FINAL REPORT

SEASONALITY OF OCEANOGRAPHIC CONDITIONS IN MASSACHUSETTS BAY

Prepared by:

David W. Townsend
Leon M. Cammen
John P. Christensen
Steven G. Ackleson
Maureen D. Keller
Elin M. Haugen
Susannah Corwin
Wendy Korjeff Bellows
Jeffrey F. Brown

Bigelow Laboratory for Ocean Sciences
McKown Point
West Boothbay Harbor, Maine 04575

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Massachusetts Water Resources Authority
100 First Avenue
Charlestown Navy Yard
Boston, Massachusetts
02129

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INTRODUCTION:

The Massachusetts Bay system is located in the western Gulf of Maine and is bounded by Cape Ann to the north, Cape Cod to the south and east and Stellwagen Bank to the west; it includes Massachusetts Bay and Cape Cod Bay as well as several smaller embayments including Boston Harbor. The Massachusetts Water Resources Authority (MWRA) is planning to relocate the discharge from its sewage plants to a site in Massachusetts Bay, approximately 9 miles east of Deer Island (42°23'03"N, 70°48'13"W to 42°23'19"N, 70°46'48"W). Aside from the expected shift in pollutants from Boston Harbor into Massachusetts Bay, there will also be an increase in the delivery of inorganic nutrients directly to the Bay.

Bigelow Laboratory was awarded a contract by the MWRA to conduct a series of six cruises to the area in 1989-1990 to collect a suite of relevant environmental data from each season. We proposed to use these data to describe the average conditions and spatial variability in hydrography, nutrient and dissolved oxygen concentrations, phytoplankton community structure and productivity, plankton biomass, and the light regime in an area encompassing the mouth of Boston Harbor out beyond Stellwagen Bank. The overall goal of this project was to provide high-quality oceanographic data from Massachusetts Bay to be used in future ecological and remote sensing modeling efforts to predict the effects of the proposed sewage outfall and to provide baseline data for future comparison.

Our stations were selected to address the requirements in the Request for Proposals issued by the MWRA, but in addition, we designed a grid system of stations to allow for a more detailed spatial analysis of the distributions of the various water column properties. All the parameters and variables we measured either affect, or are products of, primary production by phytoplankton. Measurements of the concentrations of inorganic nutrients (nitrate, nitrite, ammonium, silicate and phosphate) are needed to interpret vertical light profiles and biomass standing stocks in relation to measures of photosynthesis and P vs. I curves. Measures of particulate organic carbon and nitrogen concentrations with

phytoplankton pigment, cell size and cell concentration data can be used to evaluate the total water column biomass. These can in turn be used in future modelling efforts with the nutrient data, *P* vs. *I* curves, and light profiles to arrive at total primary productivity estimates for Massachusetts Bay, both vertical throughout the water column and areally throughout the region.

The purpose of this final report is three-fold: 1) to summarize the results of our six cruises in Massachusetts Bay (24 October 1989, 6 February, 6 March, 10 April, 5 June and 14 August 1990); 2) to highlight important findings; and 3) as a result of our work, to recommend further study in several key areas. The detailed results our work are given in three earlier technical reports (Townsend *et al.*, 1990a,b,c).

1. Summary of Results

Our results show that Massachusetts Bay is in many ways typical of the coastal waters of the Gulf of Maine in that it experiences the classical seasonal oceanographic patterns first discussed in detail by Henry Bigelow (1926, 1927). It is atypical in that there are already clear signs of anthropogenic influences on the biological oceanography, particularly for the more nearshore waters off Salem and Boston Harbors.

As expected, we found the water column in February of 1990 to be well mixed as a result of winter convective overturn. Nutrient concentrations were high throughout the area and the spring phytoplankton bloom was not yet underway. It was with great interest that we encountered nitrate concentrations higher than expected (ca. 14 μM) at our northeastern stations in February, and we offer in this report one possible explanation that suggests an influx of high nutruient waters from the north of Cape Ann (see p. 75).

The subsequent pair of cruises, in March and April of 1990, documented the spring phytoplankton bloom, which was well underway in March with chlorophyll *a* concentrations in excess of 4 $\mu g\ L^{-1}$, despite the lack of vertical stratification of the water column. This early bloom was not unusual, since the spring bloom in Gulf of Maine coastal waters can begin as early as February, depending on water depth and cloud cover (Townsend and Spinrad, 1986). Late winter-early spring phytoplankton blooms may commence in the absence of vertical stratification if the critical depth is deeper than the bottom, or conversely, if the vertical mixing rate of the water column is sufficiently slow in relation to the growth rate of the phytoplankton cells such that positive growth is possible in the well-illuminated

upper water column. We suspect that the early bloom we witnessed was the result of a combination of these two phenomena. By April, the water column was starting to stratify and phytoplankton chlorophyll *a* concentrations were beginning to decline in the inner bay. There was some indication of low salinity waters entering Massachusetts Bay from the north, which likely resulted from spring runoff from the Merrimack River and the other rivers further north, which had likely not yet reached their peak. We saw evidence of sinking phytoplankton bloom material at some of the stations in April, indicated by *in situ* flourescence spikes at depth which we interpreted to be the result of sinking diatom flocs, while in the surface waters we saw smooth fluorescence traces that represented the beginning of the summer dinoflagellate populations.

Early summer conditions were becoming established in June, with the seasonal thermocline continuing to develop and the surface nutrient concentrations nearing depletion. Phytoplankton chlorophyll *a* concentrations were still high at the inner stations and may have been in response to nutrient loadings from the vicinity of Salem as well as Boston Harbors. The water column was vertically well-stratified in August. The offshore surface waters were depleated in nutrients, particularly nitrate, and the phytoplankton chlorophyll *a* concentrations were relatively low, suggesting that nitrate, rather than silicate, limits phytoplankton production in the surface waters. There was, however, a well developed subsurface chlorophyll maximum offshore, representing dinoflagellate populations. Chlorophyll concentrations remained high in August throughout the inner stations, especially nearer Boston Harbor. The apparent influence of Salem Harbor was more evident in August, as seen in the distributions of light transmission and fluorescence, which show a plume-like turbid water feature extending into Massachusetts Bay.

Conditions in October of 1989 showed the initiation of autumn vertical mixing, with only weak thermal stratification present throughout the area, elevated surface nutrient concentrations, and increased surface chlorophyll *a* concentrations, typical of a fall phytoplankton bloom. Our results for October also showed more clearly an important transition zone in Massachusetts Bay that occurred roughly between our Stations 8 and 9 (Fig. 1). Shoreward of this point, the water column was fresher and more turbid, and phytoplankton levels were relatively low, despite enriched ammonium and silicate levels. The turbid conditions appear to have sufficiently reduced the water clarity so as to light-limit photosynthesis. This transition zone was apparent at other times of the year, but it was not as well defined; it is important because it situated very near the proposed sewage outfall.

2. Recommendations

There were several findings of this research we feel are significant. It is difficult to catagorize them as either being important for purely scientific reasons or as having a more direct bearing on the proposed relocation of Boston's sewage outfall further out into Massachusetts Bay. Nonetheless, each is significant to the biological oceanography of Massachusetts Bay and is worthy of further study. First, the nature of the transition zone, as alluded to in the previous section, should be investigated more fully with respect to mechanisms controlling its maintenance and temporal varibaility, and the dynamics of residual flows within and on either side of it. These processes are important to the biological oceanography of the inner Bay. Our results would suggest that much of the materials introduced from Boston Harbor are constrained within the coastal area bounded by this transition zone, and are transported toward the south rather than out into Massachusetts Bay. Second, the influence on biological processes of waters entering Massachusetts Bay from the vicinity of Salem Harbor and from the north of Cape Ann, including surface freshwater plumes and introductions of deep water that may be very rich in inorganic nutrients, should be examined further. We have drawn attention in later sections of this report to the possibility that a "nutrient trap" might be operating in the Bigelow Bight area of the western Gulf of Maine, which could be delivering high loads of nutrients to Massachusetts Bay, possibly as episodic influxes of deep water from the north. The magnitude, episodic nature, and interannual variability of this process should be studied as part of a field and modelling program that encompasses a significant portion of the western Gulf of Maine. Third, we have seen evidence suggestive of sinking of diatom aggregates following the spring phytoplankton bloom. The magnitude of this flux is not known. We suspect that this sinking biomass significantly affects the benthos, and the nature of this process, in view of future changes in the nutrient dynamics of the central Bay, may be very important. Fourth, the nature of particulate and dissolved materials as each affects primary production through the attenuation of light may be important in the new outfall area. We observed increased light attenuation due to dissolved materials near the entrance to Boston Harbor, but clearer waters further out into the Bay, depending on the exact location of the transition zone we just discussed. Finally, we recommend that the data made available through the efforts reported on here be integrated with the ongoing physical oceanographic studies in Massachusetts Bay, and that the combined sets of data be used to construct a coupled biological-physical model of Massachusetts Bay and that every effort be made to integrate it within a larger Gulf of Maine model.

MATERIALS AND METHODS:

Not all of the data we collected are presented in this report; however, we are presenting the details of the each of the methods we employed in each of our cruises in order to provide the reader with a sense of the quantity and quality of data available. Six research cruises were made in Massachusetts Bay aboard the Research Vessel *ARGO MAINE* on 24 October 1989, 6 February, 6 March, 10 April, 5 June and 14 August 1990. For each cruise the ship departed the Bigelow Laboratory in Boothbay Harbor, Maine, on the afternoon preceeding the sampling day and work began in Massachusetts Bay early the following morning. All stations were completed by 2000 EST the same day. The locations of the stations are given in Figure 1. The station positions and analyses performed at each were as follows:

Transect	Station	Latitude	Longitude	Type	Approx. Depth (m)
1	1	42° 34.6	70° 24.5	N	148
	2	42° 33.1	70° 30.3	H	70
	3	42° 31.8	70° 36.3	N	63
	4	42° 30.4	70° 42.5	H	51
	5	42° 29.1	70° 48.4	N	24
2	6	42° 21.0	70° 56.4	P	7
	7	42° 22.3	70° 50.3	P	28
	8	42° 24.1	70° 44.5	P	47
	9	42° 24.9	70° 38.2	N	78
	10	42° 26.5	70° 32.0	P	48
	11	42° 27.6	70° 25.8	N	68
	12	42° 29.0	70° 19.6	P	153
3	13	42° 22.1	70° 14.8	N	49
	14	42° 21.3	70° 19.5	H	27
	15	42° 19.9	70° 25.8	N	86
	16	42° 18.4	70° 32.9	H	74
	17	42° 17.1	70° 39.1	N	28
	18	42° 15.9	70° 45.0	N	21

Three types of stations were occupied:

1) Hydrography (H) -- a CTD / *in situ* fluorometer / transmissometer cast only;

2) Nutrient (N) -- a CTD/*in situ* fluorometer/ transmissometer cast and bottle samples analyzed for nutrients, dissolved oxygen, spectral absorption, phytoplankton pigments, POC and PON; and

3) Productivity (P) -- all measurements and analyses listed for the Nutrient stations plus productivity (*P* vs. *I* curves), phytoplankton community structure, and zooplankton.

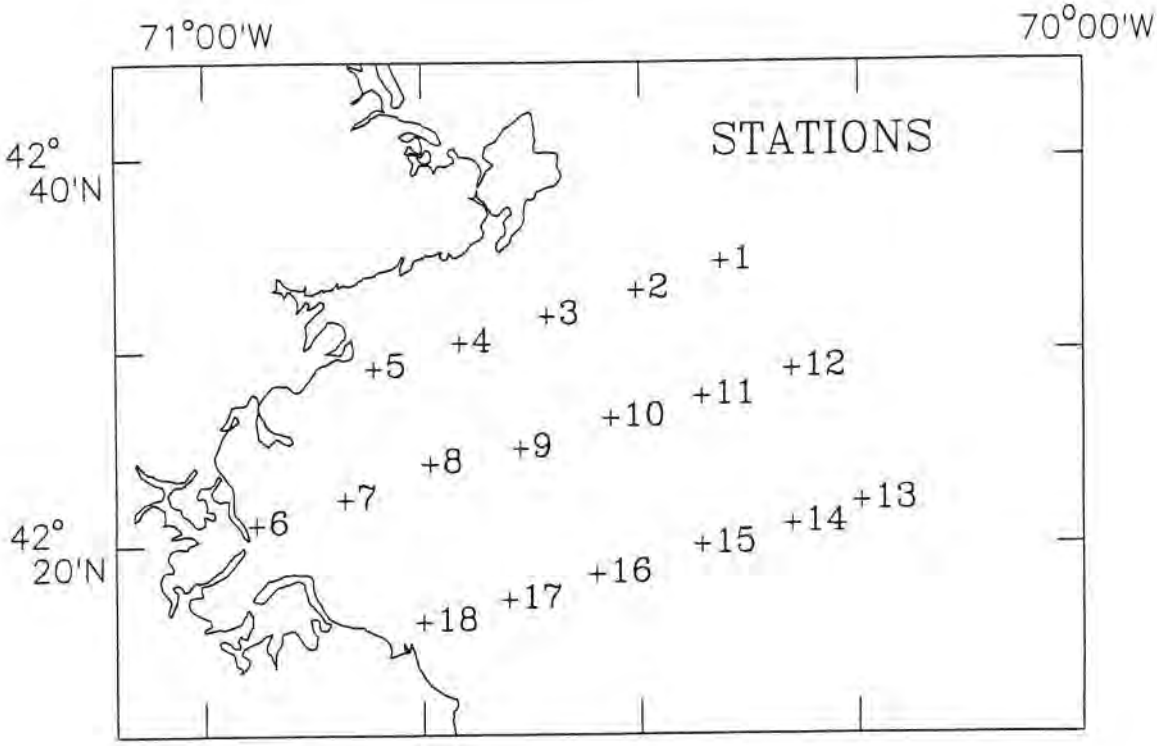

Figure 1. Station locations in Masschusetts Bay.

1. Hydrographic measurements

Continuous vertical profiles of salinity, temperature, *in situ* chlorophyll fluorescence, and beam attenuation were measured at each station using a Neil Brown Mark III CTD, equipped with a Sea Tech *in situ* fluorometer and 25-cm

path length transmissometer. All casts were made to within approximately 3 m of the bottom; data were recorded on the down cast only. The *in situ* fluorometer measures relative chlorophyll fluorescence and is set internally to read a range of approximately 0-10 μg chlorophyll *a* L^{-1}. These fluorescence values are presented as chlorophyll *a*, but they are only approximate; the reader should use only the extracted chlorophyll values (section 3 below). The CTD sensors were cleaned with a mild soap solution and rinsed with distilled water between casts. At some stations, water samples were taken on the up cast from the depths given in the Bottle Tables using a General Oceanics rosette water sampler and 5- and 10-liter Niskin bottles. Those samples were analyzed for nutrients, dissolved oxygen, spectral absorption of particulate and dissolved material, phytoplankton pigments, particulate organic carbon (POC), particulate organic nitrogen (PON), and flow cytometric measurements of phytoplankton. The CTD software "captured" and averaged 50 scans of data when the rosette bottles were closed; those values are presented in the bottle data tables.

The CTD was calibrated at the factory prior to the October 1989 cruise. Corrections for drift in the conductivity sensor for the other 5 cruises were made by adding or subtracting the salinity offset as determined from salinities measured on descrete water samples using a Guildline Model 8400 AutoSal bench salinometer standardized against Copenhagen water. Sigma-t was then calculated using the corrected salinities.

2. Nutrients and dissolved oxygen

Nutrient and dissolved oxygen concentrations were measured from the discrete bottle samples collected at the primary stations and at every other hydrographic station. The nutrient samples were frozen at sea and analyzed back at the laboratory. The nutrients -- nitrate, nitrite, ammonium, silicate, and phosphate -- were measured using a Technicon AA-2 5-channel autoanalyzer (Whitledge *et al.*, 1981, Codispoti and Christensen, 1985). Dissolved oxygen samples were taken in standard oxygen bottles and the concentrations titrated using the standard Carpenter method (Carpenter, 1965).

3. Chlorophyll a, POC, and PON

Vertical profiles of phytoplankton chlorophyll and pheopigments were determined fluorometrically (Parsons *et al.*, 1984) on each of the bottle samples by filtering 100 ml through a 25-mm GFF filter and extracting the pigments for at least 24 hrs in 90% acetone in the dark at -18°C in a freezer. POC and PON were collected by filtering 500 mls seawater from each bottle onto a

precombusted pre-ashed GF/F filter; the samples were frozen (-18°C) for later analysis. The filters were fumed with HCl to remove inorganic carbon and analyzed with a Control Equipment Model 240-XA CHN analyzer.

4. Particulate Material Analysis

A. Total Particulate Material (TPM)

Total particulate material (TPM) analysis was performed according to the methods outlined by Strickland and Parsons (1972). Watman GF/F filters were precombusted at 450°C for four hours and weighed to an accuracy of .01 mg using a Mettler balance (Model AE165). After precombustion and before weighing, filters were stored in a desiccator to prevent moisture absorption from the air. After weighing, each filter was then placed in a separate numbered plastic petri dish and the dish number and filter weights recorded.

Each TPM sample consisted of a .535 l sample volume passed through a tared Watman GF/F filter under low vacuum pressure. Sea salt was washed from each sample by passing 5-10 ml distilled water through the filter sample. After filtration, each filter was returned to its petri dish and the dish number, station identification, and sample depth recorded. Each filter was then stored frozen and dark until return to Bigelow Laboratory.

Filter samples were dried in an oven at 75 °C for 1 hour and removed to a desiccator. Each filter was then reweighed to .01 mg accuracy using the same Mettler balance. The dry weight of particulate material (TPM) was then computed using the formula

$$TPM = (W_2 - W_1)/VOL,$$

where W_1 is the tared filter weight (mg), W_2 is the dried sample filter weight (mg), and VOL is the volume of sample filtered (l). Results are expressed as mg/l.

B.Total Particulate Inorganic Material (TPIM)

Total particulate inorganic material was measured by combusting the weighed TPM filter samples at 450°C for four hours to oxidize all organic material and reweighing. The precombusted filters were stored in a desiccator prior to weighing. Total inorganic particulate material (TPIM), expressed in units of mg/l, was then computed for each filter sample using the formula

$TPIM = (W_3 - W_1)/VOL,$

where W_3 = the weight of the sample filter (mg) after muffling.

C. Total Particulate Organic Material (TOPM)

Total organic particulate material (TPOM) was computed using the formula:

$TPOM = TPM - TPIM$

where the units are mg/l.

D. Flow Cytometry

Size distribution and counts of phytoplankton were measured from water samples collected at all productivity stations. In each case, 1-litre sample volumes were collected and passed through 190 μm Nitex screen to remove zooplankton and stored cold and dark in 1-litre PVC containers. Flow cytometric analysis was performed immediately following the cruise, approximately 24 hours after sample collection.

In preparation for flow cytometric analysis, each sample was mixed and partitioned into a 20 ml volume and a 980 ml volume. The 980 ml volume was then filtered to .4 μm and used as the flow cytometer sheath fluid for the sample. This was necessary because the salinity of the sheath fluid must match the salinity of the sample in order to correctly measure coulter volume. Approximately 5 ml of the unfiltered sample volume was then passed through a 20 μm Nitex screen and into an analysis tube. The tube was then weighed to an accuracy of .01 mg using a Mettler balance (Model AE165). The sample was then attached to a Beckton Dickenson FACS Analyzer flow cytometer (FACS) and 2500 particles were analyzed. The FACS measured particle volume (using the electrical impedence technique), chlorophyll fluorescence, and side scatter. Particle counts were gated on chlorophyll fluorescence to yield phytoplankton cell counts. Immediately after analysis, the sample tube was reweighed and the volume of sample analyzed computed. Phytoplankton cell concentration was computed and recorded in units of #/μl. Mean cell volume (fl = μm^3) was computed and the total cell volume was recorded in units of fl/ml.

5. Optical measurements

During each cruise the following suite of optical measurements were collected: particulate absorption, dissolved material absorption, vertical profiles of beam attenuation (λ = 660 nm) and PAR, and Secchi depth. Absorption measurements were performed on all water samples collected at nutrient and productivity stations, beam attenuation was measured at all stations, PAR was measured at all productivity stations and, when time permitted, at nutrient stations occupied during the daylight hours, and Secchi depth was measured at all stations occupied along the center transect (stations 6 through 12).

A. Particle Spectral Absorption

Each absorption sample consisted of a 535 ml volume passed first through a 190 μm Nitex screen to remove large and optically rare particles and then through a Watman GF/F glass fiber filter using low vacuum pressure. Filters were then placed, face up, in separate plastic Millipore petri dishes and immediately stored within a dark freezer. As each filter sample was placed within a petri dish, the dish was marked with a number identifying the station location and sample depth. Upon return to Bigelow Laboratory, a Bauch and Lamb Spectrometer 2000 was used to measure the spectral transmittance [$T(\lambda)$] of each filter at 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 650 nm, 660 nm, 700 nm, and 750 nm following the method of Mitchell and Kiefer (1988).

A clean Watman GF/F filter, wetted with 0.2μm filtered sea water, was used as a sample reference. Prior to measurement, filter samples were removed from storage and allowed to thaw for 5 minutes in the dark. Filters were then secured to the spectrometer filter holder and the back of the filter wetted with several drops of 0.2μm filtered sea water. Spectral transmittance, relative to the clean filter, was then recorded to three significant digits at each wavelength. Particle absorption coefficient, $a_p(k)$, was then computed at each wavelength using the formula

$$a_p(k) = -\ln(T(k)/T_{750}) \cdot 100\pi r^2/(\beta\ VOL), \qquad [1]$$

where T_{750} is the sample filter transmittance at 750 nm, r is the radius of the used portion of the filter (1 cm) and VOL is the volume filtered (ml). The constant 100 is a factor which converts cm^{-1} to m^{-1}. The method assumes that the filter pad transmittance is monochromatic and that particle absorption at 750 nm is negligible. The term ß is an absorption amplification factor which accounts for the increase in optical path length within the GF/F filter due to light scatter

(Kishino *et al.*, 1985; Mitchell and Kiefer, 1988; Mitchell, 1990) and is defined as the ratio

$$ß = a_p/a_{ps} \quad [2]$$

where a_{ps} is the absorption coefficient for an identical concentration of material suspended within water. Unfortunately, ß could not be measured during any of the Massachusetts Bay cruises because space requirements on the *R/V ARGO Maine* and demand for the spectrometer at Bigelow Laboratory prohibited taking the instrument to sea. Had samples been stored for measurements at Bigelow Laboratory, it was feared that the optical properties of the particulate material, a large portion of which was phytoplankton and bacteria, would have changed enough to introduce large errors in measurement of a_p and a_{ps}. Published data indicates that ß ranges between 1 and 2.5 and decreases as the concentration of material deposited on the filter increases. Mitchell (1990) concluded that for GF/F filters,

$$ß = [.415 + .69\ a_p]^{-1} \quad [3]$$

Applying Eqn. [3] to the Massachusetts Bay data results in ß-values between 1.2 and 2.4. However, unpublished experiments at Bigelow Laboratory indicate that with sufficiently large concentrations of material deposited on the filter, enough to produce an obvious color change to the eye, ß is nearly 1 (D. Phinney and J.P. Cullen, personal communication). Since this was the case with all samples, and since the conclusions of Phinney and Cullen pertain to the same instrument used to analyze all of the Massachusetts Bay samples, it is assumed that ß=1 in all cases.

B. Dissolved Material Absorption

From each water sample collected, 100 ml sub-samples were drawn, passed through a 190 μm Nitex screen, and stored cold and dark in 100 ml PVC sample bottles for analysis of spectral absorption of dissolved materials (a_d). Upon completion of the cruise, each sample was filtered through a clean GF/F filter to remove all particulate material and spectral transmittance measured using a Bauch and Lamb Spectrometer 2000 equipped with a matched pair of 10 cm path length quartz cuvettes. Using a standard of distilled water, sample transmittance was measured to an accuracy of 0.1%, which translates to an absorption resolution of 0.01 m^{-1}. A portion of the filtered sample, approximately 10 ml, was used to condition the cuvette with three rinses and the remainder used for the analysis.

Dissolved material absorption was then computed at 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 670 nm, and 700 nm:

$$a_d(k) = -\ln[T(\lambda)/T(750)]/0.1 \quad [4]$$

C. Beam Attenuation

Beam attenuation was measured using a Sea Tech transmissometer. This instrument measures beam transmittance at 660 nm over a path length of 0.25 m. Before each measurement, the optical surfaces of the instrument were cleaned with a mixture of soap and distilled water and rinsed with distilled water. Before and after the cruise, an air calibration was performed in order to monitor the performance of the instrument. Beam attenuation, c, was then computed using the formula

$$c = -\ln(V_1/5 \cdot V_2/V_3)/0.25, \quad [5]$$

where V_1 is the *in situ* voltage reading, the factor 5 is the full-scale *in situ* transmission voltage and V_2 is the factory air calibration voltage (4.741). The average of the pre- and post-cruise air calibration (V_3) for each cruise was as follows: October = 4.630 volts; February = 4.600 volts; March = 4.590 volts; April = 4.585 volts; June = 4.570; and, August = 4.440. Beam attenuation was recorded as m^{-1}.

D. Photosynthetically Active Radiation (PAR)

Vertical PAR profiles were measured at all productivity stations during all cruises using a Li-Cor submersible spherical radiometer (except the October 1989 cruise, when we did not have the radiometer). The diffuse PAR attenuation coefficient (k_{PAR}) was computed for all cruises as discussed below.

The Li-Cor submersible spherical radiometer measures the integrated downwelling and upwelling scalar irradiance over the entire visible light spectrum (400-700 nm). Light units presented within this report are μMole·m^{-2}·s^{-1}. This quantity is referred to as photon flux density (PFD).

Upon arrival at each productivity station during the last 5 cruises, the ship was turned stern first into the sun and the Li-Cor was lowered by hand off the stern by 1 m increments. PFD was recorded at each depth (PFD_Z). Simultaneously, surface PAR was measured using a Biospherical radiometer, positioned in the sun atop the wench control house. Surface PAR (PFD_O) was recorded coincident

with PFD_Z and used to remove variations in the subsurface light field due to changes in the surface illumination. From vertical profiles of PFD_Z, diffuse PAR attenuation coefficient (k_{PAR}) was computed:

$$k_{PAR} = -\ln(PFD'_2/PFD'_1)/(z_2-z_1), \quad [6]$$

where the subscripts 1 and 2 indicate two different depths in meters (z positive down) and $PFD' = PFD_Z/PFD_O$. The depth of the 1% surface PAR (z_{PAR}) was recorded in meters, depending upon the station water depth.

Diffuse attenuation coefficient of photosynthetically active radiation (k_{PAR}) and the 1% surface light intensity depth (z_{PAR}) was modeled at each station from measurements of spectral particle absorption [$a_p(k)$] and spectral absorption by dissolved materials [$a_d(k)$], published values for spectral absorption by clear water [$a_w(k)$] (Smith and Baker, 1981), and total light scatter at 660nm [b_{660}]. Diffuse attenuation [$k_d(k)$] at several wavelengths representing the visible light spectrum (400nm, 450nm, 500nm, 550nm, 600nm, 650nm, and 700nm) was first computed using the relationship

$$k_d(k) = [a(k)^2 + (.425\imath - 0.19)a(k)b_{660}]^{0.5} \cdot \imath^{-1} \text{ (Kirk, 1988[)} \quad [7]$$

where

$$a(k) = a_w(k) + a_p(k) + a_d(k)$$
$$b_{660} = c - a_{660}$$
$$\imath = 0.8$$

The average cosine, $\imath$, describes the distribution of downwelling radiance and is considered within this treatment to be constant. In general, $\imath$ will change with illumination conditions, depth, and the magnitude of a and b. Field measurements of $\imath$, however, indicate a reasonably narrow range of values, 0.7 - 0.9 (Philpot, 1981; Stavn, 1988). A value of 0.8 resulted in the best correlation between measured and computed k_{PAR}. It is also assumed that light scatter computed at 660nm is a reasonable approximation for light scatter at all other wavelengths of visible light. Using a standard surface solar irradiance distribution for a clear sky [$E_o(k)$] (Gast *et al.*, 1965), subsurface downwelling irradiance intensity [$E_z(k)$] was computed at each sampling depth and for each wavelength using the relationship

$$E_z(k) = E_o(k)[1-R_s] \cdot e^{-kd(k)z} \quad [8]$$

where:

R_s = Surface Fresnel reflectance with sun directly overhead (R_s = 0.027)
z = water depth (m).

Total downwelling irradiance, $E_{PAR}(z)$, was then computed as the sum of irradiance at each wavelength, and k_{PAR} computed as

$$k_{PAR} = -\ln[E_{PAR}(z_2)/E_{PAR}(z_1)]/(z_2 - z_1). \quad [9]$$

The 1% surface light intensity depth, z_{PAR}, was then computed as

$$z_{PAR} = z_1 - \ln[E_{PAR}(z_1)/(0.1\ E_{PAR}(0+))]/k_{PAR}(z_2) \quad [10]$$

where the sample depths z_1 and z_2 bracket z_{PAR} and $E_{PAR}(O+)$ is the above surface PAR.

E. Secchi Depth (Z_S)

At each station located along the center transect, secchi depth was measured and recorded in meters. A 30 cm white disk was lowered off the sunny side of the ship to a depth there it was no longer distinguishable. The disk was then raised until visible and the depth recorded.

6. Primary productivity: Photosynthesis vs. irradiance (P vs. I)

Measurements of photosynthesis as a function of irradiance (P vs. I) were obtained using the methodology of Lewis and Smith (1983), and a "photosynthetron", which is a self-contained, temperature-controlled incubator with its own light source. Twenty-four different irradiance levels are produced with neutral density filters for each sample; this number is sufficient for acceptable statistical analysis taking into account data variance and photoadaptive state (Zimmerman *et al.*, 1987).

Water samples were pre-screened through 190 μm-Nitex mesh into rinsed 250-mL polycarbonate bottles and held at or near *in situ* irradiances and temperature until processed (which was within minutes of collection of the water samples). A subsample was placed in a 30 ml polycarbonate tube, spiked with ^{14}C bicarbonate (final activity ca 5 μCi per ml) and then dispensed in 1-mL aliquots into 24 vials in the manifold of the photosynthetron (and one vial containing 50-μL formalin to provide an initial blank). The exact amount of label added was determined by

subsampling into 7 mls of scintillation fluor plus 0.2 ml phenethylamine. Samples were incubated for 30 min, then preserved with 50-μl buffered formalin and returned to the lab for processing. The vials were acidified with 250 μl 6N HCl and placed on a shaker table for several hours to eliminate unutilized ^{14}C. Scintillation cocktail (Ecolume, ICN) was added and the samples were counted on a Beckman LS7500 scintillation counter.

The P vs. I curves were generated at five stations (Stas. 6, 7, 8, 10 and 12) as shown in Figure 1. Samples were taken at three depths: surface, at the chlorophyll maximum (or at 10% incident sunlight), and at the 0.5% incident sunlight depth, except for stations 6 and 7 where water column depth and irradiance indicated sampling only at the surface, and surface and chlorophyll maximum, respectively.

The photosynthesis vs irradiance equation of Platt *et al.* (1980) was used to model photosynthesis as a function of light:

$$Pi = Ps \cdot 1\text{-}e^{-aI/Ps} \cdot e^{-bI/Ps}$$

where Pi = instantaneous rate of photosynthesis normalized to chlorophyll *a* at PPFDi (photosynthetically active photon flux density; $\mu mol \cdot m^{-2} \cdot sec^{-1}$). The realized maximal rate of photosynthesis, P_{max} ($g C \cdot g chla^{-1} \cdot h^{-1}$) was calculated using the following equation (Platt *et al.*, 1980):

$$P_{max} = Ps \cdot [a/(a+b) \cdot b/(a+b)]^{(b/a)}$$

where Ps is the maximum rate of photosynthesis in the absence of photoinhibition, a = initial slope of the P-I curve; and b = parameter chosen to characterize the degree of photoinhibition. The error associated with P_{max} was determined according to the principles described by Zimmerman *et al.* (1987).

Parameters were fit simultaneously using the multivariate secant method (Ralston and Jennrich, 1978) of the NLIN procedure of SAS (SAS Institute, Inc., 1985). For fitting the data, the intercept Po was included as a parameter and subsequently subtracted from estimates of Pi as one would do with a dark bottle value (although Po should not be considered a reliable measure of respiration). Productivity vs. irradiance analyses were performed by John Cullen of the Bigelow Laboratory.

7. Phytoplankton community structure

Whole water samples were taken at each Productivity station from the rosette water sampler and filter-fractionated as showm in Table 1. Additionally, a vertical net tow (25 μm mesh) from the 0.5% light level to the surface was taken to sample less-common larger cells; these samples were preserved in Lugol's iodine solution.

Epifluorescent microscopy enumerations of the phytoplankton and heterotrophic microplankton were used to estimate size-fractionated biomass of various taxa (Haas, 1982; Murphy and Haugen, 1985; Booth, 1987; Shapiro and Haugen, 1988). Two 250-mL subsamples for quantitative phytoplankton analysis were preserved immediately with 50% glutaraldehyde to a final concentration of 0.5%. In the laboratory, one aliquot of each was treated with 0.03% proflavine hemisulfate, a fluorochrome that enables epifluorescence microscopy to be used to observe organelle details and to distinguish heterotrophic (non-photosynthetic) microorganisms from photosynthetic cells (Haas, 1982). Stained subsamples were serially filtered through 8 μm, 3-μm, and 0.2-μm Nuclepore polycarbonate filters. The >8-μm and 3-8-μm size fractions were enumerated for chlorophyll-dominant cells and heterotrophic eukaryotes using a Zeiss Axiomat microscope equipped with a Zeiss epifluorescence system. Additionally the chlorophyll-dominant cells were separated, where possible, into major taxa or color groups, e.g. diatoms, dinoflagellates, coccolithophores, cryptomonads, and phytoflagellates; cells comprising greater than 1% of the population were identified to genera or species, if possible. An unstained aliquot was serially filtered through a 3 μm and 0.2-μm filter set to obtain quantitative counts of chlorophyll-dominant eukaryotic ultraplankton, and the phycoerythrin-dominant cyanobacteria (photosynthetic prokaryotes), using the same epifluorescence system. No attempt was made to distinguish heterotrophic microflagellates in the smallest fraction due to stain interference and time constraints. Less common larger cells, collected with vertical 25 μm-mesh net tows from the 0.5% light level to the surface and preserved with Lugol's solution, were enumerated and identified to the lowest taxon possible with these methods, using phase microscopy.

8. Zooplankton biomass

A crude measure of the biomass of zooplankton (>160 μm) was made from vertical net hauls of an 80-cm diameter 160 μm mesh plankton net. A single net haul was made at each of the productivity stations indicated in Figure 1. The net was hauled vertically from the surface to 35m (except at Sta. 7, which was to 20m) and then back again, fishing both on the way down and on the way up. Each

sample was preserved in 4% borate-buffered Formalin. Settled volume biomass estimates were made by allowing the samples to settle for 24 hrs in Imhoff cones and recording the volume of plankton, discounting any large gelatinous zooplankton. The preserved samples are being stored for any taxonomic work that might become necessary in the future.

DISCUSSION OF RESULTS

1. General Hydrography

The discussion that follows summarizes the major hydrographic characteristics during each of our six cruises to Massachusetts Bay. Particular details of the results may be found in the earlier cruise reports (Townsend *et al.*, 1990a,b,c).

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A summary of the *in situ* hydrographic measurements, presented as both areal contour plots of surface values, and as vertical section contour plots of temperature, salinity, density, light transmittance and *in situ* chlorophyll fluorescence, are given in Figures 2-8. All contour plots were made using Surfer, Version 4, by Golden Software, Golden Colorado. The vertical section plots use all points in the 1-meter-averaged CTD/ *in situ* fluorometer/ transmissometer data files.

The initiation of fall mixing is evident in the vertical section plots of temperature, salinity and density in Figures 4-6 and by cooler water temperatures at the shallower inshore stations shown in Figure 2. The depth of the thermocline for stations in the northern transect (Stations 1-5) was fairly deep, between 50 and 60m, while it appeared to shoal to about 50m in the central transect and about 37m in the southern transect. There was also some evidence of doming of slightly more saline water between Stations 14 and 16 which may have exerted some influence in lessening vertical mixing and establishing a shallower thermocline there.

There was a frontal region between Stations 7 and 8 (Figs. 2 and 3), as expressed by cooler and fresher water inshore, which also served to demark the more turbid waters inshore (higher values of Beam C (beam attenuation coefficient)). The chlorophyll concentrations also dropped off shoreward of this region, apparently in response to the poor *in situ* light conditions nearer Boston Harbor. The two stations nearest Boston Harbor, Stations 6 and 7, had very high particulate carbon loads (POC), low chlorophyll concentrations and high dissolved ammonium and silicate concentrations (Table 1). Seaward of the front there were fairly high chlorophyll concentrations which would indicate a fall bloom in response to the nutrient injections into the surface layers resulting from the vertical mixing. The surface nitrate values, for instance, were in excess of 2 μM at all stations measured (Table 1). The dissolved oxygen concentrations were lowest

at the deeper stations within Massachusetts Bay. Oxygen values as low as 70% saturation were found at depths greater than 50m (Table 1).

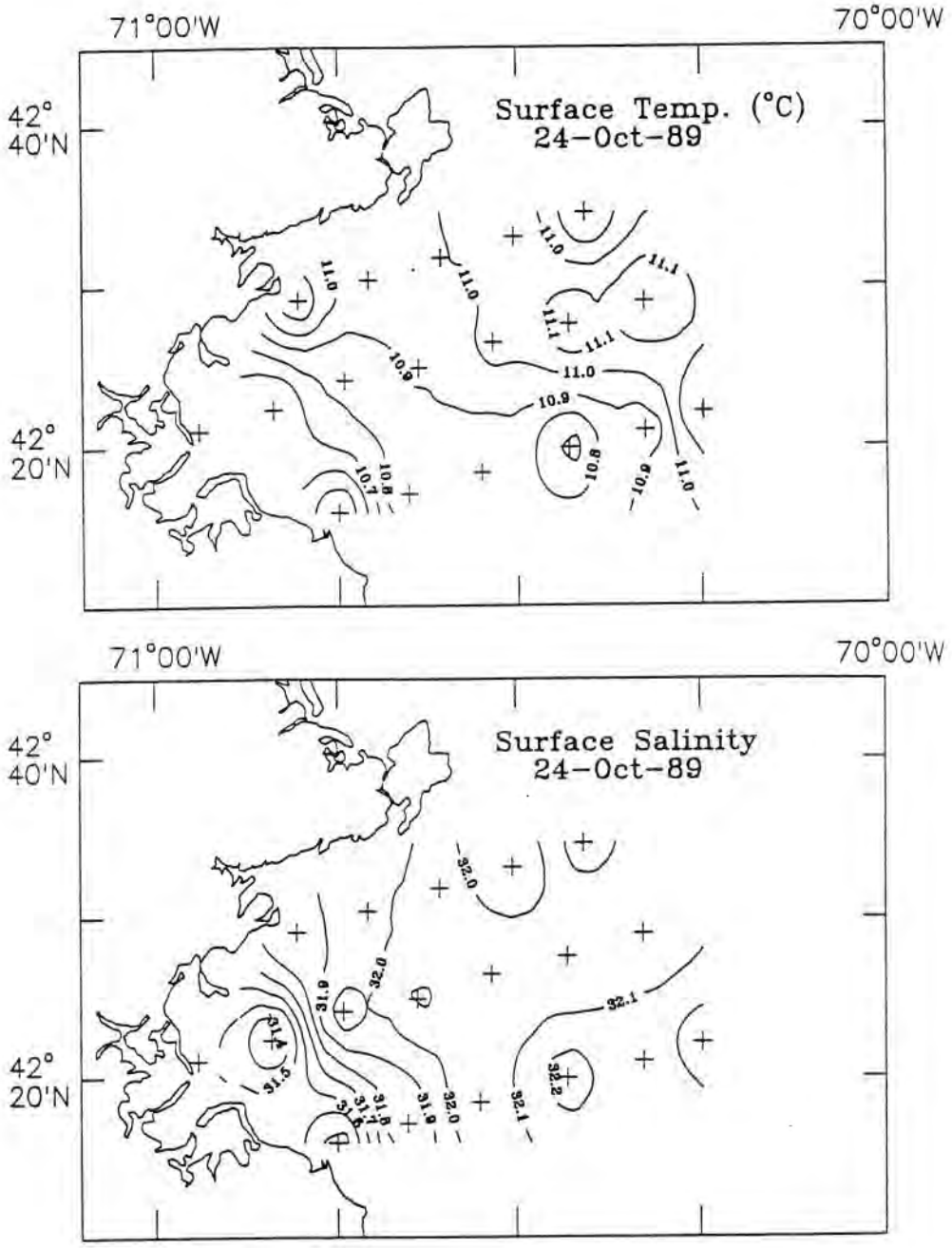

Figure 2. Surface contour plots of temperature and salinity (at 2m) for 24 October 1989.

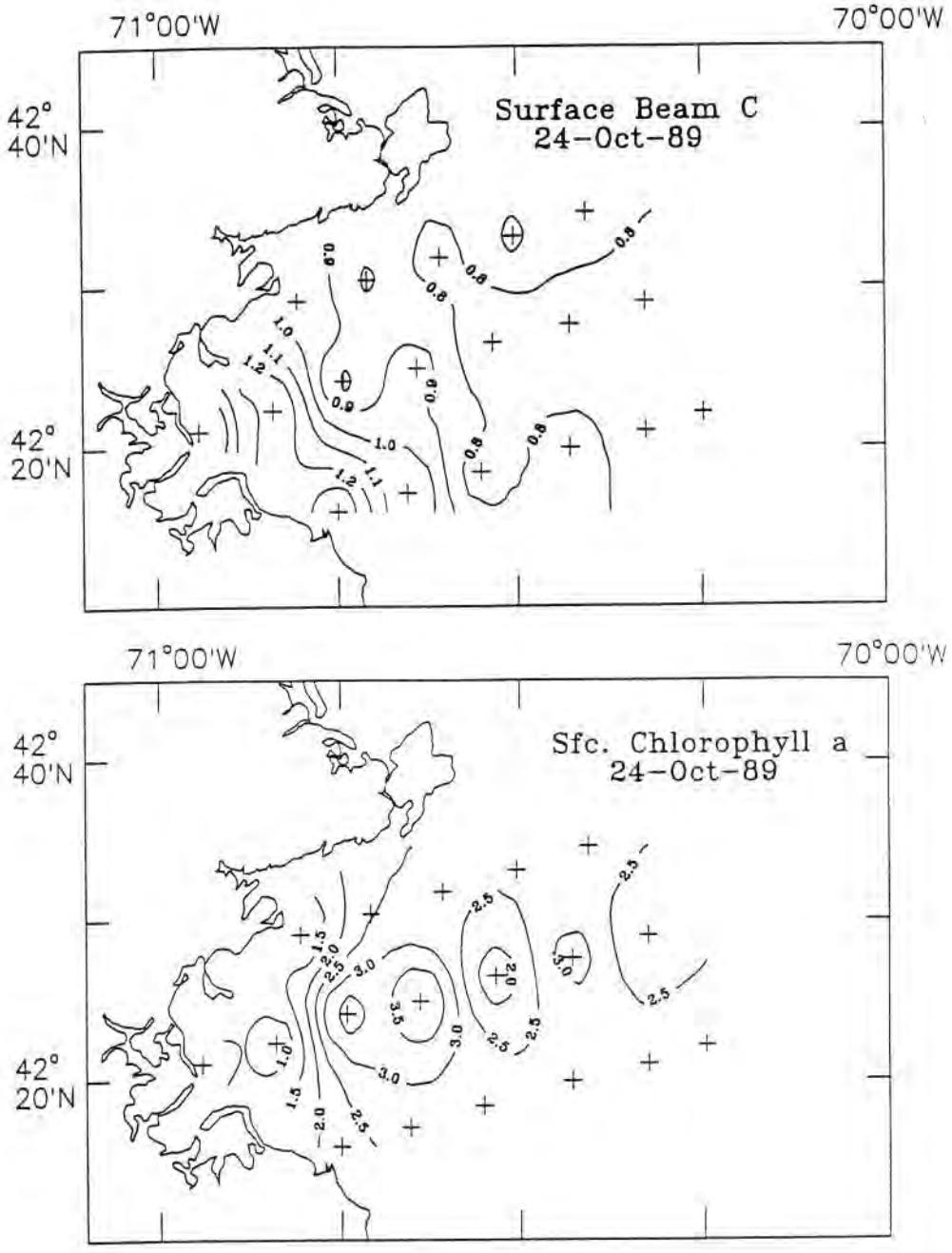

Figure 3. Surface contour plots of beam attenuation coeficient and *in situ* chlorophyll *a* fluorescence (at 2m) for 24 October 1989.

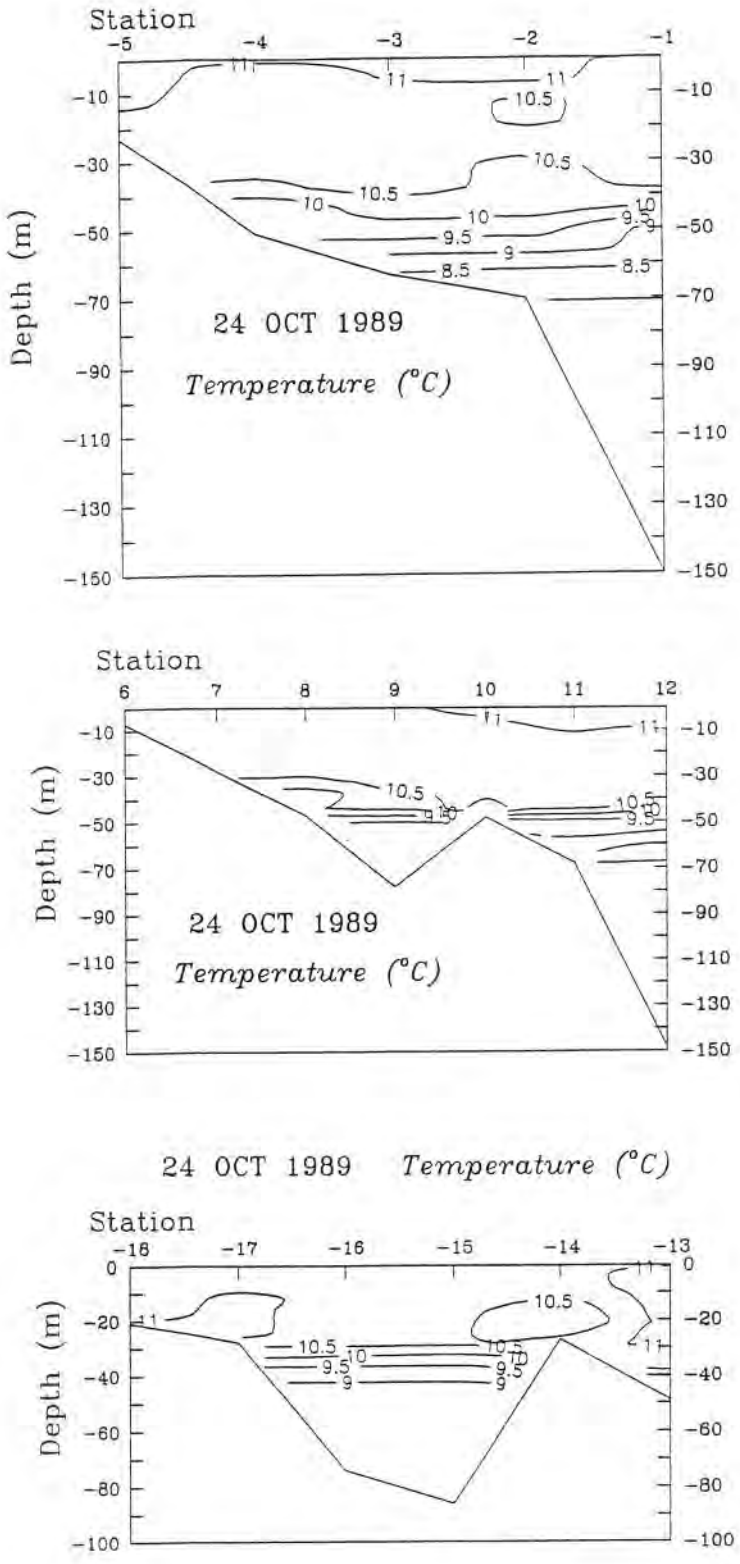

Figure 4. Vertical section contour plots of temperature on 24 October 1989 for each of the four transects in Figure 1.

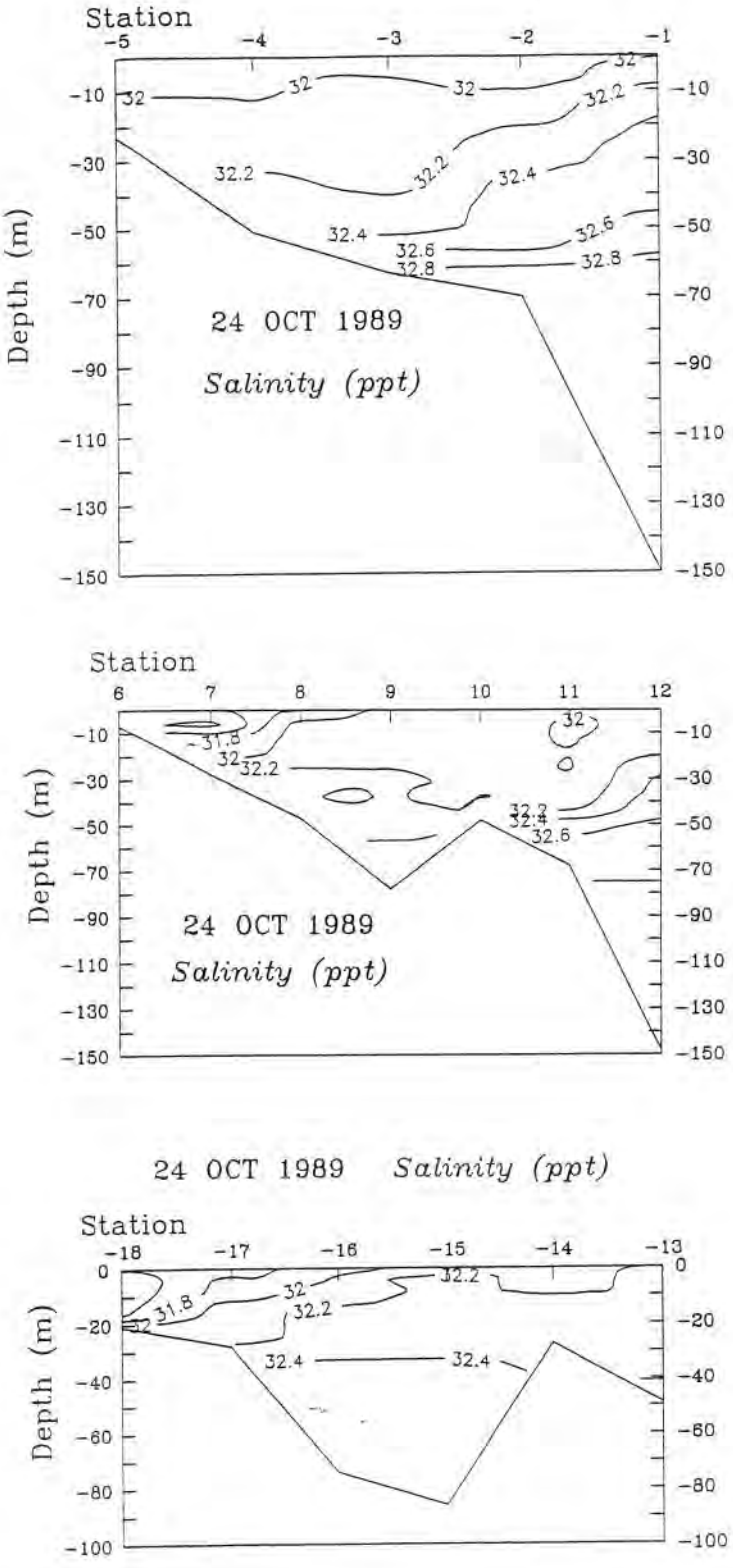

Figure 5. Vertical section contour plots of salinity on 24 October 1989 for each of the four transects in Figure 1.

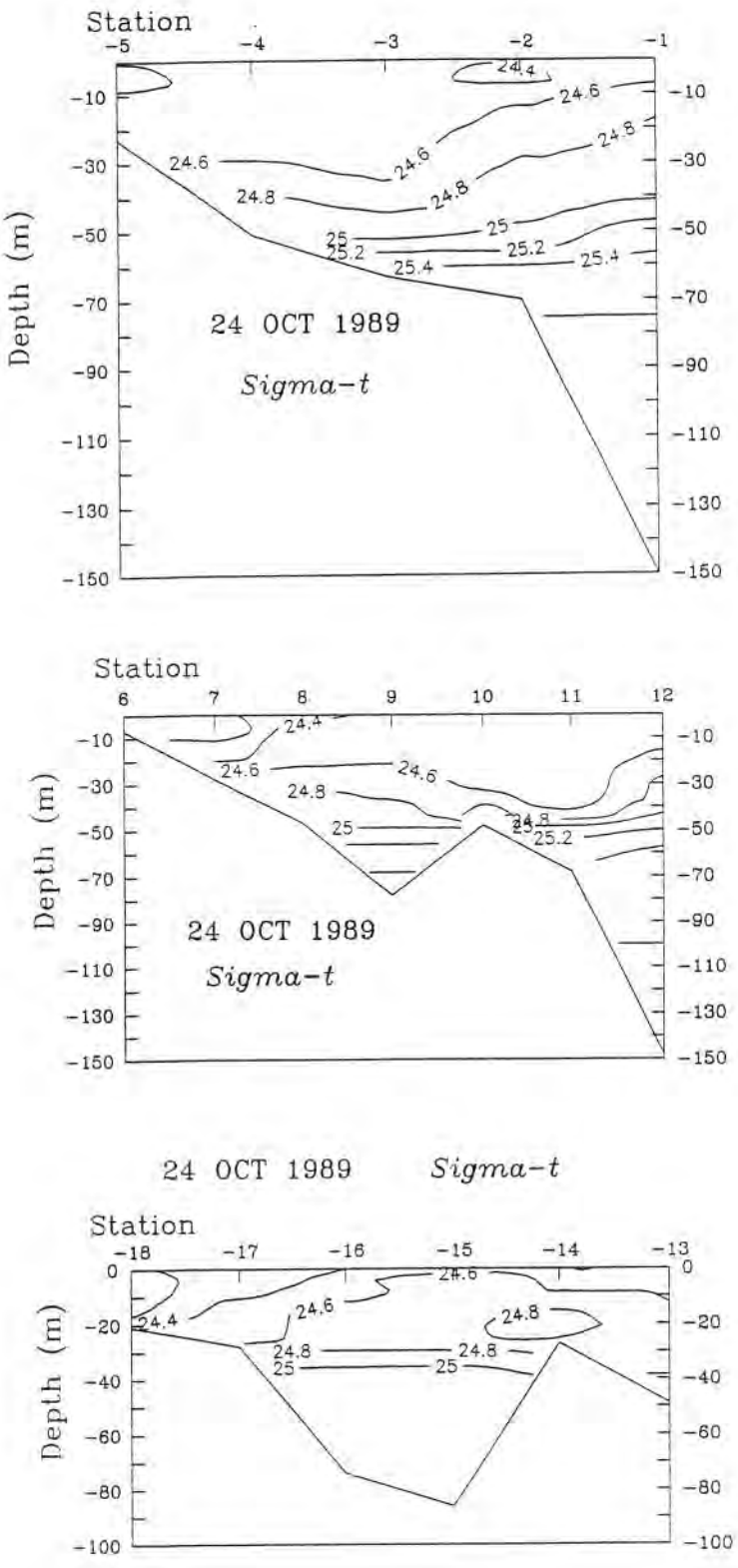

Figure 6. Vertical section contour plots of density on 24 October 1989 for each of the four transects in Figure 1.

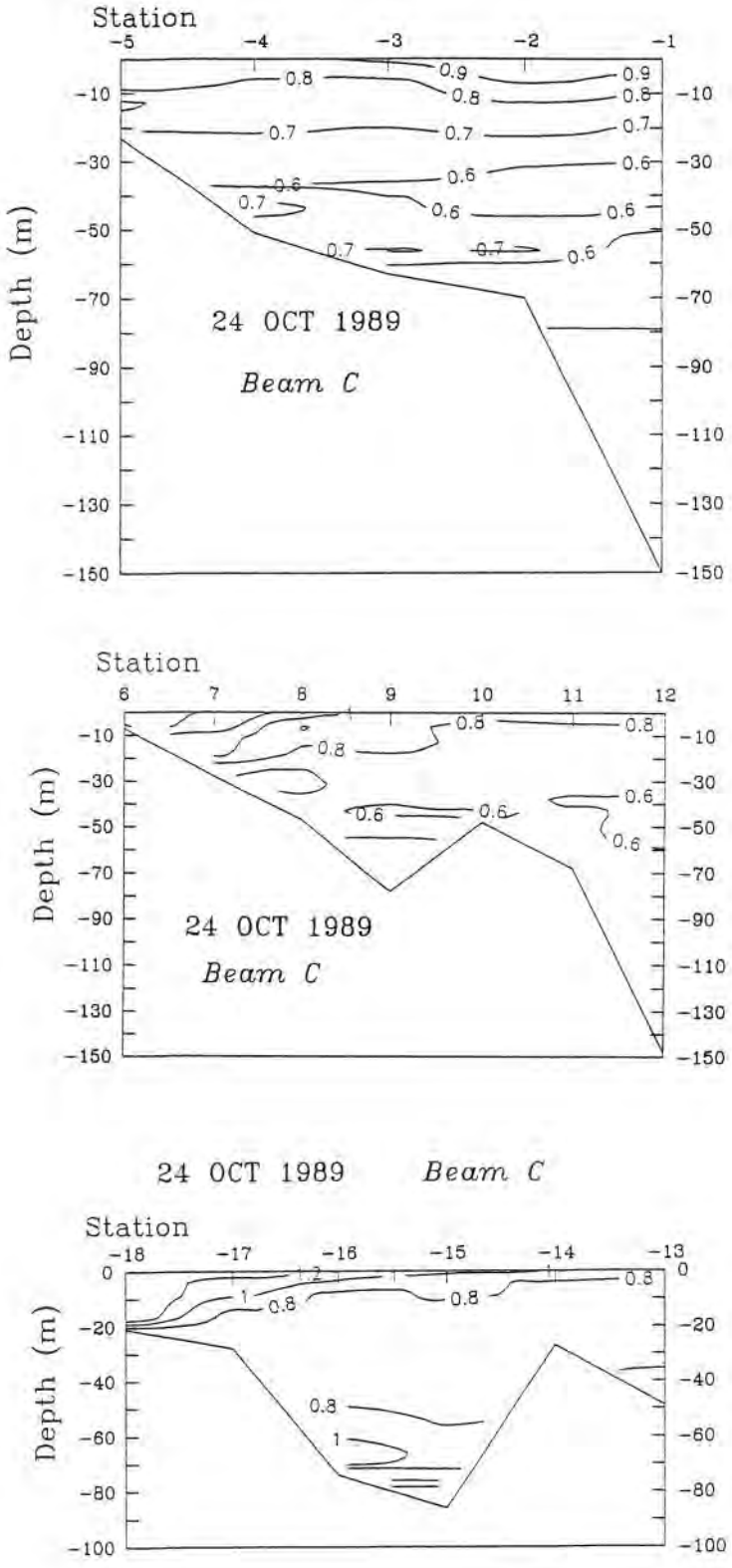

Figure 7. Vertical section contour plots of beam attenuation coefficient on 24 October 1989 for each of the four transects in Figure 1.

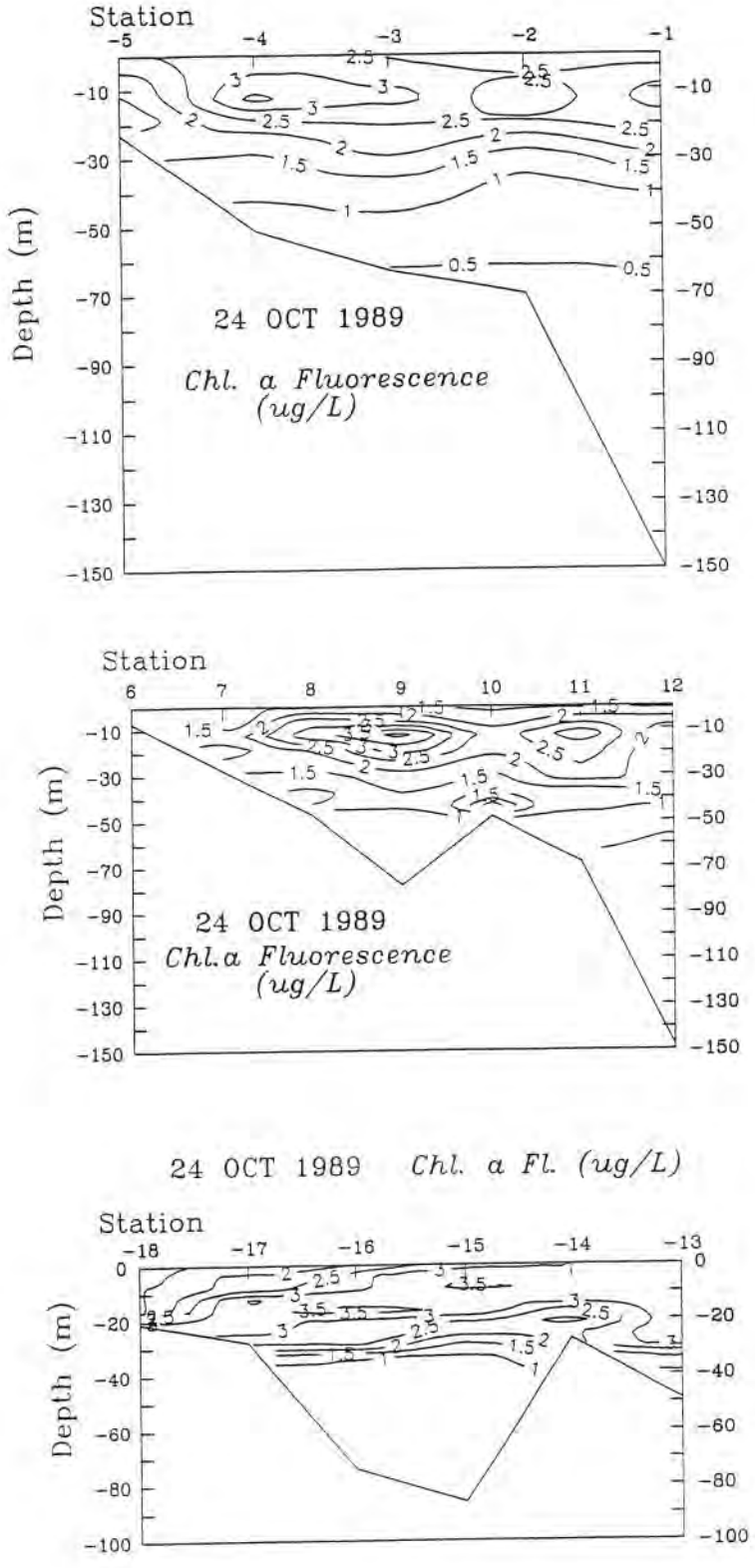

Figure 8. Vertical section contour plots of *in situ* chlorophyll *a* fluorescence on 24 October 1989 for each of the four transects in Figure 1.

TABLE 1. DISCRETE BOTTLE MEASUREMENTS – 24 OCTOBER 1989

Station	Time (EST)	Depth (m)	Temp (°C)	Salinity (ppt)	In Situ Chl (ug/L)	Trans (%)	POC (ug/L)	PON (ug/L)	Chl a (ug/L)	Pheo (ug/L)
1	1539	2.5	10.80	32.14	2.63	81.0	263.00	37.68	2.67	0.58
		16.3	10.73	32.42	2.74		195.40	29.32	2.50	0.74
		30.9	10.74	32.45	1.47		163.02	22.79	1.47	0.58
		45.7	9.19	32.65	0.65		118.00	19.14	0.42	0.36
		81.2	7.81	32.85	0.37		79.40	9.58	0.18	0.16
		100.9	7.81	32.86	0.40		71.20	6.44	0.16	0.18
		133.4	7.78	32.87	0.38		74.00	6.68	0.16	0.19
3	1809	2.5	11.00	32.02	2.88	82.2	262.40	34.56	2.52	0.65
		13.1	10.83	32.05	3.18		253.40	36.24	2.79	0.52
		30.9	10.76	32.08	1.84		114.40	16.12	1.50	0.49
		52.2	9.17	32.44	1.00		122.40	17.58	0.70	0.36
5	1835	2.5	11.17	31.88	1.48	78.6	204.20	31.06	1.01	0.52
		10.2	11.08	32.01	1.36		160.40	24.44	1.07	0.41
		22.4	10.64	32.15	1.13		143.00	18.16	0.77	0.46
6	0633	2.2	10.57	31.48	1.17	65.6	310.80	43.84	0.84	1.38
		5.8	10.58	31.49	1.10		292.40	42.20	0.93	1.46
7	0725	2.4	10.59	31.28	1.01	72.3	278.60	41.56	0.67	0.86
		5.3	10.59	31.29	1.08		321.20	39.42	0.75	0.75
		13.2	10.96	31.77	1.38		239.40	31.48	1.51	0.66
		23.2	11.10	31.98	1.11		184.80	21.46	0.76	0.61
8	0905	2.7	10.81	32.06	2.05	82.3	255.40	34.94	3.75	0.62
		15.8	10.75	32.07	3.72		230.80	34.22	3.02	0.55
		26.1	10.62	32.24	1.41		146.80	20.64	1.37	0.37
		31.0	10.44	32.30	1.19		138.00	21.08	1.05	0.42
		42.7	9.27	32.39	0.76		126.40	16.26	0.54	0.46
9	1015	2.3	10.91	32.12	2.09	79.3	310.80	43.04	4.10	0.69
		15.7	10.83	32.13	3.80		293.40	42.62	4.18	0.71
		25.9	10.78	32.20	1.81		143.20	18.64	1.47	0.43
		50.6	8.76	32.37	0.65		115.60	10.92	0.47	0.44
		71.1	7.74	32.61	0.55		815.20	166.92	0.35	0.43
10	1133	2.6	11.02	32.04	1.01	84.0	196.20	24.74	1.67	0.37
		10.6	10.85	32.04	2.26		191.80	25.72	1.89	0.50
		15.6	10.77	32.04	2.03		170.60	23.92	1.92	0.46
		25.6	10.64	32.05	1.74		200.40	30.62	1.83	0.52
		43.6	9.58	32.42	1.02		132.00	18.06	0.81	0.45
11	1240	2.6	11.19	32.00	1.67	83.0	248.60	32.08	3.19	0.62
		14.5	10.95	31.99	2.94		275.60	39.90	3.54	0.86
		29.6	10.94	32.00	2.14		176.80	26.94	2.19	0.68
		47.9	9.73	32.45	0.72		111.00	15.60	0.60	0.38
		62.7	8.63	32.67	0.48		102.60	10.02	0.27	0.29
12	1352	3.0	11.20	32.00	1.47	82.5	233.20	34.62	2.00	0.46
		10.4	11.01	32.02	2.37		176.20	28.30	1.57	0.55
		32.0	10.63	32.44	1.67		149.80	22.84	1.35	0.58
		50.7	9.41	32.63	0.68		107.80	12.92	0.42	0.29
		73.1	7.87	32.80	0.42		121.60	14.30	0.20	0.18
		145.8	7.71	32.85	0.41		269.00	30.86	0.20	0.19
13	0029	2.4	11.21	32.25	3.45	83.0	116.00	12.91	2.87	0.63
		15.1	11.19	32.25	3.38		128.80	17.73	2.96	0.73
		25.3	11.12	32.25	3.31		250.40	37.28	2.91	0.69
		35.7	10.71	32.30	1.25		286.10	40.13	1.26	0.47
		44.8	9.58	32.45	0.85		248.70	31.95	0.54	0.40
15	0204	2.6	10.67	32.25	3.33	81.4	279.60	40.54	2.96	0.63
		10.5	10.68	32.25	3.53		257.00	36.52	2.83	0.55
		20.0	10.57	32.32	3.13		218.80	32.64	2.27	0.62
		40.6	9.12	32.45	0.80		80.40	10.92	0.53	0.36
		80.5	7.65	32.59	0.68		184.80	22.24	0.36	0.47
17	0334	2.7	10.87	31.84	1.93	76.1	209.80	28.48	2.12	0.69
		15.5	11.17	32.06	3.29		281.80	41.20	3.84	0.67
		25.1	11.14	32.08	2.90		250.80	35.92	2.87	0.69
18	0415	2.1	10.41	31.36	1.17	70.8	244.80	36.06	1.16	0.81
		7.9	10.60	31.49	1.44		182.80	30.88	1.22	0.92
		16.3	10.54	31.55	1.15		128.40	15.76	0.95	0.98

TABLE 1 (CONT.). DISCRETE BOTTLE MEASUREMENTS – 24 OCTOBER 1989

Station	Time (EST)	Depth (m)	DO (mL/L)	% DO Saturation	Nitrate (uM)	Nitrite (uM)	Ammonium (uM)	Silicate (uM)	Phosphate (uM)
1	1539	2.5	6.43	101	2.95	0.18	0.49	4.74	0.66
		16.3	6.19	98	3.13	0.22	0.38	4.35	0.58
		30.9	6.12	97	3.42	0.22	0.46	4.70	0.59
		45.7	5.05	77	10.00	0.20	0.79	9.89	1.09
		81.2	5.14	76	13.49	0.03	0.07	13.23	1.21
		100.9	4.98	74	13.67	0.07	0.08	13.17	1.24
		133.4	4.95	73	13.59	0.04	0.07	13.55	1.24
3	1809	2.5	6.46	102	2.42	0.07	0.52	3.31	0.68
		13.1	6.35	100	2.56	0.09	0.52	3.29	0.66
		30.9	6.14	97	3.07	0.11	0.72	3.80	0.69
		52.2	5.20	79	8.45	0.13	0.69	10.03	1.07
5	1835	2.5	6.12	97	2.05	0.12	1.98	4.23	0.75
		10.2	5.87	93	2.98	0.09	1.28	4.53	0.75
		22.4	5.54	87	4.92	0.12	1.28	7.67	0.89
6	0633	2.2	5.67	89	2.90	0.21	6.44	6.85	1.31
		5.8	5.73	90	2.93	0.17	6.14	5.85	1.27
7	0725	2.4	5.96	93	3.17	0.19	6.79	6.46	1.23
		5.3	5.96	93	3.25	0.18	6.68	6.29	1.15
		13.2	6.04	95	2.24	0.11	3.05	4.17	0.88
		23.2	6.00	95	2.50	0.10	2.40	3.76	0.88
8	0905	2.7	6.42	101	2.60	0.10	0.48	2.51	0.66
		15.8	6.27	99	2.93	0.11	0.47	2.83	0.67
		26.1	6.01	95	4.20	0.13	0.37	6.75	0.72
		31.0	5.97	93	5.59	0.15	0.46	4.51	0.83
		42.7	5.17	79	9.79	0.17	0.46	11.62	1.16
9	1015	2.3	6.53	103	2.40	0.29	0.37	3.11	0.56
		15.7	6.51	103	2.57	0.28	0.46	3.07	0.55
		25.9	6.22	98	3.63	0.20	0.44	4.36	0.62
		50.6	4.64	70	13.34	0.18	0.13	14.90	1.31
		71.1	4.63	68	13.95	0.12	0.13	14.59	1.34
10	1133	2.6	6.28	99	3.29	0.16	0.79	3.27	0.70
		10.6	6.20	98	3.73	0.17	0.74	3.43	0.74
		15.6	6.19	97	3.15	0.17	0.83	3.45	0.75
		25.6	6.25	98	3.40	0.17	0.85	4.29	0.77
		43.6	5.76	89	5.50	0.17	0.74	6.21	0.90
11	1240	2.6	6.39	101	2.29	0.09	0.66	2.33	0.58
		14.5	6.27	99	2.28	0.09	0.72	2.44	0.62
		29.6	6.20	98	2.49	0.10	0.90	2.40	0.67
		47.9	5.35	83	8.47	0.12	0.39	7.94	0.96
		62.7	4.92	74	12.91	0.10	0.01	11.24	1.18
12	1352	3.0	6.24	99	2.72	0.16	0.92	3.65	0.62
		10.4	6.04	96	3.77	0.19	0.84	4.60	0.64
		32.0	6.28	99	3.76	0.25	0.44	4.45	0.58
		50.7	5.30	81	9.63	0.18	0.17	9.24	0.95
		73.1	4.90	73	13.44	0.07	0.15	13.34	1.24
		145.8	4.86	72	13.72	0.07	0.14	13.50	1.28
13	0029	2.4	6.37	101	2.44	0.15	0.25	2.91	0.64
		15.1	6.33	101	2.71	0.16	0.31	3.16	0.72
		25.3	6.24	99	3.03	0.16	0.38	3.45	0.77
		35.7	5.80	91	5.42	0.20	0.54	5.83	0.89
		44.8	5.23	80	8.93	0.21	0.54	10.26	1.14
15	0204	2.6	6.34	100	3.85	0.17	0.26	6.17	0.68
		10.5	6.33	100	3.53	0.16	0.27	4.28	0.67
		20.0	6.10	96	4.72	0.21	0.38	5.82	0.74
		40.6	5.18	79	9.94	0.41	0.29	12.33	1.15
		80.5	4.65	68	12.69	0.28	0.26	16.12	1.41
17	0334	2.7	6.25	98	3.00	0.15	2.09	3.98	0.90
		15.5	6.21	99	2.53	0.16	0.82	2.59	0.75
		25.1	6.16	98	2.52	0.13	0.75	2.38	0.71
18	0415	2.1	6.04	94	4.30	0.31	4.63	6.10	1.26
		7.9	6.04	94	4.37	0.25	4.33	5.72	1.16
		16.3	6.01	94	3.80	0.25	4.41	5.34	1.16

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Conditions during this cruise were generally typical for coastal Gulf of Maine waters in winter in that they were cold and rich in nutrients. The coldest waters were again nearest the shore, as were the fresher surface waters (Figs. 9 and 10), and the frontal region between Stations 7 and 8 was again evident. The more turbid water was in the nearshore area comprising Stations 6, 7 and 18 (Fig. 10), while the chlorophyll concentrations were generally low throughout the region, perhaps slightly higher at some of the more coastal stations. We might normally have expected to see evidence of a winter-spring phytoplankton bloom at the shallower inshore stations, particularly Stations 6, 7 and 18 (e.g. Townsend and Spinrad, 1986). However, such blooms are normally light-limited at this time of year, and may have been retarded as a result of the turbid conditions inshore.

The nutrient and oxygen levels were high, as is typical for this area in winter (Yentsch *et al.*, 1977), but the nitrate concentrations at the northeastern-most stations appeared to be anomalously high, exceeding 14 μM NO_3 at Station 1 (Table 2). The source of those high nutrient levels is not immediately clear, since typical deep water nutrient values in winter in the Gulf of Maine are generally somewhat lower (Townsend *et al.*, 1987). We would have expected lower nutrient concentrations in the western Gulf of Maine, given the distance away from the presumed source in the eastern Gulf and Northeast Channel. A plot of nitrate versus salinity (Fig. 16) shows that, in general, the highest nitrate concentrations were associated with the highest salinities, but the relationship is not tight. Further, the salinities that one might normally associate with such high nutrient values would be on the order of that of slope water (ca. 34 ppt; Townsend and Christensen, 1986). While there are some fairly high salinities, there are also points in Figure 16 with nitrate values in excess of 13 μM corresponding with salinities of less than 33 ppt. The T-S plot in Figure 16 shows no clear evidence of the warmer and saltier bottom water of slope water origin, which is high in nutrients, having made its way into Massachusetts Bay.

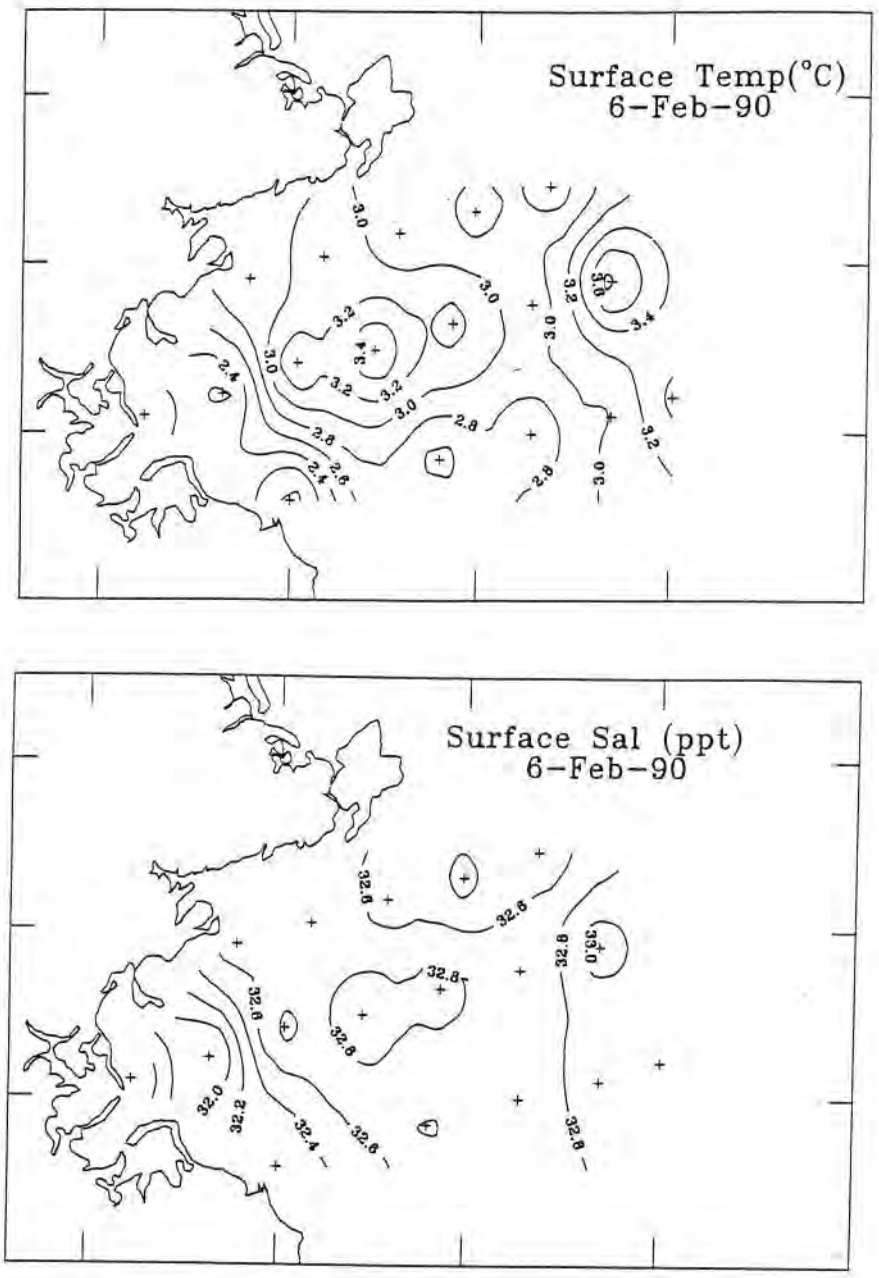


Figure 9. Surface contour plots of temperature and salinity (at 2m) for 6 February 1990.

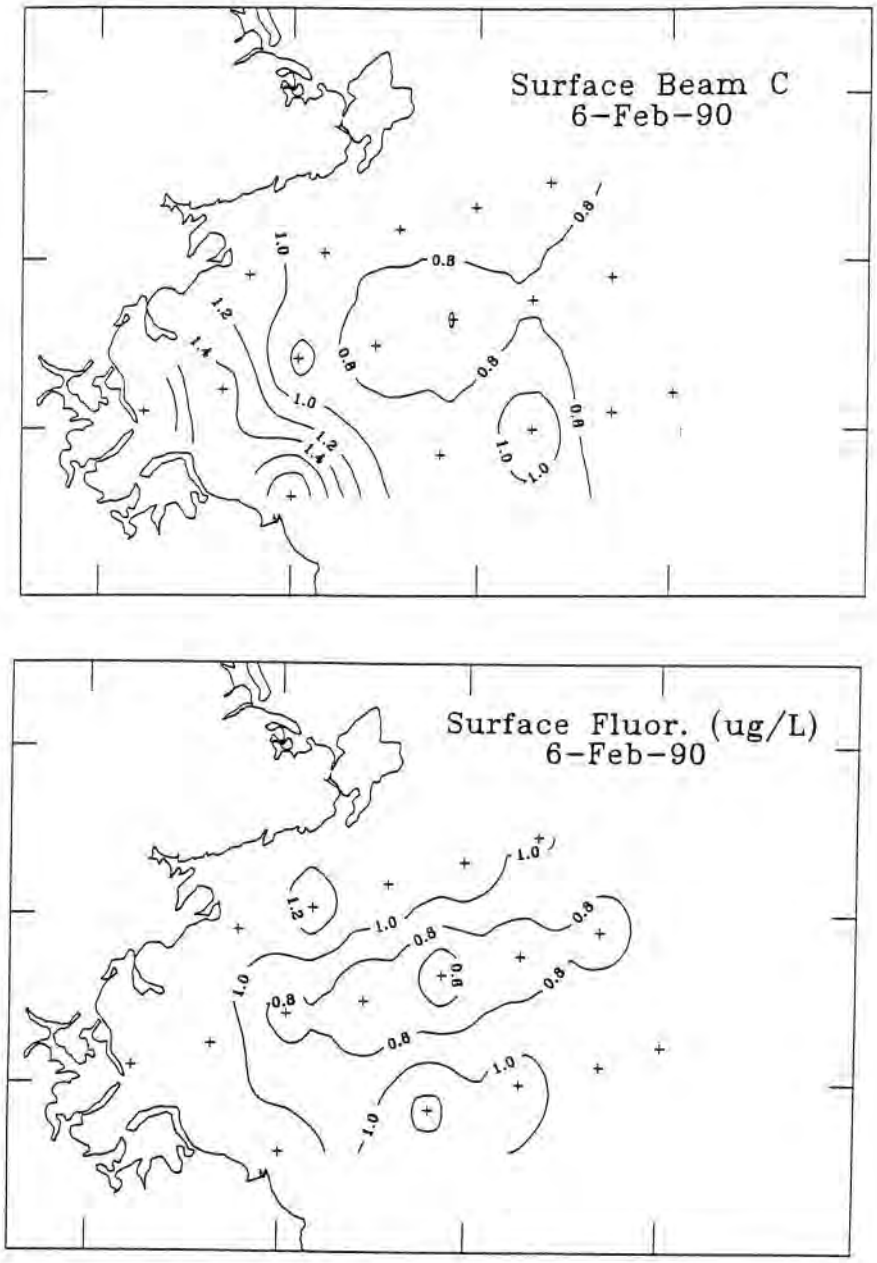


Figure 10. Surface contour plots of beam attenuation coeficient and *in situ* chlorophyll *a* fluorescence (at 2m) for 6 February 1990.

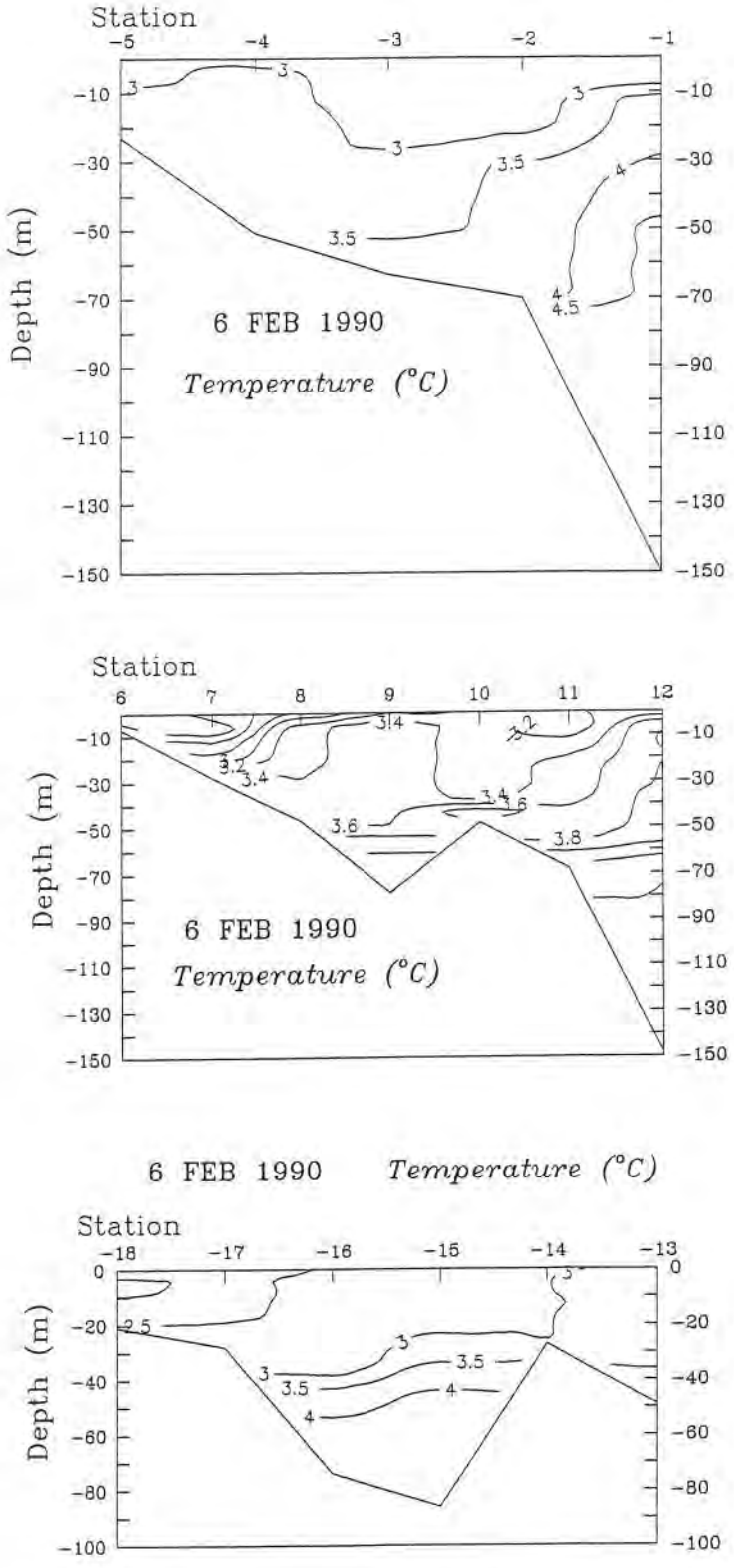


Figure 11. Vertical section contour plots of temperature on 6 February 1990 for each of the four transects in Figure 1.

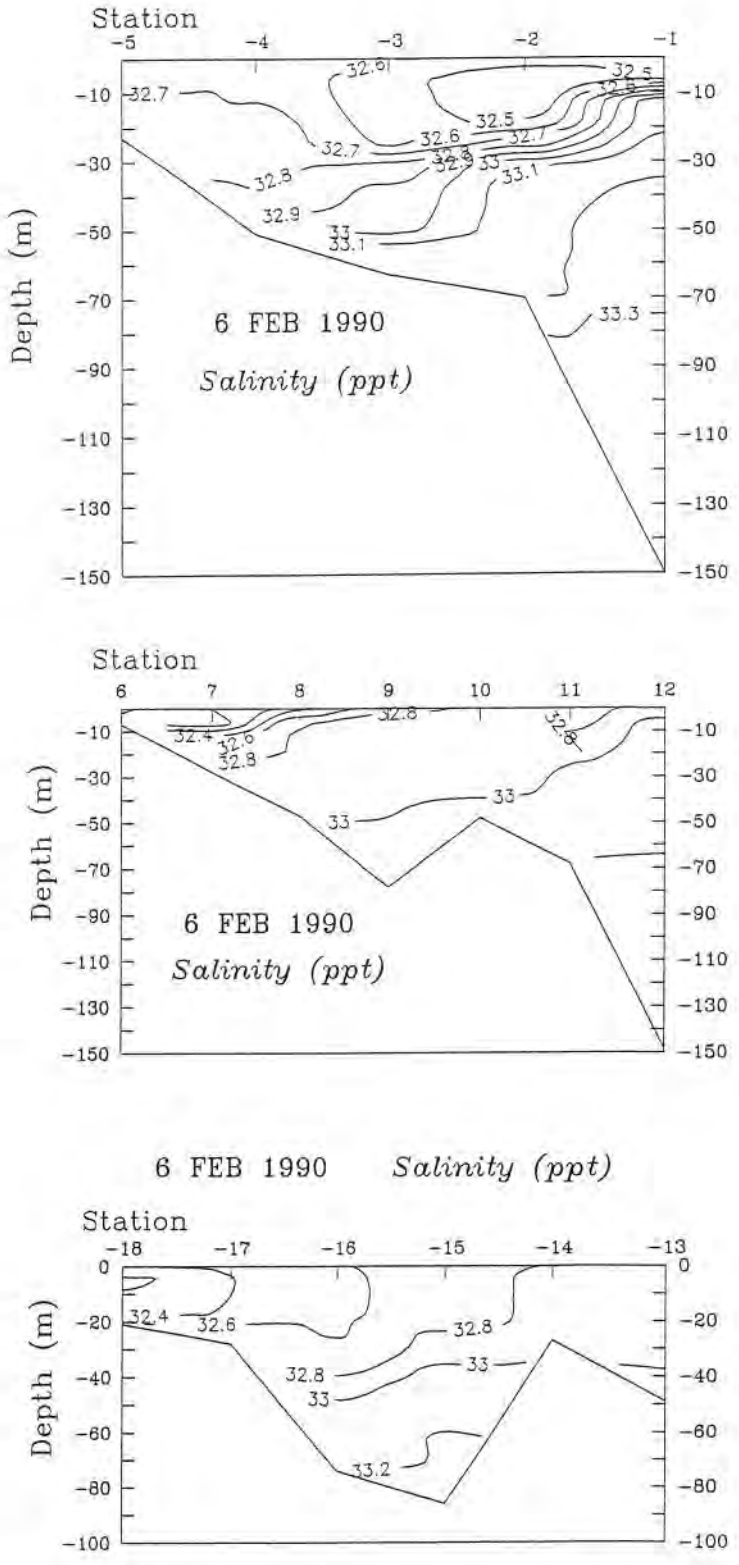


Figure 12. Vertical section contour plots of salinity on 6 February 1990 for each of the four transects in Figure 1.

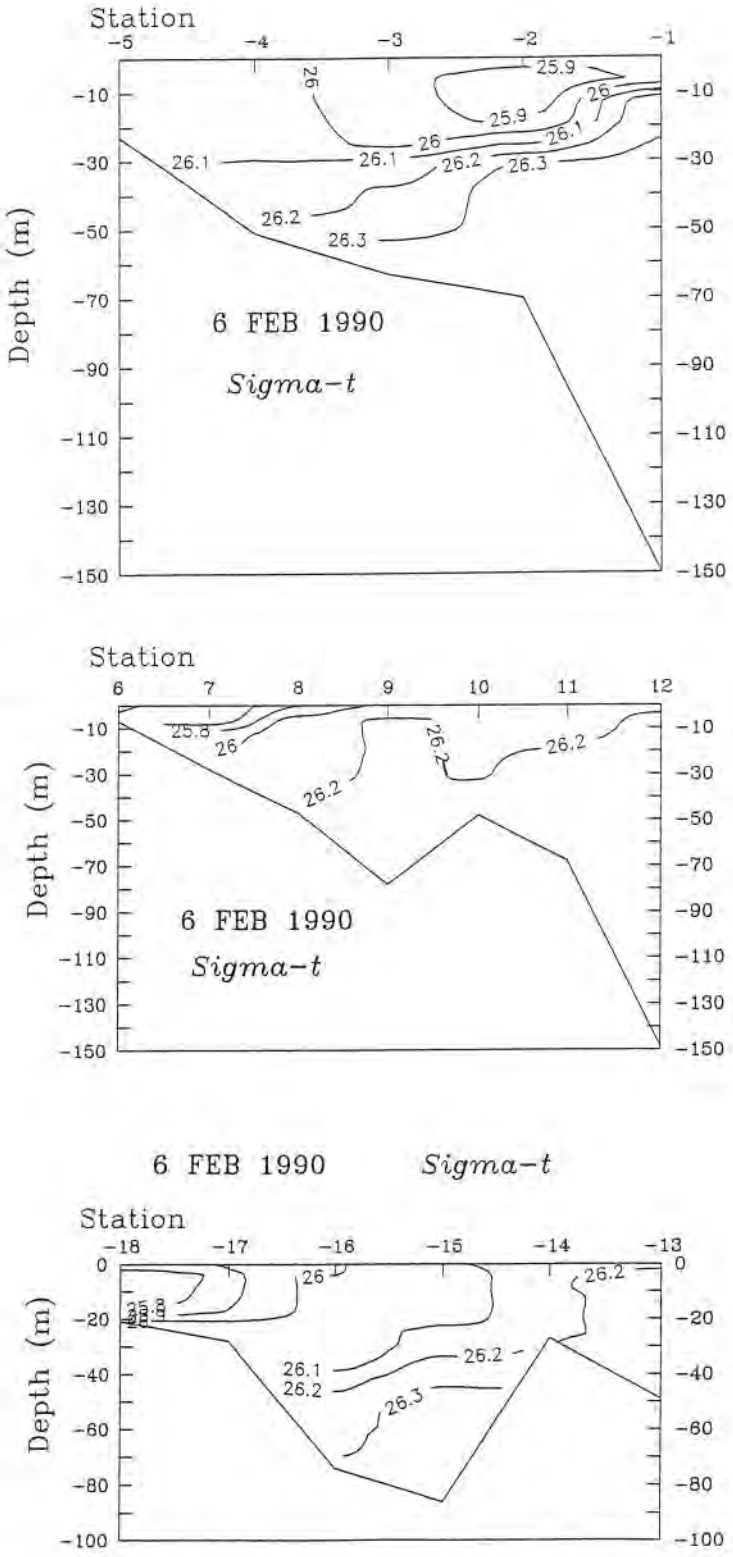


Figure 13. Vertical section contour plots of density on 6 February 1990 for each of the four transects in Figure 1.

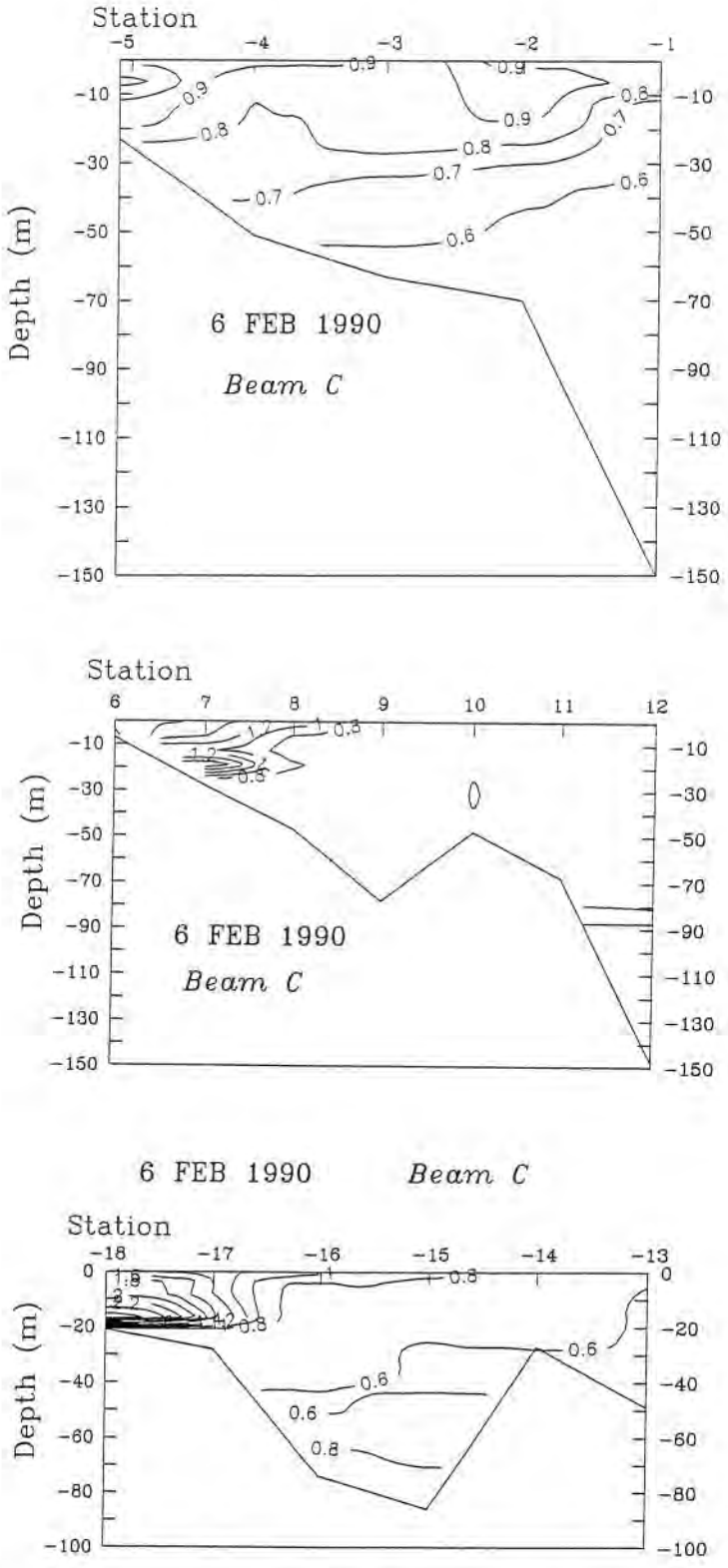


Figure 14. Vertical section contour plots of beam attenuation coefficient on 6 February 1990 for each of the four transects in Figure 1.

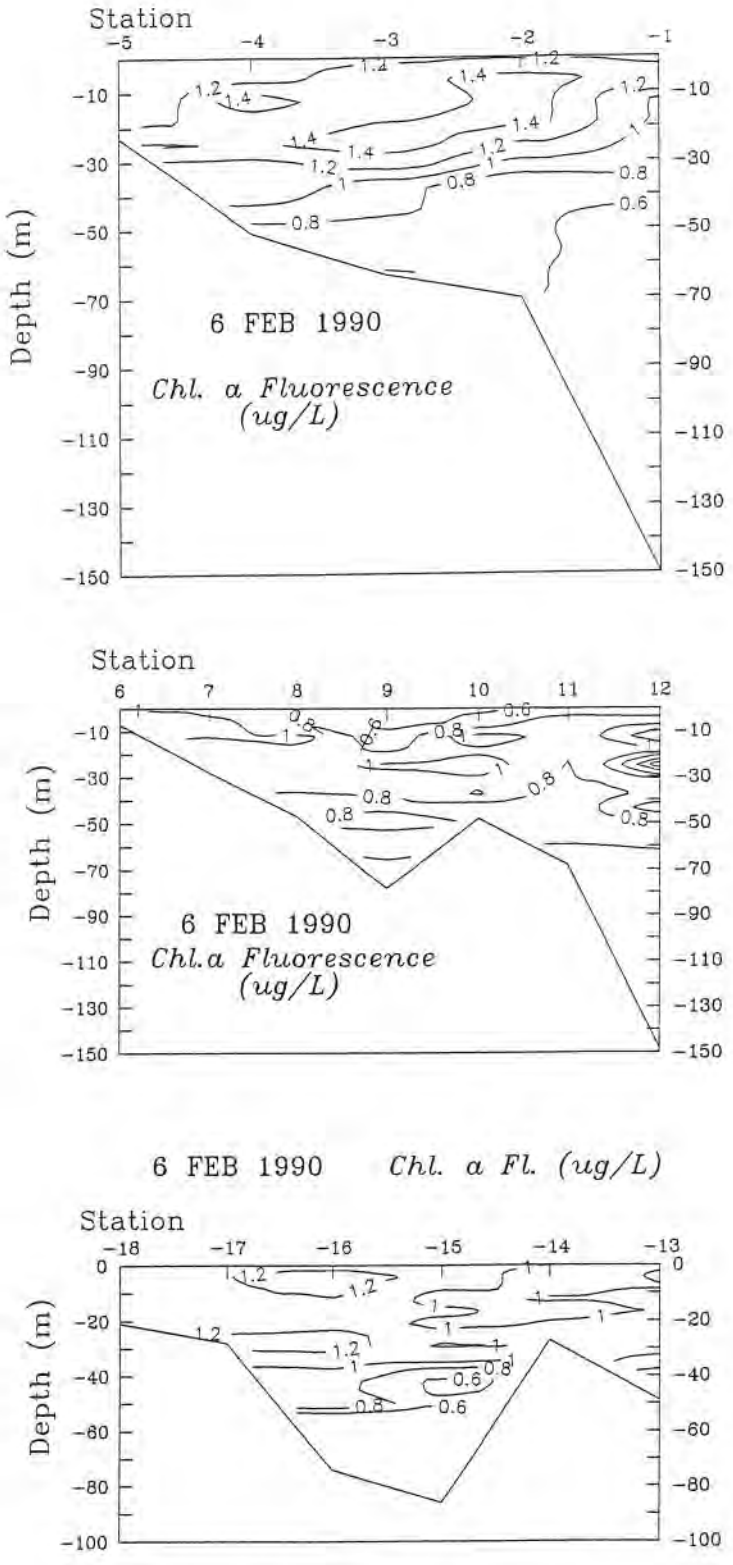


Figure 15. Vertical section contour plots of *in situ* chlorophyll *a* fluorescence on 6 February 1990 for each of the four transects in Figure 1.

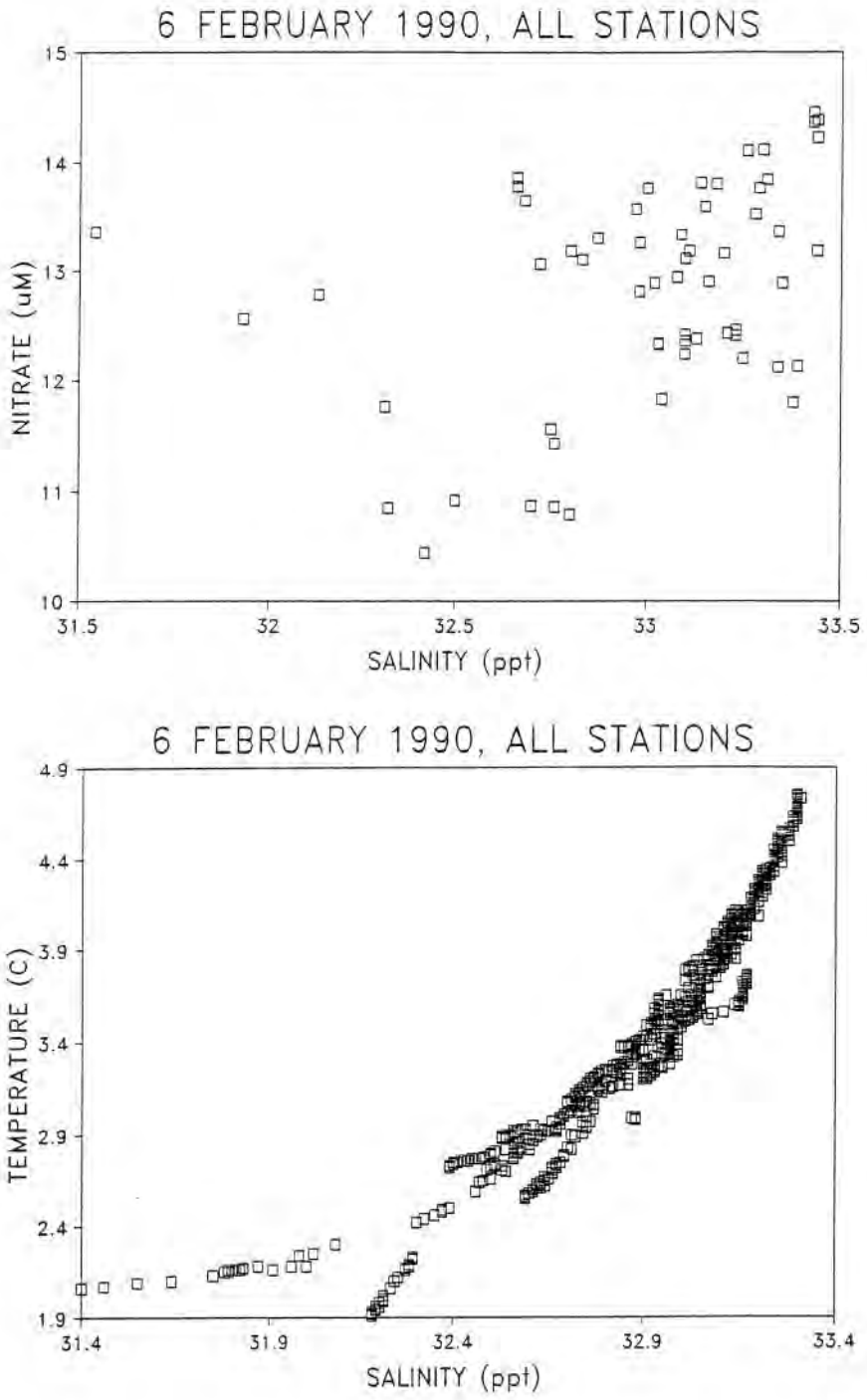


Figure 16. Nitrate versus salinity (top panel) and temperature versus salinity (lower panel) for all stations on 6 February 1990.

TABLE 2. DISCRETE BOTTLE MEASUREMENTS – 6 FEBRUARY 1990

Station	Time (EST)	Depth (m)	Temp (°C)	Salinity (ppt)	In Situ Chl (ug/L)	Beam Atten (1/m)	POC (ug/L)	PON (ug/L)	Chl a (ug/L)	Pheo (ug/L)
1	1907	2.8	2.75	32.66	0.94	0.68	17.29	6.43	0.86	0.38
		13.9	3.89	33.26	0.92	0.64	10.87	6.00	0.84	0.29
		30.3	4.05	33.30	1.21	0.60	8.75	5.65	0.59	0.25
		74.8	4.66	33.43	0.44	0.57	4.47	4.37	0.22	0.20
		100.3	4.69	33.43	0.46	0.56				
		120.2	4.72	33.44	0.43	0.57				
		131.6	4.74	33.44	0.43	0.56				
		138.8	4.75	33.44	0.42	0.57				
3	2041	2.1	2.88	32.66	1.25	0.84	19.59	5.95	1.29	0.39
		15.4	2.91	32.68	1.37	0.83	20.25	6.22	1.29	0.37
		30.7	3.17	32.97	1.50	0.76	17.57	5.80	0.90	0.35
		51.8	3.48	33.15	0.75	0.60	12.91	6.00	0.76	0.31
5	2156	1.7	2.92	32.80	0.96	1.15	22.59	5.96	0.77	0.72
		10.0	3.07	32.83	1.18	1.04	20.35	6.11	0.99	0.61
		21.0	3.14	32.87	1.32	0.92	21.85	5.68	1.03	0.61
6	1012	2.4	2.05	31.54	1.12	2.09	56.67	7.15	1.29	1.07
		5.5	2.18	32.13	1.43	2.45	57.87	7.23	1.27	1.39
7	1107	2.8	2.16	31.93	0.95	1.45	40.87	7.55	1.11	0.68
		11.9	2.49	32.50	1.06	1.05	25.75	5.37	1.03	0.52
		17.5	2.81	32.70	0.92	1.85	21.43	7.74	0.78	1.05
		22.0	2.89	32.75	0.90	1.71	22.31	7.32	0.72	0.89
8	1211	2.8	3.38	32.98	0.69	0.74	13.75	6.17	1.00	0.41
		16.6	3.37	32.98	1.14	0.74	14.45	5.54	0.98	0.42
		30.5	3.40	33.02	0.87	0.71	8.33	5.49	0.72	0.39
		45.7	3.49	33.08	0.77	0.70	10.39	6.98	0.58	0.44
9	1253	2.8	3.48	33.09	0.61	0.68	10.83	7.75	0.79	0.33
		15.7	3.51	33.10	0.85	0.67	11.65	4.85	0.62	0.30
		27.0	3.54	33.11	0.95	0.67	8.71	8.74	0.57	0.29
		52.0	3.83	33.20	0.66	0.63	11.85	7.47	0.47	0.24
		72.2	4.08	33.29	0.45	0.72	6.57	8.59	0.29	0.23
10	1411	2.5	3.26	33.03	0.58	0.61	15.51	6.86	0.81	0.29
		16.7	3.23	33.03	0.99	0.59	12.59	6.50	0.93	0.30
		32.9	3.25	33.04	1.09	0.59	11.55	5.97	0.86	0.30
		46.5	4.08	33.28	0.43	0.77	8.15	7.41	0.17	0.27
11	1454	2.5	2.88	32.72	0.91	0.80	17.49	5.72	0.93	0.29
		14.9	3.31	33.00	0.82	0.71	13.05	5.96	0.75	0.32
		30.9	3.52	33.14	0.90	0.64	9.17	8.98	0.63	0.30
		51.0	3.62	33.18	0.90	0.63	8.41	10.79	0.50	0.30
		65.9	4.11	33.31	0.47	0.67	8.23	5.20	0.28	0.23
12	1557	3.0	3.85	33.23	0.76	0.63	13.25	5.03	0.75	0.27
		15.8	3.82	33.23	0.82	0.63	10.77	7.38	0.77	0.29
		30.2	3.86	33.25	0.82	0.63	11.01	7.79	0.58	0.25
		72.1	4.28	33.34	0.60	0.61	5.85	4.65	0.33	0.24
		111.2	4.47	33.38	0.46	0.60				
		144.8	4.54	33.39	0.51	0.63				
13	0351	1.9	3.33	33.10	0.91	0.60	11.79	9.10	0.83	0.32
		14.9	3.34	33.10	0.98	0.59	16.29	11.11	0.97	0.39
		25.0	3.39	33.10	1.04	0.59	16.33	10.14	0.89	0.39
		35.3	3.49	33.13	0.99	0.59	12.95	7.87	0.74	0.33
		45.5	3.61	33.16	0.84	0.57	15.95	7.31	0.79	0.36
15	0610	2.5	2.62	32.76	1.08	1.21	15.31	9.10	1.03	0.44
		10.0	2.62	32.76	1.14	0.72			1.12	0.54
		20.0	2.72	32.80	1.04	0.71	19.51	7.12	0.55	0.28
		40.0	3.90	33.21	0.57	0.57	9.61	6.95	0.30	0.27
		60.0	4.29	33.34	0.49	0.77	8.87	7.80		
		85.0	4.34	33.35	0.46	0.91	11.99	7.20	0.30	0.29
18	0839	2.6	1.92	32.31	0.97	1.96	33.79	6.55	0.92	1.28
		9.2	1.95	32.32	1.04	2.04	34.49	7.30	0.94	1.37
		17.4	2.21	32.42	1.19	2.99	45.49	7.33	0.89	1.85

TABLE 2 (CONT.). DISCRETE BOTTLE MEASUREMENTS – 6 FEBRUARY 1990

Station	Time (EST)	Depth (m)	DO (mL/L)	% DO Saturation	Nitrate (uM)	Nitrite (uM)	Ammonium (uM)	Silicate (uM)	Phosphate (uM)
1	1907	2.8	7.42	97	13.86	0.17	0.27	16.36	0.76
		13.9	7.09	96	14.10	0.15	0.07	15.74	0.77
		30.3	6.76	92	14.11	0.14	0.07	15.74	0.78
		74.8	6.75	93	14.36	0.12	0.02	13.50	0.78
		100.3	6.78	94	14.45	0.11	0.01	12.85	0.78
		120.2	6.79	94	14.38	0.12	0.01	13.39	0.80
		131.6	5.97	82	13.18	0.11	0.05	12.99	0.76
		138.8	6.91	95	14.22	0.11	0.06	13.05	0.75
3	2041	2.1	7.40	97	13.78	0.17	0.41	16.17	0.78
		15.4	7.43	98	13.65	0.16	0.38	16.22	0.78
		30.7	7.29	97	13.57	0.14	0.28	16.15	0.78
		51.8	7.30	98	13.59	0.13	0.24	16.00	0.75
5	2156	1.7	7.41	98	13.18	0.18	0.84	13.56	1.40
		10.0	7.31	97	13.10	0.19	0.56	14.05	1.33
		21.0	7.31	97	13.30	0.17	0.50	13.75	1.29
6	1012	2.4	7.32	93	13.36	0.38	7.68	15.43	1.80
		5.5	7.31	94	12.78	0.28	4.71	14.47	1.75
7	1107	2.8	7.37	95	12.56	0.28	5.18	13.89	1.68
		11.9	7.37	96	10.92	0.21	2.94	11.18	1.42
		17.5	7.20	94	10.87	0.17	1.89	12.06	1.44
		22.0	7.21	95	11.56	0.16	1.71	12.83	1.48
8	1211	2.8	7.31	97	12.81	0.15	0.26	13.80	1.35
		16.6	7.28	97	13.26	0.16	0.31	14.56	1.47
		30.5	7.25	97	12.89	0.16	0.26	13.89	1.40
		45.7	7.18	96	12.94	0.16	0.23	14.19	1.40
9	1253	2.8	7.25	97	13.33	0.17	0.21	14.08	1.37
		15.7	7.18	96	13.11	0.15	0.20	14.39	1.38
		27.0	7.19	96	13.18	0.16	0.23	14.37	1.40
		52.0	7.08	96	13.16	0.17	0.19	13.80	1.39
		72.2	6.96	95	13.76	0.17	0.13	15.27	1.44
10	1411	2.5	7.35	98	12.33	0.15	0.37	13.04	1.34
		16.7	7.34	97	12.34	0.16	0.40	12.33	1.34
		32.9	7.31	97	11.83	0.15	0.27	12.59	1.33
		46.5	6.90	94	13.52	0.14	0.31	14.69	1.51
11	1454	2.5	7.45	98	13.06	0.16	0.32	14.90	1.43
		14.9	7.29	97	13.76	0.16	0.16	15.42	1.48
		30.9	7.20	96	13.81	0.18	0.12	14.83	1.45
		51.0	6.52	88	13.80	0.18	0.10	15.21	1.45
		65.9	6.79	92	13.84	0.16	0.05	15.27	1.47
12	1557	3.0	7.29	98	12.41	0.13	0.00	14.20	1.38
		15.8	ND	ND	12.46	0.15	0.00	14.70	1.40
		30.2	6.92	94	12.20	0.15	0.00	14.79	1.42
		72.1	6.93	95	12.12	0.15	0.00	14.92	1.43
		111.2	6.86	94	11.80	0.14	0.00	14.95	1.43
		144.8	6.84	94	12.13	0.12	0.00	15.27	1.44
13	0351	1.9	7.28	97	12.36	0.15	0.24	13.90	1.40
		14.9	7.28	97	12.42	0.16	0.23	13.99	1.40
		25.0	7.30	97	12.24	0.16	0.25	13.79	1.40
		35.3	7.29	98	12.38	0.15	0.17	13.95	1.37
		45.5	7.28	98	12.90	0.17	0.21	14.06	1.41
15	0610	2.5	7.44	97	11.43	0.19	1.53	12.71	1.40
		10.0	7.50	98	10.86	0.18	1.47	12.45	1.40
		20.0	7.41	97	10.79	0.18	0.97	13.03	1.44
		40.0	7.03	95	12.43	0.17	0.18	14.53	1.42
		60.0	6.82	93	13.36	0.15	0.15	16.24	1.52
		85.0	6.75	92	12.89	0.14	0.13	16.35	1.53
18	0839	2.6	7.62	97	11.76	0.24	3.23	12.82	1.57
		9.2	7.68	98	10.85	0.25	3.18	12.30	1.50
		17.4	7.40	95	10.44	0.25	3.06	13.48	1.65

6 March 1990:

Due to a late winter storm, only 11 of the 18 stations were sampled on our March cruise, and thus we did not construct surface contour plots. Still, we can see that winter conditions had advanced beyond that in February, as indicated by colder water temperatures (Fig. 17). Again there was evidence of a surface temperature and salinity front between Stations 7 and 8 (Figs. 17 and 18). There was a slight halocline at about 50m between Stations 8 and 10 (Fig. 18) which may have been sufficient to stabilize the water column for net phytoplankton growth there (Fig. 21), although the D sigma-t was only 1-2 units (Fig. 19). On the other hand, these waters might have been shallower than the critical depth at this time of year, thus enabling the phytoplankton to grow in the high nutrient regime (Table 3) despite the lack of significant water column stratification. Unfortunately, because of the sea state and snowy conditions on deck, we were unable to make light profile measurements to check this hypothesis. But, with chlorophyll levels in excess of 4 μg/L, and the apparent absence of vertical water column stratification, it would appear that indeed we were either witnessing a bloom phenomenon in responce to the critical depth being deeper than the bottom, or conversely, that the vertical mixing rate of the water column was sufficiently slow in relation to the growth rate of the phytoplankton cells such that positive growth was possible in the upper water column.

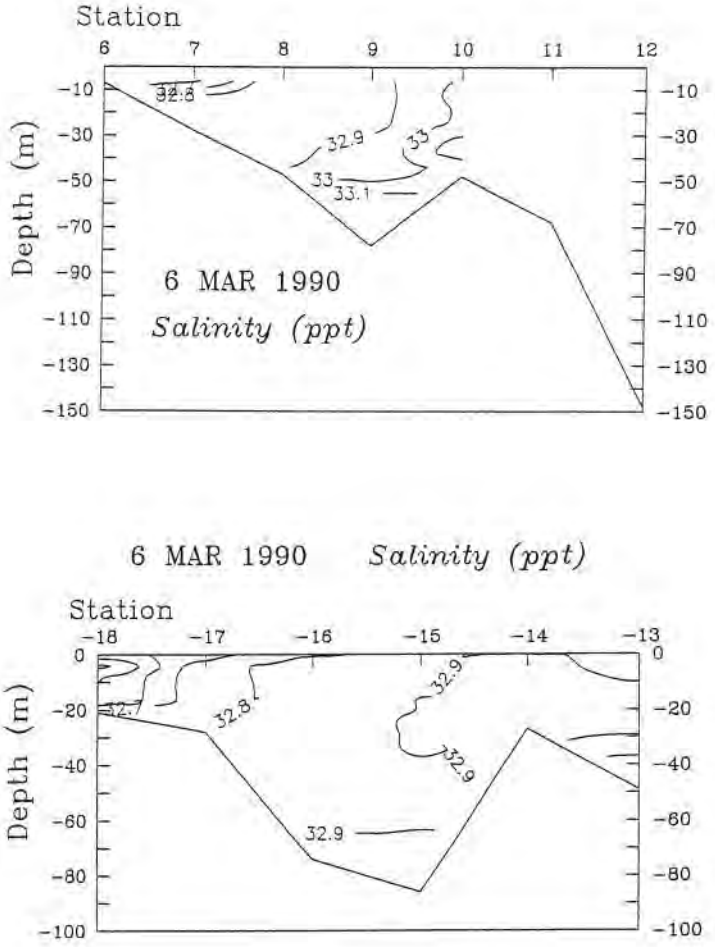


Figure 17. Vertical section contour plots of temperature on 6 March 1990 for the two southern transects in Figure 1.

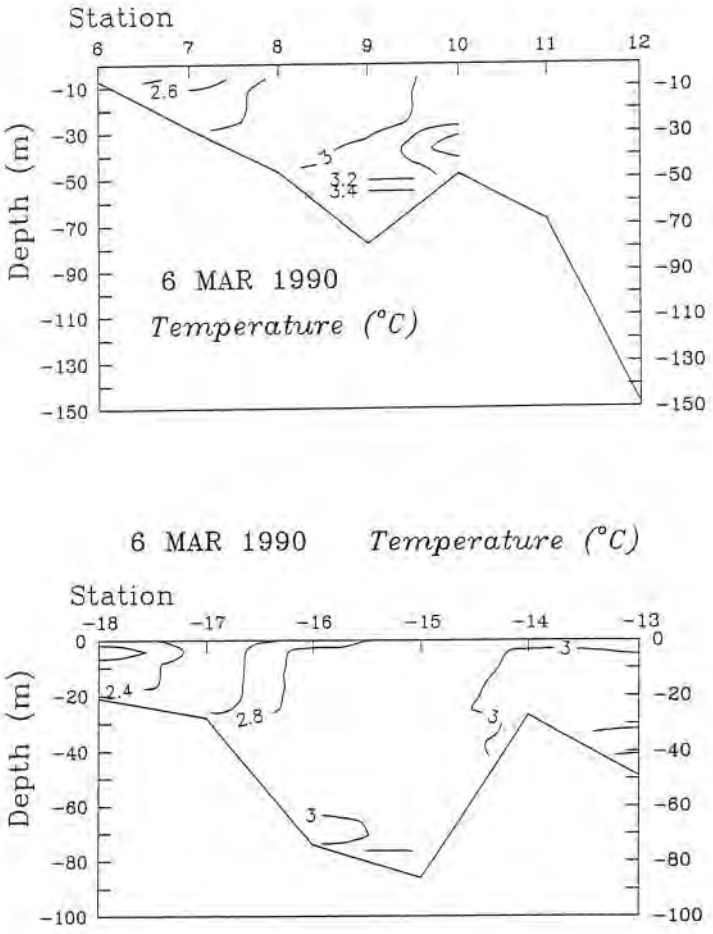


Figure 18. Vertical section contour plots of salinity on 6 March 1990 for the two southern transects in Figure 1.

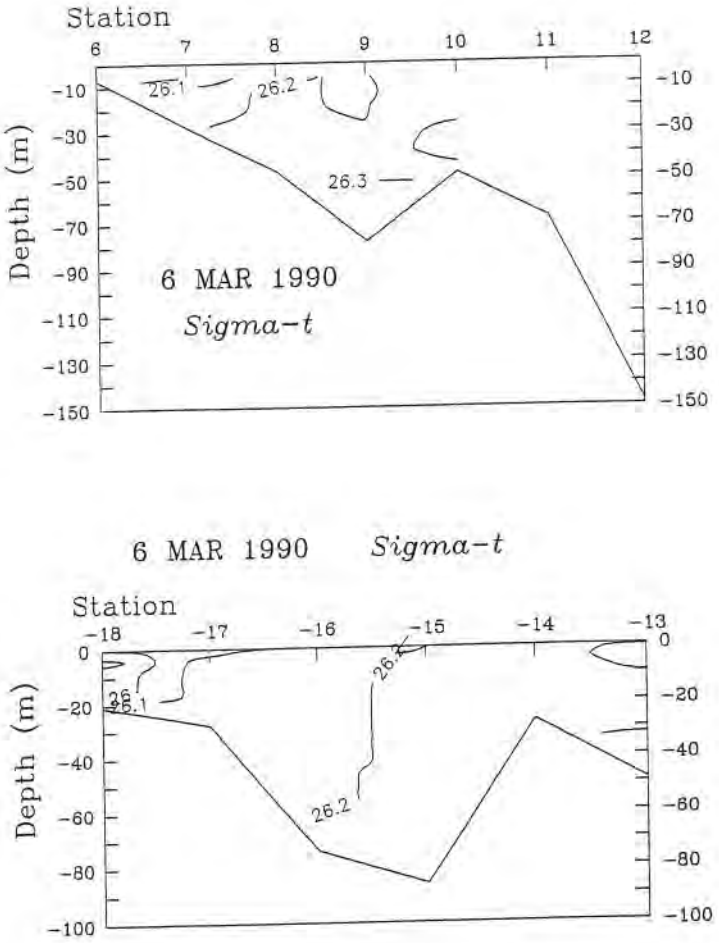


Figure 19. Vertical section contour plots of density on 6 March 1990 for the two southern transects in Figure 1.

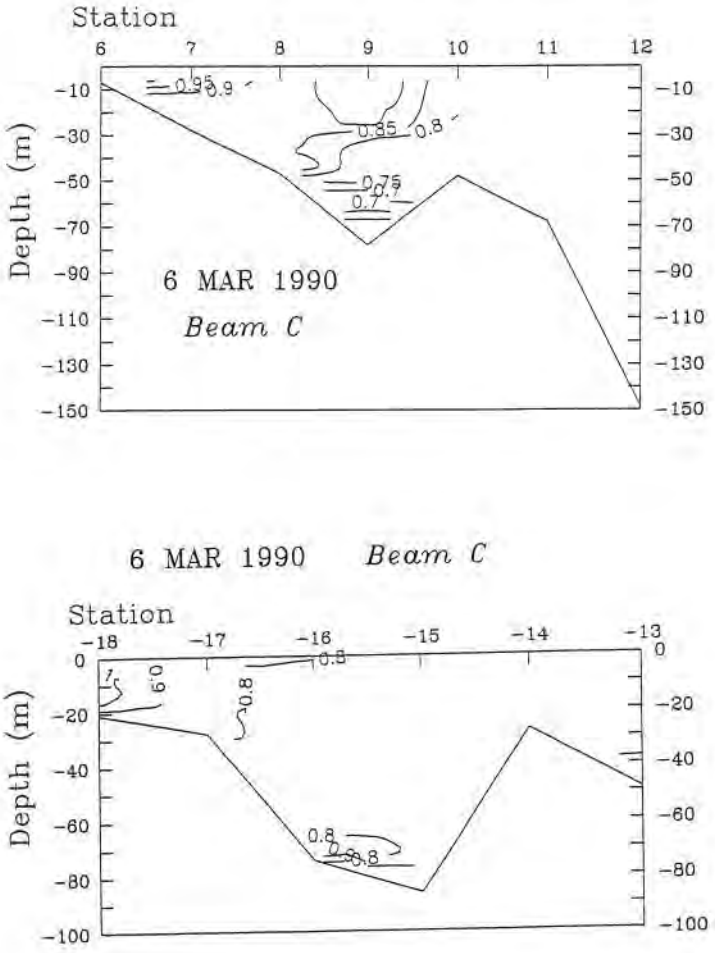


Figure 20. Vertical section contour plots of beam attenuation coefficient on 6 March 1990 for the two southern transects in Figure 1.

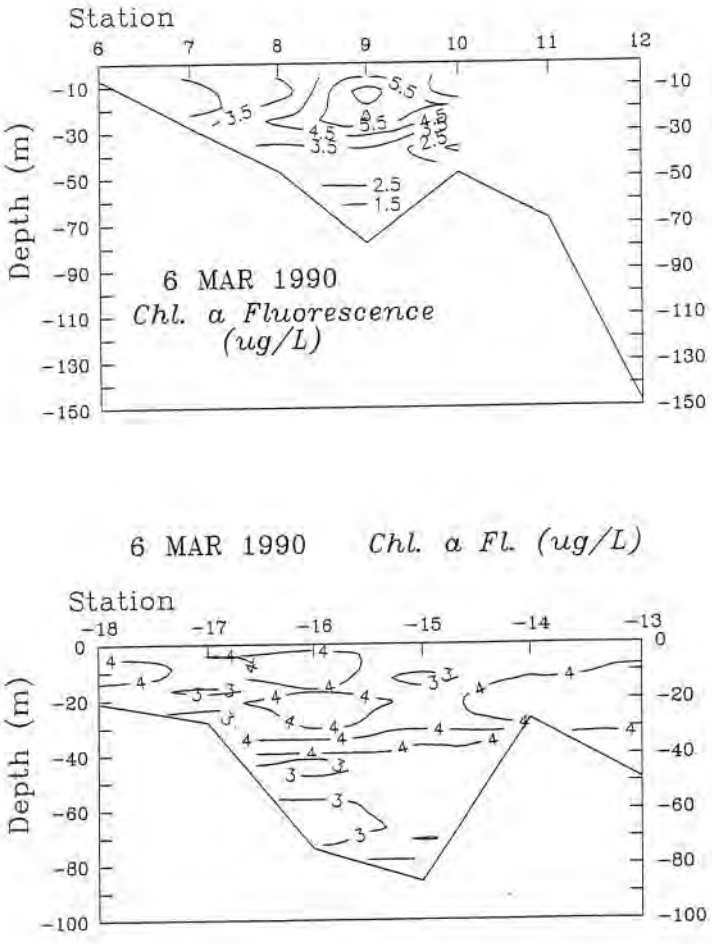


Figure 21. Vertical section contour plots of *in situ* chlorophyll *a* fluorescence on 6 March 1990 for the two southern transects in Figure 1.

TABLE 3. DISCRETE BOTTLE MEASUREMENTS – 6 MARCH 1990

Station	Time (EST)	Depth (m)	Temp (°C)	Salinity (ppt)	In Situ Chl (ug/L)	Beam Atten (1/m)	POC (ug/L)	PON (ug/L)	Chl a (ug/L)	Pheo (ug/L)
6	0726	2.7	2.22	32.21	2.40	1.19	508.48	94.36	3.60	0.54
		6.2	2.20	32.66	1.70	1.10	387.48	72.16	3.51	0.46
7	0843	1.9	2.31	32.57	2.75	1.04	338.28	64.96	3.66	0.38
		9.4	2.55	32.87	2.59	0.99			4.30	0.58
		16.1	2.66	32.96	2.34	0.86	151.28	35.76	3.64	0.74
		25.8	2.68	33.00	3.15	0.88	172.48	33.16	3.74	0.65
8	0953	2.4	2.86	33.04	3.93	0.88	291.08	55.36	6.50	0.84
		6.7	2.86	33.04	3.96	0.86	282.08	54.96	6.91	0.60
		9.9	2.87	33.04	4.11	0.87	257.28	47.96	5.78	0.81
		20.4	2.87	33.04	3.52	0.88	243.68	47.36	5.98	0.99
		45.3	2.91	33.04	3.66	0.91	187.88	36.16	5.58	0.85
9	1104	2.9	2.89	33.03	6.48	0.95	389.48	83.36	13.99	0.69
		14.7	2.88	33.02	7.78	0.96	480.88	96.56	13.05	0.83
		25.7	2.93	33.04	6.03	0.90	361.68	79.16	11.80	0.70
		50.3	3.26	33.21	2.96	0.76	150.48	28.36	3.94	0.38
		70.9	3.60	33.33	1.54	1.05	99.88	19.56	1.73	0.36
13	0143	2.6	3.00	33.10	3.47	0.78	203.48	37.36	5.59	0.79
		15.8	3.10	33.16	4.11	0.77	228.48	44.56	5.99	0.73
		26.2	3.14	33.18	4.17	0.77	212.48	42.76	5.21	0.64
		35.1	3.31	33.25	3.25	0.73	147.88	31.36	3.58	0.85
		45.3	3.44	33.30	2.73	0.66	103.48	26.76	3.06	0.61
15	0311	1.7	2.84	33.04	2.76	0.76	178.28	34.76	4.39	0.68
		9.8	2.87	33.04	4.01	0.77	200.28	42.36	4.34	0.82
		20.1	2.93	33.06	4.00	0.80	256.88	49.56	4.71	0.67
		40.7	2.92	33.06	3.65	0.77	210.08	42.96	4.75	0.63
		60.9	2.92	33.06	3.23	0.77	221.28	45.36	4.39	0.60
		82	3.22	33.13	1.85	1.20			4.38	0.61
17	0445	2.2	2.47	32.92	2.68	0.81	177.08	41.36	4.59	0.59
		15.1	2.49	32.92	2.60	0.82	195.08	39.96	2.46	0.69
		30.7	2.88	33.01	1.24	0.83	168.28	24.16	5.18	0.65
18	0524	2.1	2.03	32.53	3.13	1.02	255.68	53.56	5.95	0.70
		10.3	2.30	32.65	4.56	1.02	283.48	60.56	5.63	0.67
		19	2.30	32.65	3.75	1.01	272.68	56.16	0.95	0.98

TABLE 3 (CONT.). DISCRETE BOTTLE MEASUREMENTS – 6 MARCH 1990

Station	Time (EST)	Depth (m)	DO (mL/L)	% DO Saturation	Nitrate (uM)	Nitrite (uM)	Ammonium (uM)	Silicate (uM)	Phosphate (uM)
6	0726	2.7	7.88	101	11.36	0.27	4.60	11.09	1.49
		6.2	7.84	101	11.30	0.27	4.37	11.19	1.50
7	0843	1.9	7.84	101	11.76	0.21	3.07	10.93	1.41
		9.4	7.87	103	11.54	0.19	1.63	10.68	1.32
		16.1	7.66	100	11.15	0.15	0.59	10.65	1.21
		25.8	7.73	101	11.52	0.16	0.49	10.78	1.22
8	0953	2.4	7.88	104	10.94	0.13	0.21	10.19	1.14
		6.7	7.90	104	11.21	0.14	0.21	10.56	1.19
		9.9	7.89	104	9.81	0.14	0.23	9.01	1.09
		20.4	7.80	103	10.29	0.13	0.23	9.54	1.15
		45.3	7.80	103	11.14	0.15	0.19	10.50	1.19
9	1104	2.9	8.20	108	8.95	0.13	0.06	8.37	0.95
		14.7	8.20	108	8.92	0.14	0.11	8.44	0.96
		25.7	8.13	107	9.14	0.14	0.11	9.00	0.99
		50.3	7.65	102	13.10	0.13	0.27	13.95	1.32
		70.9	7.38	99	13.08	0.13	0.18	13.88	1.29
13	0143	2.6	7.85	104	10.61	0.17	0.34	11.14	1.16
		15.8	7.83	104	10.85	0.15	0.24	11.47	1.20
		26.2	7.81	104	11.09	0.15	0.08	11.47	1.20
		35.1	7.67	102	11.69	0.14	0.12	11.85	1.24
		45.3	7.61	102	11.74	0.13	0.24	12.09	1.24
15	0311	1.7	7.83	103	11.18	0.15	0.19	11.30	1.22
		9.8	7.82	103	11.02	0.16	0.10	11.40	1.23
		20.1	7.86	104	10.69	0.16	0.19	11.40	1.21
		40.7	7.84	103	10.84	0.15	0.29	11.61	1.22
		60.9	7.77	102	10.89	0.15	0.19	12.45	1.25
		82	7.55	100	11.36	0.13	0.35	13.28	1.33
17	0445	2.2	7.87	102	11.05	0.14	0.41	9.71	1.21
		15.1	7.86	102	10.78	0.16	0.54	9.64	1.22
		30.7	7.48	98	11.89	0.13	0.92	12.50	1.33
18	0524	2.1	8.13	104	9.51	0.17	0.43	7.35	1.05
		10.3	7.91	102	11.40	0.18	0.85	9.19	1.22
		19	7.92	102	10.93	0.18	0.79	8.81	1.20

10 April 1990:

The water column was beginning to stabilize by April when we observed a shallow thermocline of about 0.5 °C between 10 and 20m (Fig. 24). The surface water temperatures were warmer inshore of the thermal front between Stations 7 and 8, and there was some indication of a fresher surface flow entering Masachusetts Bay from the north (Fig. 22). Those fresher waters may have contributed to the establishment of a pycnocline prior to the surface warming, since the halocline was well pronounced throughout the region (Fig. 25) and the sigma-t isolines were highly correlated with salinity rather than temperature (Figs. 24-26). The spring phytoplankton bloom that appeared to have been underway in March, although not triggered initially by the classical Sverdrup upper mixed layer model as might have been expected (Townsend and Spinrad, 1986) (i.e. with the establishment of a thermocline), was continuing in April at the offshore stations (Figs. 23 and 28). Both nitrate and silicate concentrations remained quite high at all stations measured, while ammonium, silicate and phosphate were higher in the vicinity of Boston Harbor (Table 4). Phytoplankton chlorophyll was distributed throughout the upper water column and was not closely associated with the relatively shallow pycnocline. Interestingly, there was not a good correlation on this cruise between the *in situ* chlorophyll fluorescence and the descrete chlorophyll samples (Table 4). This relationship is shown in Figure 29 for all six cruises. Some of the scatter may be the result of the rosette bottle samples being collected about 1m above the height of the *in situ* fluorometer on the CTD package, but the April data clearly stand out as anomolous in that the extracted chlorophyll values were nearly always greater than the *in situ* values.

There is evidence of the bloom material sinking through the water column at several of the stations (see profiles in cruise report). These stations show what we interpret to be aggregates of phytoplankton cells that have a patchy vertical distribution pattern in relation to the background cells, thus causing the *in situ* fluorometer to spike upon encountering them in the relatively confined sensing area (about 1 cm^3). Station 13 (Fig. 30) is an example of an *in situ* fluorescence profile with large spikes throughout the 45m water column. Stations 1 and 2 (Fig. 30) show relatively smooth fluorescence traces down to about 30m depth followed by spikes the rest of the way to the bottom. These stations are within the freshwater plume eminating from the north (Fig. 22), and the smooth surface fluorescence traces in the upper water column likely represent a developing summertime dinoflaggelate population with its characteristic subsurface chlorophyll maximum layer.

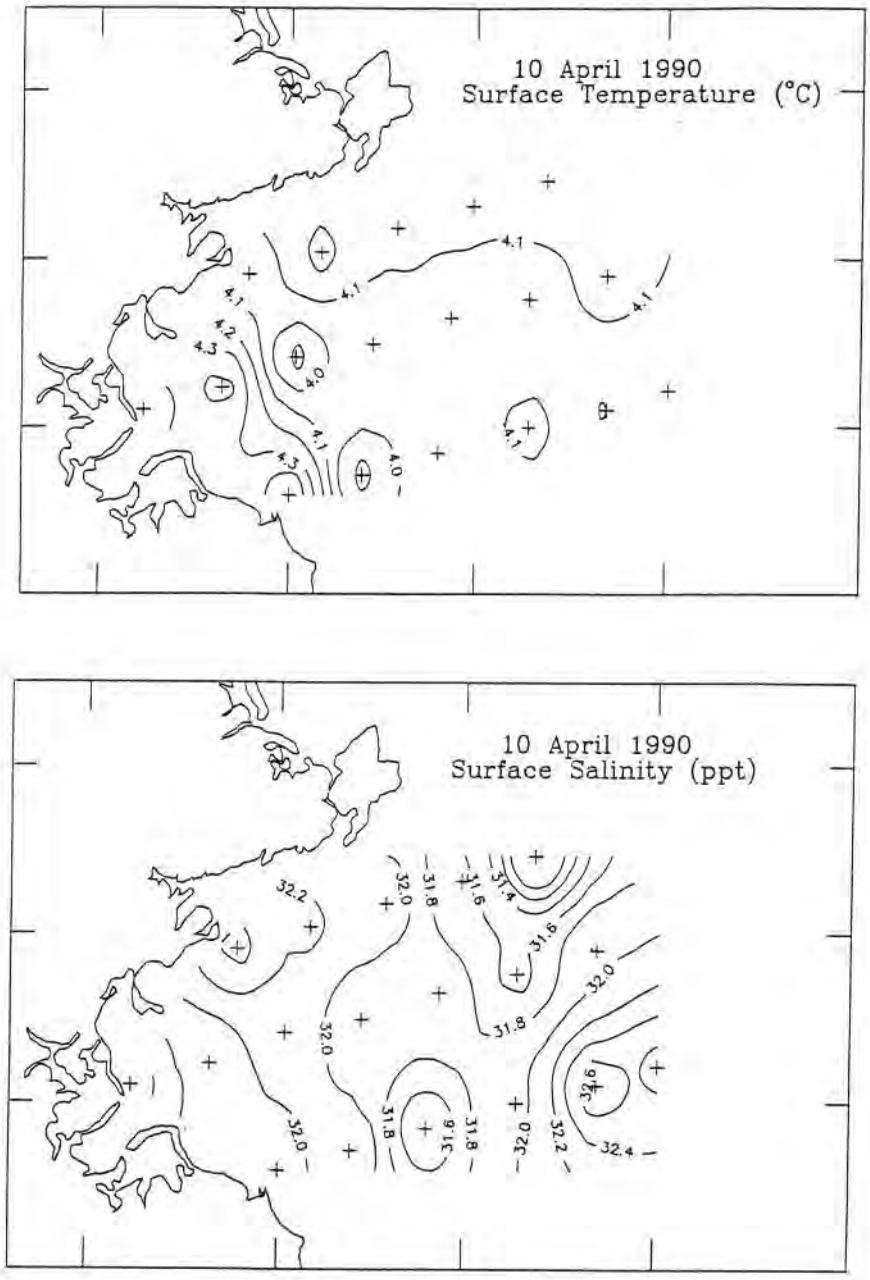


Figure 22. Surface contour plots of temperature and salinity (at 2m) for 10 April 1990.

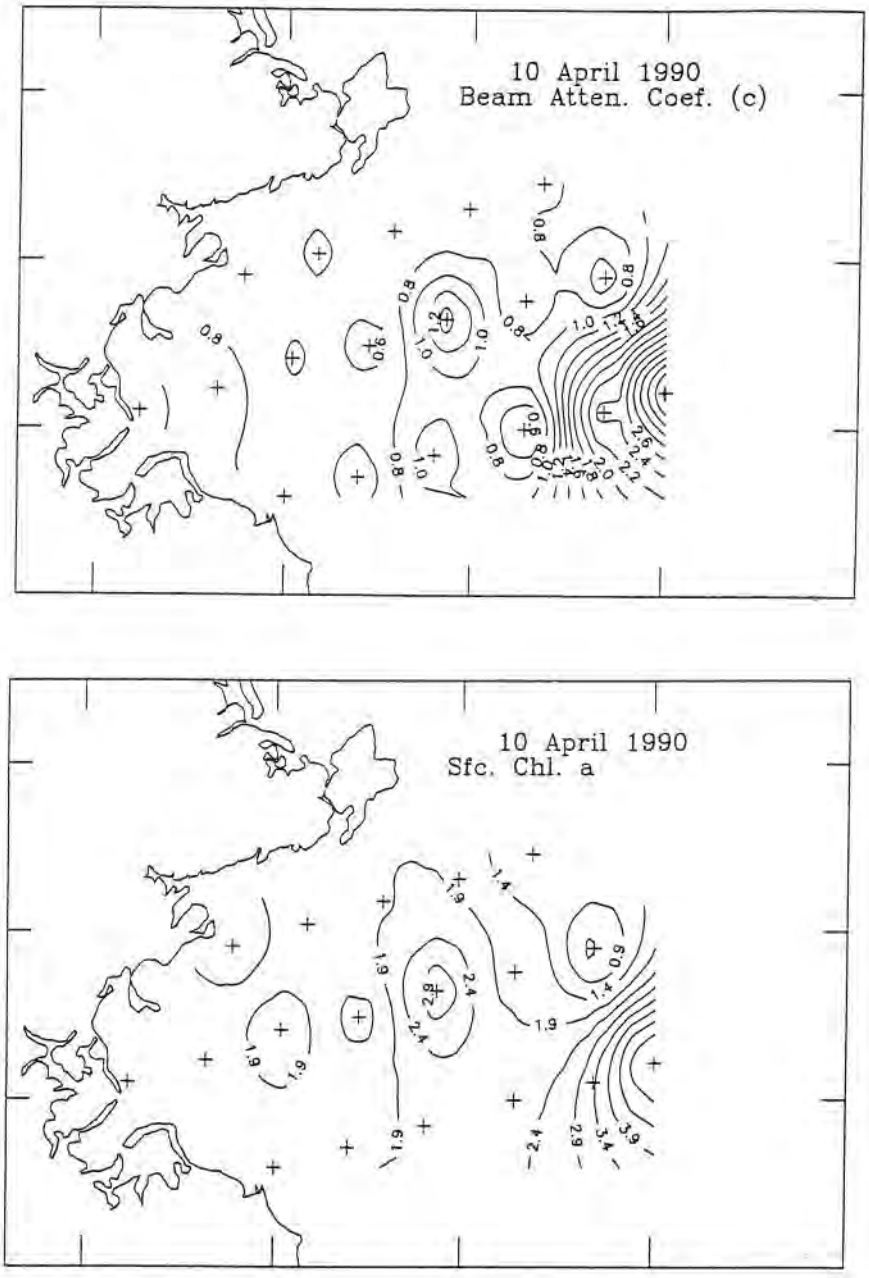


Figure 23. Surface contour plots of beam attenuation coeficient and *in situ* chlorophyll *a* fluorescence (at 2m) for 10 April 1990.

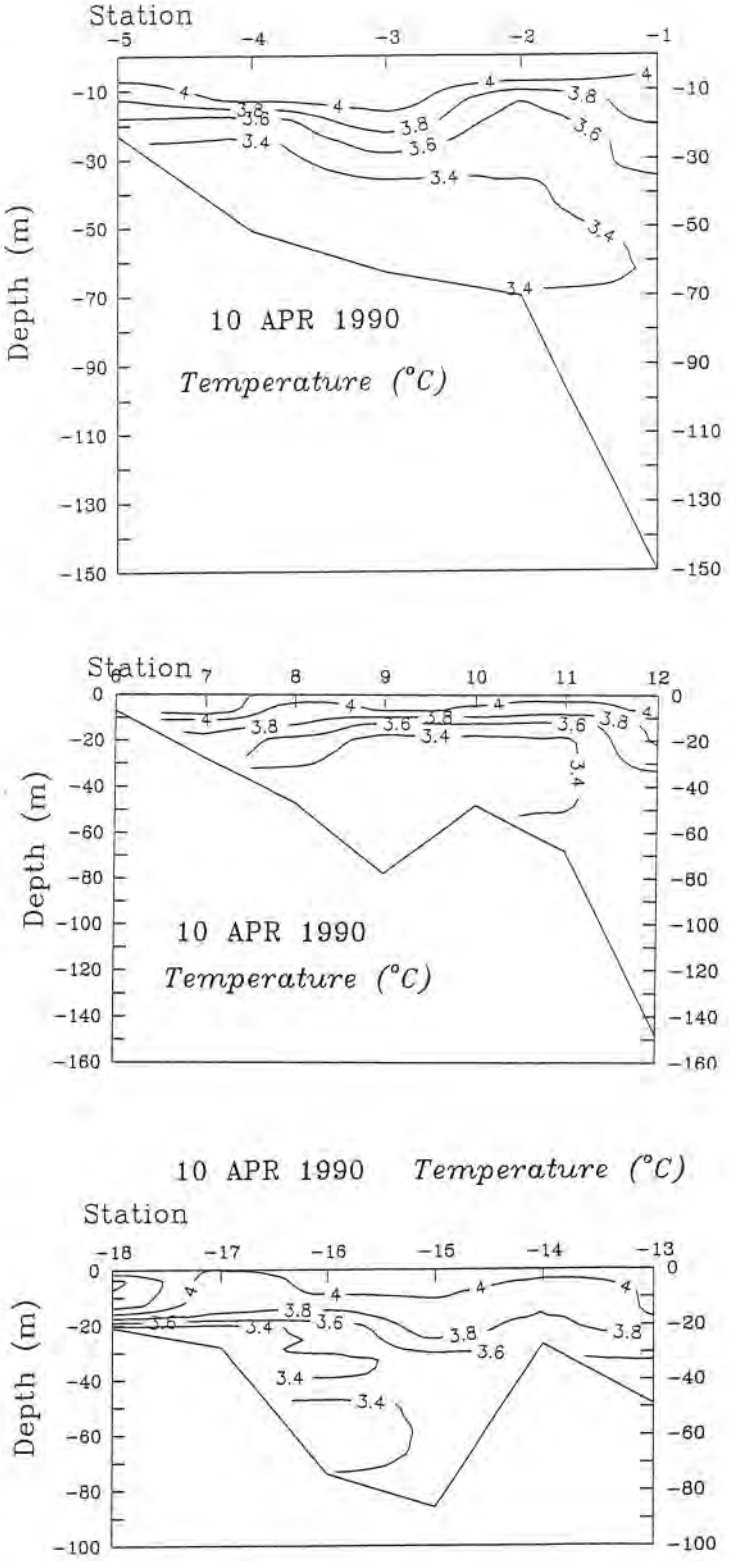


Figure 24. Vertical section contour plots of temperature on 10 April 1990 for each of the four transects in Figure 1.

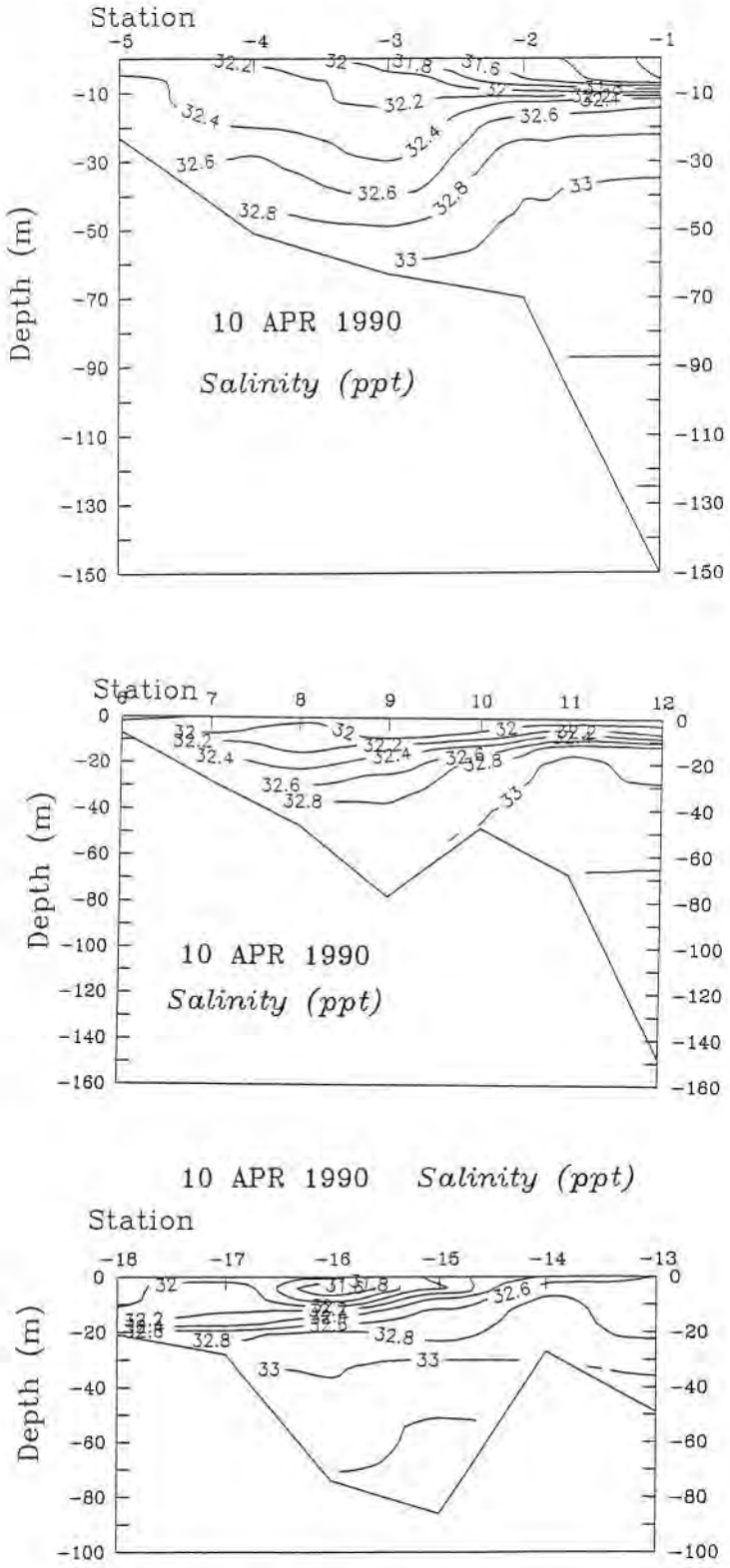


Figure 25. Vertical section contour plots of salinity on 10 April 1990 for each of the four transects in Figure 1.

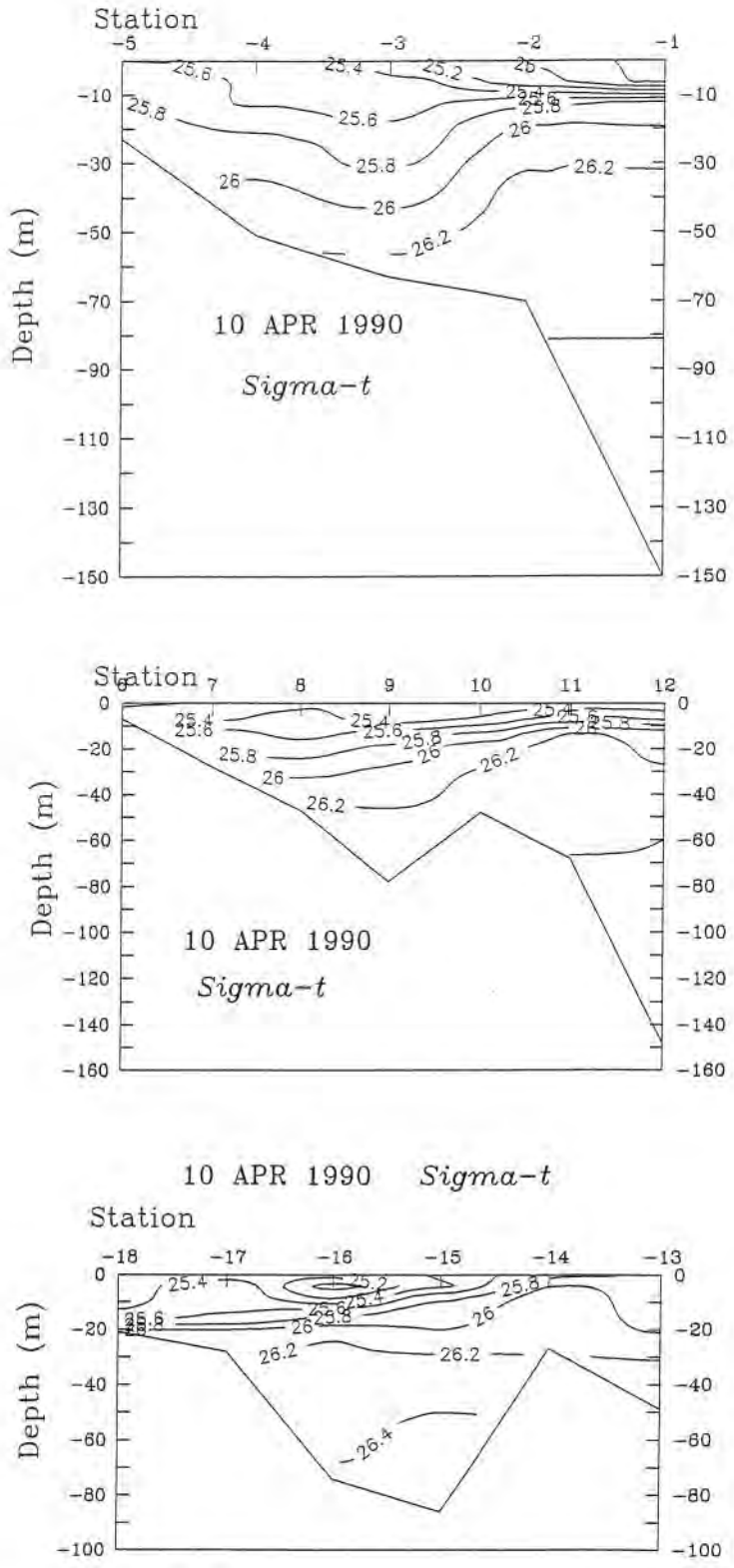


Figure 26. Vertical section contour plots of density on 10 April 1990 for each of the four transects in Figure 1.

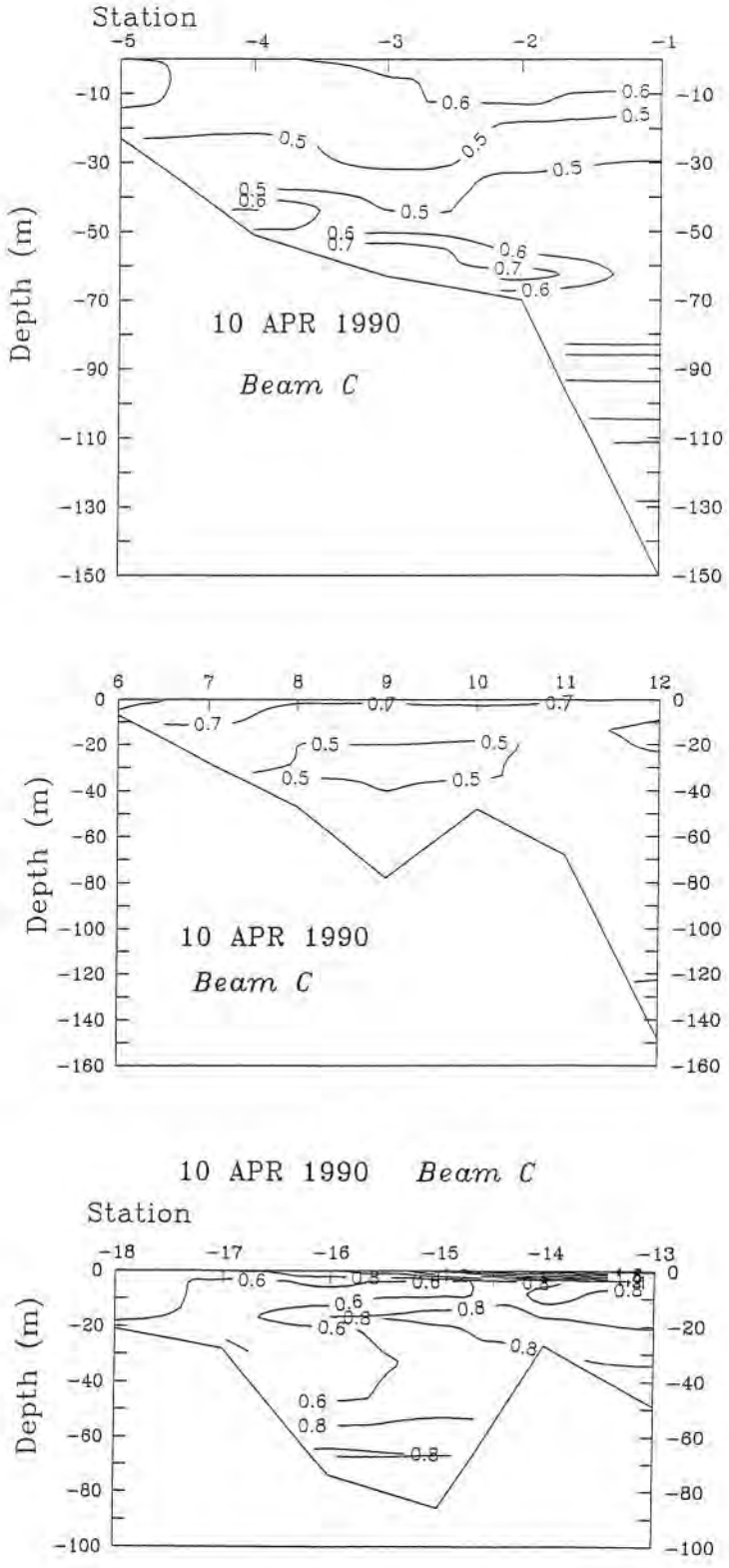


Figure 27. Vertical section contour plots of beam attenuation coefficient on 10 April 1990 for each of the four transects in Figure 1.

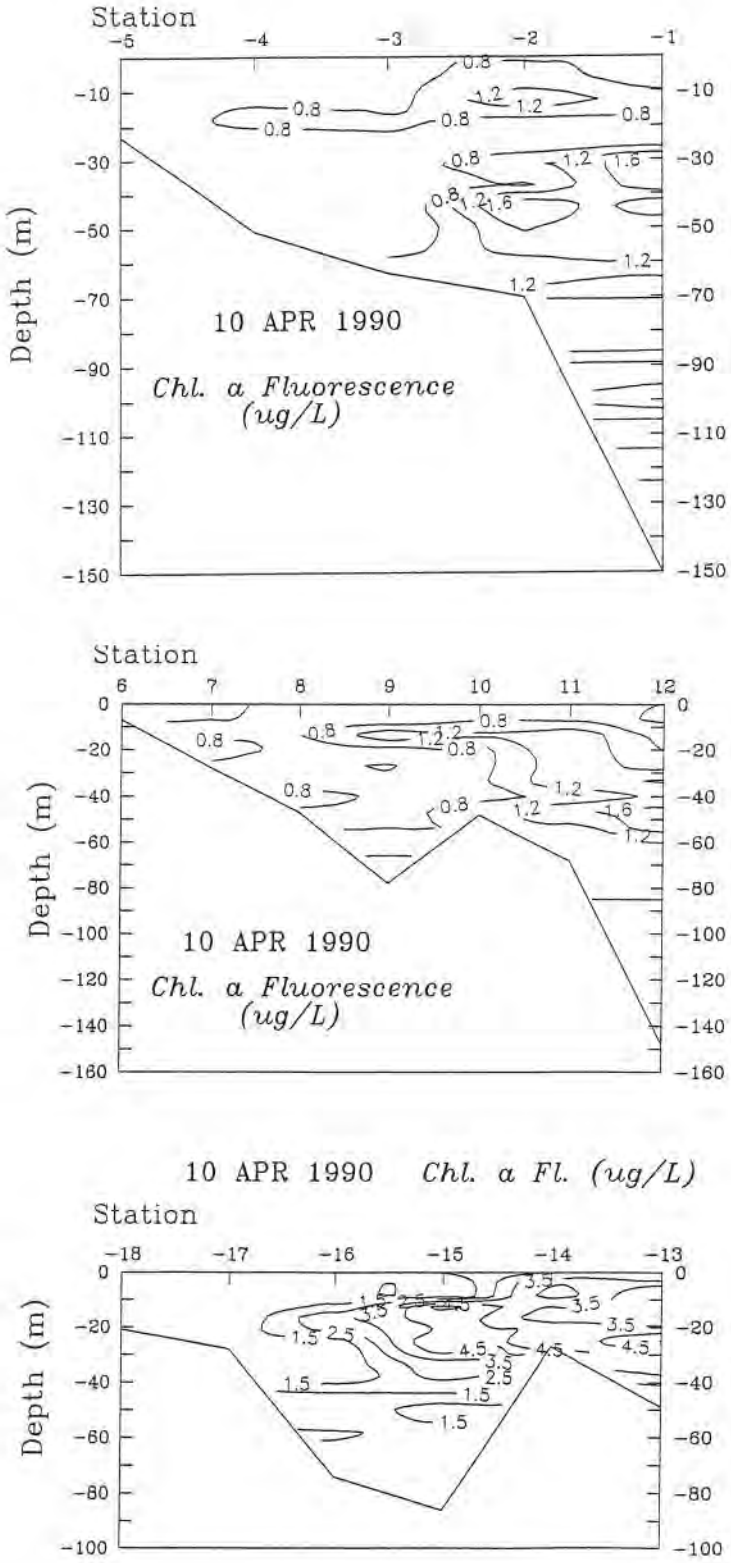


Figure 28. Vertical section contour plots of *in situ* chlorophyll *a* fluorescence on 10 April 1990 for each of the four transects in Figure 1.

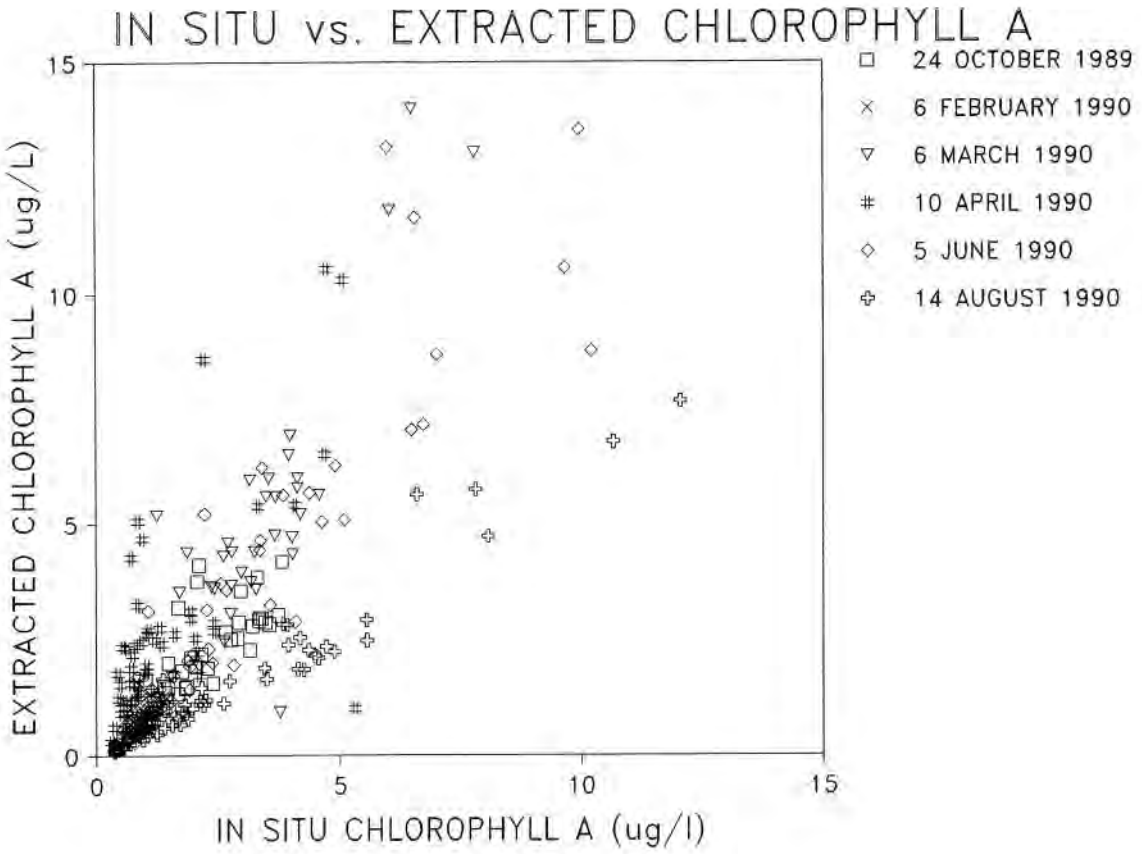


Figure 29. Relationship between the Sea Tech *in situ* chlorophyll *a* fluorescence versus chlorophyll *a* concentrations based on acetone extractions on descrete samples for each of the six cruises.

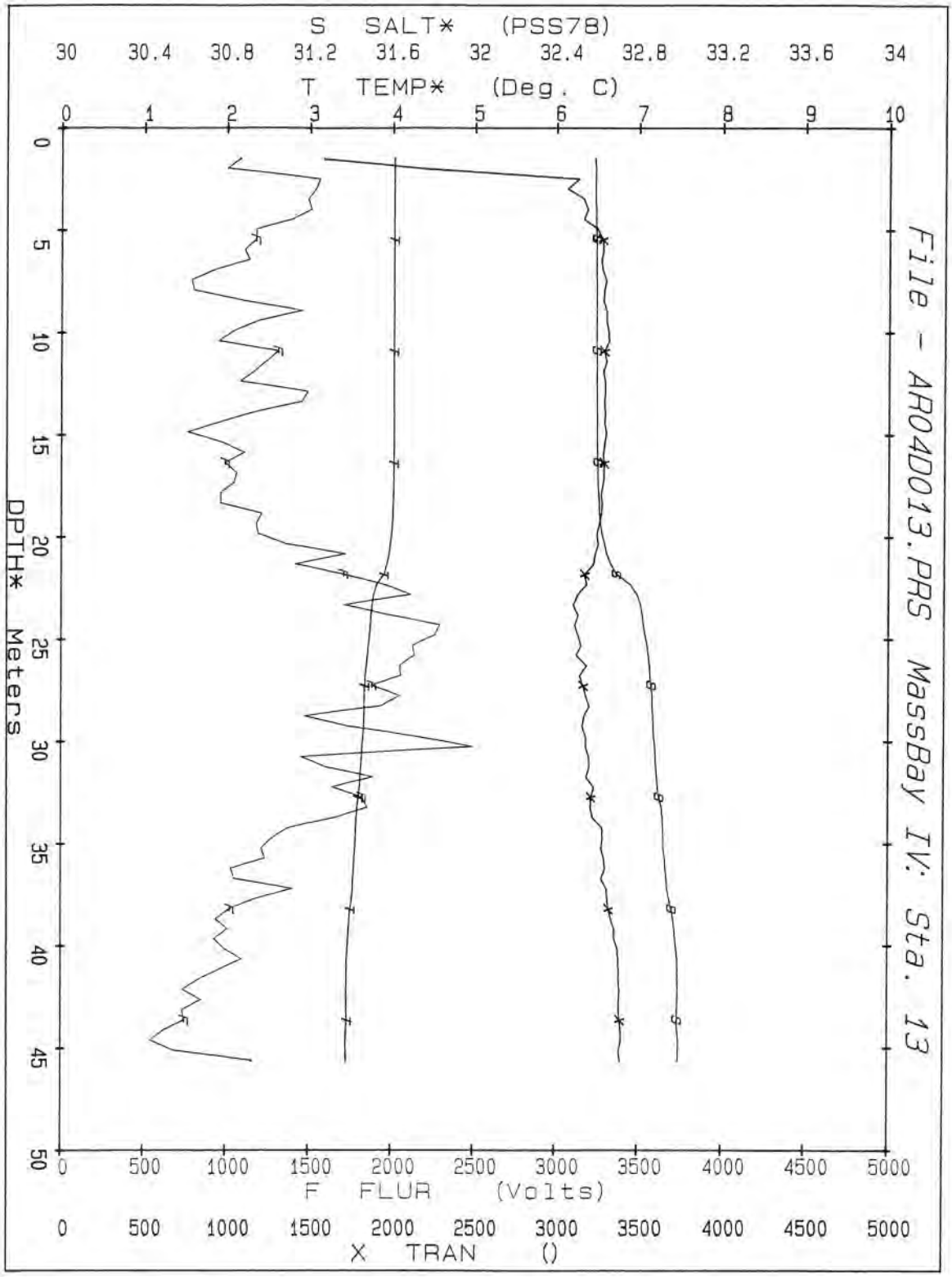


Figure 30. Vertical profiles of temperature, salinity, *in situ* fluorescence, and light transmission on 10 April 1990 for: a) Sta. 13; b) Sta. 1; c) Sta. 2.

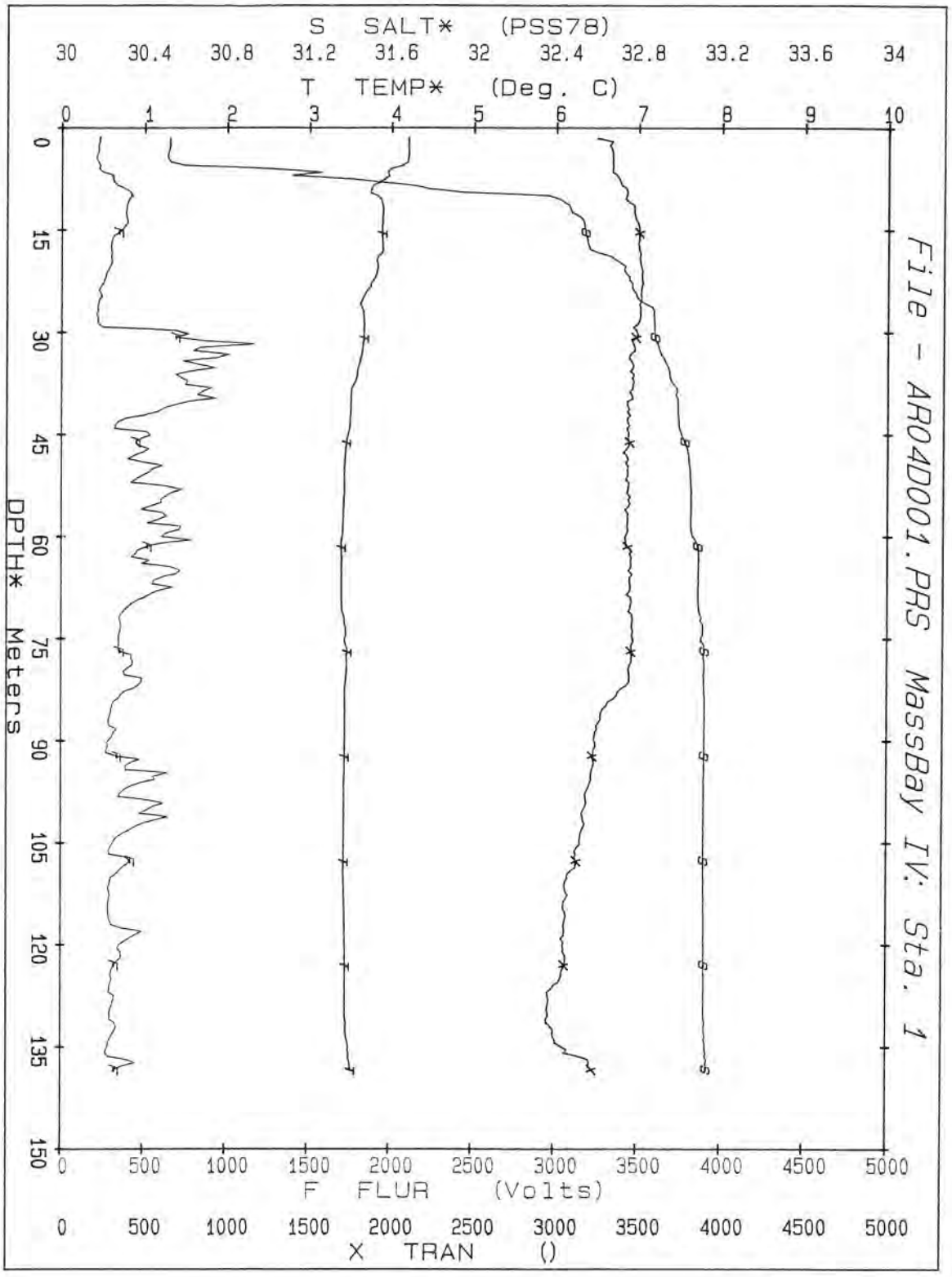


Figure 30. (Con't)

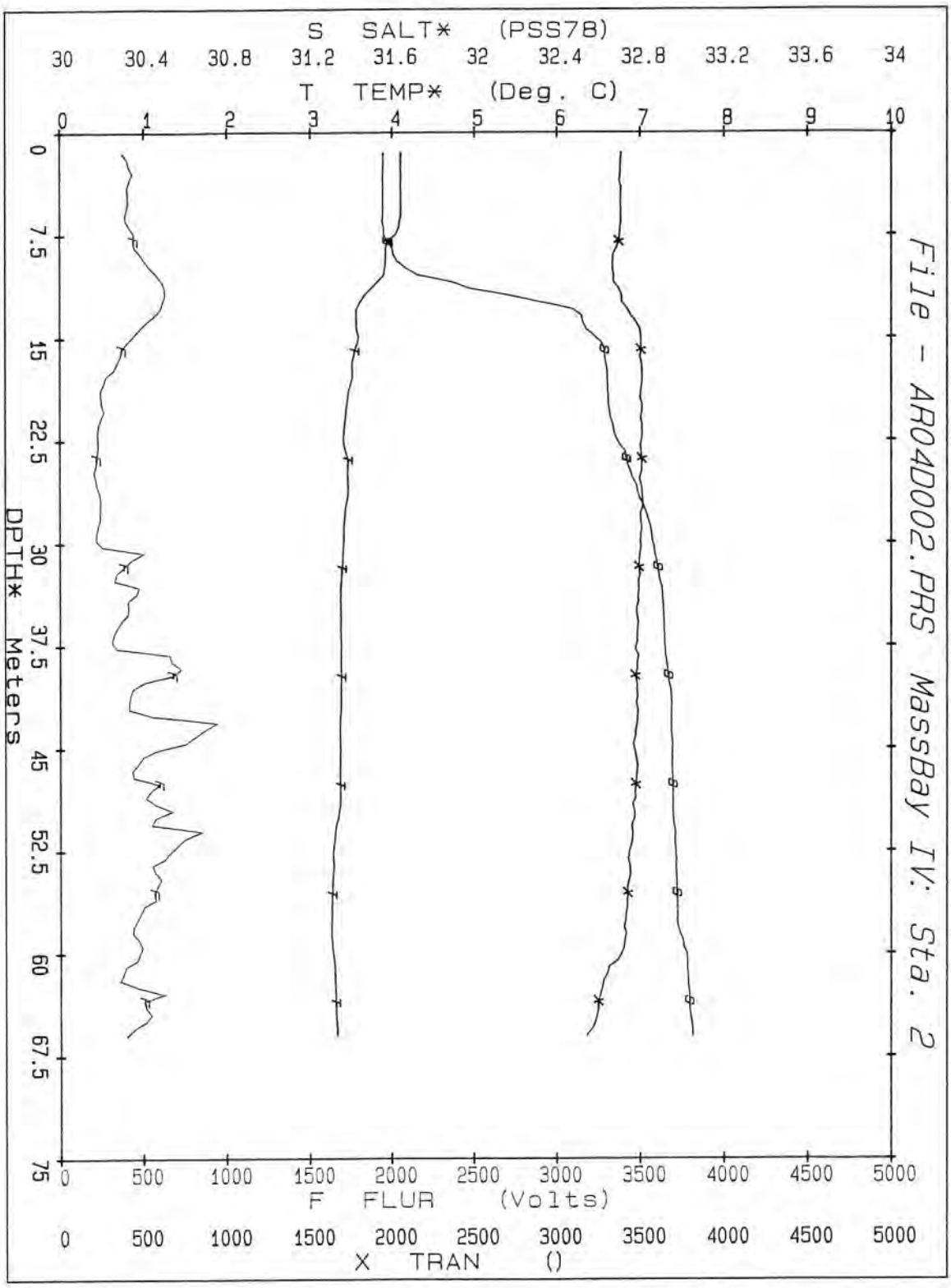


Figure 30. (Con't)

TABLE 4. DISCRETE BOTTLE MEASUREMENTS – 10 APRIL 1990

Station	Time (EST)	Depth (m)	Temp (°C)	Salinity (ppt)	In Situ Chl (ug/L)	Beam Atten (1/m)	POC (ug/L)	PON (ug/L)	Chl a (ug/L)	Pheo (ug/L)
1	1548	1.7	4.27	30.49	0.58	0.78	106.78	23.39	0.96	0.25
		10.2	3.73	31.93	1.29	0.57	275.78	49.39	2.75	0.45
		20.4	3.83	32.81	0.63	0.47	193.58	34.19	2.32	0.46
		35.5	3.61	33.01	2.40	0.52	171.58	29.39	2.85	0.88
		50.2	3.44	33.12	2.40	0.56	208.98	32.19	2.67	0.95
		75.4	3.46	33.19	1.35	0.52				
		100.3	3.44	33.19	0.85	0.86				
		139.2	3.53	33.21	0.75	0.83				
3	1730	2.1	4.14	32.17	0.72	0.61	155.18	28.99	1.89	0.17
		14.6	4.12	32.19	0.80	0.61	484.18	80.79	2.38	0.21
		35.2	3.38	32.50	0.52	0.48	114.78	22.79	1.05	0.22
		60.6	3.35	32.98	0.87	0.98	132.18	23.99	1.37	0.82
5	1845	2.5	4.04	32.46	0.58	0.66	146.18	23.39	1.05	0.19
		10.5	3.90	32.48	0.52	0.65	130.98	23.39	0.93	0.26
		19.0	3.55	32.57	0.57	0.53	104.58	19.19	0.60	0.25
6	0844	1.2	4.45	31.62	1.14	1.10	260.18	44.19	1.42	0.57
		5.7	4.13	32.06	0.65	0.90	244.38	40.79	1.17	0.58
7	0943	1.8	4.43	31.82	1.01	0.91	288.38	46.79	1.83	0.34
		9.9	4.05	32.26	0.72	0.70	146.98	27.19	1.58	0.40
		21.0	3.74	32.48	0.58	0.65	89.18	16.59	1.20	0.53
		27.2	3.71	32.51	1.04	0.69	208.18	34.39	1.83	0.42
8	1105	2.7	3.83	32.11	0.74	0.52	195.18	36.99	2.19	0.13
		9.8	3.83	32.11	0.71	0.52	304.18	58.99	4.27	0.18
		15.9	3.57	32.23	0.85	0.52	223.78	47.99	5.06	0.25
		27.0	3.50	32.51	0.49	0.48	147.98	27.39	1.55	0.21
		43.7	3.31	32.92	0.82	0.71	138.78	24.39	1.55	0.53
9	1201	2.4	4.03	31.82	0.46	0.53	151.98	26.19	1.24	0.12
		12.4	3.55	32.26	2.18	0.53	482.18	87.39	8.56	0.33
		25.0	3.30	32.64	0.38	0.45	172.58	32.59	0.62	0.28
		50.3	3.34	32.96	1.22	0.50	109.98	19.19	0.84	0.56
		77.6	3.39	33.07	2.09	0.71	144.58	24.79	1.75	0.97
10	1259	2.1	4.06	31.98	0.84	0.86	301.98	51.39	3.24	0.12
		8.4	3.97	32.03	0.94	0.53	219.78	41.99	4.68	0.29
		27.8	3.24	32.92	0.68	0.49	106.38	19.99	0.86	0.54
		47.0	3.30	33.00	0.86	0.62	103.38	15.79	0.92	0.75
11	1341	2.0	4.03	31.55	0.44	0.62	150.78	28.99	1.78	0.19
		11.9	3.52	32.96	1.92	0.51	154.58	29.59	3.10	-0.22
		25.3	3.36	33.07	2.06	0.56	181.78	33.59	2.22	0.93
		46.3	3.38	33.12	1.59	0.64	112.98	21.99	1.76	0.94
		68.1	3.49	33.20	0.75	0.72	236.38	37.59	1.21	0.88
12	1443	2.3	4.13	32.08	0.31	0.49	79.78	15.59	0.31	0.14
		12.4	3.86	32.89	0.92	0.50	170.78	27.99	1.70	1.07
		20.9	3.78	32.95	1.60	0.50	138.58	25.99	2.62	0.49
		34.6	3.60	33.10	1.33	0.53	131.38	23.99	2.41	0.56
		45.9	3.58	33.12	1.19	0.52	151.78	29.39	2.50	0.41
		81.3	3.54	33.21	1.35	0.53				
		121.1	3.56	33.25	0.46	0.67				
		159.0	3.57	33.25	0.70	0.80				
13	0326	1.9	4.04	32.68	4.06	2.37	271.18	45.19	5.41	0.63
		16.0	4.04	32.68	3.30	0.74	313.58	61.59	5.38	0.56
		25.3	3.73	32.91	5.05	0.90	350.58	66.59	10.30	1.08
		36.0	3.56	33.00	4.67	0.73	215.38	42.59	6.50	1.11
		45.5	3.46	33.07	1.93	0.62	150.58	21.79	2.95	1.37
15	0459	1.6	4.12	31.99	0.51	0.36	96.58	17.39		
		10.3	4.00	32.59	5.31	0.83	133.18	21.79	1.03	0.21
		20.5	3.90	32.75	4.71	0.83	400.38	76.79	10.54	0.73
		41.0	3.43	33.19	2.01	0.71	138.38	27.99	2.53	0.66
		61.2	3.42	33.23	0.83	0.83	141.38	26.19	1.29	0.60
		79.8	3.41	33.24	0.92	0.85				
17	0634	2.0	3.87	32.19	1.03	0.59	148.78	28.99	1.94	0.17
		14.3	3.85	32.21	0.90	0.51				
		28.3	3.34	32.86	1.07	0.63	148.78	27.39	2.71	0.62
18	0713	2.0	4.47	31.95	0.92	0.80	248.38	42.792	2.45	0.37
		9.9	4.39	31.98	1.04	0.78	195.38	34.992	2.62	0.38
		18.0	3.78	32.37	0.54	0.64	197.18	36.192	2.35	0.39

TABLE 4 (CONT.). DISCRETE BOTTLE MEASUREMENTS – 10 APRIL 1990

Station	Time (EST)	Depth (m)	DO (mL/L)	% DO Saturation	Nitrate (uM)	Nitrite (uM)	Ammonium (uM)	Silicate (uM)	Phosphate (uM)
1	1548	1.7	7.95	107	5.18	0.08	1.51	10.53	0.78
		10.2	8.05	107	4.76	0.09	1.27	9.42	0.77
		20.4	8.06	108	4.28	0.10	1.15	5.44	0.71
		35.5	7.76	104	5.78	0.14	1.40	6.06	0.83
		50.2	7.52	100	7.76	0.15	1.62	7.89	1.02
		75.4	7.42	99	8.85	0.13	1.83	9.22	1.13
		100.3	7.27	97	9.59	0.17	1.95	10.76	1.22
		139.2	7.33	98	9.60	0.16	1.80	10.35	1.20
3	1730	2.1	7.83	106	3.61	0.16	1.59	5.73	0.71
		14.6	7.81	105	3.65	0.09	1.54	5.66	0.74
		35.2	7.72	102	4.12	0.15	1.65	5.41	0.74
		60.6	7.43	99	5.92	0.12	2.27	8.23	1.01
5	1845	2.5	7.65	103	3.95	0.15	1.72	5.24	0.78
		10.5	7.68	103	3.96	0.12	1.67	5.14	0.75
		19.0	7.66	102	4.14	0.14	1.74	5.35	0.78
6	0844	1.2	7.28	99	4.61	0.24	5.87	6.53	1.17
		5.7	7.31	99	4.47	0.21	5.14	5.83	1.08
7	0943	1.8	7.54	102	4.07	0.25	4.68	5.05	0.98
		9.9	7.54	102	3.75	0.16	2.53	4.78	0.81
		21.0	7.52	101	3.72	0.23	2.33	4.79	0.80
		27.2	7.54	101	3.86	0.23	3.67	4.90	0.90
8	1105	2.7	7.93	106	3.82	0.14	1.29	6.69	0.80
		9.8	8.00	107	3.73	0.12	1.27	6.48	0.73
		15.9	7.94	106	4.03	0.12	1.23	6.47	0.72
		27.0	7.90	105	4.53	0.10	1.30	6.23	0.73
		43.7	7.61	101	5.76	0.10	2.01	7.40	0.91
9	1201	2.4	7.91	106	3.56	0.12	1.52	6.18	0.66
		12.4	8.04	107	4.01	0.12	1.11	5.86	0.74
		25.0	7.69	102	4.66	0.13	1.87	5.03	0.74
		50.3	7.73	103	5.41	0.13	1.84	5.40	0.81
		77.6	7.57	101	6.31	0.11	1.99	6.76	0.93
10	1259	2.1	8.02	108	3.12	0.17	1.08	6.28	0.60
		8.4	7.99	107	3.37	0.17	1.03	6.07	0.63
		27.8	7.71	102	5.25	0.16	2.19	5.72	0.74
		47.0	7.61	101	5.83	0.15	2.04	6.99	0.90
11	1341	2.0	8.05	108	4.41	0.00	1.03	7.38	0.59
		11.9	7.78	104	5.72	0.01	0.96	5.94	0.71
		25.3	6.72	90	6.96	0.03	1.58	7.09	0.83
		46.3	7.48	100	7.84	0.12	1.80	8.20	0.96
		68.1	7.39	99	8.56	0.13	1.66	9.66	1.16
12	1443	2.3	7.87	106	4.35	0.00	1.36	7.16	0.63
		12.4	7.99	108	4.64	0.00	1.16	5.44	0.66
		20.9	7.91	106	5.23	0.00	1.21	5.65	0.73
		34.6	7.71	103	6.83	0.26	1.27	6.68	0.84
		45.9	7.69	106	5.52	0.25	1.23	6.29	0.83
		81.3	7.42	99	9.64	0.02	1.49	9.28	1.03
		121.1	7.28	98	10.35	0.10	1.52	11.17	1.26
		159.0	7.29	98	10.42	0.11	1.51	11.38	1.24
13	0326	1.9	8.02	108	3.00	0.10	0.83	3.52	0.49
		16.0	8.06	109	2.85	0.10	0.75	3.69	0.50
		25.3	7.93	106	4.00	0.07	0.85	4.40	0.60
		36.0	7.57	101	6.08	0.12	1.74	6.16	0.85
		45.5	7.37	98	7.26	0.13	2.34	7.63	1.02
15	0459	1.6	7.91	107	4.31	0.12	1.62	6.95	0.67
		10.3	7.85	106	4.77	0.13	1.49	7.19	0.70
		20.5	8.17	110	1.55	0.06	0.83	1.90	0.32
		41.0	7.19	96	10.09	0.12	2.04	9.54	1.20
		61.2	7.08	95	10.67	0.13	2.09	11.12	1.27
		79.8	7.05	94	10.76	0.13	2.03	11.45	1.31
17	0634	2.0	8.03	108	3.30	0.10	1.09	5.46	0.58
		14.3							
		28.3	7.63	102	4.94	0.11	1.96	5.29	0.79
18	0713	2.0	7.54	103	3.70	0.19	2.98	4.11	0.86
		9.9	7.63	104	3.56	0.19	2.69	4.27	0.81
		18.0	7.52	101	3.63	0.20	2.93	4.16	0.85

5 June 1990:

Vertical stratification of the water column was well underway by June, with surface temperatures exceeding 11 °C (Figs. 31 and 33). A fresher surface water layer extended diagonally across the Bay from the northeast to the southwest (Fig. 34) and contributed to the steepening density gradient at 10-15m (Figs. 33-35). Chlorophyll concentrations were quite high at the inner stations (Figs. 32 and 37) and may reflect sustained growth stemming from injections of anthropogenic nitrogen loadings from both Salem and Boston Harbors. Surface nitrate and silicate concentrations were low or depleated at those stations (Table 5). Surface values of ammonium and silicate were higher near the mouth of Boston Harbor (Table 5). The freshwater plume or lens eminating from the northeast was not associated with the increased chlorophyll concentrations. The flourescence traces were, in general, smoother than in April, with a few exceptions. There was again some suggestion of sinking phytoplankton material, particularly at Stations 9, 10 and 11, which also showed relatively deep secondary chlorophyll maximum layers (Fig. 38). Oxygen concentrations appeared to be somewhat lower in the deeper waters (>50m) within Massachusetts Bay, although all concentrations were greater than 85% saturation.

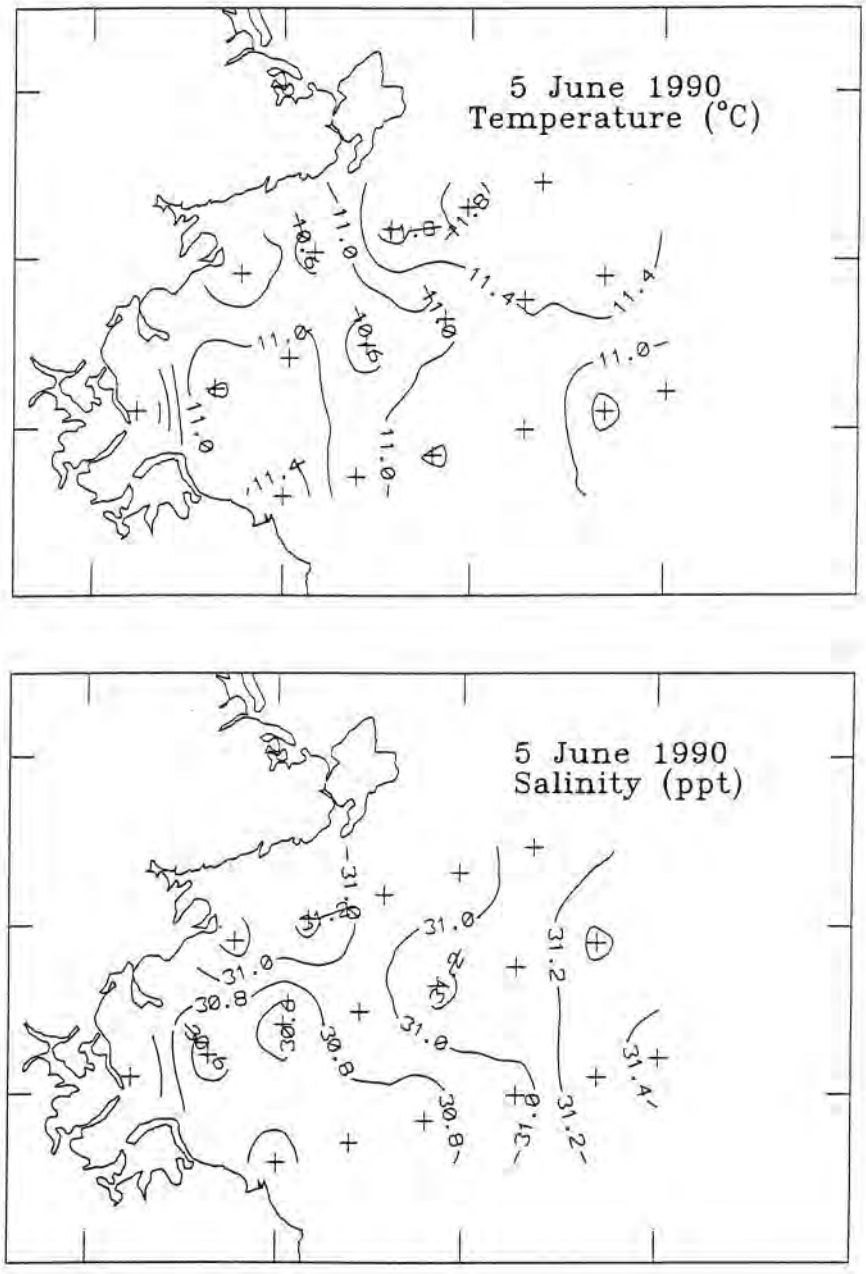


Figure 31. Surface contour plots of temperature and salinity (at 2m) for 5 June 1990.

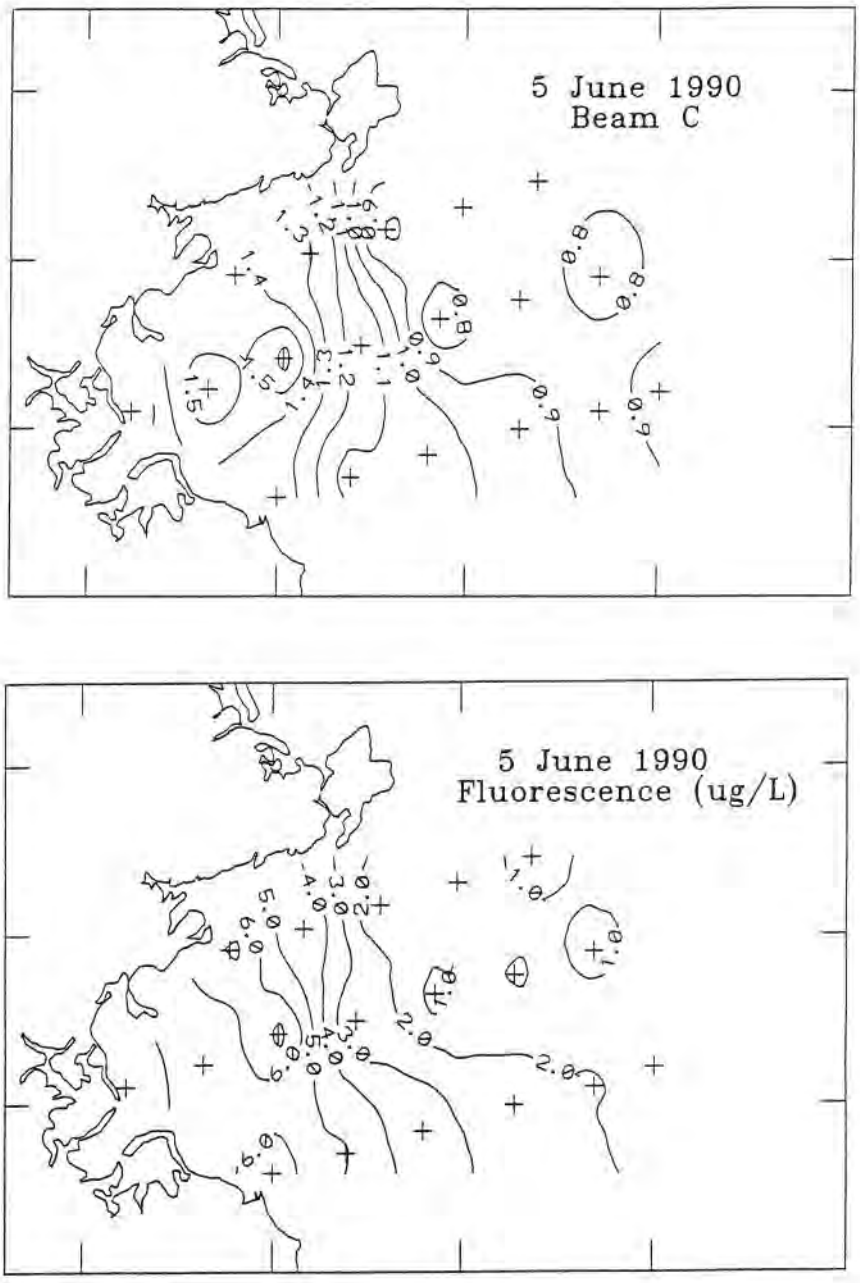


Figure 32. Surface contour plots of beam attenuation coeficient and *in situ* chlorophyll *a* fluorescence (at 2m) for 5 June 1990.

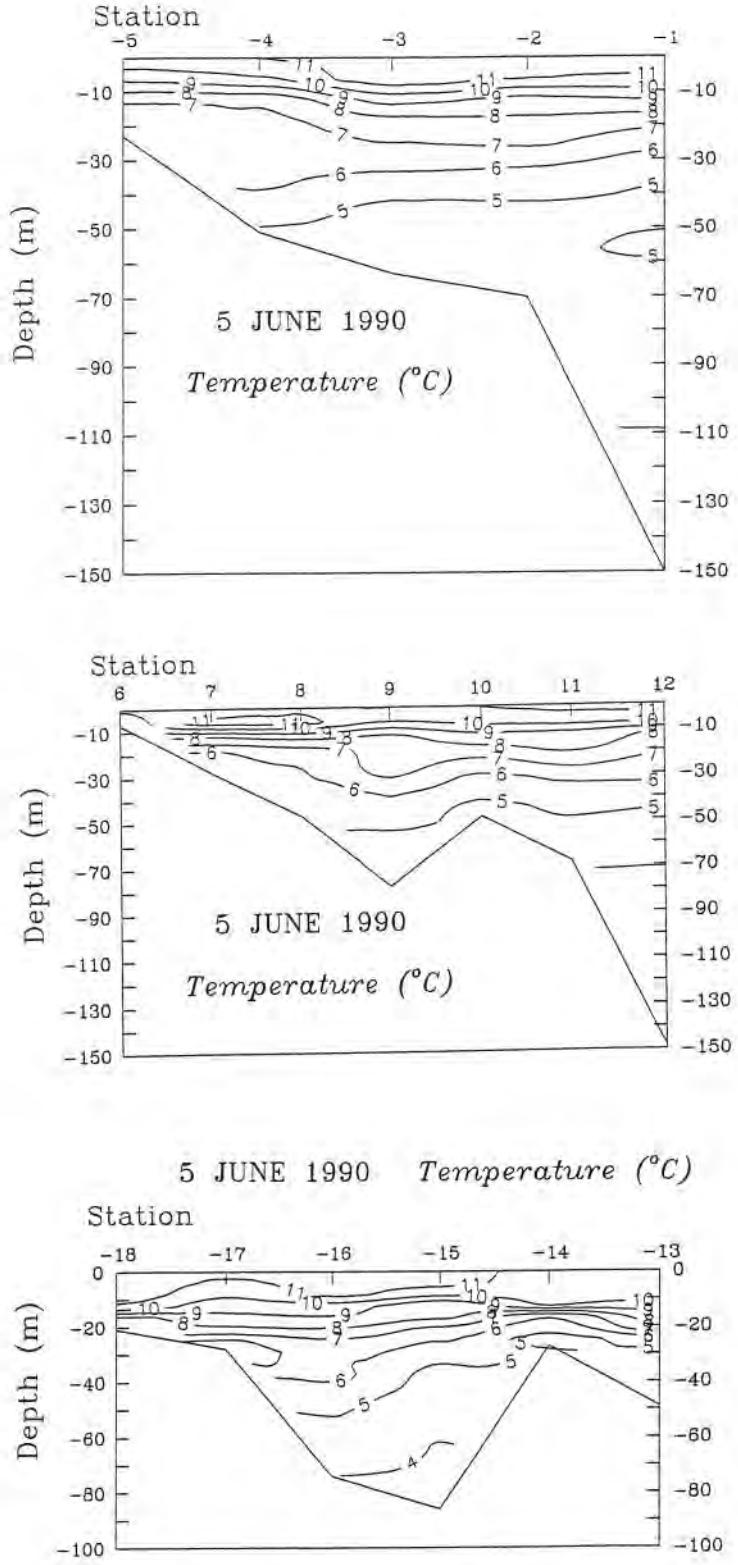


Figure 33. Vertical section contour plots of temperature on 5 June 1990 for each of the four transects in Figure 1.

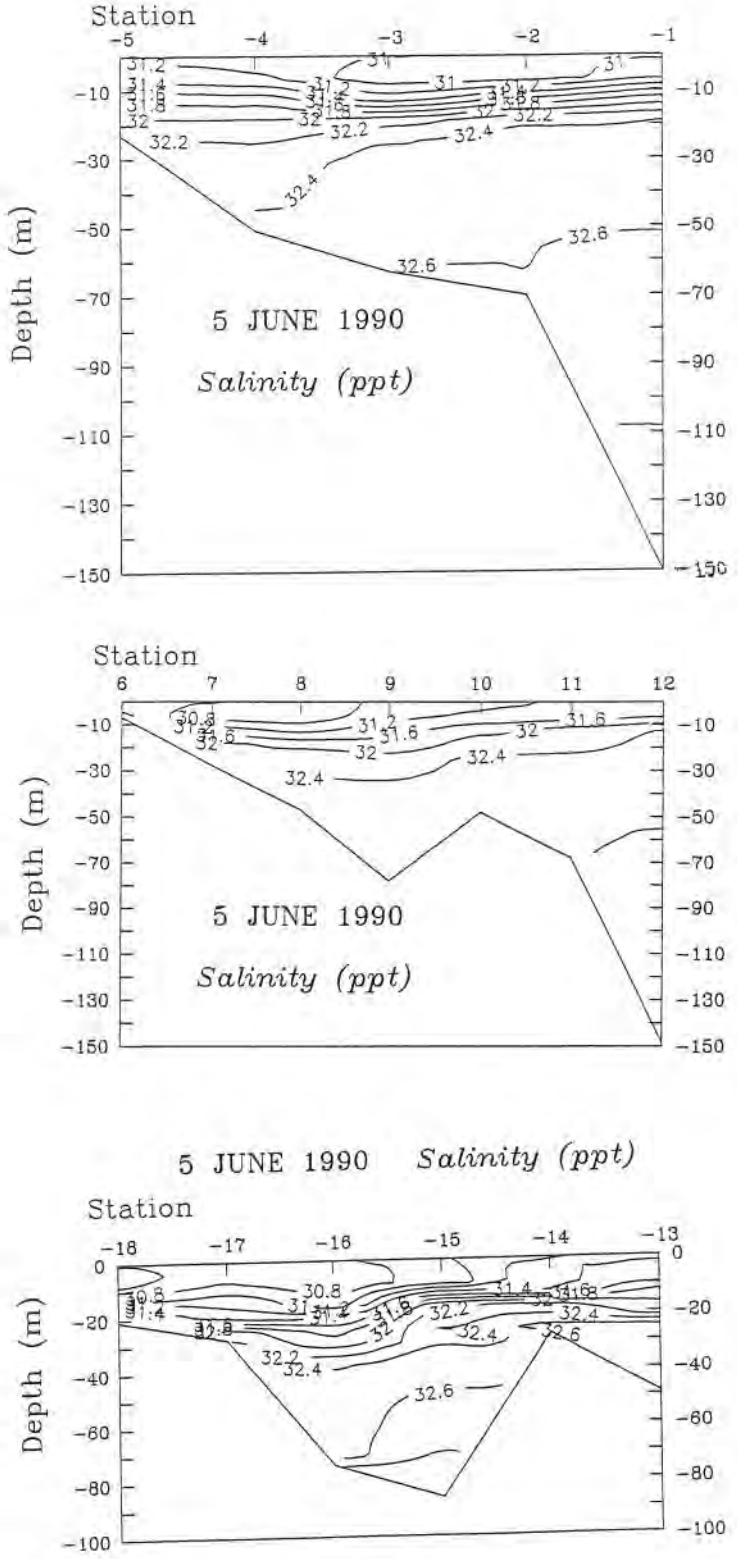


Figure 34. Vertical section contour plots of salinity on 5 June 1990 for each of the four transects in Figure 1.

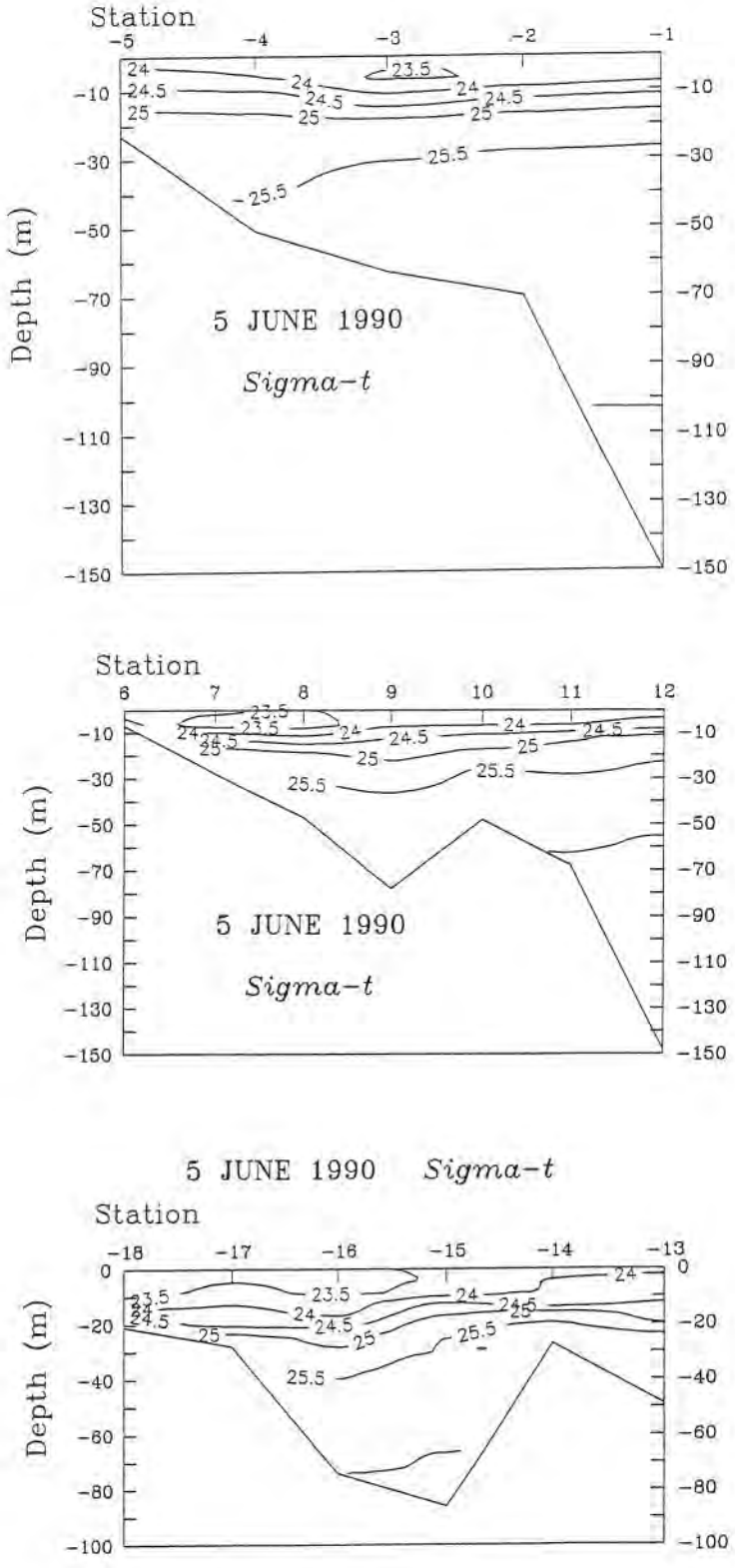


Figure 35. Vertical section contour plots of density on 5 June 1990 for each of the four transects in Figure 1.

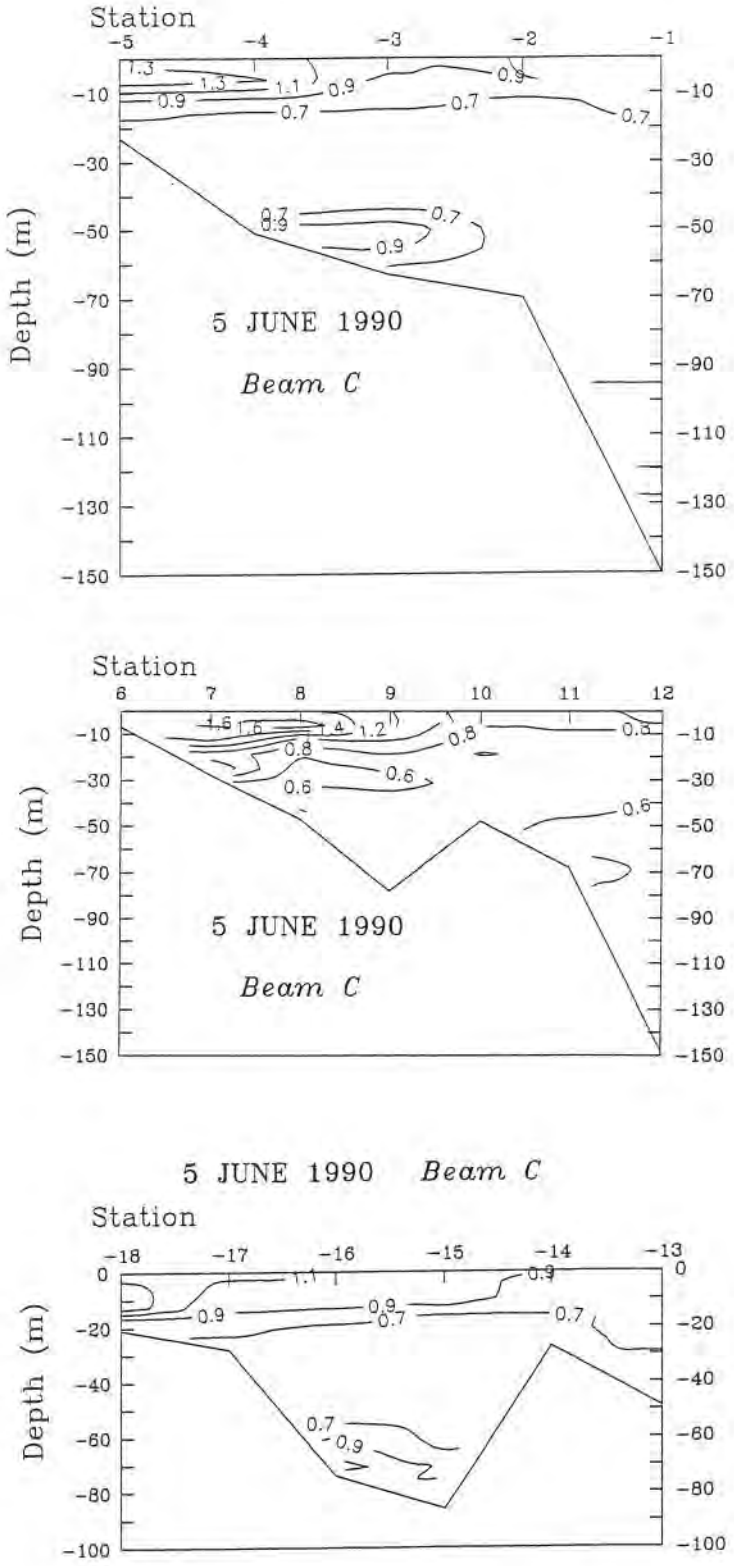


Figure 36. Vertical section contour plots of beam attenuation coefficient on 5 June 1990 for each of the four transects in Figure 1.

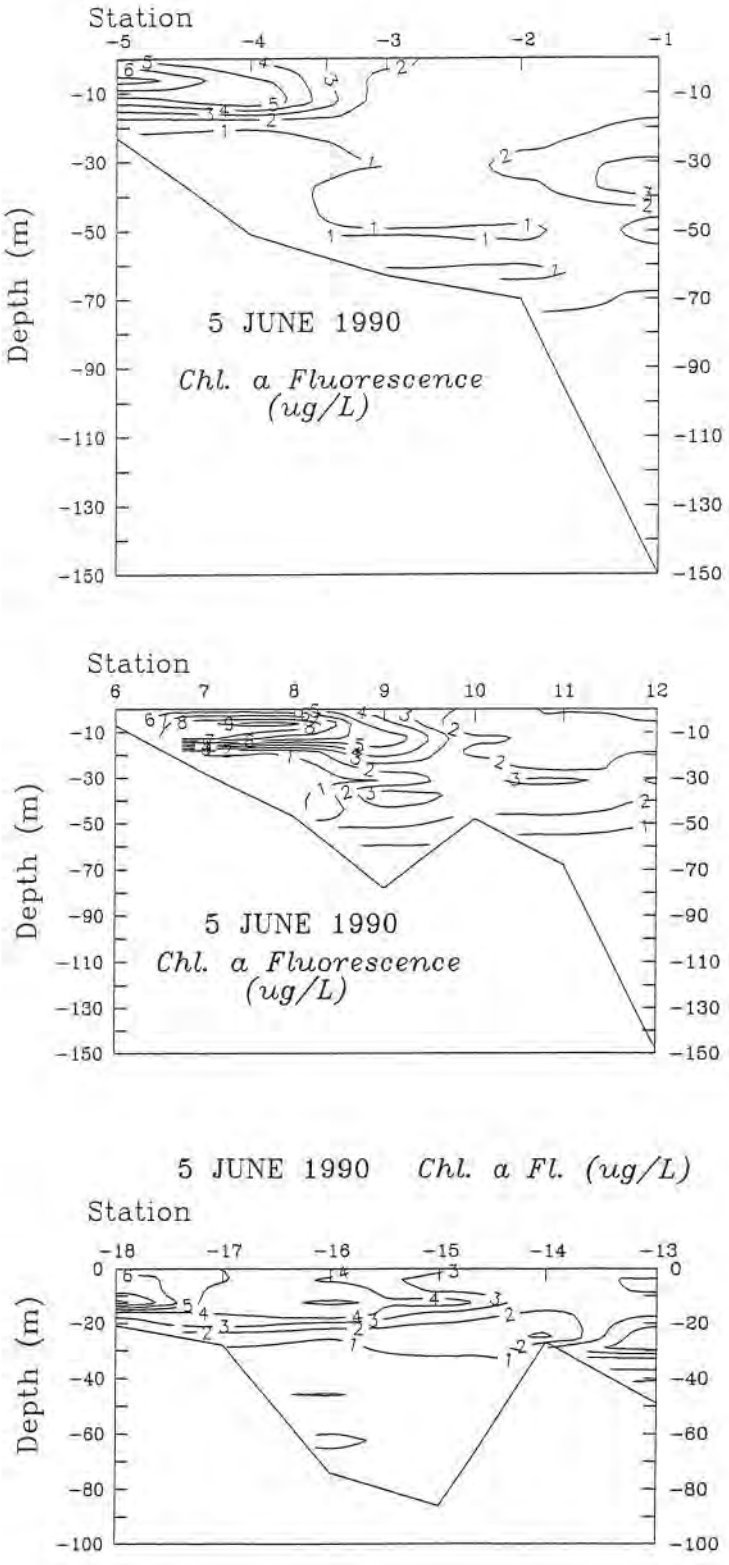


Figure 37. Vertical section contour plots of *in situ* chlorophyll *a* fluorescence on 5 June 1990 for each of the four transects in Figure 1.

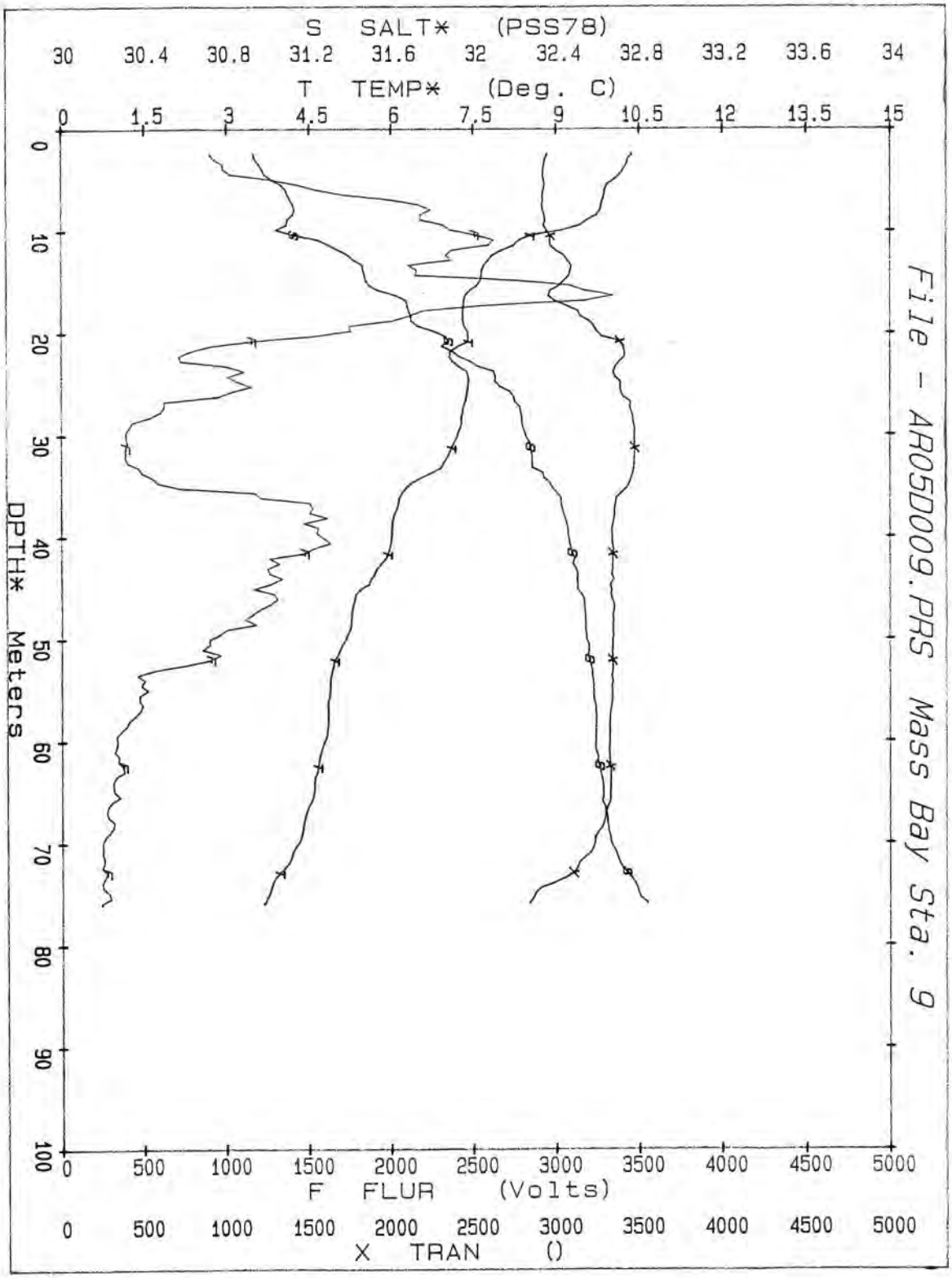


Figure 38. Vertical profile plots of temperture, salinity, *in situ* fluorescence and light transmission for 5 June 1990 at Stas. 9-11.

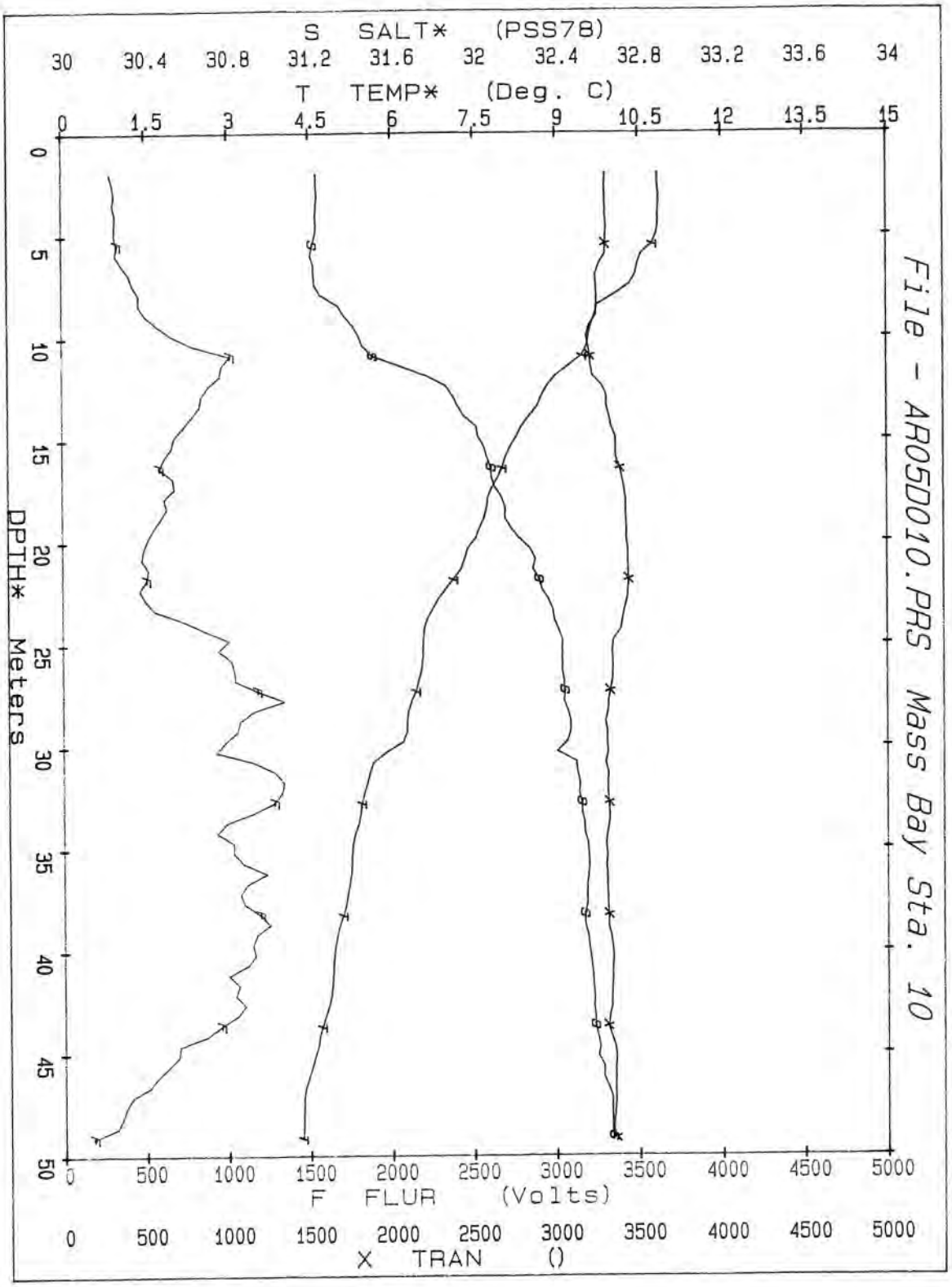


Figure 38. (Con't)

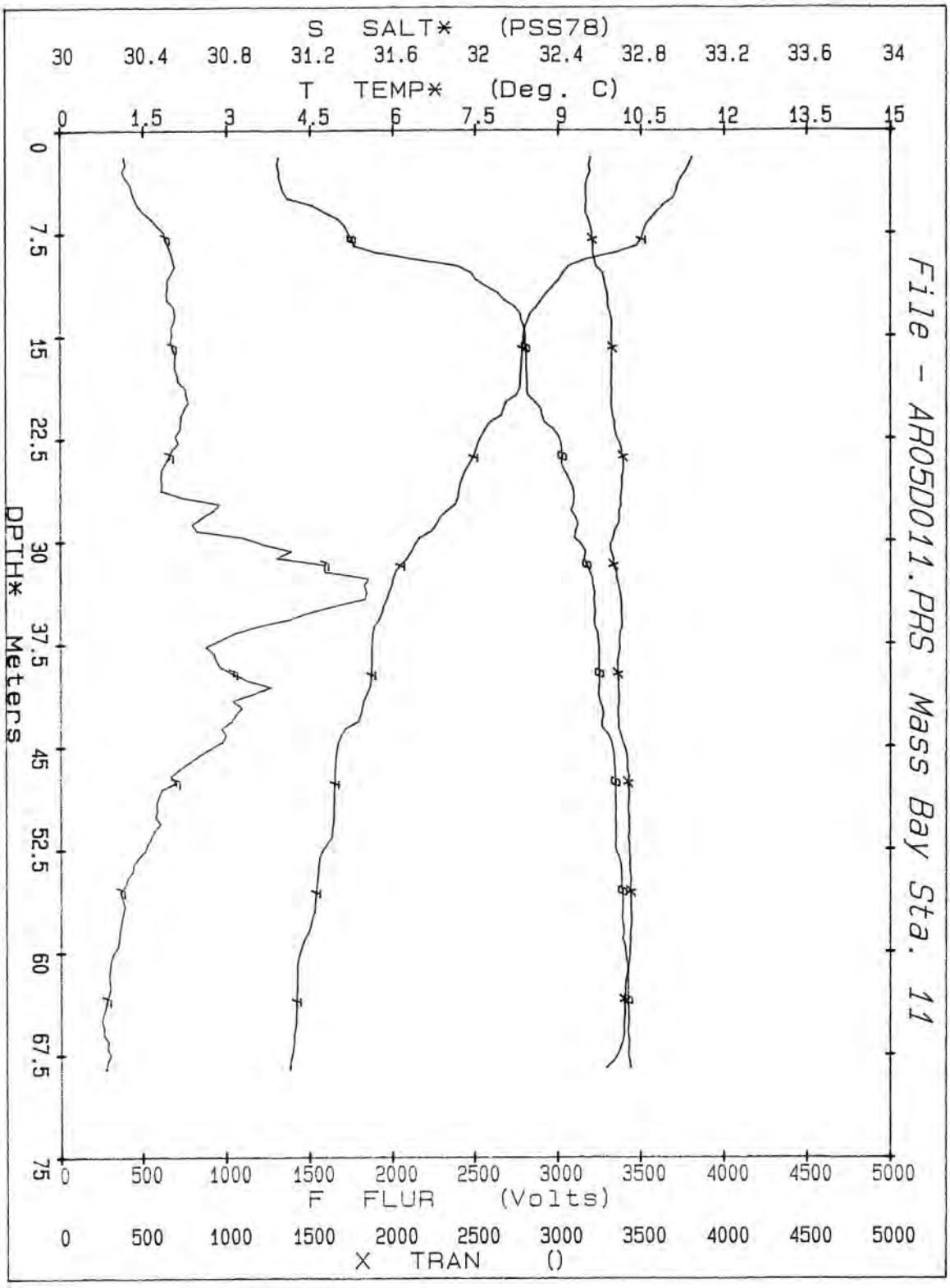


Figure 38. (Con't)

TABLE 5. DISCRETE BOTTLE MEASUREMENTS – 5 JUNE 1990

Station	Time (EST)	Depth (m)	Temp (°C)	Salinity (ppt)	In Situ Chl (ug/L)	Beam Atten (1/m)	POC (ug/L)	PON (ug/L)	Chl a (ug/L)	Pheo (ug/L)
1	1350	2.2	11.31	31.07	0.91	0.82	346.94	44.80	1.32	0.35
		10.2	8.97	31.87	1.91	0.80	592.94	75.40	1.94	0.40
		20.2	7.35	32.42	3.34	0.67	412.94	65.20	4.43	0.70
		37.0	4.99	32.47	3.82	0.65	320.94	50.60	5.62	1.13
		50.7	5.11	32.61	1.97	0.61	248.94	35.40	2.20	0.66
		75.6	4.33	32.70	0.77	0.64				
		100.8	4.15	32.75	0.56	0.74				
		137.3	3.83	32.87	0.50	0.87				
3	1516	2.4	11.91	30.87	1.20	0.84	370.94	55.80	1.14	0.21
		20.1	7.40	32.19	1.30	0.58	330.94	47.80	1.45	0.43
		41.0	4.82	32.56	1.12	0.63	216.94	30.20	1.46	0.83
		60.7	4.68	32.58	0.83	1.31	250.94	26.40	0.97	0.83
5	1642	2.2	10.34	31.27	6.48	1.44	862.94	125.00	7.03	0.86
		9.9	7.55	31.67	4.06	1.00	370.94	51.00	2.88	1.02
		18.8	6.21	32.08	0.77	0.67	140.94	14.80	0.49	0.81
6	0605	2.1	9.35	31.26	4.36	1.30	544.94	95.20	5.67	1.37
		5.6	8.40	31.50	3.38	1.17	700.94	139.00	6.22	1.31
7	0705	2.2	11.47	30.52	6.55	1.59	800.94	149.20	11.64	1.71
		10.3	10.07	30.90	9.96	1.87	860.94	174.80	13.54	2.62
		17.9	6.02	32.08	0.82	0.96	176.94	16.40	0.47	1.16
		26.0	5.63	32.21	0.78	1.63	240.94	22.40	0.29	1.05
8	0825	2.1	11.41	30.49	5.98	1.70	962.94	168.00	13.16	1.75
		9.9	10.86	30.57	10.21	1.55	728.94	112.80	8.77	1.59
		20.1	6.22	32.00	0.63	0.60	152.94	18.40	0.32	0.70
		30.5	5.78	32.38	0.70	0.54	238.94	32.20	0.70	1.34
		45.4	5.17	32.46	0.65	0.81	352.94	43.80	0.37	1.28
9	0930	2.2	10.41	30.97	2.21	1.19	776.94	132.20	5.21	1.16
		16.4	7.35	31.66	9.66	1.11	656.94	99.80	10.56	2.60
		30.9	7.04	32.33	1.06	0.51	332.94	47.20	3.12	1.37
		40.1	5.95	32.52	3.35	0.68	420.94	61.20	4.64	2.03
		76.1	3.72	32.87	0.62	1.32	290.94	25.80	0.40	0.79
10	1024	2.7	10.85	31.28	0.83	0.71	500.94	69.00	1.71	0.39
		10.3	9.54	31.54	2.10	0.83	476.94	74.40	1.99	0.57
		27.3	6.43	32.50	2.53	0.70	328.94	51.00	3.71	1.61
		48.4	4.36	32.71	0.64	0.67	138.94	19.00	0.35	0.56
11	1130	1.9	11.62	31.10	0.90	0.86	398.94	51.20	1.41	0.33
		14.0	8.32	32.29	1.87	0.69	478.94	73.20	2.06	0.60
		32.9	5.96	32.63	2.65	0.64	406.94	61.60	3.56	1.57
		50.9	4.87	32.73	1.11	0.56	190.94	21.60	1.24	1.28
		69.0	4.13	32.80	0.56	0.74	348.94	23.60	0.58	0.82
12	1221	2.5	11.61	31.46	0.74	0.74	350.94	42.40	1.15	0.22
		10.0	10.13	31.76	1.57	0.78	496.94	69.80	1.73	0.40
		27.6	6.68	32.58	2.28	0.60	294.94	43.80	2.30	1.14
		39.5	5.65	32.67	2.36	0.61	216.94	33.20	2.00	1.38
		59.8	4.10	32.84	0.70	0.55	272.94	22.40	0.38	0.54
		80.6	3.85	32.88	0.47	0.59				
		120.9	3.80	32.88	0.42	0.59				
		142.2	3.78	32.89	0.42	0.67				
13	0040	2.3	10.82	31.51	1.90	0.82	448.94	82.20	1.43	0.37
		15.1	8.66	32.02	3.55	0.80	558.94	82.60	3.24	1.05
		23.5	5.32	32.65	4.90	0.77	576.94	80.40	6.26	2.14
		35.5	4.67	32.67	0.83	0.60	116.94	16.20	0.70	0.94
		44.9	4.64	32.68	0.78	0.59	130.94	15.00	0.55	0.78
15	0240	2.7	11.39	30.92	2.80	1.04	568.94	78.20	1.96	0.65
		10.6	8.52	31.28	5.09	0.90	638.94	104.40	5.08	1.35
		20.9	7.53	32.36	1.53	0.59	350.94	48.20	1.19	0.61
		40.7	4.67	32.55	0.72	0.60	154.94	19.20	0.56	0.83
		60.9	4.06	32.71	0.49	0.66	174.94	24.60	0.26	0.63
		85.2	3.55	32.88	0.52	1.11				
17	0403	2.7	10.71	30.72	4.61	1.06	864.94	126.80	5.04	1.13
		20.9	7.86	31.43	2.25	0.74	454.94	59.00	3.14	1.61
		32.2	5.25	32.32	0.65	1.34	202.94	22.40	0.40	0.95
18	0440	2.0	11.76	30.53	6.72	1.34	778.94	123.6	7.15	1.36
		12.1	10.97	30.82	7.00	1.46	728.94	132.2	8.69	1.83
		20.2	6.41	31.95	0.90	1.07	202.94	21.2	0.49	1.29

TABLE 5 (CONT.). DISCRETE BOTTLE MEASUREMENTS – 5 JUNE 1990

Station	Time (EST)	Depth (m)	DO (mL/L)	% DO Saturation	Nitrate (uM)	Nitrite (uM)	Ammonium (uM)	Silicate (uM)	Phosphate (uM)
1	1350	2.2	7.20	114	0.03	0.00	0.07	0.79	0.13
		10.2	7.93	120	0.01	0.02	0.12	0.76	0.21
		20.2	7.78	114	1.37	0.08	0.58	1.28	0.51
		37.0	7.15	99	2.37	0.16	1.69	3.27	0.84
		50.7	7.10	98	5.45	0.20	1.38	3.15	0.82
		75.6	7.08	96	6.78	0.29	2.12	7.25	1.06
		100.8	7.09	96	6.83	0.33	2.21	8.33	1.09
		137.3	7.04	95	7.54	0.41	2.28	10.06	1.21
3	1516	2.4	7.21	115	0.11	0.01	0.34	0.88	0.11
		20.1	8.02	117	0.01	0.01	0.36	0.57	0.23
		41.0	7.17	99	4.94	0.19	2.27	6.56	0.93
		60.7	7.11	98	5.21	0.21	2.23	7.38	1.04
5	1642	2.2	7.46	116	0.00	0.01	0.03	1.49	0.34
		9.9	6.90	101	1.68	0.12	1.67	5.54	0.73
		18.8	6.85	97	2.39	0.14	2.47	7.25	0.83
6	0605	2.1	6.75	102	0.83	0.12	0.91	3.96	0.65
		5.6	6.77	101	0.72	0.10	0.75	3.61	0.60
7	0705	2.2	7.33	116	0.15	0.01	0.08	0.88	0.26
		10.3	6.95	107	0.28	0.04	0.55	2.28	0.51
		17.9	6.48	92	3.65	0.16	3.41	11.20	1.16
		26.0	6.56	92	3.99	0.15	3.04	11.90	1.19
8	0825	2.1	7.58	120	0.00	0.04	0.20	0.39	0.20
		9.9	7.27	114	0.33	0.07	0.85	1.83	0.35
		20.1	7.11	101	1.94	0.13	2.36	5.79	0.71
		30.5	7.20	101	3.09	0.17	2.34	5.03	0.91
		45.4	7.01	97	4.12	0.20	2.71	7.32	1.01
9	0930	2.2	7.31	113	0.00	0.01	0.11	0.91	0.19
		16.4	7.30	106	0.63	0.05	0.76	2.03	0.44
		30.9	7.69	111	1.59	0.08	0.98	1.69	0.45
		40.1	7.43	105	3.02	0.14	1.46	3.01	0.68
		76.1	6.45	87	7.74	0.22	3.43	15.77	1.47
10	1024	2.7	7.33	115	0.00	0.00	0.13	0.67	0.15
		10.3	7.83	120	0.00	0.00	0.14	0.60	0.20
		27.3	7.33	105	2.33	0.11	1.34	2.90	0.69
		48.4	7.12	97	6.27	0.28	2.57	8.45	1.12
11	1130	1.9	7.25	116	0.04	0.00	0.15	0.71	0.21
		14.0	7.90	118	0.03	0.01	0.23	0.40	0.29
		32.9	7.42	105	2.35	0.13	1.42	1.78	0.68
		50.9	7.21	100	5.57	0.31	2.16	5.91	0.93
		69.0	7.12	97	6.74	0.34	2.38	8.72	1.02
12	1221	2.5	7.13	114	0.01	0.00	0.14	0.66	0.07
		10.0	7.68	119	0.02	0.00	0.14	0.61	0.13
		27.6	7.47	108	1.18	0.08	0.99	1.20	0.41
		39.5	7.30	103	3.55	0.20	1.84	3.45	0.65
		59.8	7.17	97	6.84	0.39	2.45	7.54	0.98
		80.6	7.10	96	7.49	0.42	2.45	8.77	1.06
		120.9	7.09	95	7.58	0.41	2.41	8.77	1.06
		142.2	7.03	95	7.64	0.43	2.41	9.07	1.09
13	0040	2.3	7.03	110	0.03	0.01	0.00	0.40	0.22
		15.1	7.49	113	0.02	0.02	0.00	0.38	0.27
		23.5	7.38	103	3.88	0.19	0.85	2.91	0.78
		35.5	7.05	97	5.54	0.21	2.24	7.18	1.06
		44.9	7.00	96	5.61	0.22	2.31	12.05	1.07
15	0240	2.7	7.16	114	0.00	0.00	0.11	0.35	0.09
		10.6	7.40	110	0.00	0.02	0.10	0.68	0.18
		20.9	7.90	116	0.00	0.01	0.28	1.16	0.21
		40.7	6.97	96	5.16	0.16	2.80	8.04	0.97
		60.9	6.76	91	6.51	0.20	3.09	10.49	1.20
		85.2	6.47	87					
17	0403	2.7	7.15	111	0.21	0.02	0.15	0.78	0.36
		20.9	7.01	103	0.41	0.29	1.23	3.06	0.61
		32.2	6.77	94	3.84	0.38	2.95	9.32	1.14
18	0440	2.0	7.08	113	0.00	0.02	0.06	0.46	0.16
		12.1	6.82	107	0.14	0.05	0.10	1.67	0.44
		20.2	6.37	91	3.11	0.21	2.97	9.14	1.10

14 August 1990:

Stratification was maximal in August, with surface temperatures exceeding 20 °C at the offshore stations (Fig. 39), forming a steep, shallow thermocline at about 10m in the inner Bay and at about 15m at the outer Bay (Fig. 41). There was again evidence of fresher surface water entering from the northeast (Fig. 40). The contours of beam attenuation coefficient (Fig. 44) suggest the introduction of particulates into Massachusetts Bay from the area of Salem Harbor. This turbid-water plume extended to the south across the Bay, and together with the effluent from Boston Harbor, apparently supplied the required nutrients for fairly high phytoplankton biomass (Fig. 40; Table 6). There is also evidence of other fluorescing material, possibly dissolved, that contributed to the high *in situ* fluorescence readings at the inshore stations (Table 6) but which did not appear in our extracted chlorophyll samples (see Fig. 29). The nitrate levels were much reduced, but not exhausted, and the silicate levels remained fairly high, suggesting that the system is not silicate limited (Table 6). Ammonium and silicate levels were elevated near the mouth of Boston Harbor. Contrary to what one might expect, given the sharp vertical stratification of the water column, the oxygen concentrations still exceeded 80% of saturation values at all stations and depths.

The deep water nitrate levels at the northeastern-most stations in August were higher than in June. This can be seen in Figure 46 as a separate trend in nitrate levels at depth. Should this deep water in June be the same water mass sampled in August (i.e. with no advection and export of deeper waters during the intervening two months), then the increase in nitrate might be explained as oxidation of the ammonium and nitrite present in June. For instance, the total dissolved inorganic nitrogen at the deepest sample depth at Station 1 is 10.23 μM in June and 11.04 μM in August. Thus, nitrogen recycling at depth could explain most, but not all, of the nitrate present in August at the northeastern stations. However, T-S analyses of these waters between the two cruises revealed that the deeper waters in August were about 0.2 ppt fresher than in June, suggesting that the water mass in June has been replaced, and, since the salinity was fresher, the source of the nitrate-rich waters in August was not related to Maine Bottom Water (of offshore slope water origin). Rather, these data, along with the apparently anomalously high nitrate levels at the same northeastern stations in February, suggest to us that the waters to the north of Cape Ann, i.e. the Bigelow Bight - Jeffreys Basin area of the western Gulf of Maine, might be contributing a significant flux of nitrogen to the Massachusetts Bay system.

The ultimate source of inorganic nutrients to the Gulf of Maine is slope water, which enters the Gulf at depth through the Northeast Channel, and which has

nitrate concentrations of 15 to 20 µM NO_3. The slope water spills into the major basins throughout the Gulf, but a significant portion rises to the surface off western Nova Scotia and eastern Maine, where surface NO_3 levels are the highest in the Gulf during the warmer, biologically productive months of the year. We have seen in the past that winter nutrient levels are sometimes highest in the Bigelow Bight portion of the western Gulf -- far removed from the suspected source in the eastern Gulf (Fig. 47; Townsend *et al.*, 1987). We suggest here that these high nutrient levels could result from a nutrient trap that may be operating in the Bigelow Bight - Jeffreys Basin area, whereby nutrient recycling at depth acts in concert with the overlying surface flow of productive waters. The nontidal circulation along the coasts of western Maine, New Hampshire and northern Massachusetts is influenced by freshwater runoff from major rivers, mainly the Penobscot, Kennebec, and Merrimac Rivers, which flow into the Bigelow Bight area. It would appear that carbon and nitrogen are biologically fixed in the overlying flow, and that the biogenic particles then sink to the more sluggish waters beneath where the nitrogen is regenerated, thereby enriching the deep waters. Surface nutrient concentrations in the Gulf during winter are thus greatest here, as a result of vertical convective mixing with the deeper, nitrogen-enriched waters in Bigelow Bight. These waters appear to escape the area throughout the year and flow to the south, and thus may affect the nutrient budget of Massachusetts Bay as we witnessed in February for the northeastern-most stations of our sampling grid. This process must be studied further if we are to be able to sort out the relative contributions of nitrogen from the new sewage outfall against a brackdrop of "naturally" elevated nitrogen loadings possibly flowing into the system from Bigelow Bight.

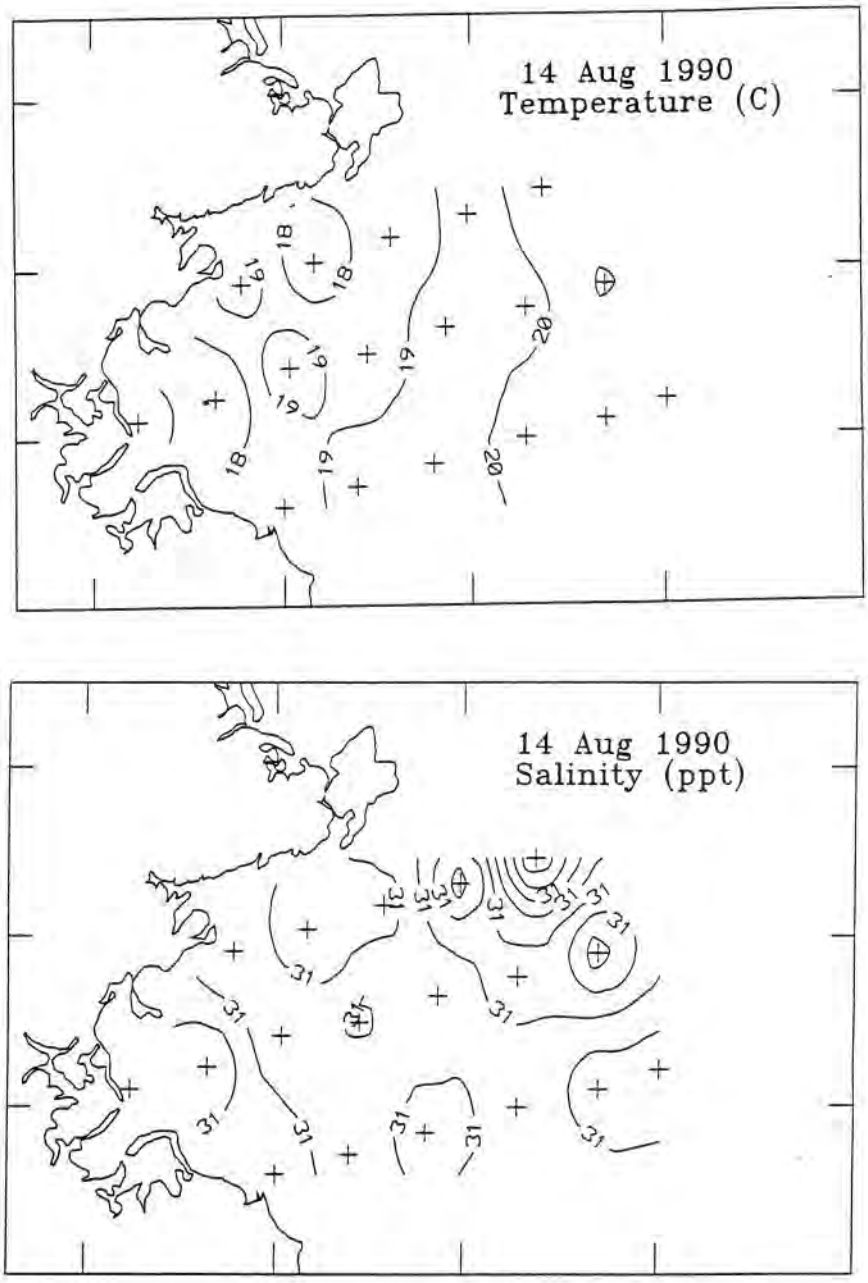


Figure 39. Surface contour plots of temperature and salinity (at 2m) for 14 August 1990.

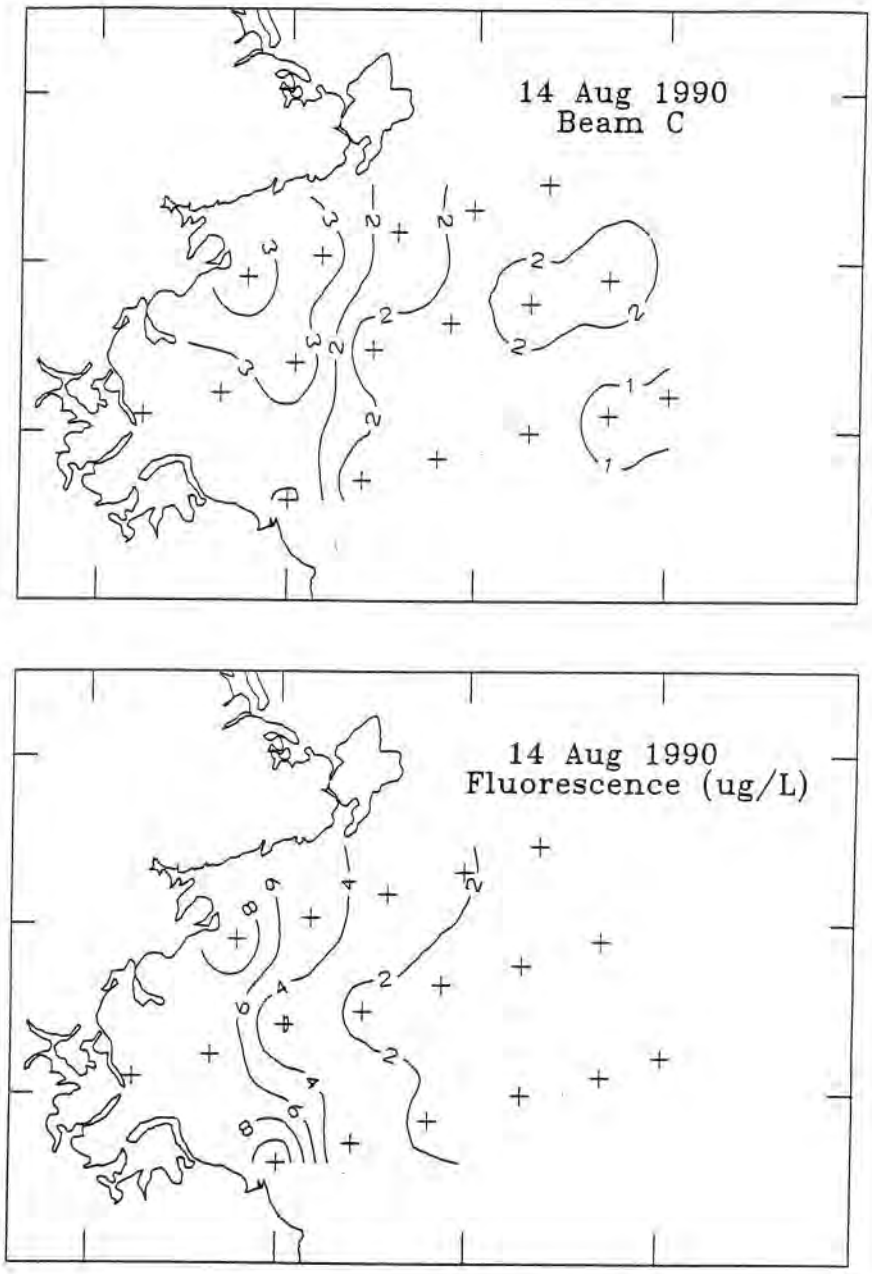


Figure 40. Surface contour plots of beam attenuation coeficient and *in situ* chlorophyll *a* fluorescence (at 2m) for 14 August 1990.

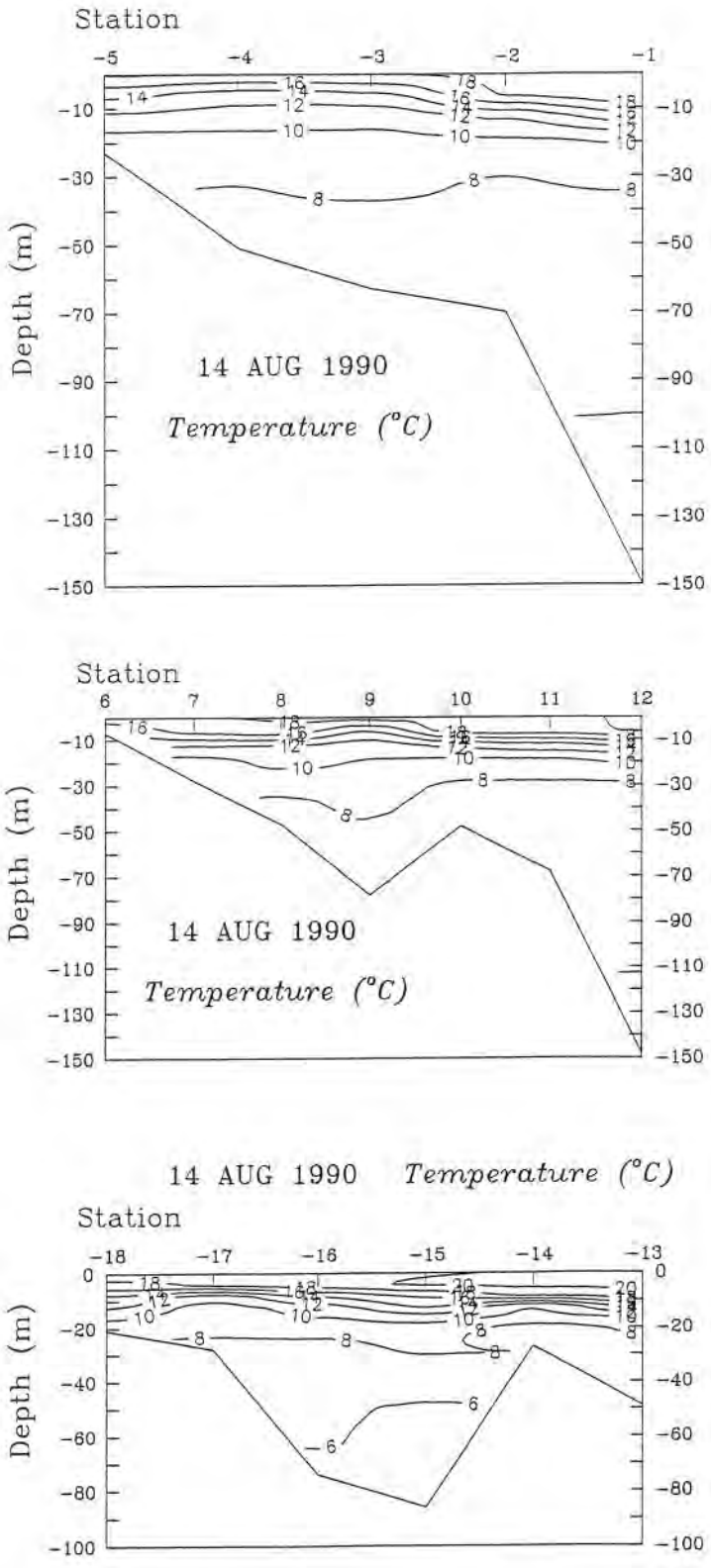


Figure 41. Vertical section contour plots of temperature on 14 August 1990 for each of the four transects in Figure 1.

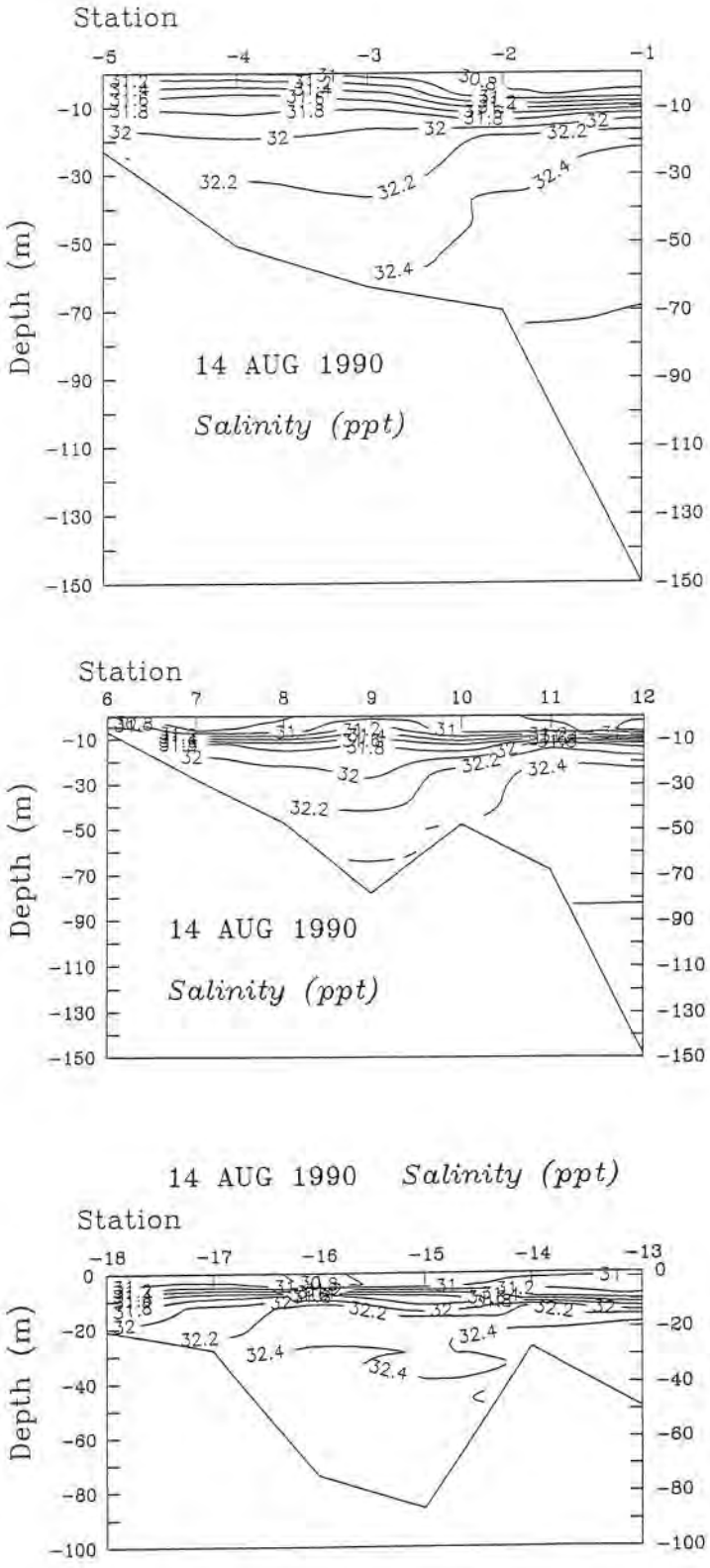


Figure 42. Vertical section contour plots of salinity on 14 August 1990 for each of the four transects in Figure 1.

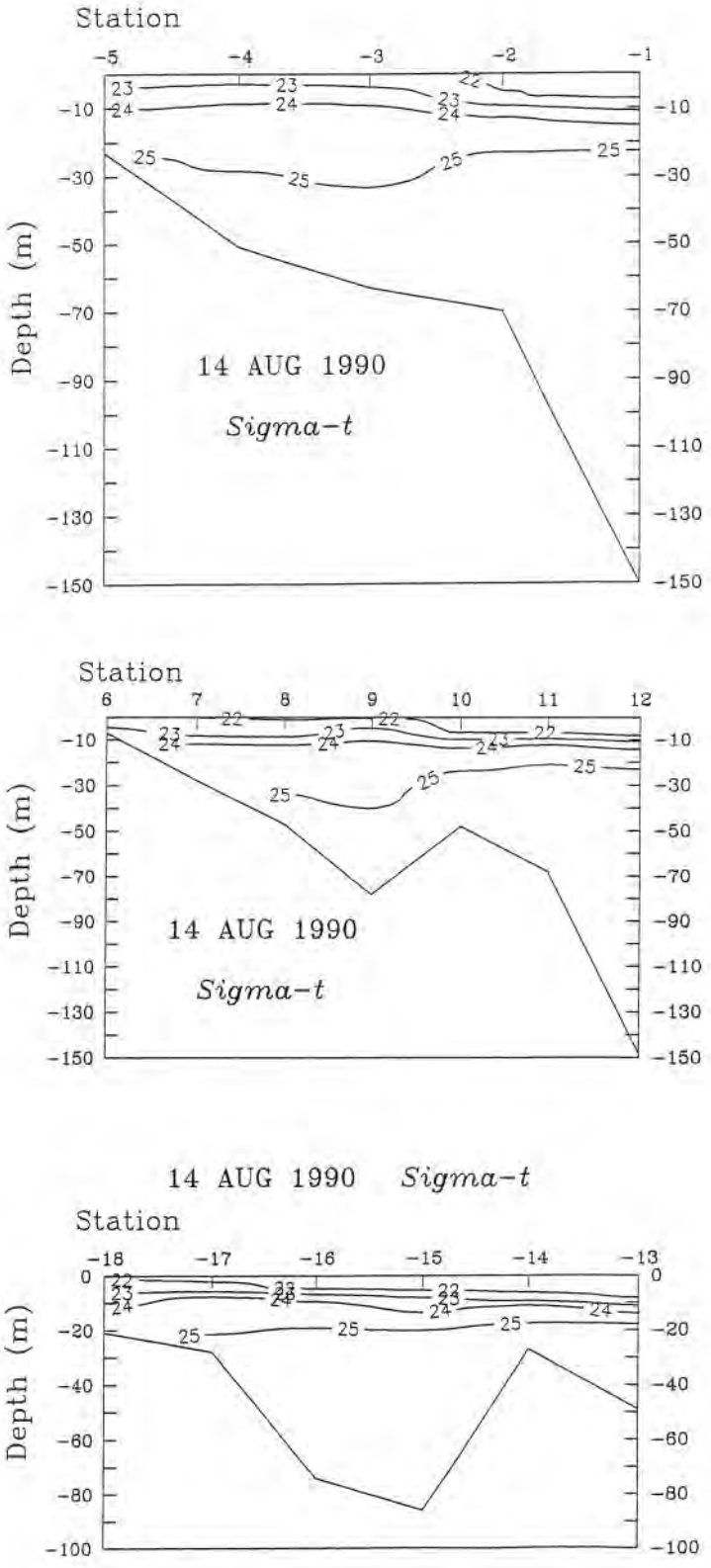


Figure 43. Vertical section contour plots of density on 14 August 1990 for each of the four transects in Figure 1.

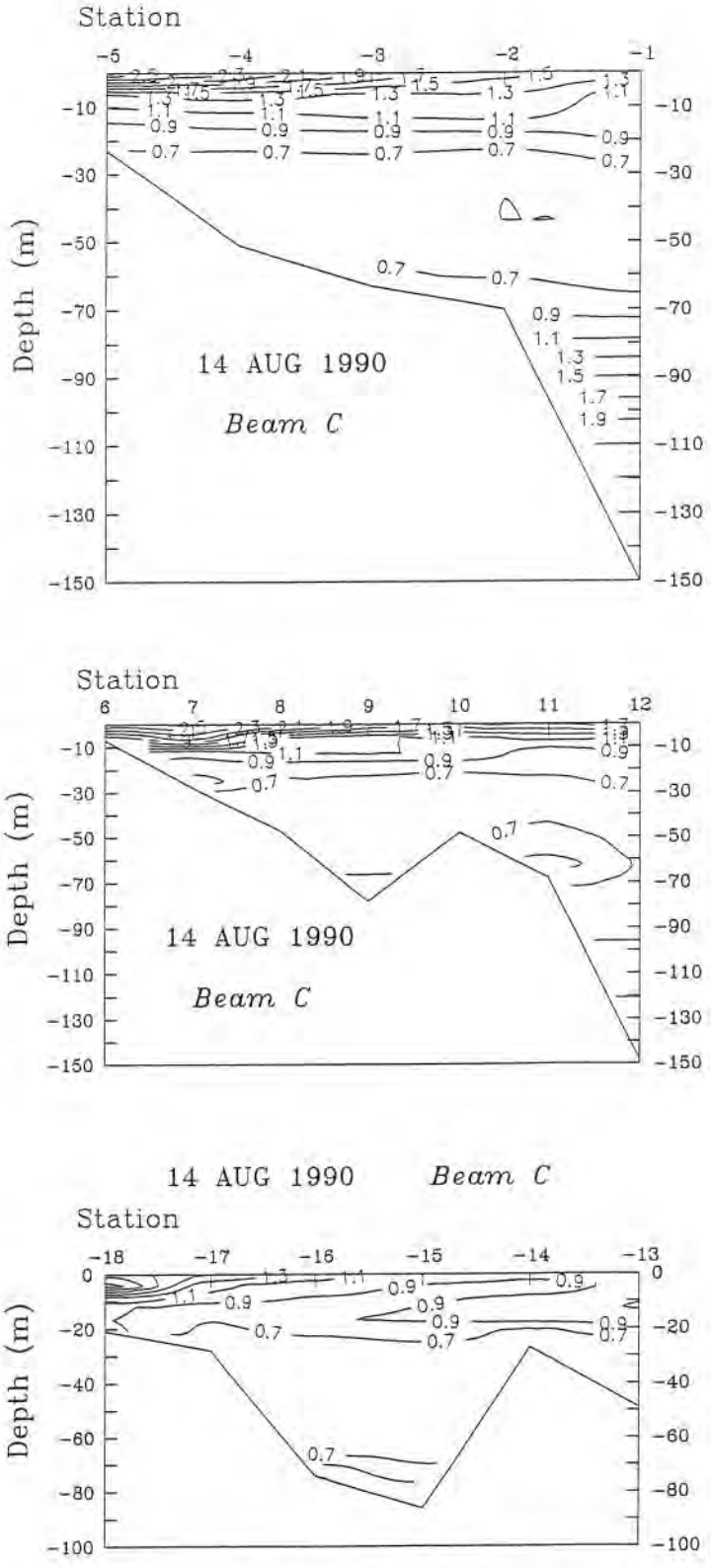


Figure 44. Vertical section contour plots of beam attenuation coefficient on 14 August 1990 for each of the four transects in Figure 1.

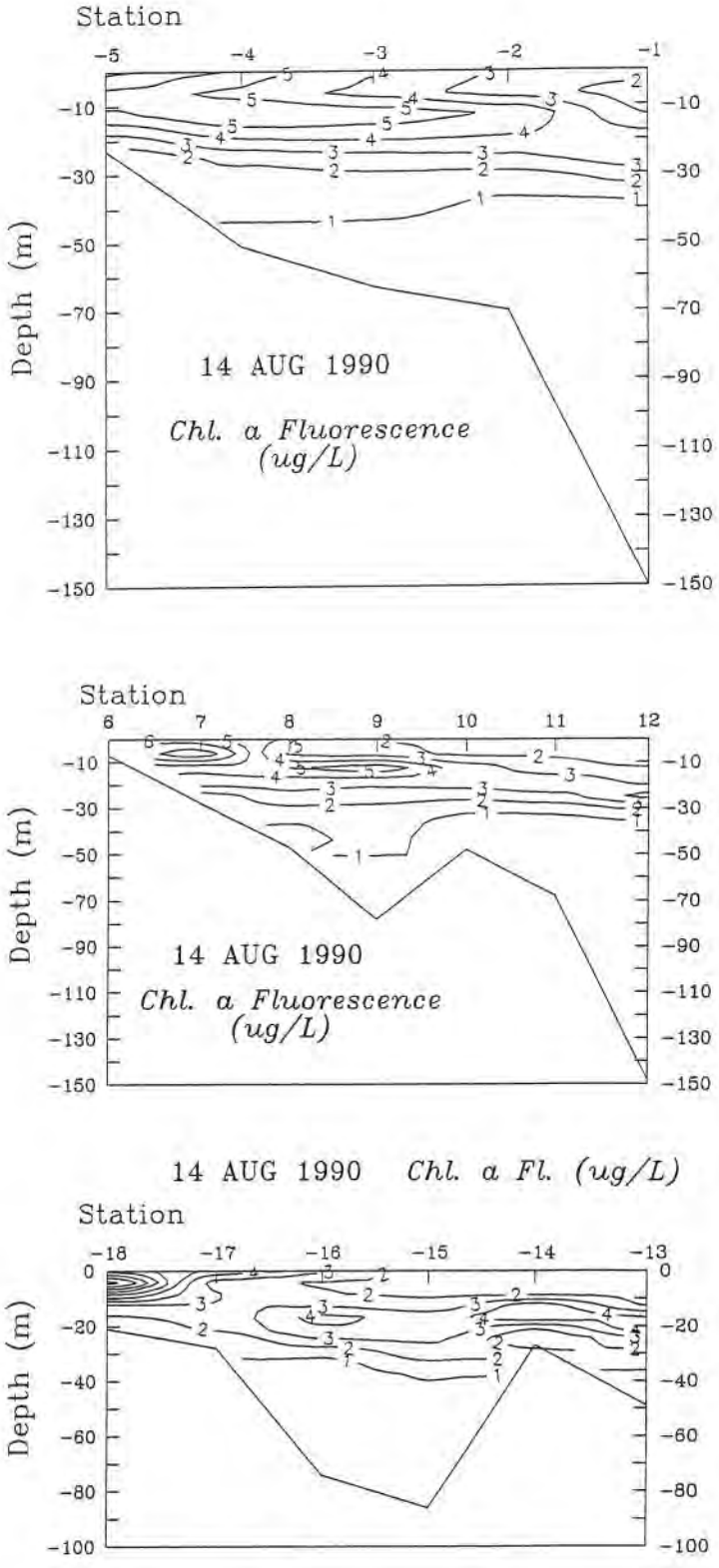


Figure 45. Vertical section contour plots of *in situ* chlorophyll *a* fluorescence on 14 August 1990 for each of the four transects in Figure 1.

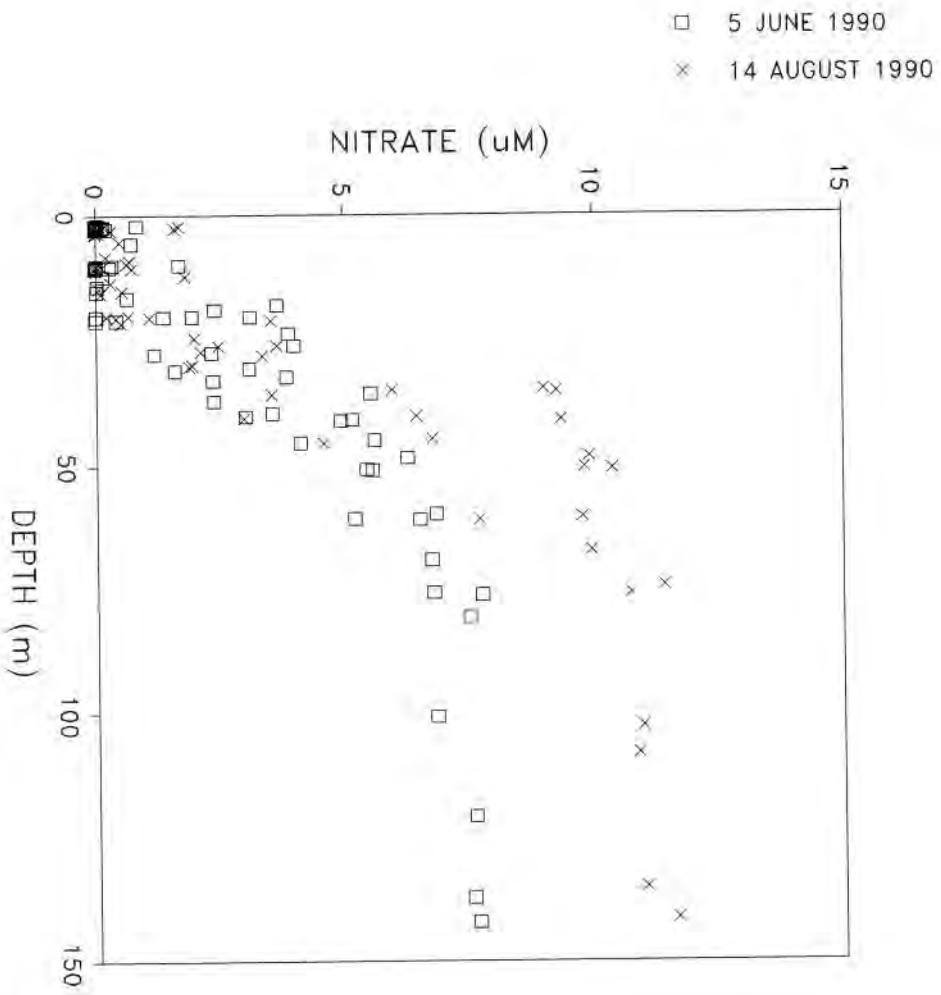


Figure 46. Nitrate concentrations as a function of depth for all stations sampled during 5 June and 14 August 1990. Note the higher nitrate concentrations at depth in August.

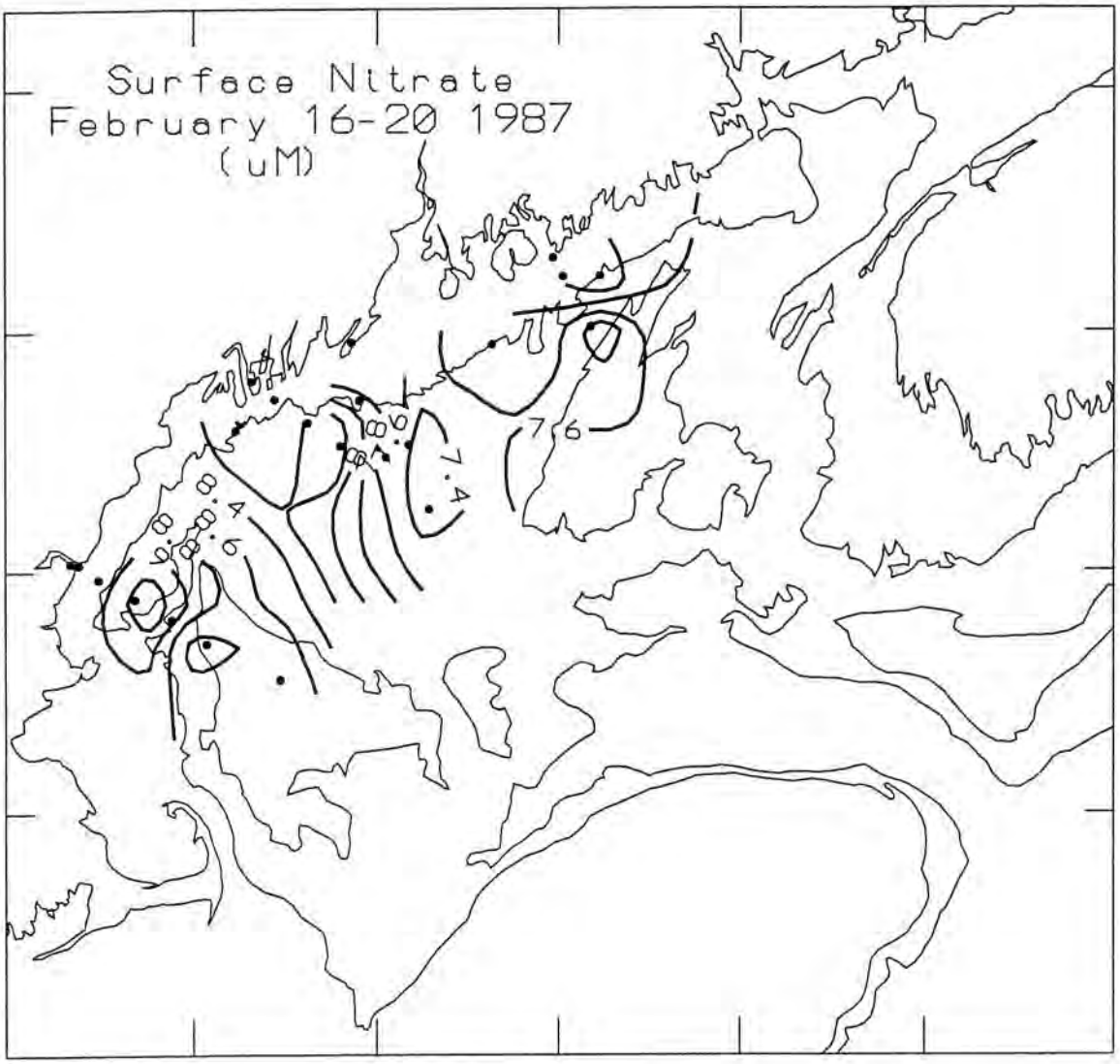


Figure 47. Surface nitrate concentrations in winter 1987 (from Townsend et al., 1987).

TABLE 6. DISCRETE BOTTLE MEASUREMENTS – 14 AUGUST 1990

Station	Time (EST)	Depth (m)	Temp (°C)	Salinity (ppt)	In Situ Chl (ug/L)	Beam Atten (1/m)	POC (ug/L)	PON (ug/L)	Chl a (ug/L)	Pheo (ug/L)
1	1409	3.6	21.19	30.75	1.13	0.97	214.16	30.49	0.76	0.30
		11.0	19.74	30.87	1.95	0.96	296.96	46.09	1.03	0.44
		21.4	9.75	32.44	4.47	1.03	239.56	42.49	2.15	1.03
		34.8	7.79	32.55	0.95	0.54	57.35	11.29	0.36	0.28
		50.3	6.70	32.57	0.38	0.54	37.16	5.29	0.11	0.15
		75.7	6.17	32.62	0.29	0.99				
		102.6	5.99	32.65	0.27	1.89				
		135.1	5.98	32.65	0.29	2.58				
3	1531	2.0	18.09	31.06	3.92	1.58	505.56	69.69	2.39	0.88
		13.4	10.51	31.94	5.55	1.06	360.56	64.49	2.92	1.48
		35.7	7.97	32.21	1.24	0.59			0.47	0.58
		60.8	6.61	32.35	0.43	0.75	98.76	11.09	0.14	0.26
5	1646	2.1	19.57	30.87	10.67	3.27	1084.16	97.49	6.77	1.44
		10.2	12.28	31.89	4.71	1.10	341.76	69.09	2.35	1.35
		25.9	7.92	32.23	0.88	0.68	116.36	20.69	0.44	0.59
6	0630	2.2	16.63	30.20	6.59	2.36	815.56	139.49	5.63	3.02
		9.0	13.37	31.63	3.90	1.30	328.56	63.49	2.82	2.11
7	0738	2.6	16.82	30.41	7.80	2.25	545.76	106.89	5.74	2.73
		8.2	14.66	31.61	3.81	1.49	409.16	73.09	2.84	2.06
		15.1	10.64	31.98	4.34	0.96	226.96	47.29	2.28	1.45
		27.1	8.85	32.13	1.07	1.00	237.96	44.09	0.83	0.86
8	0827	2.6	19.59	30.94	1.80	1.17	300.76	47.49	1.11	0.44
		14.5	11.91	31.72	5.56	1.18	390.36	73.49	2.48	1.32
		30.1	8.86	32.13	1.68	0.61	169.56	31.69	0.82	0.69
		45.4	7.27	32.31	0.68	0.59	93.95	14.89	0.27	0.44
9	0925	3.0	18.43	31.03	1.36	1.04	252.16	47.49	1.65	0.80
		10.5	10.93	31.86	4.54	1.29	252.96	55.29	2.11	1.06
		20.3	9.84	31.95	2.59	0.71	148.56	30.29	1.14	0.98
		29.8	8.98	32.06	1.55	0.63	106.76	27.29	0.67	0.67
		40.5	8.18	32.25	1.23	0.59	94.36	18.89	0.54	0.48
10	1057	2.6	19.51	30.88	1.40	0.37	341.56	59.69	0.99	0.36
		15.5	11.28	31.96	4.16	1.04	316.16	67.09	2.54	1.36
		26.0	8.43	32.32	1.83	0.57	158.36	28.49	0.94	0.84
		44.6	7.02	32.39	0.55	0.59	104.76	20.09	0.19	0.29
11	1155	3.0	19.73	30.77	2.12	1.13	306.16	47.09	1.20	0.53
		10.4	14.08	32.17	2.22	0.97	196.76	37.49	1.21	0.61
		20.4	9.50	32.47	3.43	0.81	224.16	46.29	1.89	1.38
		40.8	6.60	32.46	0.41	0.72	48.96	8.69	0.13	0.20
		67.1	6.43	32.47	0.41	1.16	69.96	13.89	0.13	0.16
12	1307	3.4	21.16	30.30	1.29	1.08	280.16	41.69	1.03	0.41
		12.1	15.55	31.90	2.14	0.92	173.76	32.49	1.47	0.80
		24.4	8.83	32.51	3.48	0.81	175.96	32.09	1.66	0.85
		35.0	6.65	32.48	0.57	0.51	52.16	11.89	0.27	0.20
		50.6	6.30	32.49	0.38	0.66	45.96	8.89	0.10	0.14
		74.2	6.21	32.55	0.34	0.68				
		108.1	6.03	32.66	0.30	0.78				
		141.4	5.80	32.64	0.30	1.19				
13	0103	3.5	20.59	31.06	1.71	0.93			0.69	0.28
		10.4	19.10	31.28	1.86	1.34	165.36	25.29	0.81	0.28
		20.1	9.88	32.44	4.88	0.87	275.36	51.89	2.24	1.06
		34.5	6.75	32.52	0.93	0.53	89.76	18.09	0.46	0.44
		48.1	6.51	32.53	0.54	0.57	51.76	9.09	0.18	0.28
15	0254	3.3	20.22	30.80	1.76	0.85	224.56	39.69	0.96	0.40
		10.0	14.27	31.86	2.71	0.84	228.36	42.09	1.62	0.71
		20.0	9.65	32.36	4.24	0.88	274.56	54.49	1.86	0.89
		40.1	6.91	32.38	1.04	0.54	80.56	18.29	0.45	0.39
		60.3	5.61	32.50	0.36	0.60	64.96	9.69	0.13	0.12
17	0429	2.8	20.05	30.81	2.18	1.12	278.36	43.69	1.11	0.44
		9.5	10.53	31.93	4.12	1.04	236.16	43.09	1.87	0.91
		27.9	7.69	32.27	1.39	0.62	106.56	21.69	0.62	0.66
18	0505	2.2	18.24	30.70	12.06	2.54	668.76	124.29	7.66	3.14
		5.3	14.96	31.52	8.06	1.82	479.36	101.09	4.72	2.09
		21.0	9.08	32.08	0.98	0.96	137.56	22.29	0.62	0.83

TABLE 6 (CONT.). DISCRETE BOTTLE MEASUREMENTS – 14 AUGUST 1990

Station	Time (EST)	Depth (m)	DO (mL/L)	% DO Saturation	Nitrate (uM)	Nitrite (uM)	Ammonium (uM)	Silicate (uM)	Phosphate (uM)
1	1409	3.6	6.05	116	0.00	0.01	0.00	1.73	0.09
		11.0	6.50	122	0.00	0.01	0.00	1.75	0.10
		21.4	7.07	109	0.50	0.09	0.00	2.35	0.42
		34.8	6.23	92	5.97	0.27	0.00	5.88	0.79
		50.3	6.03	87	9.80	0.05	0.00	9.10	1.04
		75.7	5.94	85	10.73	0.05	0.00	11.45	1.16
		102.6	5.97	85	10.96	0.03	0.00	12.02	1.19
		135.1	5.96	84	11.00	0.04	0.00	12.01	1.22
3	1531	2.0	6.74	123	0.08	0.01	0.09	2.30	0.33
		13.4	6.66	104	0.30	0.07	0.23	4.51	0.58
		35.7	6.14	91	3.54	0.26	1.96	7.57	0.94
		60.8	5.73	82	7.69	0.23	2.14	12.24	1.23
5	1646	2.1	7.28	136	0.17	0.01	0.08	1.13	0.33
		10.2	7.15	116	0.13	0.05	0.25	3.45	0.46
		25.9	5.97	88	3.64	0.28	1.86	9.15	1.02
6	0630	2.2	5.22	92	1.69	0.35	11.82	9.71	2.07
		9.0	5.81	96	0.68	0.19	2.39	5.76	0.88
7	0738	2.6	5.58	99	1.59	0.32	4.16	7.33	1.29
		8.2	6.72	115	0.20	0.09	1.24	3.74	0.59
		15.1	6.65	104	0.53	0.08	0.54	4.46	0.55
		27.1	6.03	91	2.11	0.24	2.02	8.35	0.80
8	0827	2.6	6.36	119	0.06	0.02	0.00	1.64	0.26
		14.5	6.62	107	0.06	0.02	0.00	3.86	0.53
		30.1	6.25	94	1.87	0.22	1.53	6.05	0.85
		45.4	6.02	88	4.58	0.24	1.79	8.07	1.03
9	0925	3.0	6.34	116	0.32	0.05	0.24	3.21	0.38
		10.5	6.30	99	0.73	0.12	0.84	4.99	0.65
		20.3	6.18	95	1.08	0.16	1.20	5.68	0.74
		29.8	6.13	93	1.94	0.23	1.82	6.44	0.86
		40.5	6.22	93	2.97	0.22	1.38	6.18	0.86
10	1057	2.6	6.12	114	0.06	0.00	0.00	1.99	0.18
		15.5	6.66	106	0.10	0.05	0.11	3.41	0.45
		26.0	6.68	100	2.47	0.29	0.87	4.55	0.73
		44.6	5.95	86	6.77	0.21	1.41	9.04	1.13
11	1155	3.0	6.33	119	0.00	0.01	0.10	1.94	0.19
		10.4	7.42	125	0.05	0.01	0.02	1.43	0.23
		20.4	7.11	109	0.41	0.07	0.06	2.15	0.45
		40.8	5.94	85	9.34	0.29	0.54	14.95	1.13
		67.1	5.94	85	9.94	0.27	0.33	15.53	1.19
12	1307	3.4	6.59	126	0.04	0.02	0.10	1.62	0.19
		12.1	6.85	119	1.80	0.10	0.07	3.27	0.53
		24.4	6.74	102	1.98	0.15	0.07	3.63	0.69
		35.0	6.05	87	9.25	0.27	0.12	8.23	1.07
		50.6	5.89	84	10.36	0.33	0.20	10.83	1.22
		74.2	5.91	84	11.40	0.01	0.05	10.97	1.24
		108.1	6.00	85	10.87	0.04	0.06	10.91	1.22
		141.4	6.02	85	11.63	0.06	0.05	12.49	1.32
13	0103	3.5	5.94	113	0.00	0.01	0.01	0.90	0.13
		10.4	6.13	114	0.00	0.01	0.03	1.09	0.14
		20.1	7.31	113	0.21	0.03	0.03	2.02	0.45
		34.5	6.08	88	8.99	0.25	0.04	7.31	1.06
		48.1	5.92	85	9.90	0.26	0.20	9.02	1.17
15	0254	3.3	6.68	126	0.01	0.00	0.02	1.35	0.14
		10.0	7.42	126	0.00	0.01	0.01	1.56	0.27
		20.0	6.95	107	0.65	0.05	0.15	2.16	0.46
		40.1	6.13	89	6.45	0.15	1.33	7.43	1.00
		60.3	5.75	81	9.76	0.08	1.91	14.99	1.43
17	0429	2.8	6.28	118	0.02	0.00	0.07	1.71	0.24
		9.5	6.54	102	0.62	0.09	0.44	4.80	0.63
		27.9	6.12	90	3.35	0.25	1.68	7.05	0.94
18	0505	2.2	6.24	114	0.00	0.01	0.15	3.77	0.67
		5.3	6.07	104	0.48	0.11	1.41	4.58	0.73
		21.0	5.53	84	3.53	0.35	2.43	10.29	1.14

2. Primary Production: Photosynthesis vs. Irradiance

We have presented data in our cruise reports on the *in situ* light field and photosynthesis vs. irradiance relationships. With the exception of the October cruise, we measured PAR (Photosynthetically Active Radiation) at each of the stations where P vs. I experiments were performed. The distribution of PAR for the October cruise can be calculated from the various components of light absorption, which in general, agrees quite well with the measured PAR values (Fig. 48).

With these data one can model primary production using the relationships given in the Materials and Methods section, along with daily surface irradiance data collected for the area. An example of such a calculation is given here for the surface sample collected at Station 10 on 5 June 1990. The P vs. I parameters given in the cruise report (Townsend *et al.*, 1990c) are:

P_s = 3.39 mgC mgChla^{-1} hr^{-1}
a = 0.025 (mgC mgChla^{-1} hr^{-1})/(μM m^{-2} s^{-1})
b = 0.001 (mgC mgChla^{-1} hr^{-1})/(μM m^{-2} s^{-1})
Measured PAR at 2.7m = 1400μM m^{-2} s^{-1}
Chlorophyll *a* at 2.7m = 1.7 mg m^{-3}

and the chlorophyll-specific rate of production is:

$$Pi = Ps \cdot 1\text{-}e^{-aI/Ps} \cdot e^{-bI/Ps}$$

Pi = 2.2431 mgC (mg Chl *a*)$^{-1}$ hr^{-1}

x 1.7 mgChl*a* m^{-3} = 3.81 mgC m^{-3} hr^{-1}

This same calculation can be made for each of the sample depths at that station and the integrated production for the water column computed for those light conditions. Likewise, one can model the *in situ* light field over the course of a day using actual light measurements at Logan and compute the daily production. This then could be taken further to compute the areal production of Massachusetts Bay using the P vs. I parameters for the various stations and the chlorophyll data.

There did not appear to be any significant diel effect on the photosynthetic parameters. Figure 49 shows that there was a slight increase in P_{max} around mid-

day, which was not significant. In addition, although P_{max} is affected by temperature, the variations we observed within a day were not temperature-dependent (Fig. 50).

We have focused upon the P vs. I relationships from two of our cruises to illustrate differences, both seasonally and spatially, in the phytoplankton populations in this area of Massachusetts Bay. During our 6 February 1990 cruise there was very little photosynthetic activity, and at the inshore stations there was little difference with depth, suggesting strong vertical mixing and uniform light limitation (Fig. 51). At Station 8, which appeared to represent a transitional area between offshore and inshore conditions, there appeared to be significant photoinhibition with depth (Fig. 52). Unfortunately there was significant clumping of cells in these samples and, combined with the very low rate of photosynthesis, it is difficult to interpret the data. The amount of scatter may have produced inaccurate curve-fitting, and these data should be treated with some skepticism.

During our 14 August 1990 cruise, the inshore stations again displayed few signs of photoinhibition with depth, suggesting again well-mixed and uniformly light-limited conditions (Fig. 53). Conditions offshore exhibited a classical stratified system, with increased light-limitation with depth (P_{max} decreasing, b increasing; Fig. 54).

If we compare P_{max} versus station for these two cruises, these trends in light limitation become more obvious(Figure 55). The February P_{max} values for Station 8 may be artificially high due to the curve-fitting problem alluded to above. Alternatively, it may represent an actual set of conditions based on differences in phytoplankton species composition. Note the difference in scales between the two graphs in Figure 55. The P_{max} values are very low for the February data, indicating very low productivity. The August data are typical for a productive coastal system. It is somewhat surprising that the more offshore stations do not have higher P_{max} values, since more light is available to these populations. This may be an indication of nutrient limitation or a shift in species composition, i.e. populations with different photosynthetic capacities, which may also be a function of nutrient limitation. The following discussion of phytoplankton distributions during this time period supports both suppositions.

3. Phytoplankton Community Structure

Quantitative and qualitative phytoplankton cell counts have been presented in the three cruise reports.

The 24 October 1989 sampling period followed a major meteorological event, Hurricane Hugo, in the month of September. Qualitatively, the data are somewhat anomalous, in that the bulk of species present were more usual for mid-Atlantic shelf areas, i.e., south of Cape Cod (Hulburt, 1963; Marshall and Ranasinghe, 1989; Marshall and Cohn, 1983, than for Gulf of Maine coastal areas, and in that all stations sampled on the central productivity transect (Stations 6-12; Fig. 1) showed similar dominant net species in each major taxonomic division. However, the two inner stations, 6 and 7, were markedly lower in total cell numbers for the >8 um chlorophyll-containing cell fraction, the 3-8 um chlorophyll-containing cell fraction and the cyanobacteria in the picoplankton fraction. This may reflect the low light values (quantity and quality) due to turbidity at the inner stations. The chlorophyll dominant eucaryote picoplankton (the 0.2-3 um fraction) are more prolific and efficient photosynthetically in low light conditions (Murphy and Haugen, 1985; Glover *et al.*, 1986; Olson *et al.*, 1990); here their cell numbers did not change significantly over the transect. However, Station 8 did show the same pattern that is evident at other sampling periods and is discussed below; it appears to be a "fulcrum" point, where adequate light availability and inshore nutrient enrichment enhance total cell numbers as compared to inshore stations (Stas. 6 and 7), which are light-limited because of increased turbidity, or offshore stations (Stas. 10 and 12) which are probably nutrient limited (Fig. 56). Recall from the above discussion of hydrography that this transition between Stations 7 and 8 also is reflected in a surface temperature and salinity front.

We include as examples several graphs from the February sampling period, a time of turbulence and therefore adequate nutrient supply at both inshore and offshore stations, but also a time of low light availability in general due to seasonal insolation. In contrast, we also present several graphs from the August sampling period, where insolation was maximal, and nutrient availability was high inshore at Stations 6 and 7, but low at offshore at Stations 8, 10 and 12

In February, the peak surface cell numbers occurred at Station 8, although bulk chlorophyll measurements at alternate stations would indicate that the optimal light-nutrient situation occurred at Station 9; in August, when light intensity was highest, maxima were shifted towards Station 7 (Fig. 57a and b).

On a qualitative basis, we can show, with similar graphs, that inshore and offshore populations were distinctly different taxonomically (Figs. 58-60). Although the sampling periods were widely spaced, the overall data suggest that phytoplankton populations are seeded from offshore, and are retained as distinguishable populations much longer in the shallower, inshore stations, due to

local mixing events. Temperature, except as it is related to solar energy available, does not appear to be a controlling factor that distinguishes inshore from offshore populations. As an example, counts of the prymnesiophyte *Phaeocystis* for February and March show the inshore progression of this population (Fig. 61).

The inshore-offshore separation of phytoplankton populations along this transect during these sampling periods demonstrate the need to be cautious in the interpretation of bulk chlorophyll measurements and therefore overall productivity estimates since either one could be linked to cells of extremely different volumes and/or different photosynthetic efficiencies, affecting trophic interactions and nutrient kinetics.

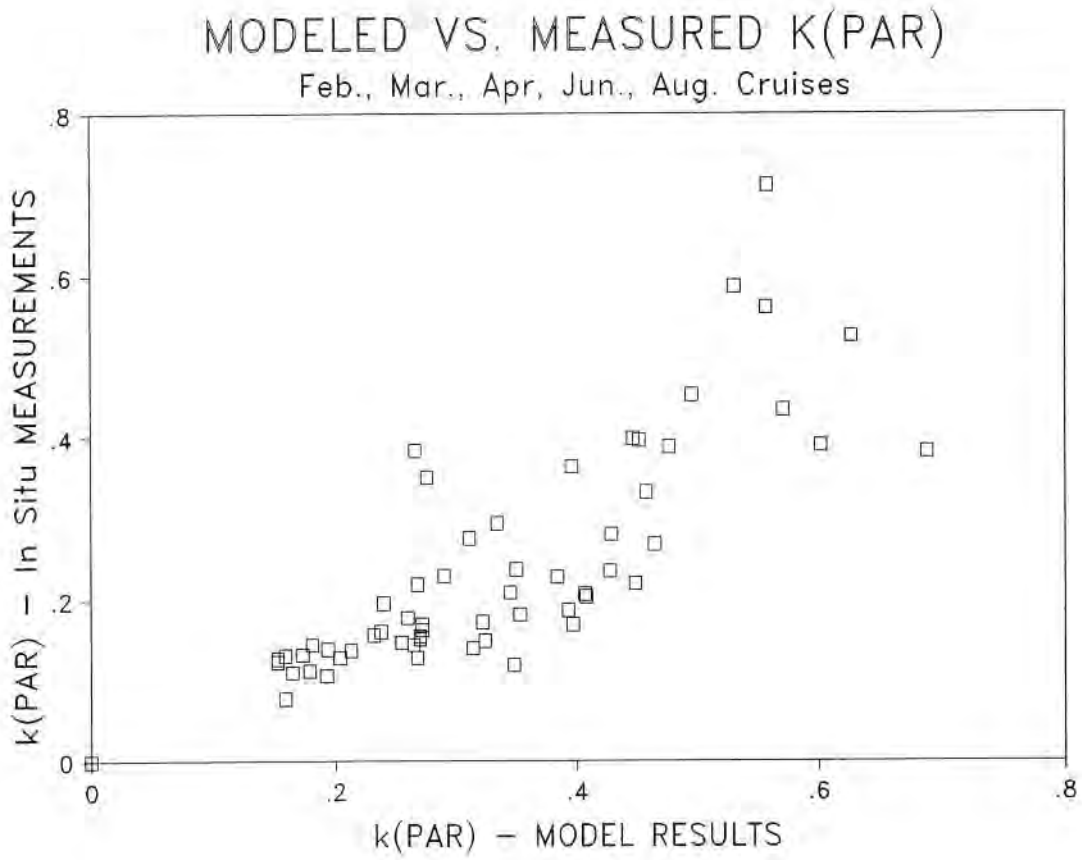


Figure 48. Comparison of modelled versus measured k_{PAR} for all cruises except October 1989.

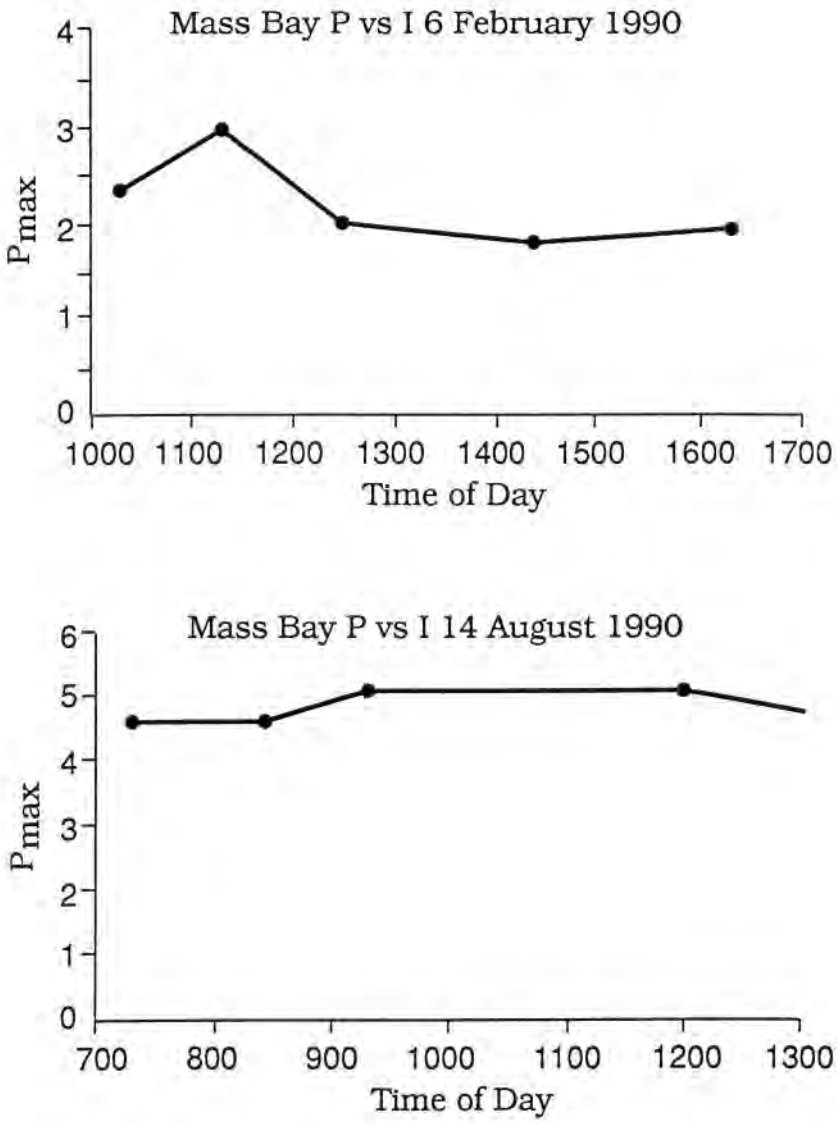


Figure 49. Pmax as a function of the time of day on 14 August 1990.

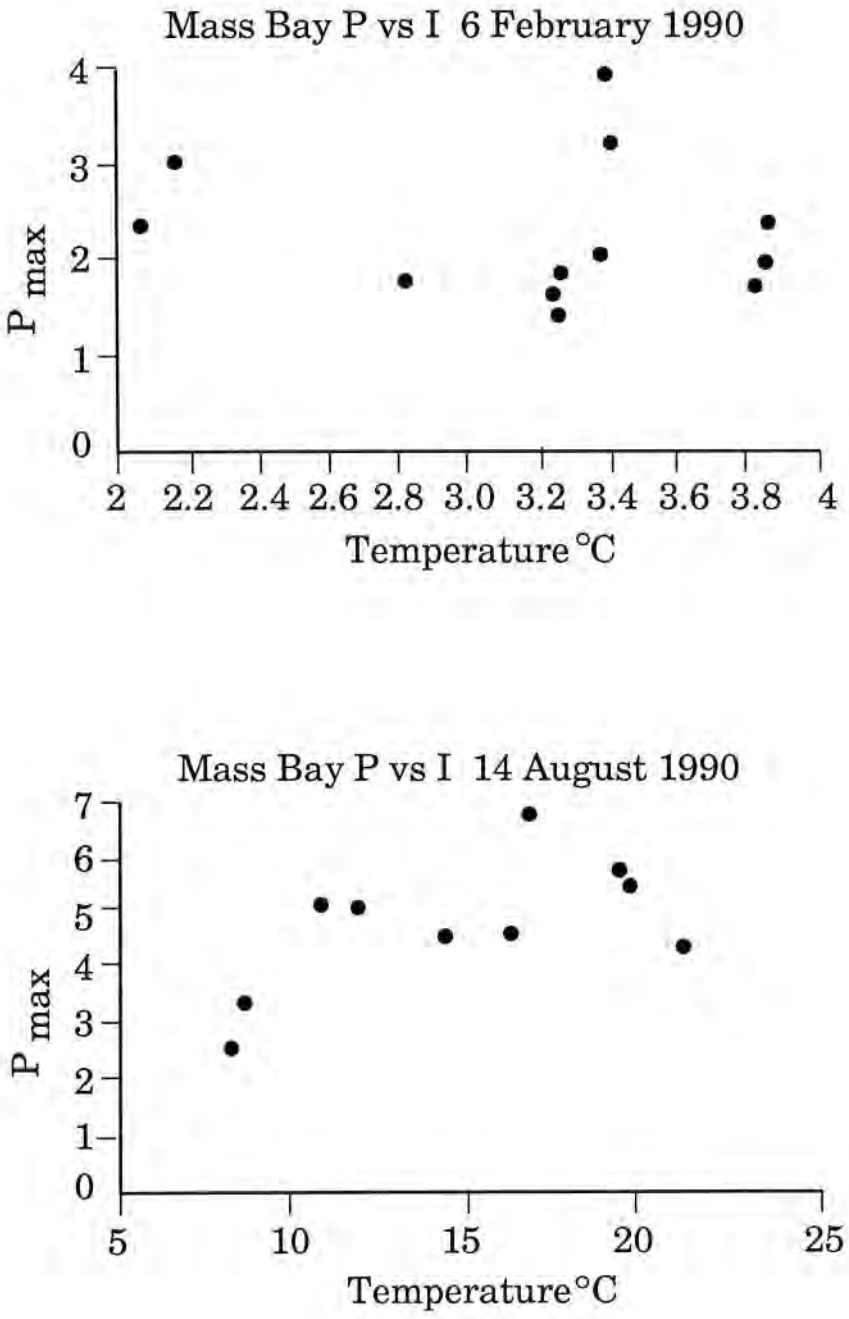
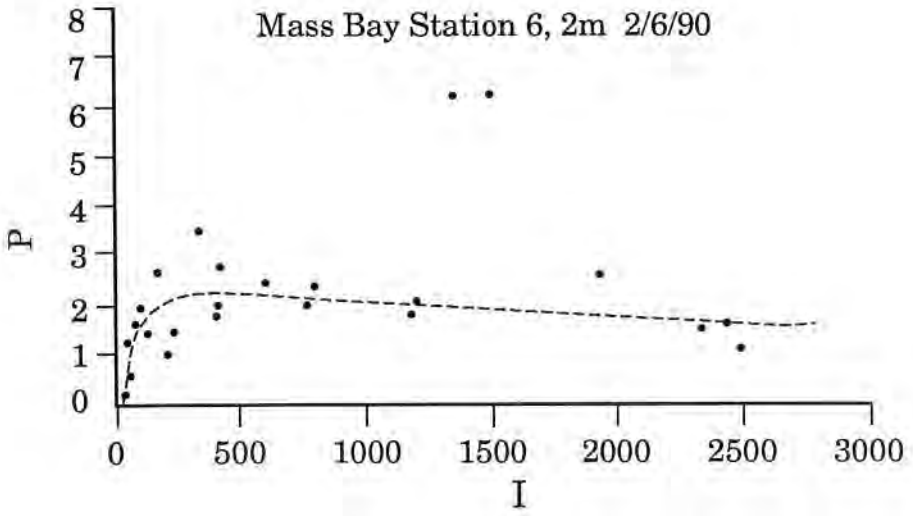
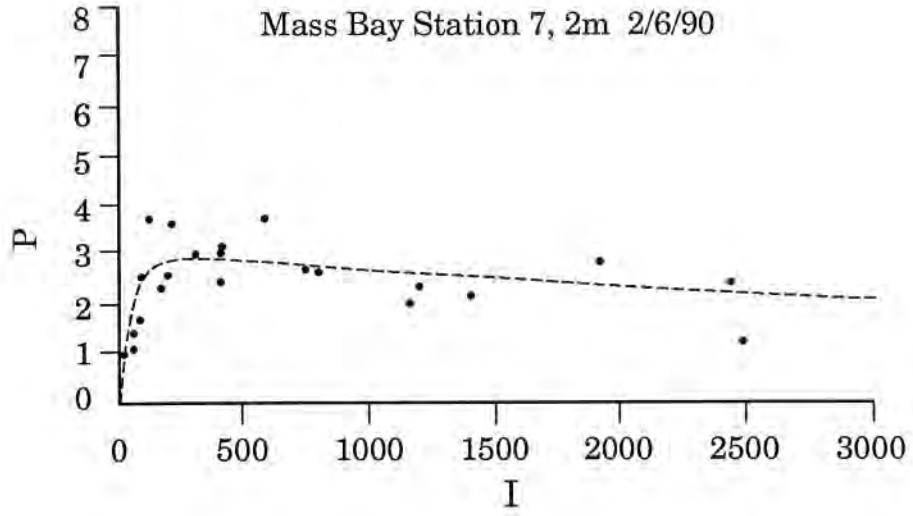


Figure 50. Pmax as a function of temperature for 6 February and 14 August 1990





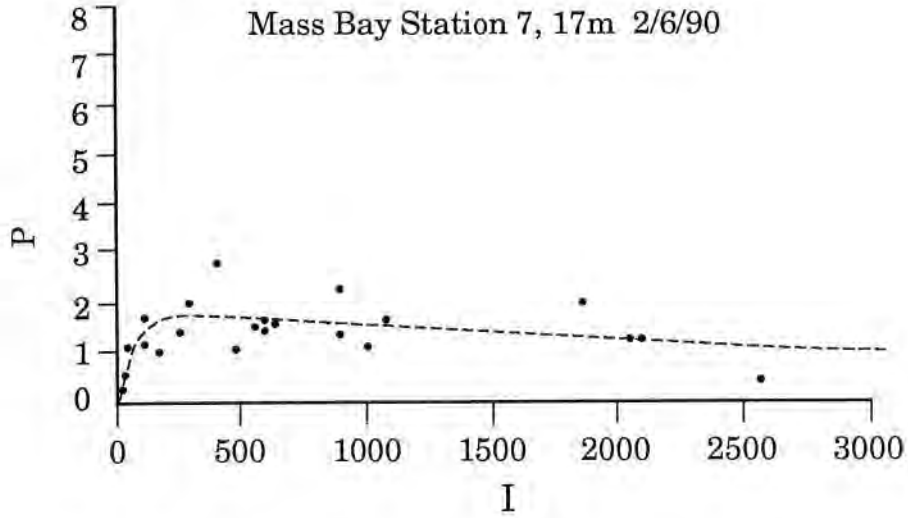
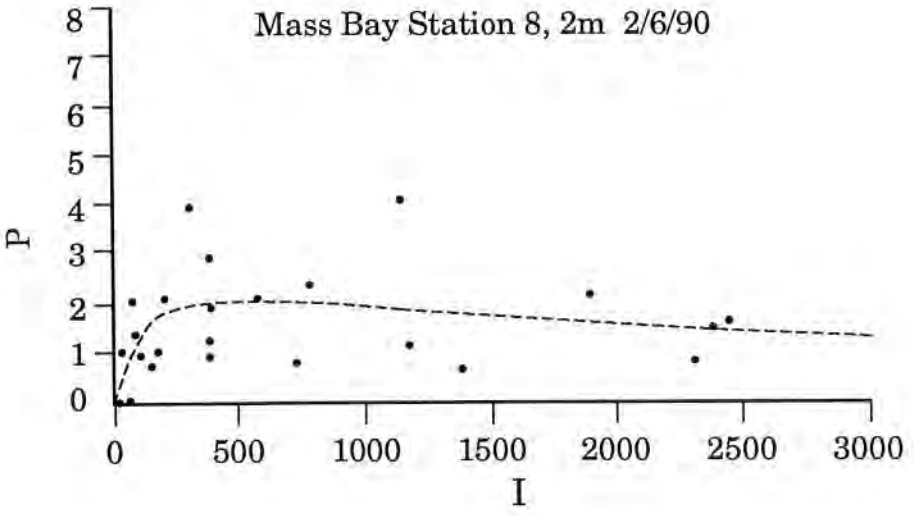
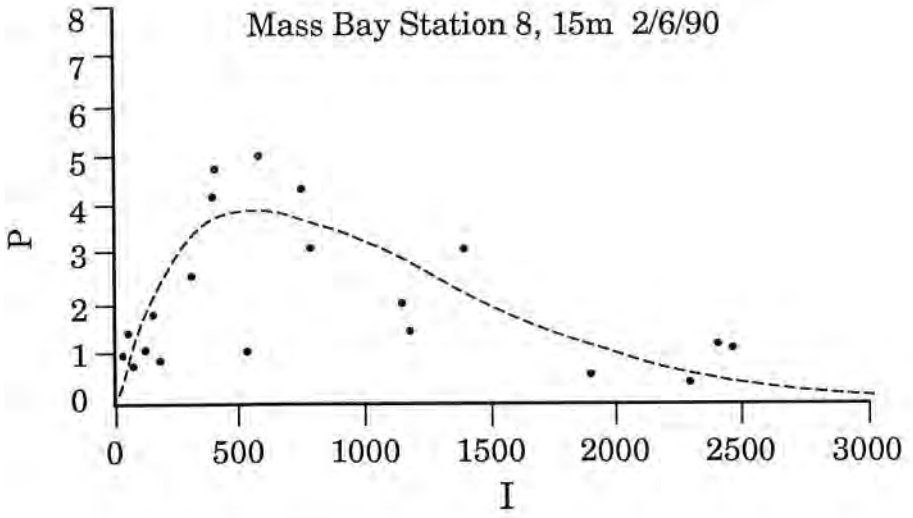


Figure 51. P vs. I curves for station 6 and 7, 6 February 1990. P is in mgC/mgChla/ h and I is in μEin/ m^2/s.





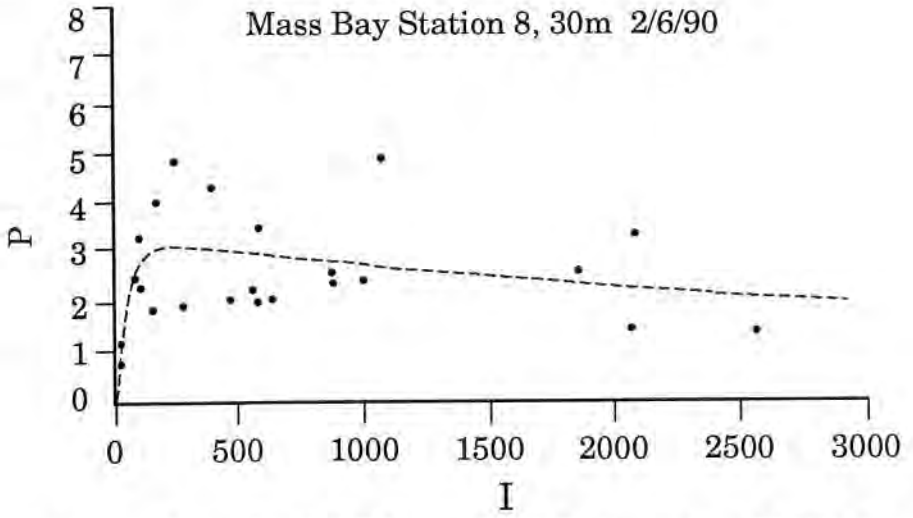
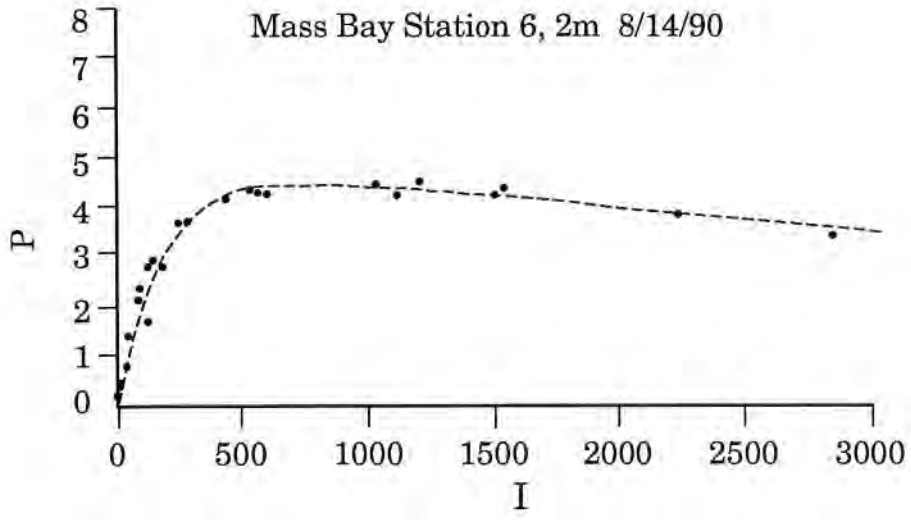
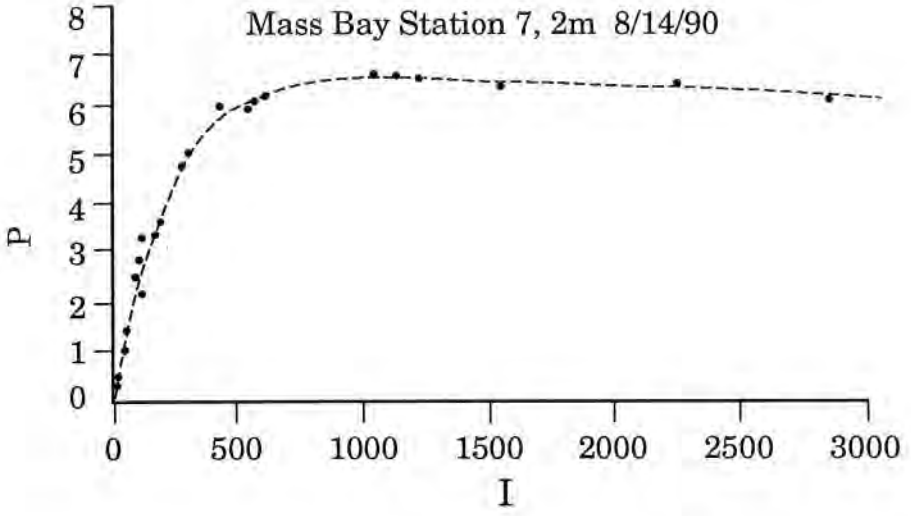


Figure 52. P vs. I curves for station 8, 6 February 1990. P is in mgC/mgChla/ h and I is in μEin/ m^2/s.





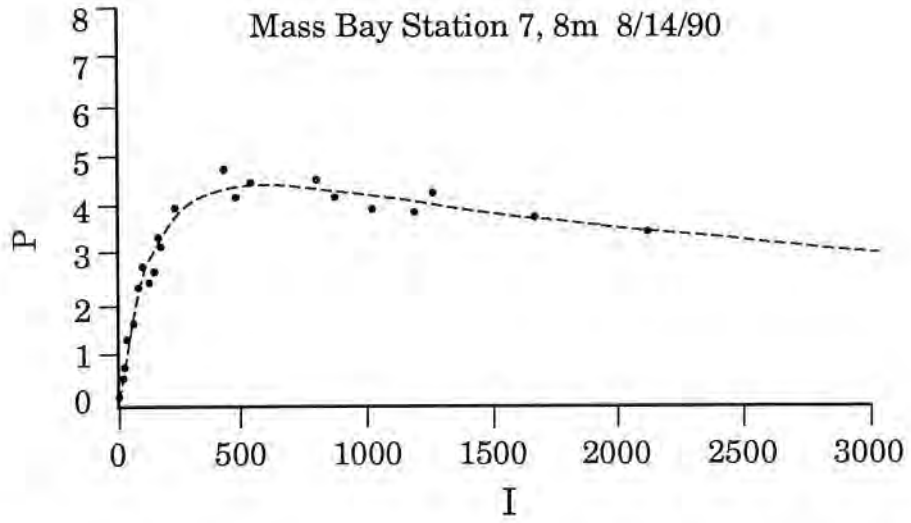


Figure 53. P vs. I curves for station 6 and 7, 14 August 1990. P is in mgC/mgChla/ h and I is in μEin/ m^2/s.

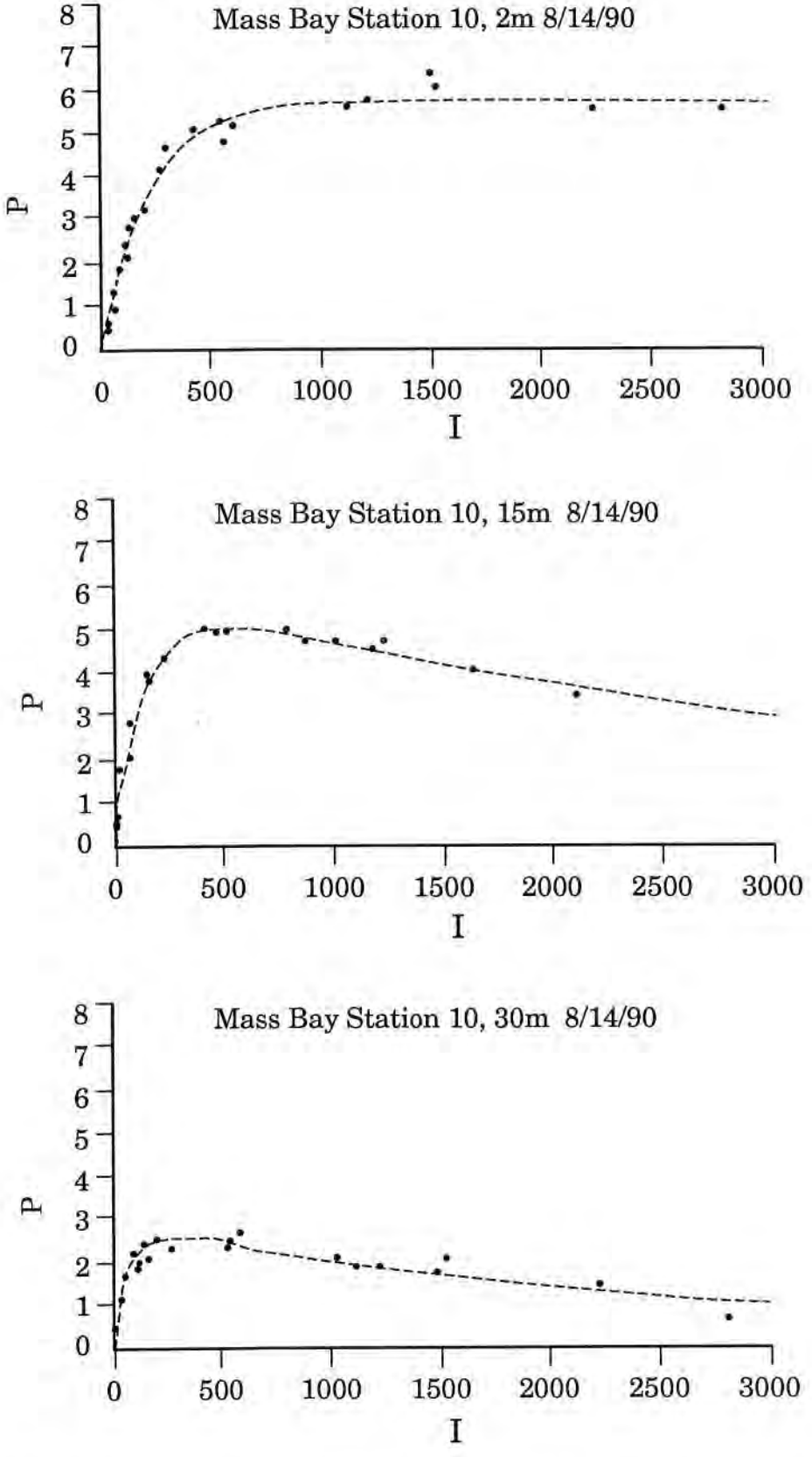


Figure 54. P vs. I curves for station 10, 14 August 1990. P is in mgC/mgChla/ h and I is in μEin/ m^2/s.

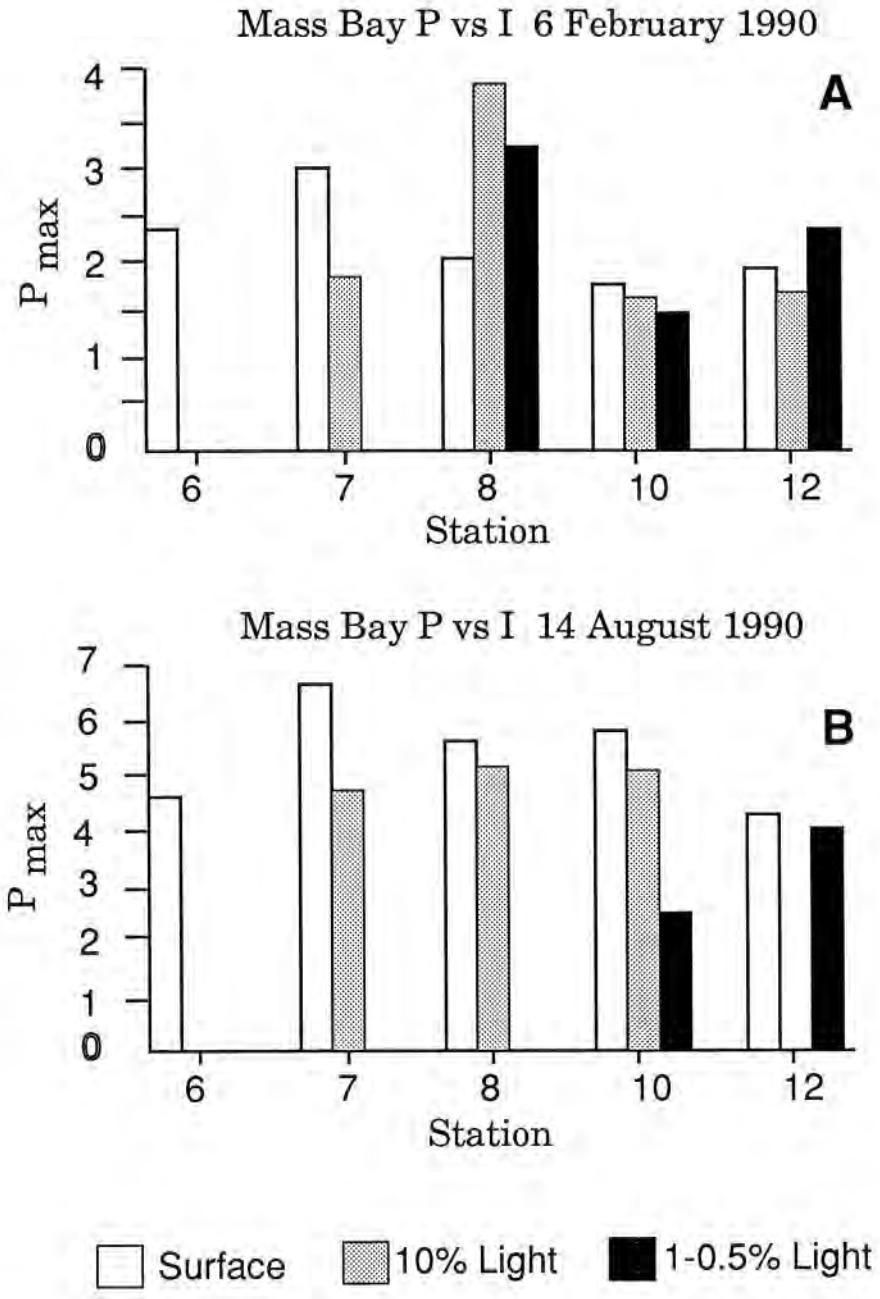


Figure 55. Values of Pmax at Stations 6-12 under different light regimes for 6 February and 14 August 1990.

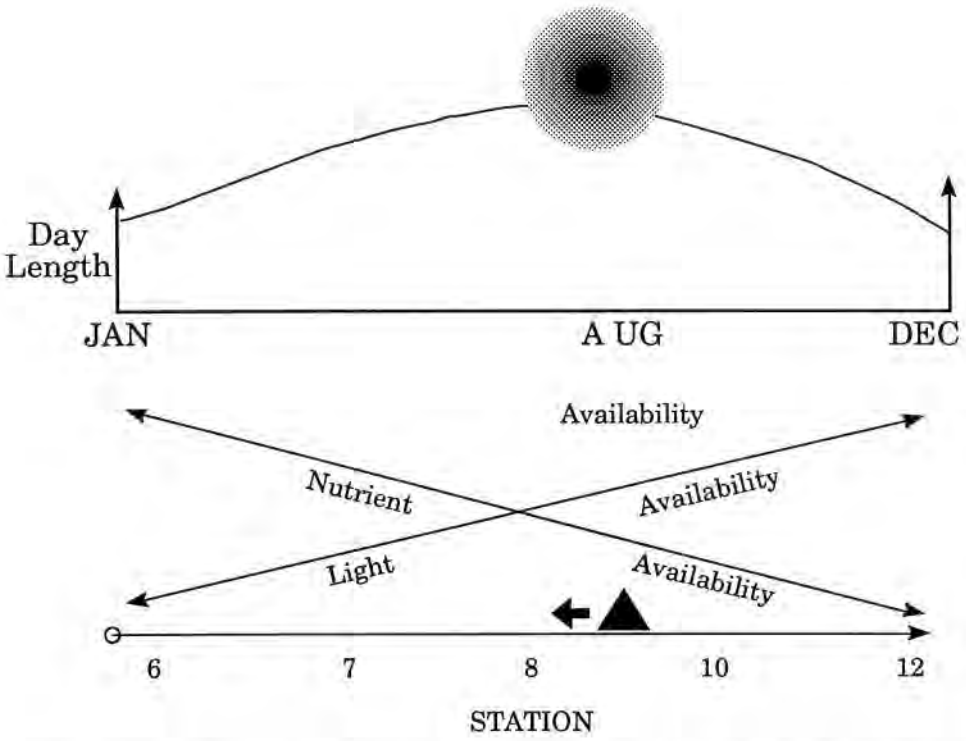


Figure 56. Schematic diagram relating sunlight and nutrient availability to seasonal cycle.

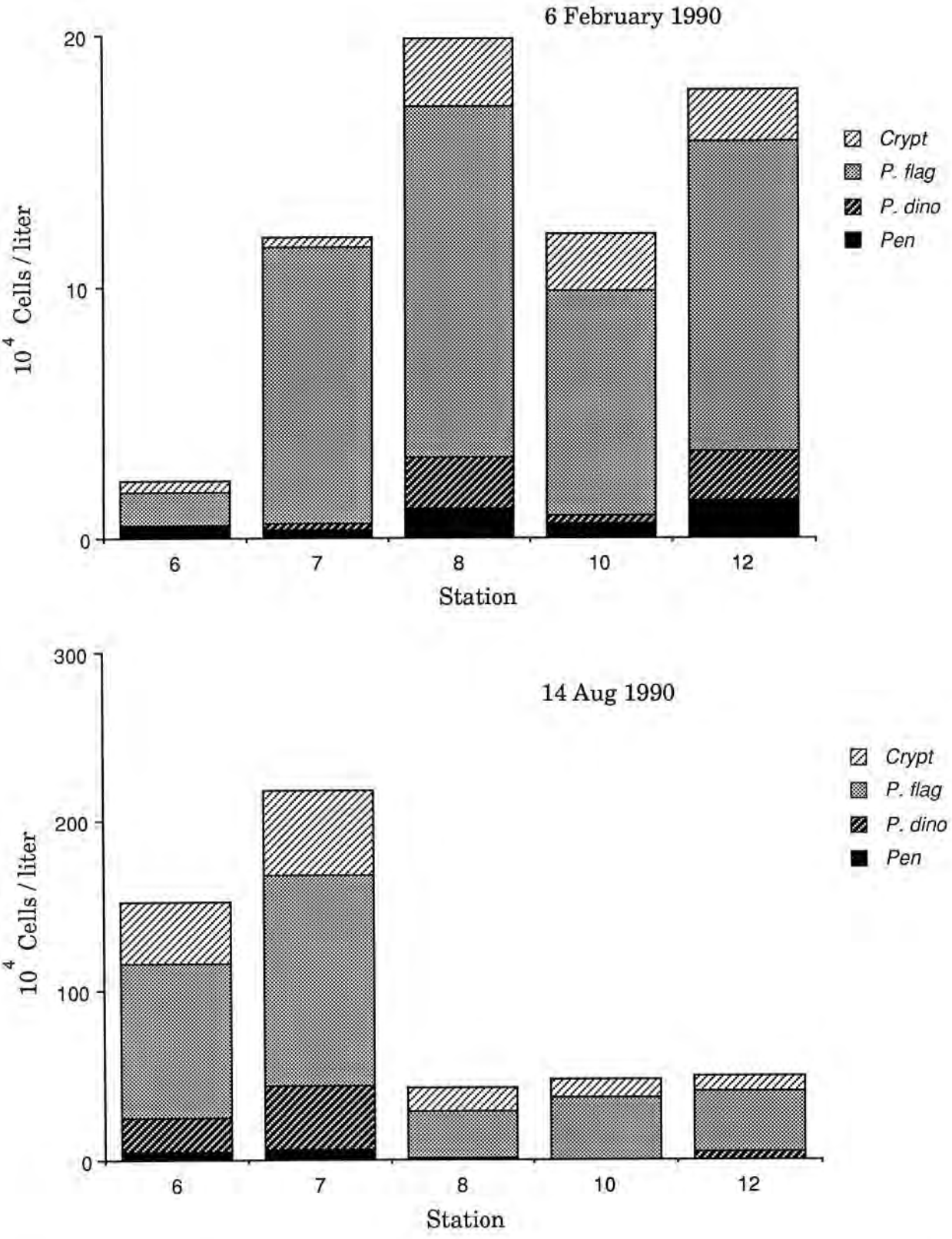


Figure 57. Abundances of cells (net and nanoplankton) for surface populations by major taxon. This does not include centric diatoms due to scale. *Crypt = cryptomonads; P. flag = phytoflagellates; P dino = photosynthetic dinoflagellates; Pen = pennate diatoms.*

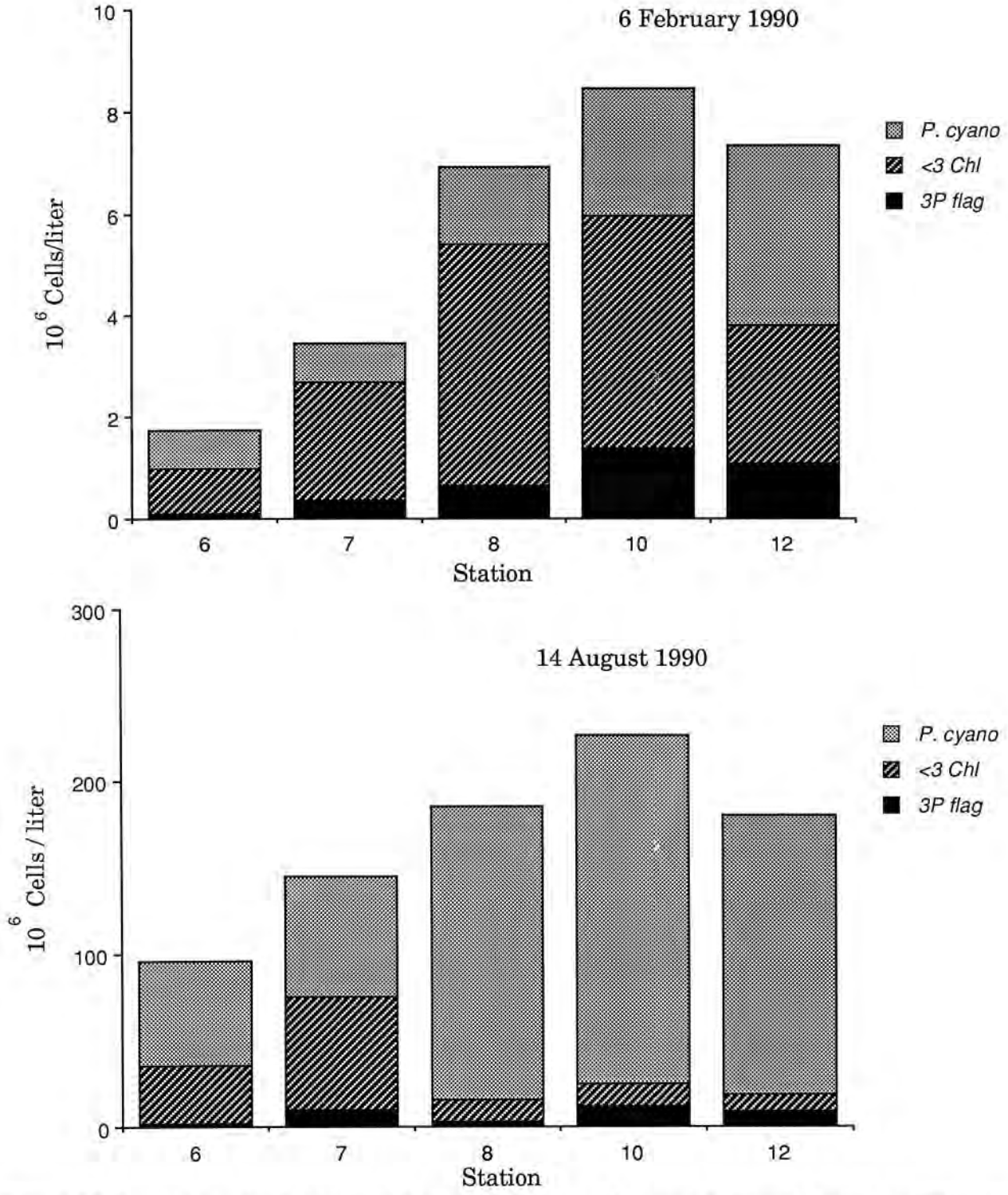


Figure 58. Surface cell abundances for ultraphytoplankton. *P. cyano* = coccoid cyanobacteria; *<3 Chl* = 0.2-3.0 μm eucaryotic picoplankton; *3P flag* = 3.0-8.0 μm phytoflagellate ultraplankton.

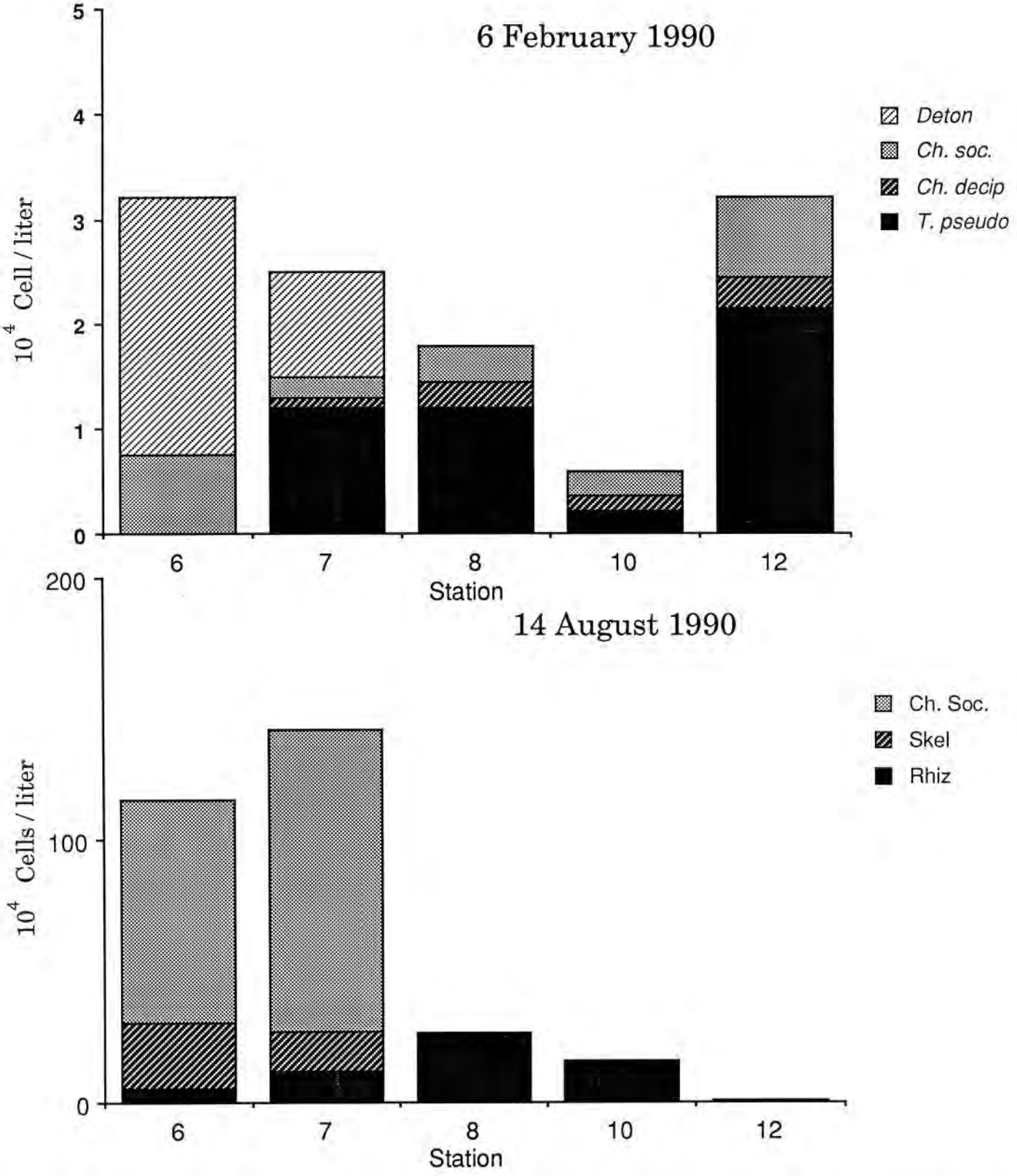


Figure 59. Distribution of several dominant centric diatom species. *T. pseudo = Thalassiosira pseudonana; Ch decip = Chaetoceras decipiens; Ch. soc. = Chaetoceras socialis; Deton = Detonula confervacea; Rhiz = Rhizosolenia spp.; Skel = Skeletonema costatum*

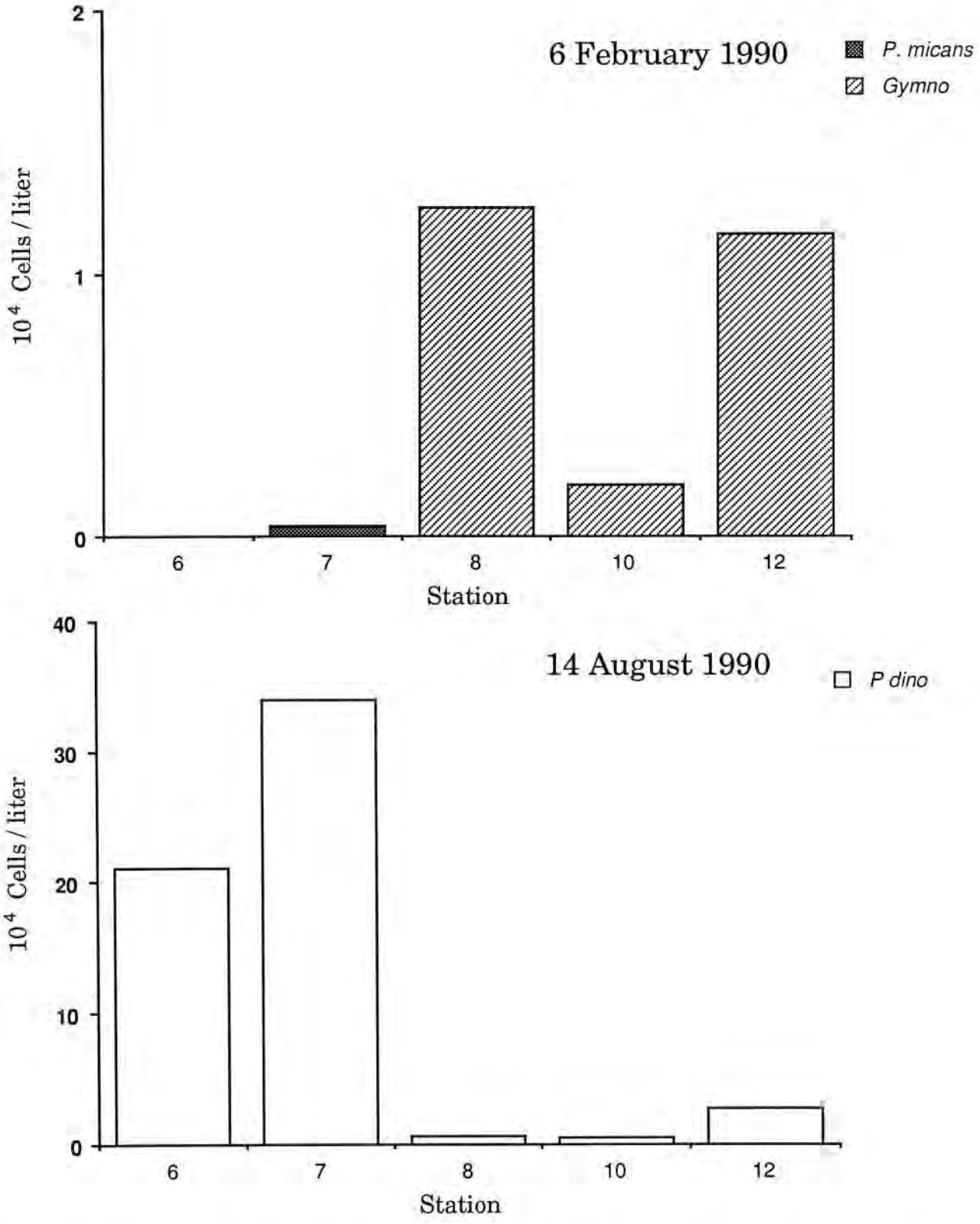


Figure 60. Distribution of several dominant photosynthetic dinoflagellates along the central transect. *Gymno = Gymnodinium spp.; P.micans = Prorocentrum micans; P. dino = photosynthetic dinoflagellates.*

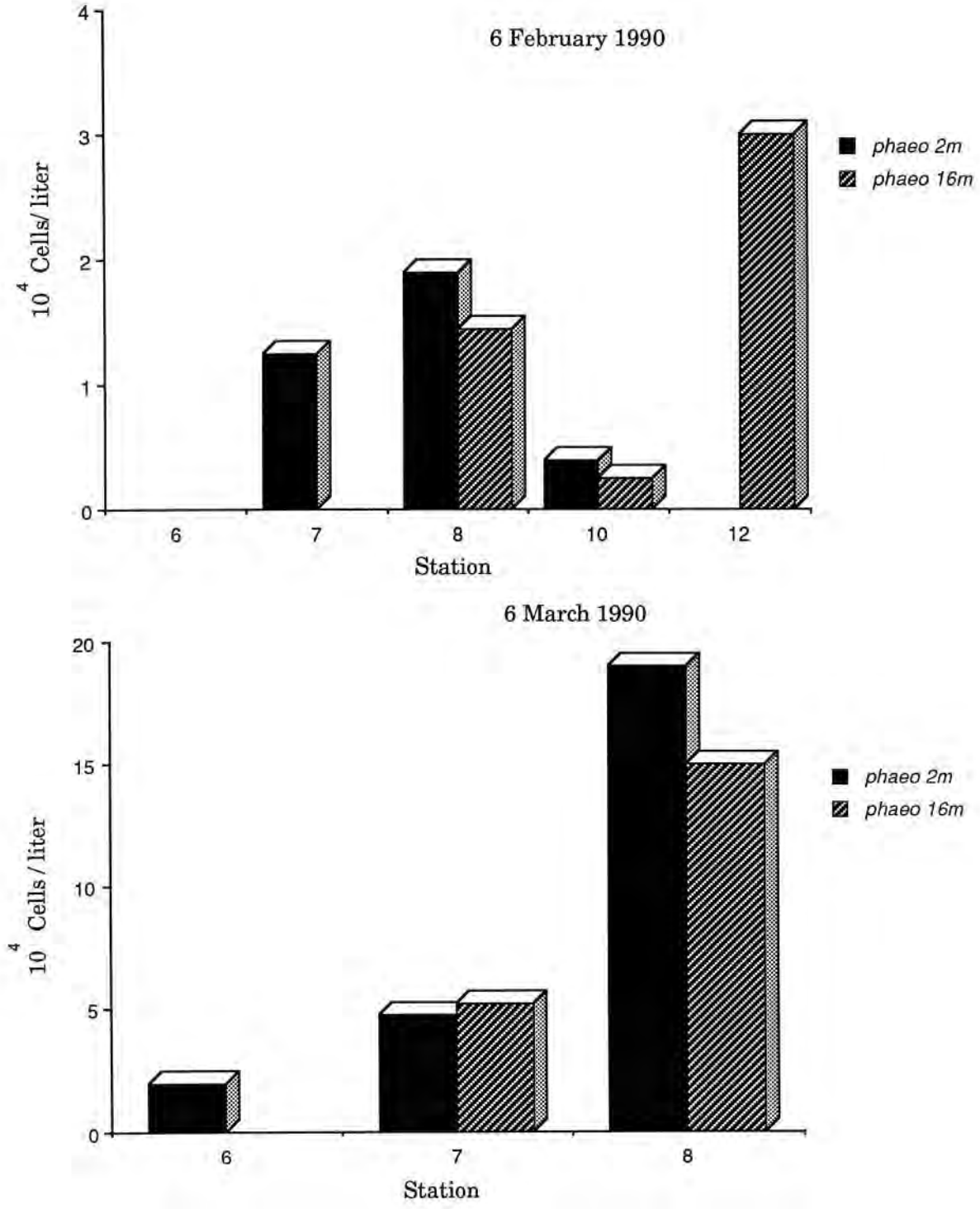


Figure 61. Distribution and abundance of Phaeocystis at 2 and 16m depth in February and March, 1990.

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Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
http://www.mwra.state.ma.us