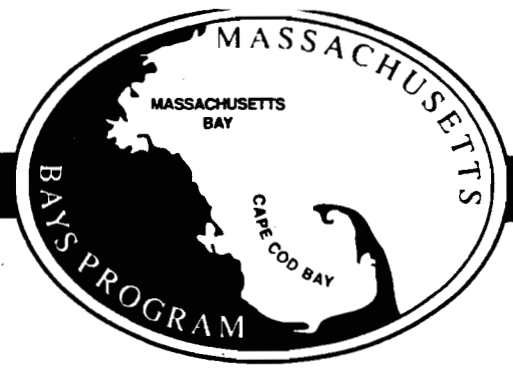


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Report to the
MASSACHUSETTS BAYS PROGRAM

**PHYSICAL OCEANOGRAPHIC INVESTIGATION OF
MASSACHUSETTS AND CAPE COD BAYS**

EXECUTIVE SUMMARY

Prepared by

- W. Rockwell Geyer, Ph.D.
- George B. Gardner, Ph.D.
- Wendell S. Brown, Ph.D.
- James Irish, Ph.D.
- Bradford Butman, Ph. D.
- Theodore Loder, Ph.D.
- Richard P. Signell, Ph.D.

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The Massachusetts Bays Program is a cooperative venture of
Massachusetts Coastal Zone Management Office, U.S. Environmental
Protection Agency, and Massachusetts Environmental Trust

931/282



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



MASSACHUSETTS BAYS PROGRAM

100 Cambridge Street, Room 2006, Boston, Massachusetts 02202 (617) 727-9530 fax (617) 727-2754

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 Outdated and poorly maintained sewage treatment plants on Deer Island and Nut Island were being overwhelmed daily by sewage from the forty-three communities in the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 million 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.

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W. Rockwell Geyer, Ph.D.¹, George B. Gardner, Ph.D.², Wendell S. Brown, Ph.D.³,
James Irish, Ph.D.¹, Bradford Butman, Ph.D.⁴,
Theodore Loder, Ph.D.³, and Richard Signell, Ph.D.⁴

OCTOBER, 1992

¹ Woods Hole Oceanographic Institution, Department of Applied Ocean Physics & Engineering, Woods Hole, MA 02543

² University of Massachusetts, Environmental Sciences Program, Boston, MA 02125

³ University of New Hampshire, Department of Earth Sciences, Durham, NH 03824

⁴ Woods Hole Oceanographic Institution, Department of Applied Ocean Physics & Engineering, Woods Hole, MA 02543

This physical oceanographic study of the Massachusetts Bays (fig. 1) 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 (fig. 2), hydrographic surveys to document the changes in water properties (fig. 3), 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 (figs. 4-5). 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 (fig. 6). 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 (fig. 7). 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 (fig. 8), 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.

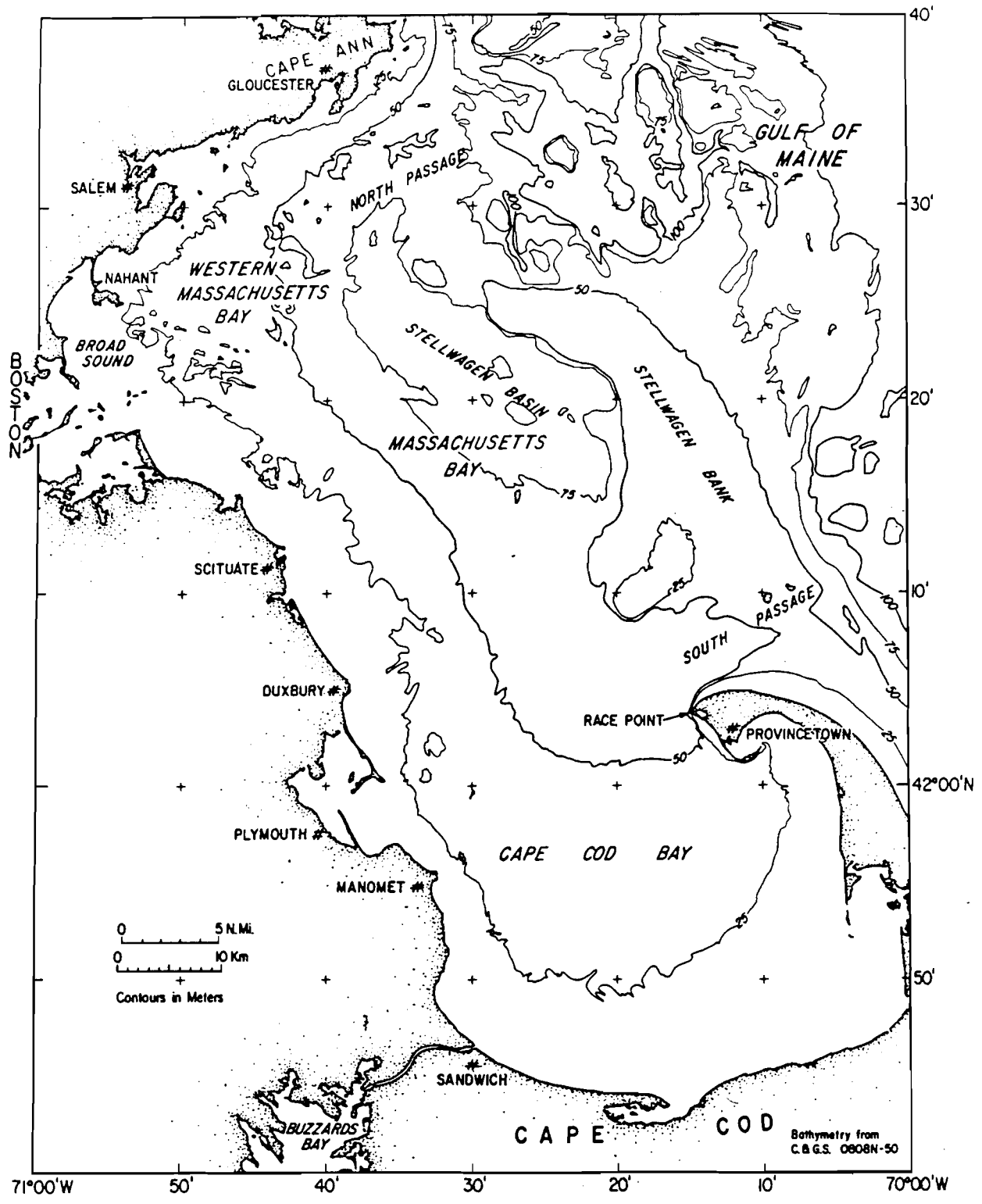


Figure 1. Bathymetry of Massachusetts/Cape Cod Bay system, indicating the major bathymetric features.

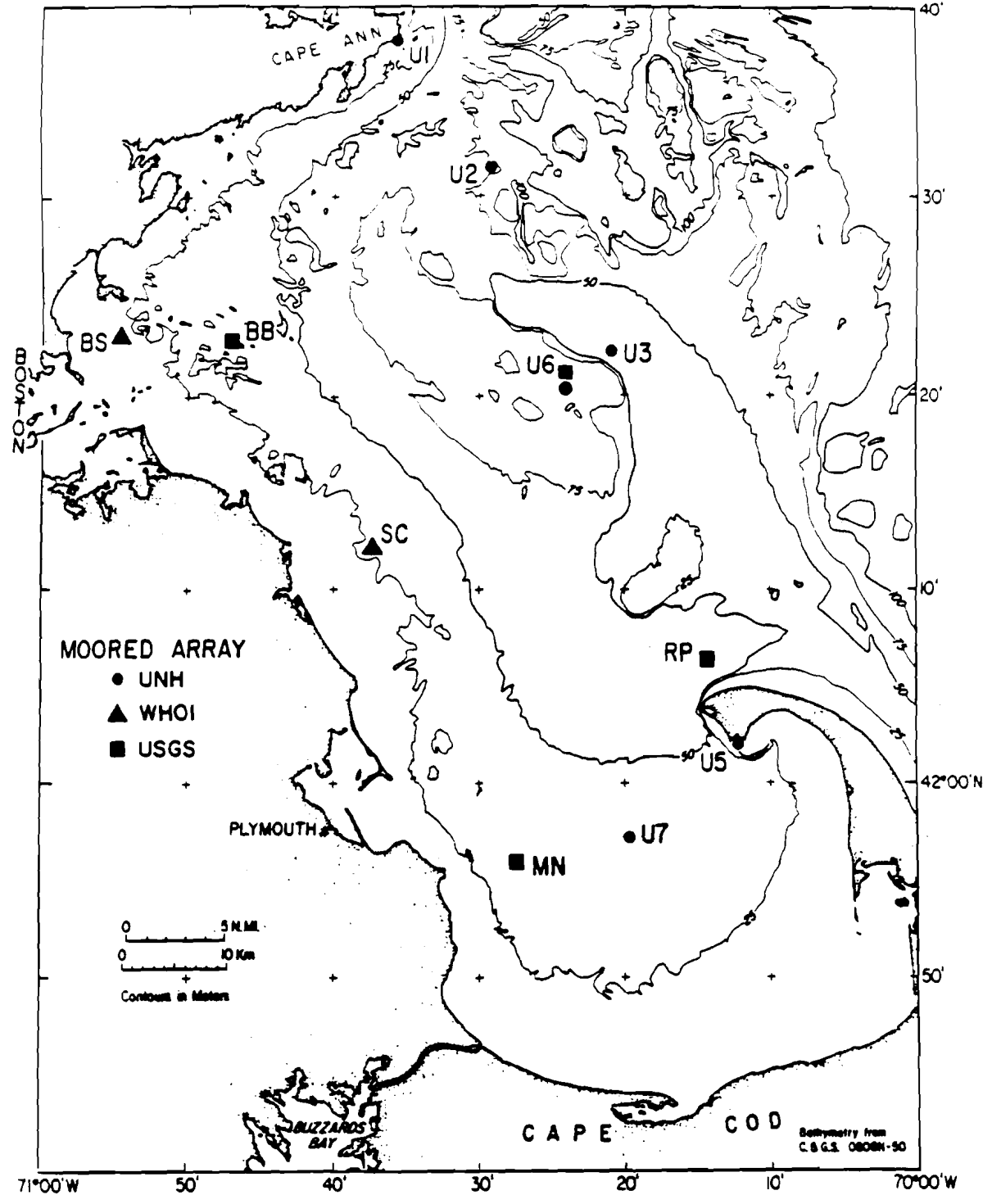


Figure 2. The combined Massachusetts Bays Program-USGS moored array.



Figure 3. 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.

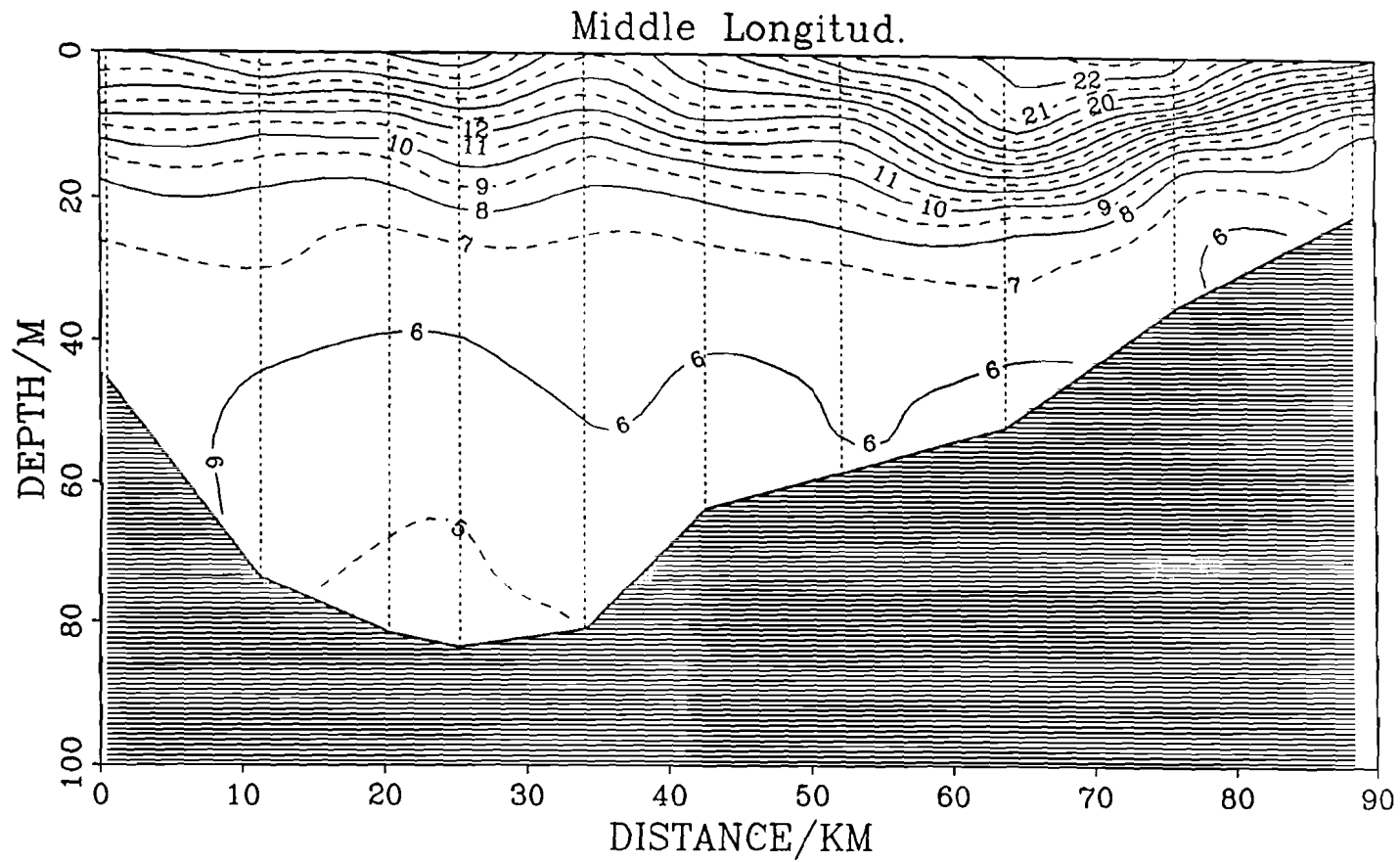


Figure 4a. Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature ($^{\circ}\text{C}$) for the July 24–25, 1990 cruise. The contour interval is 1.0°C for all plots. Total temperature variation is 16.0°C , with little surface mixed layer.

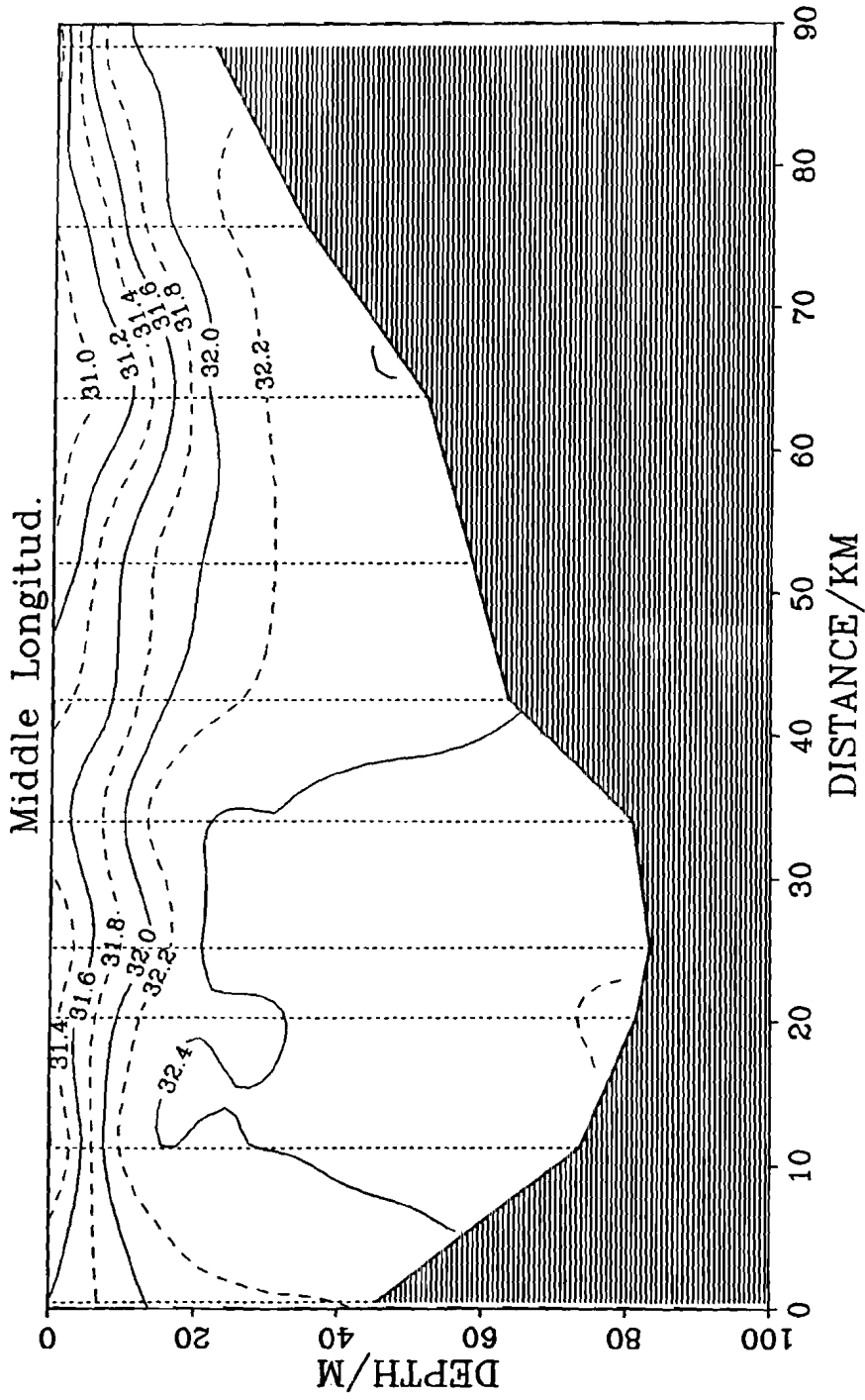


Figure 4b. Mid-bay longitudinal section contour plot of salinity (PSU) for the July 24-25, 1990 cruise. The contour interval is 0.2 PSU for all plots. Salinity was higher at the north end of the section with a low salinity lens in Cape Cod Bay.

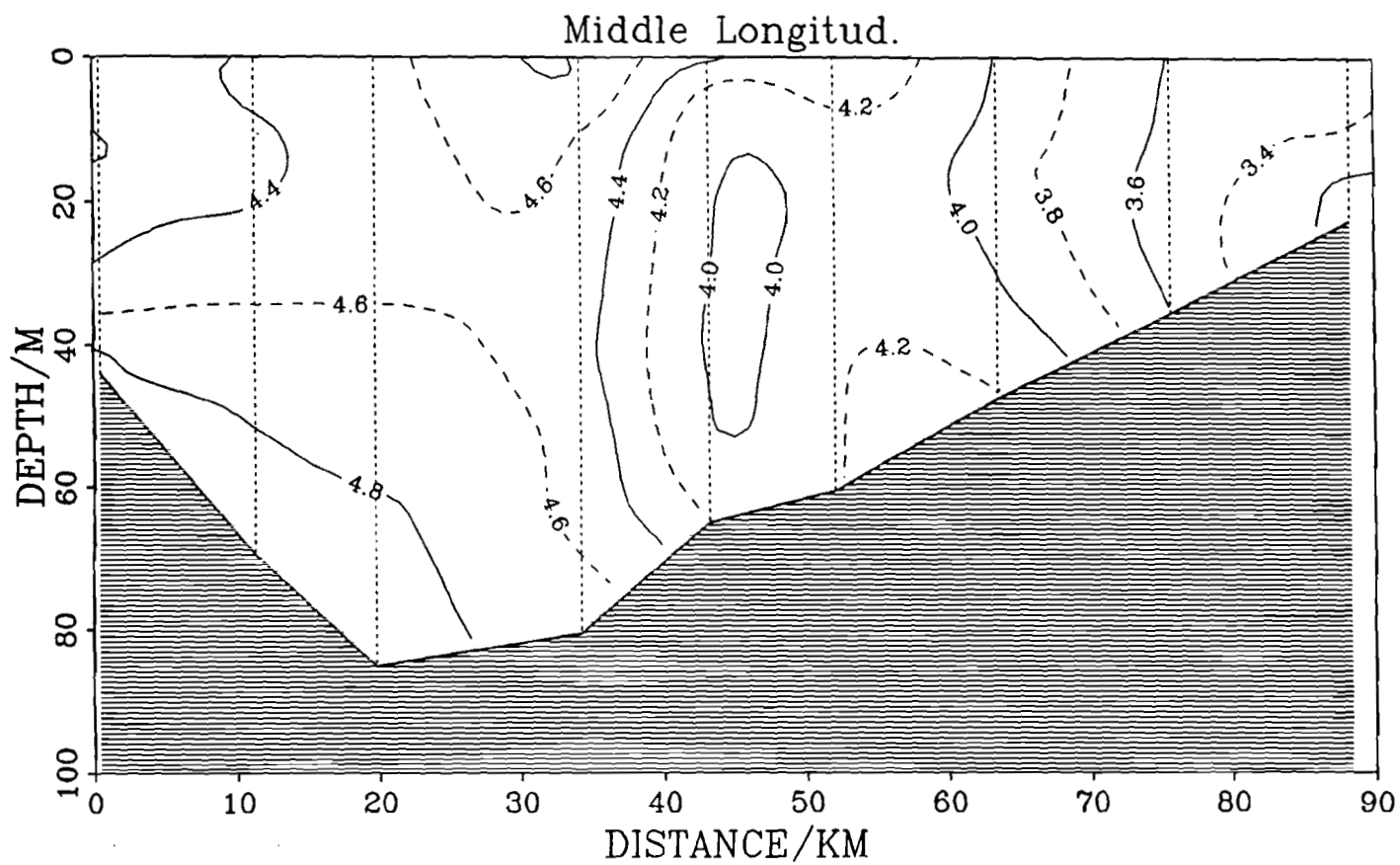


Figure 5a. Mid-bay longitudinal section (Cape Ann to Cape Cod) contour plot of temperature ($^{\circ}\text{C}$) for the February 4–6, 1991 cruise. The contour interval is 0.2°C . Cold water in Cape Cod Bay extended northward into the southern portion of Massachusetts Bay.

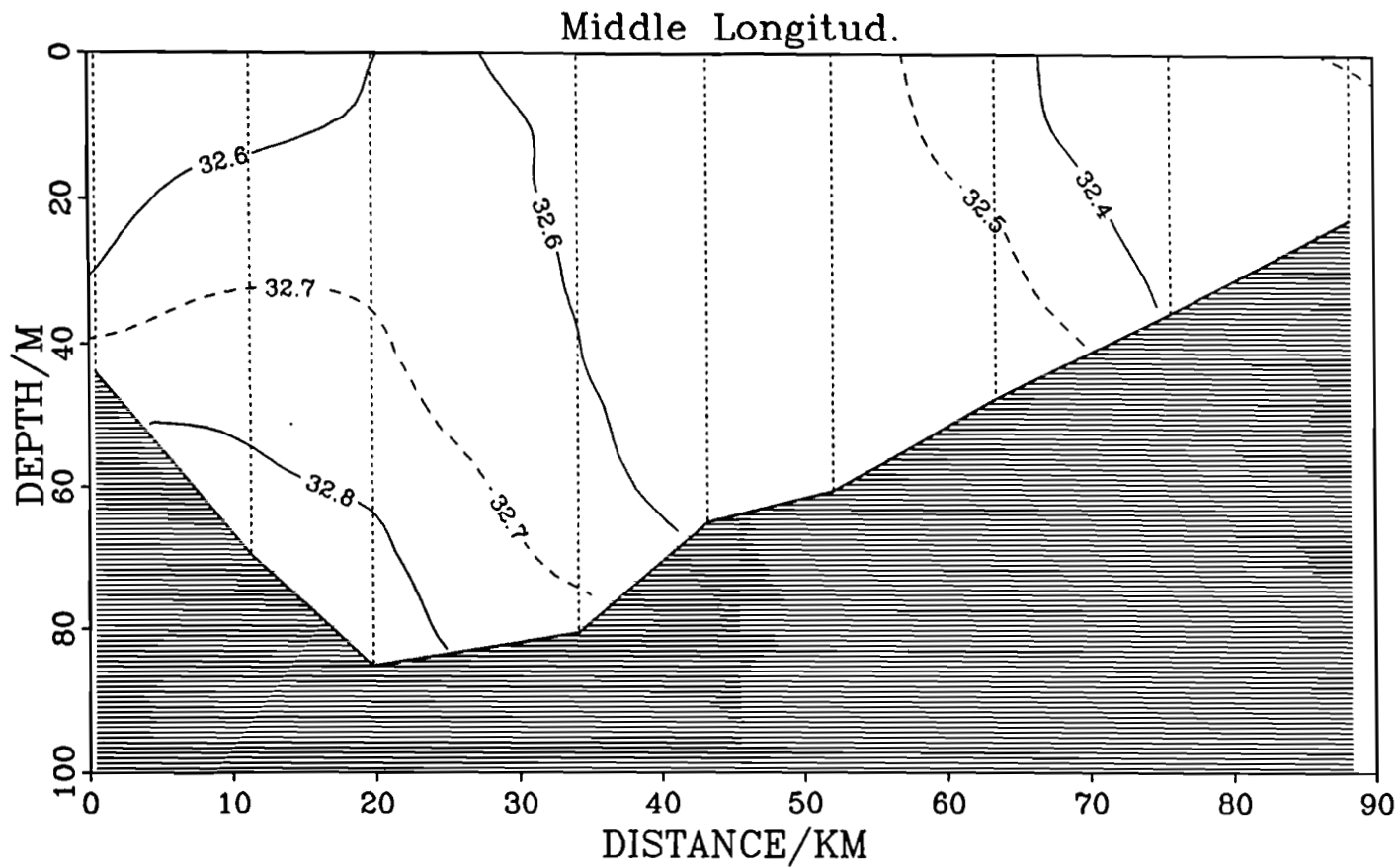


Figure 5b. Mid-bay longitudinal section contour plot of salinity (PSU) for the February 4-6, 1991 cruise. The contour interval is 0.1 PSU. Note that there is a slight stratification in the deep water of Massachusetts Bay.

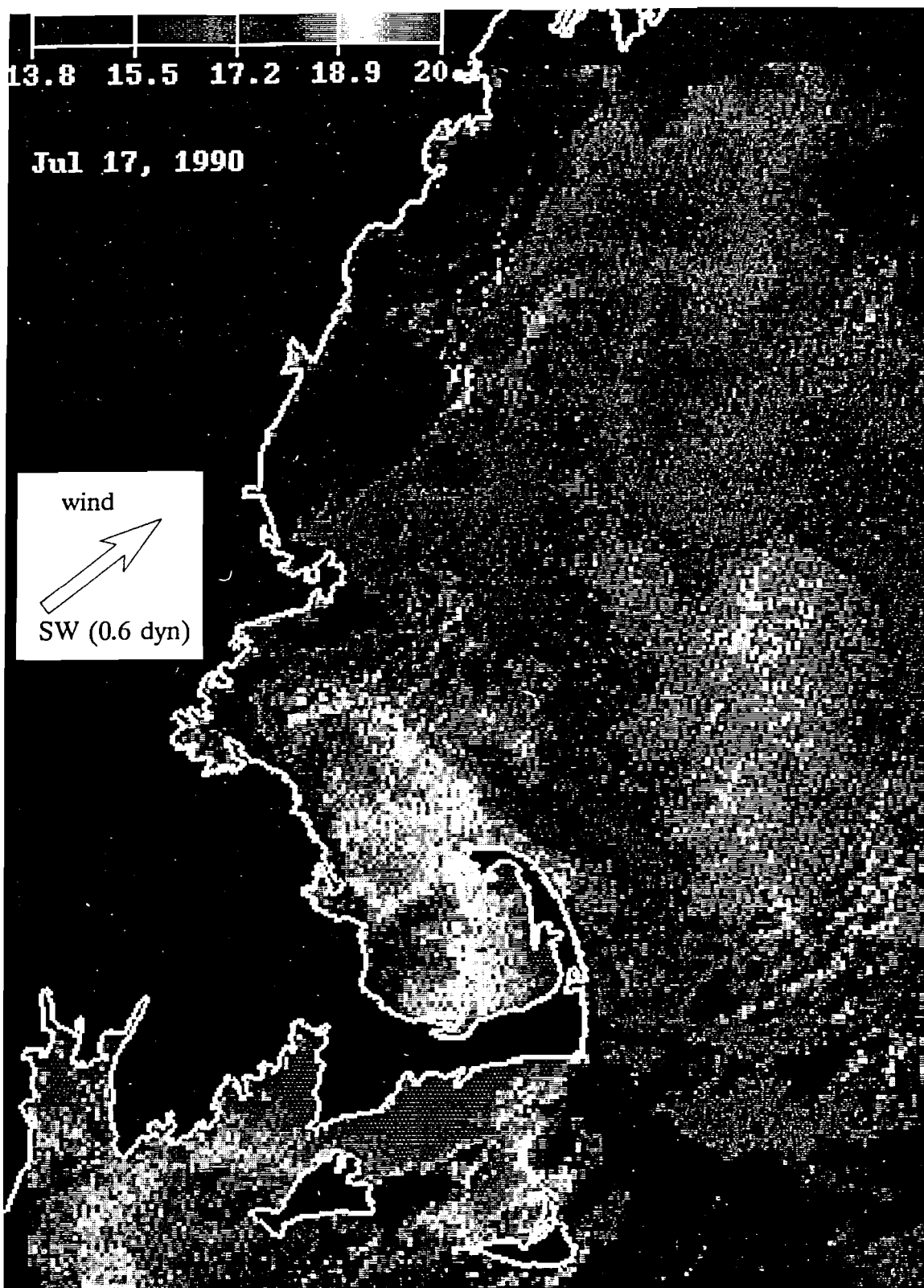


Figure 6. Satellite image of upwelling, July 17, 1990. Moderate wind forcing from the SW produced strong upwelling in northern Massachusetts Bay and western Cape Cod Bay. Based on the moored temperature data at Broad Sound, this was the strongest upwelling event of the year.

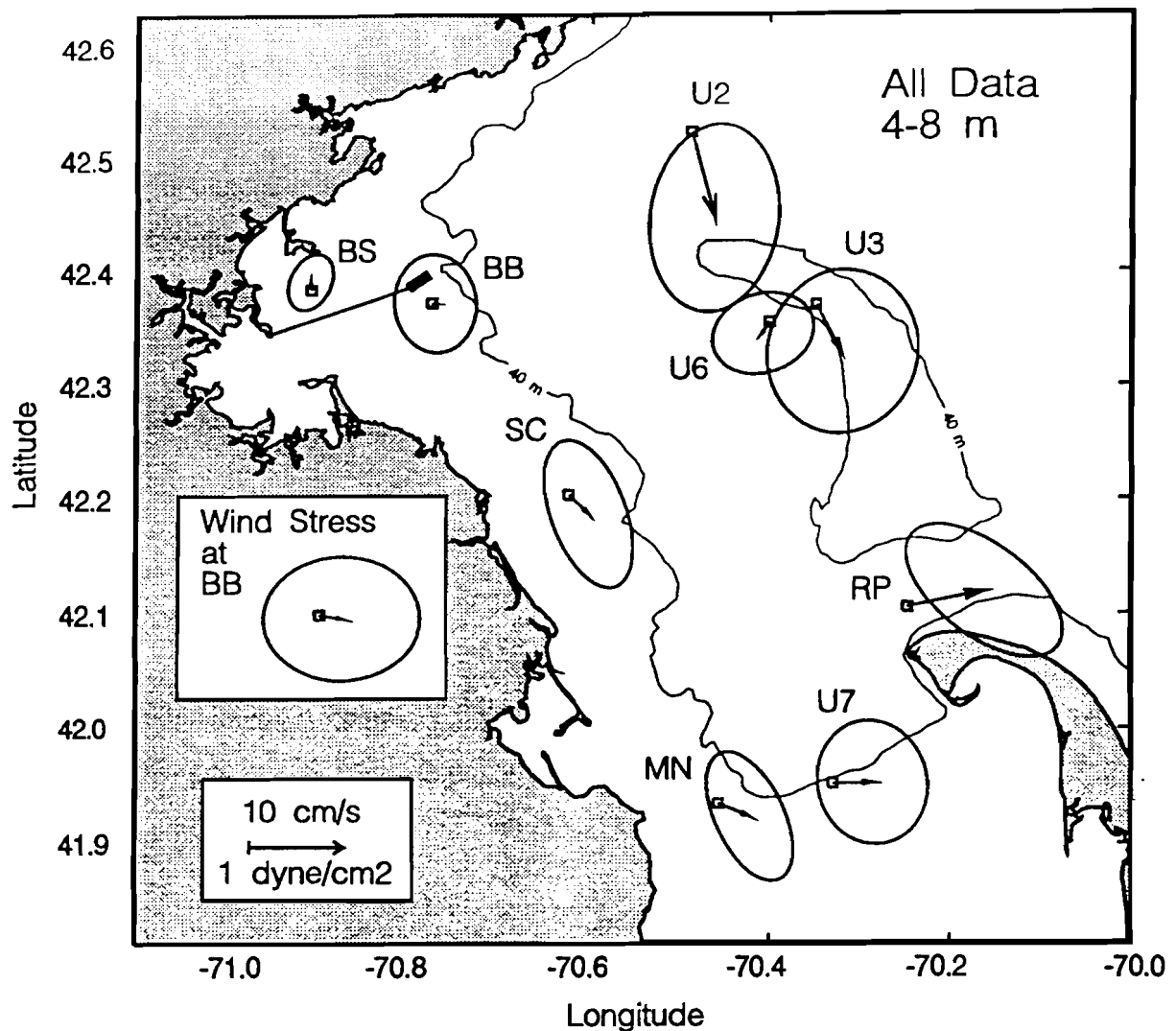


Figure 7a. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) for all near-surface (4–8 m depth) current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates at the 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.

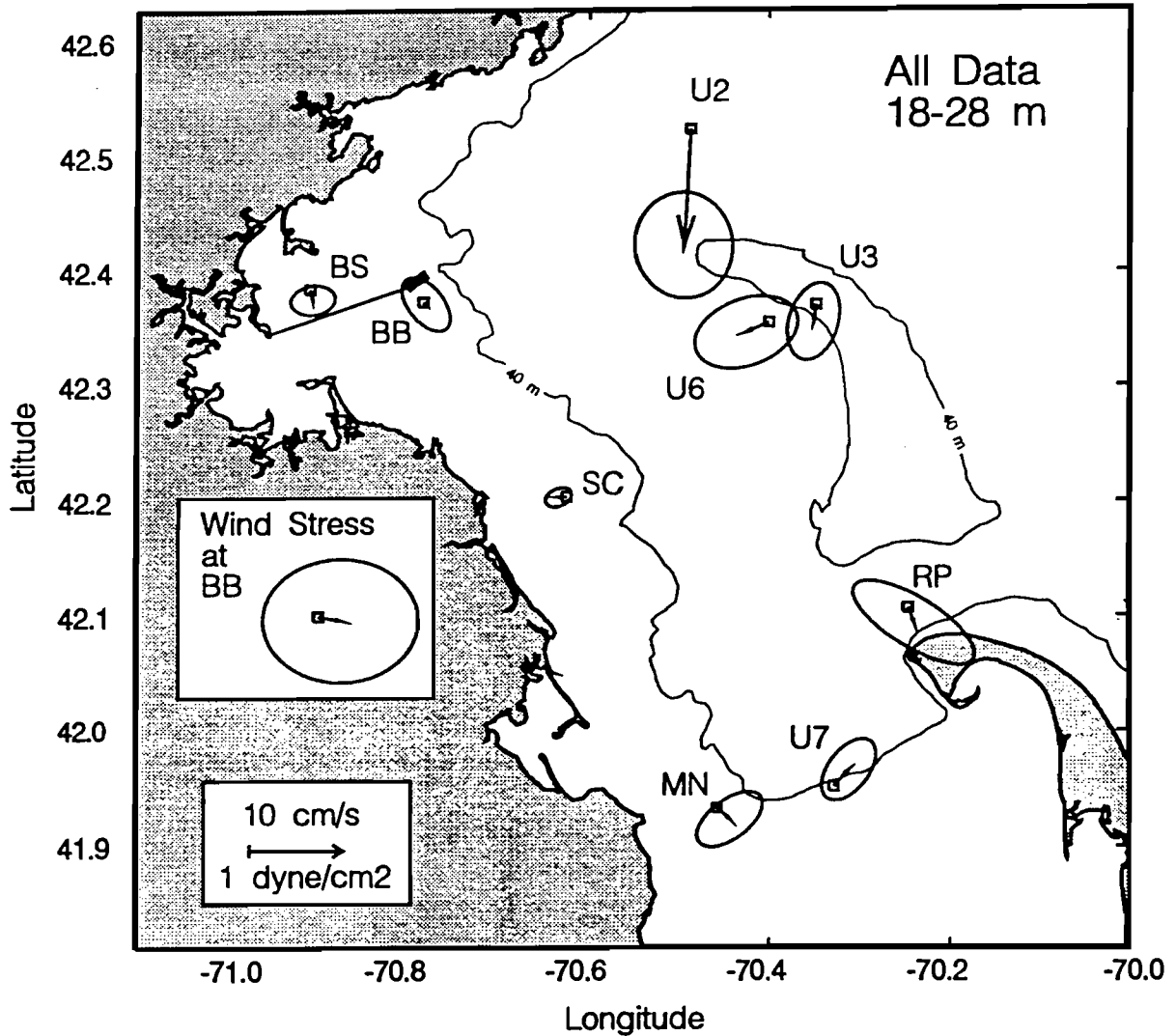


Figure 7b. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) at depths between 18 and 28 m from the surface for all current measurements made from December 1989 to September 1991. Typically, the daily-averaged current 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. Note that the strong flow to the east out of Massachusetts Bay at station RP at 4–8 m does not occur at 18–28 m.

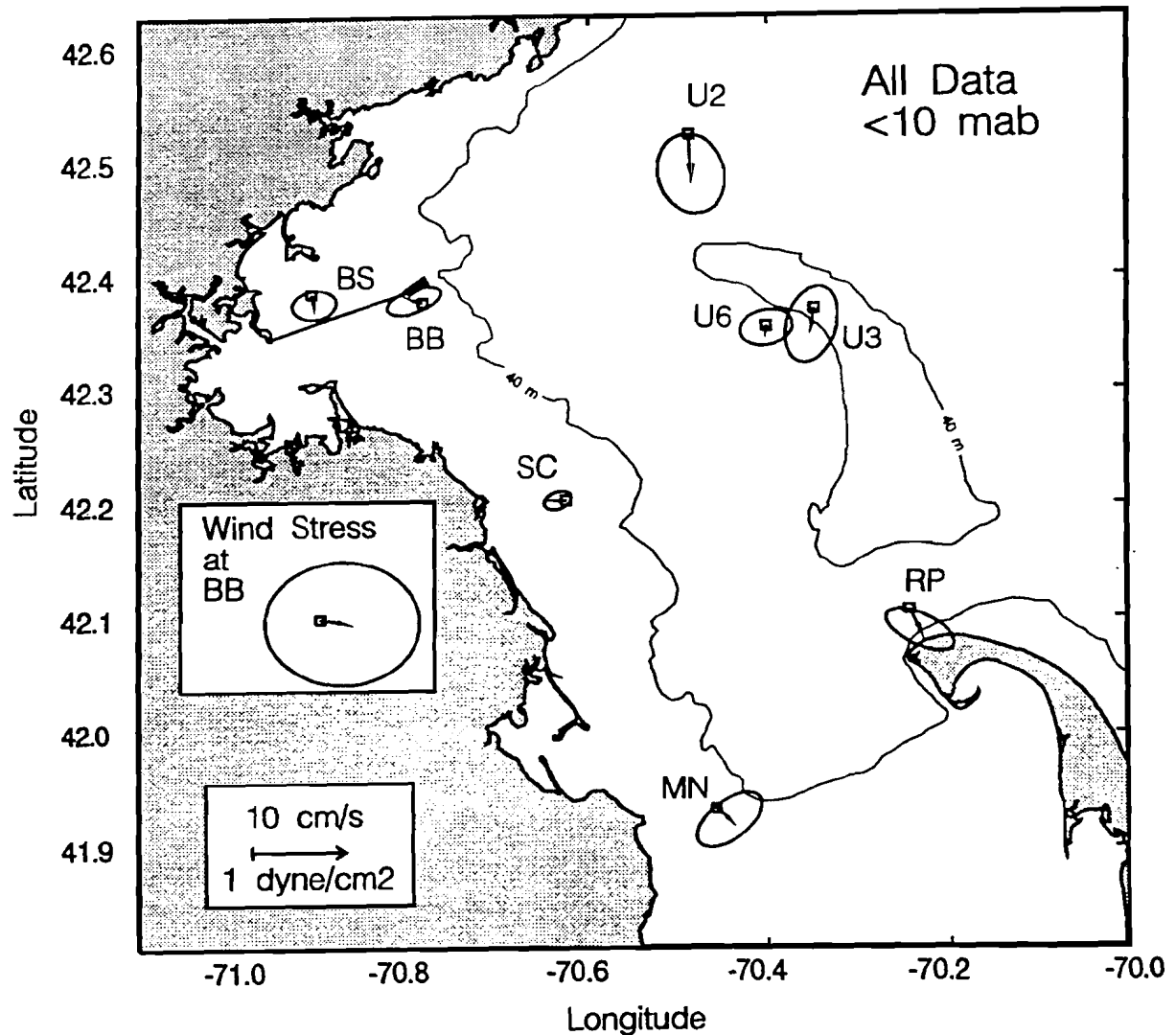


Figure 7c. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) at depths within 10 m of the bottom for all current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates 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.

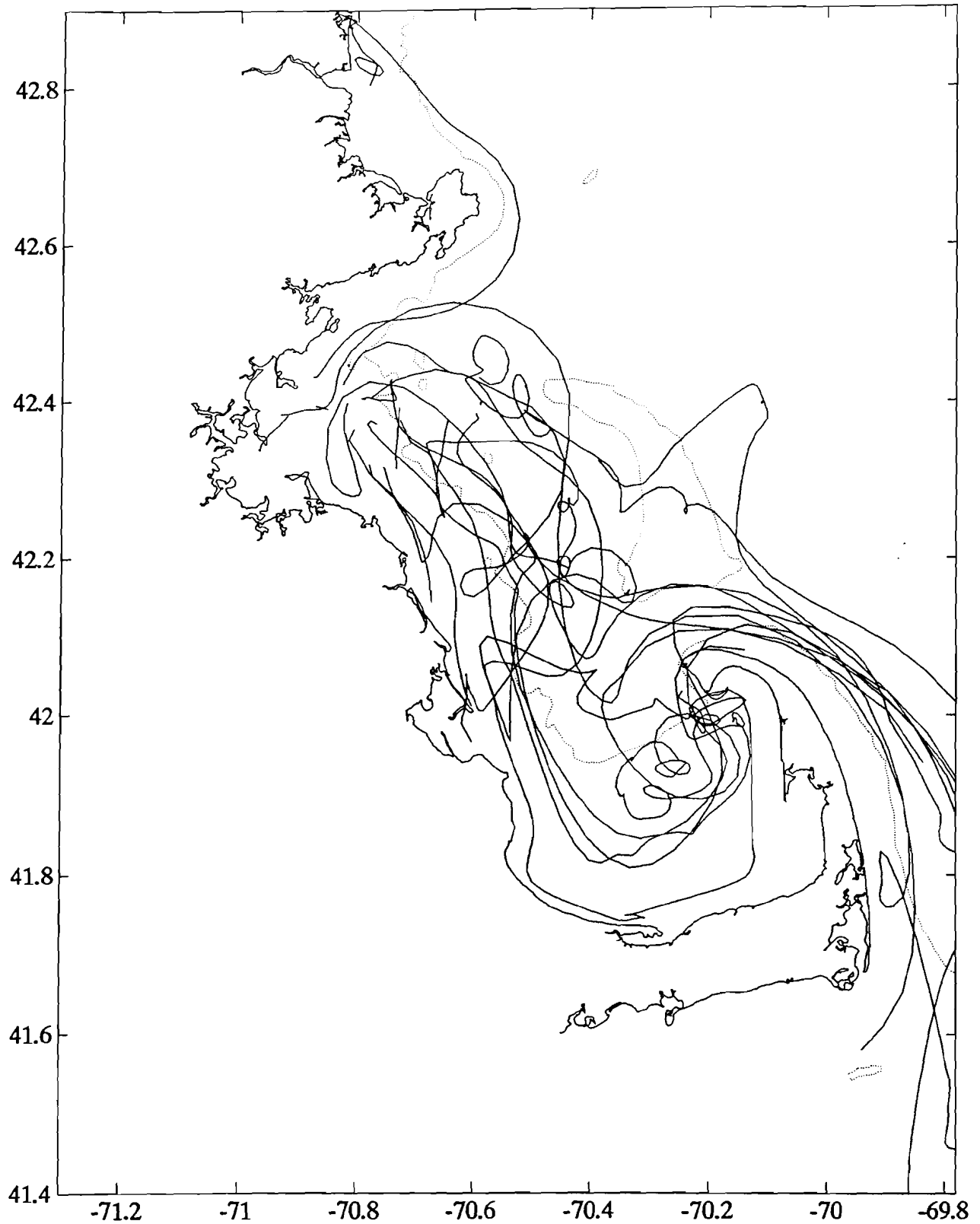


Figure 8. Composite of trajectories of all of the drifters released during the Massachusetts Bays Program. All but one of the drifters was released in Massachusetts Bay or the northern portion of Stellwagen Basin. One drifter was released off the mouth of the Merrimack River. Note that nearly all of the drifters exited the Bays just north of the tip of Cape Cod.