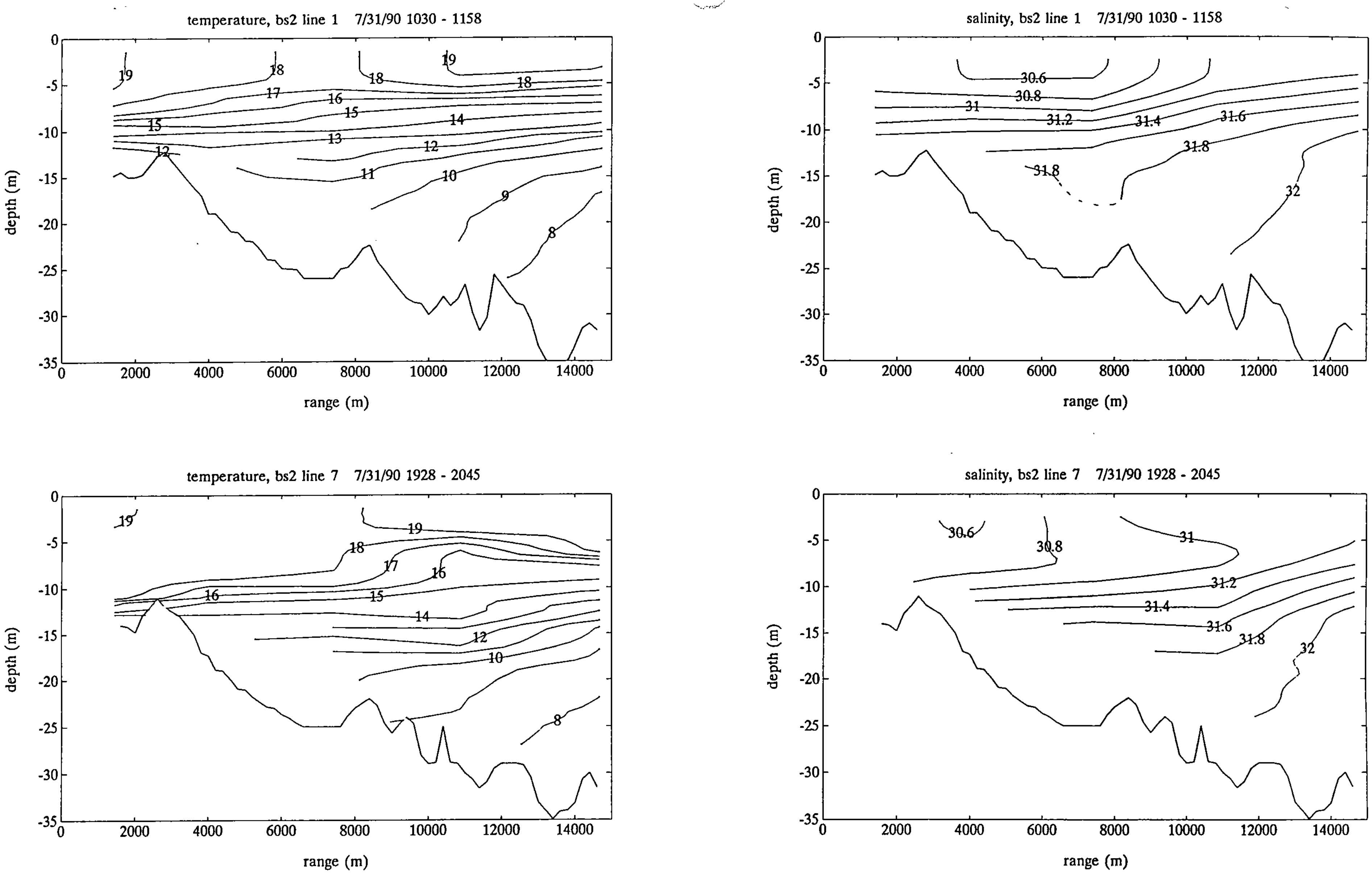


Figure 2.5-10 Water properties at Broad Sound section, 7/31/90.

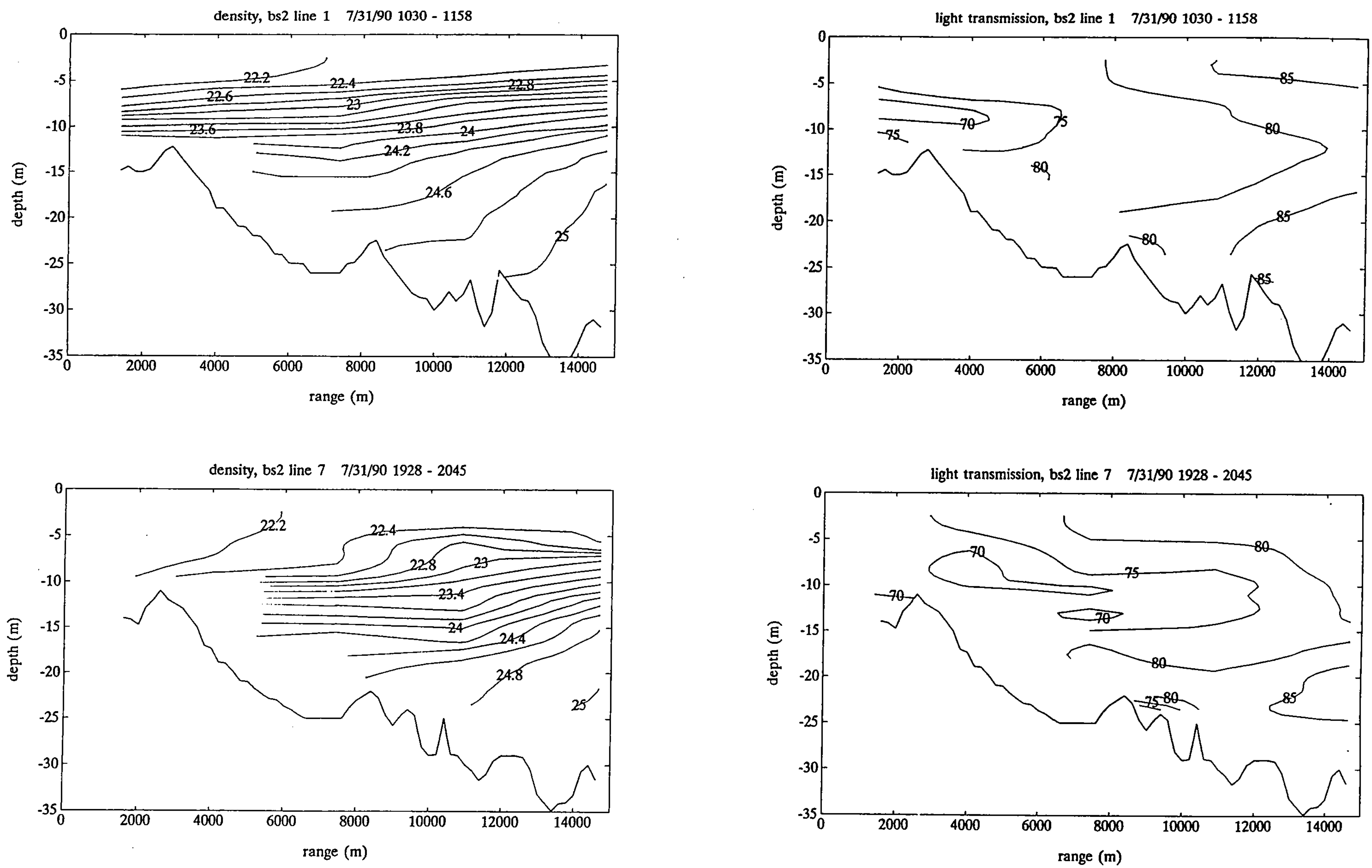


Figure 2.5-10 (Con't) Water properties at Broad Sound section, 7/31/90.

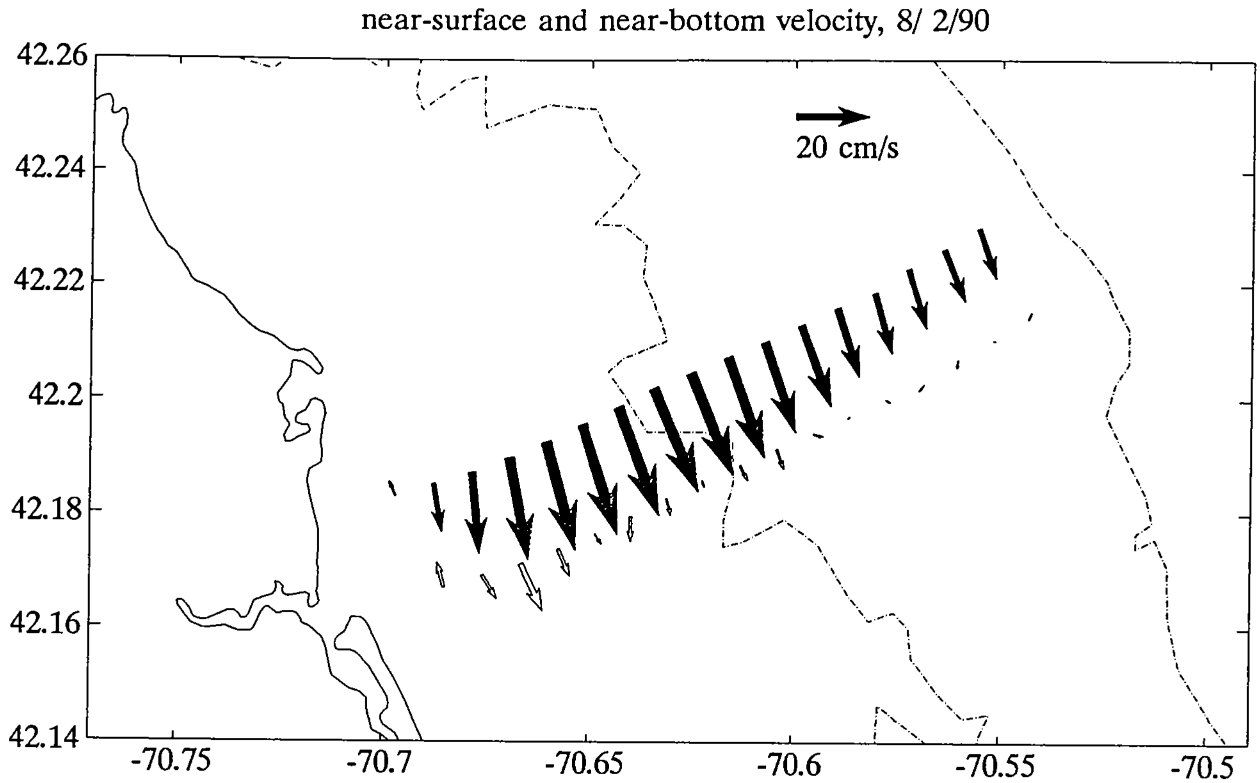


Figure 2.5-11 Near-surface and near-bottom velocity at Scituate section, 8/2/90, as in fig. 2.5-2.

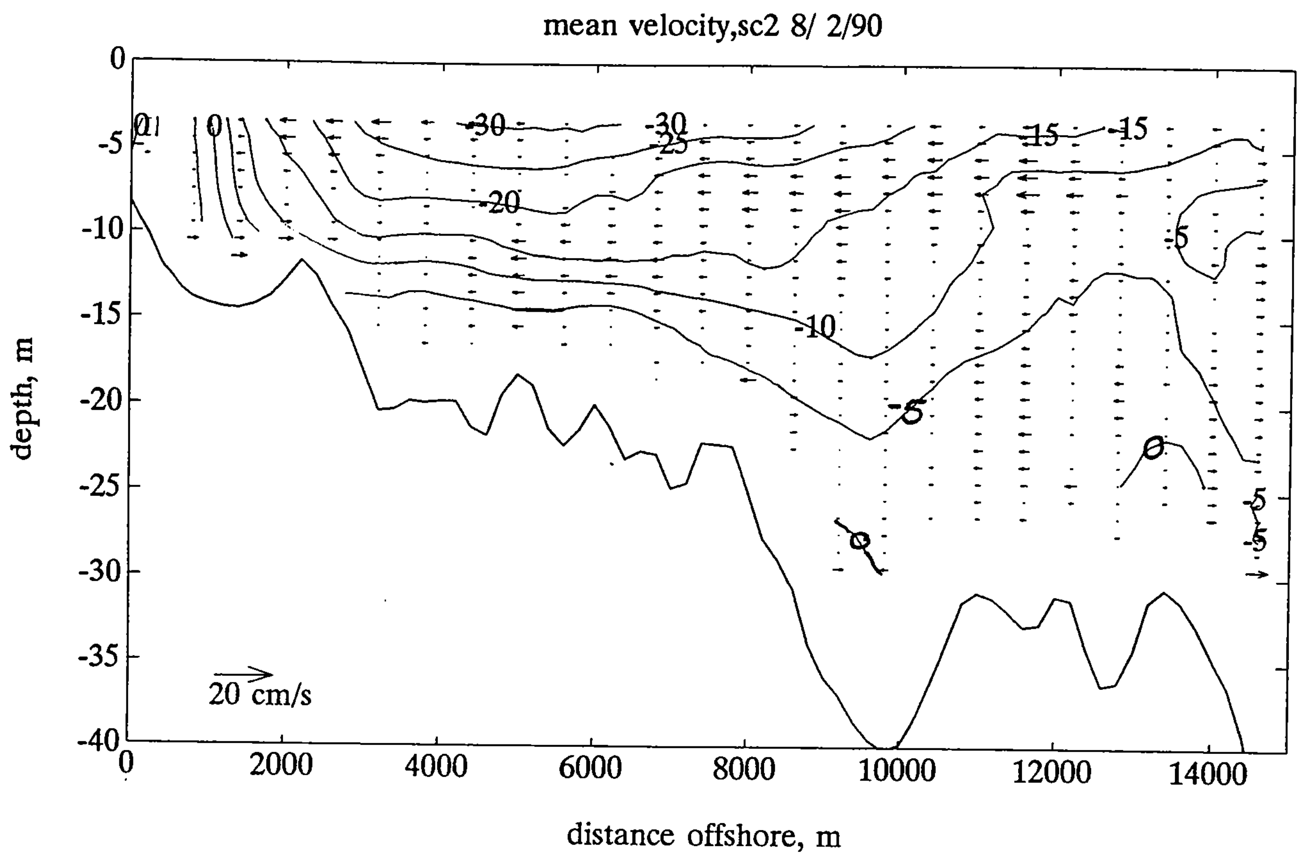


Figure 2.5-12 Cross section of currents at Scituate section, 8/2/90, as in fig. 2.5-3.

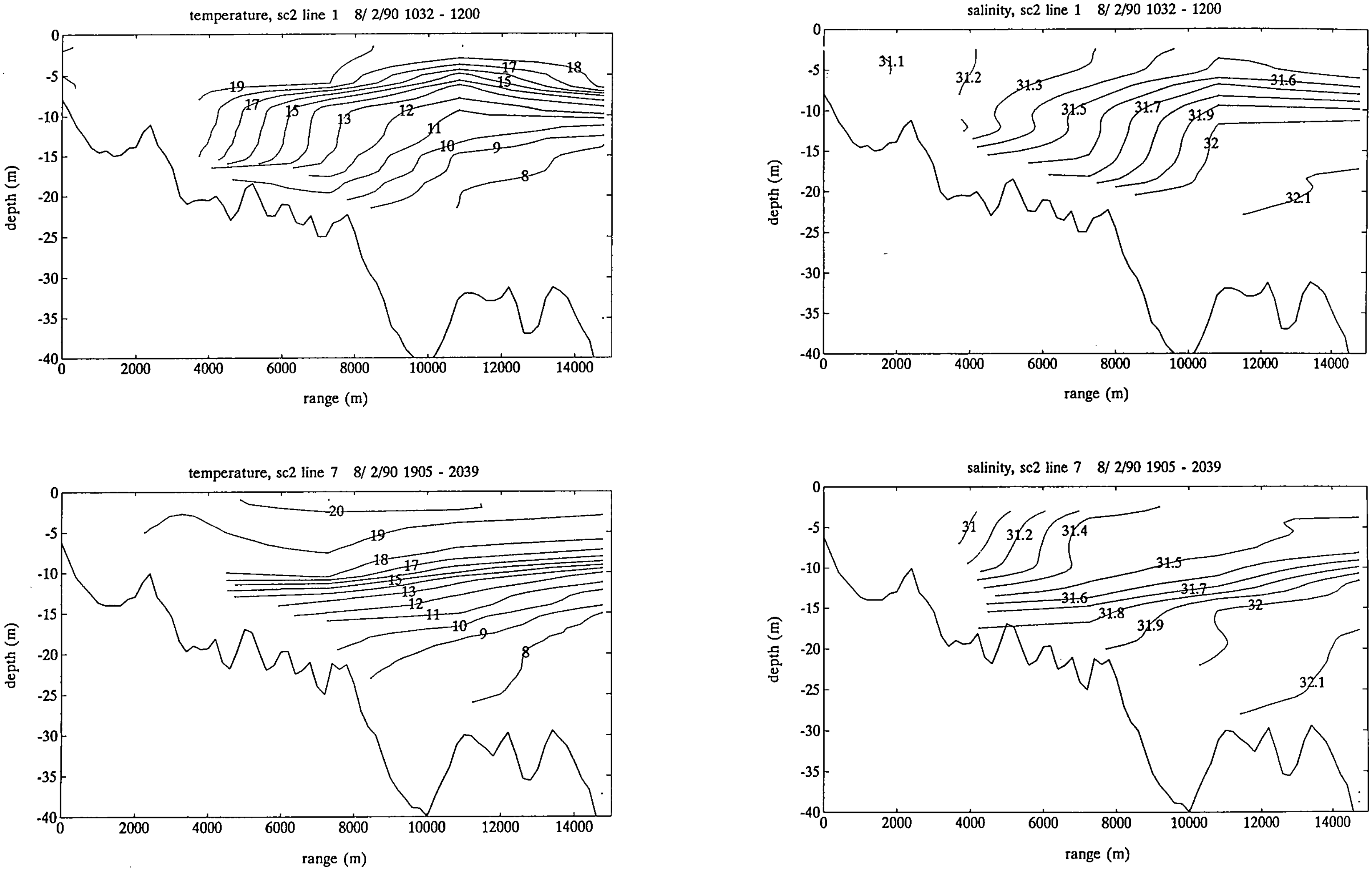


Figure 2.5-13 Water properties at Scituate section, 8/2/90.

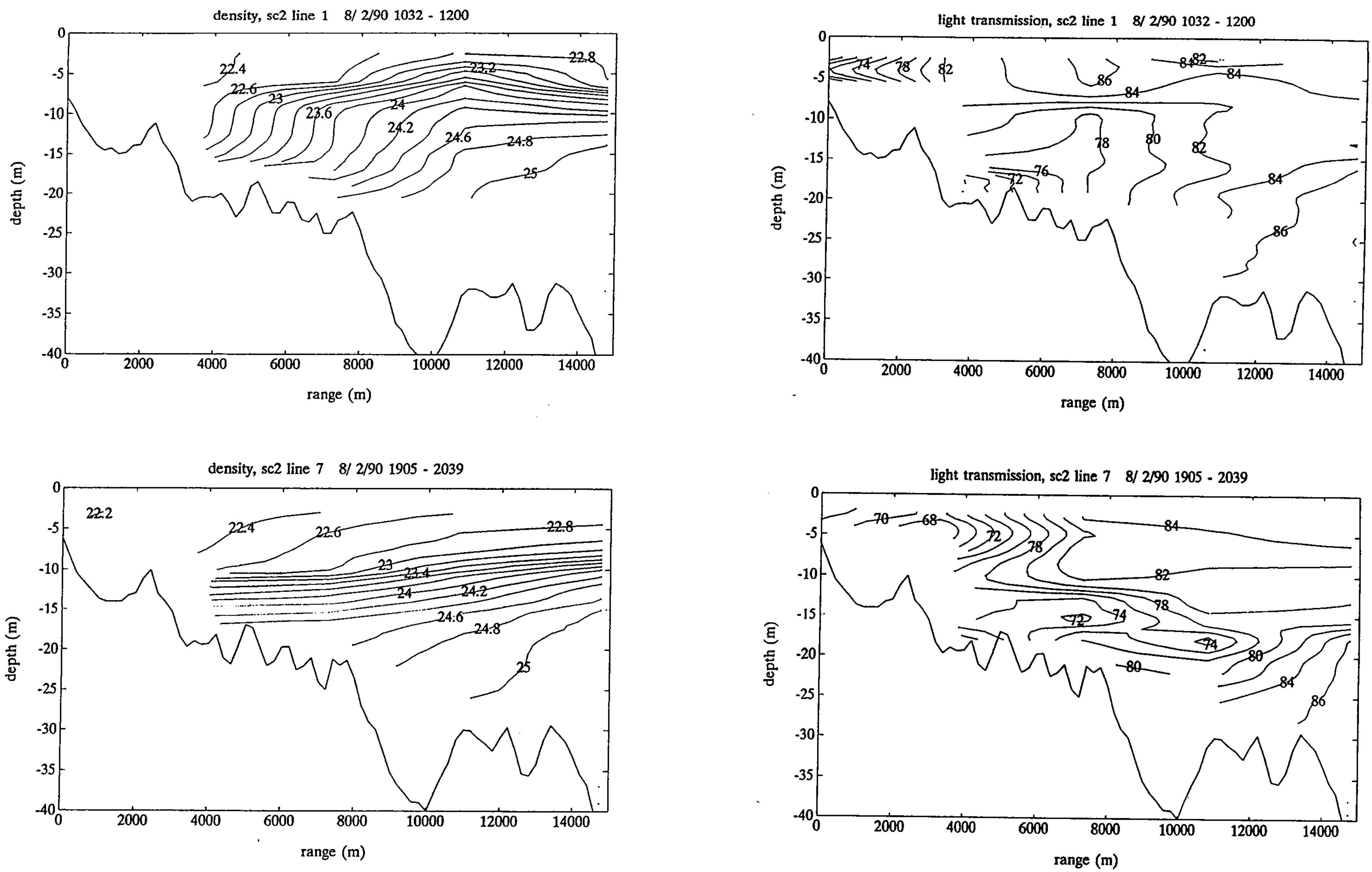
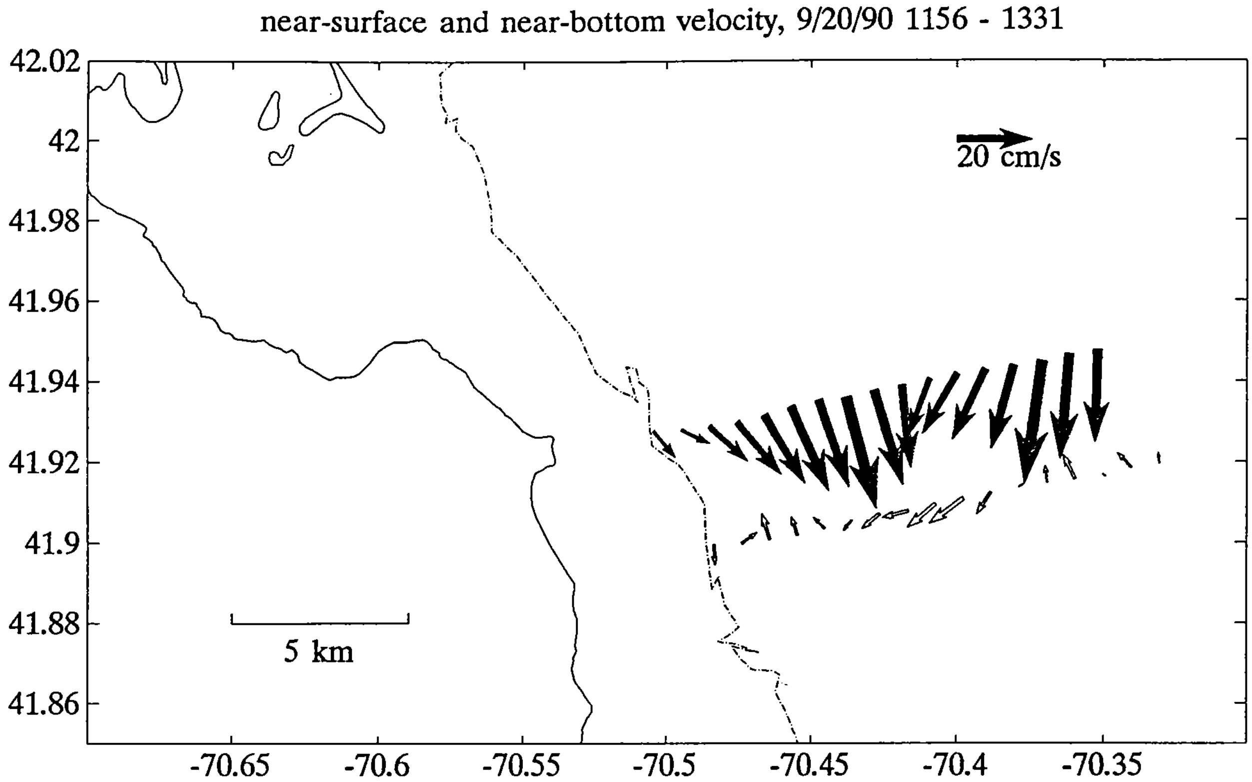


Figure 2.5-13 (Con't) Water properties at Scituate section, 8/2/90.



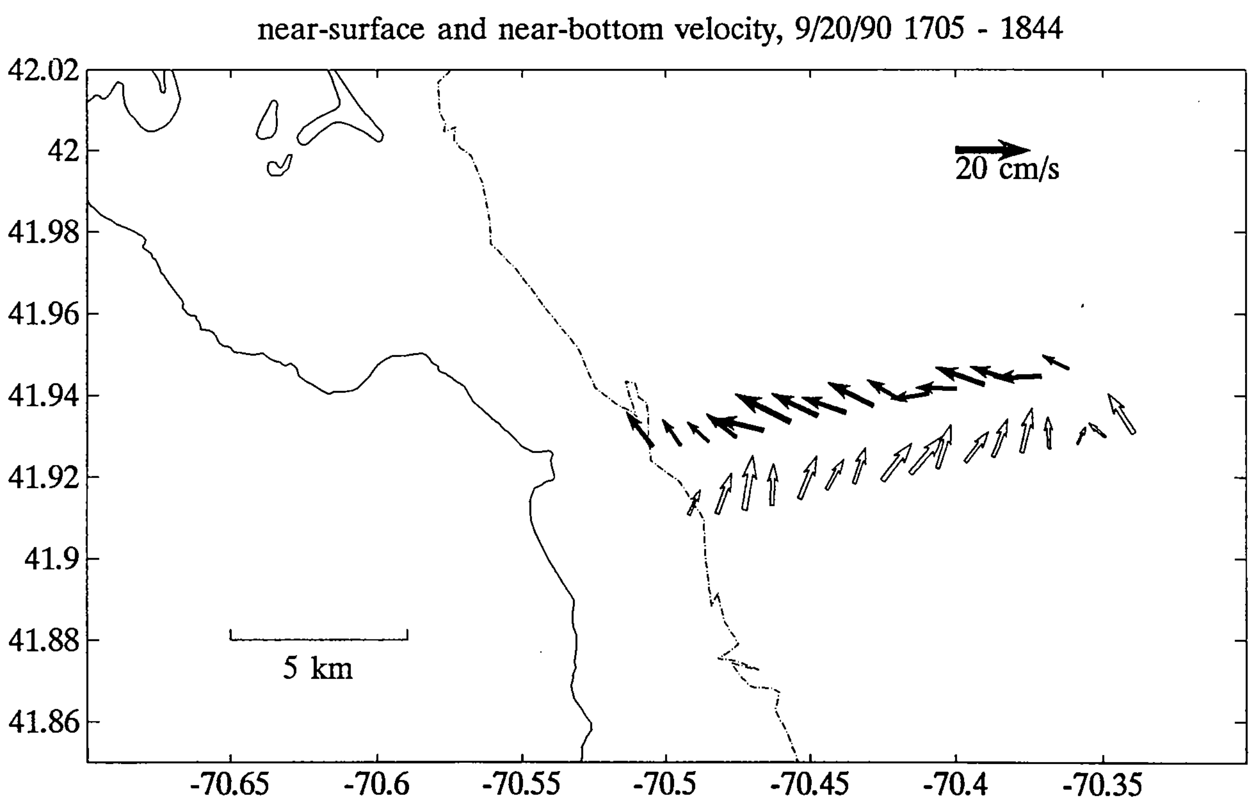


Figure 2.5-14 Near-surface and near-bottom velocity at Manomet section, 9/20/90. Times (GMT) are noted in the heading of each plot. Data are instantaneous measurements, so they include tidal velocities.

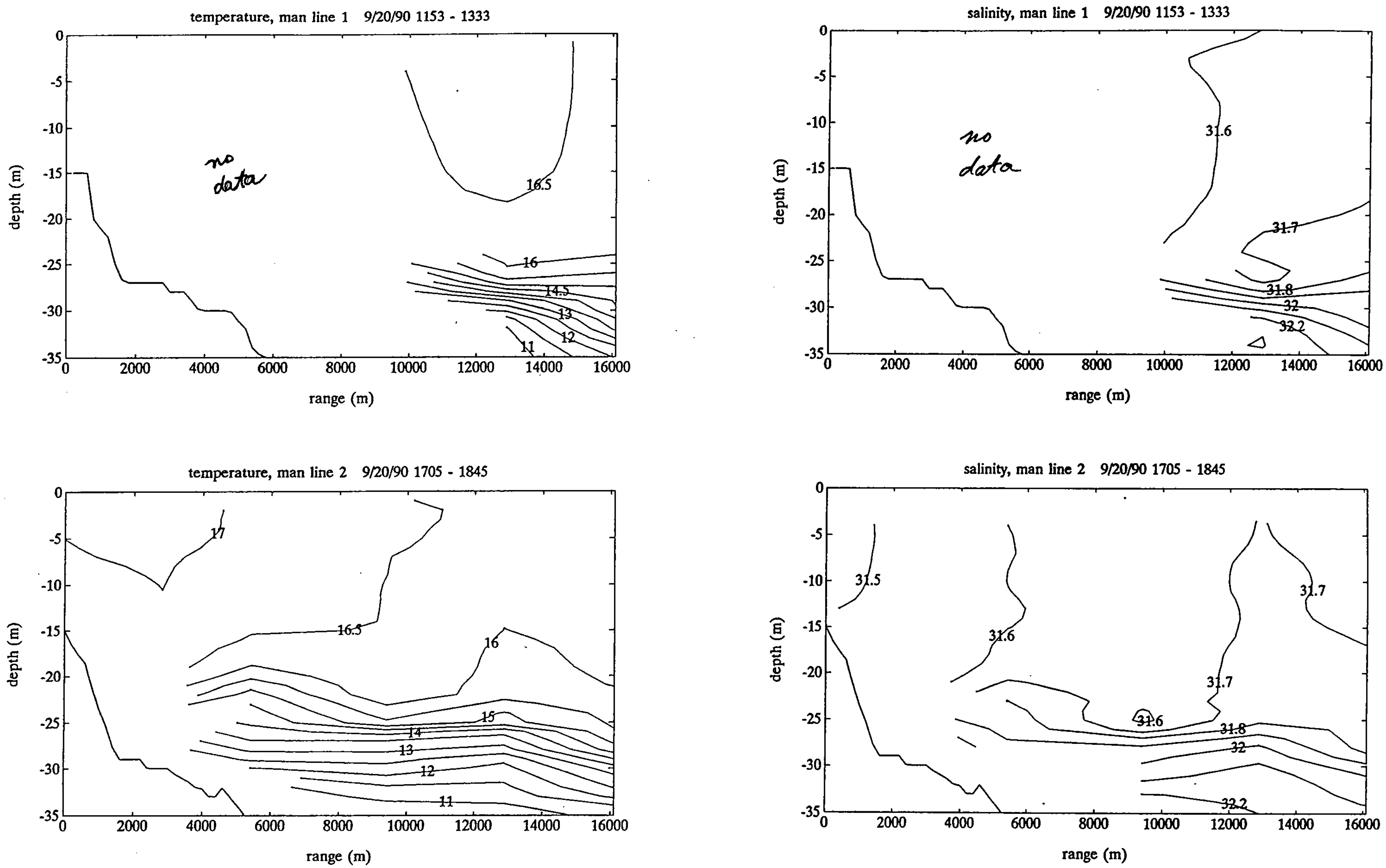


Figure 2.5-15 Water properties at Manomet section, 9/20/90.

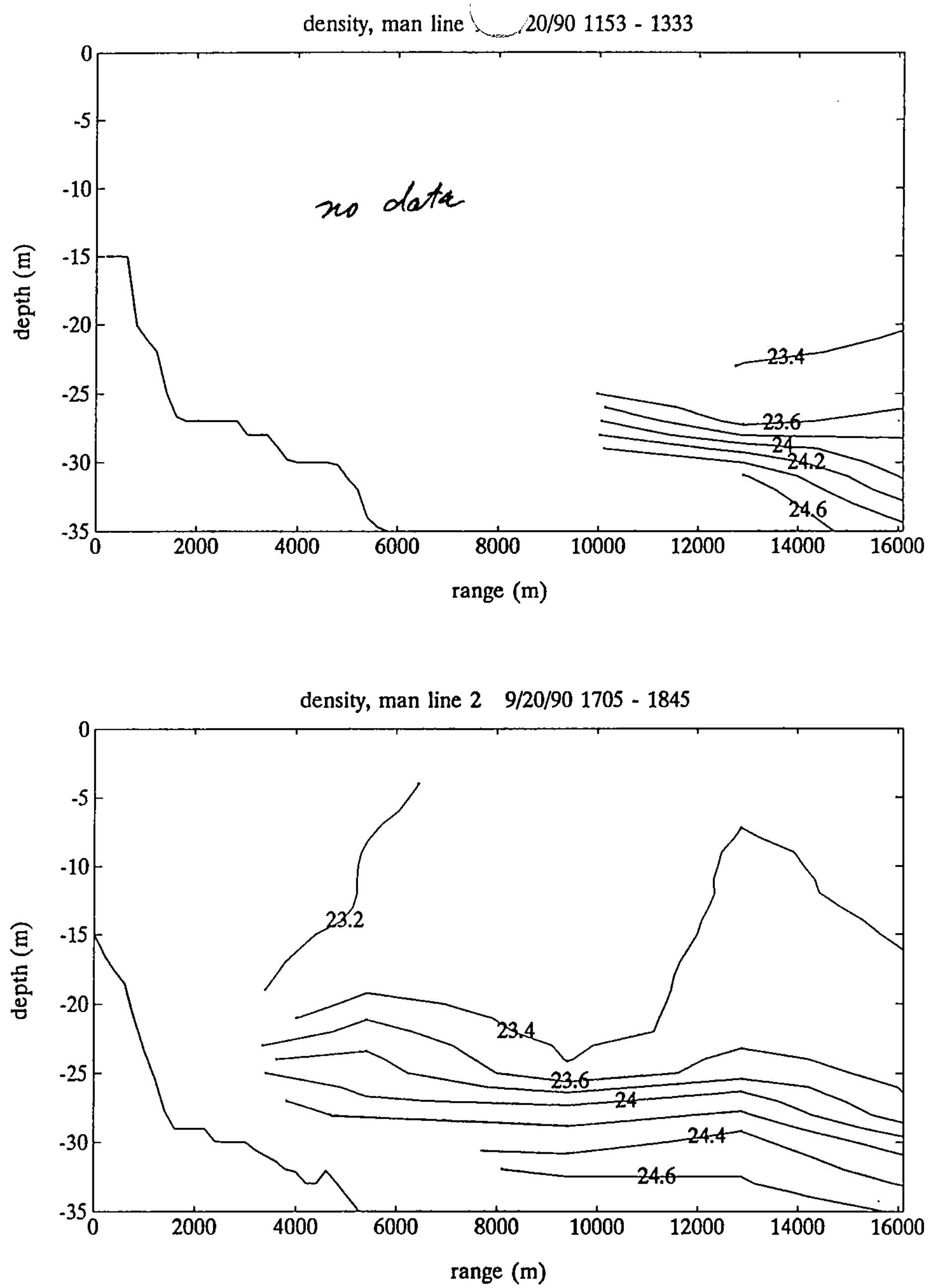


Figure 2.5-15 (Con't) Water properties at Manomet section, 9/20/90.

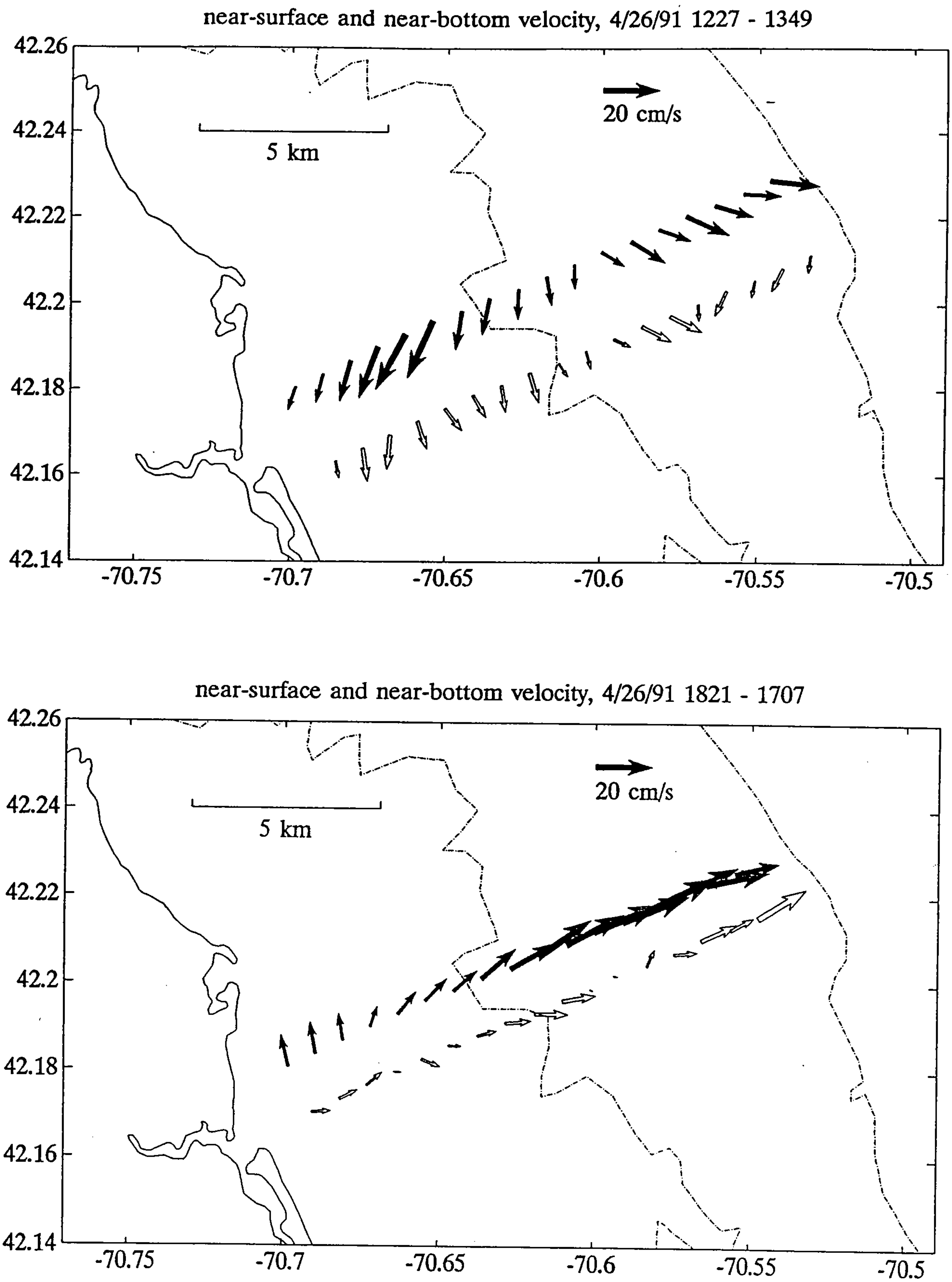


Figure 2.5-16 Near-surface and near-bottom velocity at Scituate section, 4/26/91.

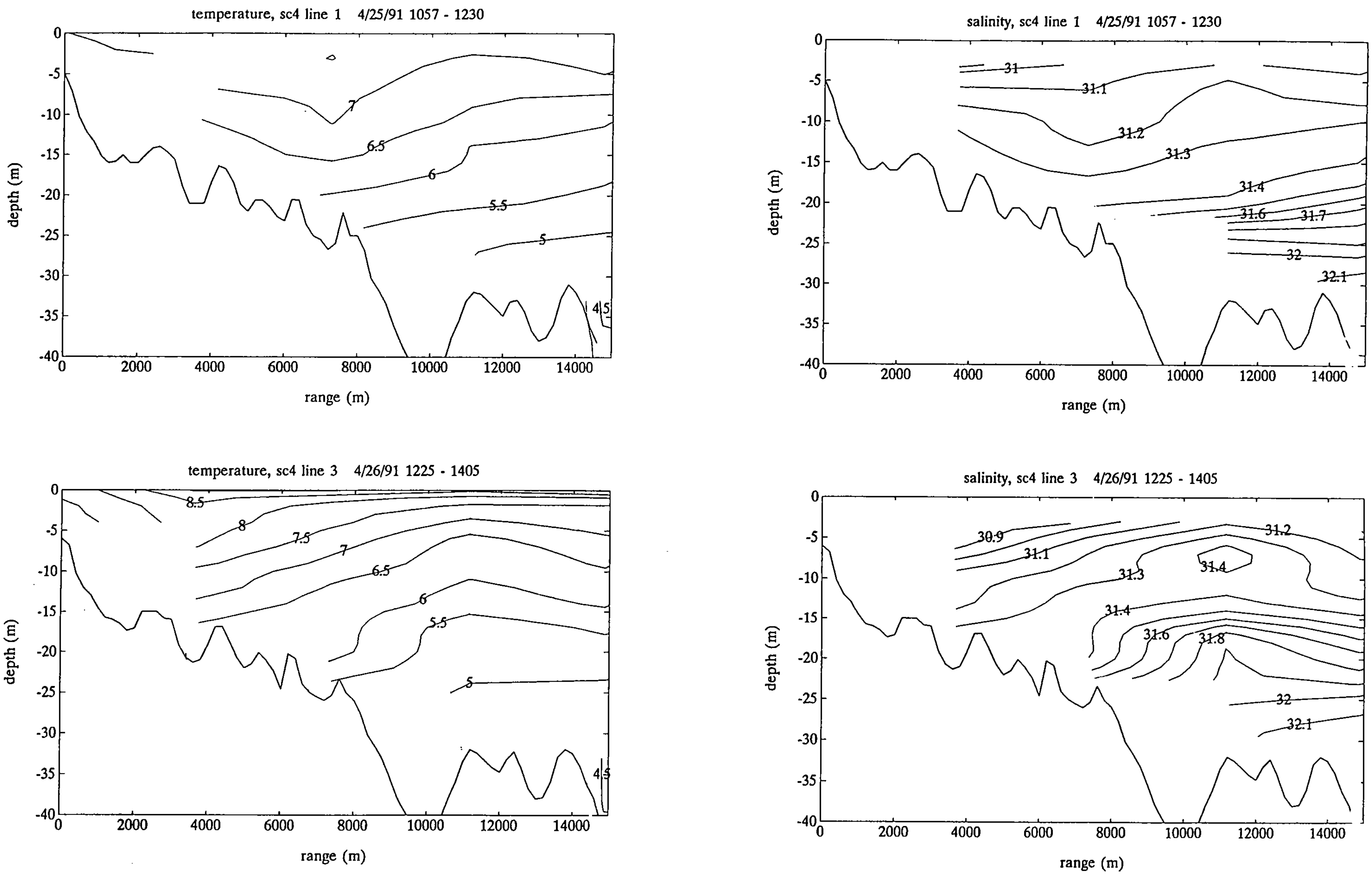


Figure 2.5-17 Water properties at Scituate section, 4/25/91–4/26/91. Note that these do not conform to the same times as the sections in fig. 2.5-16.

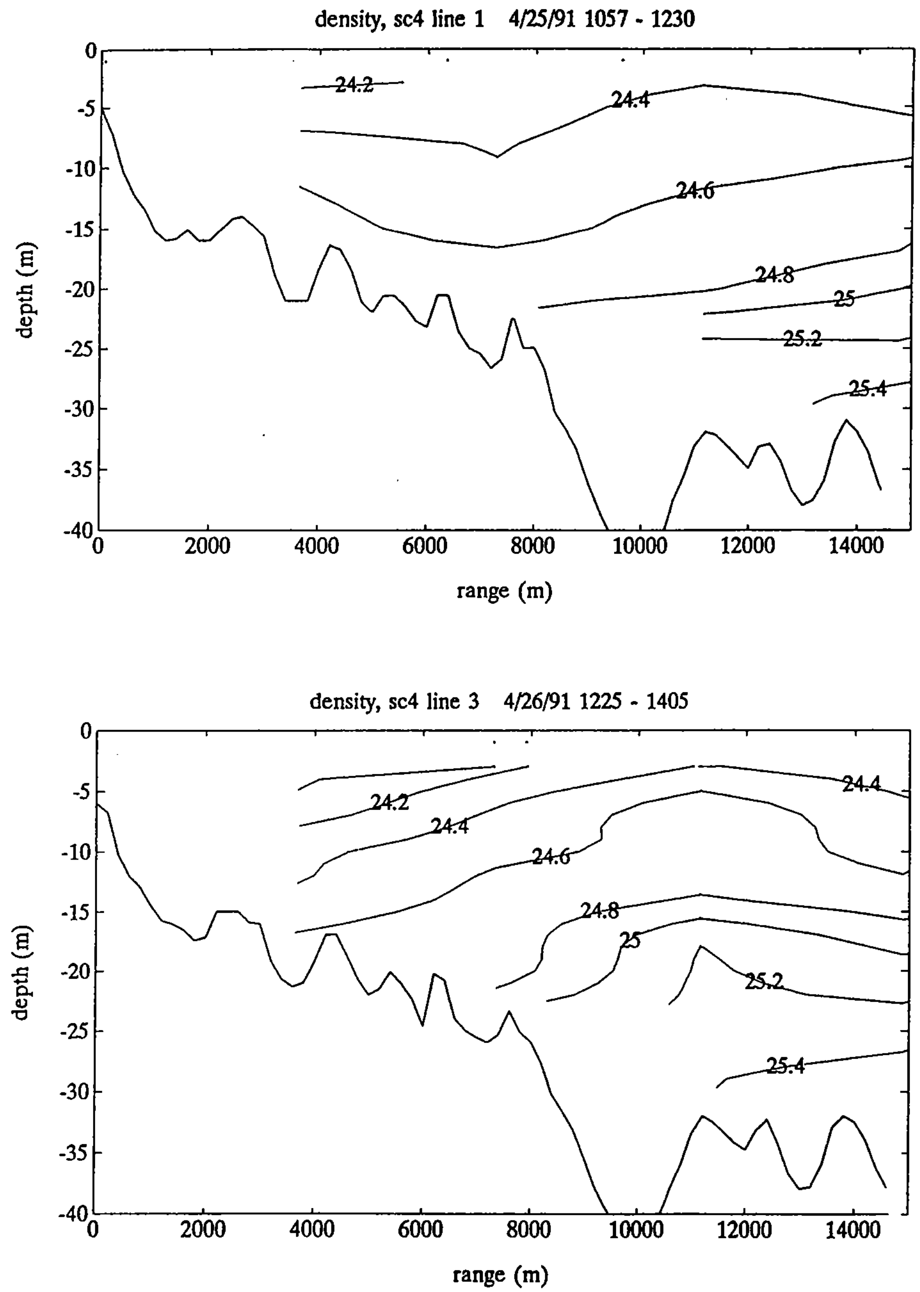


Figure 2.5-17 (Con't) Water properties at Scituate section, 4/25/91–4/26/91. Note that these do not conform to the same times as the sections in fig. 2.5-16.

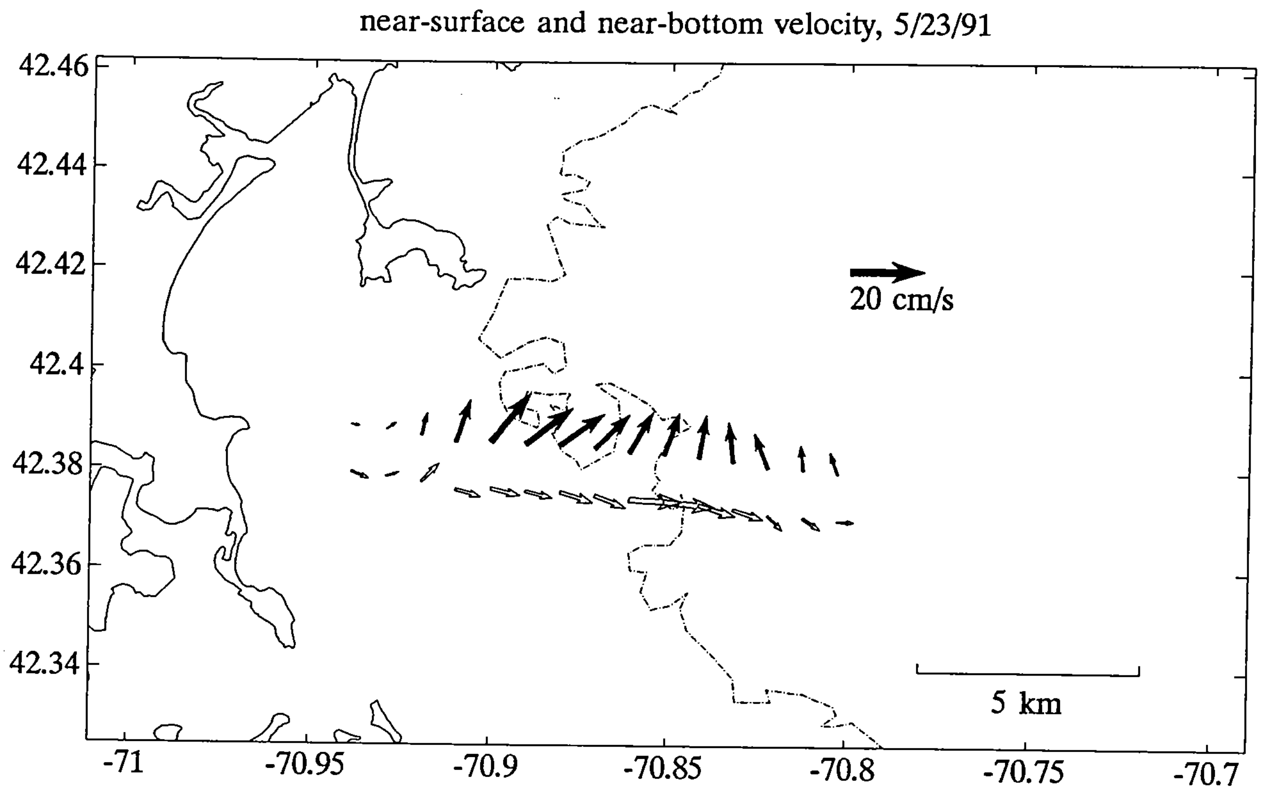


Figure 2.5-18 Near-surface and near-bottom velocity at Broad Sound section, 5/23/91.

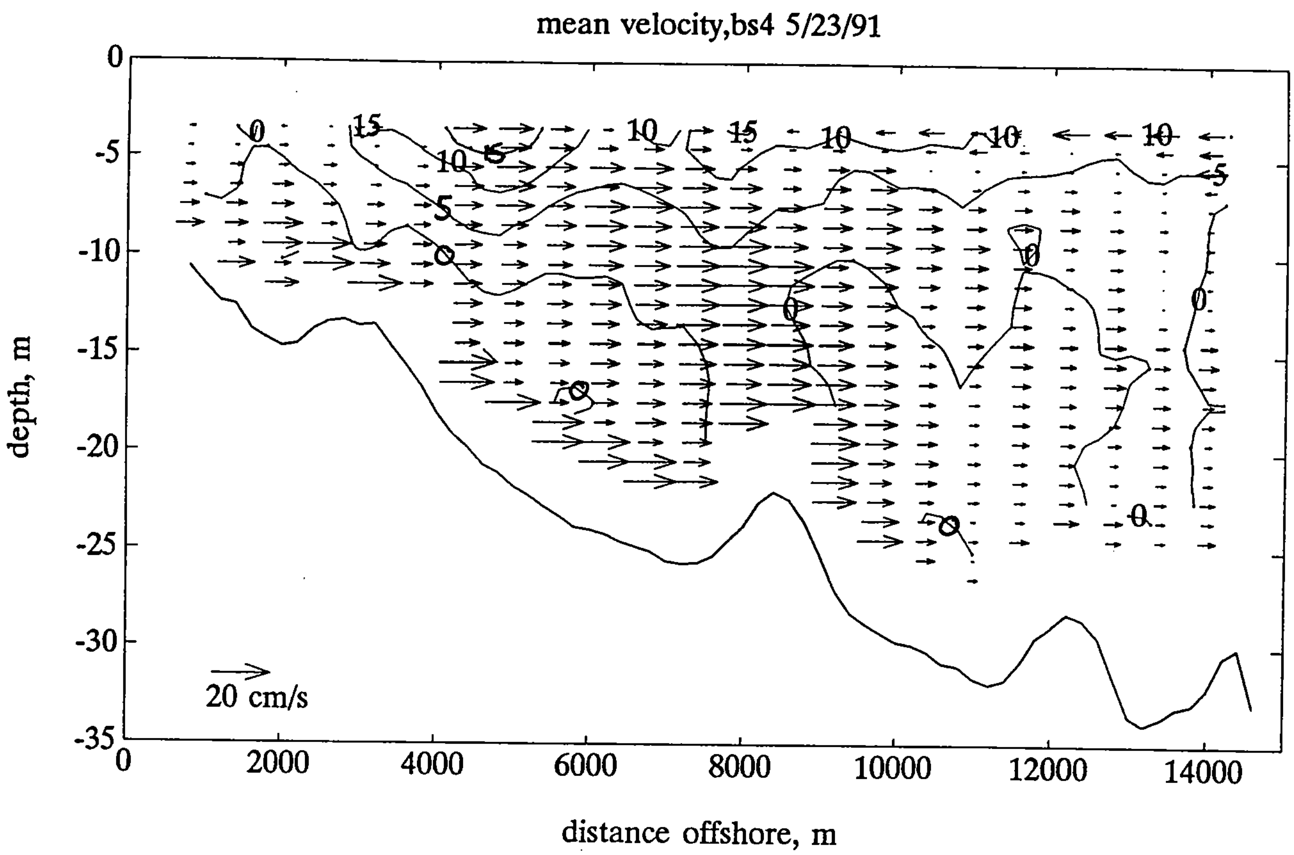


Figure 2.5-19 Cross section of currents at Broad Sound section, 5/23/91, as in fig. 2.5-3.

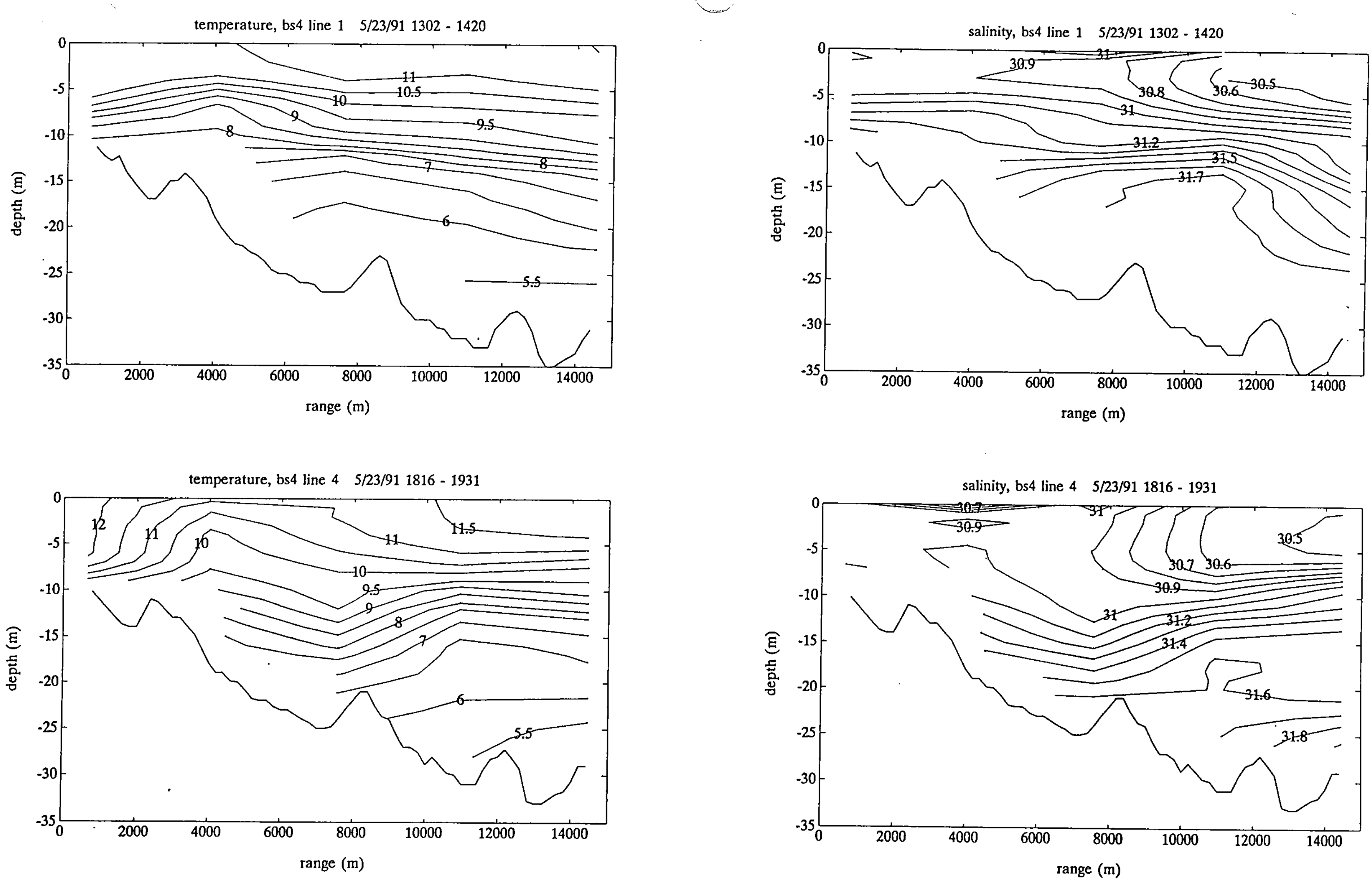
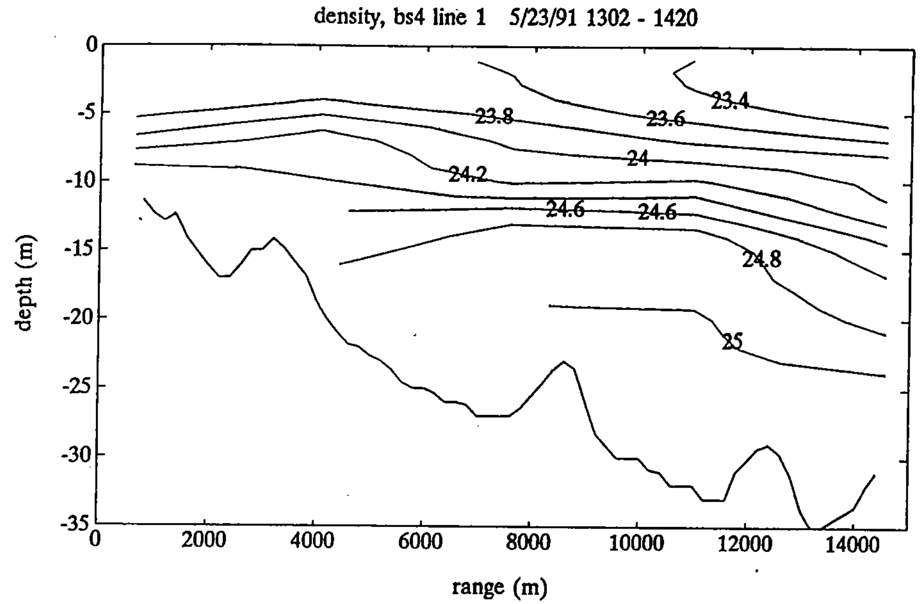


Figure 2.5-20 Water properties at Broad Sound section, 5/23/91.



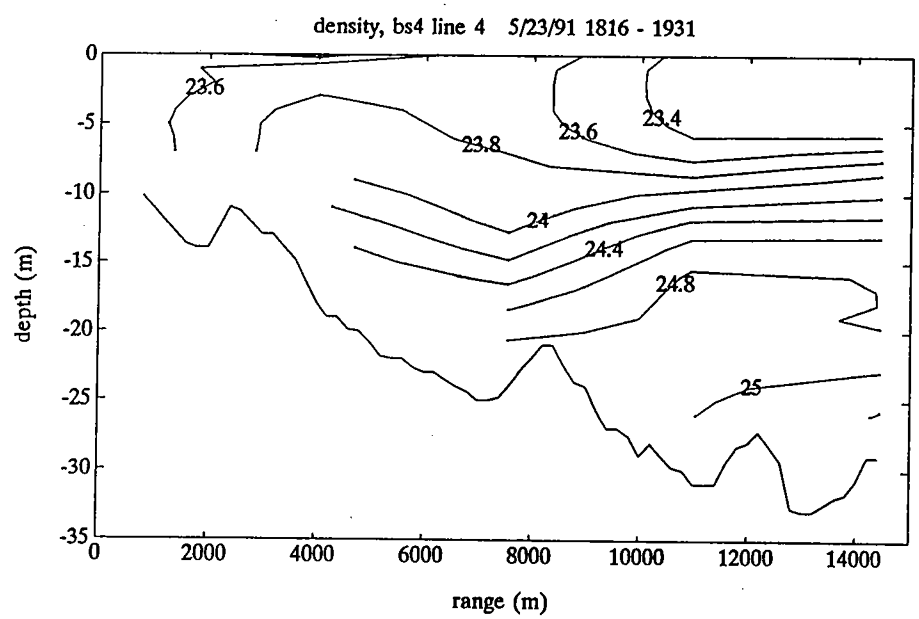


Figure 2.5-20 (Con't) Water properties at Broad Sound section, 5/23/91.