Water quality monitoring in Massachusetts and Cape Cod Bays: June and July 1993.

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FINAL

WATER QUALITY MONITORING
IN
MASSACHUSETTS AND CAPE COD BAYS:
JUNE AND JULY 1993

by

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EXECUTIVE SUMMARY

This report is the third of five periodic water column reports for water quality monitoring conducted in 1993 by Battelle Ocean Sciences for the Massachusetts Water Resources Authority (MWRA) Harbor and Outfall Monitoring Program. The report includes results from three surveys conducted during June and July of 1993; each of these surveys included sampling at twenty-one stations in the nearfield area. The June survey was a combined farfield/nearfield survey that covered 25 additional stations throughout Massachusetts Bay and Cape Cod Bay. Data on physical, chemical, and biological measurements at the stations are presented and interrelationships of these measurements are examined.

A main feature during this period of monitoring was the strong thermal and density stratification in the water column of the Bays. This is an expected seasonal feature and was found consistently throughout the period except in shallow waters along the coast from Boston south to Cape Cod Bay. In large measure stratification controlled the nutrient and chlorophyll distributions in the water column during the June and July surveys.

A second feature, the main geographic trend of note, was a gradient from the edge of Boston Harbor to the middle of the nearfield area about 15 km offshore. For some parameters, the gradient also extended southward along the coast for a similar distance. Although the enrichment of dissolved inorganic nutrients close to the Harbor was detectable, it was slight. An enrichment and sharper gradient of decrease in water column concentrations with distance from the Harbor area into the surface waters of the Bay was found for chlorophyll, turbidity, and total nitrogen (including organic forms). This spatial trend has been documented in the previous summer's monitoring and, in general, the data for the nearfield in 1992 and 1993 showed similar concentration ranges and only subtle differences in temporal trends for most parameters.

Because of weaker stratification inshore and the Harbor's extended influence on surface water quality in adjacent Bay waters, there was a distinct trend in the distribution of chlorophyll from inshore to offshore. Near the Harbor and along the western side of the nearfield area (about 5 km west of the center of the proposed diffuser track), chlorophyll was relatively high and found within the surface layer above the pycnocline (the sharp transition layer between the warm surface layer and the cold bottom water layer). In contrast, further offshore, including virtually all water deeper than about 30 m, maximum chlorophyll concentrations were lower and were generally found within the pycnocline itself (about 10-20 m).

Besides these general trends, specific findings were as follows:

■   Nutrients — Concentrations were low or undetectable in most surface waters. Below the pycnocline, concentrations increased and were generally highest (e.g., 9 μM for dissolved inorganic nitrogen and 10-14 μM for silicate) in deep water in Stellwagen Basin stations. Maintained by stratification, the vertical distribution changed little through the period of surveys.

■ Chlorophyll — Main trends have been mentioned above. High values were 5-7 μg Chl a L^{-1}. There was a strong linear relationship between chlorophyll and total nitrogen (TN) that confirmed the previously-reported pattern, on average, of about 1 μg Chl a L^{-1} increase for each 1 μM increase in TN.

■ Phytoplankton — Roughly similar communities were seen throughout the ten special stations sampled in the Bays. A mixed diatom-microflagellate-crytomonad community was regularly observed and dinoflagellates were not numerically dominant. Diatom species, especially *Leptocylindrus danicus*, were the main individual dominants in the nearfield area through June and July. Results in 1993 differ from 1992. In 1992, a dinoflagellate, *Ceratium longipes*, reached very high abundances in Cape Cod Bay, making it biologically distinctive from Massachusetts Bay. In contrast, there were only slight phytoplankton differences noted between Massachusetts and Cape Cod Bay stations in June 1993, and *Ceratium*, although again present everywhere, had not attained dominance anywhere.

■ Zooplankton — The main zooplankton taxa in terms of abundance was again *Oithona similis*, as has been almost consistently the case in 1992 and 1993. A number of other larger copepods were present in most locations. *Acartia tonsa*, more typically an estuarine species than a shelf-water species, was present at stations in the Bay that had higher surface chlorophyll and appeared to be influenced by export from Boston Harbor.

■ Dissolved oxygen (DO) — Surface waters were generally supersaturated and a distinct mid-depth maximum sometimes was found associated with a subsurface chlorophyll maximum. DO, as percent of saturation, decreased below the pycnocline, and reached values as low as 90-95 % ($\approx$9.6-10.2 mg L^{-1}) at depth in Stellwagen Basin in June and about 95 % ($\approx$9.8-9.9 mg L^{-1}) in the deeper waters of the eastern nearfield by late July.

■ Metabolism — There were some relatively consistent differences in production estimates based on surface sample and subsurface chlorophyll maximum sample incubations. Production rates were high, generally well above 1 g C m^{-2} d^{-1}, and averaged about 2.5 g C m^{-2} d^{-1} for nearfield stations in June. Most of the production was within the top 15 m and the vertical pattern closely followed the chlorophyll distribution. An extra examination was conducted to examine the potential of detecting metabolism as reflected by diurnal changes in free-water DO during sampling of twenty-one stations in the nearfield. The rate and vertical distribution of production that was estimated by following diurnal changes was remarkably similar to that derived from production modeled from P-I incubations. The detection of diurnal changes is possible at the high production rates in surface layers. Respiration was detectable in only a portion of the incubations, mostly in samples from the surface than at depth. Statistically significant rates were about 0.006 to 0.03 mg O_2 L^{-1} d^{-1}. Both bottle incubations and free-water diurnal patterns suggested that bottom waters had low to undetectable respiration rates on the timescale of hours. Although production was high, metabolism in general was within the range recorded in previous monitoring. The correlation between the two production estimates and the respiration estimates suggests a near-balance in the surface waters during the June nearfield survey.

CONTENTS

Note to reader:

    Appendices A-G are bound separately from this technical report. To request the Appendices, contact the MWRA and ask for one of the MWRA Miscellaneous Publications entitled "Appendices to Water Quality Monitoring in Massachusetts and Cape Cod Bays: June and July 1993."

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1.0 INTRODUCTION

This report is the third of five periodic water column reports for water quality monitoring conducted in 1993 for the Massachusetts Water Resources Authority (MWRA) Harbor and Outfall Monitoring Program. The report includes results from three surveys conducted during June and July of 1993; each of these surveys included sampling at twenty-one stations in the nearfield area. The June survey was a combined farfield/nearfield survey that covered 25 additional stations throughout Massachusetts Bay and Cape Cod Bay. Data on physical, chemical, and biological measurements at the stations are presented and interrelationships of these measurements are examined.

The structure of this report is as follows:

Section 1. Background information on the water quality surveys conducted in 1993.

Section 2. Field, laboratory, and data analysis methods.

Sections 3-5. Results of surveys, in chronological order (June farfield/nearfield survey, early July nearfield survey, late July nearfield survey).

Section 6. Discussion of the mid-summer period of surveys.

All tables and figures are presented at the end of each section. An extensive set of appendices is bound separately. The appendices provide supporting tables and plots that represent the data being stored in the MWRA database.

1.1 Background

The MWRA is implementing a long-term monitoring plan for the future MWRA effluent outfall that will be located in Massachusetts Bay (Figure 1-1). The purpose of the monitoring is to verify compliance with the conditions of the NPDES discharge permit and to assess the potential environmental impact of effluent discharge into Massachusetts Bay. A detailed description of the monitoring and its rationale are given in the Effluent Outfall Monitoring Plan (MWRA, 1991).

To help establish the present conditions with respect to water properties, nutrients, and other important parameters of eutrophication, the MWRA contracted with Battelle Ocean Sciences to

conduct baseline water-quality surveys throughout Massachusetts Bay during 1992 to 1994. Results of the 1992 surveys were presented in a series of three reports similar to this report (Kelly *et al.*, 1992; Kelly *et al.*, 1993a,b), summarized in an annual report (Kelly *et al.*, 1993c), and used to examine nutrient issues related to the offshore outfall (Kelly, 1994). Two earlier periodic water column reports for 1993 covered surveys conducted from February through May (Kelly *et al.*, 1993d,e).

Serving the MWRA's need for rapid dissemination of data and information, the periodic report series also provides a preliminary synthesis of monitoring results. The technical approach used in 1993 to implement the water quality portion of this monitoring plan is presented in a combined work/quality assurance project plan (CW/QAPP) (Albro *et al.*, 1993) that was developed specifically for water quality monitoring. The CW/QAPP describes the technical activities performed at sea and in the laboratory, as well as the data quality requirements and assessments, project management, and a schedule of activities and deliverables. In addition, individual survey plans are submitted to MWRA for each survey to provide important operational details. The survey reports submitted for the three surveys discussed in this report describe actual survey tracks, samples collected, and other survey details (Albro, 1993a,b; West, 1993). The survey reports should be consulted for pertinent details, for example, on sampling tracks and samples obtained at each station. Data reports on nutrients, plankton, and pelagic metabolism have been submitted to MWRA for the surveys conducted during June and July 1993; these data form a portion of the appendices to this report.

1.2 Survey Objectives

The objectives of the water quality surveys are discussed in detail in the MWRA Effluent Outfall Monitoring Plan (MWRA, 1991) and are summarized as follows:

Physical Oceanography

■   Obtain high-resolution measurements of water properties throughout Massachusetts Bay.

■   Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in water properties, and to provide supporting data to help interpret biological and chemical data.

■   Use high-resolution, near-synoptic, water-property measurements along transects within the nearfield area for analysis of smaller-scale spatial (kilometers) and temporal (semi-monthly) variability in water properties, and develop a three-dimensional picture of water properties near the future outfall.

Nutrients

■   Obtain nutrient measurements in water that is representative of Massachusetts and Cape Cod Bays.

■   Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in nutrient concentrations and to provide supporting data to help to interpret biological data.

■   Use vertical-profile data along transects of closely-spaced stations within the nearfield area for analysis of smaller-scale spatial (kilometers) and temporal (semi-monthly) variability in nutrient concentrations, and develop a three-dimensional understanding of the nutrient field near the future outfall.

Plankton

■   Obtain high-quality identification and enumeration of phytoplankton and zooplankton in water that is representative of Massachusetts and Cape Cod Bays.

■   Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in plankton distribution.

Water Column Respiration and Production

■   Using water that is representative of Massachusetts and Cape Cod Bays, obtain a reasonable estimate of the rates of water-column respiration and production as a function of irradiance.

General

■   Evaluate the utility of various measurements to detect change or to help to explain observed change.

■   Provide data to help modify the monitoring program to allow a more efficient means of attaining monitoring objectives.

■   Use the data appropriately to describe the water-quality conditions (over space and time) in Massachusetts and Cape Cod Bays.

1.3 Survey Schedule for 1993 Baseline
Water Quality Monitoring Program

Throughout 1993 and 1994, Battelle and its subcontractors, the University of Rhode Island (URI) and the University of Massachusetts at Dartmouth (UMD), are conducting surveys similar to those initiated in 1992. The actual (to date) and planned schedule of surveys in 1993 is given in Table 1-1. The survey schedule was designed to match the schedule conducted in 1992. The surveys discussed in this report were conducted during the weeks planned: June 22-26 (Survey W9307), July 7-8 (Survey W9308), and July 28-29 (W9309).

1.4 Summary of Accomplishments:
June to Late July 1993

For the combined farfield/nearfield survey in June (W9307), *in situ* measurements were taken and samples were collected at the stations shown in Figure 1-1. Samples for laboratory analyses were collected to obtain the following types of data:

- Dissolved inorganic nutrients: nitrate, nitrite, ammonium, phosphate, and silicate.

- Chlorophyll *a* and phaeopigments in extracts of filtered water.

- *In situ* fluorometric measurements of chlorophyll, optical-beam transmittance (attenuation), light irradiance, salinity, temperature, and dissolved oxygen.

- Total suspended solids and dissolved oxygen in discrete water samples.

- Organic nutrients: dissolved carbon, nitrogen, and phosphorus; particulate carbon and nitrogen.

- Phytoplankton and zooplankton identification and enumeration.

- Rates of water-column production (^{14}C) vs. irradiance from shipboard incubations.

- Rates of water-column dark respiration (dissolved oxygen) from shipboard incubations.

For the nearfield surveys, one day was dedicated to vertical profiling, including collection of the following data:

■   Dissolved inorganic nutrients: nitrate, nitrite, ammonium, phosphate, and silicate.

■   *In situ* fluorometric measurements of chlorophyll, optical-beam transmittance (attenuation), light irradiance, salinity, temperature, and dissolved oxygen.

■   Chlorophyll *a* and phaeopigments in extracts of filtered water, as well as oxygen samples for titration, all to be used to calibrate *in situ* readings.

■   Phytoplankton samples for analysis and archival purposes.

A second day of a nearfield survey was dedicated to high-resolution "tow-yo" profiling. A towfish containing *in situ* sensors (as above, minus irradiance) was performed along nearfield tracks set between the vertical stations with the towfish oscillating from near surface to near bottom as the ship progressed at 4 to 7 kt. An example trackline from survey W9307 is provided in Figure 1-2.

Samples that were collected for analysis have been analyzed, and *in situ* sensor measurements have been calibrated and processed. Both types of data are presented in this report and all are summarized in accompanying Appendices A through G.

Table 1-1. Schedule of water quality surveys for calendar year 1993. This report provides data from the surveys conducted in June and July 1993.

SURVEY	SURVEY DATES
W9301 (Combined Farfield/Nearfield)	Feb 23-27
W9302 (Combined Farfield/Nearfield)	Mar 09-12
W9303 (Nearfield)	Mar 24-25
W9304 (Combined Farfield/Nearfield)	Apr 06-10
W9305 (Nearfield)	Apr 29-May 1
W9306 (Nearfield)	May 20-21
W9307 (Combined Farfield/Nearfield)	Jun 22-26
W9308 (Nearfield)	Jul 07-08
W9309 (Nearfield)	Jul 28-29
W9310 (Nearfield)	Aug 11-12
W9311 (Combined Farfield/Nearfield)	Aug 24-28
W9312 (Nearfield)	Sep 08-09
W9313 (Nearfield)	Sep 28-29
W9314 (Combined Farfield/Nearfield)	Oct 12-16
W9315 (Nearfield)	Nov 03-04
W9316 (Nearfield)	Dec 01-02
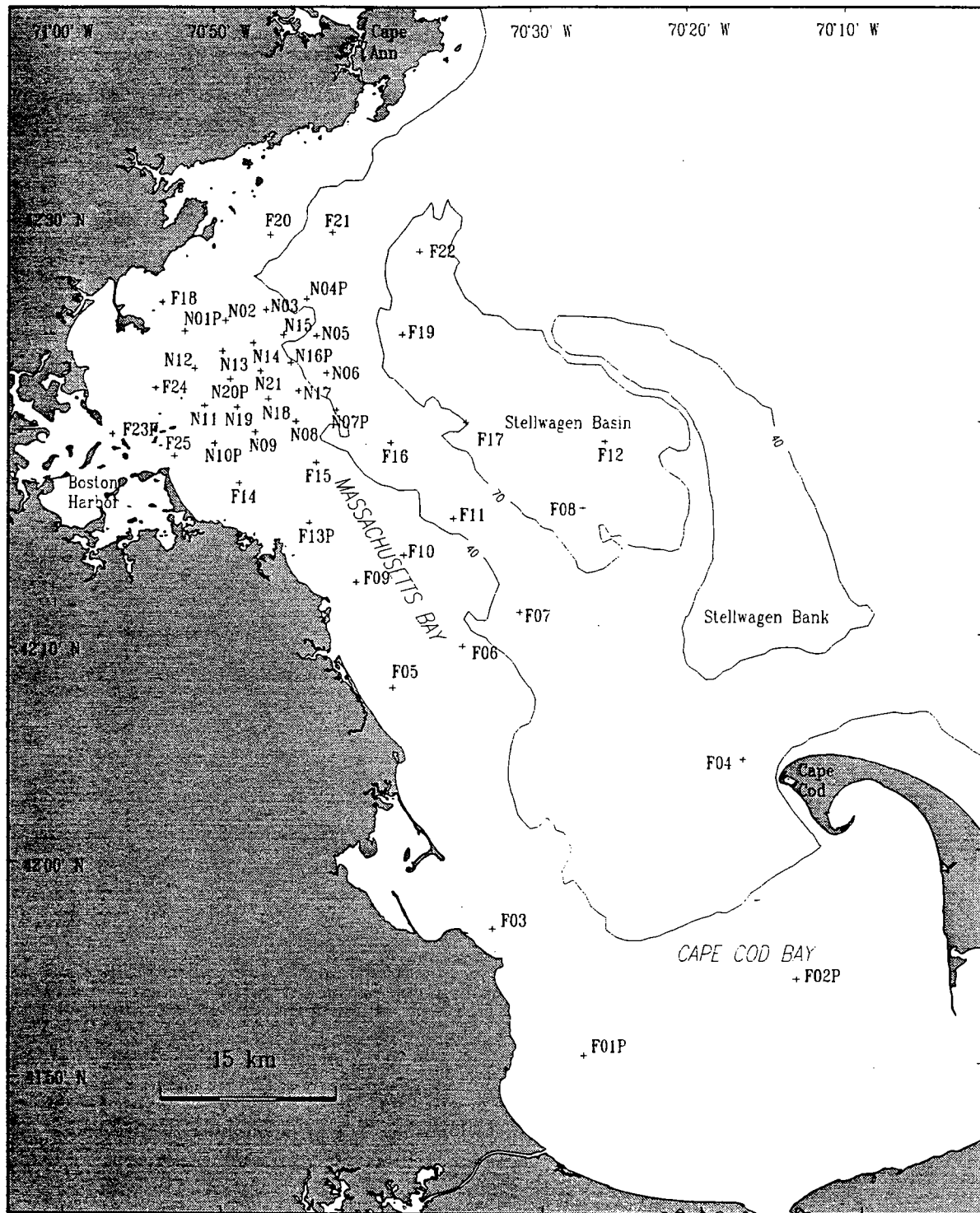
Figure 1-1. **Water quality sampling stations in Massachusetts and Cape Cod Bays.
Station codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Depth
contours are in m.**

NEARFIELD SURVEY TRACKLINES FOR_06-26-1993
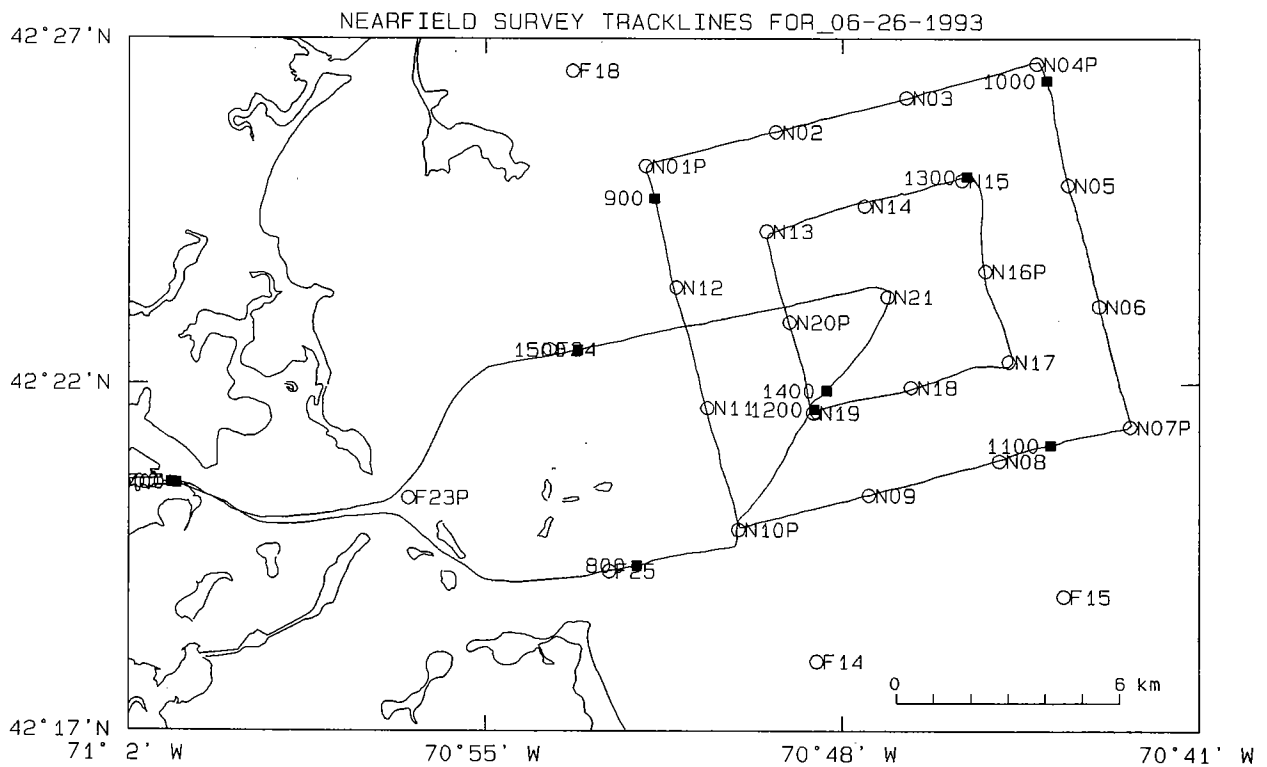
Figure 1-2. Nearfield survey tracklines for June 26, 1993. Tow-yo operations were conducted clockwise from N10P to N10P, N19 to N19, and N19 to N21. The hour of the day is indicated (800-1500) along the track.

2.0 METHODS

Field sampling equipment and procedures, sample handling and custody, sample processing and laboratory analysis, and instrument performance specifications and data quality objectives are discussed in the water quality monitoring CW/QAPP (Albro *et al.*, 1993). The plan is detailed and should be consulted for standard survey methods. In general, only deviations from the CW/QAPP are provided in this report.

2.1 Field Procedures

2.1.1 Hydrographic and Water Sampling Stations

Tables 2-1 and 2-2 summarize the planned sampling, and indicate the types of measurements and samples taken at nearfield and farfield stations (Albro *et al.*, 1993). For a combined farfield/nearfield survey, a subset of 10 stations (4 farfield and 6 nearfield) has additional biology/productivity measurements and, henceforth, these stations are termed "BioProductivity" stations and labeled with a "P" (see Figure 1-1). The six "P" stations in the nearfield are repeatedly sampled for a broad suite of parameters as part of the farfield survey, again during hydrographic profiling—dissolved nutrient stations on the vertical sampling day of nearfield survey, and lastly as part of the towing track sampled on a second day of the nearfield survey. Nearly all planned samples were collected. Principal deviations from the CW/QAPP plan for each survey are given below; most are reported in the appropriate survey report, prepared after the completion of each survey.

In addition to the procedures described in the CW/QAPP, the following methods were used for the combined farfield/nearfield survey in June (W9307):

- No samples were collected for oxygen incubations to determine production. Production measurements were made using ^{14}C (described below). However, oxygen samples were collected at 21 stations at 3 to 5 depths and were used to calibrate the dissolved oxygen sensors (Appendix A). Also, samples were incubated for determination of dark-bottle respiration rates. This was the first survey of the year for which respiration was measured.

2-1

■   Chlorophyll samples were taken at 15 stations (2 or 3 depths) and were used to calibrate the *in situ* fluorescence sensor (Appendix A). Total suspended solids, in addition to chlorophyll, was sampled at station F25, as well as at planned stations.

In addition to the procedures described in the CW/QAPP, the following method was used for the nearfield survey in early July (W9308):

■   Dissolved oxygen samples were collected at six "P" stations at five depths and were used to calibrate the dissolved oxygen sensor (Appendix A).

In addition to procedures described in the CW/QAPP, the following methods were used for the nearfield survey in late July (W9309):

■   Dissolved oxygen samples were collected at six "P" stations at four or five depths and at mid-depth at station N17, and used to calibrate the dissolved oxygen sensor (Appendix A).

2.1.2 Productivity Measurements

Productivity measurements differ slightly from those described in the CW/QAPP. First, at the request of the MWRA and due to the preference of the Outfall Monitoring Task Force, only the ^{14}C method was used to estimate primary production; the oxygen light-dark method was not used. At two depths of each BioProductivity station, ^{14}C primary production was measured by exposing samples to a light gradient as described by Albro *et al.* (1993) for the oxygen method. Fifteen-300 mL BOD bottles were inoculated with 2.5 μCi of ^{14}C-sodium bicarbonate. Three bottles were incubated in the dark. The remaining 12 bottles were exposed to irradiance levels ranging from about 20 to 2000 μE m^{-2} sec^{-1}, with several bottles exposed in the range of 200-600 μE m^{-2} sec^{-1}. Samples for dissolved inorganic carbon (DIC) were taken from the same GO-FLO bottle as samples used for productivity incubations. DIC was analyzed as described in the next section and was used in calculating primary production rates (Section 2.3).

2.1.3 Respiration Measurements

Dark bottle incubations in 300-mL BOD bottles were conducted for 8-10 h, rather than 6 h as given in the CW/QAPP. Respiration data for 1992 were reviewed prior to this June 1993 cruise. The review suggested that longer incubations were warranted to measure the relatively low rates indicated by 4-6 h incubations in the summer 1992 studies. Note that results of calculations for respiration are indicated in Appendix E and follow the procedures described in the CW/QAPP.

2.2 Laboratory Procedures

Table 2-3 summarizes laboratory methods for chemistry and biology samples as detailed in the CW/QAPP. The dissolved inorganic carbon (DIC) method was not described in the CW/QAPP. The DIC analysis used by URI is a "purge-and-trap" method (I.O. Corp., 1984). Samples are collected in a 40-mL screw-cap VOC vial with a septum. The bottle is filled and overflown, the sample is then "killed" with mercury chloride, and the bottle is sealed. In the laboratory, the vial is placed in a total carbon analyzer where the vial septum is pierced. A sample is then withdrawn, acidified, bubbled with nitrogen (N_2) and the carbon dioxide (CO_2) in the gas stream is caught on a molecular sieve. The sieve is heated to 200°C, releasing the CO_2 into a new stream of N_2, the carrier gas that transports the CO_2 to an IR detector where the CO_2 content is measured.

The average difference between replicates, estimated from samples taken and reported in the first 1993 periodic report (Kelly et al., 1993d), averaged less than 1% ($\bar{x}\pm\sigma$ = 0.47% ± 0.73%, range = 0.08-2.68%, n = 12). The average difference between sampling replicates was also less than 1% ($\bar{x}\pm\sigma$ = 0.25% ± 0.31%, range = 0.01-0.81%, n = 6).

2.3 Data Analyses

To calculate ^{14}C production rates, the data for light bottles were first corrected by subtracting uptake measured in dark bottles. Volumetric production rates were then calculated, as described in the CW/QAPP (Albro et al., 1993). The dark bottle uptake was calculated as the mean of the three dark

bottles, excluding samples where a value was an outlier as determined by statistical testing using the Dixon Criterion (Appendix E).

The Dixon Criterion (Natrella, 1963) evaluates the relative range between values in an ordered set. Thus, if three values (X_1, X_2, and X_3) are arranged from lowest to highest, the criterion for the *highest* value being an outlier is

$$X\_3 = (X_3 - X_2)/(X_3 - X_1)$$

The criterion for the *lowest* value being an outlier is

$$X\_1 = (X_2 - X_1)/(X_3 - X_1)$$

These calculated values may be compared to a tabled value. For example, if X_3 or X_1 exceed 0.941 then there is a 95% chance that the value in question is an outlier.

X_3 and X_1 are calculated for each set of three dark bottles replicates. When X_3 or X_1 exceeds the tabled value of 0.941 for n=3, the outlier is rejected and not used in calculations. Appendix E provides results of testing for survey W9307.

The P-I curve modeling for ^{14}C differed slightly from that described for oxygen in the CW/QAPP. A sequence of two models was used to fit data from ^{14}C incubations. Dark-corrected values were normalized to chlorophyll determined for the sample depth being measured. Following this, a sequence of two models was used to fit the data.

The first model fit three parameters, including a photoinhibition term, and followed Platt *et al.* (1980). The Platt *et al.* (1980) model to predict net production is

$$P_B = P_{SB} (1 - e^{-a}) e^{-b}$$

P_B = production (chlorophyll-normalized) and

P_{SB} = theoretical maximum production (chlorophyll-normalized) without photoinhibition

where $a = \alpha \, I/P_{SB}$, and $b = \beta I/P_{SB}$.

α = initial slope of the rise in net production with light increasing from zero irradiance [units of (μg C/μg Chl/hr)/(μE/m^2/sec)], calculated from I (light irradiance level, μE/m^2/sec) and P_{SB}.

In the CW/QAPP and in the first periodic report for 1993 (Kelly *et al.*, 1993d), the second model used was a hyperbolic tangent function (Platt and Jassby, 1976). Although Platt *et al.* (1980) claim equivalence of the two models in terms of α and P_{max}, Frenette *et al.* (1993) have shown this not to be the case. For the second model, following the suggestion of Frenette *et al.* (1993), the negative exponential formulation given by Webb *et al.* (1974) was used.

Here, P_B = $P_{max} \, [1 - e \, (-\alpha \, I/P_{max})]$

P_{max} = light saturated maximal productivity

and α = the initial slope for the curve where productivity is proportional to light intensity (I)

The two models are equivalent where the photoinhibition term (b) is zero. Note that use of this second model marks a return to that used in initial modeling for 1992, minus only a respiration term (cf. Kelly *et al.*, 1992).

The parameters in each model were fit simultaneously by least squares using the NLIN procedure in SAS (1985) for each incubation series that measured paired P_B and irradiance. Fitting was accomplished where parameters were estimated if, within 50 iterations, the model converged on a suitable simultaneous fit (SAS, 1985). A derivative-free method was used that compares favorably with methods using partial derivatives (Frenette *et al.*, 1993). If the three-parameter model (Platt *et al.*, 1980) fitting did not converge on a fit, the two-parameter model (Webb *et al.*, 1974) was used.

Volumetric production rates, chlorophyll-normalized P-I curves, and model coefficients (Appendix E), were used to calculate integrated water column rates of production, which were expressed as a rate per square meter of surface. Production rate calculations generally followed the procedure described by Kelly *et al.* (1993c) and are described briefly in the following text.

Because irradiance varies throughout the day and stations are sampled at different times, the light conditions were standardized. Within a survey, the average incident irradiance (I_o) measured by the deck cell during a mid-day (1000 to 1400 h) period was used to standardize conditions. Then, for each station, an extinction coefficient (k) was determined by regressing $\ln(I_z/I_o)$ vs. depth, where I_z is the irradiance at depth Z, and the slope of the resultant line estimates k. The coefficient (k) was then used with the survey I_o to generate the standardized light profile using the model $I_o = I_z e^{-kz}$ and to determine $Z_{0.5\% \, Io}$. Estimated rates were expressed per square meter of surface and integrated to the depth where photosynthetically active radiation (PAR) equals 0.5% of PAR incident at the surface. A 1% to 0.5% isolume is commonly accepted as the level to which net production (in excess of respiration) is achieved by plankton.

Next, for each station and each incubation series ("surface" or "chlorophyll maximum" sample), the fitted P-I model was combined with the standardized light profile to yield chlorophyll-normalized production rates (μg C μg Chl^{-1} h^{-1}) at 0.5-m intervals to coincide with 0.5-m BIN-averaged chlorophyll values generated from a vertical downcast. To calculate depth-integrated rates, the predicted hourly, chlorophyll-normalized rate was then multiplied by the chlorophyll fluorescence at each depth interval from the surface to the $Z_{0.5\% \, Io}$. The values were then appropriately summed over depth and units were converted to m^{-2} from a volumetric basis.

The above procedure estimated hourly mid-day rates (μg C m^{-2} h^{-1}). Conversion to full day time rates was made by multiplying by 7, a factor which recognizes that about 55-60% of the production generally occurs during the 4-hour period (1000-1400 h) when the irradiance is highest (Vollenweider, 1966). Final modeled rates provide an estimate of daytime primary production as mg C m^{-2} d^{-1}.

The same procedure was applied to both surface and chlorophyll-maximum samples and, thus, yielded independent production estimates. These estimates are given for each productivity survey in a table which provides a summary of P-I modeling results (provided in detail in Appendix E).

Parameter	Stations	Sample Volume	Sample Containers	Shipboard Processing/ Preservation
Table 2-1. Field samples and measurements [from Albro et al., 1993].				
Following samples are subsampled from water collected with Poly Vinyl Chloride Niskin GO-FLO Bottles				
Dissolved Inorganic Nutrients	All	60 mL	100 mL polyethylene bottle	Pass through a filter. Fix with chloroform.
Dissolved Oxygen	10 Biology/ Productivity and 3 Nearfield	300 mL	300 mL glass BOD	Fix per Oudot et al. (1988). Titrate within 24 h.
Dissolved Organic Carbon	10 Biology/ Productivity and F25	50 mL	100 mL amber glass bottle	Pass through a pre-ashed glass fiber filter. Fix with 0.5 mL of phosphoric acid.
Dissolved Organic Nitrogen	10 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 h.
Dissolved Organic Phosphorus	10 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 h.
Particulate Organic Carbon	10 Biology/ Productivity and F25	50 mL	Whatman GF/F glass fiber filter	Pass through a pre-ashed glass fiber filter. Freeze (-5°C).
Particulate Organic Nitrogen	10 Biology/ Productivity and F25	50 mL	Whatman GF/F glass fiber filter	Pass through a pre-ashed glass fiber filter. Freeze (-5°C).
Total Suspended Solids	10 Biology/ Productivity and 3 Nearfield	200 mL	Petri dish	Pass through a filter. Freeze (-5°C)
Chlorophyll a/ Phaeopigments	10 Biology/ Productivity and 3 Nearfield	2 x 10 mL	Whatman GF/F glass fiber filter	Pass through filter. Fix with 1% $MgCO_3$ solution, wrap in foil, store over desiccant, and refrigerate.
Phytoplankton (Whole Water)	10 Biology/ Productivity	800 mL	1000 mL glass bottle	Preserve with Utermohl's solution.
Phytoplankton (Screened Water)	10 Biology/ Productivity	2000 mL	100 mL polyethylene bottle	Strain through a 20-μm mesh; wash retained organisms into a jar. Fix with Utermohl's solution.
^{14}C Production	10 Biology/ Productivity	300 mL	300 mL glass BOD	Inoculate with 2.5 μCi of $Na_2^{14}CO_3$ and incubate.
Following sample is collected with a vertically towed net				
Zooplankton	10 Biology/ Productivity	800 mL	1000 mL glass bottle	Wash into jar. Fix with a 5-10% formalin solution.
The following measurements are collected by the Battelle Ocean Sampling System				**Precision**
Conductivity	All	---	Floppy disk	0.01 mS/cm
Temperature	All	---	Floppy disk	0.001 °C
Pressure	All	---	Floppy disk	0.01 decibars
Dissolved Oxygen	All	---	Floppy disk	0.05 mg/L
Chlorophyll a Fluorescence	All	---	Floppy disk	0.01 μg/L
Transmissometry	All	---	Floppy disk	0.01 m^{-1}
In situ Irradiance	All	---	Floppy disk	1 μE m^{-2} s^{-1}
Surface Irradiance	All	---	Floppy disk	1 μE m^{-2} s^{-1}
Bottom Depth	All	---	Floppy disk	1 m
Navigational Position	All	---	Floppy disk	0.000017 deg

Table 2-2. Water samples to be collected from Niskin or GO-FLO bottles [from Albro et al., 1993].															
	Nearfield Nutrient/Hydrography Surveys							Biology/Productivity Surveys			Farfield Nutrient/ Hydrography Surveys				
Refer to Notes Below for Stations IDs	Note 1	Note 2	Note 3	Note 4	Note 5	Totals per Survey	Totals for 32 Surveys	Note 6	Totals per Survey	Totals for 12 Surveys	Note 7	Note 8	Totals per Survey	Totals for 12 Surveys	Totals for all Surveys
Number of Hydrographic Stations	1	5	3	3	9	21	672	10	10	120	20	1	21	252	1044
Dissolved Inorganic Nutrients	5	5	5	5	5	105	3360	5	50	600	5	5	105	1260	5220
Chlorophyll a and Phaeopigments (2 reps)			2			6	192	2	20	240				0	432
Total Suspended Solids (2 reps)			2			6	192	2	20	240				0	432
Dissolved Organic Nitrogen and Phosphorus (2 reps)								2	20	240		2	2	24	264
Dissolved Organic Carbon								2	20	240		2	2	24	264
Particulate Carbon and Nitrogen (2 reps)								2	20	240		2	2	24	264
Phytoplankton (whole water) to analyze	1					1	32	2	20	240					272
Phytoplankton (whole water) to archive		1				5	160	3	30	360					520
Phytoplankton (screened) to analyze	1					1	32	2	20	240					272
Phytoplankton (screened) to archive		1				5	160	3	30	360					520
Initial Dissolved Oxygen (Note 9)				2		6	192	9	90	1080					1272
Respiration (Note 9)								9	90	1080					1080
Pmax by Carbon-14 (Note 10)								12	120	1440					1440
Pmax by Oxygen (Note 11)								6	60	720					720
P(I) by Carbon-14 (Note 12)								20	200	2400					2400
P(I) by Oxygen (Note 12)								20	200	2400					2400
Zooplankton								1	10	120					120

Notes:

1. Station N10P
2. Stations N01P, N04P, N07P, N16P, and N20P
3. Any 3 nearfield stations
4. Any 3 nearfield stations (the same or different ones from Note 3)
5. Nine Stations not used for oxygen or chlorophyll a calibrations
6. Stations F01P, F02P, F13P, F23P, N01P, N04P, N07P, N10P, N16P, and N20P
7. All farfield stations except F25
8. Station F25
9. Collect 3 samples at 3 depths
10. Collect 6 samples at 2 depths
11. Collect 3 samples at 2 depths
12. Collect 10 samples at 2 depths

Table 2-3. Laboratory Analysis and Methods [From Albro et al., 1993]

Parameter	Units	Method	Reference[1]	Maximum Holding Time	Preservation
Dissolved Ammonia	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Nitrate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Nitrite	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Phosphate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Silicate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Oxygen	mg L^{-1}	Autotitrator	Oudot et al. (1988)	24 h	dark/cool
Dissolved Organic Carbon	μM	O.I. Model 700 TOC Analyzer	Menzel and Vaccaro (1964)	3 mo.	Fix with 0.5 mL of phosphoric acid.
Dissolved Organic Nitrogen	μM	Technicon II AutoAnalyzer	Valderrama (1981)	3 mo.	Add reagents immediately, heat to 100°C within 8 hours.
Dissolved Organic Phosphorus	μM	Technicon II AutoAnalyzer	Valderrama (1981)	3 mo.	Add reagents immediately, heat to 100°C within 8 hours.
Particulate Organic Carbon	μM	Carlo Erba Model 1106 CHN elmental analyzer	Lambert and Oviatt (1986)	3 mo.	Dry over desiccant.
Particulate Organic Nitrogen	μM	Carlo Erba Model 1106 CHN elmental analyzer	Lambert and Oviatt (1986)	3 mo.	Dry over desiccant.
Total Suspend Solids	mg L^{-1}	Cahn Electrobalance	See Section 12.7.7	6 mo.	Dry over desiccant.
Chlorophyll a/ Phaeopigments	μg L^{-1}	Model 111 Turner Fluorometer	Lorenzen (1966)	2 wk	Fix with 1% MgCO$_3$ solution, wrap in foil, store over desiccant, and refrigerate.
Phytoplankton (Whole Water)	Cells L^{-1}	Sedgwick-Rafter counting chambers	Turner et al. (1989)	3 y	Preserved with Utermohl's solution, store at room temperature.
Phytoplankton (Screened Water)	Cells L^{-1}	Sedgwick-Rafter counting chambers	Turner et al. (1989)	3 y	Fix with Utermohl's solution, store at room temperature.
[14]C Production	[14]C hr^{-1}	Liquid Scintillation Counter (Bechman LS-3801)	Strickland and Parsons (1972)	2 wk	Scintillation fluid
Zooplankton	Cells L^{-1}	Dissecting Microscope	Turner et al. (1989)	3 y	Fix with a 5-10% Formalin solution, store at room temperature.

[1]See Section 20 of Albro et al., 1993 for literature references.

3.0 RESULTS OF JUNE 1993 COMBINED FARFIELD/NEARFIELD SURVEY (W9307)

3.1 Farfield Survey

3.1.1 Horizontal Distribution of Surface Water Properties

Surface water temperatures measured during the June survey at twenty-seven stations in Massachusetts Bay ranged from about 10 to 15.6 °C (Figure 3-1). The coolest region was north of the middle of the nearfield area, particularly at stations N01P and F18 off Nahant. The surface waters in the southern half of the nearfield were ≈ 13.7 to 14.6 °C, a range which encompasses surface temperatures throughout much of Massachusetts Bay. A group of stations southeast of the nearfield had surface temperatures above 15 °C.

The temperature range of surface water at four stations in Cape Cod Bay was smaller, from < 14 to > 16 °C. The eastern side of Cape Cod Bay (station F02P) had the warmest surface temperature.

Surface salinity was confined to a small range of about 30.5 to 31.1 PSU (Figure 3-2). The salinity at the edge of Boston Harbor was similar to much of Massachusetts Bay. The colder water off Nahant was distinct also for a slightly higher salinity (> 31 PSU). The warm water at station F02P had the lowest salinity measured during the survey. In general, the spatial patterns for surface salinity and temperature were similar in the Bays (cf. Figures 3-1, 3-2).

Turbidity, as suggested by beam attenuation measurements (Figure 3-3), had a different pattern. High values occurred near the Harbor, particularly at station F23P. A zone of higher beam attenuation appeared to radiate from the Harbor, east about 15 km to the middle of the nearfield and south towards Cohasset/Scituate, where it extended about 5-10 km from the shoreline. Relatively high beam attenuation was seen off Salem Harbor at station F20 of the northern transect. Cape Cod Bay beam attenuation readings were low and similar to offshore water of Massachusetts Bay.

Surface water fluorescence concentrations had a spatial pattern similar to turbidity (Figure 3-4 vs. Figure 3-3). A distinct zone of higher fluorescence readings extended from Boston Harbor to the nearfield and southward along the shore. Relatively high concentrations were also indicated off Salem Harbor. Surface fluorescence in Cape Cod Bay was low and similar to readings at offshore, deepwater stations in Massachusetts Bay.

Dissolved inorganic nitrogen (DIN) concentrations were very low throughout the surface layer in the Bays (Figure 3-5). DIN concentrations were generally less than 0.5 μM and usually were at detection limits ($\approx$ 0.05-0.1 μM). The exception was the transect from the northern exit from Boston Harbor to the nearfield (stations F23P-F24-N20P), where the DIN concentration was about 1 μM or higher. The slight enrichment of DIN outside the Harbor was principally in the form of ammonium (NH_4). Nitrate (NO_3) was virtually undetectable everywhere except at the Harbor edge (station F23P), where it was 0.54 μM (Figure 3-6).

Phosphate (PO4) concentrations in surface waters were low, with the exception of one usual measurement at station F13P, and a distinct spatial pattern was not evident (Figure 3-7). The Harbor's edge, and a number of other near-shore stations, had measurable concentrations (0.1 to 0.3 μM). Surface waters at other stations were less than 0.1 μM in PO_4 and often approached detection limits (about 0.05 μM).

Silicate (SiO_4) concentrations in surface waters were relatively high ($>$ 2 μM) near the Harbor and along the shoreline north and south of the Harbor (Figure 3-8). The remainder of Massachusetts Bay and Cape Cod Bay had silicate concentrations $\leq$ 1.5 μM. The middle of the nearfield had among the lowest SiO_4 concentrations.

3.1.2 Water Properties Along Selected Vertical Sections

Vertical downcast profiles for each station are provided in Appendix B. Standard vertical section transects of stations running from nearshore to offshore (Figure 3-9) were produced from these

profiles. They illustrate strong vertical gradients, trends related to water depth, and perhaps some subtle geographic trends.

Characteristically, the water column was sharply stratified with a warmer, less saline layer in the surface 5-15 m. Some profiles showed a simple two-layer structure and others had more complex vertical structure. At many shallow inshore stations physical properties were fairly uniform over depth, showing that stratification was not maintained as strongly as in deeper waters offshore, probably due in part to tidal stirring action, but also possibly due to winds.

Surface water was usually from 12 to 16 °C; an exception was station F24, which was slightly cooler (Figure 3-10). Below the warm surface water, a general pattern of thermal layering was observed in relation to increasing water column depth. For example, at shallow depths (≈ 20 m), no cold bottom layer was present (Figure 3-10a). At 30-40 m water depth, surface and bottom layers were evident, but the thermocline extended close to the bottom. Below about 40 m, a continuous bottom layer existed; note that the decrease in bottom water temperature with increasing depth was relatively small. Deepest offshore stations in Stellwagen Basin (F22, F19, F17, F08, F12) had bottom water temperatures slightly less than 4 °C. In terms of geographic trends, it appeared that the surface warm-water layer may have extended to slightly greater water depth in the most southerly transect (cf. Figure 3-10a — the Marshfield transect).

The vertical salinity structure generally followed the transect patterns described for temperature, even though the range in salinity was small, about 1.5 PSU (Figure 3-10b). The most saline water was detected in the cold, deep water of Stellwagen Basin. Density (σ_T) is a function of both temperature and salinity and vertical layering of increasingly dense water is obvious across the transects (Figure 3-10c). The sharpest density change (the pycnocline) usually extended from 5-10 m to about 20-30 m. Horizontally, subtle gradations (e.g. F24 to N16P), depressions (e.g. F08), or elevations (F15, N16P) of the depth of the surfacemost layer across the transects may suggest where slightly different surface-water pools lay beside each other.

Chlorophyll (from fluorescence) had an interesting distribution across the transects (Figure 3-11). Higher concentrations were found near the surface of most shallow stations. In the case of the Boston-nearfield transect, high near-surface chlorophyll concentrations were found out to the middle of the nearfield (station N20P). In waters deeper than 30-40m, the chlorophyll maximum at a station was a distinct sub-surface band within the pycnocline (cf. Figure 3-10c). Beam attenuation readings (Figure 3-12) indicated the presence of high turbidity near the surface at shallower stations and extended to the middle of the nearfield, thus mimicking the chlorophyll pattern. Interestingly, however, except for the thin band near 25-30 m at stations F08-F12, there was no subsurface maximum in turbidity coincident with the subsurface chlorophyll maximum. Beam attenuation was high near the bottom in deep water, an indication of the presence of a near-bottom nepheloid layer. This feature was especially prominent in southern stations of Stellwagen Basin (F17, F08, F12).

Dissolved oxygen (DO) concentrations were supersaturated throughout the surface water layer (Figure 3-13). The exceptional station, with respect to surface water DO values, was station F23P near the Harbor, where readings showed slight undersaturation (95-100%). In most cases, DO supersaturation extended from the surface to the depth of the chlorophyll maximum (cf. Figure 3-11 and 3-13). For the Marshfield transect, where there was low surface chlorophyll and a thin, but deep chlorophyll maximum layer at about 30 m (Figure 3-11), there was also a distinct mid-depth maximum in percent DO saturation (>110%). This layer extended across the Stellwagen Basin stations (F07-F08-F12), and was also apparent to the north at Basin stations F17 and F19, where the subsurface chlorophyll maximum was broader and extended closer to the surface. Aside from the mid-depth maximum at the Marshfield transect and F23P, generally the % saturation decreased with depth. However, only in the deepest Basin water (stations F08 and F12) was DO less than 95% saturated. There, deeper than about 70 m, DO was 85-95% of saturation.

The patterns for DIN and silicate across the transects were similar in their gradation with depth (Figure 3-14a,b). Surface waters were generally depleted. At depth, an increase in nutrient concentrations generally marked the position of the pycnocline at a station. Only the surface water near Boston Harbor (F23P and F24) showed an enrichment in DIN and silicate, although it was much more pronounced for DIN (cf. Figures 3-5, 3-8). Although enriched, nutrient concentrations near the

Harbor were generally lower than the concentrations found in nearfield bottom waters and all deep water offshore.

3.1.3 Analysis of Water Types

There were a few minor geographical, though fairly localized, differences in physical properties. For example, as noted, a cooler temperature water mass was suggested north/northwest of the nearfield. Interestingly, station N01P had warmer surface temperature when occupied 2 days later on the nearfield survey. It had a deeper thermocline on the farfield survey (Appendix B); coupled with the cooler temperature and higher salinity the data suggest deeper mixing on the farfield day. Another example of difference in physical properties was found within Cape Cod Bay, where a thermal and stratification difference was noted. The eastern-side station (F02P) was warmer and fresher at the surface and the water column was strongly stratified. In contrast, the western-side station (F01P) was cooler and essentially unstratified. Both of these examples suggest that some spatial and temporal differences may be dynamic short-term features, possibly driven more by differences in vertical mixing processes (including wind) coupled with variability in diurnal heat flux than by advection.

A main geographic pattern was horizontal banding of chlorophyll, following the pycnocline and therefore deepening as a function of distance from shore and increasing water depth. Also, as usually has been the case, the data show that the Harbor and its proximal Bay receiving waters were distinctive for relatively high chlorophyll, turbidity, and nutrients.

Except for shallow and near-Harbor areas, the principal feature throughout the Bays was strong vertical layering for physical, chemical, and biological parameters. The vertical gradients dominate the Bays; this is expected because freshwater sources are generally low at this time. Only the strong source from the Harbor appears reflected (in some parameter distributions); otherwise, there was no indication of distinct surface water masses, including any emanating from the north. The data for all stations show a fairly confined temperature-salinity relation (Figure 3-15a); high surface temperature and slightly lower salinity generally grade to near bottom temperature below 5 °C and salinity greater than 31.75 PSU. The relative similarity of T-S patterns supports the observation that distinct water

masses were not apparent in the Bays; moreover, it also supports the notion that local spatial and temporal variability, as well as much of the general inshore-offshore gradient, may be primarily influenced by local variations in vertical, rather than horizontal, mixing processes at this time.

The vertical variation in most parameters was similar. The pattern near the Harbor — where some near-surface features were apparent — was the only main distinction across stations. Beam attenuation at stations near the Harbor was higher in the lower salinity surface waters, while at a few other stations high turbidity was coincident with the higher salinity bottom waters. Other than these, no general pattern was seen and beam attenuation was not highly variable (Figure 3-15a). The stations with higher chlorophyll near the Harbor also had high beam attenuation, but again, no general relationship was apparent. The apparent nepheloid layer in Basin bottom waters (high beam attenuation at high salinity) did not have an associated high chlorophyll concentration.

The overall pattern of chlorophyll concentration with depth based on all vertical profiles (Figure 3-15b) follows directly from the strong vertical layering. A mid-depth maximum from about 15-25 m is readily apparent. In a small selection of profiles (mostly near the Harbor), the highest chlorophyll concentrations were measured near the surface.

The general pattern for DO also derives from vertical water column structure. It can be seen that %DO saturation was, in part, a function of depth, especially from the pycnocline ($\approx$20-30 m) to deeper bottom waters. There were a few anomalous points with low % saturation. One point at about 6-8 m is from Station F19 in the offshore region (See Appendix B). This point appears to be and electronic spike, not an accurate reading. However, a string of points at about 23-28 m, which reach % saturation < 80% may be valid readings. The were found at Station F02P in Cape Cod Bay in a confined near-bottom layer (Appendix B).

To examine whether geographic differences existed in nutrient concentrations, standard groups of stations from different regions (Figure 3-16) have been identified in nutrient-nutrient and nutrient-salinity plots (Figures 3-17 through 3-22). Such plots are diagnostic tools to discriminate differences in water mass geochemistry.

Increases in nutrient concentrations below the pycnocline indicate the influence of stratification (see Figure 3-14; described more in Section 3.2) and in general on the nutrient-nutrient plots (Figures 3-17 and 3-18), increasing nutrient concentrations represent increasing depth within the water column. For this June survey, regional differences were not pronounced. For example, the relationship between DIN or NO_3 and PO_4 was strong and independent of geographic position of the stations (Figure 3-17). N/P ratios were always well below a Redfield value (16:1) and therefore suggestive of relative nitrogen limitation. The N/P ratio was lowest in the surface layer where DIN was virtually absent at measurable phosphate concentrations. With respect to NO_3 and PO_4, a strong relation was evident, with the N/P ratio tending towards about 4:1 (Figure 3-17). The coastal stations had slightly lower nitrate for a given phosphate concentration than other areas; it was noted before that NH_4 makes up a significant portion of the DIN at stations near the Harbor. In contrast to nitrate, DIN at these coastal stations was often higher than other areas.

No sharp regional distinction in the pattern of DIN/silicate was apparent (Figure 3-18). In general, the ratios were low (below 2:1) and silicate, like phosphate was detectable where DIN was virtually absent. There was less scatter in the NO_3/SiO_4 relationship than for DIN/SiO_4. This indicates that NH_4 and SiO_4 were less broadly related, in part because of relatively high NH_4 near the Harbor. Note, however, that DIN was about 50% NH_4 in deeper bottom waters. The highest silicate concentrations were found in near-bottom waters: at several stations in Stellwagen Basin, as well as station F04 off Provincetown and especially F02P ($SiO_4 > 16$ μM at 23-26 m) on the eastern side of Cape Cod Bay. Station F02P had a relatively early and prolonged winter-spring diatom bloom in 1993 as well as 1992 (Kelly *et al.*, 1993c; Kelly *et al.*, 1993d). High rates of remineralization of silicate in underlying sediments where diatom tests accumulate are likely as bottom temperatures begin a seasonal rise. Benthic fluxes could help explain the very high silicate concentrations in station F02P bottom waters; unfortunately Cape Cod Bay benthic fluxes were only measured in August of 1993 (Giblin *et al.*, 1994).

The pattern of DIN relative to salinity did allow some regional discrimination. Coastal stations, near Boston Harbor, had relatively high DIN at low salinity (Figure 3-19). The two high-silicate samples from 23-26 m at station F02P in eastern Cape Cod Bay fall into the same category, being rich in N

for the salinity. Few other distinctions were possible, but as depth (and thus salinity) increased, the concentration of DIN generally increased. The pattern for NH_4 largely influenced the DIN results although similar regional distinctions could be made on the basis of nitrate as well (Figure 3-20). Finally, some coastal samples and again the deeper water at station F02P were distinct for relative phosphate and silicate enrichment at low to intermediate salinity (Figure 3-21). Aside from the Cape Cod Bay anomaly, Figure 3-21 shows a most striking general relationship of silicate with salinity.

Combined forms of nitrogen (DIN + PON and Total N) at the group of nearfield stations were at best weakly correlated to salinity (Figure 3-22). Lower salinity points were found at the surface at several stations throughout the nearfield and the salinity distribution in this case did not represent a spatial-distance gradient from west to east across the nearfield as it often does. Characteristically, the two Cape Cod Bay stations were fairly low in nitrogen and station F23P near the Harbor (coastal group) had the highest concentrations.

In summary, the main factor influencing distributions in the Bays in June was density stratification. Chlorophyll and nutrient patterns were related to the strength of stratification and the depth of the pycnocline. Geographic distinctions were not striking, the principal one being the observation of slightly enriched nutrients near the Harbor. Even near the Harbor, the nutrient concentrations were not higher than concentrations in the very deep waters of the Bay, which themselves were not as high as winter concentrations in surface waters prior to the 1993 winter-spring bloom.

3.1.4 Distribution of Chlorophyll and Phytoplankton

A set of extracted chlorophyll samples provide the basis for the post-survey calibration of fluorescence (Appendix A). These extracted chlorophyll samples are also used in normalizing production rates, etc., so they are considered here. The patterns with depth (Figure 3-23) illustrate that coastal stations and a few nearfield stations (especially N10P and N20P) had higher concentrations near the surface of the water column. In contrast, Cape Cod Bay stations and most of the nearfield stations had a subsurface chlorophyll maxima.

The chlorophyll-fluorescence calibration for this June survey had much scatter. A number of samples from stations near the Harbor had relatively high chlorophyll for their *in situ* fluorescence reading; subsequently, when using the overall calibration and the continuous fluorescence readings, the "true" (extracted) concentrations were underestimated. In contrast, other samples, especially when chlorophyll exceeded 2 μg/L were slightly overestimated from fluorescence and the overall calibration. Interestingly, the high chlorophyll group included the principal stations most often influenced by Harbor outflow from the southern Harbor exit through Nantasket Roads. However, not all samples from these stations (i.e. samples from different depths and from repeated visits during the combined farfield/nearfield) consistently fell into the category. Barring separate calibrations on a sample-by-sample basis, which is somewhat problematic since even for an individual station the two samples from different depths may be different, our use of a single calibration line to use fluorescence as a measure of chlorophyll *a* has an imprecision for this June survey that must be recognized. Kelly and Albro (1994) also discuss recalibration for a select group.

The extracted chlorophyll concentration was highly correlated with the abundance of phytoplankton cells (Figure 3-24). One anomalous sample was from the surface at station N10P. This anomaly could be due to a low chlorophyll reading as the extracted chlorophyll from this sample was very low compared to the flourometer values. Nevertheless, this sample was also distinctive in its phytoplankton composition. This sample was the only one in the figure that came from sampling on the nearfield day of the survey (June 25), rather than the farfield portion of the survey days earlier (see Appendix F). The nearfield-day surface sample was dominated by a population of diatoms, *Leptocylindrus danicus* (3.6 million cells per liter) and *Skeletonema costatum* (0.5 million cells per liter). In contrast, samples taken from station N10P on the farfield portion of the survey (June 22) followed the main trend. The farfield-day surface samples were dominated by the same diatoms listed above, in lower numbers (1 and 0.27 million cells per liter, *L. danicus* and *S. costatum* respectively), and had a relatively higher proportion of total counts due to microflagellates.

Throughout the Bays, most samples revealed a more mixed community than at station N10P from the nearfield day: diatoms and microflagellates with some dinoflagellates and cryptomonads (Figure 3-25). Nearfield and coastal stations with chlorophyll higher than 3 μg/L had high cell counts, over 1.5

million cells per liter. These high counts were noted at stations N10P, N20P, F13P, and F23P, all of which had relatively high diatom counts (Figure 3-25a,b). The other six stations with lower cell counts in surface samples often were numerically dominated by microflagellates (Figure 3-25a). The chlorophyll maximum sample community composition was also dominated by microflagellates at stations N04P, N07P, N16P and the two Cape Cod Bay stations, whereas diatoms were a high percentage of the total counts elsewhere (Figure 3-25b). Dinoflagellates were proportionally highest at the chlorophyll maximum at station F02P, although they were never numerically dominant in any sample.

Dominant taxa for surface and chlorophyll maxima are given for whole-water samples in Tables 3-1a,b and 20-μm screened samples in Tables 3-2a,b. For near-surface samples, a predominant organism was *Leptocylindrus danicus*, although this species was less prevalent in Cape Cod Bay. Three other diatoms were occasionally among the dominants — *Skeletonema costatum*, *Chaetoceros* spp. and *Rhizosolenia delicatula*. Microflagellates and cryptomonads were the other main forms, both numerically important in Cape Cod Bay (F01P and F02P). However, phytoplankton community differences were not striking across the stations, and thus regions, of the Bays.

The list of dominants for subsurface chlorophyll maximum samples was more lengthy, indicating slightly more variability in communities at depth across the Bay. But the principal species were the same as in surface samples and little regional distinctiveness was indicated. Two minor features to the data were of interest: (1) station F02P in eastern Cape Cod Bay had some minor diatoms (*Cerataulina* and *Cylindrotheca*) that were not dominant elsewhere and (2) strongly stratified (deeper water stations) in general had the dinoflagellate *Ceratium longipes* among the top dominants.

The screened samples confirmed that *Ceratium longipes* and other *Ceratium* species were present at all stations and sampled depths and were most abundant at the subsurface chlorophyll maximum at a station (cf. Table 3-2a and b). In general, *C. longipes* was the most abundant dinoflagellate, and ranged as high as 10^4 cells/L. *C. fusus*, *C. lineatum*, and *Dinophysis norvegica* reached 10^2 cells/L (station N01P). There were very small numbers of a handful of other dinoflagellates. *Alexandrium*

tamarense, the organism of interest with respect to Paralytic Shellfish Poisoning (PSP), was only found at station F23P at the Harbor's edge and station F02P in Cape Cod Bay.

3.1.5 Distribution of Zooplankton

In June, the zooplankton community was generally similar across stations (Figure 3-26). Copepods and the nauplii were dominant everywhere. At F23P and N10P, strongly influenced by the Harbor, and the two mid-nearfield stations N16P and N20P, a sizable percentage of the total organism counts were contributed by temporary zooplankton — mollusc veligers (mostly bivalve, but also gastropod veligers). In part because of this component, total zooplankton abundance was highest at these four stations and was 40-50 x 10^3 individuals per cubic meter. For other stations, abundance was generally in the range of 20-30 x 10^3 individuals per cubic meter. Station N16P has the highest counts for copepods (all forms).

Taxonomic listings for each station are provided in Appendix G. With respect to copepod species, the numerical dominant consistently was the small copepod *Oithona similis*, in the range of about 6-23 x 10^3 individuals per cubic meter. This species has been consistently a dominant zooplankton in virtually all samples taken in the bays for the MWRA monitoring program. Often *Paracalanus parvus*, another small copepod, was second in abundance and usually exceeded 10^3 individuals per cubic meter. Other common, and larger-sized, species were *Temora longicornis* and *Calanus finmarchicus*, both of which were frequently found in the range of 500-2500 individuals per cubic meter. Few stations stood out as obviously taxonomically distinct, although *Acartia tonsa*, a species more typical in estuarine rather than shelf environments, was the secondmost numerous species (8,296 individuals/m^3) at station F23P, the Harbor edge station. *A. tonsa* was also relatively numerous at stations N10P (752 individuals/m^3), N20P (748 individuals/m^3), and F13P (364 individuals/m^3); elsewhere it was < 100 individuals/m^3. The distribution of this organism was similar to surface chlorophyll and turbidity and supports the notion that Harbor source water was dispersed to surface waters in the mid-nearfield and southward along the coast during this June sampling (see also Kelly and Albro, 1994).

3.1.6 ^{14}C Production and Dissolved Oxygen Respiration Measurements

Using the P-I incubations, light, and fluorescence profiles at each station, modeling was performed to provide estimates of ^{14}C productivity. All P-I curve-fitting results are in Appendix E. The data were generally well-behaved, all yielding $r^2 \geq 0.80$, with 75% having $r^2 \geq 0.94$. An integrated rate for production, expressed per square meter of surface to the depth of the 0.5% isolume ($Z_{0.5\% \text{ Io}}$), was calculated for each of the surface and chlorophyll-maximum samples taken at a station. The depth of the 0.5% isolume was shallowest at station F23P near the Harbor and deepest at the three stations (N16P, N04P, N07P) on the eastern side of the nearfield (Table 3-3), a trend following the inshore-offshore gradient in beam attenuation (Figure 3-3).

Note that $Z_{0.5\%}$ was at or near the bottom sediments at Cape Cod Bay stations, as well as station N01P and N10P on the western side of the nearfield (see also vertical profiles in Appendix B). In the case of station F02P, which was stratified, the pycnocline and subsurface chlorophyll maximum were at about 21 m, compared to deeper $Z_{0.5\%}$. At station N01P, the $Z_{0.5\%}$ was clearly lower than the subsurface chlorophyll maximum, found at a sharp pycnocline at about 13 m. At station N10P, there was high chlorophyll in the surface layer. There were a couple cases with a small secondary deep chlorophyll maximum at a pycnocline near the $Z_{0.5\%}$ level. But reviewing the profiles in Appendix B one observes that the pycnocline was where a subsurface chlorophyll peak characteristically occurred, and this depth was characteristically shallower than either the 0.5 or 1% isolumes.

There were differences in integrated water column production calculated from surface sample incubations compared to that calculated from a deeper chlorophyll maximum sample incubation. These have previously been noted and reported by Kelly (1993). At 8 of the 10 stations, the surface-based production value was substantially higher. Essentially, this was true because the maximum production (P_{SB} or P_{max}, depending on the model fit), was higher for surface samples (Table 3-3). Figure 3-27a gives an example, which shows that the two curves are different near the surface, in higher light, but tend to merge at depth. Samples from depth may be unacclimated to higher light regimes, because stratification was strong and these were not freely mixed (physically) communities but indeed represent a depth strata. Moreover, the populations at depth may receive a constant flux

of nutrients through the pycnocline that is terminated in bottle incubations. For either of these reasons, the results might be explained easily.

Regardless of the mechanism, estimating water column production is somewhat problematic with the disparity. In a sense, the production calculated from the surface incubation may be the better estimate because the sample came from the surface and best represents the high production layer. The rates are also appropriate at depth because the two estimates converge. It seems, however, that the rate calculated from the deeper sample may not provide a good estimate of the whole water column rate. Other than some complex, depth-weighting scheme, an alternate estimate is the simple mean rate from the two samples.

Using the mean rate, it was apparent that integrated production was sensitive to the average chlorophyll biomass in the water column (Figure 3-27b). Production appeared to be highest at station N20P, almost 5 mg C m^{-2} d^{-1}, followed by N10P, F23P, and F13P, the latter three being above 2.5 mg C m^{-2} d^{-1}. This suite of stations is within the zone radiating east and south from the Harbor that had high chlorophyll and beam attenuation in the surface layer. The high surface chlorophyll, high production zone also was south of the distinctly cooler, higher salinity surface water including station N01P off Nahant (cf. Figures 3-1, 3-2, 3-3, and 3-4) — a locale for which the possibility of deeper vertical mixing has been raised (see above).

Dark respiration rates were estimated from initial-final DO samples after an 8-h incubation. There were three incubations — surface, chlorophyll maximum, and intermediate bottom (sub-pycnocline) depth samples — at each of the 10 productivity stations. Given replicate variability, 6 of 10 surface sample incubations, 4 of 10 chlorophyll maximum sample incubations, and 2 of 10 intermediate bottom sample incubations had significantly (95% level) lower final DO concentrations (Appendix E). For those that were significant, calculated respiration rates were on the order of 0.007-0.033 mg O$_2$ L^{-1} h^{-1}. High rates were characteristic of stations F23P (throughout the water column) and N20P (surface), both of which had high chlorophyll and high production rates. Interestingly, station F23P also had lower % DO saturation than other stations (e.g. Figure 3-13). Lower respiration rates were characteristic of stations on the eastern side of the nearfield.

3.2 Nearfield Survey

3.2.1 Distribution of Water Properties from Vertical Profiling

In addition to sampling the six nearfield "P" stations during the farfield survey, vertical profiling was performed at the planned twenty-one nearfield stations on June 25 (Appendices A,B). Scatter plots for all nearfield sampling, based on *in situ* sensors, are given in Figure 3-28a,b and nutrient concentrations for all data from the nearfield are compared to other regions from the farfield sampling in Figure 3-29a,b,c.

Most of the nearfield was quite similar, driven by the strong stratification. A few profiles showed high chlorophyll and beam attenuation, which both occurred in the surface layer (about 0-20 m). As described already, these stations were on the western side of the nearfield. Otherwise, a strong chlorophyll maximum occurred around 20 m and below this, DO tended to decrease (Figure 3-28b).

NH_4, NO_3, and thus DIN, began to increase below the pycnocline at most stations, from about 15 m to the bottom — a pattern similar to other Bay stations of similar depth. Surface-layer DIN was not as high in the nearfield as it was at coastal stations. Both PO_4 and SiO_4 showed a pattern with depth similar to DIN, but surface concentrations were not as depleted. In general, the nearfield had only minor geographic variability in nutrients and the main distributional feature was in the vertical dimension. Refer to previous plots of nutrients vs. salinity (Figures 3-19 to 3-22) to see that patterns across the nearfield show a general trend of increasing nutrients with increasing salinity, arising because of the increase in nutrients with depth.

3.2.2 Distribution of Water Properties from Towing

The strong vertical structure in temperature and density was clearly revealed and better defined by the tow-yo profiling (Figures 3-30 and 3-31). A thin surface "lens" of slightly higher temperature was apparent approximately in the center of the nearfield and a less dense surface layer was apparent across the northeast portion. This resulted in a slight sloping of the top of the pycnocline, which was

deeper at N04P. But in general the position of the thermocline and pycnocline varied within ±5 m and was found at about 15-20 m everywhere and the layering was rather uniform.

The chlorophyll distribution was uniform in the sense that a distinct and continuous subsurface maximum layer was found at the pycnocline. The chlorophyll layer even sloped gently to greater depth at station N04P, following the pycnocline (Figure 3-32a and b). The intensity of the maximum varied by a factor of about 2, but peak values were quite localized as patches that were 10's to 100's of meters rather than kilometers in length. High chlorophyll in the surface layer was restricted to the western track stations (N10P and N11), where peak maxima for the whole nearfield were localized.

3.2.3 Water Types and Analysis of Small-Scale Variability

The only notable geographic variation was along the inshore edge of the field and this may be attributed to water advecting from the Harbor. Kelly and Albro (1994) have already described the inshore area, including these western track survey data. They also extensively examined small spatial and temporal variability related to tidal dynamics.

In addition to tidal-scale dynamics, however, there was some interesting temporal variability in the nearfield over the course of the nearfield-farfield surveys. This is apparent from inspection of profiles at "P" stations occupied on June 22 [or 23] (farfield survey), then again on the 25th (nearfield vertical profiling) and 26th (nearfield tow-yo). As prime examples, consider stations N20P and N01P (refer to Appendix B).

Station N20P had high surface chlorophyll on June 22, but this feature was absent on June 25 and 26. Interestingly, the vertical physical structure (T, S, σ_T) was not markedly different over time. Station N01P was the local cold spot on June 23 (Figure 3-1). On June 25 the surface was warmer, similar to the rest of the field, salinity was lower, and the depth of the pycnocline had risen from 12-13 m to about 5 m. The chlorophyll distribution changed from a sharp layer at the 12-13 m interface to a broader maximum extending from about 10 to 25 m. The 26th looked more like the 25th (Figures 3-30 to 3-32). Without comprehensive high-resolution sampling on each day, one can not easily see

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whether such changes relate to sampling time relative to the tidal phase, changes in local wind-driven mixing, or advection. It remains useful, however, to point out changes like these so that we will continue to recognize that some of the local anomalies that appear on our broad-scale images of the Bays are indeed ephemeral (i.e., temperature and chlorophyll in Figures 3-1 and 3-4), although they represent pronounced differences in some key monitoring variables.

Table 3-1a. Abundance of top five dominant phytoplankton taxa in near-surface samples collected in June 1993.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
CERATIUM LONGIPES			0.011 (4)						0.007 (5)	
CHAETOCEROS DECIPIENS					0.011 (5)					
CHAETOCEROS SPP.(<10UM)	0.173 (5)					0.086 (5)	0.028 (4)	0.161 (4)	0.015 (4)	0.016 (3)
CRYPTOMONADS	0.235 (4)	0.075 (4)		0.021 (4)	0.022 (4)		0.062 (3)		0.018 (3)	0.093 (2)
LEPTOCYLINDRUS DANICUS	1.061 (1)	1.354 (1)	0.514 (1)	0.429 (1)	0.297 (1)	1.080 (1)	0.218 (2)	1.142 (1)	0.116 (2)	0.011 (5)
MICROFLAGELLATES	0.301 (3)	0.335 (2)	0.110 (2)	0.265 (2)	0.241 (2)	0.642 (2)	0.382 (1)	0.284 (3)	0.280 (1)	0.240 (1)
RHIZOSOLENIA DELICATULA		0.128 (3)	0.062 (3)	0.160 (3)	0.050 (3)		0.021 (5)	0.129 (5)		0.012 (4)
SKELETONEMA COSTATUM	0.747 (2)	0.075 (4)				0.273 (3)		0.671 (2)		
THALASSIOSIRA SPP.						0.102 (4)				
UNID. NAKED DINOFLAGELLATE			0.009 (5)	0.010 (5)						

Units are 10^6 cells L^{-1}

Table 3-1b. Abundance of top five dominant phytoplankton taxa near the chlorophyll maximum collected in June 1993.

	Coastal Stations				Nearfield Stations				Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
CERATAULINA PELAGICA										0.023 (4)
CERATIUM FUSUS					0.001 (5)					
CERATIUM LONGIPES			0.022 (4)	0.011 (5)	0.018 (3)		0.027 (3)			0.010 (5)
CHAETOCEROS SPP.(<10UM)						0.044 (5)	0.007 (4)	0.123 (5)	0.022 (4)	
CRYPTOMONADS	0.143 (4)	0.084 (4)		0.055 (3)	0.050 (2)	0.158 (4)	0.094 (2)		0.054 (3)	0.033 (2)
CYLINDROTHECA CLOSTERIUM										0.010 (5)
DINOPHYSIS NORVEGICA					0.001 (5)					
EBRIA TRIPARTITA					0.005 (4)					
LEPTOCYLINDRUS DANICUS	0.790 (2)	1.004 (1)	0.212 (1)	0.092 (2)	0.001 (5)	0.397 (2)		0.635 (2)	0.105 (2)	0.027 (3)
MESODINIUM RUBRUM			0.017 (5)							
MICROFLAGELLATES	0.373 (3)	0.318 (2)	0.114 (2)	0.222 (1)	0.173 (1)	0.536 (1)	0.269 (1)	0.487 (3)	0.405 (1)	0.268 (1)
RHIZOSOLENIA DELICATULA	0.032 (5)	0.107 (3)	0.043 (3)	0.039 (4)				0.136 (4)	0.011 (5)	
SKELETONEMA COSTATUM	0.854 (1)	0.065 (5)				0.236 (3)		0.820 (1)		
UNID. NAKED DINOFLAGELLATE					0.001 (5)					0.010 (5)
THALASSIONEMA NITZSCHOIDES					0.001 (5)		0.005 (5)			
PYRAMIMONAS/TETRASELMIS					0.001 (5)					

Units are 10^6 cells L^{-1}

Table 3-2a. Abundance of all identified taxa in near-surface screened (20um) samples collected on the farfield survey in June 1993.

SPECIES	F01P	F02P	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P
STATION / SAMPLE	W93070443	W93070424	W93070317	W93070531	W93070271	W93070291	W93070303	W93070097	W93070073	W93070046
ALEXANDRIUM TAMARENSE	0	13	0	0	0	0	0	0	0	0
ALORICATE CILIATES	10	8	55	20	8	25	10	38	10	63
CERATIUM FUSUS	195	393	285	85	653	410	310	78	173	95
CERATIUM LINEATUM	8	0	20	15	60	13	0	8	3	20
CERATIUM LONGIPES	1554	295	2282	706	9550	2658	1929	1331	1549	651
CERATIUM MACROCEROS	0	5	0	0	0	0	5	0	0	0
CERATIUM TRIPOS	108	163	28	3	10	13	15	5	50	8
DICTYOCHA SPECULUM	0	0	0	0	13	0	0	5	0	10
DINOPHYSIS NORVEGICA	48	35	120	578	85	33	30	153	20	358
DINOPHYSIS OVUM	0	33	13	28	0	13	0	25	15	53
DINOPHYSIS SPP.	0	0	0	0	3	0	0	0	0	0
DISSODINIUM SPP.	0	0	0	0	0	0	0	0	0	0
GONYAULAX SPINIFERA	0	8	0	0	0	0	0	0	0	0
GONYAULAX SPP.	0	0	0	0	0	0	0	0	0	0
GYMNODINIUM SPP.	0	0	0	3	3	3	0	5	0	5
GYRODINIUM SPIRALE	0	3	0	0	0	0	0	10	0	5
GYRODINIUM SPP.	0	0	0	0	0	0	0	5	0	0
HETEROCAPSA TRIQUETRA	0	0	0	0	0	0	0	8	0	0
KATODINIUM SPP.	0	3	0	0	0	0	0	0	0	3
MESODINIUM RUBRUM	0	0	3	0	0	0	0	5	0	5
PROROCENTRUM MICANS	0	3	0	0	3	0	3	3	0	0
PROROCENTRUM MINIMUM	0	0	0	0	0	0	0	0	0	3
PROTOPERIDINIUM (CF) BREVIPES	0	0	0	0	0	0	0	8	0	3
PROTOPERIDINIUM BIPES	0	0	0	0	0	0	0	0	0	0
PROTOPERIDINIUM BREVE	3	5	0	3	3	3	0	20	5	10
PROTOPERIDINIUM DEPRESSUM	13	3	10	13	123	3	5	18	0	10
PROTOPERIDINIUM PELLUCIDUM	0	3	25	23	10	0	0	8	28	28
PROTOPERIDINIUM PENTAGONUM	0	0	0	0	0	0	0	0	0	0
PROTOPERIDINIUM SPP.	3	50	8	38	3	8	0	75	5	45
SCRIPPSIELLA TROCHOIDEA	0	8	5	0	3	0	0	0	0	8
TINTINNIDS	3	20	123	130	40	10	28	238	33	143
UNID. ATHECATE DINOFLAGELLATE	0	10	0	3	0	5	5	18	0	30
UNID. THECATE DINOFLAGELLATES	3	28	8	0	3	8	0	35	0	35

Values are cells/L

Table 3-2b. Abundance of all identified taxa in chlorophyll maximum screened (20um) samples collected on the farfield survey in June 1993.

SPECIES	F01P W93070441	F02P W93070422	F13P W93070315	F23P W93070529	N01P W93070269	N04P W93070289	N07P W93070301	N10P W93070095	N16P W93070072	N20P W93070045
STATION SAMPLE										
ALEXANDRIUM TAMARENSE	0	163	0	5	0	0	0	0	0	0
ALORICATE CILIATES	5	3	8	35	110	60	8	285	38	40
CERATIUM FUSUS	303	856	248	100	951	443	313	128	313	253
CERATIUM LINEATUM	5	596	23	15	148	5	0	38	3	75
CERATIUM LONGIPES	1481	871	1574	1572	12675	8779	5911	1717	14557	2125
CERATIUM MACROCEROS	0	0	0	0	0	0	0	0	0	0
CERATIUM TRIPOS	68	80	15	10	20	30	20	3	3	28
DICTYOCHA SPECULUM	0	40	0	28	40	0	0	30	23	10
DINOPHYSIS NORVEGICA	65	215	40	1019	586	493	105	648	23	425
DINOPHYSIS OVUM	3	3	0	13	25	25	0	35	0	48
DINOPHYSIS SPP.	0	0	0	0	0	0	0	13	0	0
EBRIA TRIPARTITIA	0	0	0	0	0	0	0	0	0	3
GONYAULAX SPINIFERA	0	3	0	0	0	0	0	0	0	0
GYRODINIUM SPIRALE	0	0	5	5	13	0	3	10	0	0
GYRODINIUM SPP.	0	0	0	0	0	0	0	0	0	3
HETEROCAPSA TRIQUETRA	0	3	3	0	0	0	0	0	0	0
MESODINIUM RUBRUM	0	0	0	0	3	0	3	5	0	3
PROROCENTRUM MICANS	0	0	0	0	0	0	0	10	0	3
PROTOPERIDINIUM BIPES	0	18	0	0	0	0	0	0	0	3
PROTOPERIDINIUM BREVE	0	15	0	15	23	5	0	3	3	8
PROTOPERIDINIUM DEPRESSUM	8	33	15	15	135	153	53	30	140	30
PROTOPERIDINIUM PELLUCIDUM	0	5	15	15	33	23	10	38	18	43
PROTOPERIDINIUM SPP.	3	113	33	65	65	30	15	40	10	30
SCRIPPSIELLA TROCHOIDEA	0	3	10	0	0	0	0	0	0	0
TINTINNIDS	0	75	98	188	155	65	30	320	50	523
UNID. ATHECATE DINOFLAGELLATE	0	13	13	0	0	10	5	0	5	35
UNID. THECATE DINOFLAGELLATES	3	90	8	3	20	25	10	20	3	20

Values are cells/L

Table 3-3. C^{14} production (mg C m^{-2} d^{-1}) estimated for euphotic layer at BioProductivity stations in June 1993.

	Coastal Stations						Nearfield Stations										Cape Cod Bay Stations			
	F23P		F13P		N01P[6]		N04P		N07P		N10P		N16P		N20P		F01P[6]		F02P	
Waterdepth, (m)	22.0		25.0		30.0		49.0		43.5		23.0		40.5		31.0		23.5		29.0	
$Z_{(0.5\% \, Io)}$, (m)	14.0		19.5		29.0		35.0		34.5		20.0		33.0		24.0		33.0		28.0	
Samples[1]	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C
Rate (mg C m^{-2}d^{-1})	3437	3193	2532	3156	1800	1206	1968	1130	2099	907	3953	2396	2565	975	6424	3327	2086	2216	1455	566
Model[2]	P	W	W	W	W	W	W	W	W	W	W	P	W	P	W	W	P	W	W	P
P_{SB} or P_{MAX}[3]	12.79	10.04	6.56	6.71	8.12	4.70	7.44	3.39	8.77	3.46	10.53	6.20	9.69	4.81	11.33	5.22	15.89	13.80	10.83	6.83
α[4]	0.071	0.088	0.043	0.086	0.040	0.040	0.043	0.074	0.057	0.030	0.066	0.082	0.051	0.066	0.058	0.073	0.068	0.087	0.045	0.028
β[5]	0.001	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.001	NA	0.006	NA	NA	0.002	NA	NA	0.008

[1] S: Surface sample and P-I incubations on it.
C: Chlorophyll max sample and P-I incubations on it.
[2] P: Platt et al. (1980).
W: Webb et al. (1974).
[3] P_{SB}: Production parameter for Platt et al. model.
P_{MAX}: Production parameter for Webb et al. model.
[4] Parameter for both models.
[5] Parameter for Platt et al. model.
[6] $Z_{(0.5\% \, Io)}$ was greater than the profile depth as stations N01P (26.5 m) and F01P (21.5 m).
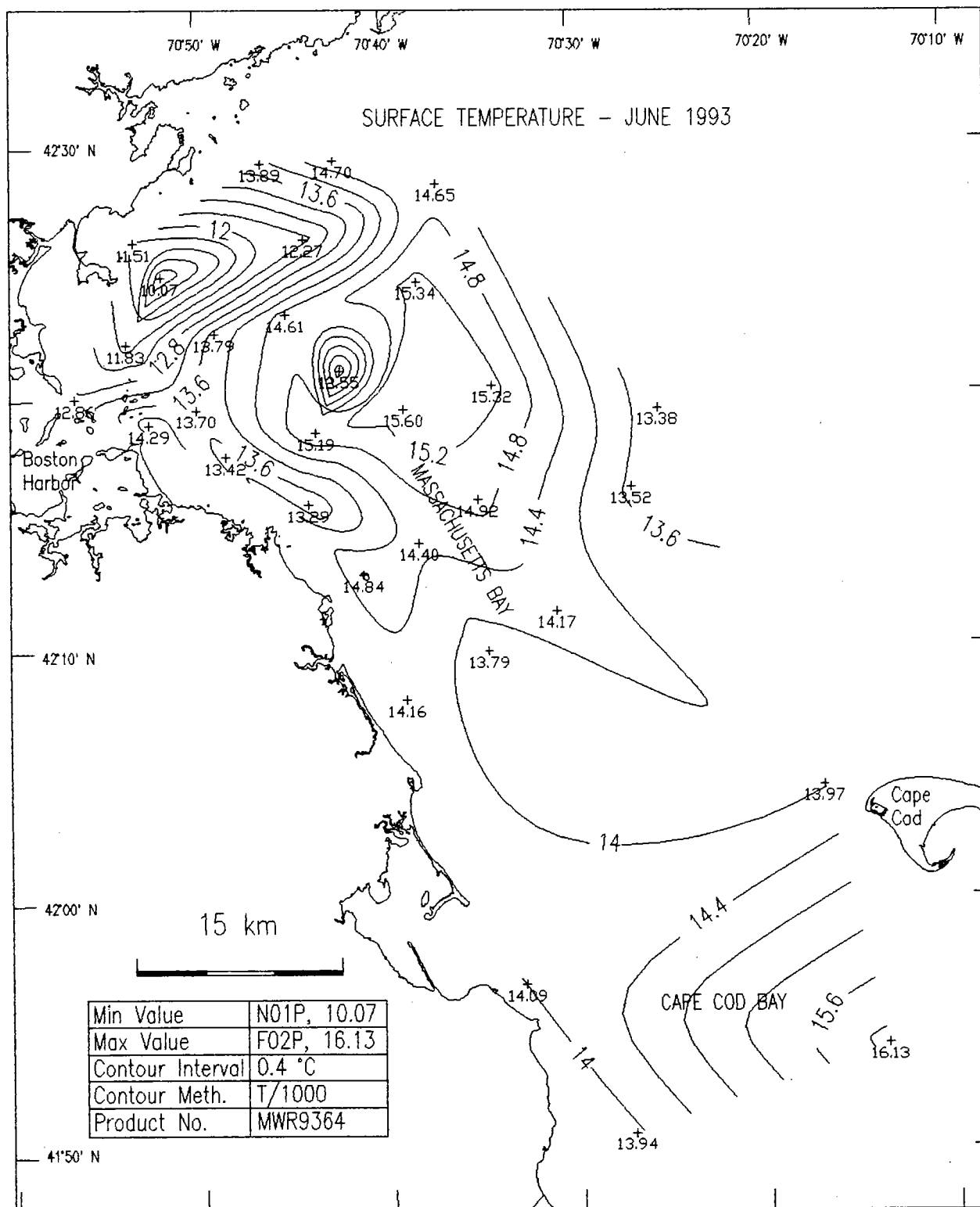
Figure 3-1. Surface temperature (°C) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
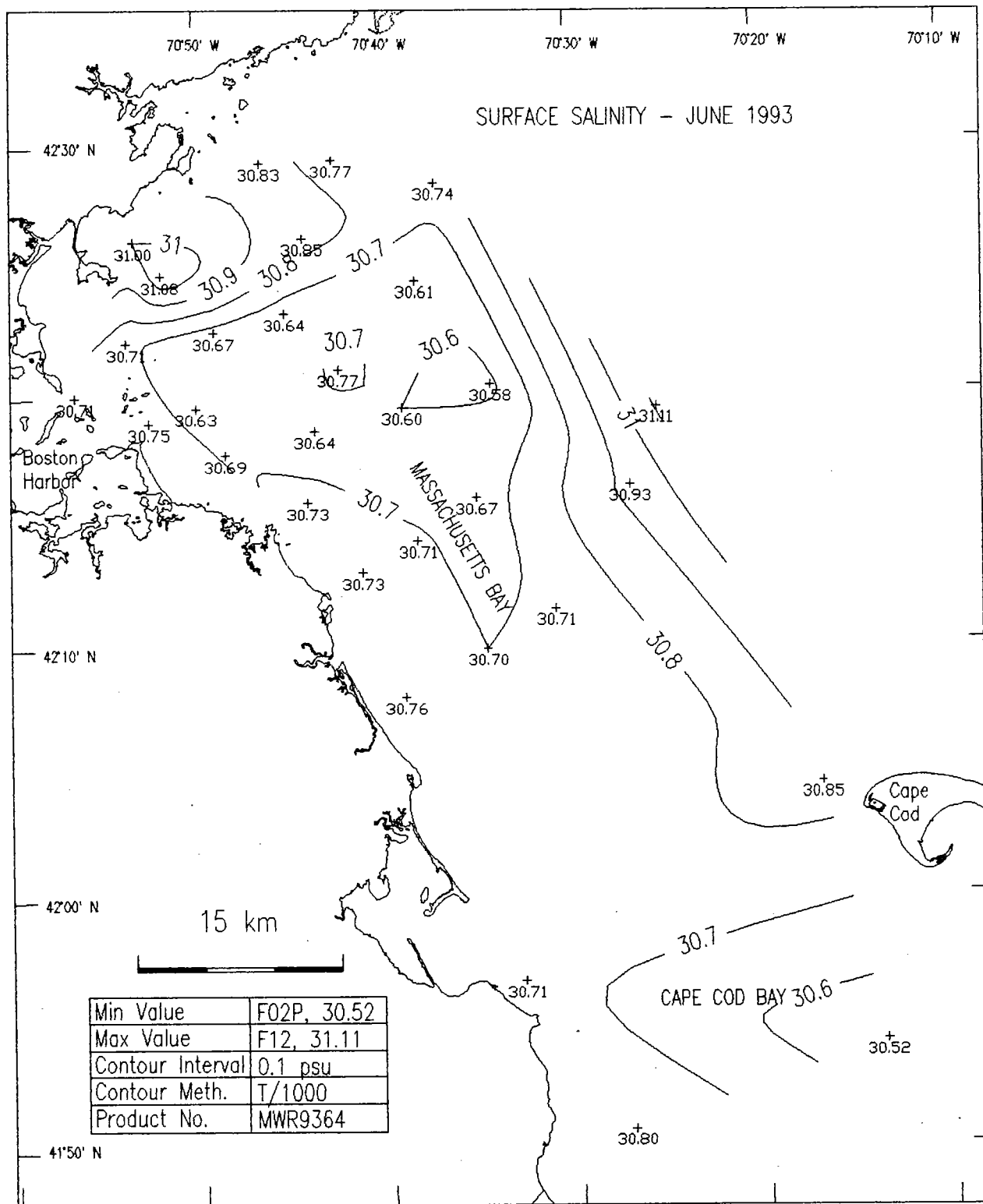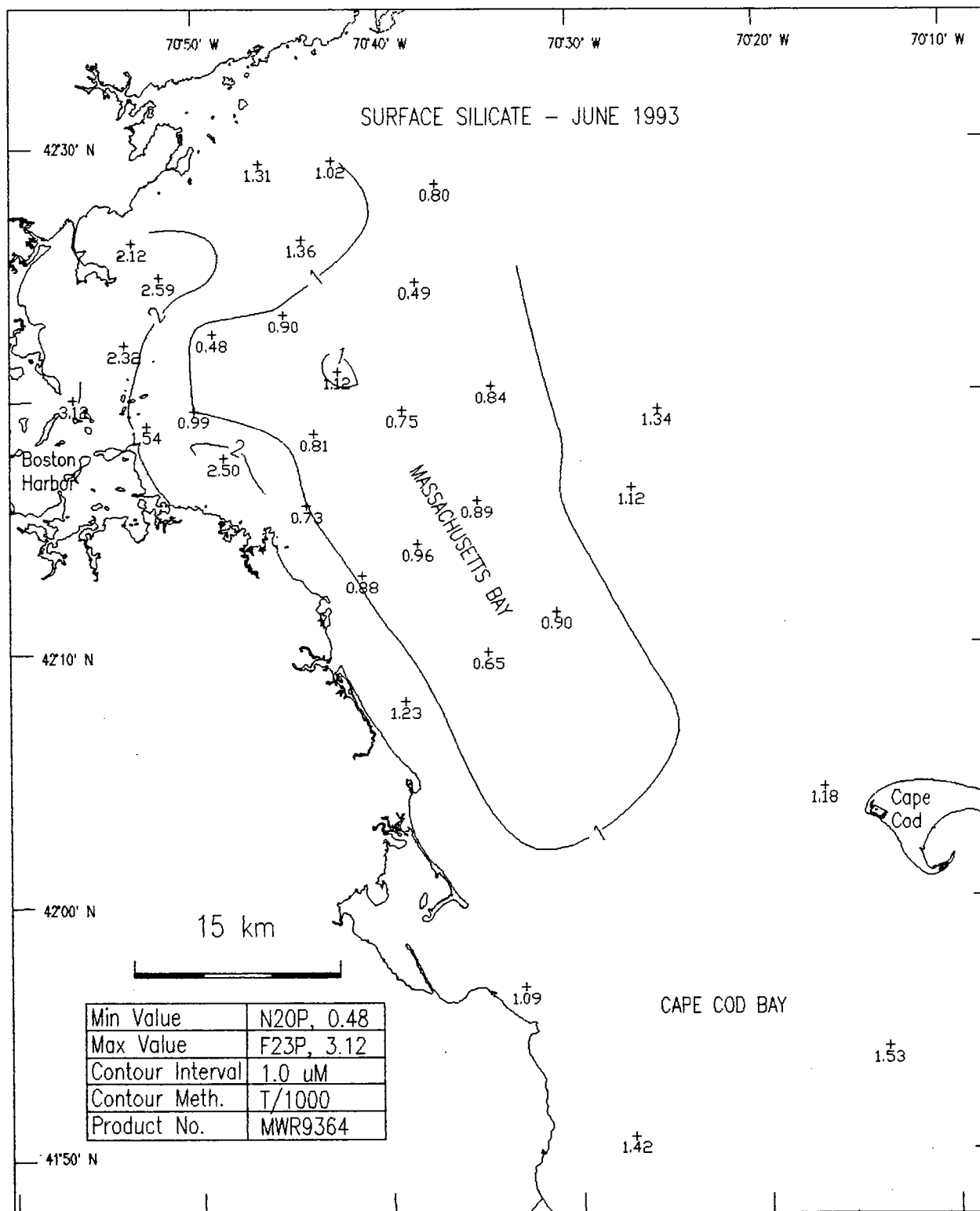
Figure 3-2. Surface salinity (PSU) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
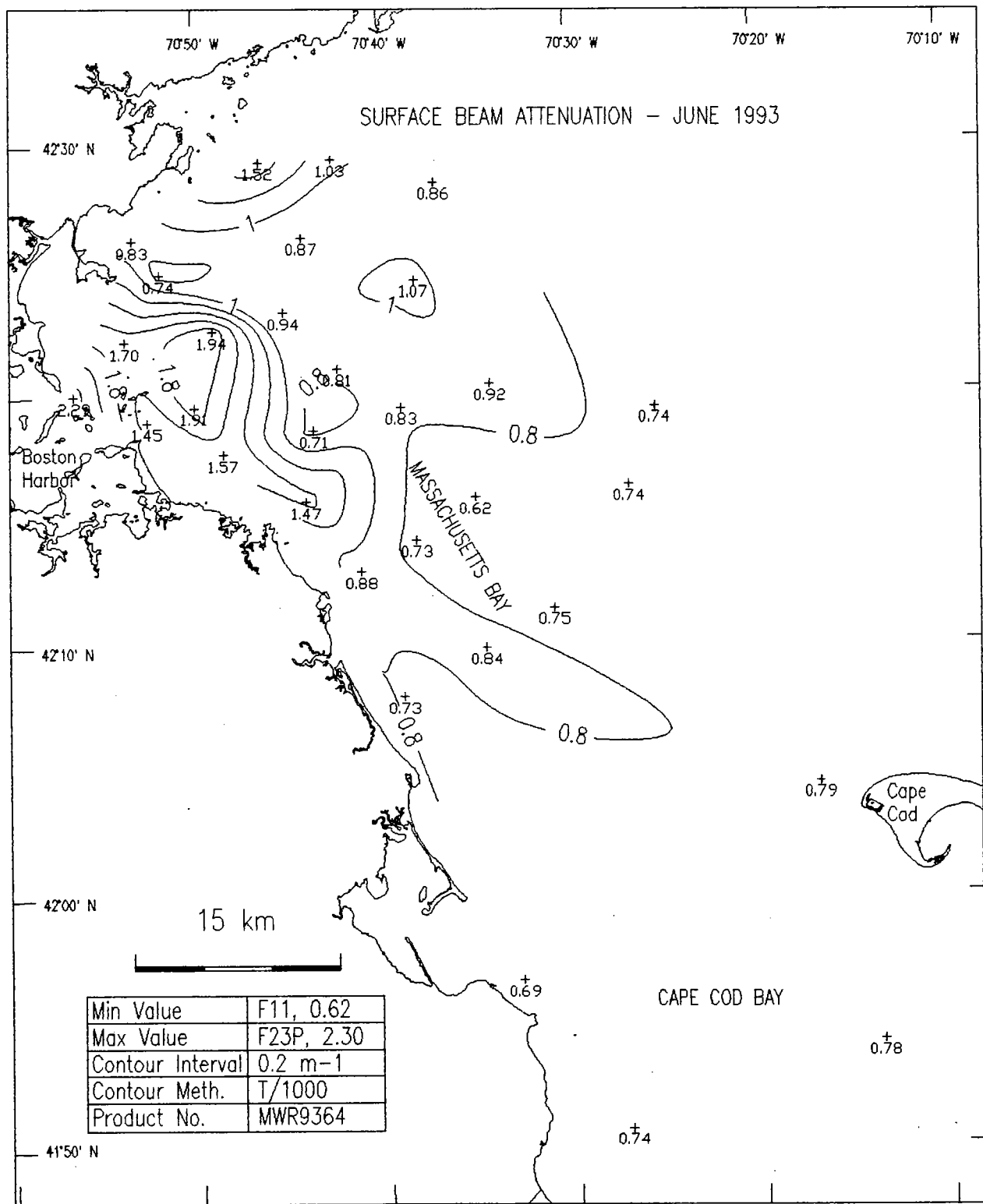
Figure 3-3. Surface beam attenuation (m^{-1}) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
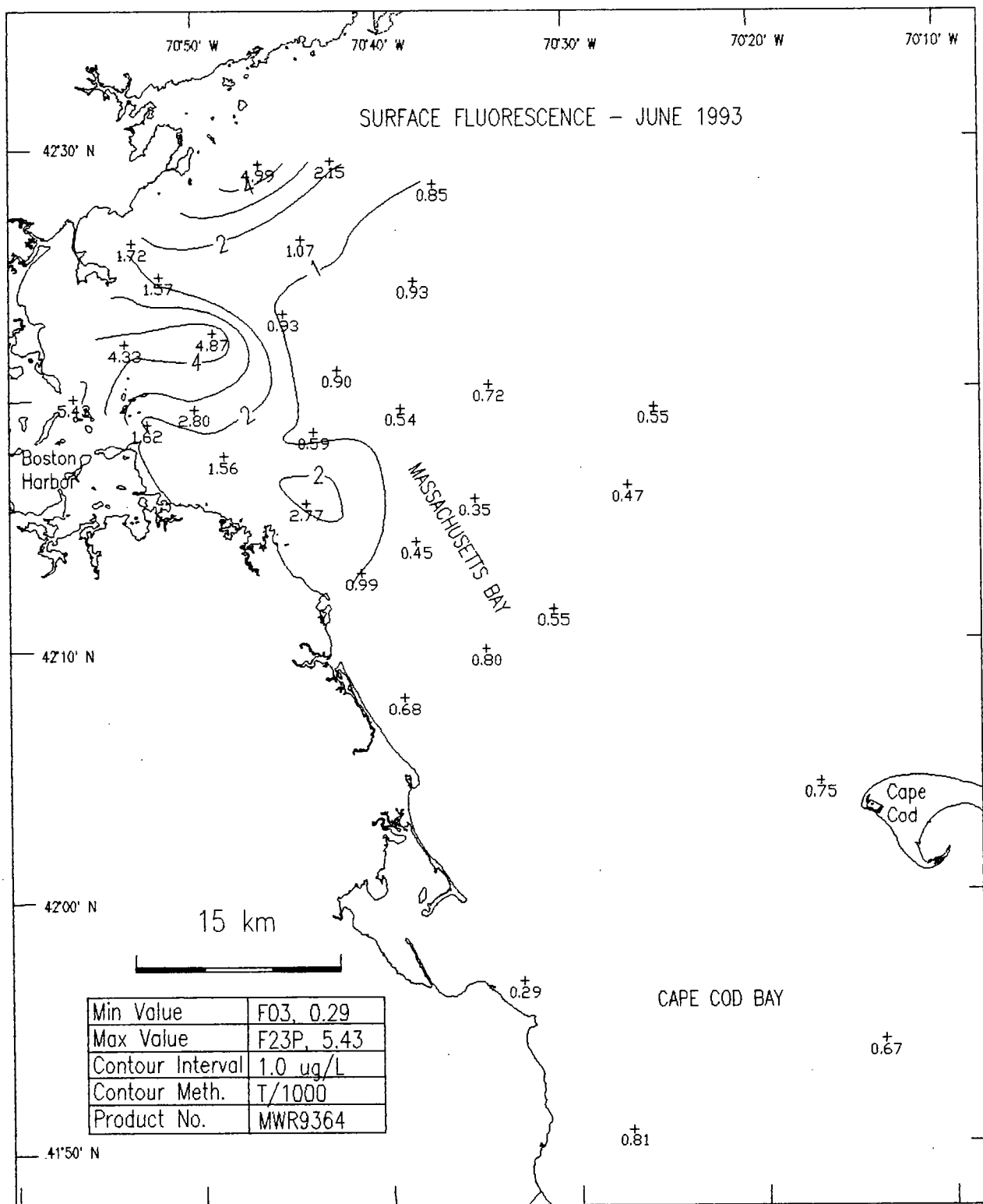
Figure 3-4. Surface *in situ* fluorescence (as μg Chl L^{-1}) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
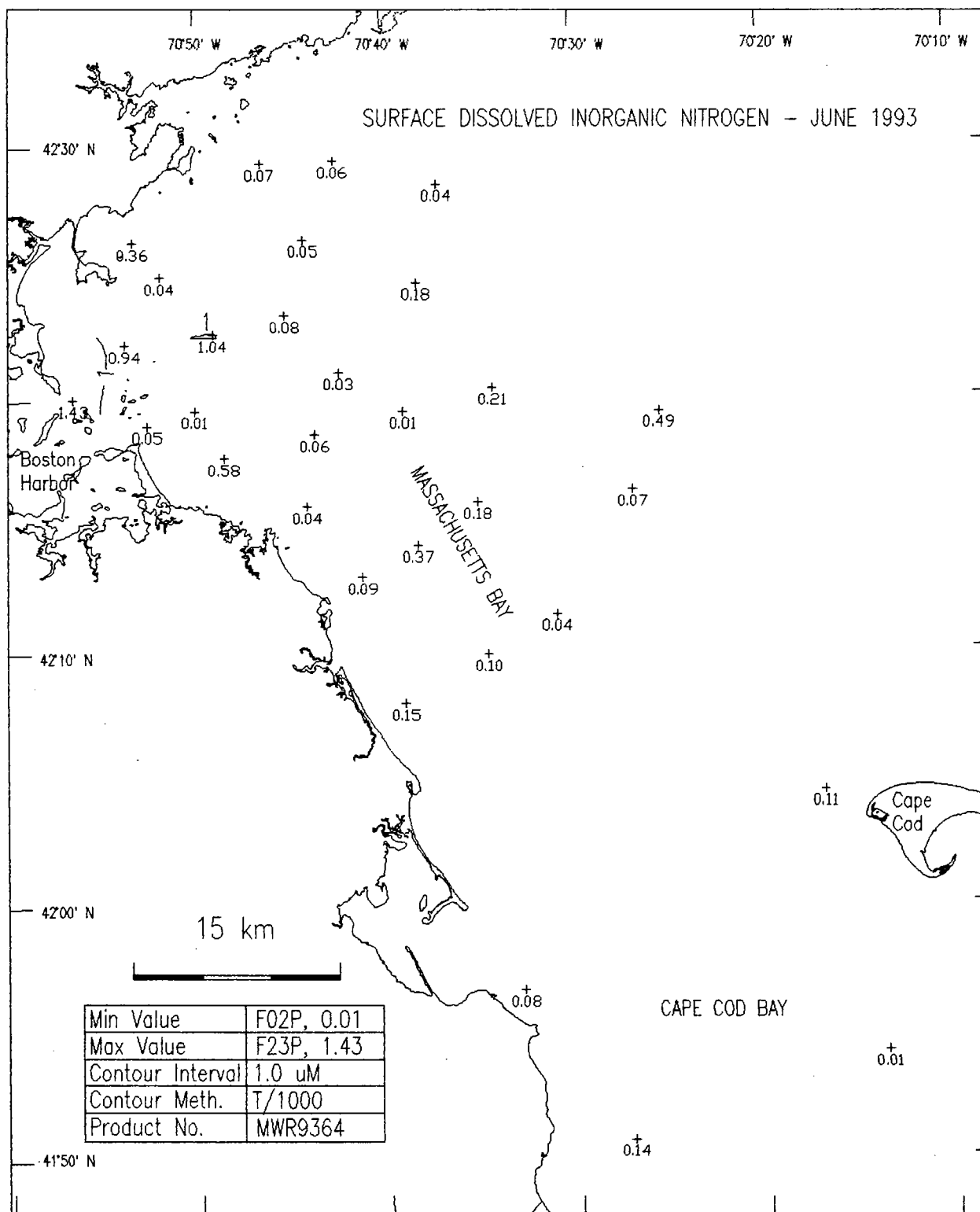
Figure 3-5. Surface dissolved inorganic nitrogen (DIN, μM) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
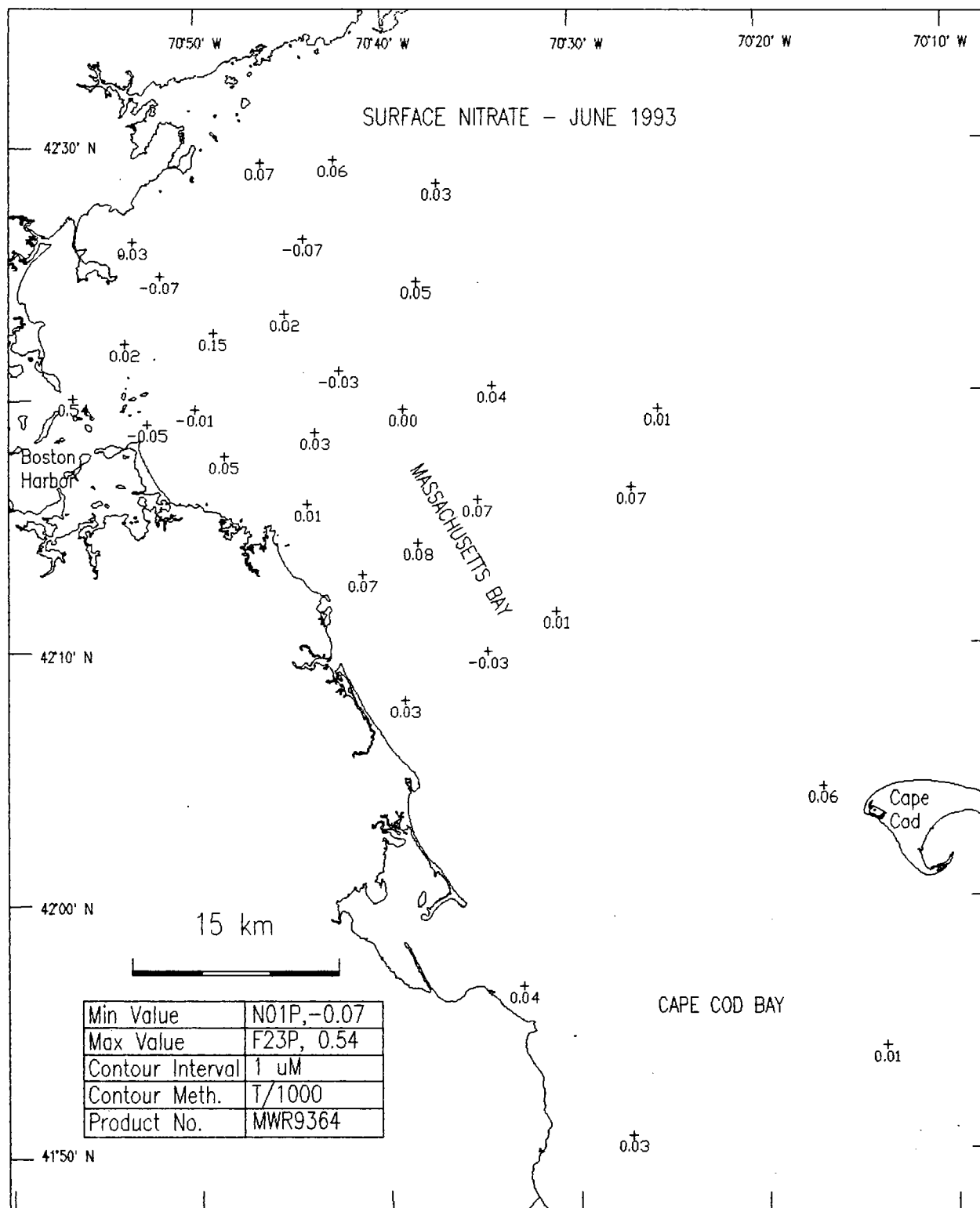
Figure 3-6. Surface nitrate (NO$_3$, μM) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
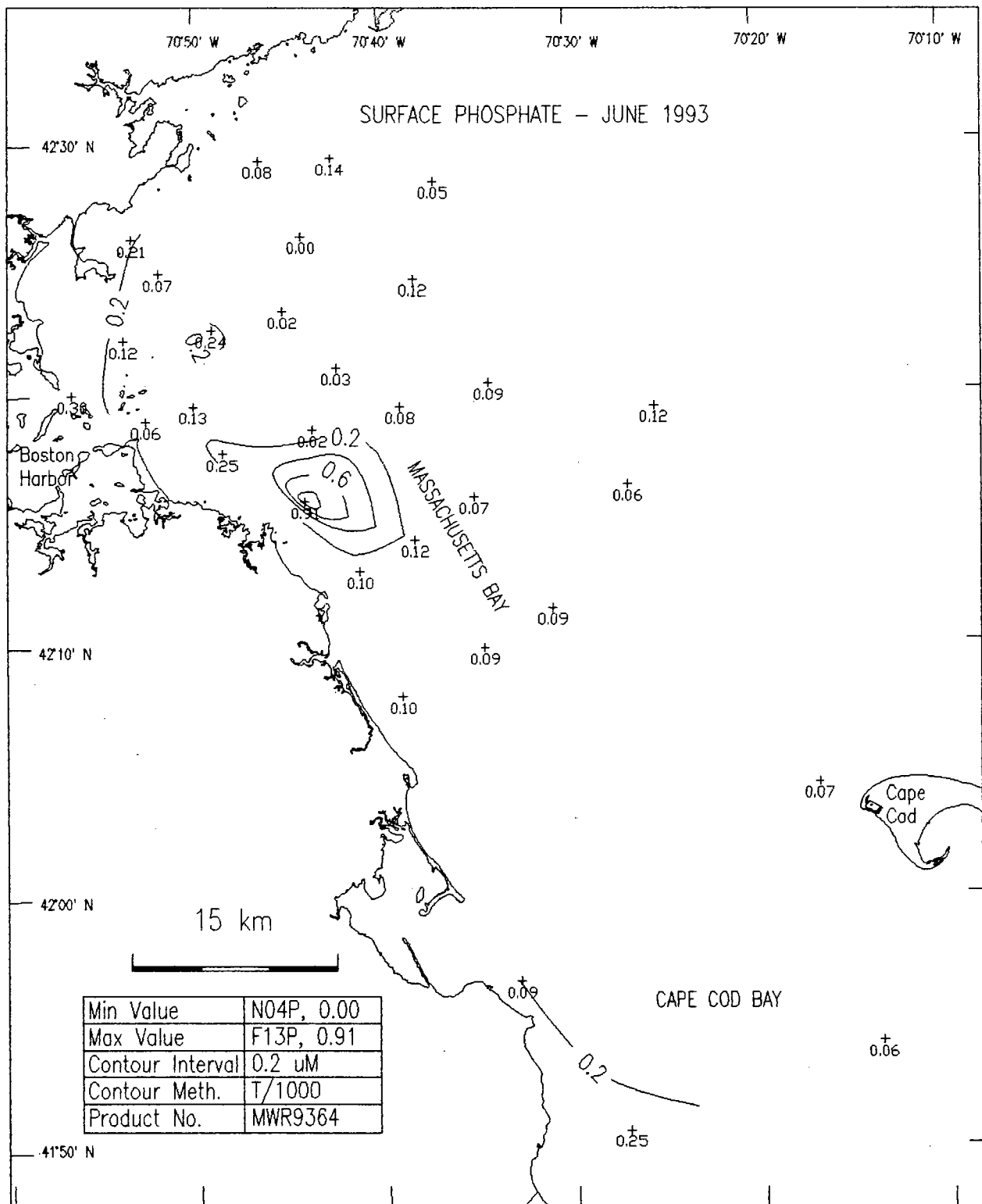
Figure 3-7. Surface phosphate (PO$_4$, μM) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).

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Min Value	N20P, 0.48
Max Value	F23P, 3.12
Contour Interval	1.0 uM
Contour Meth.	T/1000
Product No.	MWR9364

Figure 3-8. Surface silicate (SiO$_4$, μM) in the study area in June 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).
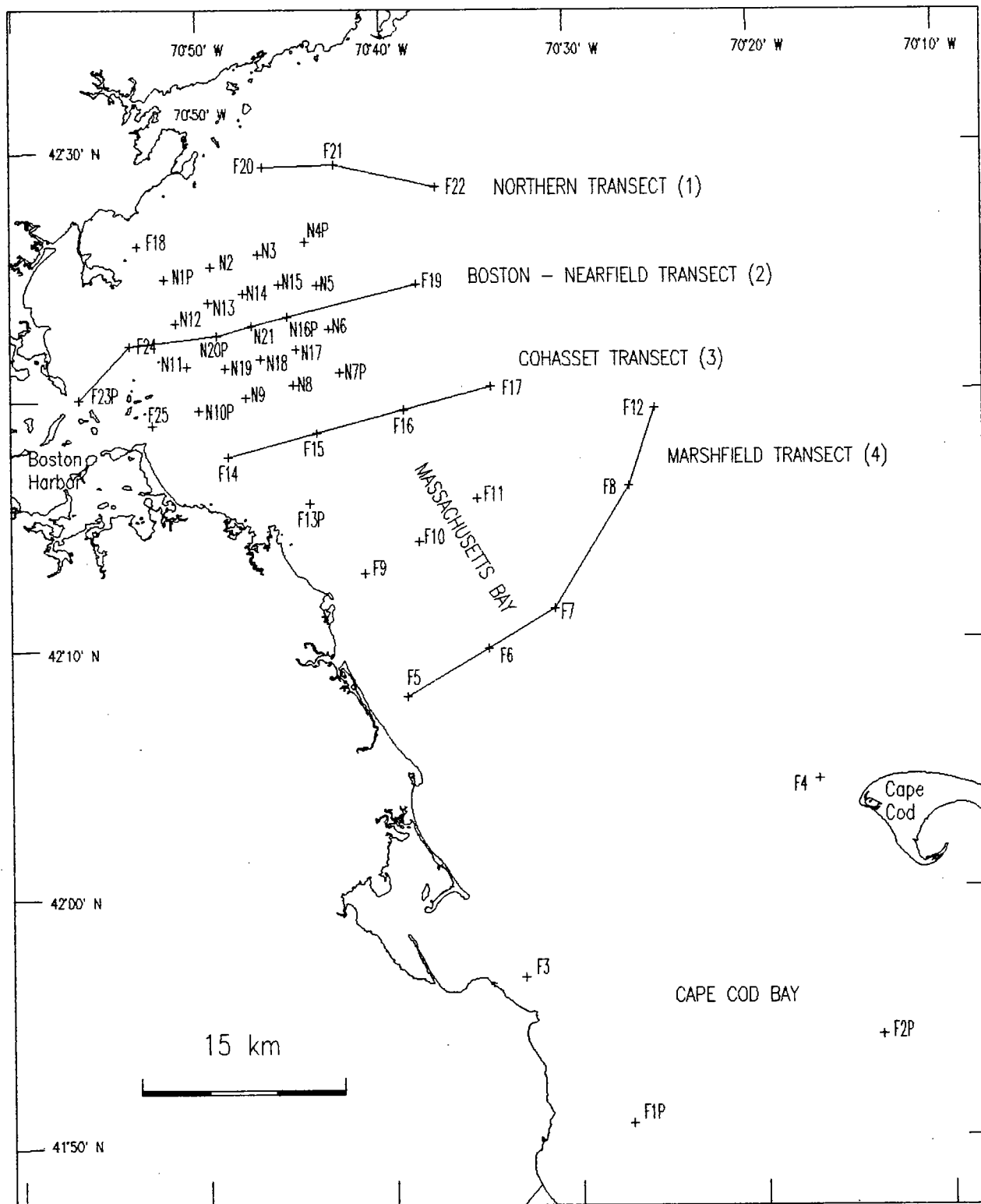
Figure 3-9. Map showing position of four standard transects for which vertical contour plots were produced in following Figures 3-10 to 3-14.
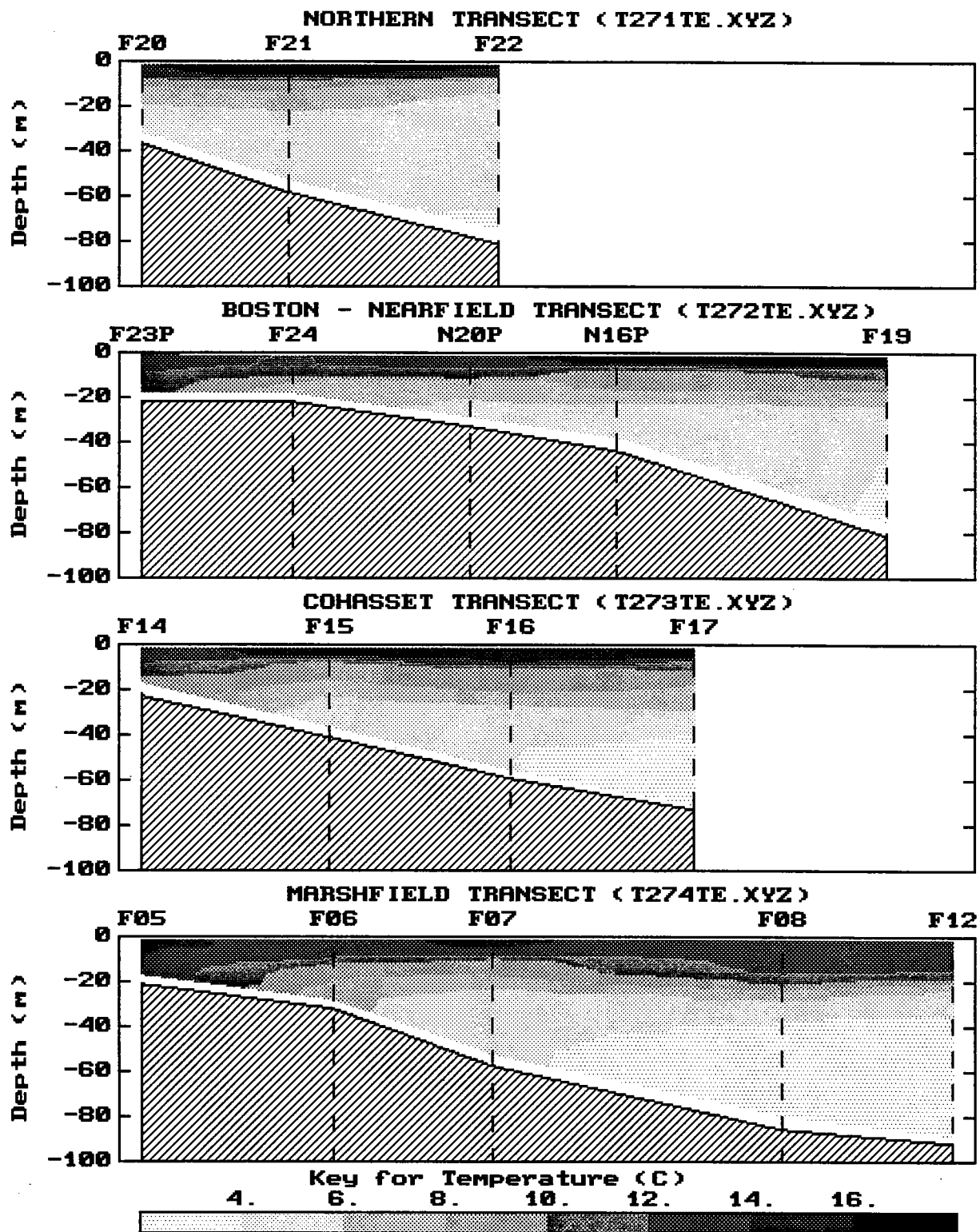
Figure 3-10a. Vertical section contours of temperature in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.
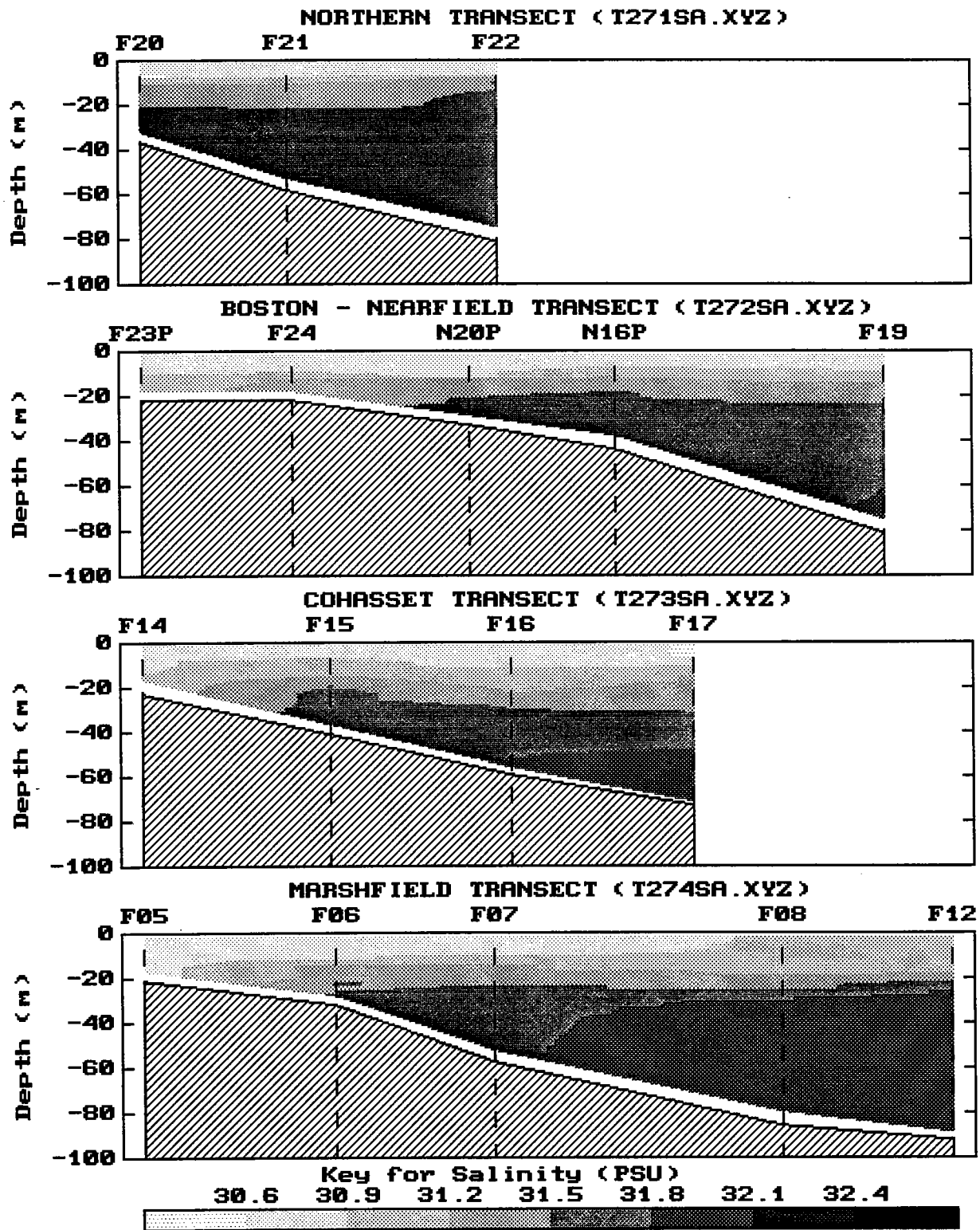
Figure 3-10b. Vertical section contours of salinity in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.
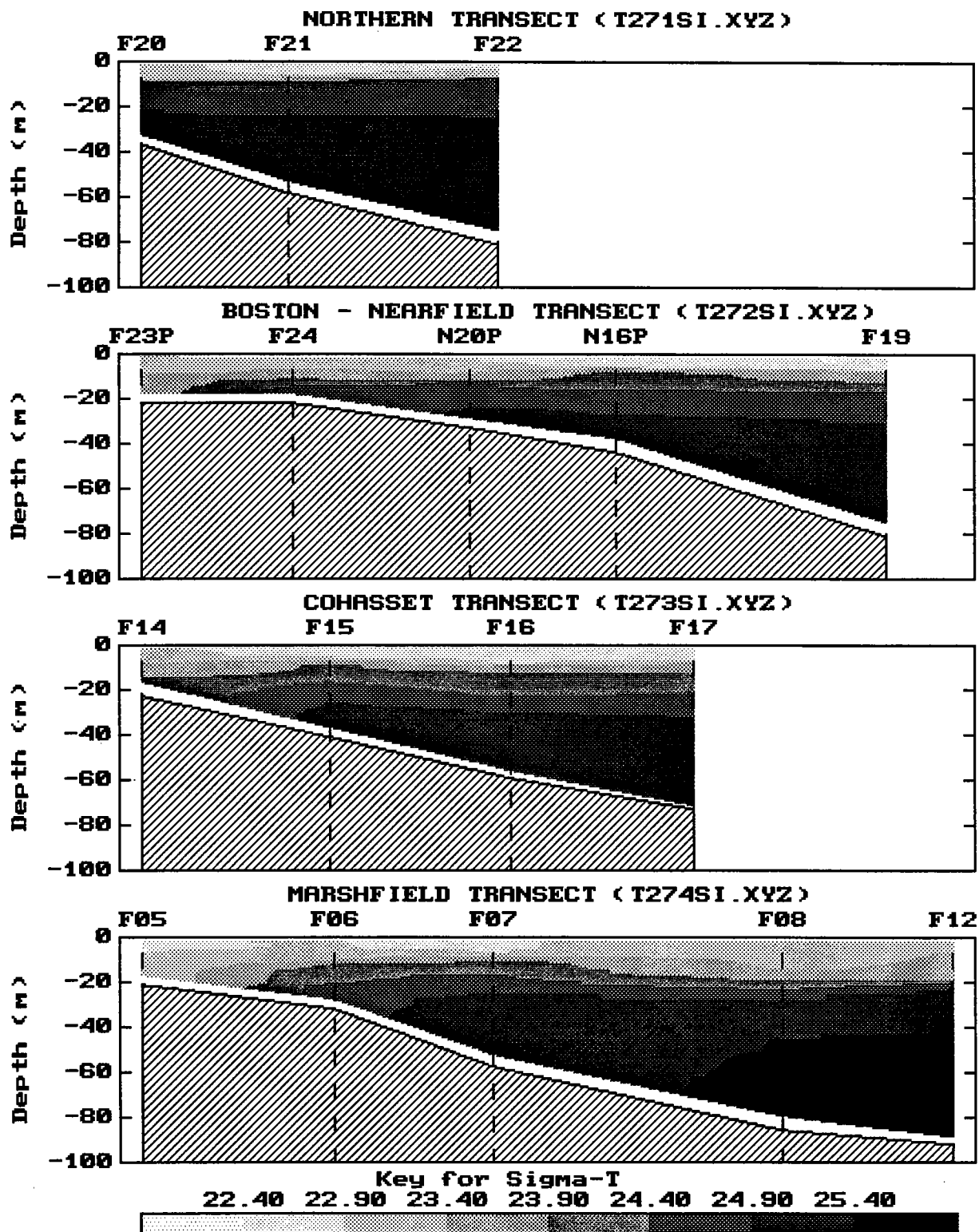
Figure 3-10c. Vertical section contours of density (σ_T) in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.
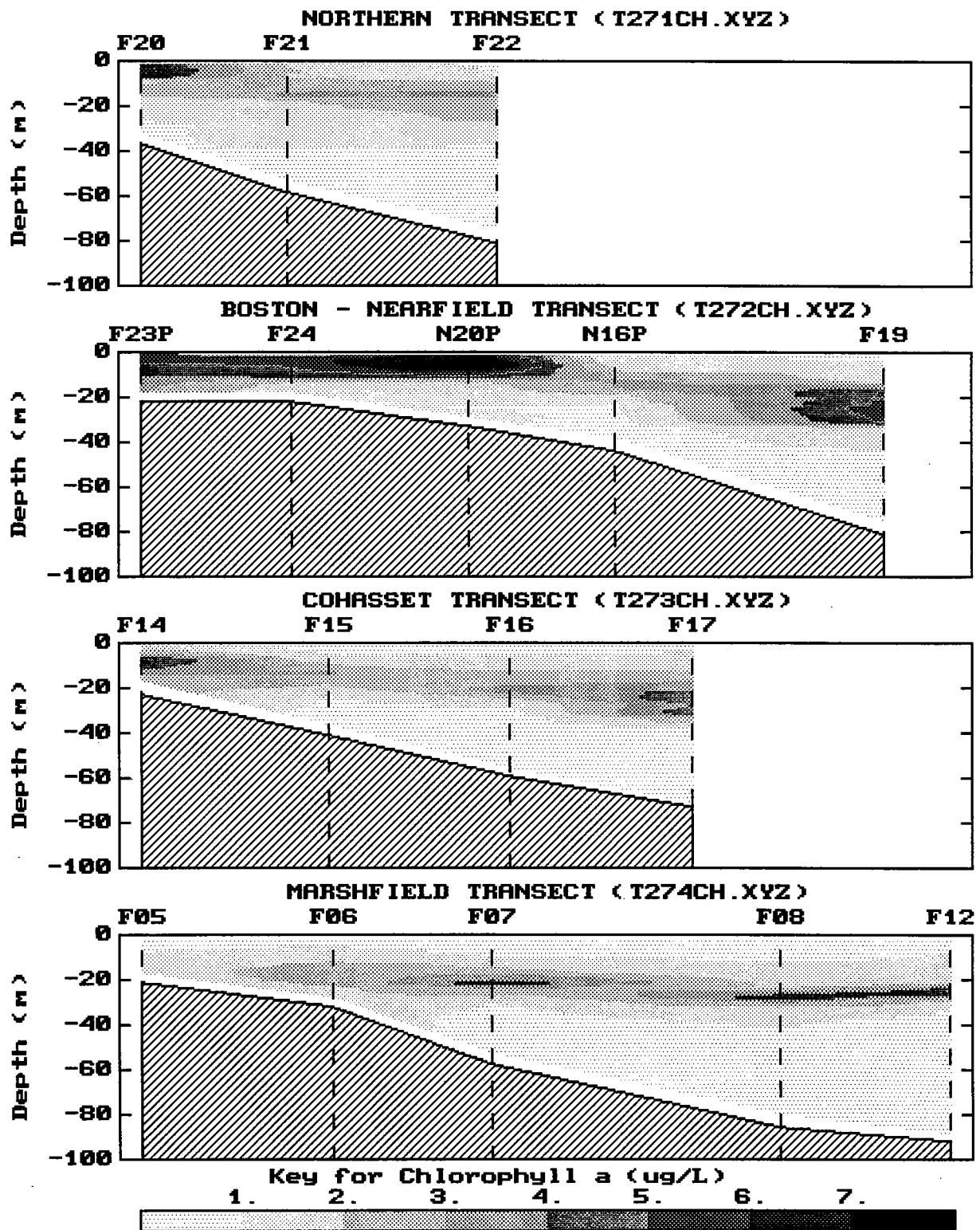
Figure 3-11. Vertical section contours of fluorescence (as μg Chl L^{-1}) in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.
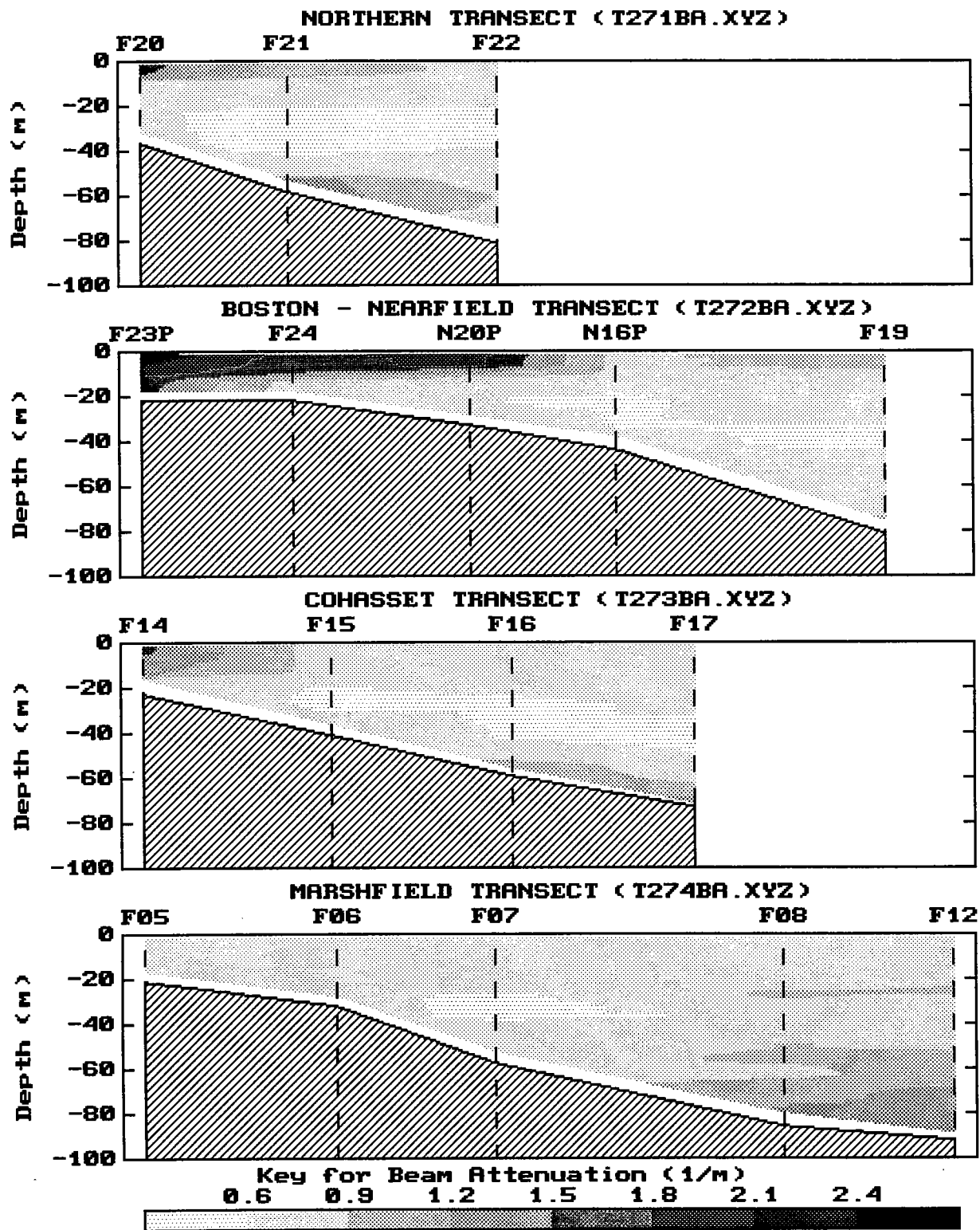
Figure 3-12. Vertical section contours of beam attenuation in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.
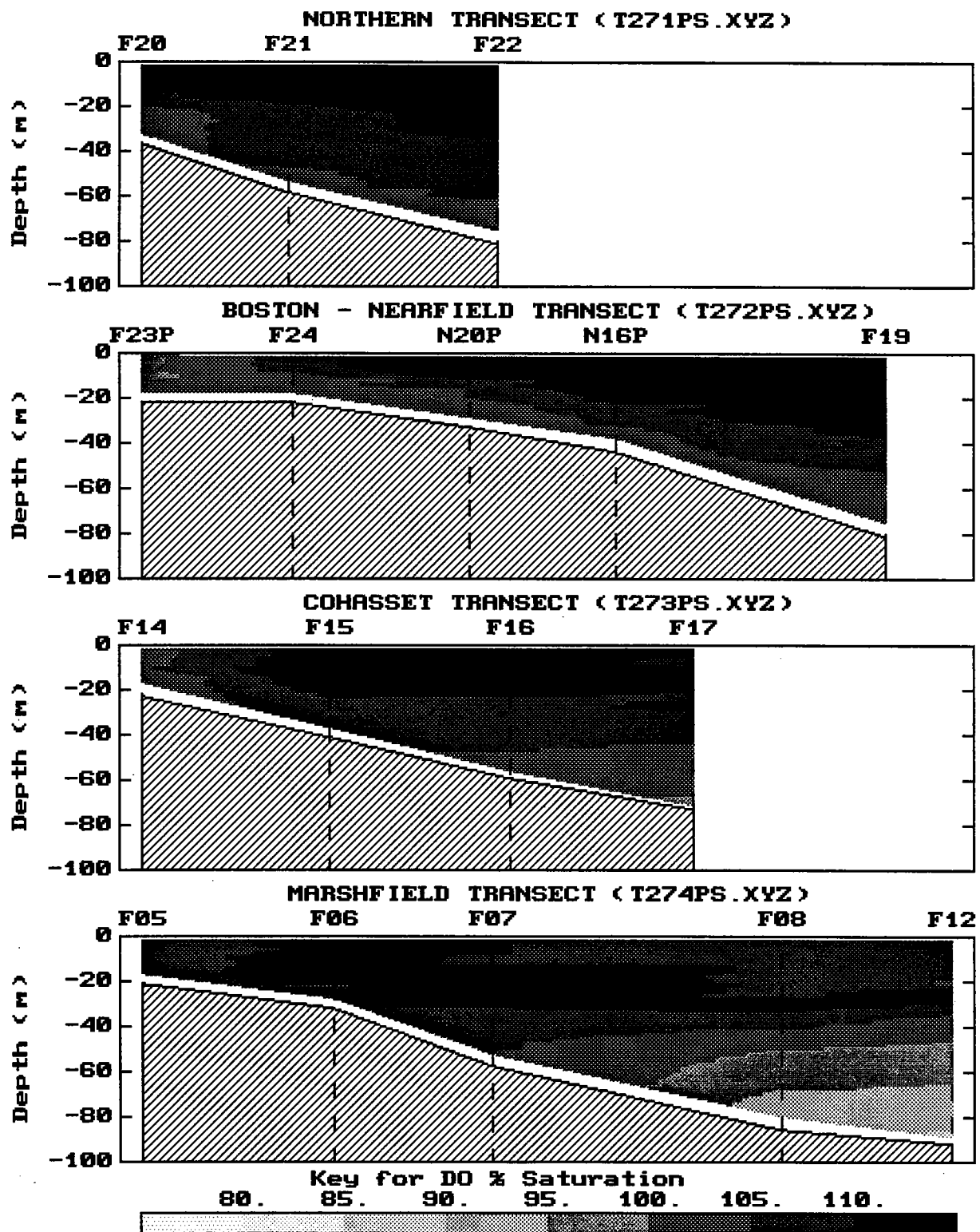
Figure 3-13. Vertical section contours of dissolved oxygen (% saturation) in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.
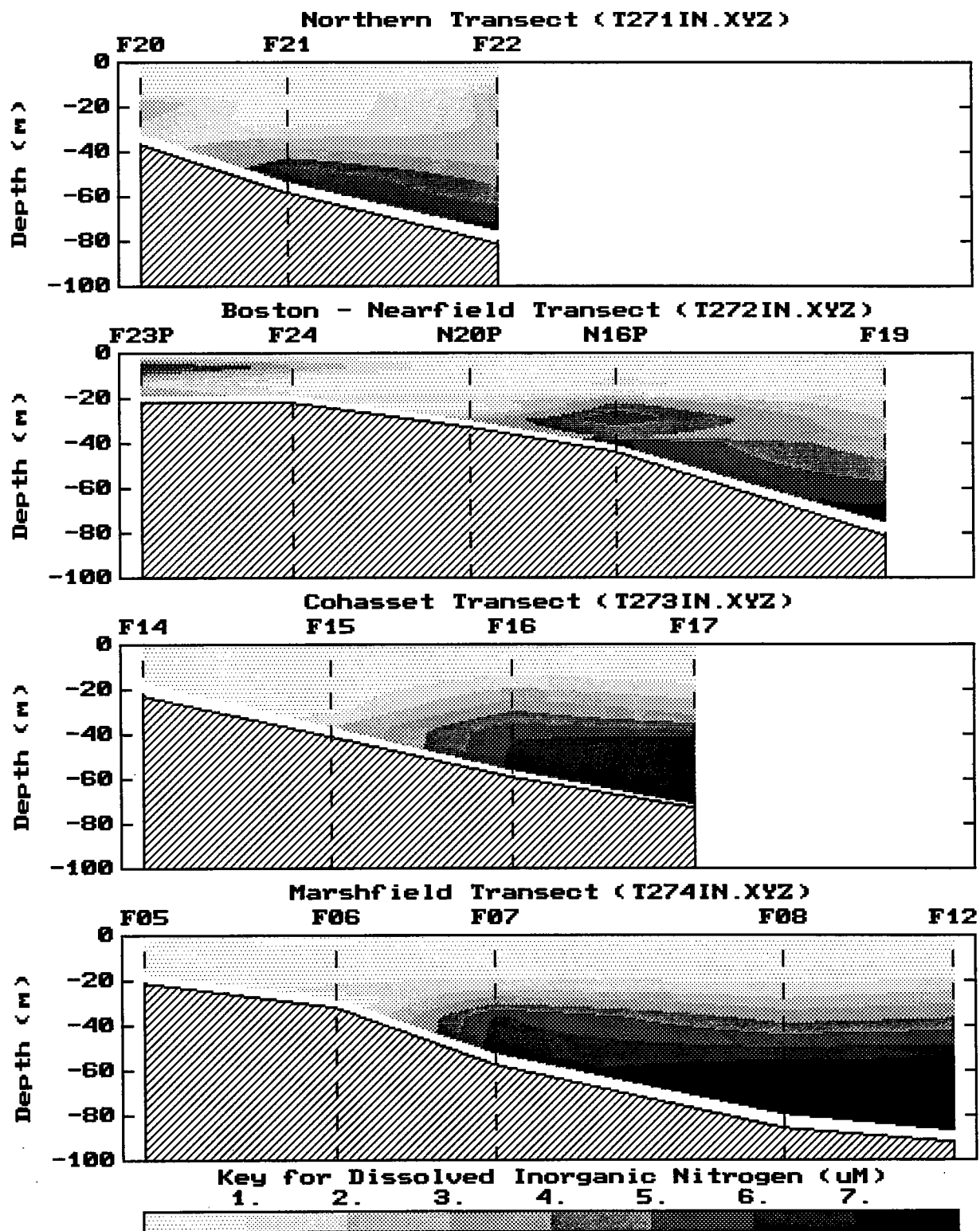
Figure 3-14a. Vertical section contours of dissolved inorganic nitrogen (DIN, μM) in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from discrete bottle samples (Appendix A).
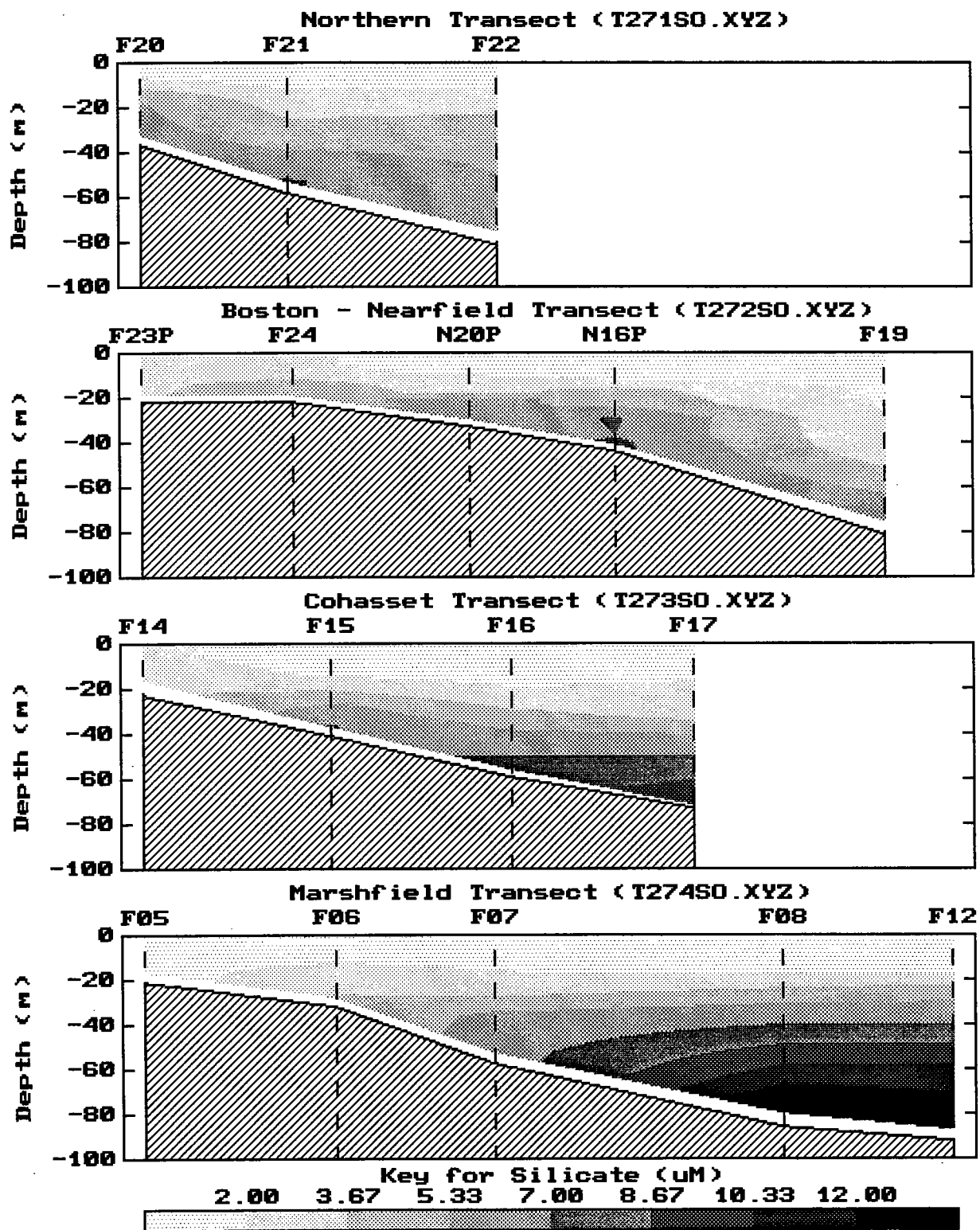
Figure 3-14b. Vertical section contours of silicate (SiO_4, μM) in June 1993 for standard transects (see Figure 3-9). The data used to produce contours are from discrete bottle samples (Appendix A).
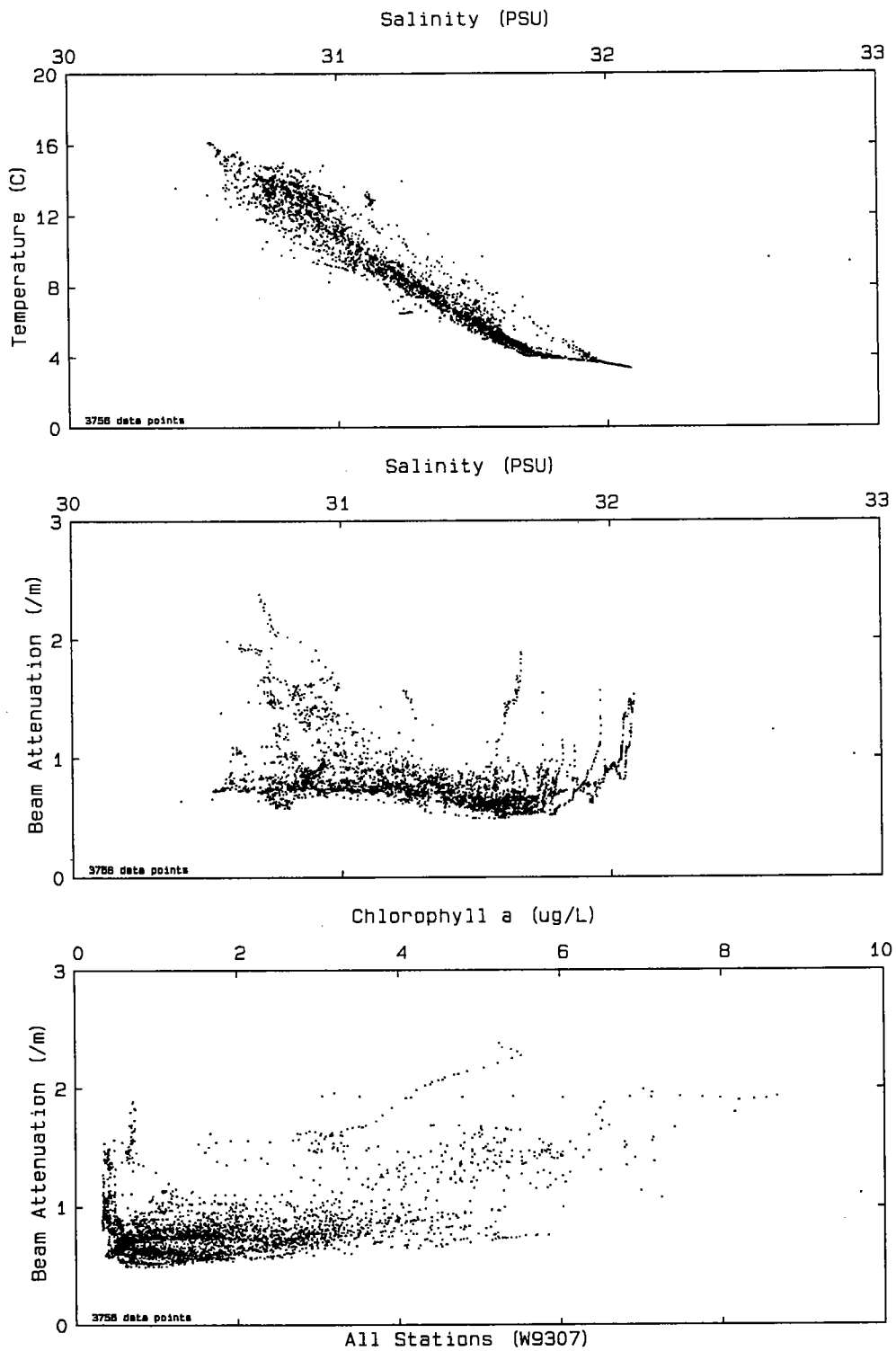
Figure 3-15a. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in June 1993. Regional plots are in Appendix C. Chlorophyll is estimated from *in situ* fluorescence.
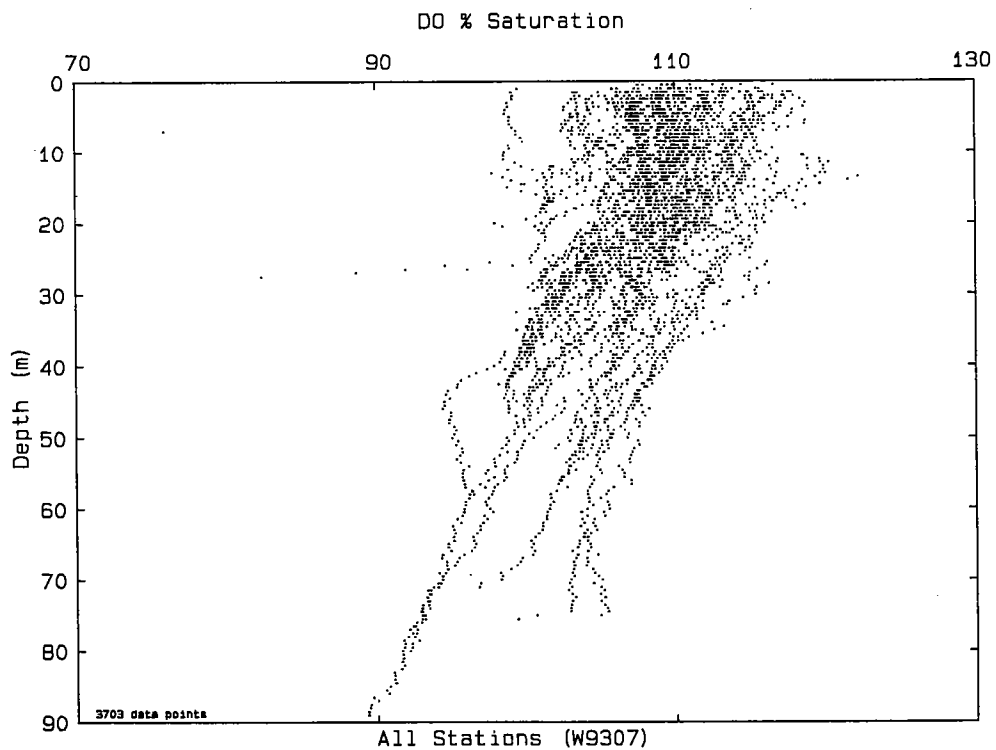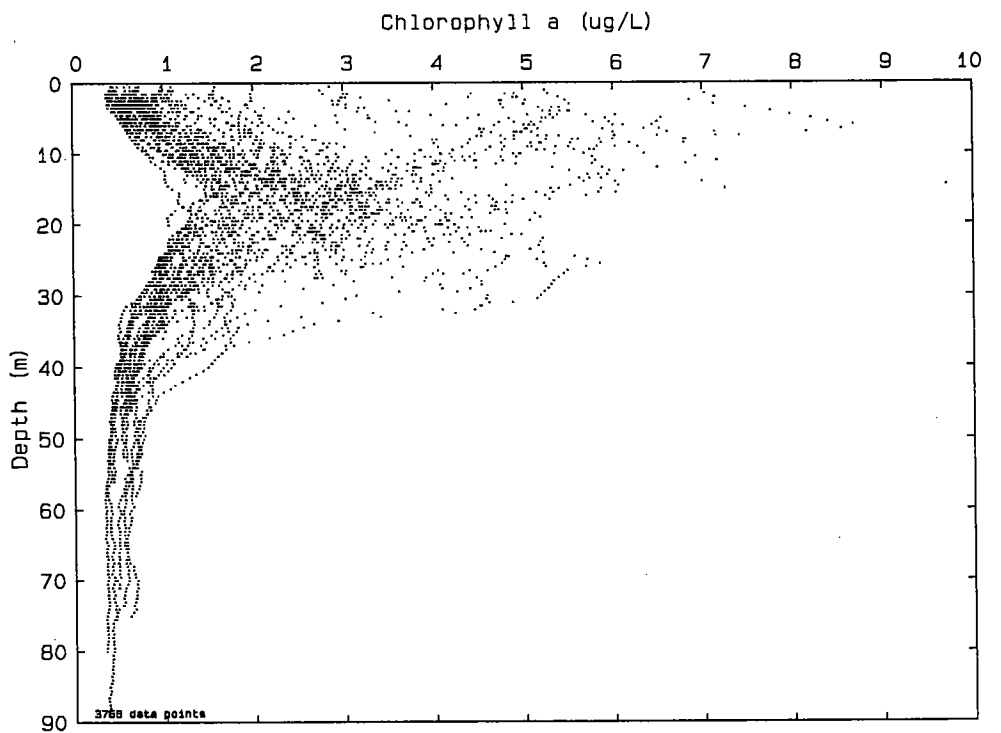
Figure 3-15b. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in June 1993. Regional plots are in Appendix C. Chlorophyll is estimated from *in situ* fluorescence.
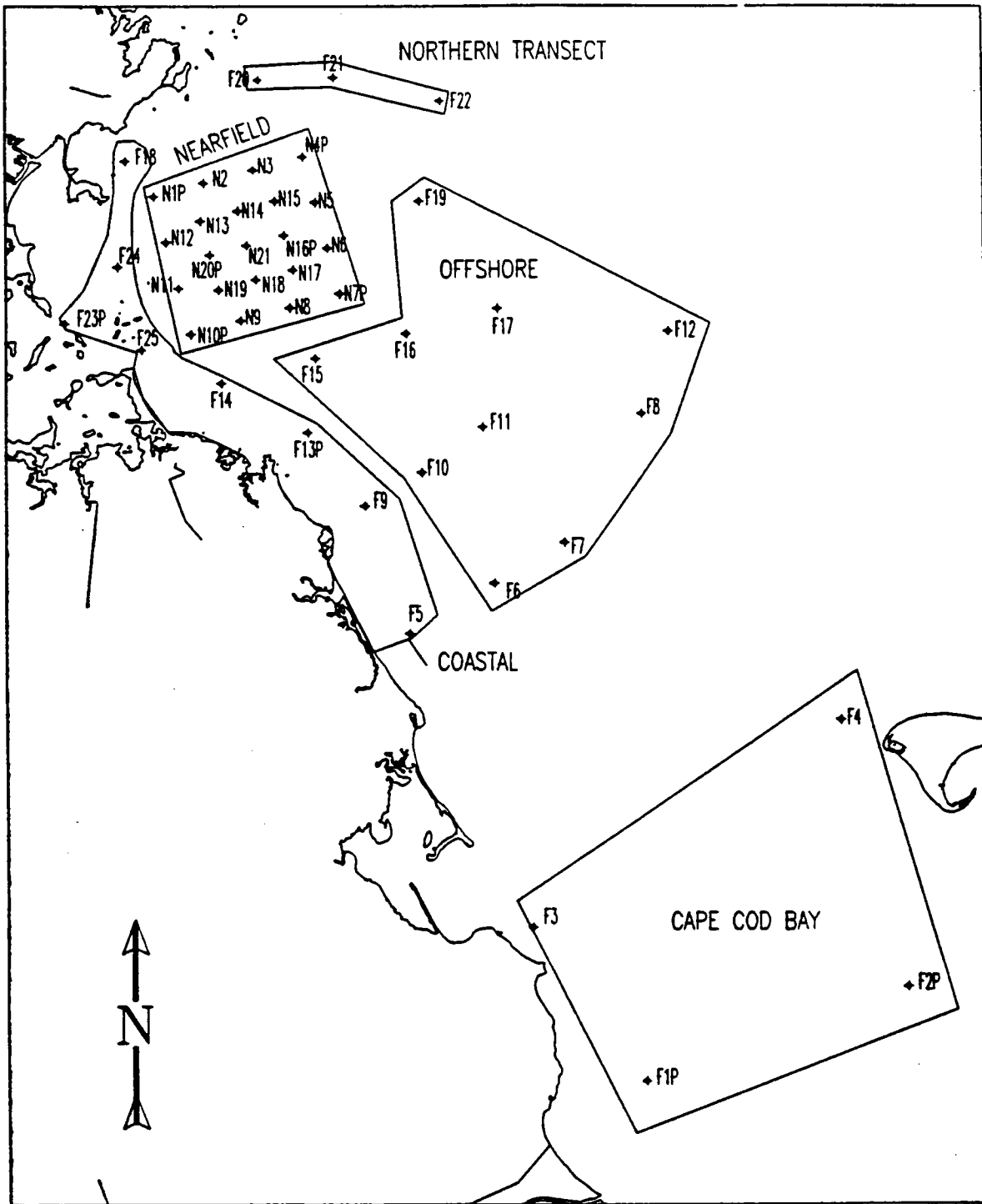
Figure 3-16. Map to show station groups designated in Figures 3-17 through 3-22. Massachusetts Bay stations were separated into four groups based on water depth and geographic position; Cape Cod Bay has four stations.
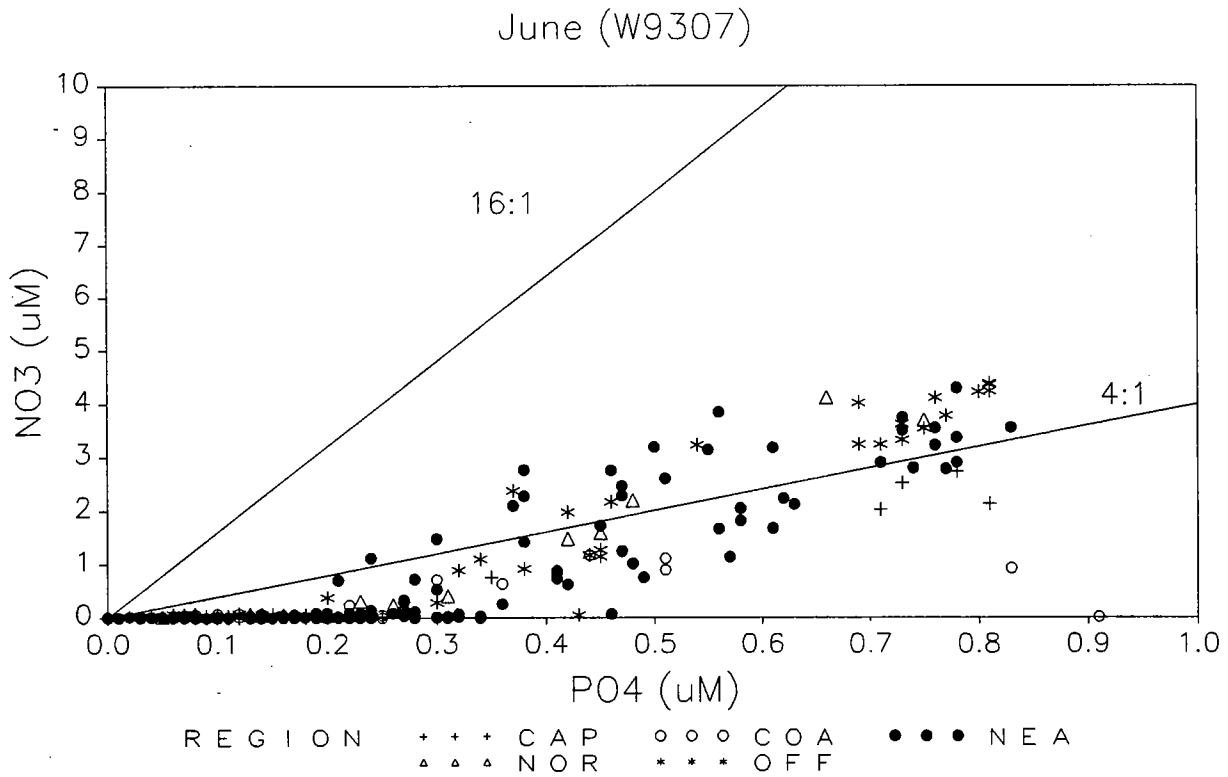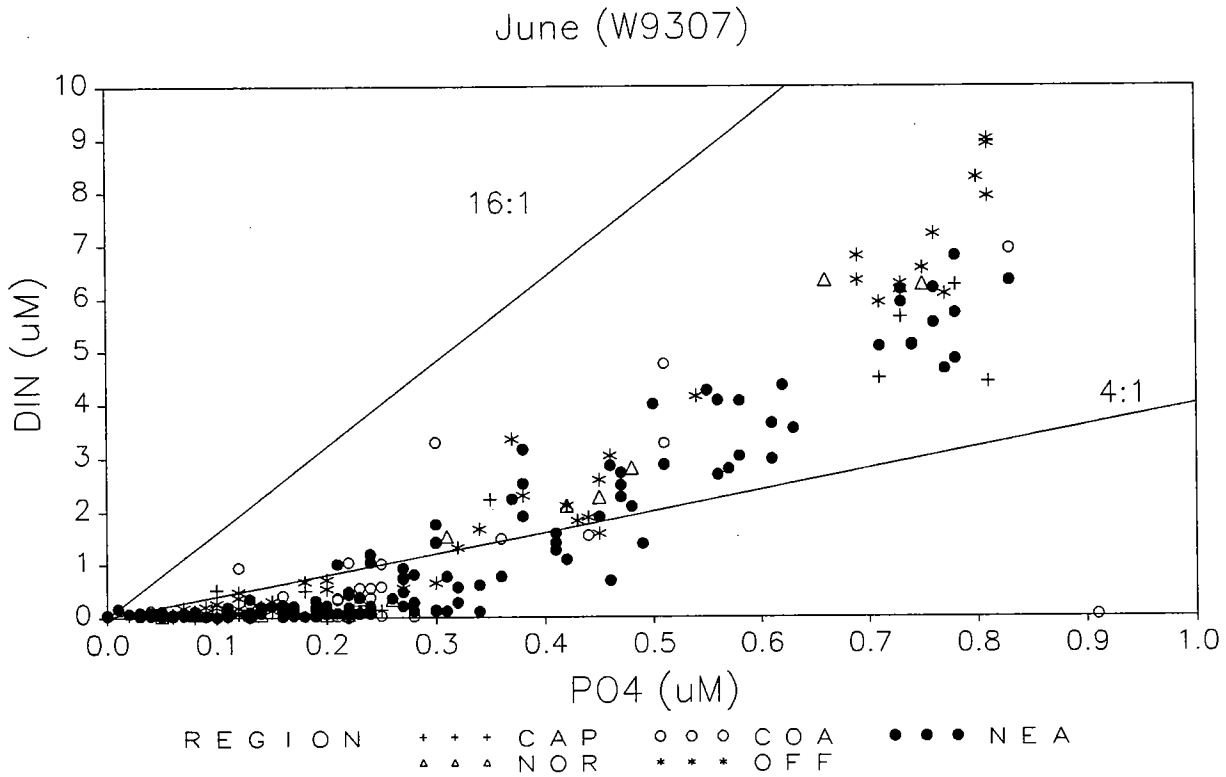
Figure 3-17. Scatter plots of nitrogen forms vs. phosphate during June 1993. All stations and depths are included. Lines show constant proportions of nitrogen relative to phosphate. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.
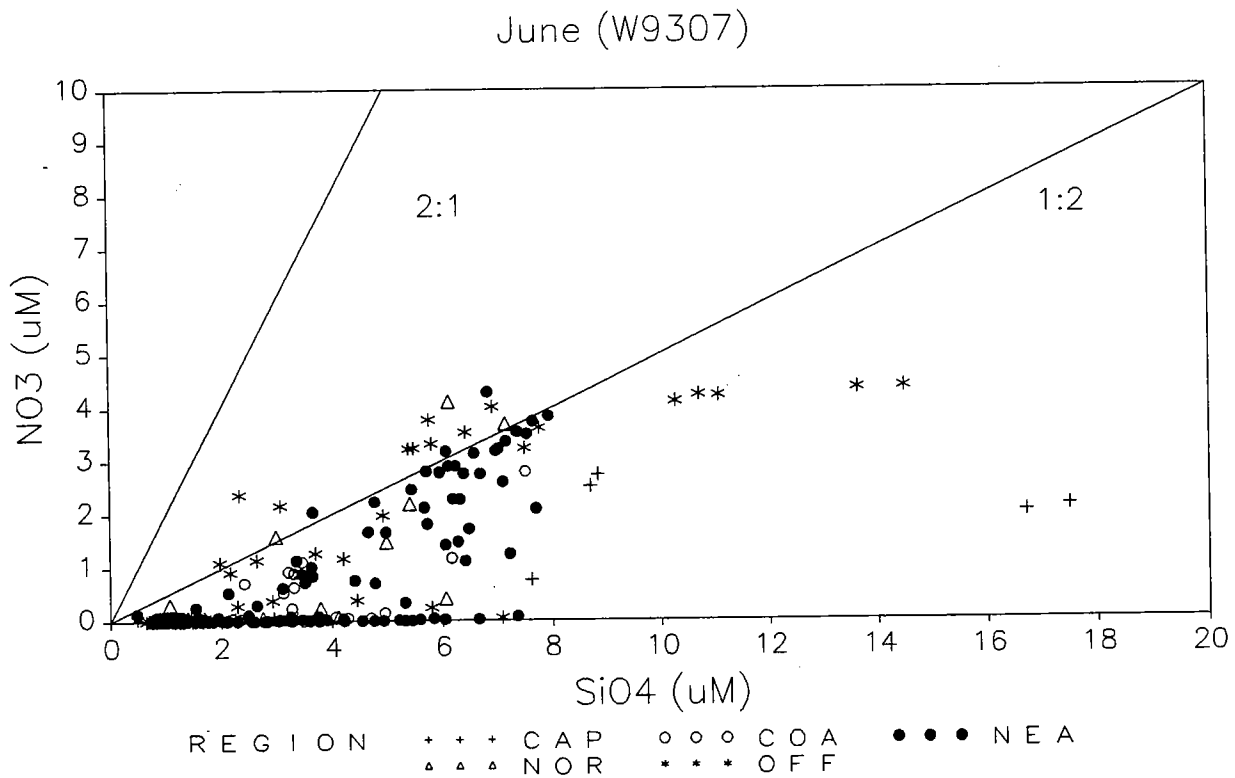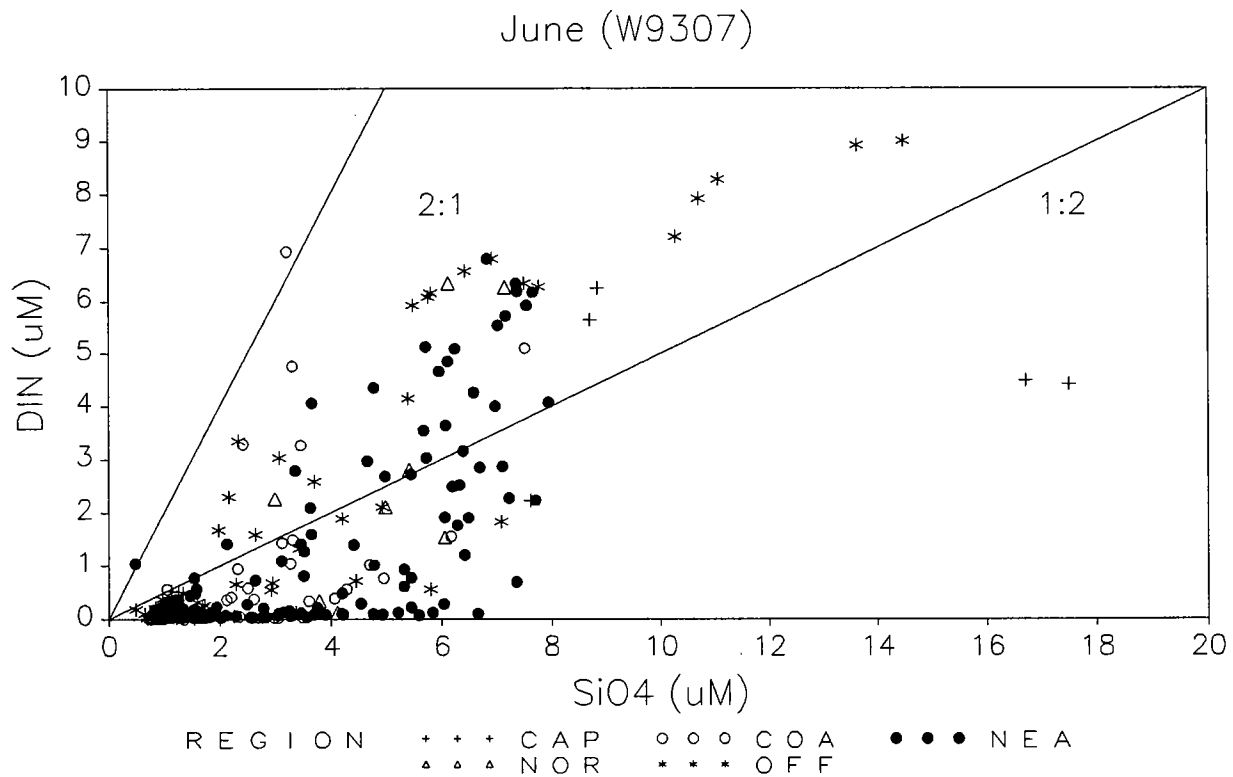
Figure 3-18.   Scatter plots of nitrogen vs. silicate during June 1993. All stations and depths
are included. Lines show constant proportions of nitrogen relative to silicate.
Data are given in Appendix A. The regions correspond to the groups of stations
shown in Figure 3-16.

June (W9307)

REGION   + + + C A P   o o o C O A   ● ● ● N E A
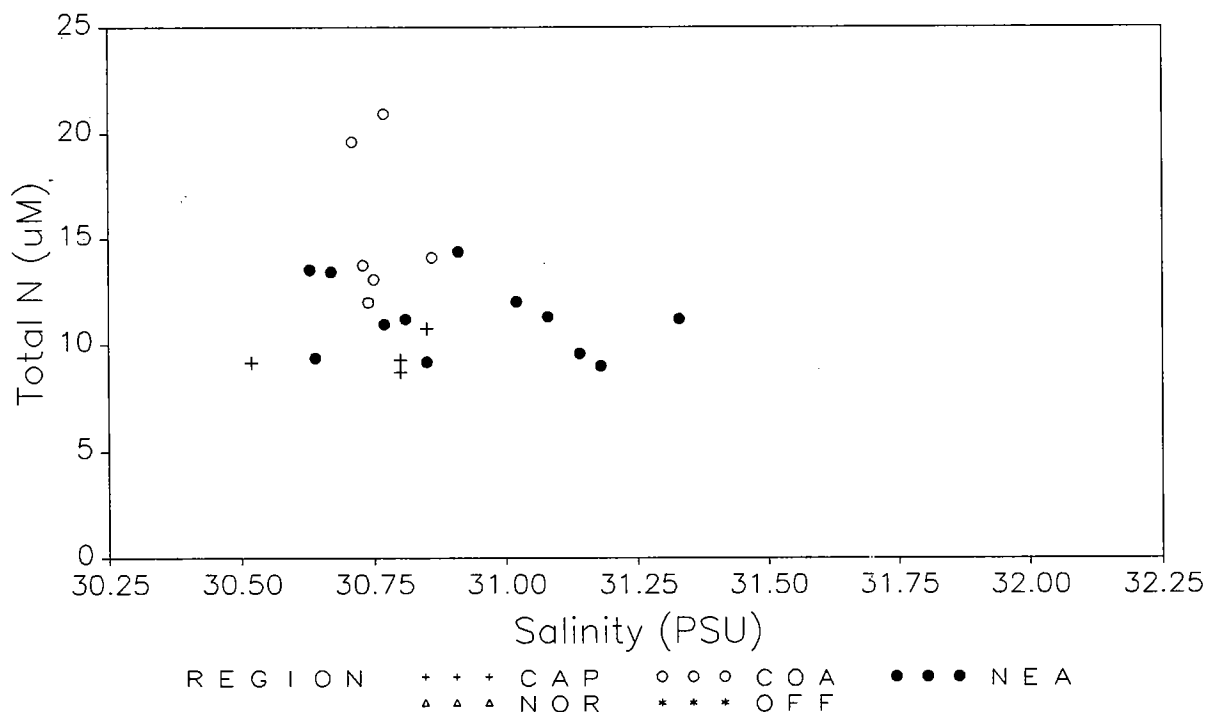   △ △ △ N O R   * * * O F F
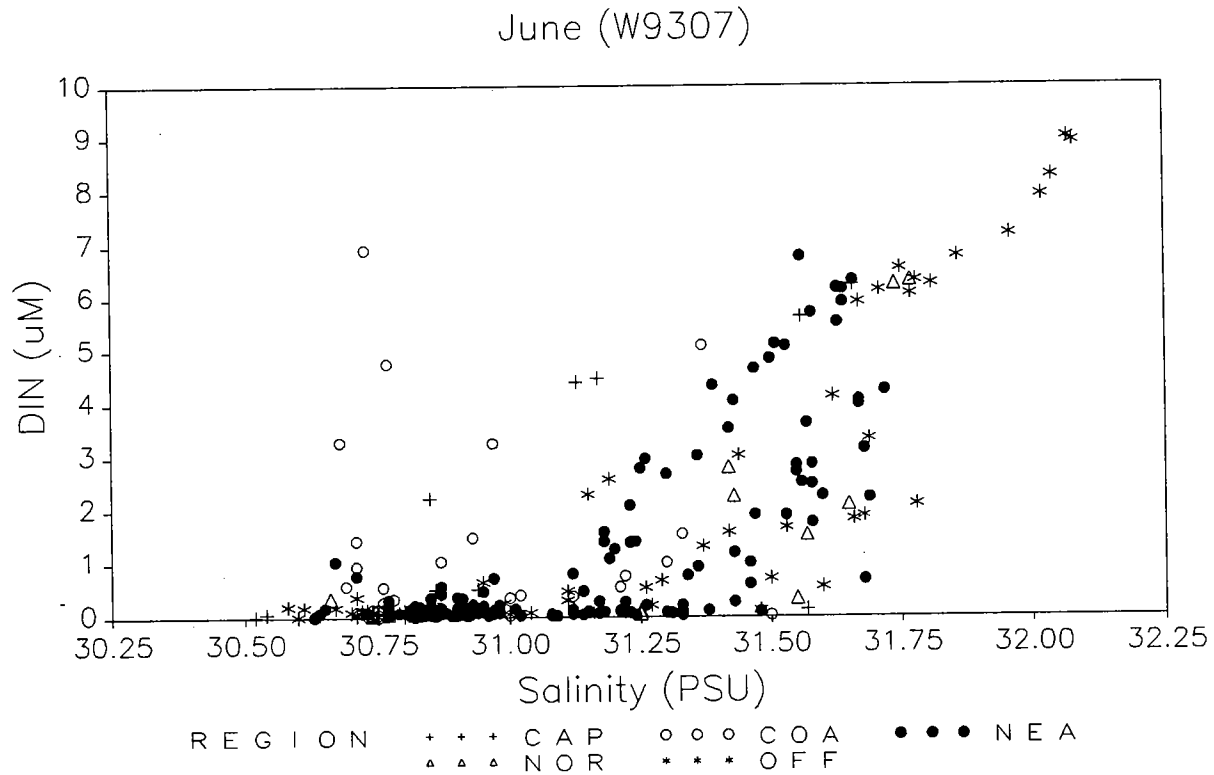
Figure 3-19.   **Dissolved inorganic nitrogen vs. salinity in June 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.**
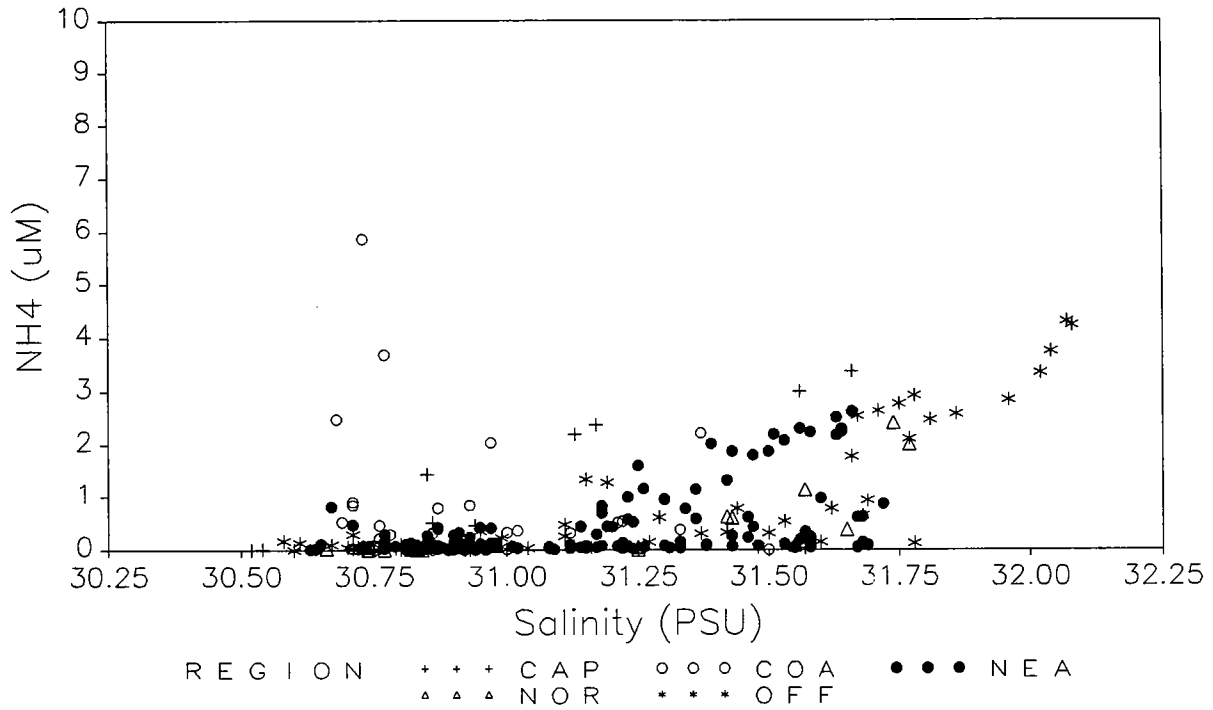
Figure 3-20. Ammonia and nitrate vs. salinity in June 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

June (W9307)
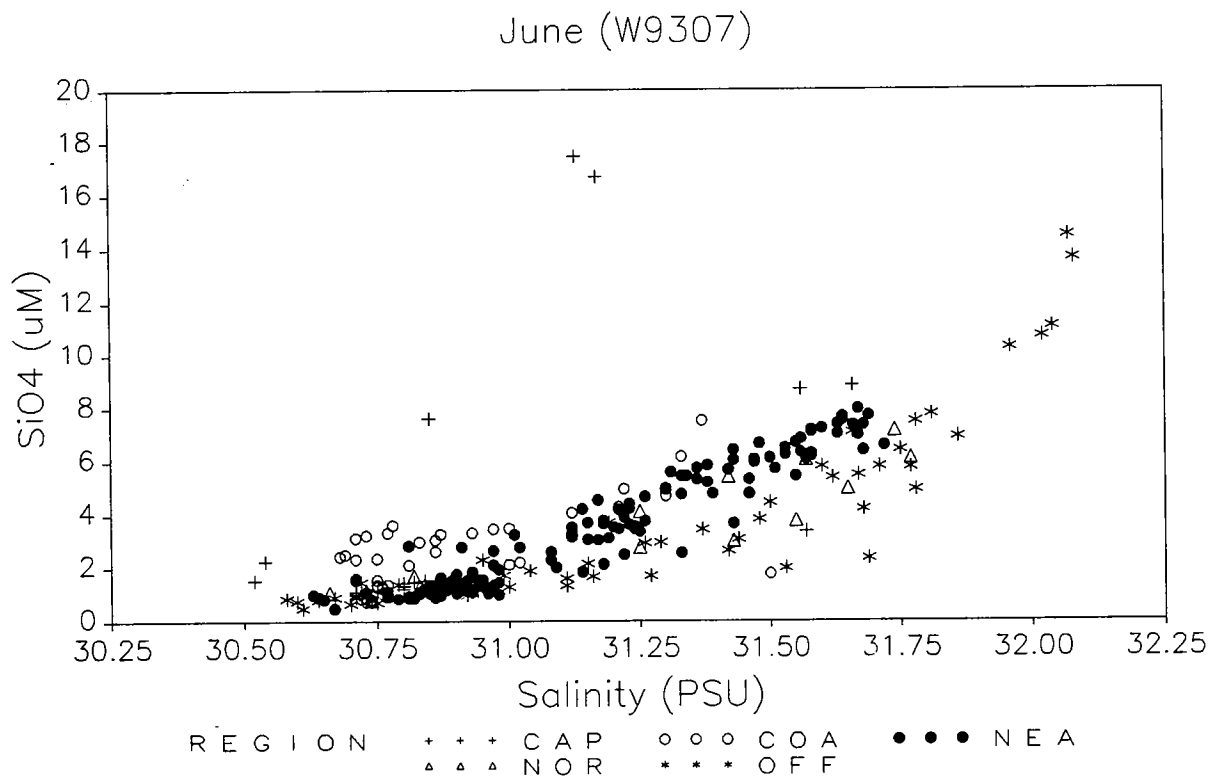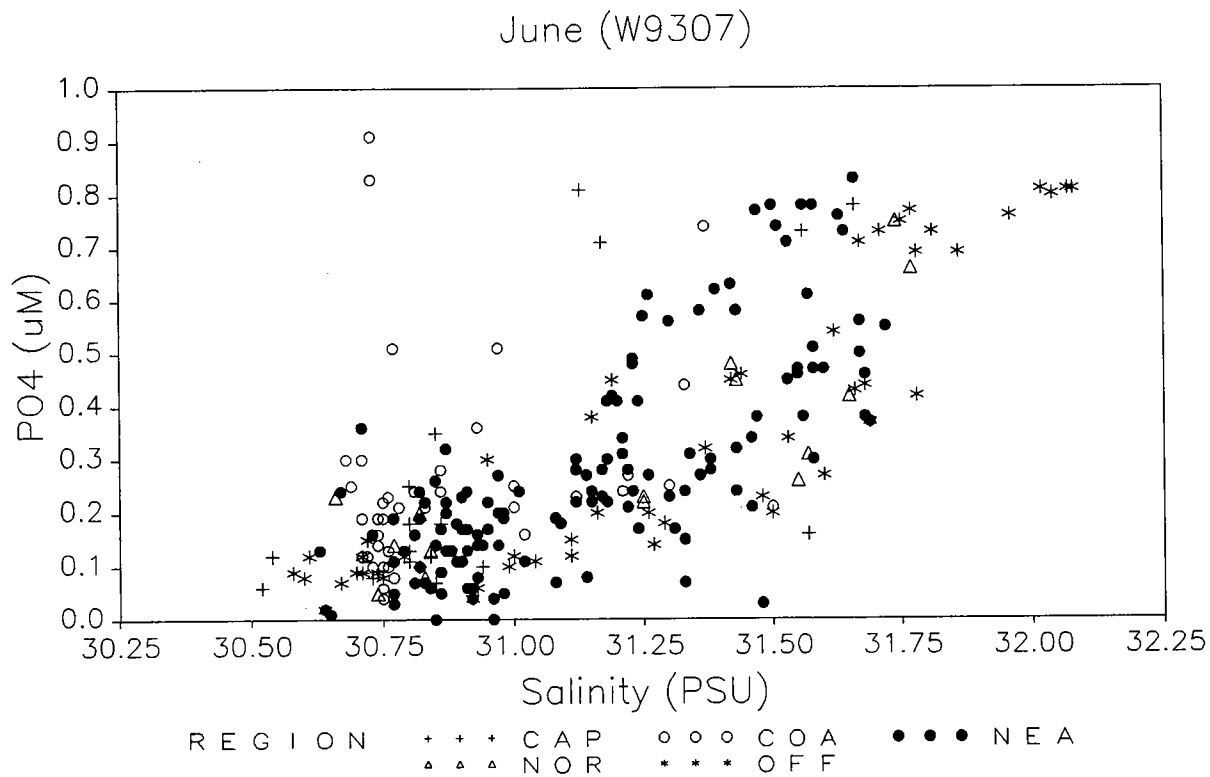
June (W9307)

Figure 3-21. Phosphate and silicate vs. salinity in June 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

June (W9307)

REGION + + + CAP   o o o COA   ● ● ● NEA
         △ △ △ NOR   * * * OFF

June (W9307)

REGION + + + CAP   o o o COA   ● ● ● NEA
         △ △ △ NOR   * * * OFF
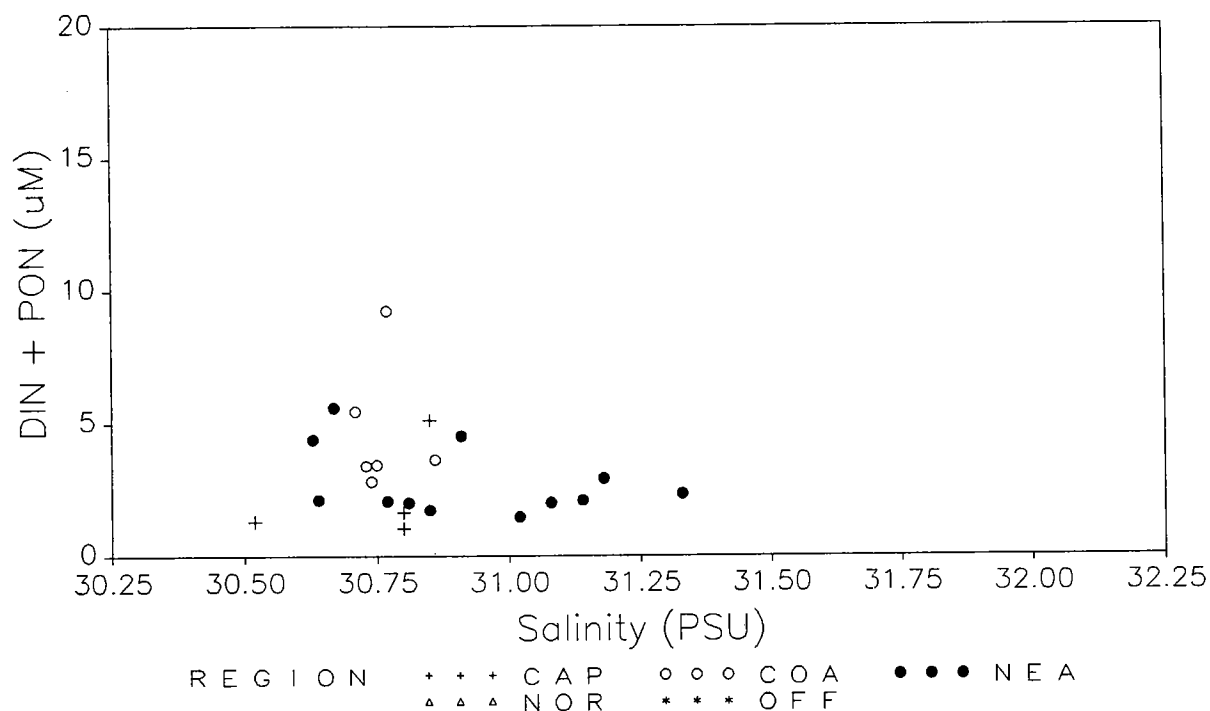
Figure 3-22. Nitrogen forms vs. salinity in June 1993. Data are from BioProductivity stations and special station F25. The station groups are coded as given in Figure 3-16; there are no BioProductivity stations in the offshore or northern transect groups. Data are given in Appendix A. Dissolved inorganic nitrogen = DIN, Particulate organic nitrogen = PON, total nitrogen (TN) = total dissolved nitrogen (TDN) + PON. The regions correspond to three of the groups of stations shown in Figure 3-16.

Figure 3-23. Chlorophyll (extracted samples) at BioProductivity stations and special station F25 as a function of depth in June 1993. Data are from farfield (n=22) and nearfield (n=12) surveys. The regions correspond to three of the groups of stations shown in Figure 3-16.
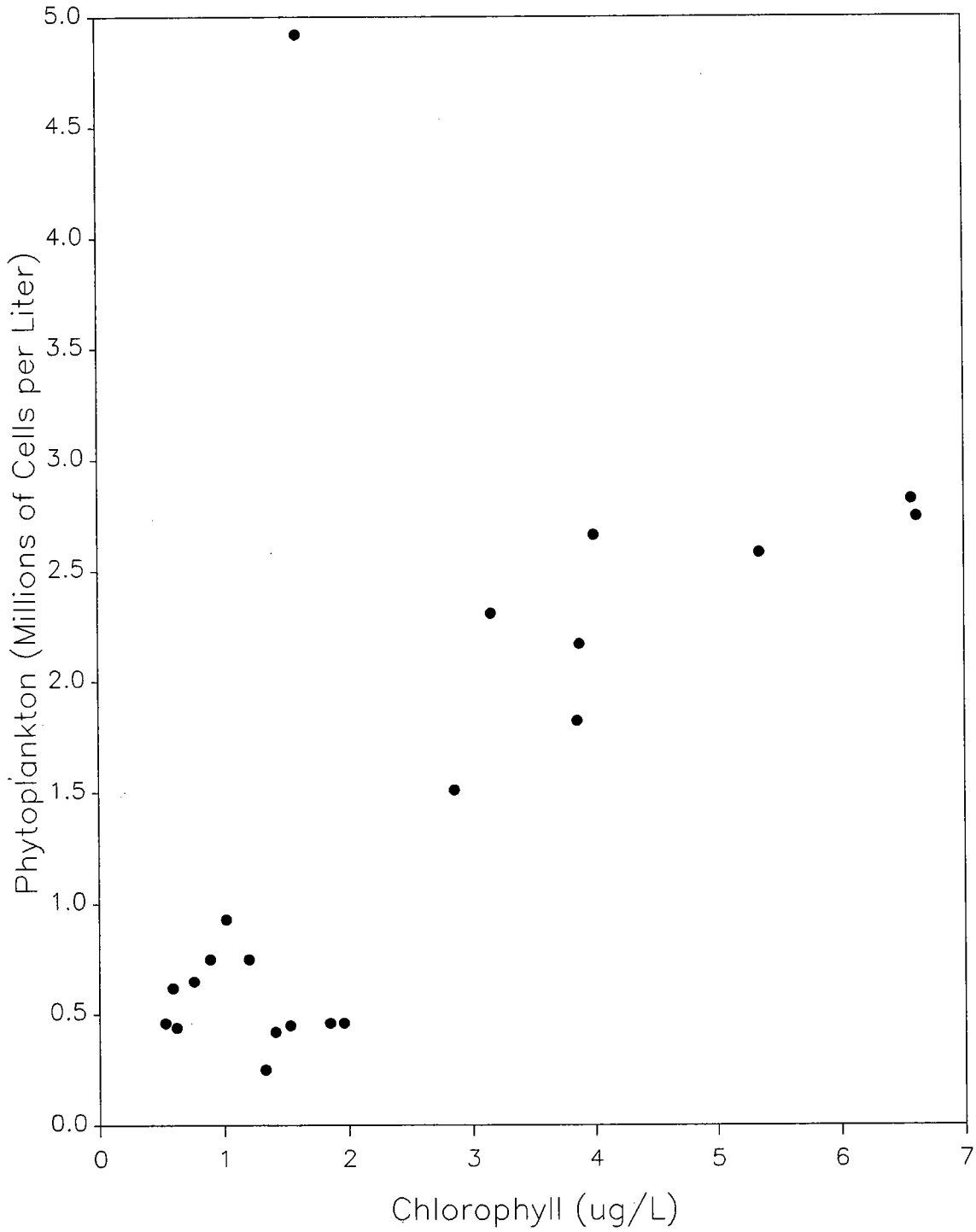
Figure 3-24. Total phytoplankton abundance vs. chlorophyll (extracted samples) at BioProductivity stations in June 1993. Station N10P surface was analyzed for both farfield and nearfield surveys. Data are given in Appendices A and F.
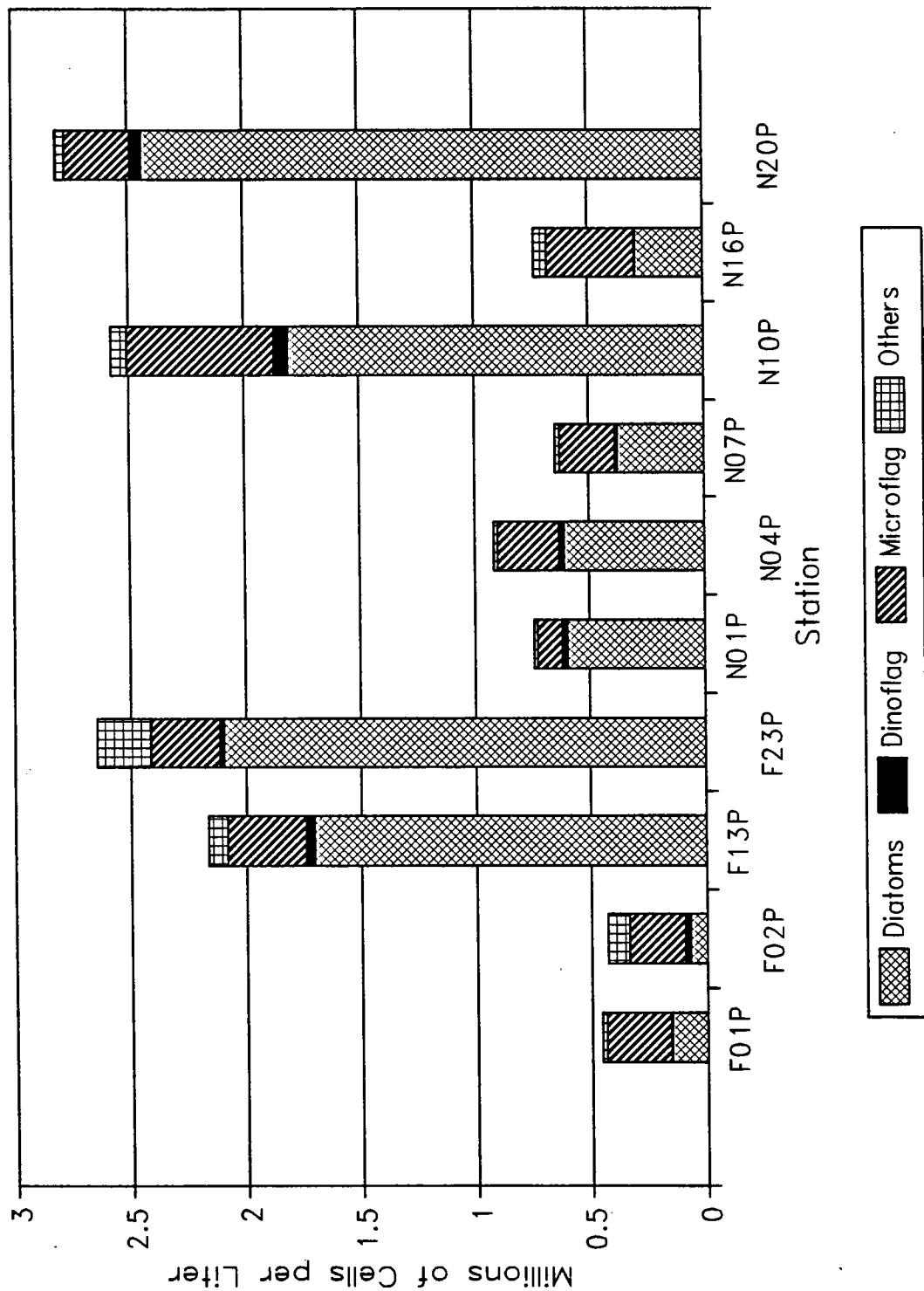
Figure 3-25a. Total phytoplankton abundance, by taxonomic groups, at the surface of BioProductivity stations in June 1993. Data are given in Appendix F.
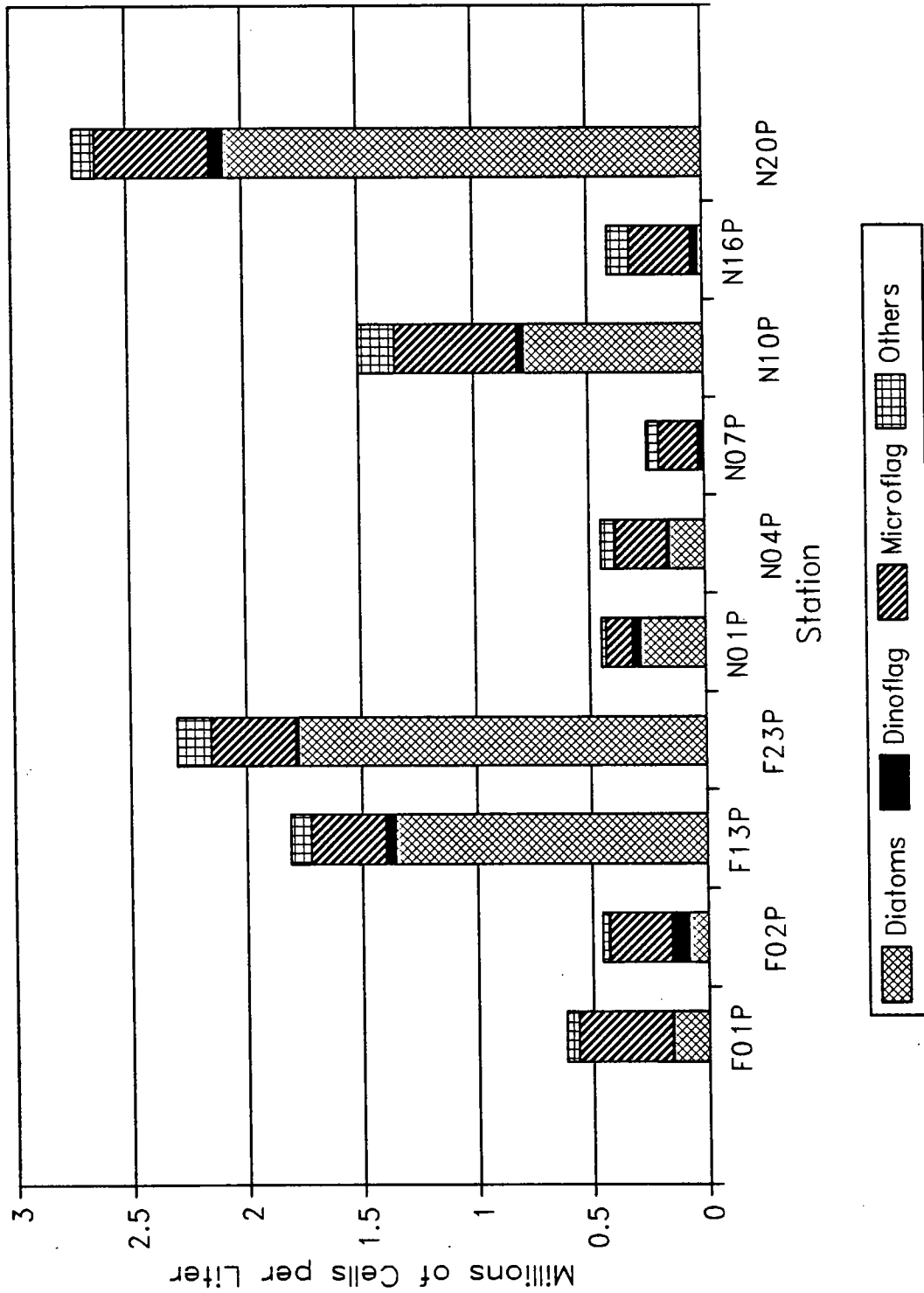
Figure 3-25b. **Total phytoplankton abundance, by taxonomic groups, at the chlorophyll maximum at BioProductivity stations in June 1993. Data are given in Appendix F.**
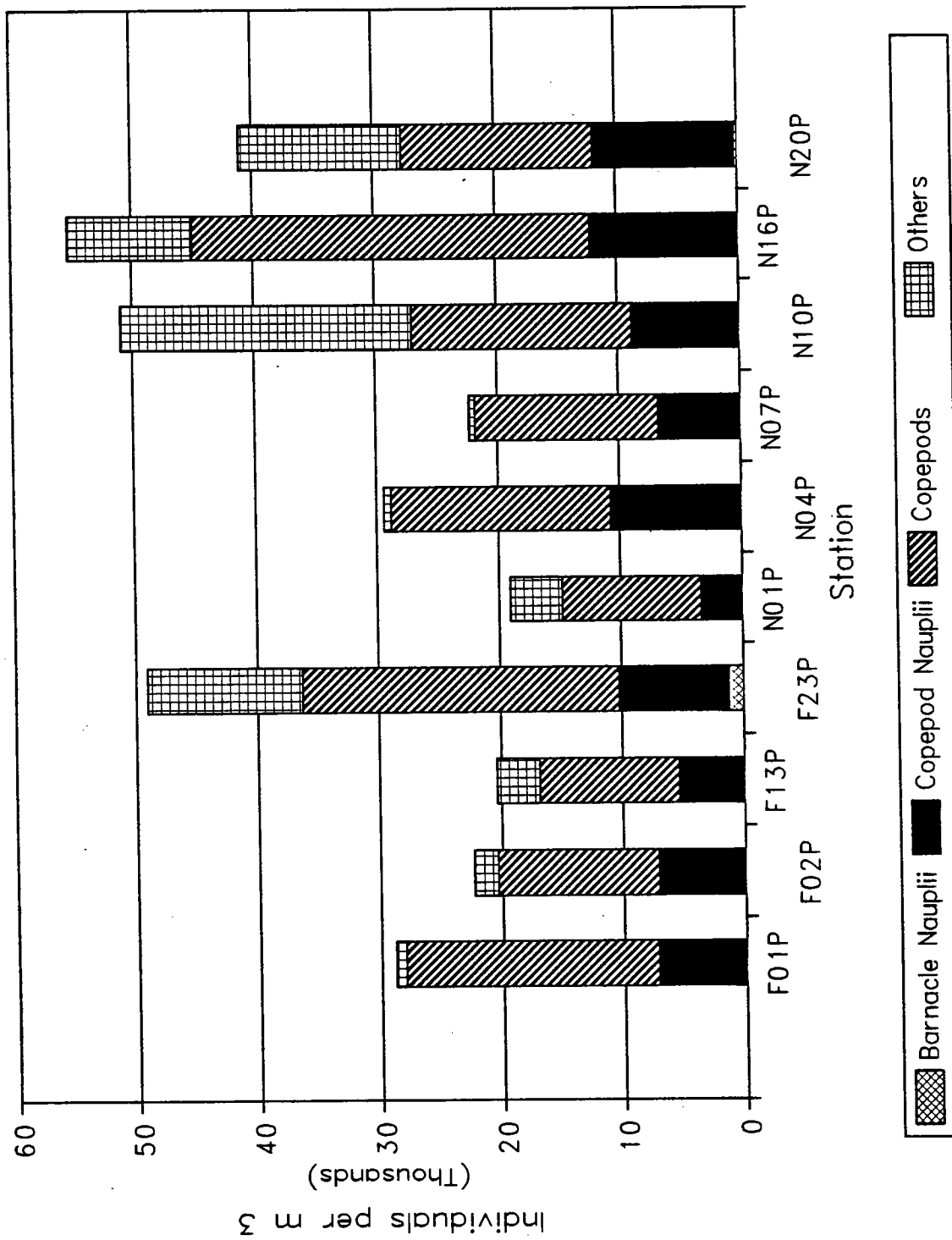
Figure 3-26. Zooplankton abundance, by groups, at BioProductivity stations in June 1993. Data are given in Appendix G.
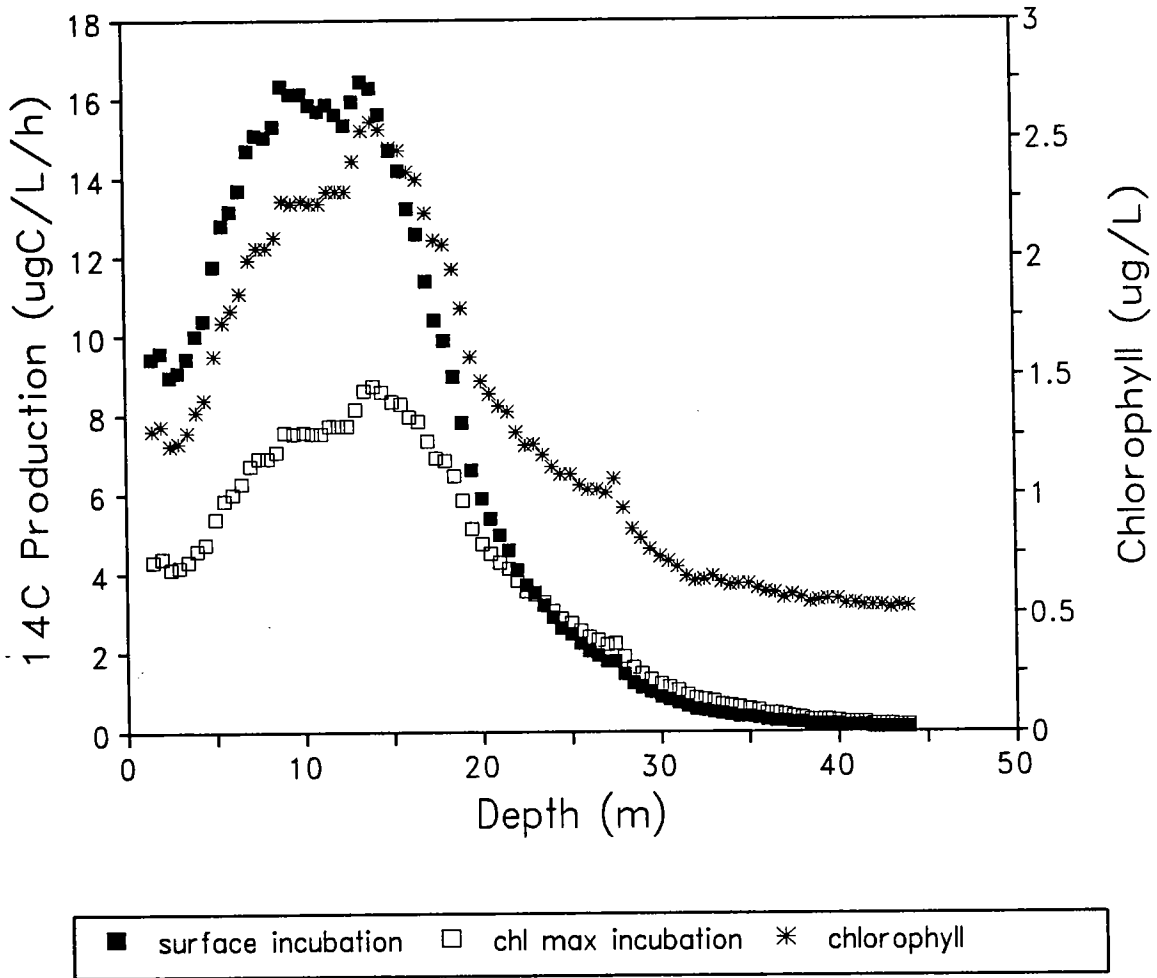
Figure 3-27a. Modeled volumetric net production and measured fluorescence (as chlorophyll) over depth at Station N04P in June 1993 is based upon P-I curves for samples taken at about 2.1 m (surface incubation) and 14 m (chl max incubation) on the upcast. The chlorophyll profile is based on fluorescence readings from the downcast.
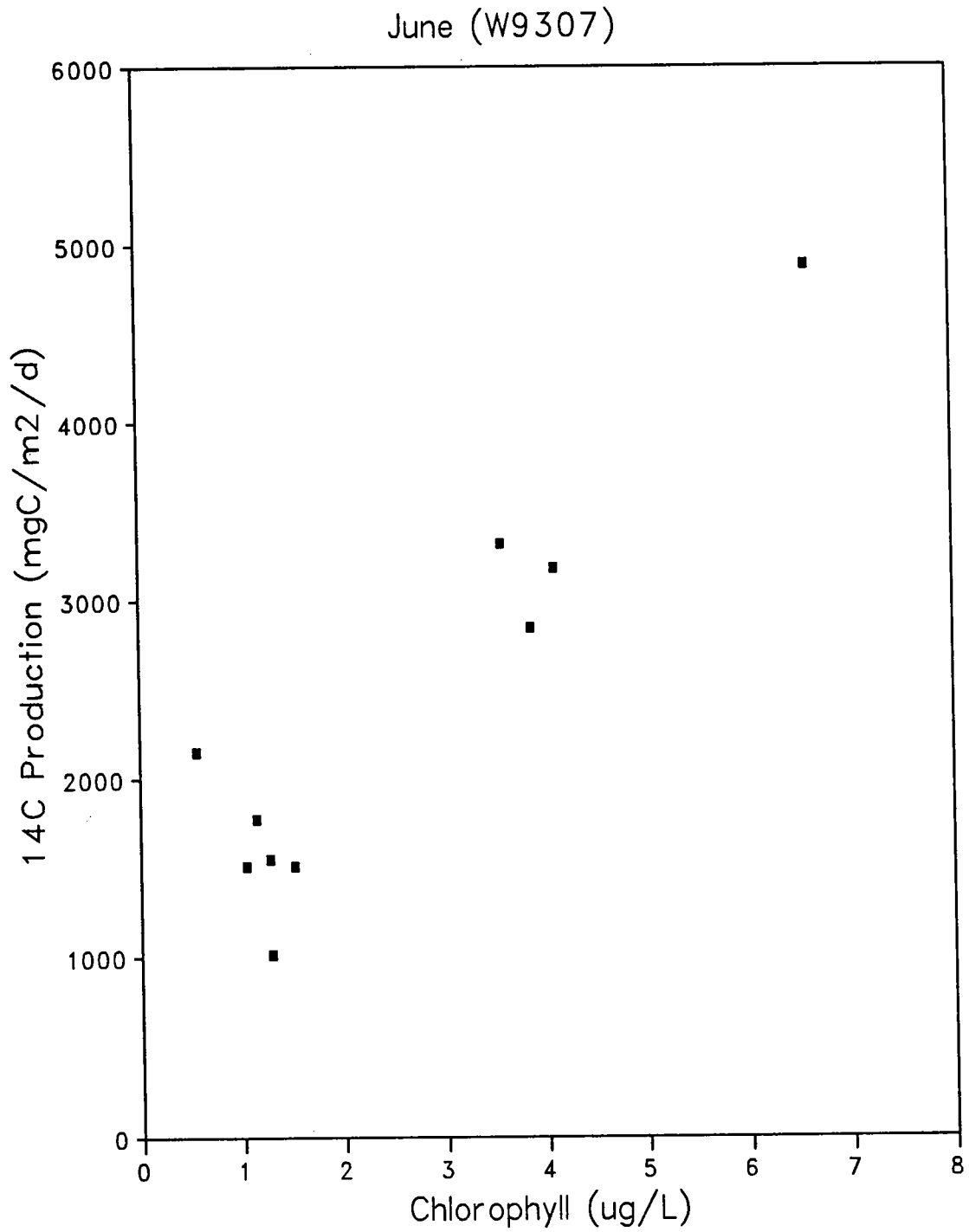
Figure 3-27b. Integrated water column production (mean of surface and chl max incubations) relative to chlorophyll (mean of surface and chl max sample extractions).
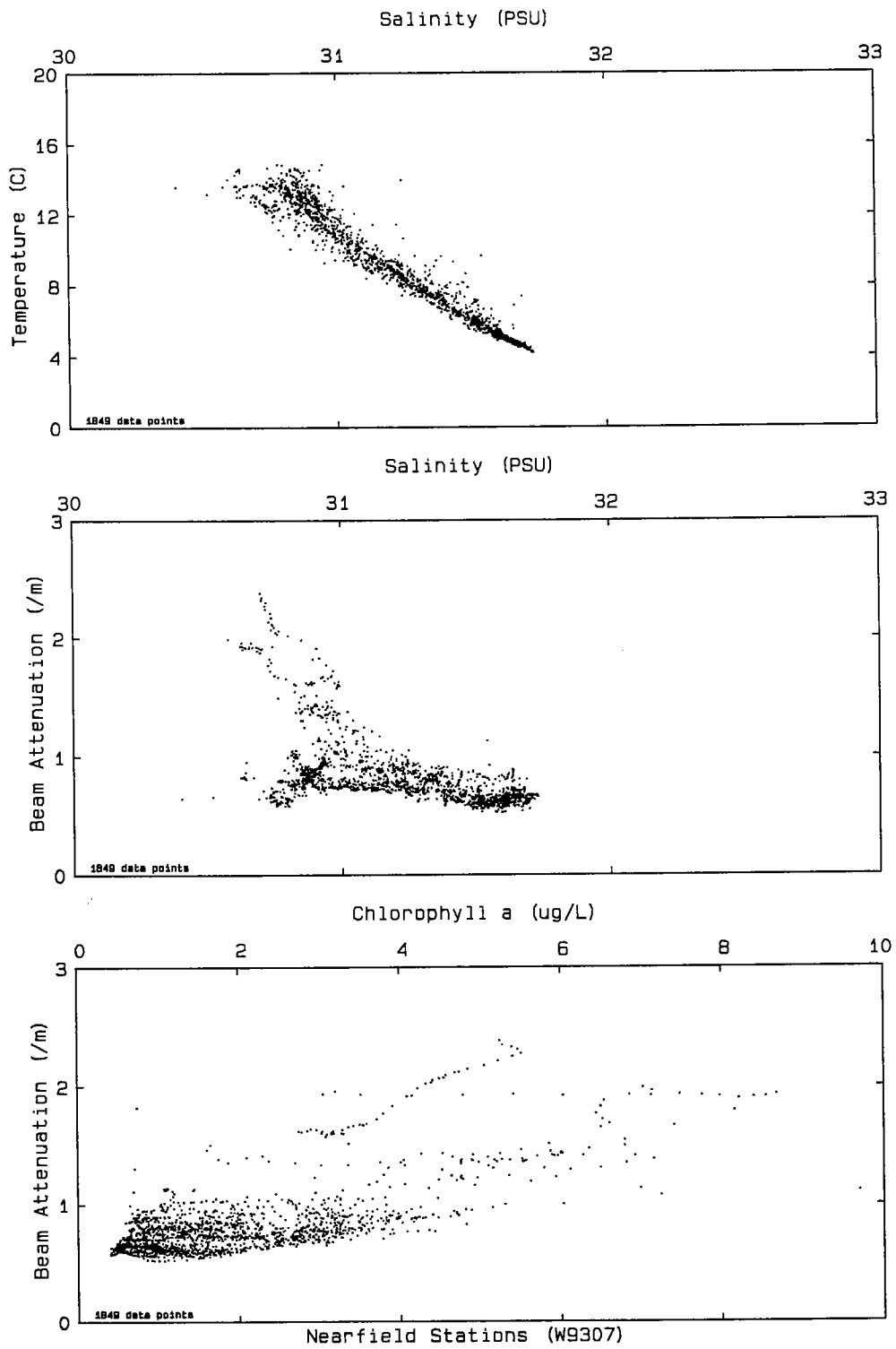
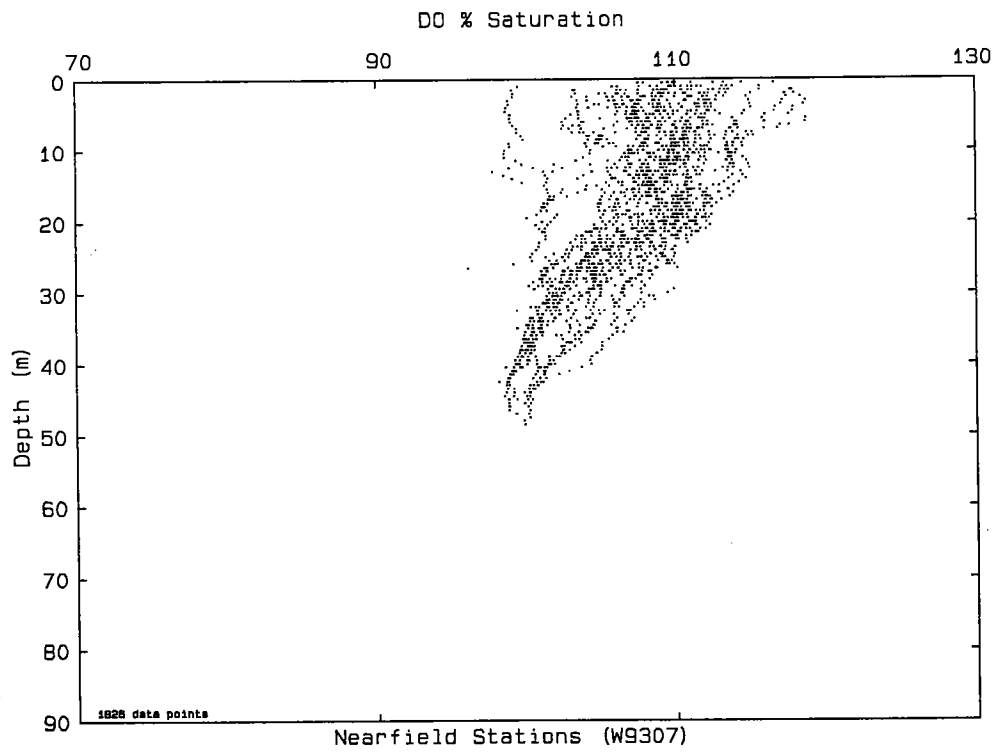Figure 3-28a. Scatter plots for nearfield stations in June. Compare to Figure 3-15a.
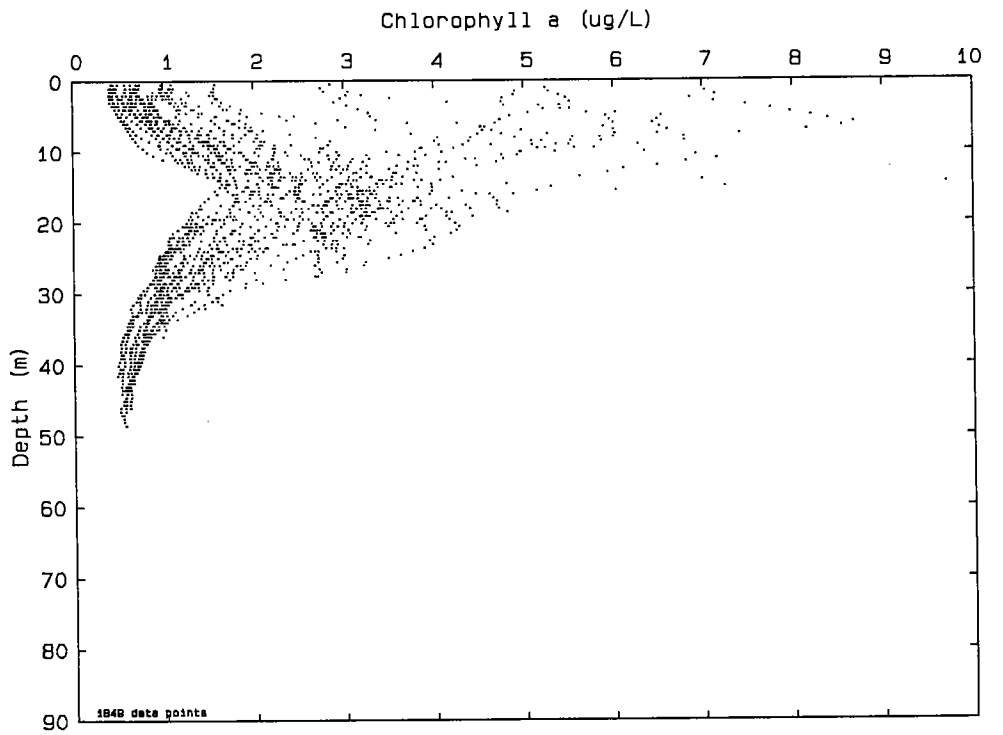
Figure 3-28b. Scatter plots for nearfield stations in June. Compare to Figure 3-15b.
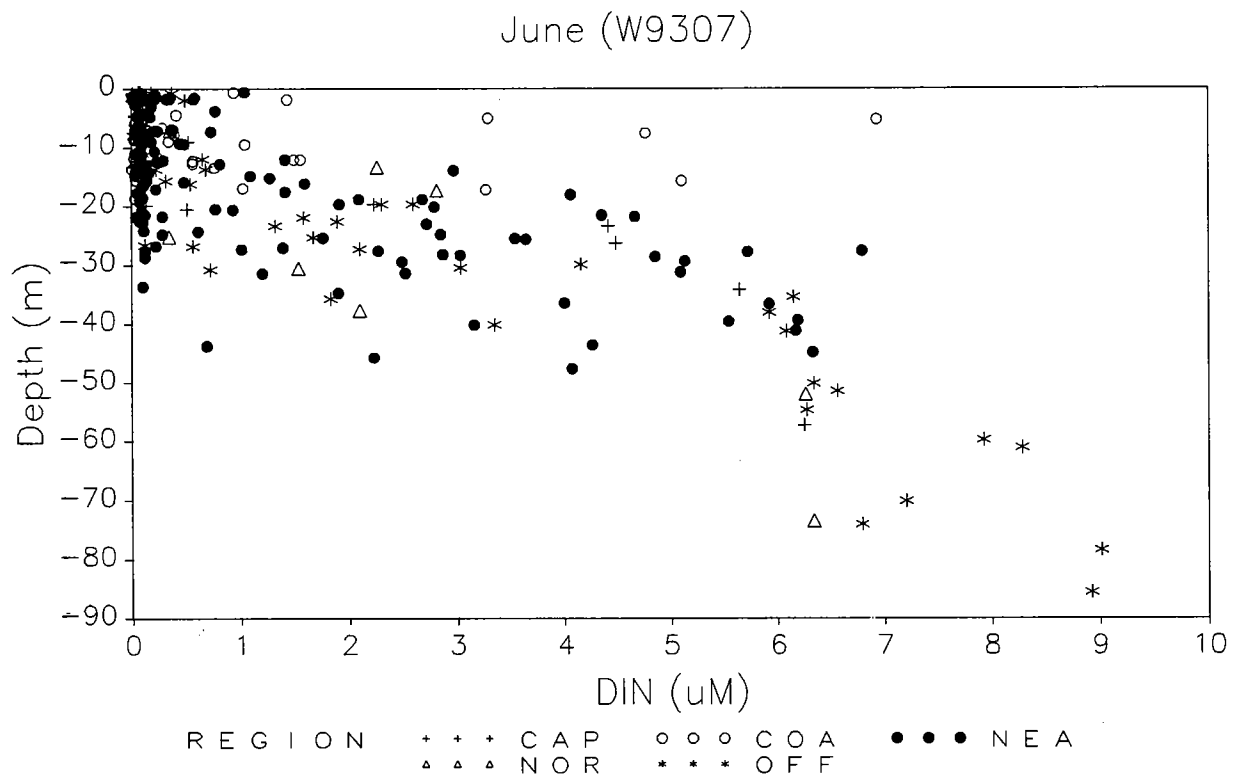
Figure 3-29a. DIN vs. depth in June 1993. The regions correspond to the groups of stations shown in Figure 3-16.
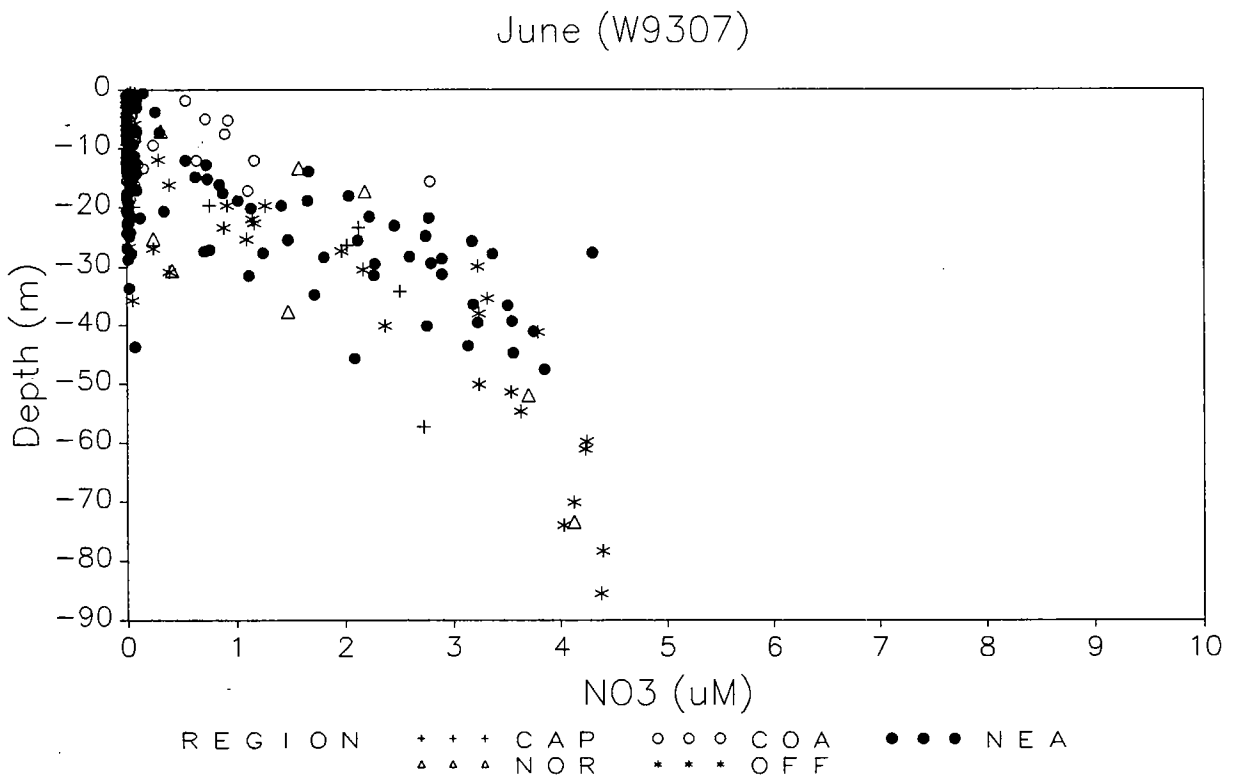
June (W9307)

REGION   + + + C A P   o o o C O A   ● ● ● N E A
                        △ △ △ N O R   * * * O F F

June (W9307)

REGION   + + + C A P   o o o C O A   ● ● ● N E A
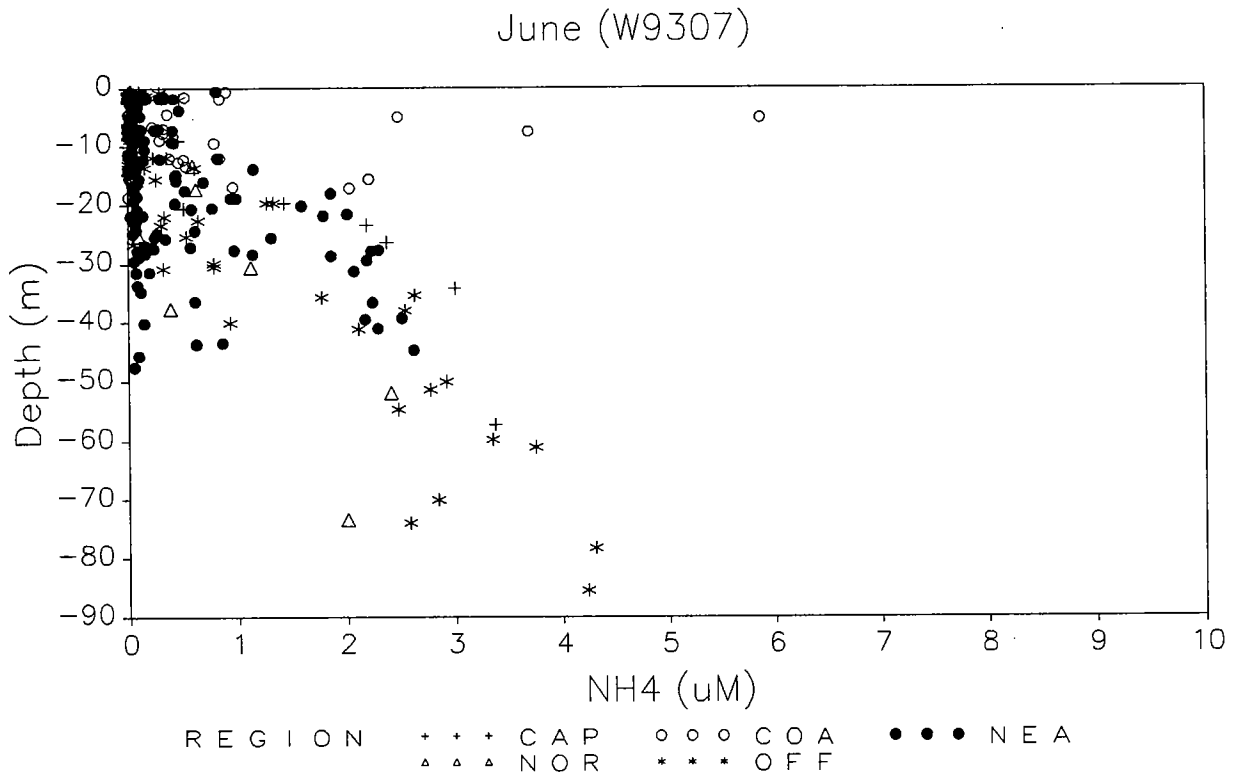   △ △ △ N O R   * * * O F F

Figure 3-29b. NH$_4$ and NO$_3$ vs. depth in June 1993. The regions correspond to the groups of stations shown in Figure 3-16.
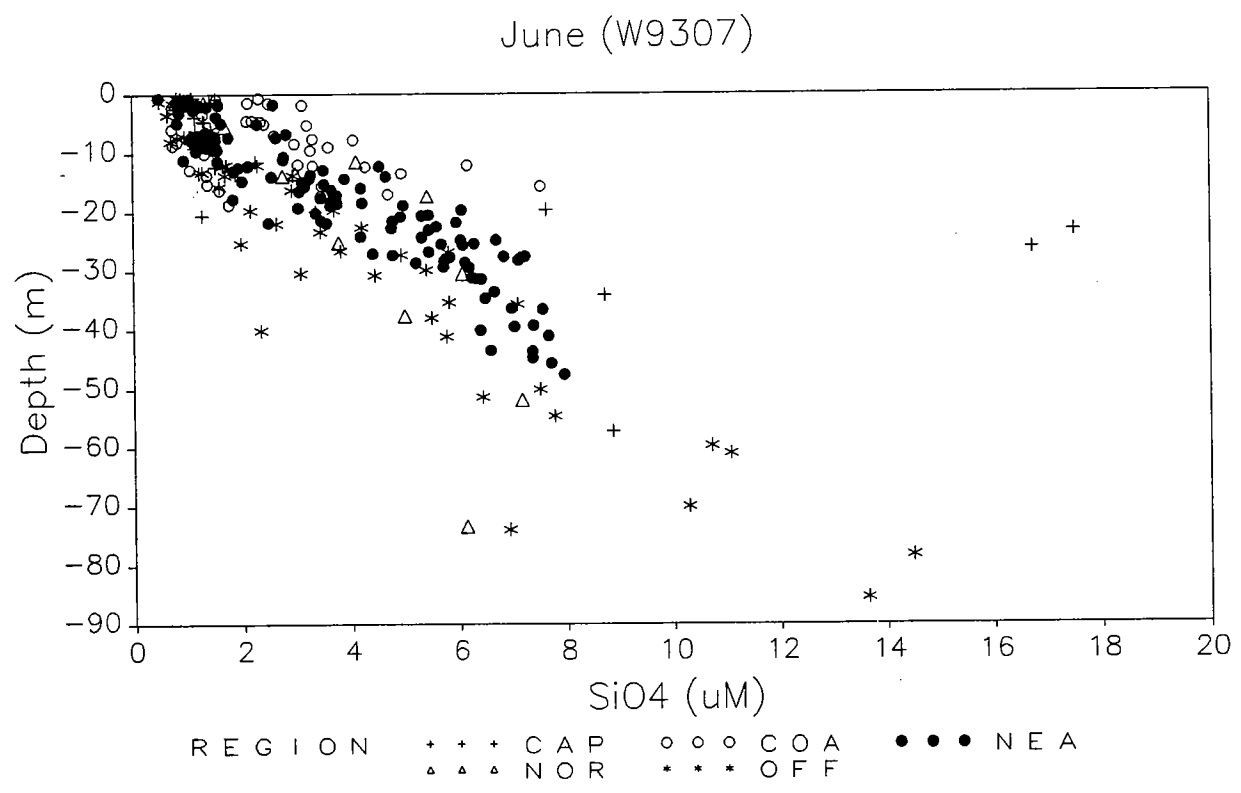
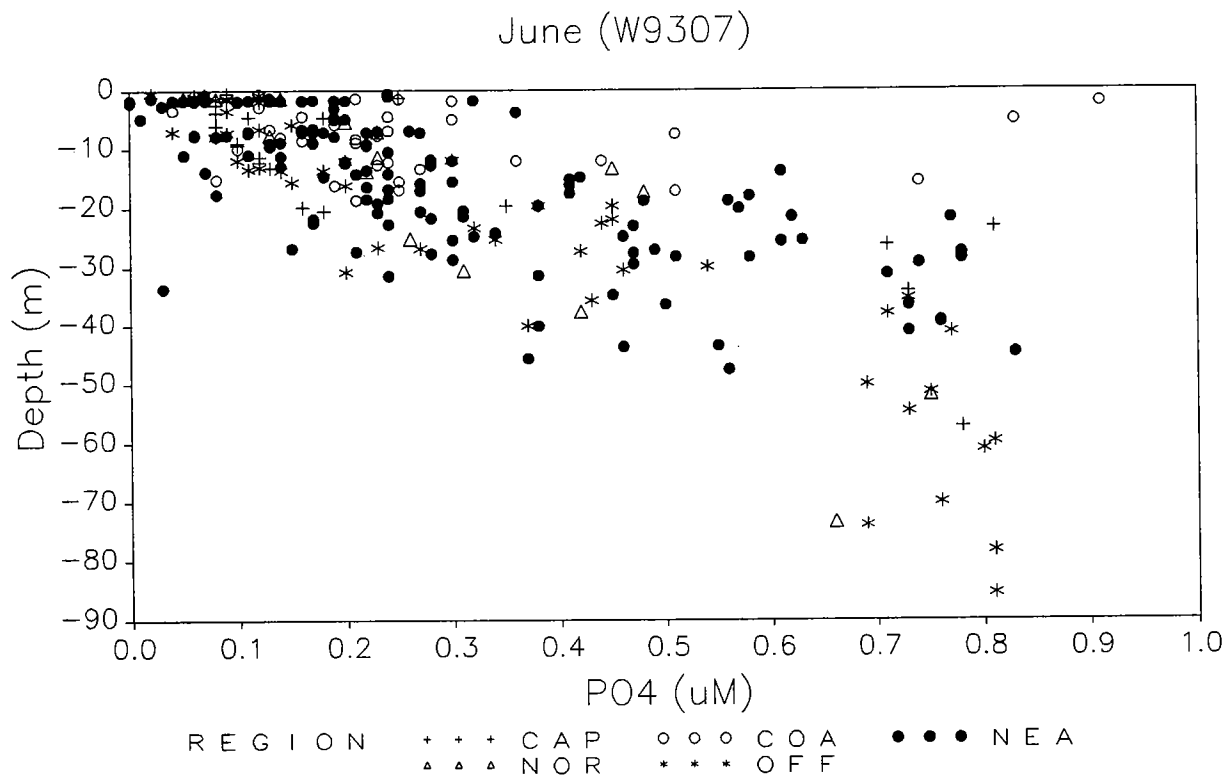Figure 3-29c. PO_4 and SiO_4 vs. depth in June 1993. The regions correspond to the groups of stations shown in Figure 3-16.

Figure 3-30a. Vertical section contours of temperature generated for tow-yo profiling conducted in June 1993. The view is towards the north.

Figure 3-30b. Vertical section contours of temperature generated for tow-yo profiling conducted in June 1993. The view is towards Boston Harbor.
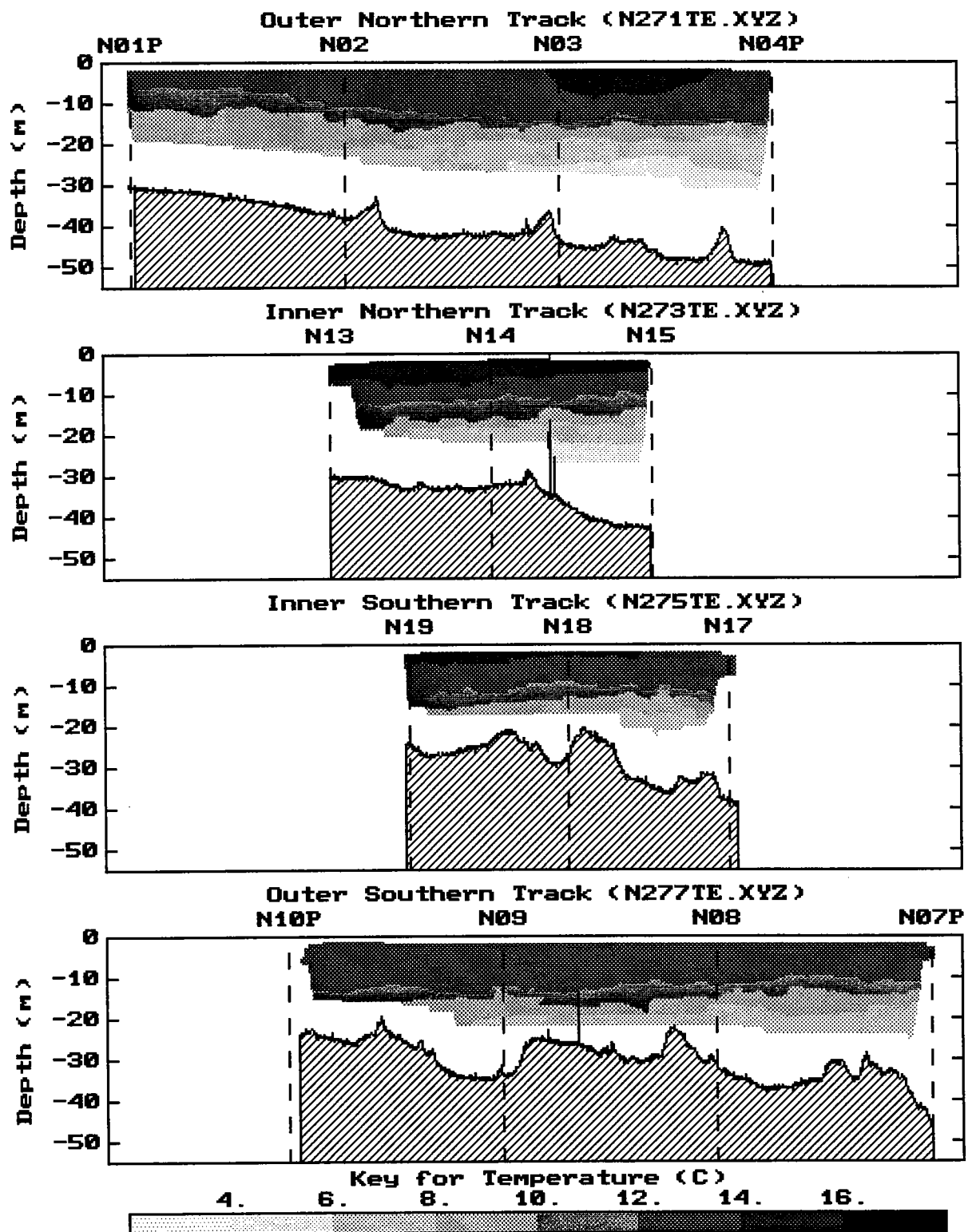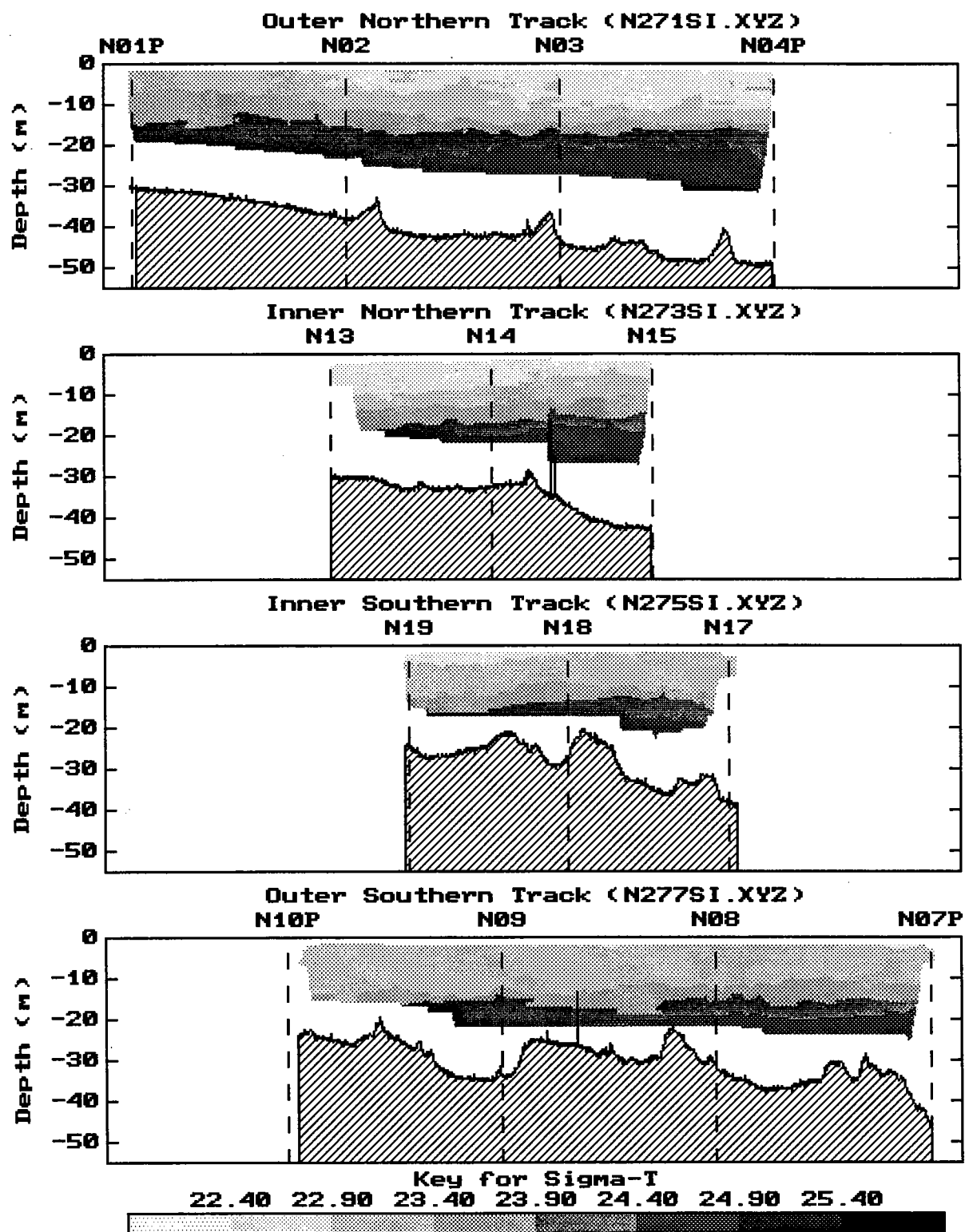
Figure 3-31a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in June 1993. The view is towards the north.
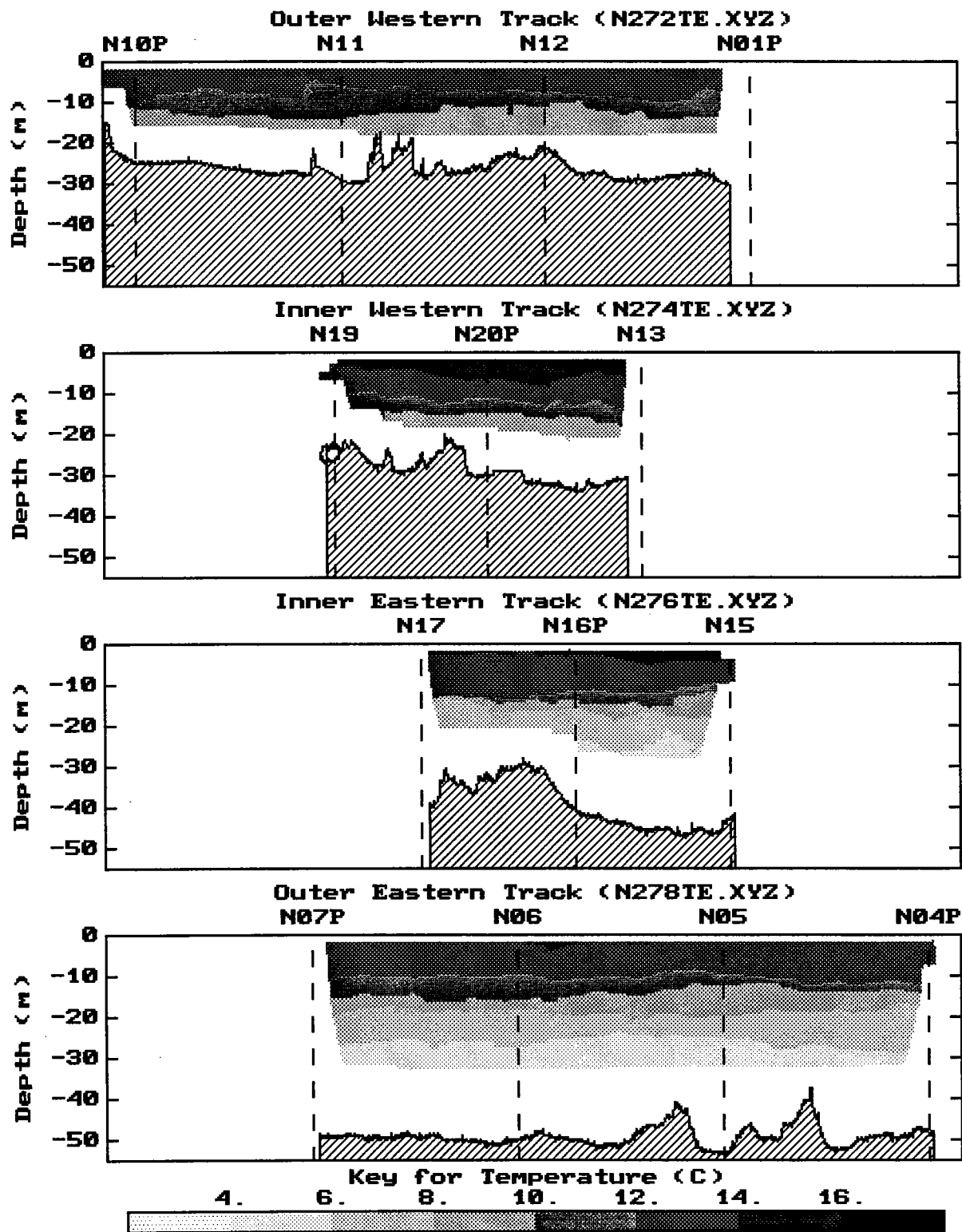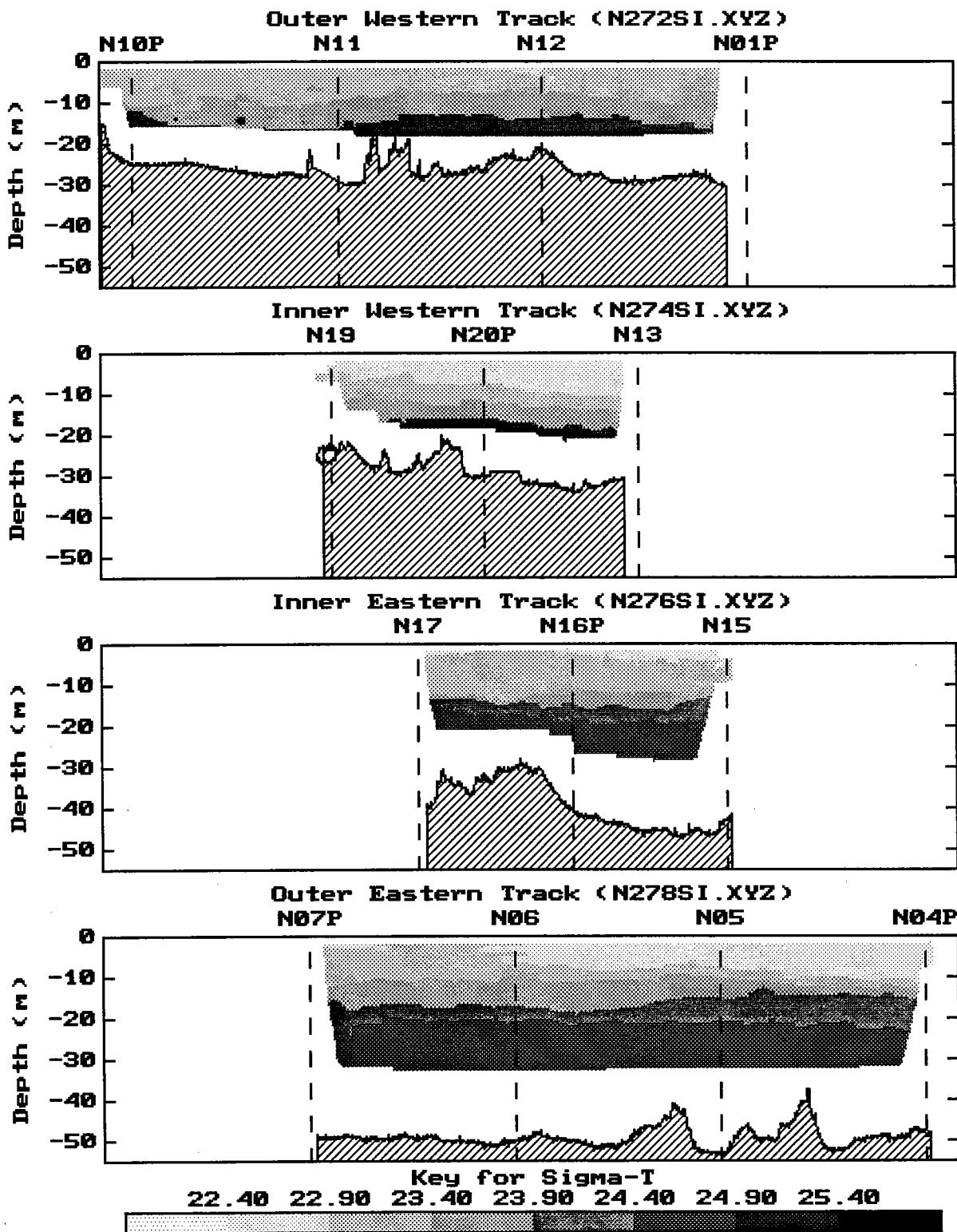
Figure 3-31b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in June 1993. The view is towards Boston Harbor.

Figure 3-32a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in June 1993. The view is towards the north.

Figure 3-32b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in June 1993. The view is towards Boston Harbor.
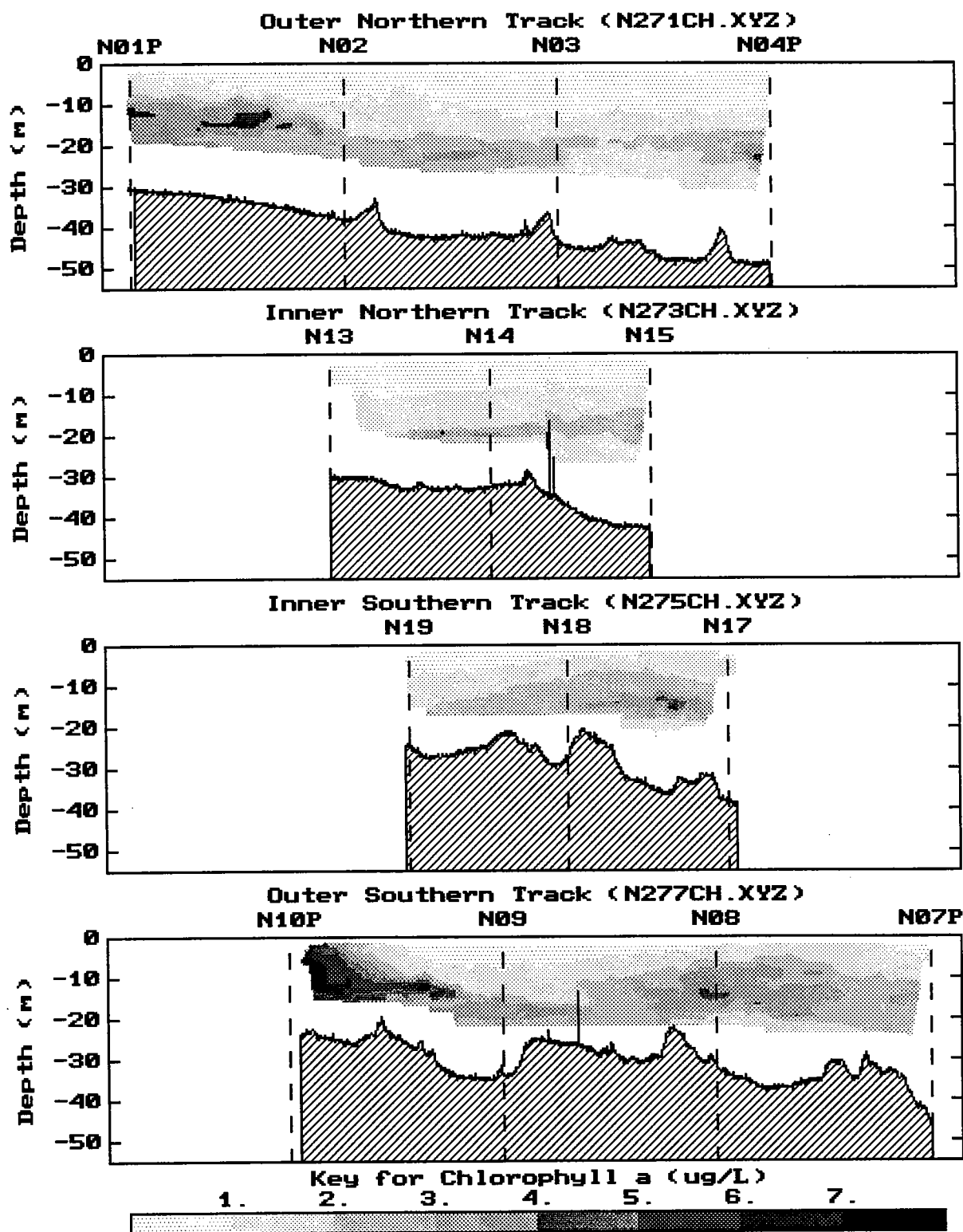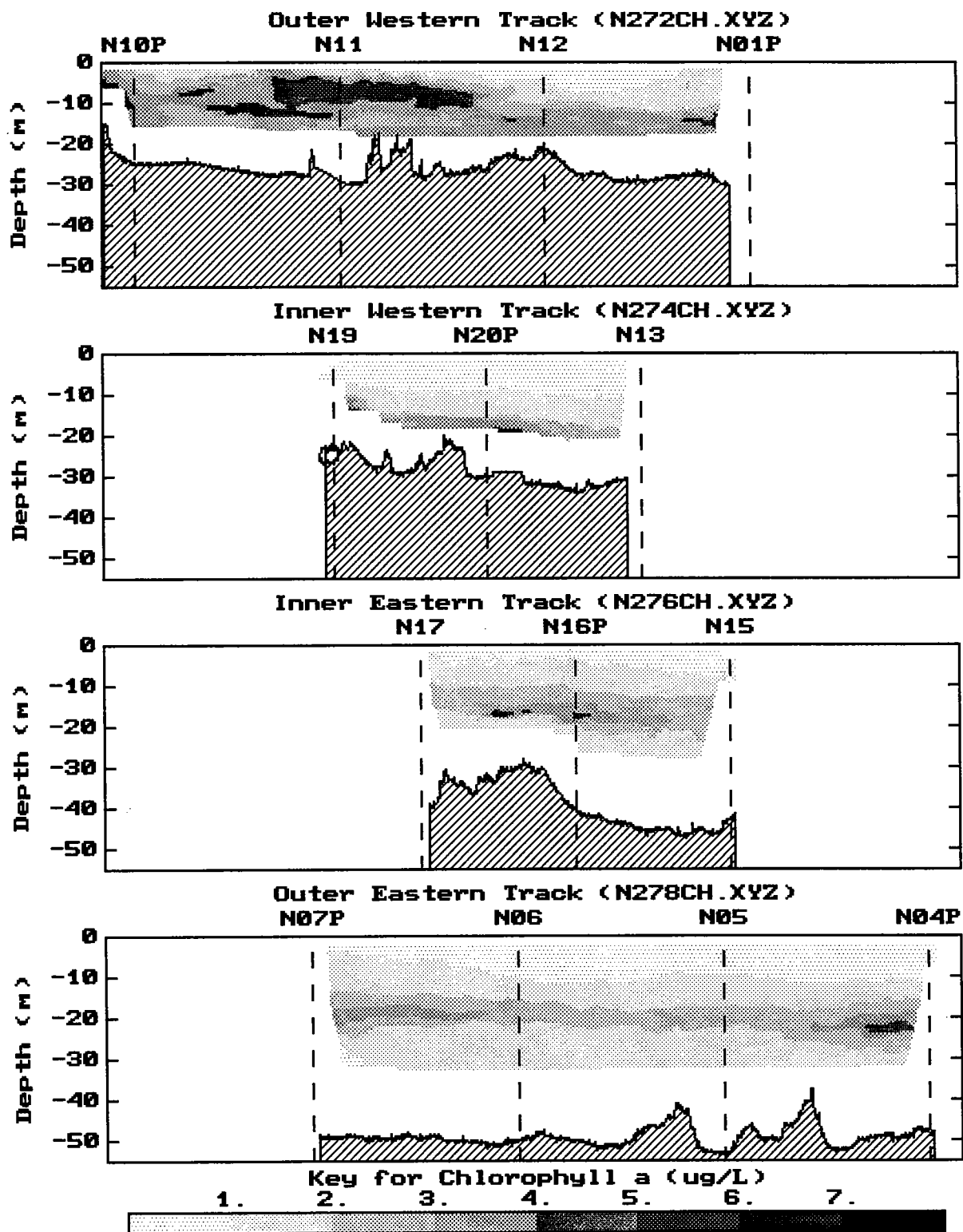
4.0 RESULTS OF EARLY JULY 1993 NEARFIELD SURVEY (W9308)

4.1 Distribution of Water Properties from Vertical Profiling

Scatter plots using *in situ* sensor data are shown in Figure 4-1 and profiles for all twenty-one stations are given in Appendices A and B. The T-S plot was similar to that obtained in June (only two weeks earlier) in the relative coherence across stations, but the range from surface to bottom for temperature had expanded considerably (about 4 to over 19 °C). Concomitantly, the salinity range narrowed: low surface values were about 30.8 PSU and deepest waters were about 31.6 PSU.

As in June, a few stations had higher surface chlorophyll (and turbidity), but most had chlorophyll less than 2 μg L^{-1}. The deep chlorophyll maximum was generally at about 20-25 m and chlorophyll concentrations above 2 μg L^{-1} were found only in the surface layer. DO showed a mid-water peak in saturation that was slightly above the chlorophyll maximum and values throughout the water column were about 94% saturation or higher.

The vertical distribution of DIN still reflected a strongly stratified system, with low or undetectable concentrations in the top 15 m and generally increasing concentrations with increasing depth (Figure 4-2). Bottom water DIN reached values of about 5-6 μM by 40 m, which was similar to June. NH$_4$, NO$_3$, and PO$_4$ concentrations over depth also were very similar to the previous June survey. Silicate was similar to June in terms of bottom water concentrations (6-8 μM), but the surface concentrations generally seemed to have increased by 1-2 μM in early July (Figure 4-2). Again, there was virtually no pattern of nutrients with the small (1.5 PSU) variability in salinity in near surface samples, although the increase in nutrients with depth created a relationship of increasing nutrient concentration with increasing salinity (Figures 4-3 and 4-4).

4.2 Distribution of Water Properties from Towing

The tow-yo survey again revealed a strong and uniform thermal layering (Figure 4-5). Surface water was slightly warmer offshore, the surface layer being thicker and extending to a more uniform depth (Figure 4-6). Generally, a distinct bottom water layer started at about 20-25 m, which marked the bottom of the pycnocline.

As seen previously, high surface layer chlorophyll ($>4 \mu g \, L^{-1}$) was regularly found along the western track (stations N10P to N01P) and occasionally near the middle of the field (e.g. stations N19-N20P) as more isolated patches (Figure 4-7). Only deep subsurface chlorophyll maxima were found elsewhere and in fact these appeared to be below the pycnocline in most of the eastern half of the nearfield. Peaks there were found at 30-40 m; this depth approximates the 0.5 to 1% isolume that was determined on the vertical profile day for the eastern stations, as can be seen in profile plots in Appendix B.

An interesting feature in Figure 4-7 is the discontinuity between the layer of chlorophyll on the shallower western side and deeper eastern side of the field. Each side has a somewhat continuous layer. But the two layers do not join smoothly or follow the gradual change in the pycnocline but, rather, appear to abruptly shift (e.g. see station N09 in Figure 4-7a) from near the top of the pycnocline to well below it. The other interesting feature is that the chlorophyll distribution seems to be patchy mostly at the scale of kilometers, so the features are rather large and often stretch the distance from one vertical station to another (over 3 km).

4.3 Water Types and Analysis of Small-Scale Variability

The data for early July again suggest a relatively uniform field with minor physical variability horizontally and strong stratification being the governing feature. There were no geographic distinctions for nutrients, but there was an obvious gradient from inshore to offshore in chlorophyll, both in terms of peak concentrations and the vertical distribution of concentrations.

In terms of time-variability, the only feature of note was an apparent deepening, offshore, in the subsurface chlorophyll maximum layer between days. This can be seen in comparing Figure 4-1b to 4-7 and also reviewing Appendix B. Maximum concentrations were generally between 2 and 3 μg L^{-1} in both cases, but on the second day the chlorophyll concentration was distinctly lower and there was not a sharp peak in the pycnocline as had been seen the day before (Appendix B). Whether this change represents fallout of chlorophyll, migration, or cell buoyancy change in the phytoplankton cannot be determined.

Figure 4-1a. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in early July 1993. Individual station casts that were used to produce this composite are included in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.

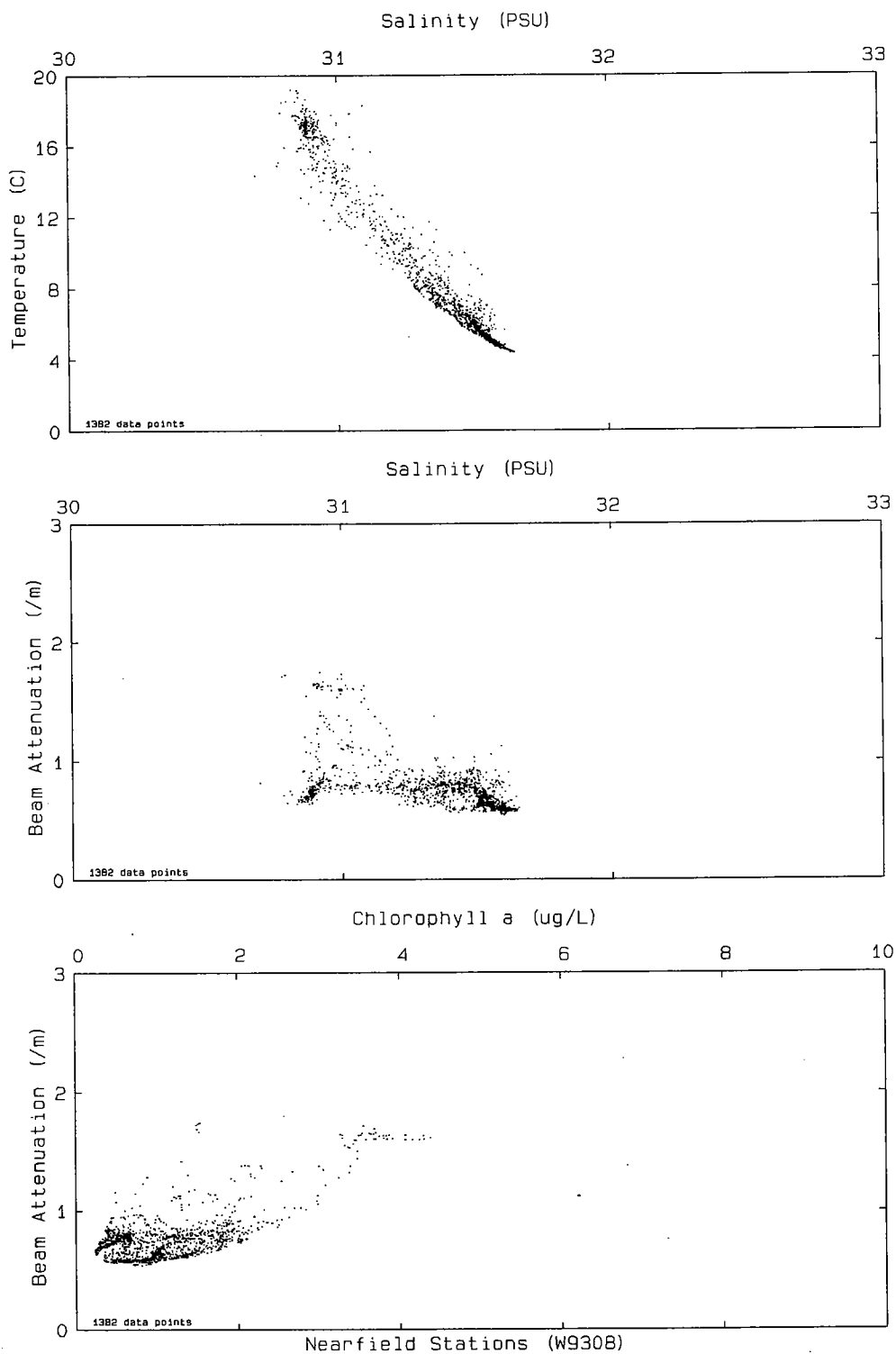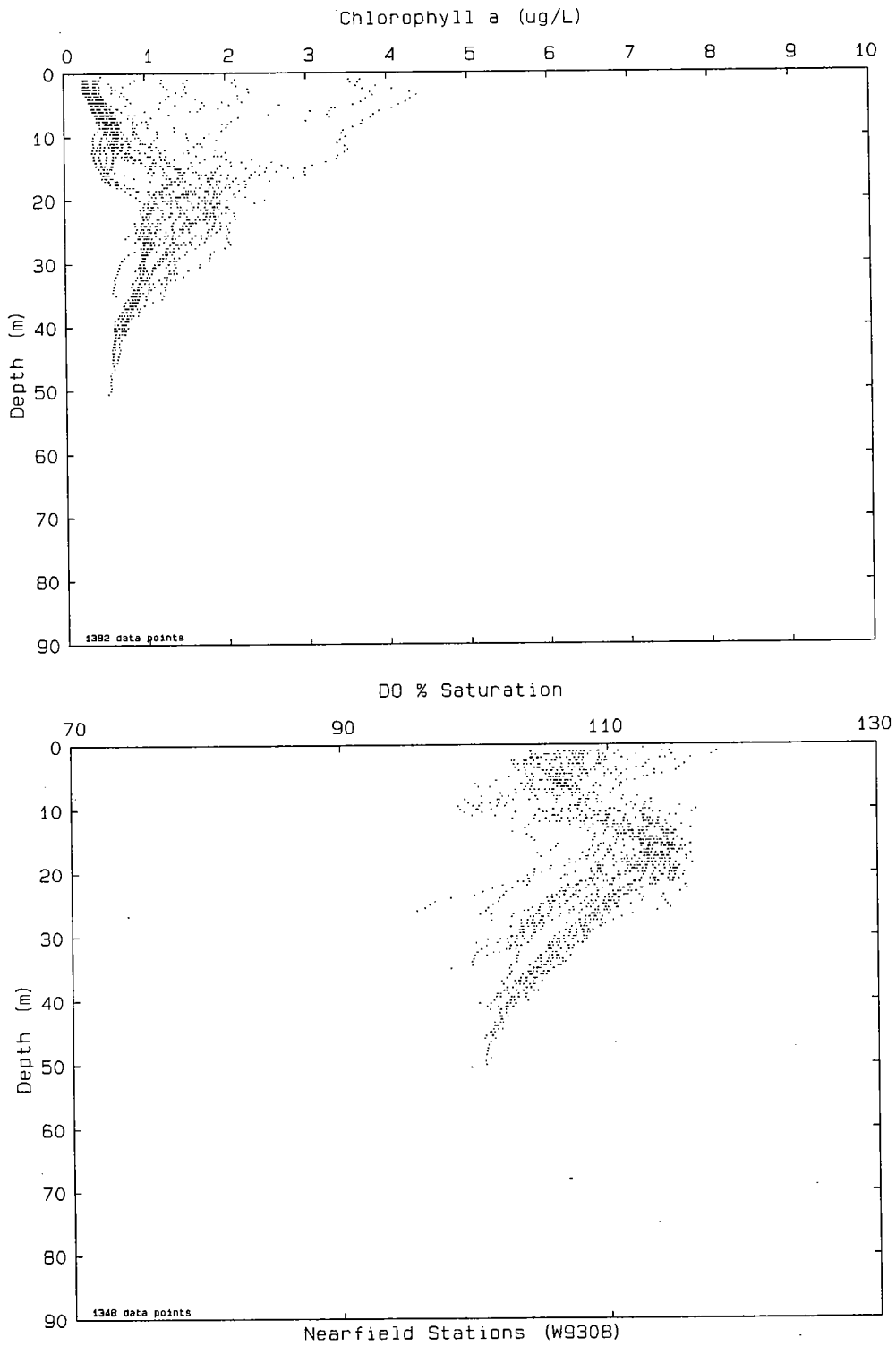**Figure 4-1b.** Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in early July 1993. Individual station casts that were used to produce this composite are included in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.
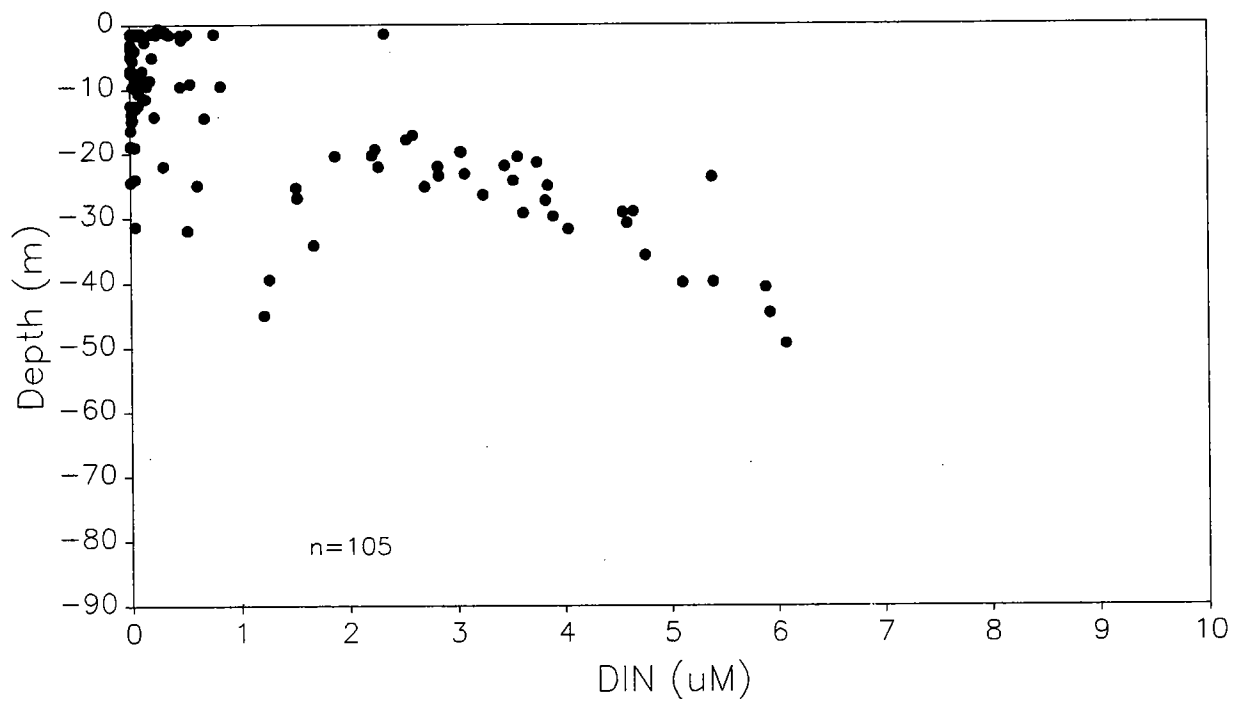
Figure 4-2a. DIN vs. depth in early July 1993.
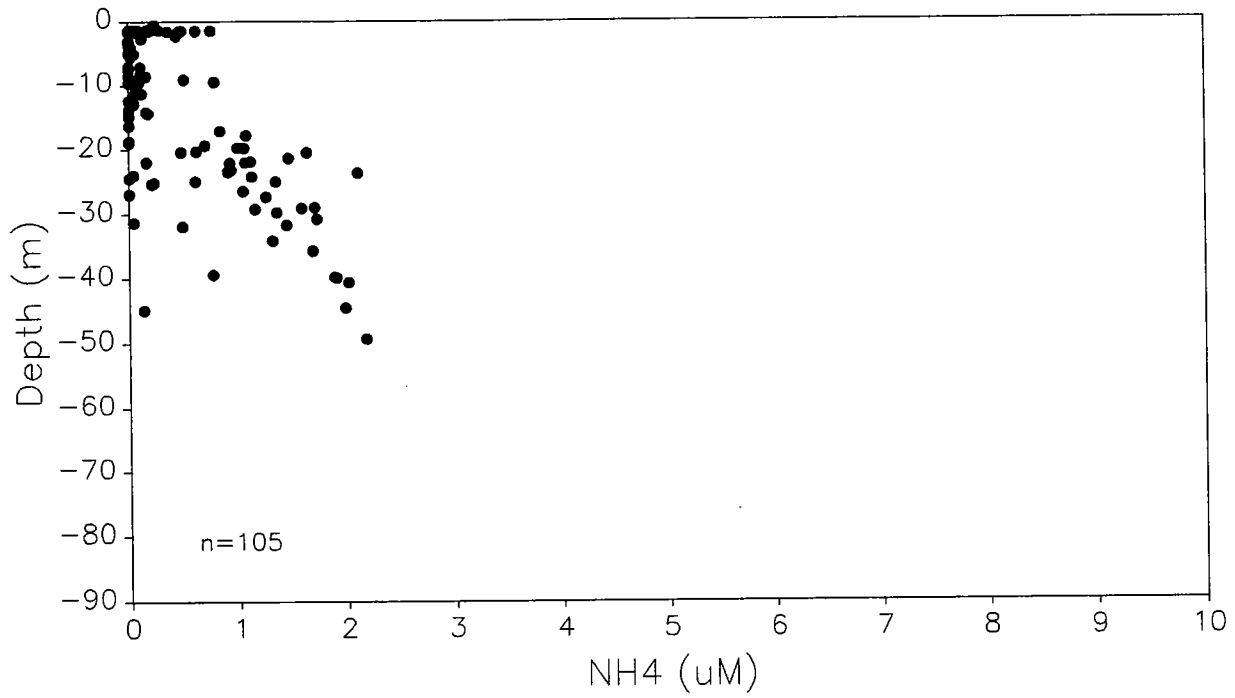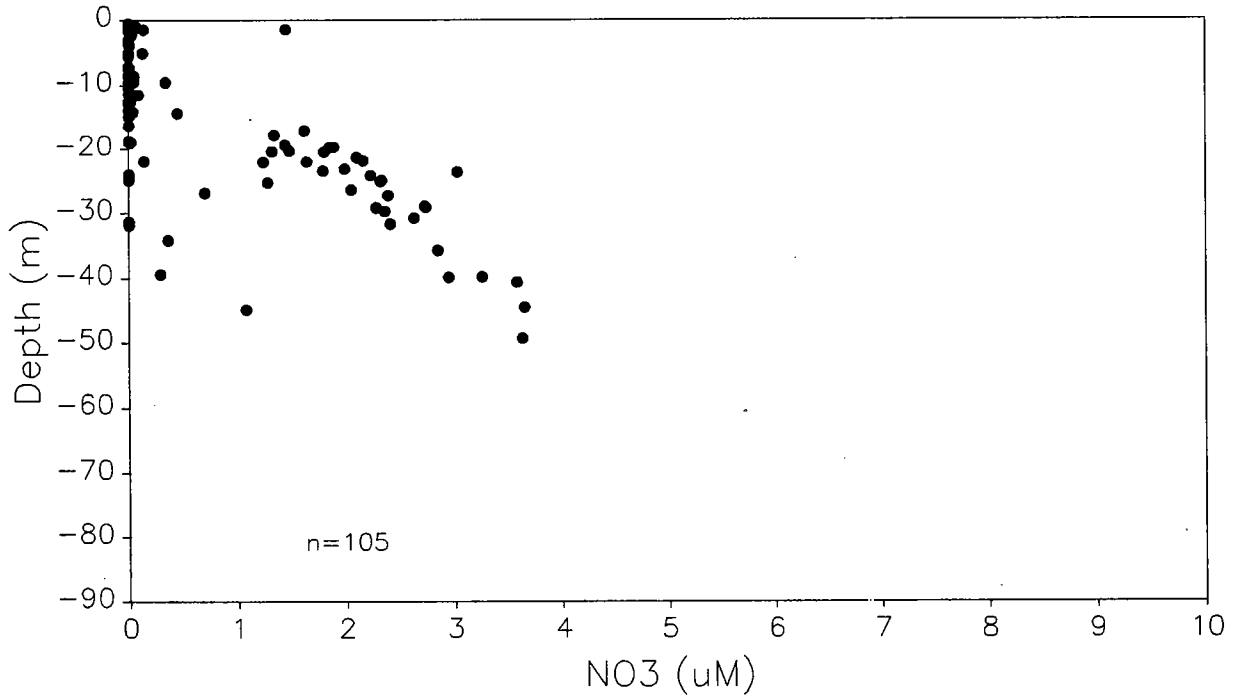
Figure 4-2b. NH_4 and NO_3 vs. depth in early July 1993.

Early July (W9308), Nearfield Stations

n=105

Early July (W9308), Nearfield Stations

n=105
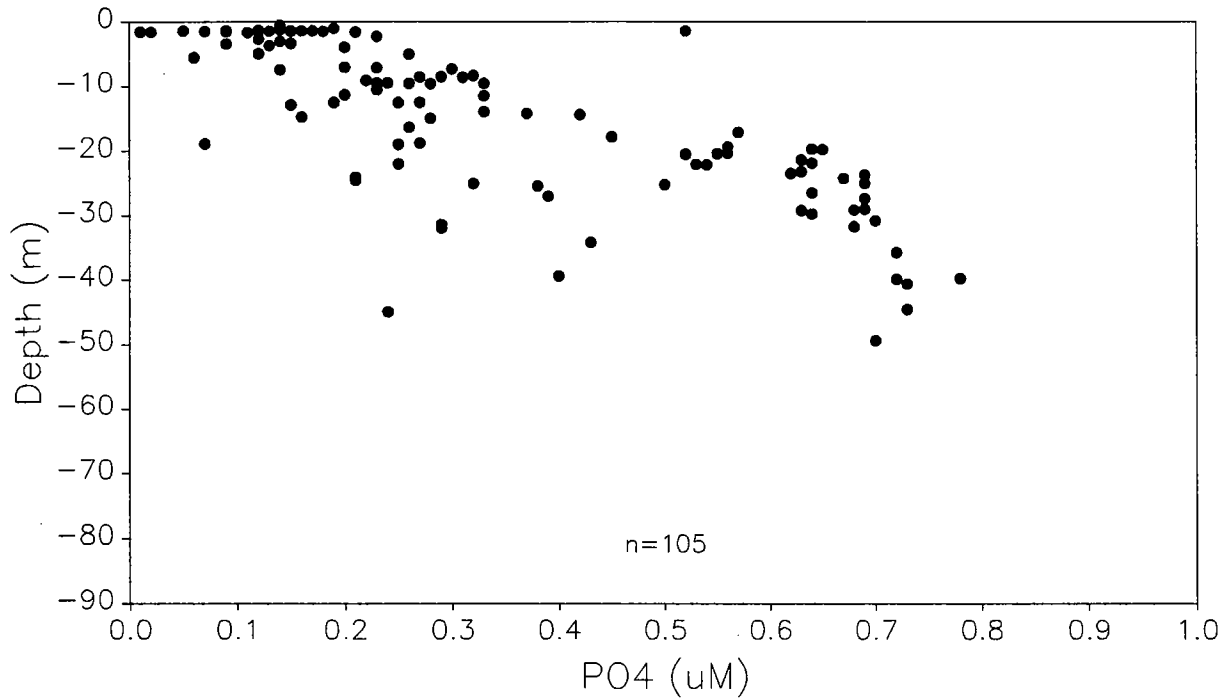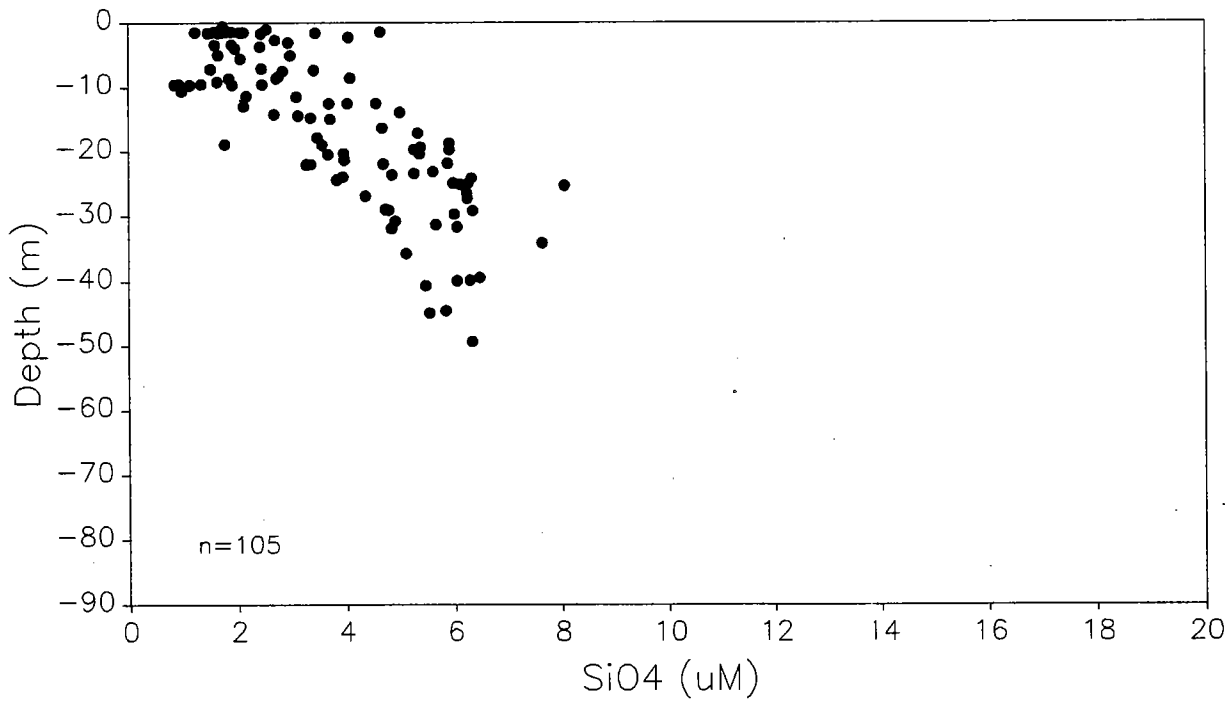
Figure 4-2c. PO$_4$ and SiO$_4$ vs. depth in early July 1993.

Early July (W9308), Nearfield Stations
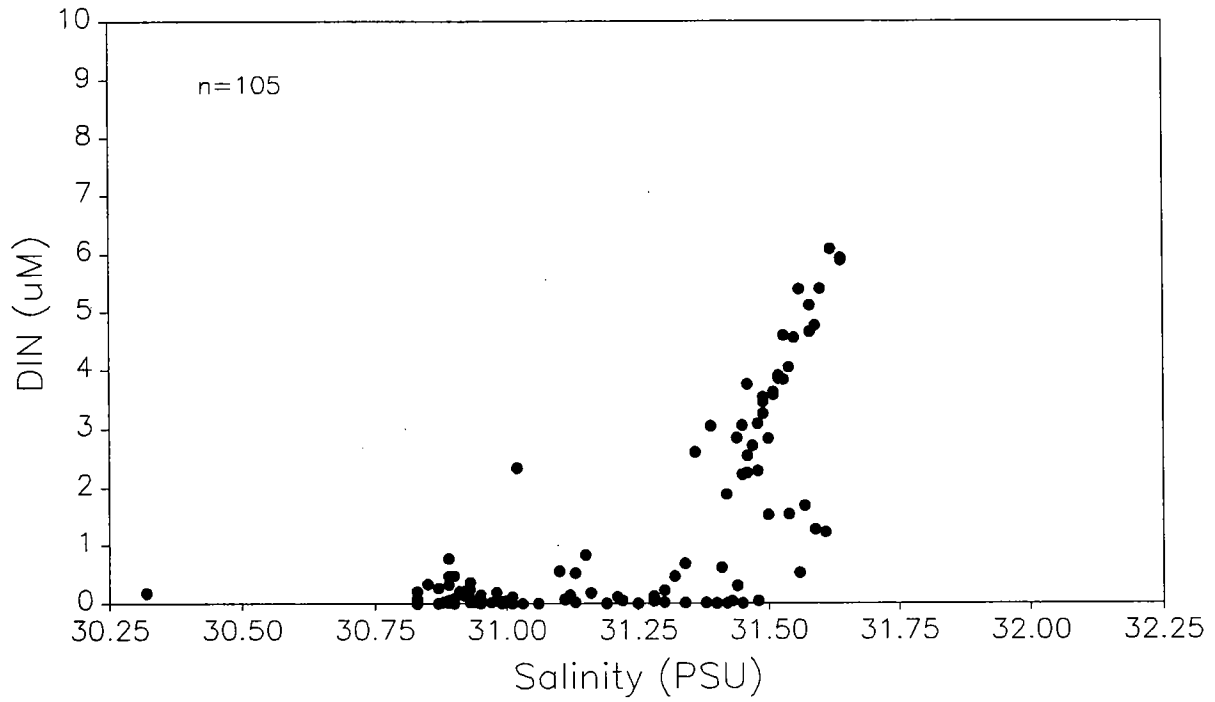
Early July (W9308), Nearfield Stations
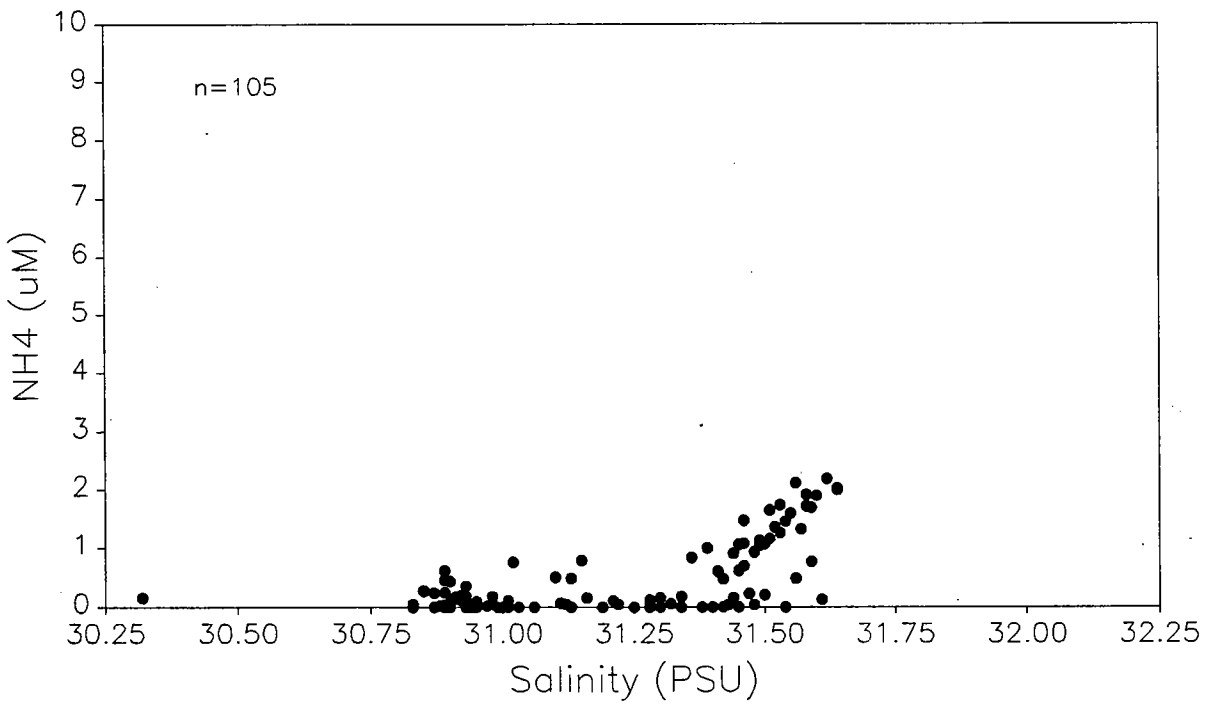
Figure 4-3. DIN and NH$_4$ vs. salinity in early July 1993.

Early July (W9308), Nearfield Stations
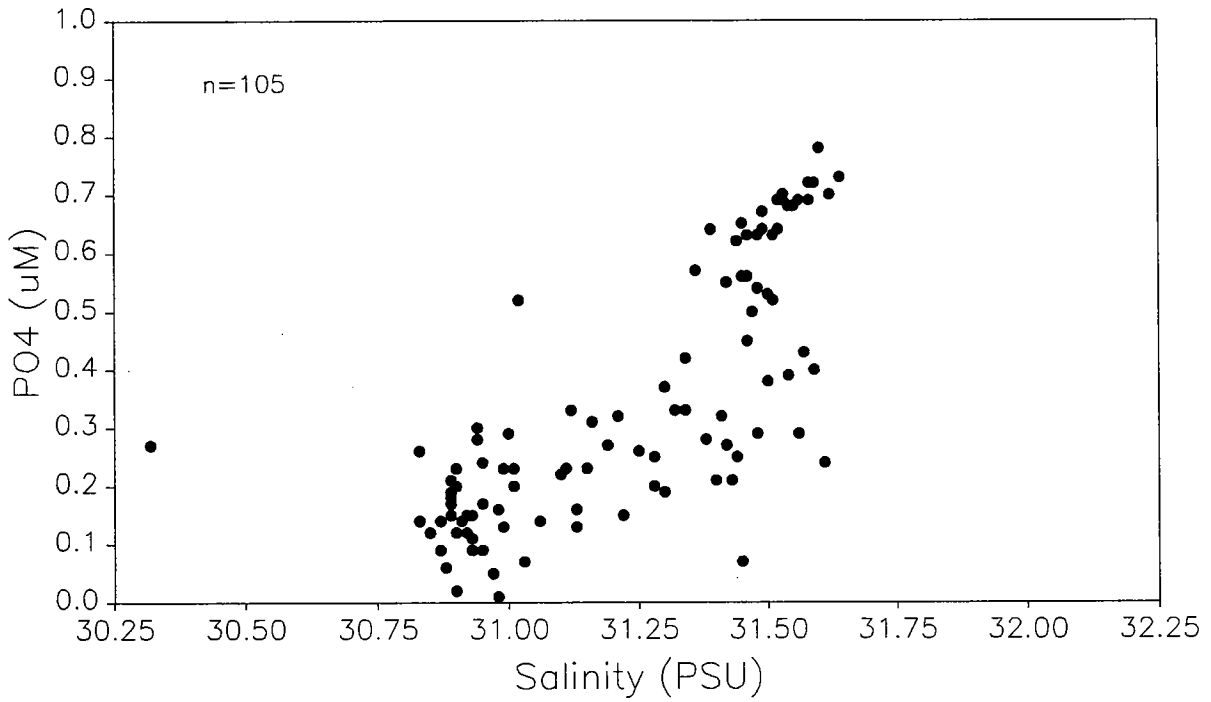
Early July (W9308), Nearfield Stations
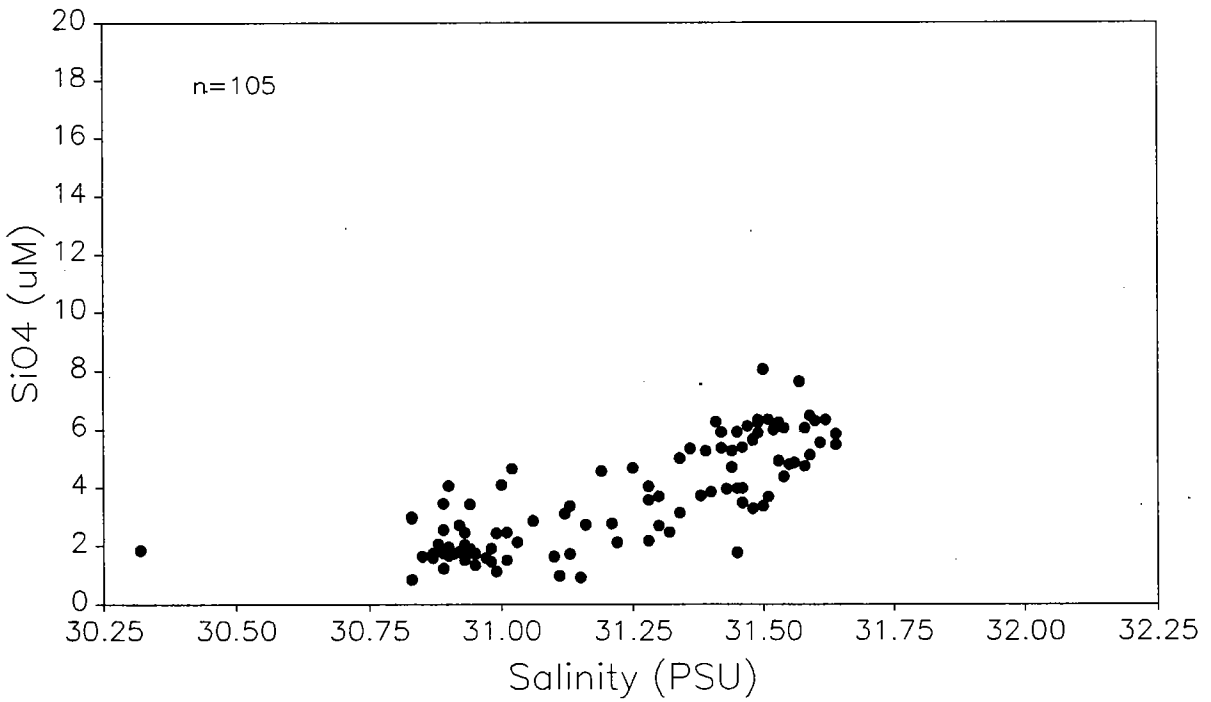
Figure 4-4. PO$_4$ and SiO$_4$ vs. salinity in early July 1993.

Outer Northern Track (N281TE.XYZ)

Inner Northern Track (N283TE.XYZ)

Inner Southern Track (N285TE.XYZ)

Outer Southern Track (N287TE.XYZ)

Key for Temperature (C)
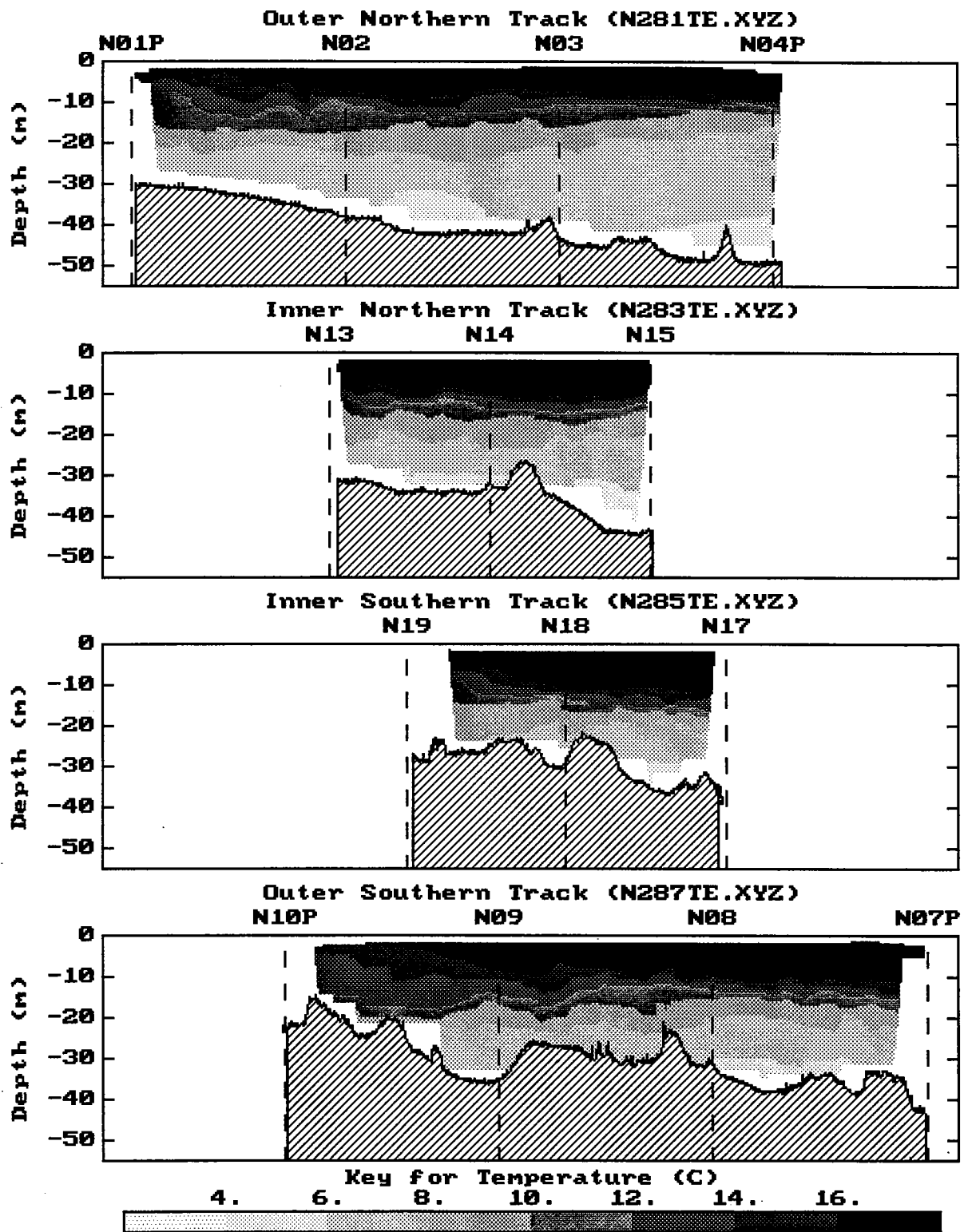
Figure 4-5a. Vertical section contours of temperature generated for tow-yo profiling conducted in early July 1993. The view is towards the north.
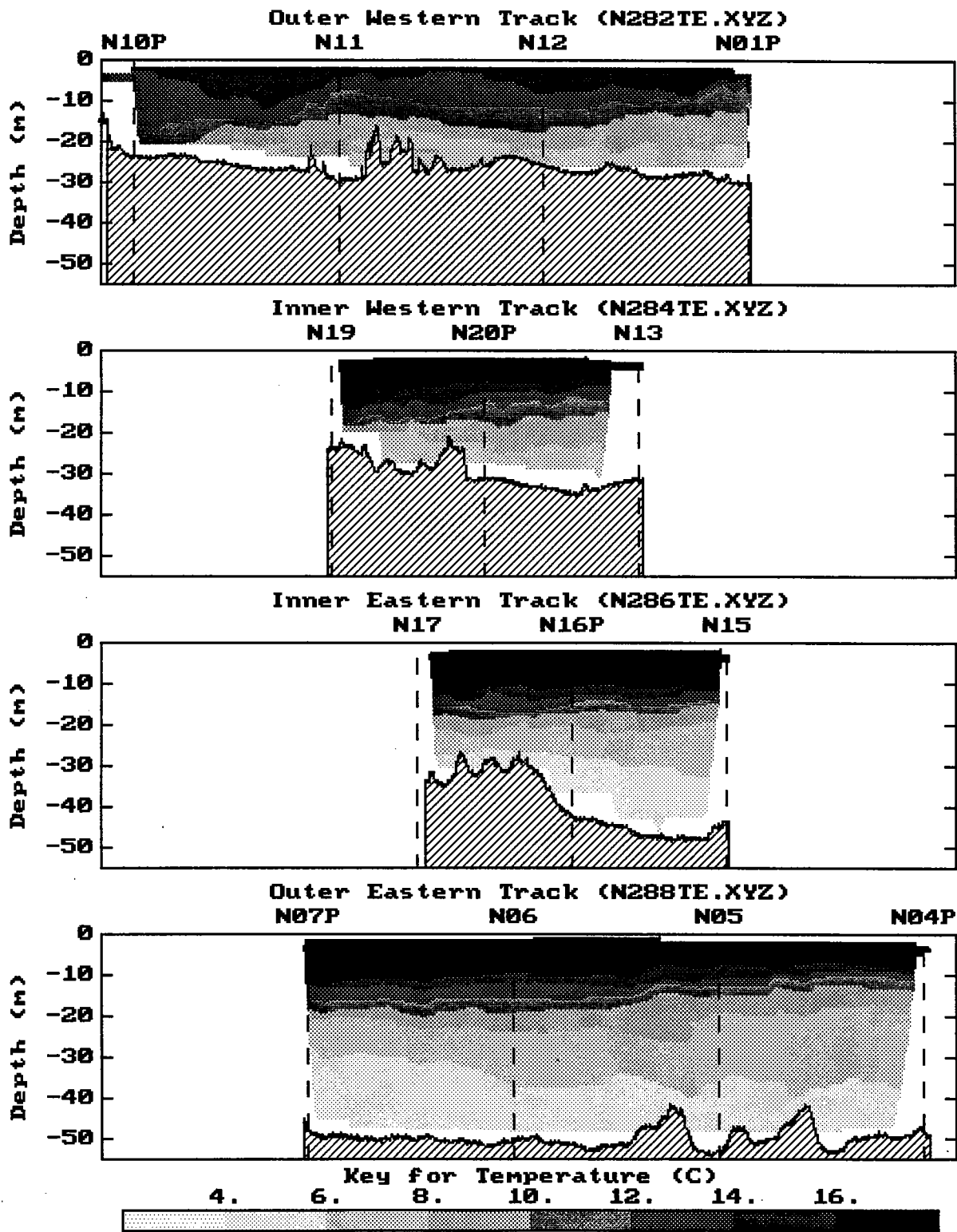
Figure 4-5b. Vertical section contours of temperature generated for tow-yo profiling conducted in early July 1993. The view is towards Boston Harbor.
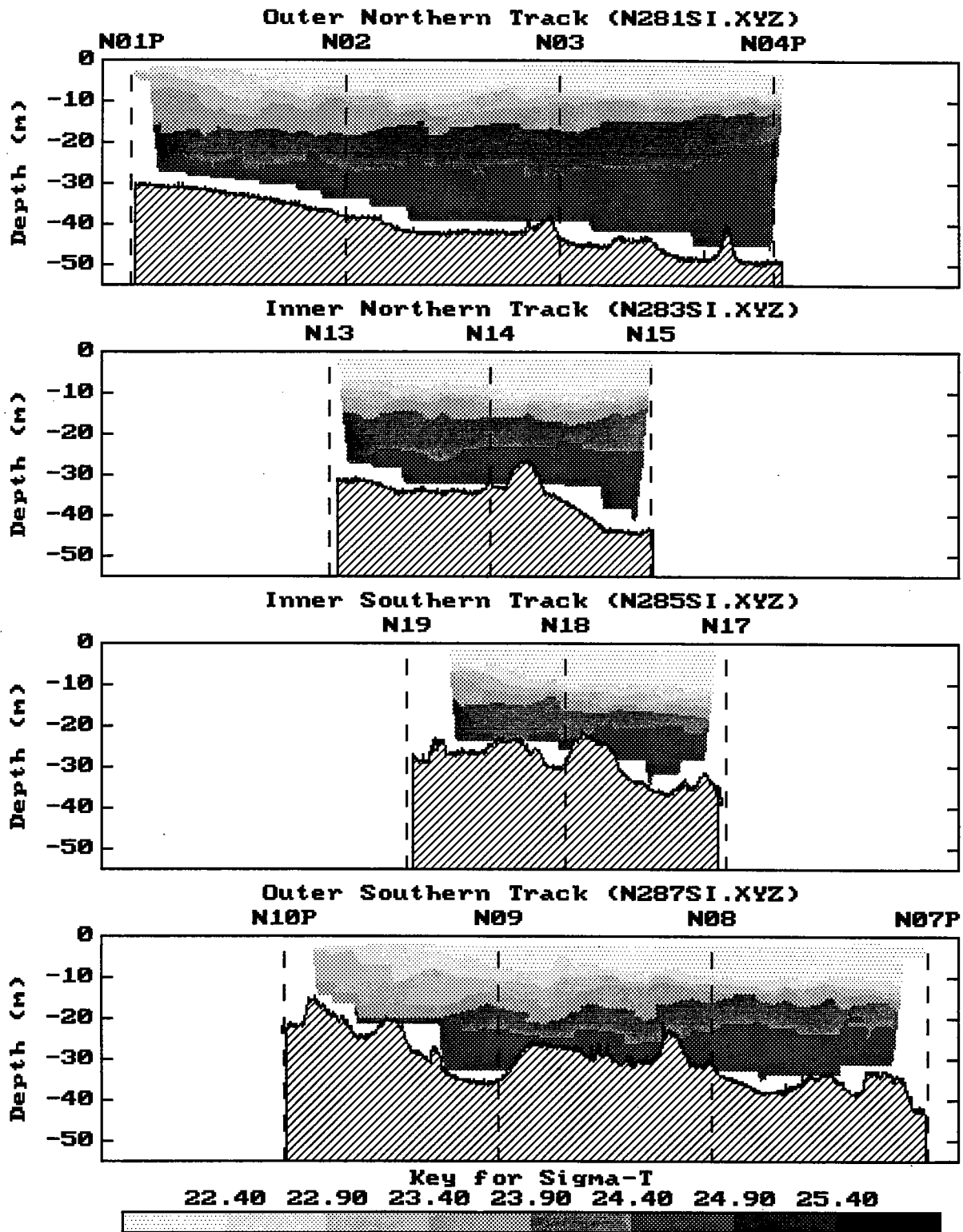
Figure 4-6a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in early July 1993. The view is towards the north.
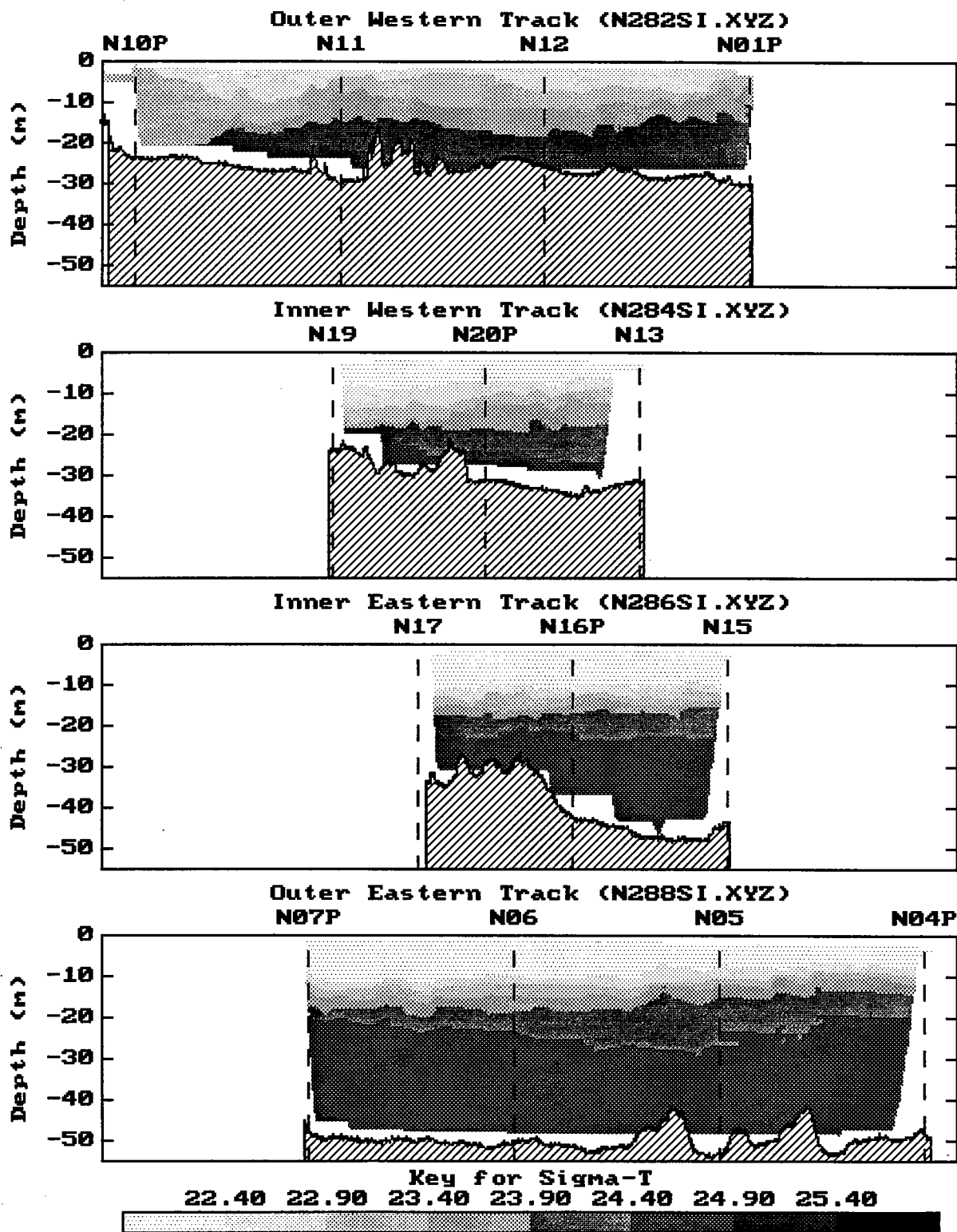
Figure 4-6b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in early July 1993. The view is towards Boston Harbor.

Outer Northern Track (N281CH.XYZ)

N01P   N02   N03   N04P

Inner Northern Track (N283CH.XYZ)
N13   N14   N15

Inner Southern Track (N285CH.XYZ)
N19   N18   N17

Outer Southern Track (N287CH.XYZ)
N10P   N09   N08   N07P

Key for Chlorophyll a (ug/L)
1.   2.   3.   4.   5.   6.   7.
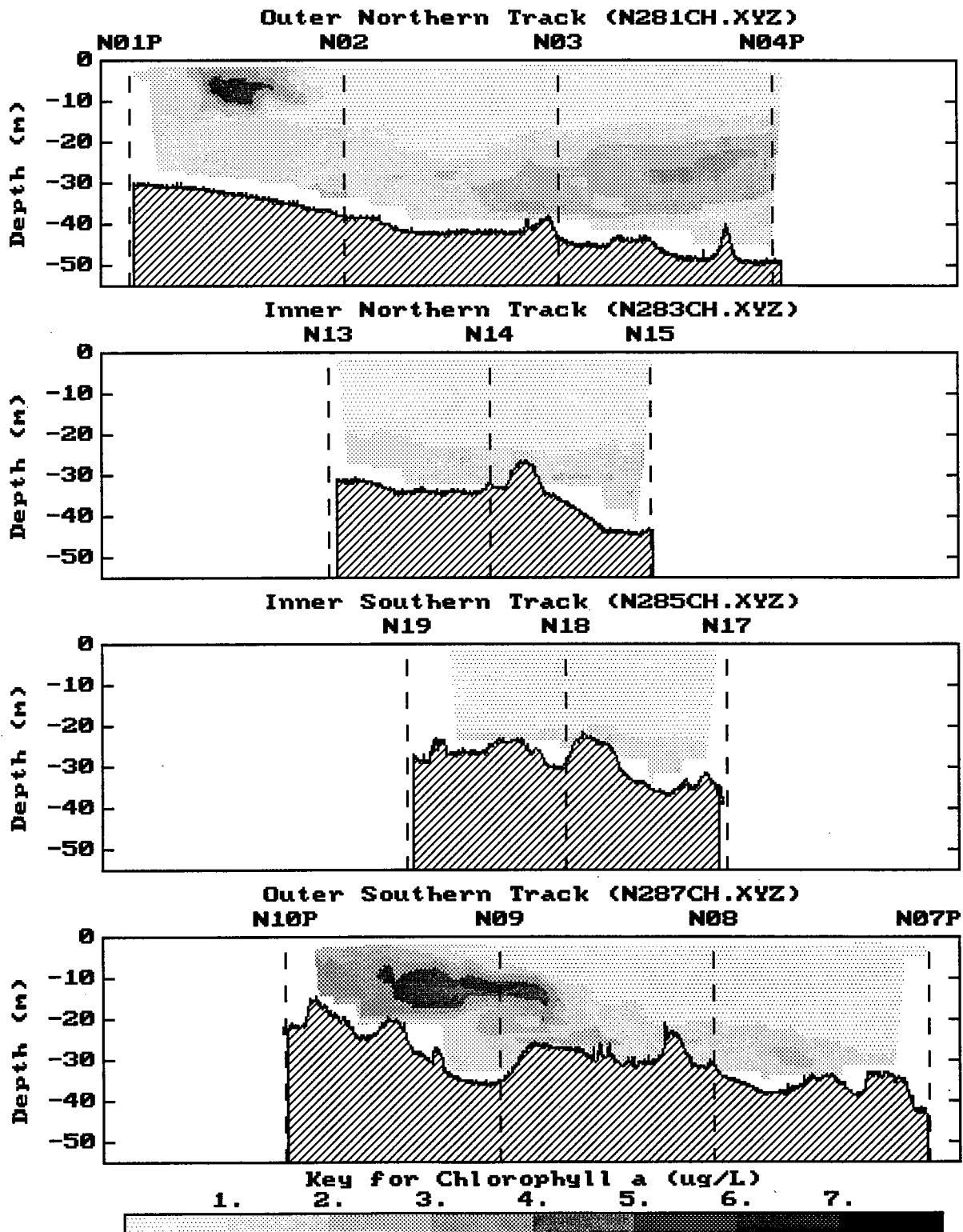
Figure 4-7a.   Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo
profiling conducted in early July 1993. The view is towards the north.
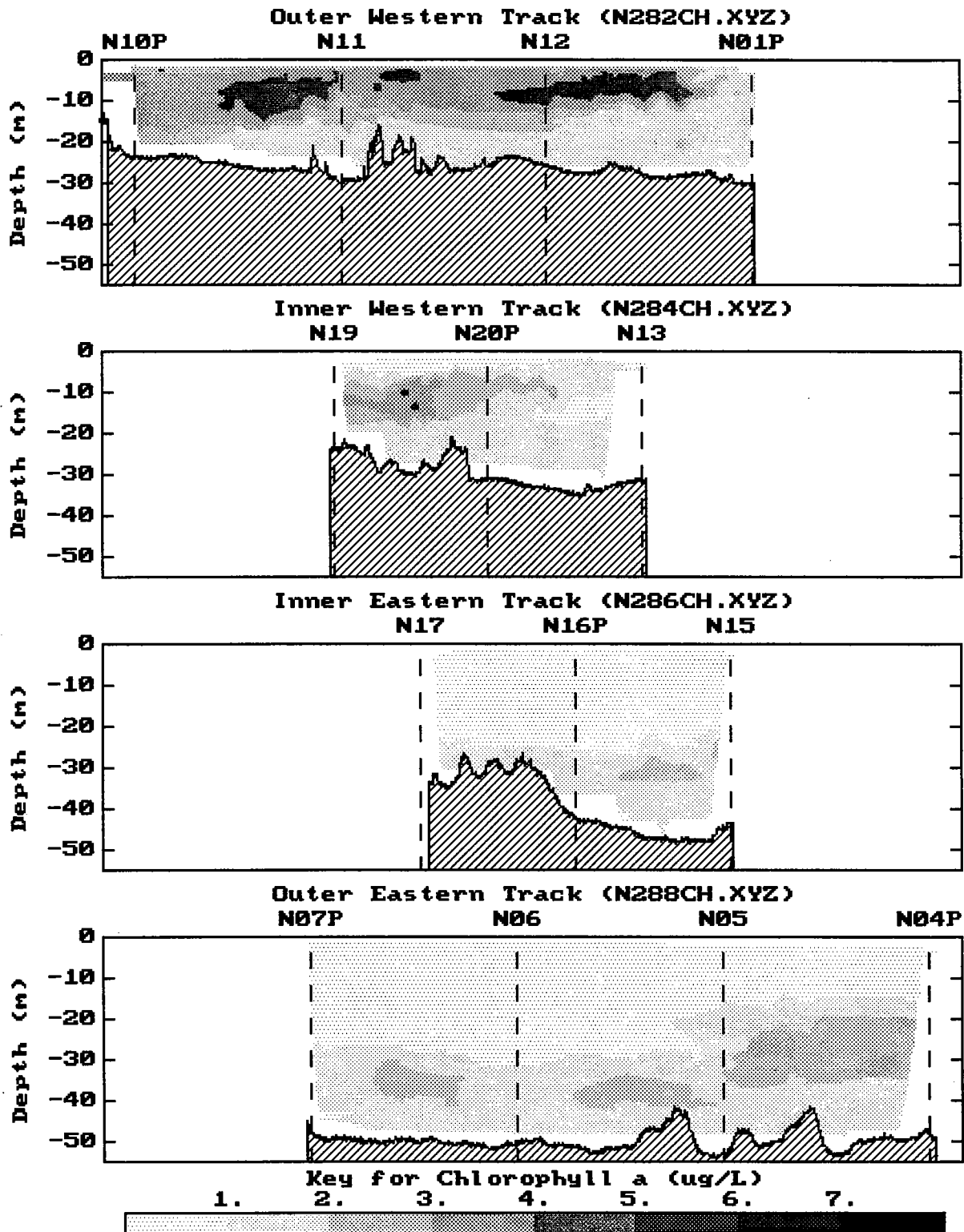
Figure 4-7b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in early July 1993. The view is towards Boston Harbor.

5.0 RESULTS OF LATE JULY 1993 NEARFIELD SURVEY (W9309)

5.1 Distribution of Water Properties from Vertical Profiling

When one overlays the parameter-parameter plots of the early July survey with the late July survey conducted about three weeks later (Figure 5-1a) the data distributions can be seen to be virtually identical. Temperature, salinity, beam attenuation, and chlorophyll ranges are essentially unchanged.

Chlorophyll and DO patterns with depth are quite similar too (Figure 5-1b vs. 4-1b), but the depth of the deep chlorophyll maximum was higher in the water column (about 15 m). Bottom water DO reached about 94% saturation in late July (Figure 5-1b and Appendix A). As in early July, some stations had surface chlorophyll concentrations above 3 μg L^{-1} and the surface waters were still slightly supersaturated.

Bottom water DIN in late July reached slightly higher concentrations than in June and early July (Figure 5-2a) and a few high concentrations were measured in the surface 10 m and these were limited to discrete locations. Higher surface DIN values were due to NH$_4$, as NO$_3$ showed a similar profile to the previous two surveys (Figure 5-2b).

PO$_4$ and SiO$_4$ continued to show the same pattern of increase with depth (Figure 5-2c) and perhaps a slight increase in maximum deepwater concentrations. Interestingly, PO$_4$ in surface waters generally increased 0.1-0.2 μM, while SiO$_4$ became nearly depleted.

For all the nutrients, the relationship to salinity remained about the same as it had been for the previous two surveys (Figures 5-3 and 5-4). Note that the few higher near-surface NH$_4$ concentrations were at intermediate, rather than lowest salinity.

5.2 Distribution of Water Properties from Towing

Temperature and density profiles again demonstrated a field with uniform and continuous vertical stratification (Figures 5-5, 5-6). There were few notable features.

Chlorophyll was high (>6 μg L^{-1}) on the western track, and stretched as an apparent extensive, thin, very near-surface layer for almost the entire track, about 10 km (Figure 5-7). This surface layer appeared to extend to stations N02, N13, and N09, all stations a few kilometers to the east. Offshore, the subsurface maximum was found from 10-15 m deep, and this was within the pycnocline. This deeper chlorophyll layer had a very uniform peak concentration (2-3 μg L^{-1}) with no notable high patches.

5.3 Water Types and Analysis of Small-Scale Variability

As for the previous surveys, a gradient of decreasing chlorophyll with distance from shore was apparent, both in peak concentrations and in the depth of the peak layer. In contrast to the early July survey, the subsurface chlorophyll maximum was relatively high in the water column and well within the pycnocline. Otherwise, the field remained rather strikingly stable in all measured parameters, for values were similar to measurements made three weeks prior and consistent between the two days of the survey. Obviously, the field remained strongly determined by the consistent and uniform stratification.

Salinity (PSU)

Salinity (PSU)

Chlorophyll a (ug/L)

Nearfield Stations (W9309)
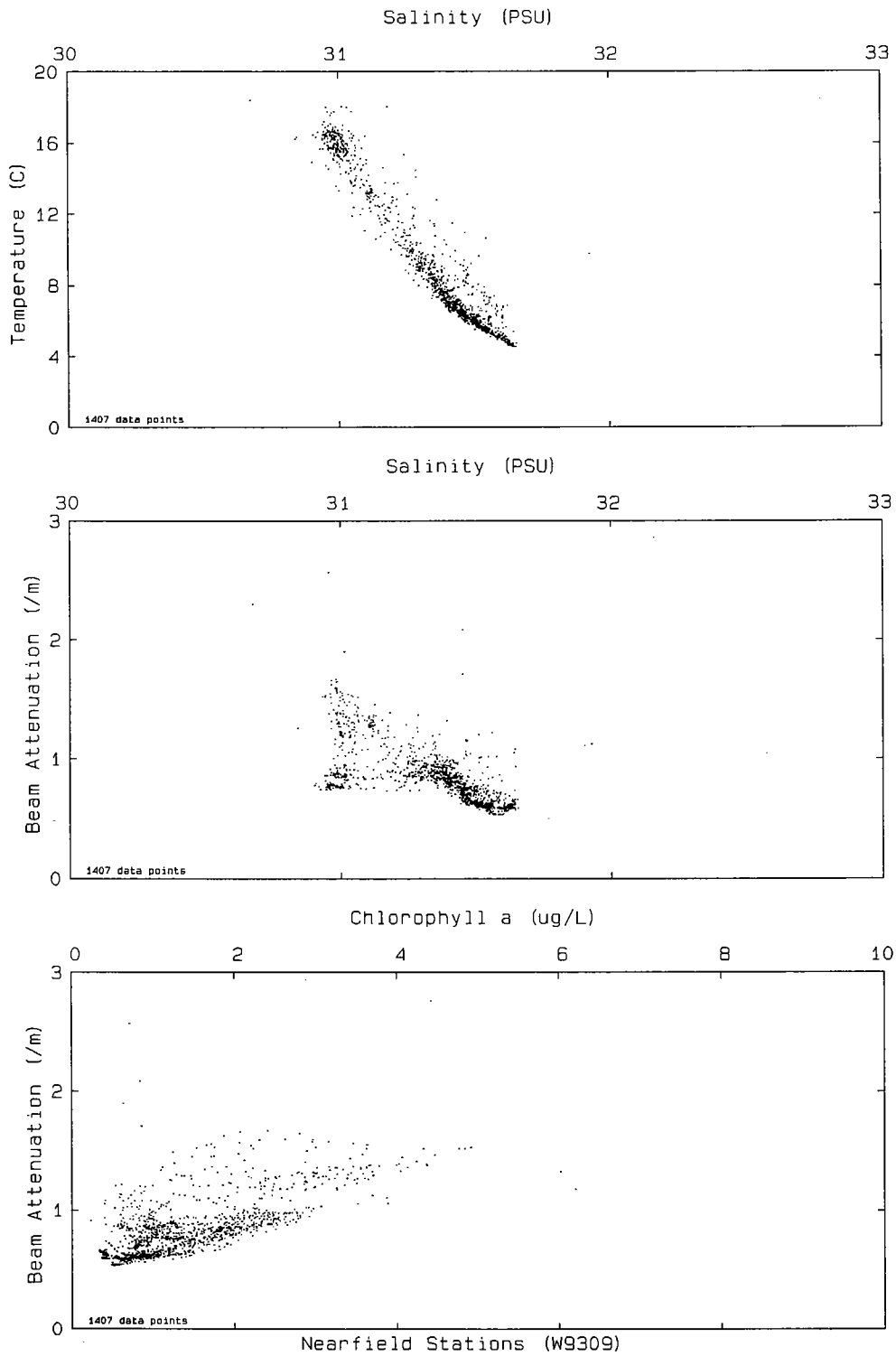
Figure 5-1a. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late July 1993. Individual station casts that were used to produce this composite are included in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.

Chlorophyll a (ug/L)

DO % Saturation

Nearfield Stations (W9309)
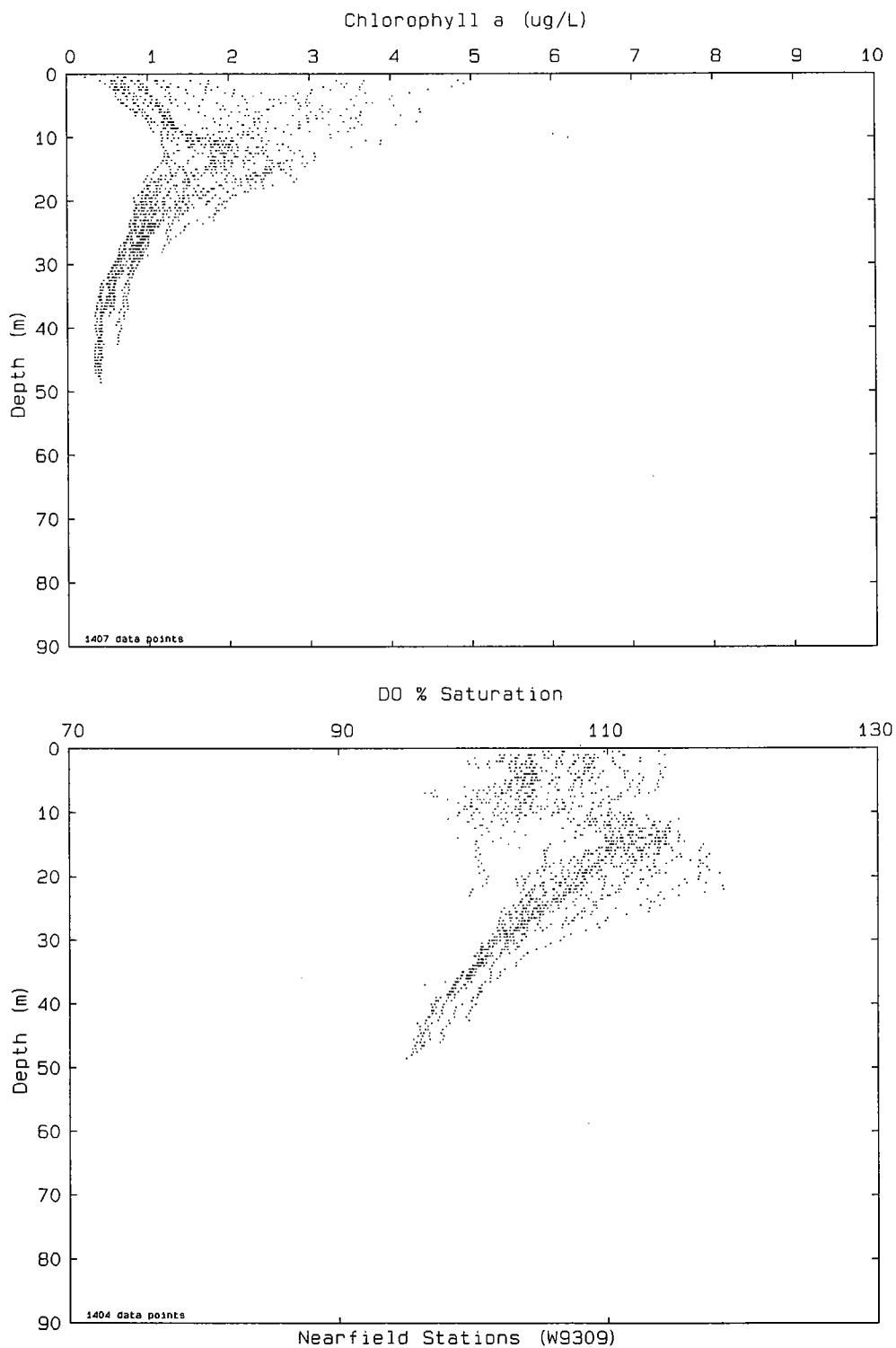
Figure 5-1b. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late July 1993. Individual station casts that were used to produce this composite are included in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.
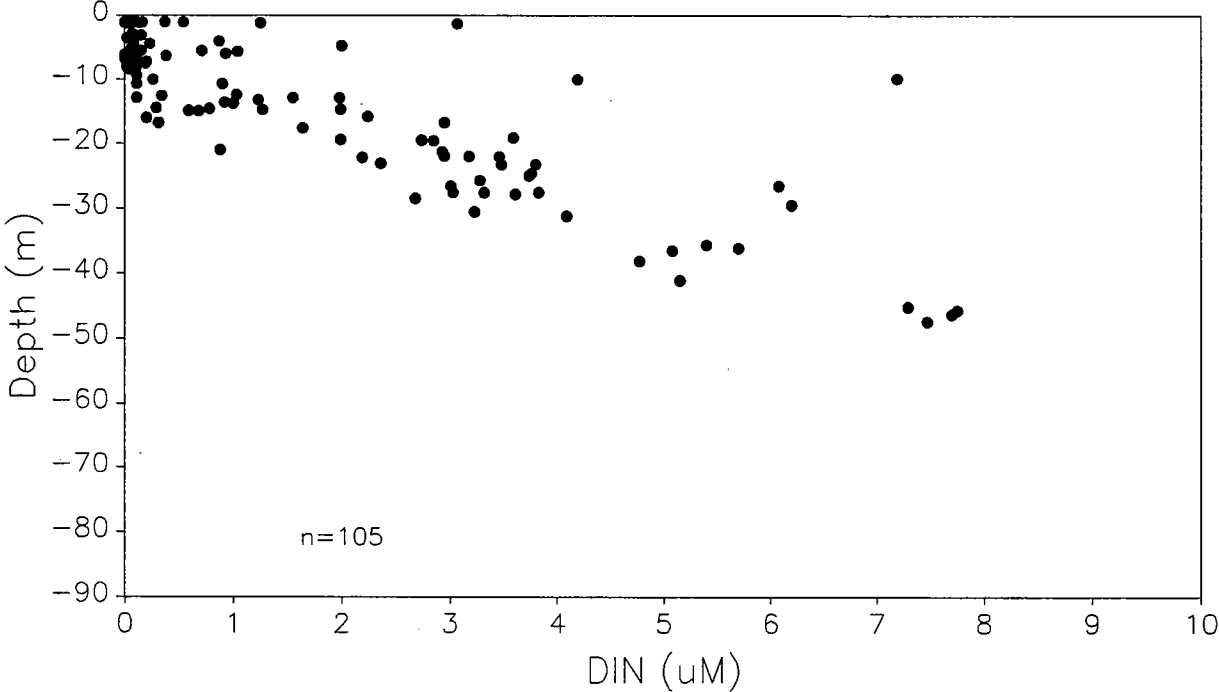
Figure 5-2a. DIN vs. depth in late July 1993.

Late July (W9309), Nearfield Stations
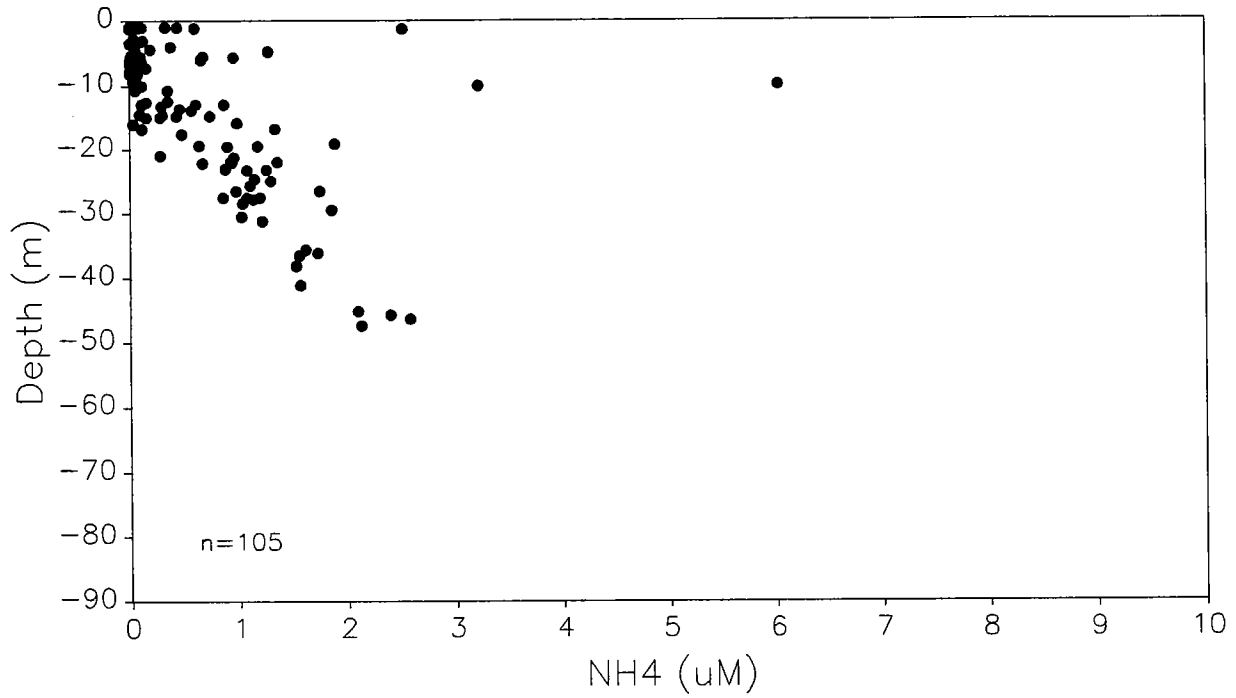
Late July (W9309), Nearfield Stations
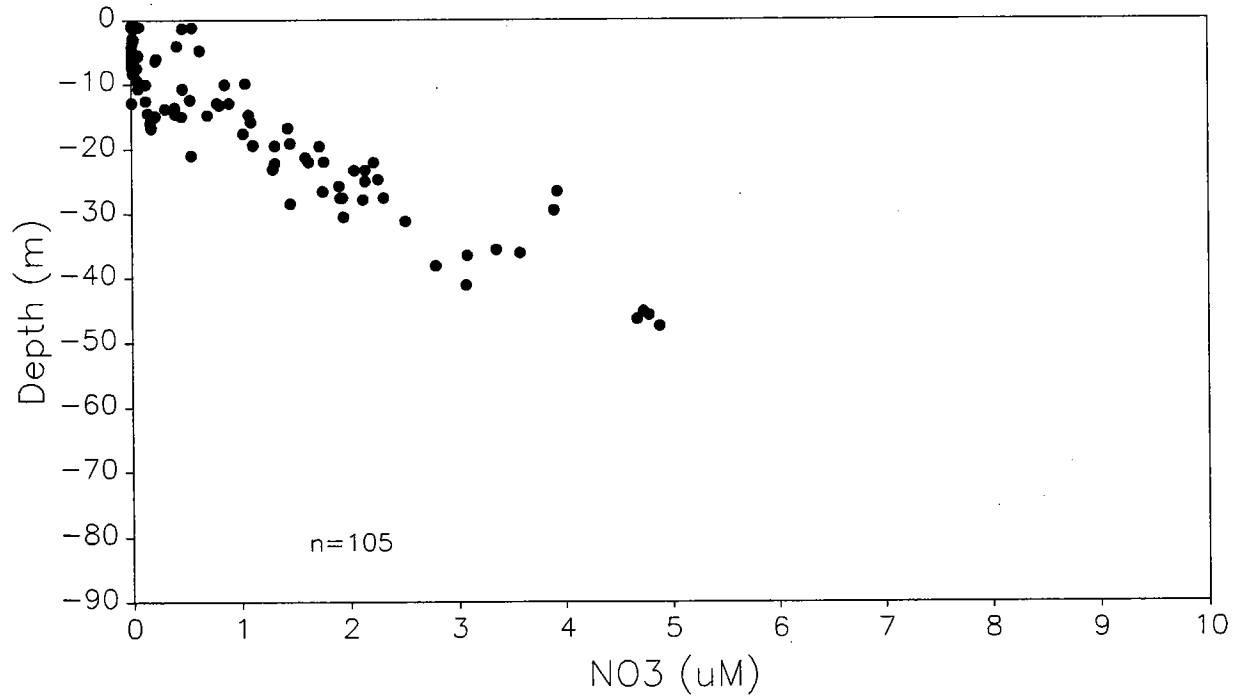
Figure 5-2b. NH$_4$ and NO$_3$ vs. depth in late July 1993.

Late July (W9309), Nearfield Stations
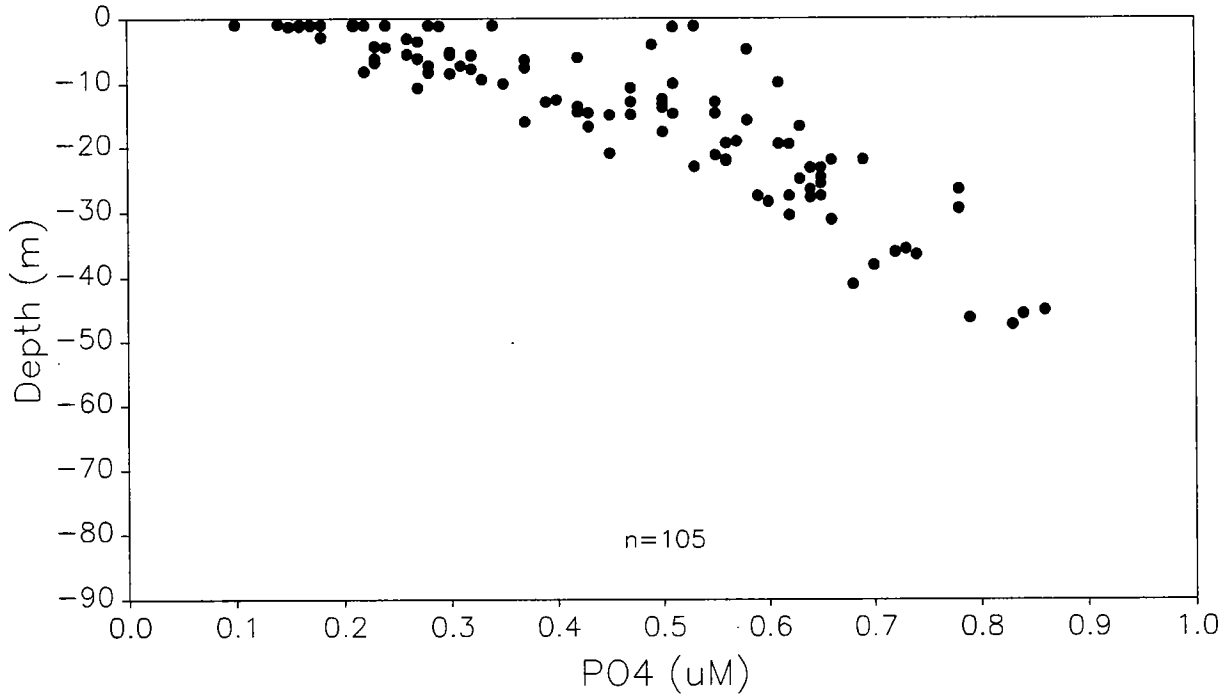
Late July (W9309), Nearfield Stations
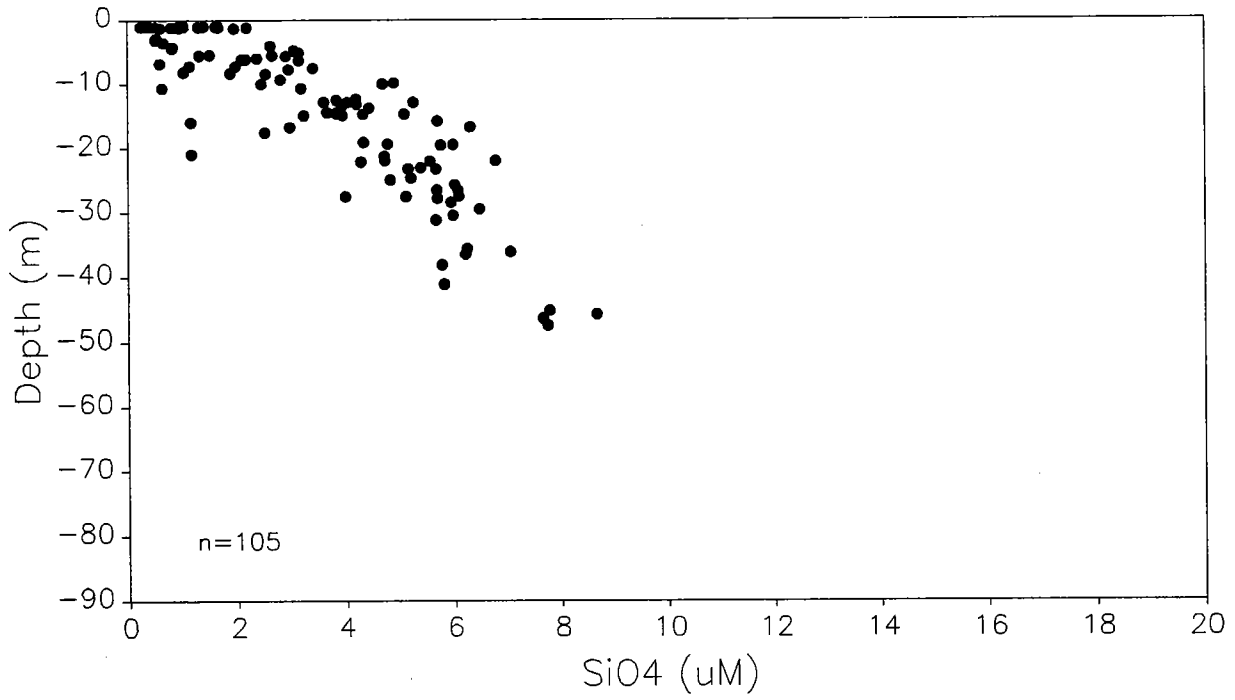
Figure 5-2c. PO$_4$ and SiO$_4$ vs. depth in late July 1993.
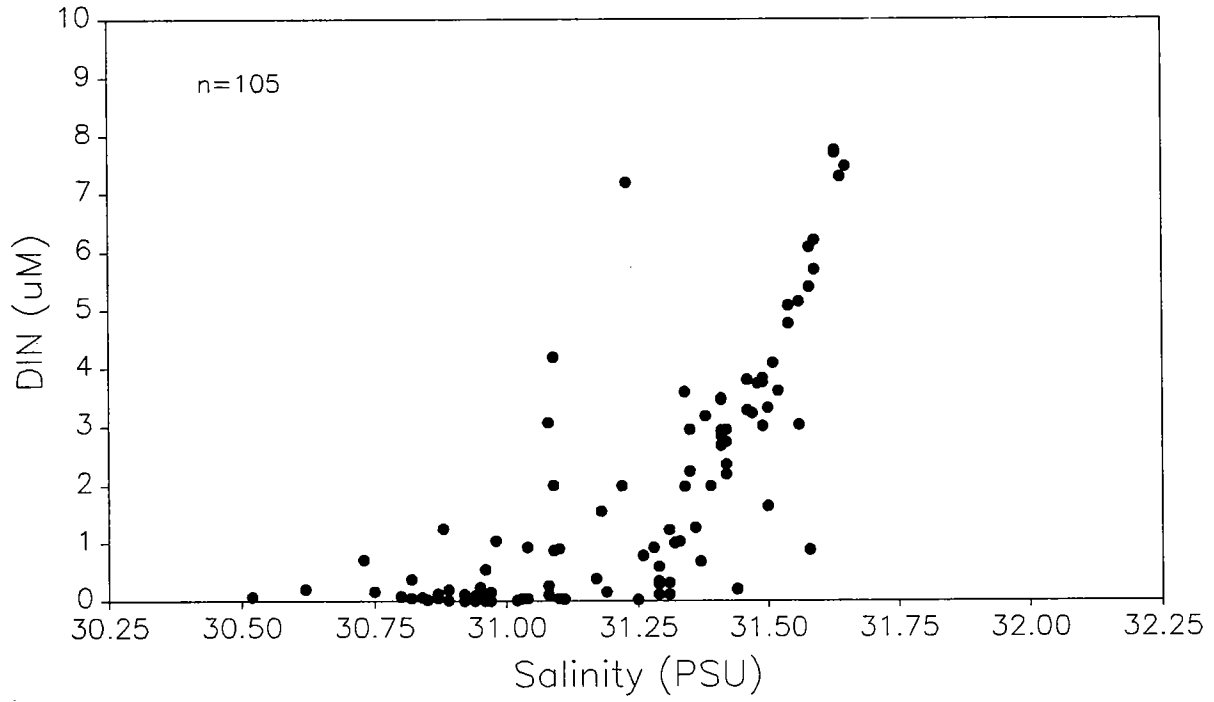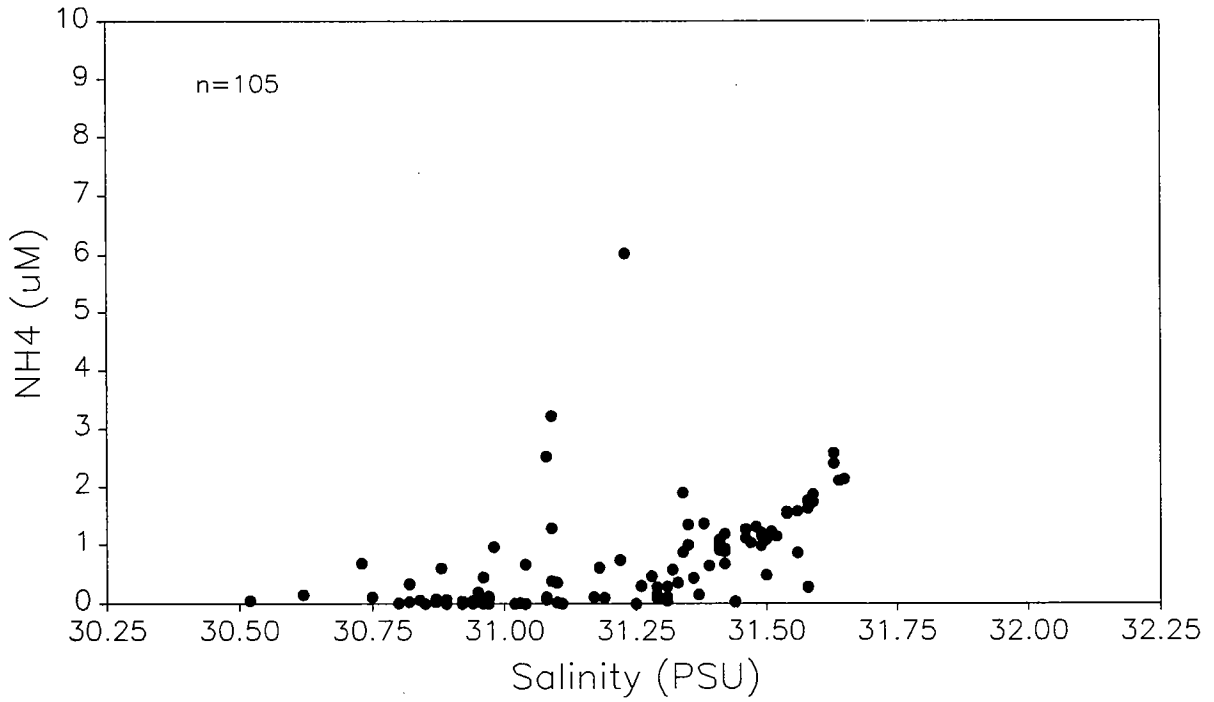
Figure 5-3. DIN and NH$_4$ vs. salinity in late July 1993.

Late July (W9309), Nearfield Stations
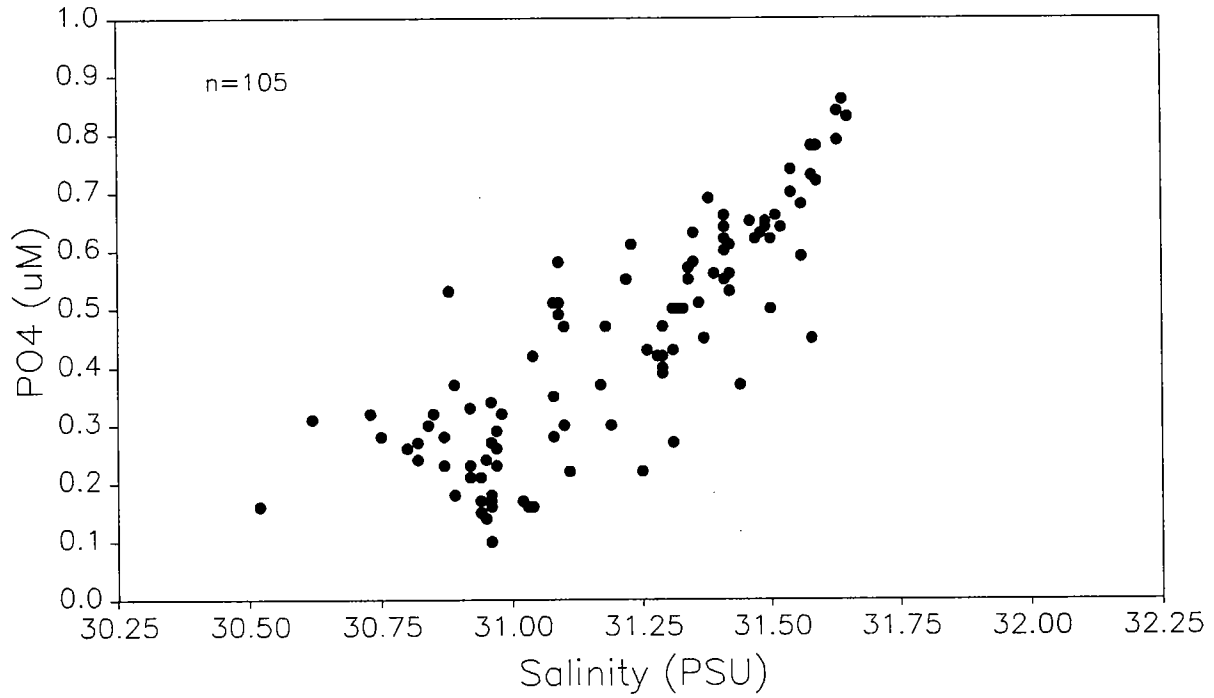
Late July (W9309), Nearfield Stations
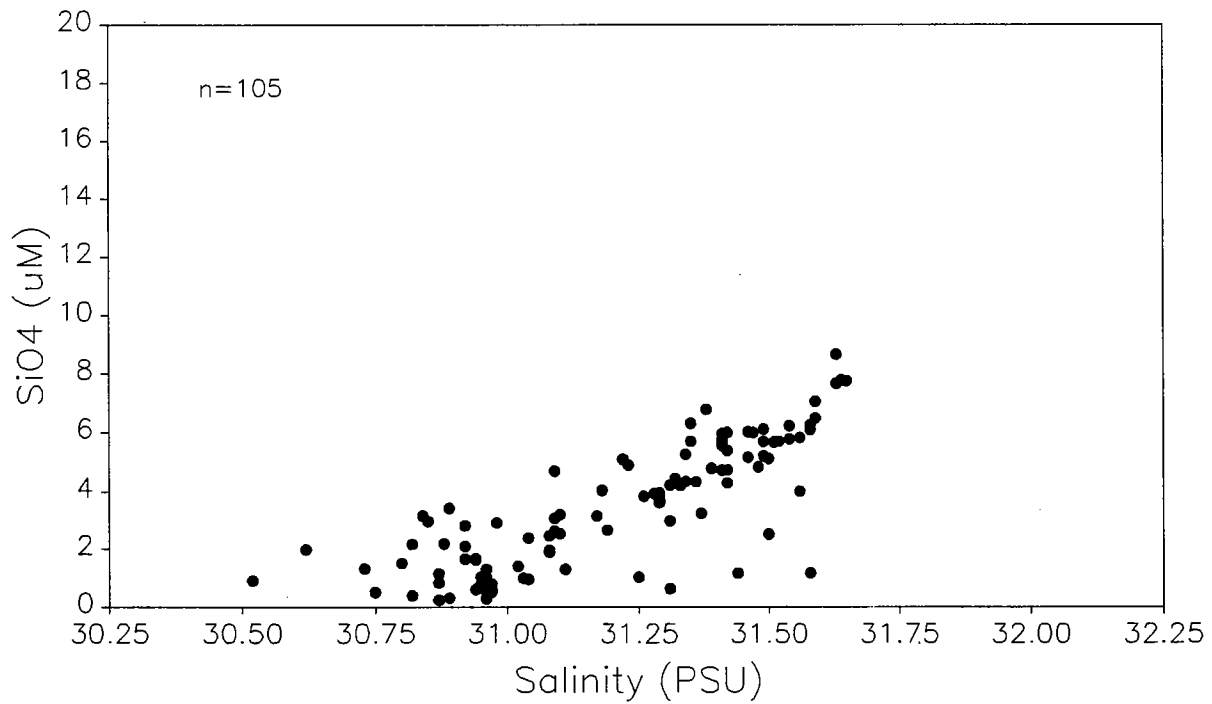
Figure 5-4. PO$_4$ and SiO$_4$ vs. salinity in late July 1993.
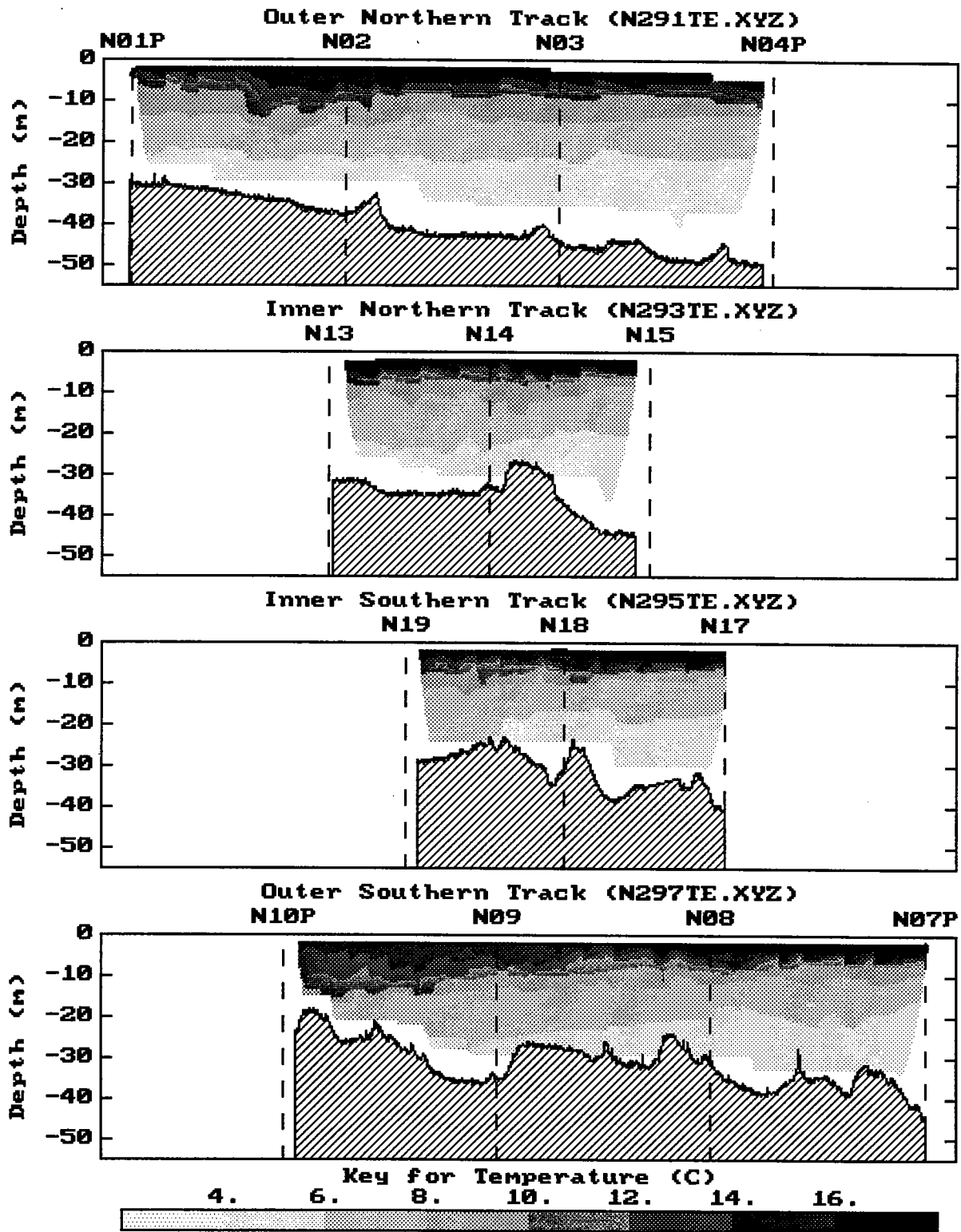
Figure 5-5a. Vertical section contours of temperature generated for tow-yo profiling conducted in late July 1993. The view is towards the north.
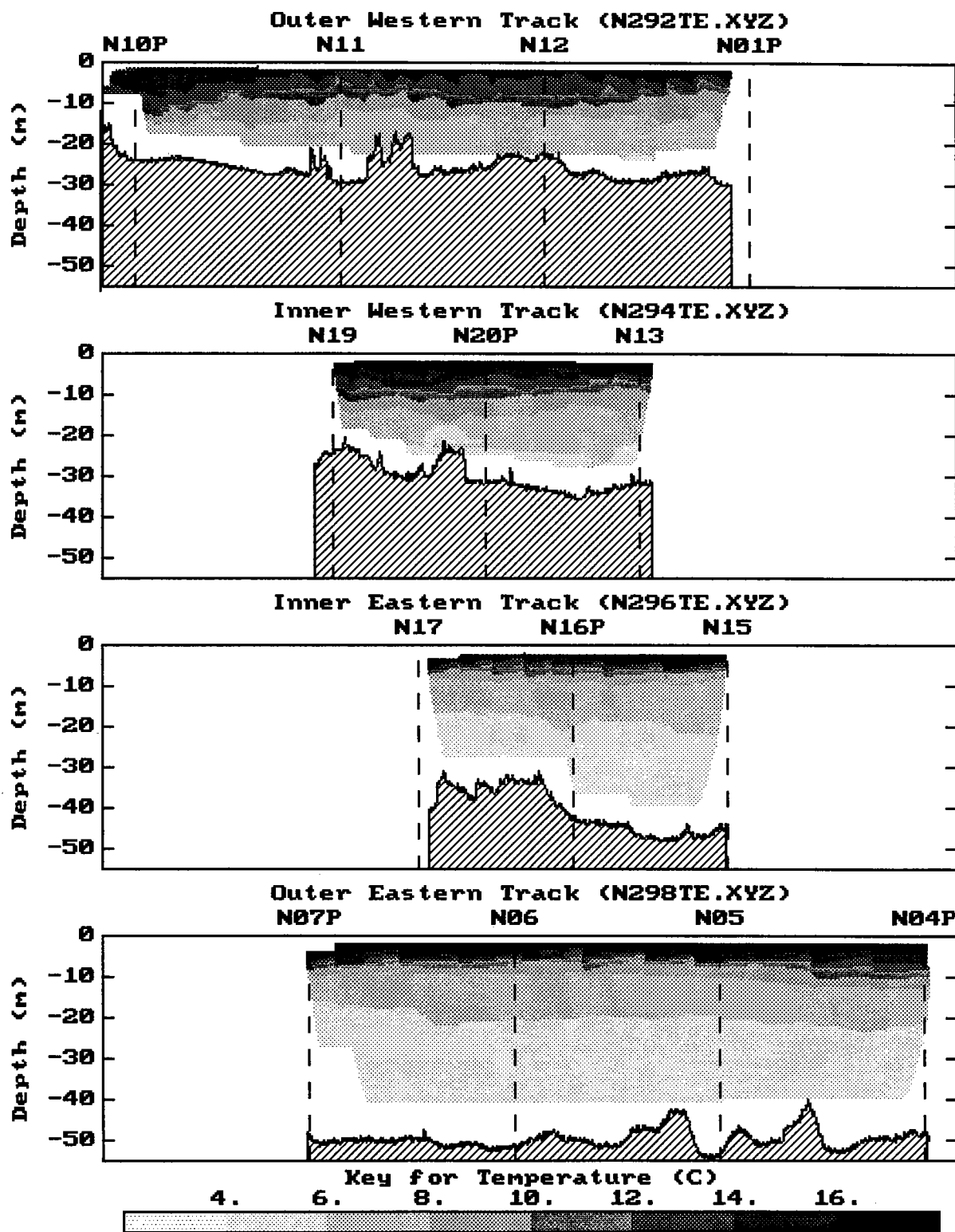
Figure 5-5b. Vertical section contours of temperature generated for tow-yo profiling conducted in late July 1993. The view is towards Boston Harbor.
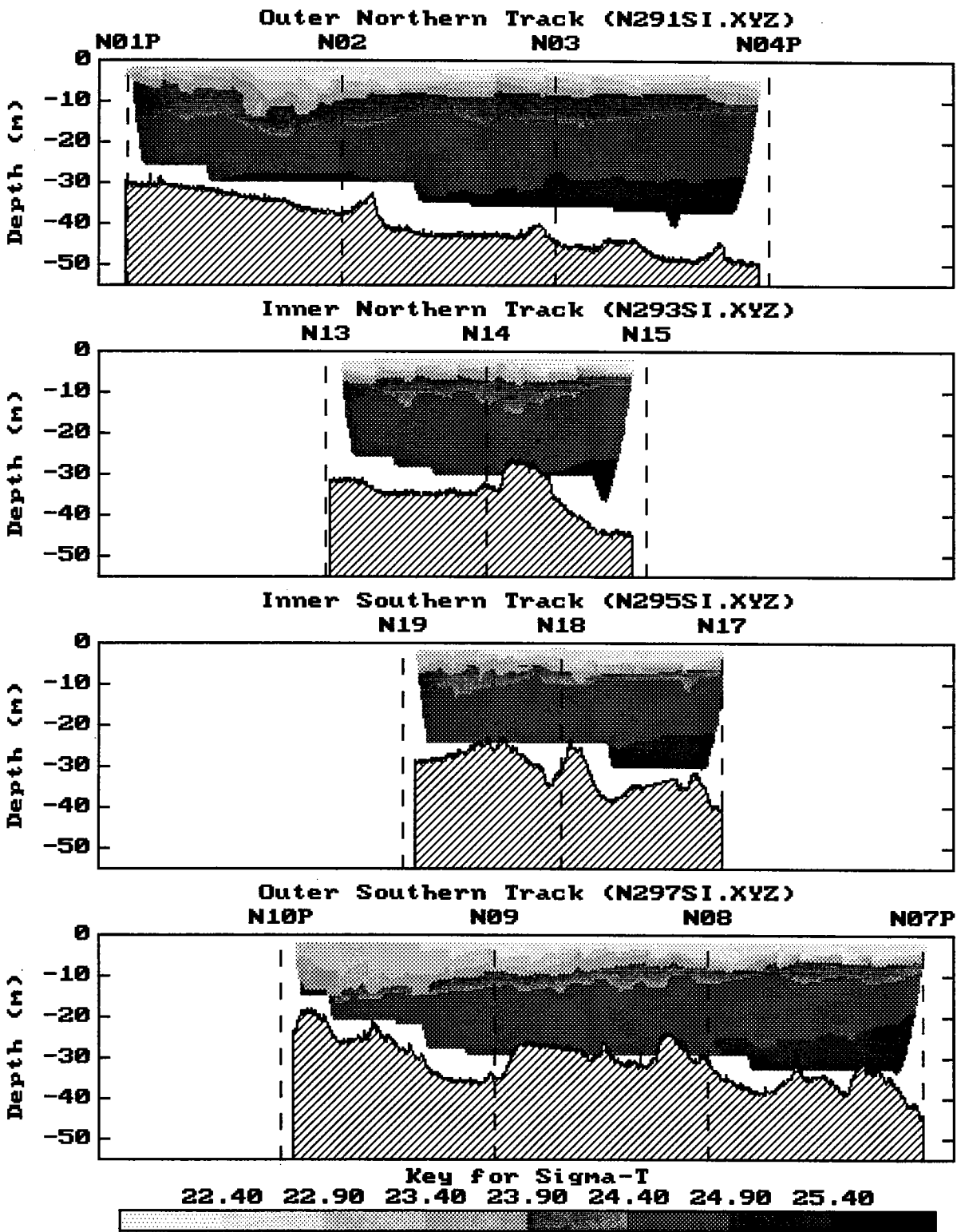
Figure 5-6a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in late July 1993. The view is towards the north.
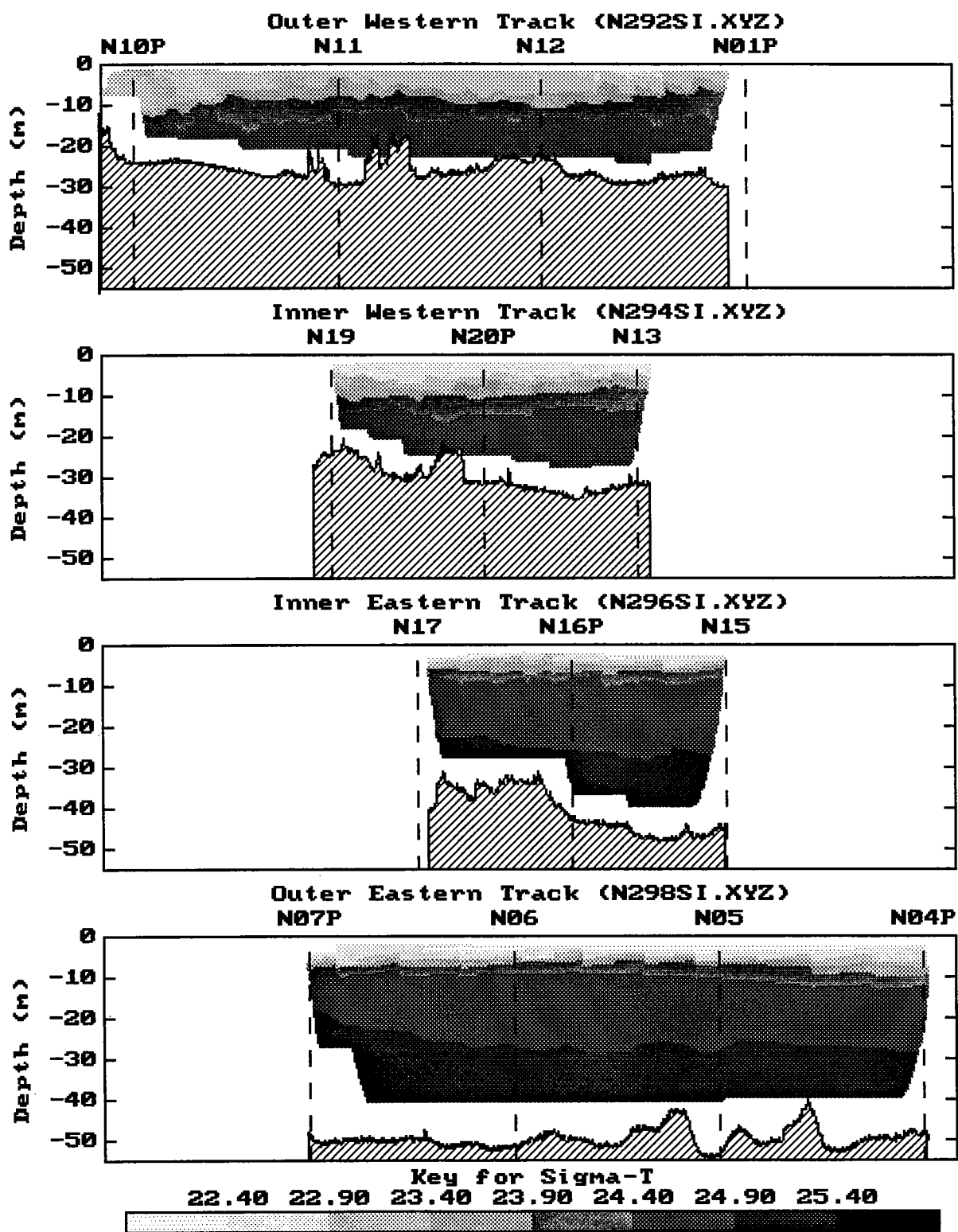
Figure 5-6b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in late July 1993. The view is towards Boston Harbor.

Outer Northern Track (N291CH.XYZ)

N01P **N02** **N03** **N04P**

Inner Northern Track (N293CH.XYZ)

N13 **N14** **N15**

Inner Southern Track (N295CH.XYZ)

N19 **N18** **N17**

Outer Southern Track (N297CH.XYZ)

N10P **N09** **N08** **N07P**

Key for Chlorophyll a (ug/L)

1.   2.   3.   4.   5.   6.   7.
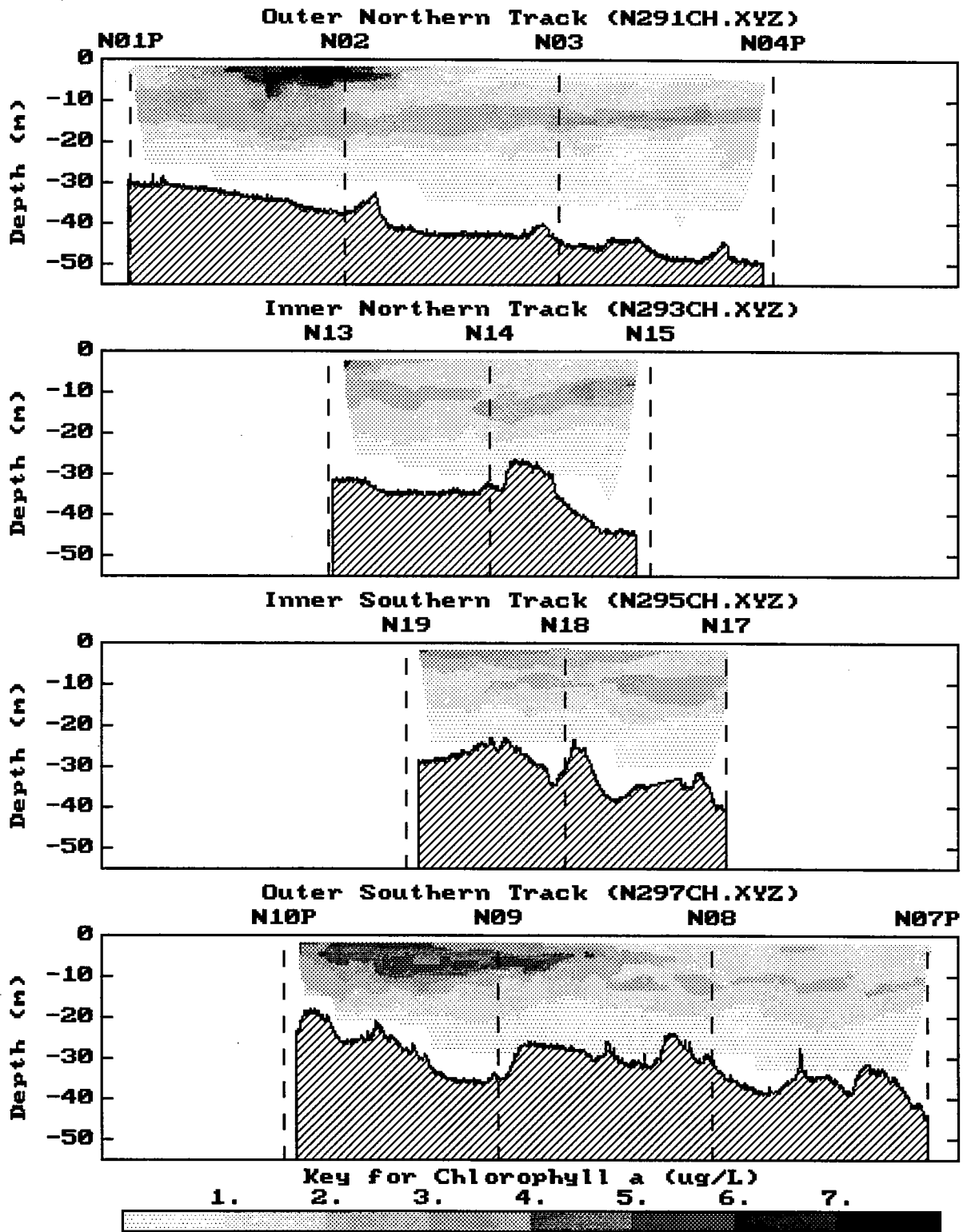
Figure 5-7a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in late July 1993. The view is towards the north.
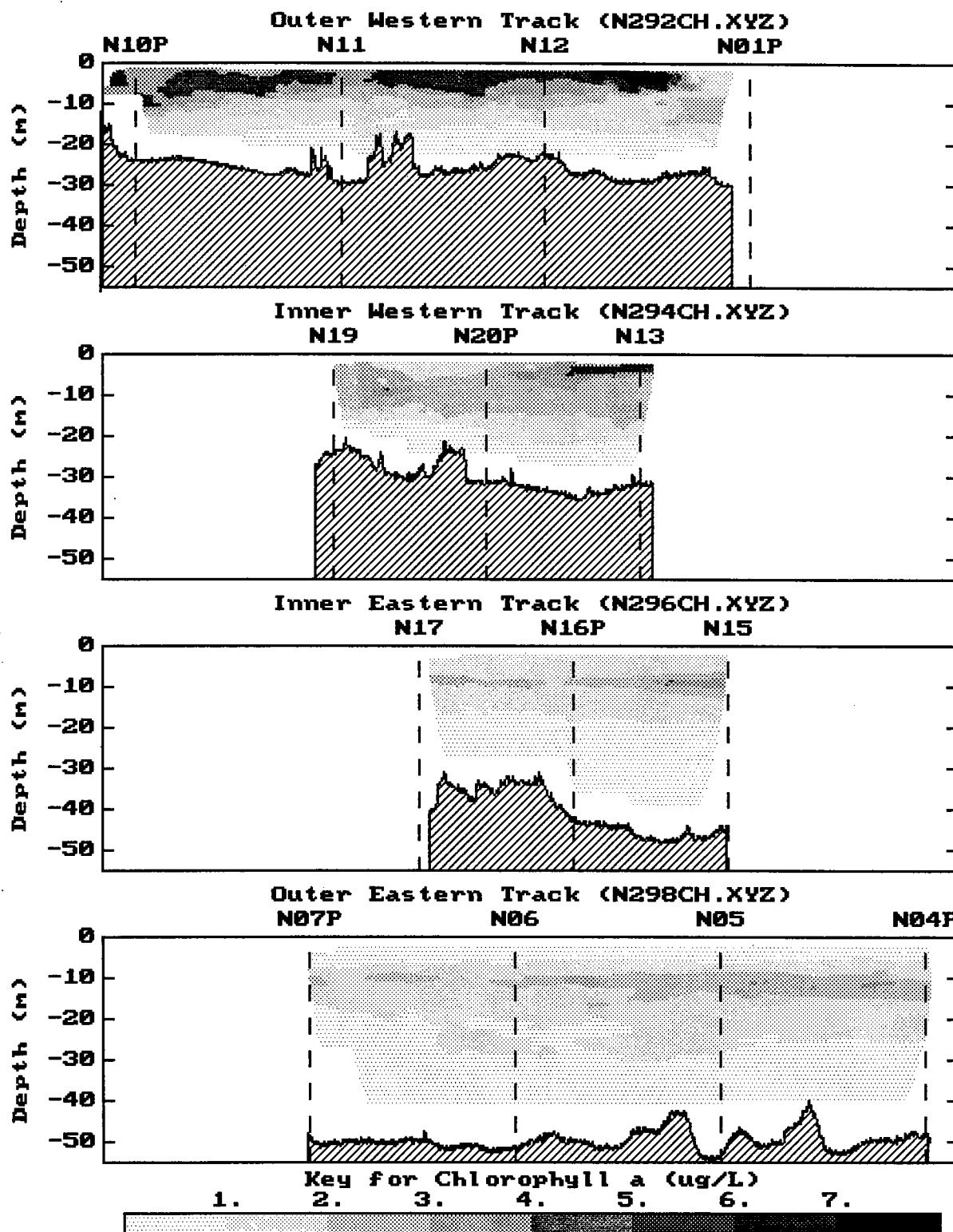
Figure 5-7b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in late July 1993. The view is towards Boston Harbor.

6.0 DISCUSSION OF THE EARLY SUMMER PERIOD OF SURVEYS

6.1 Water Properties

6.1.1 Variability at the Regional Scale

In June 1993, some minor regional-scale distinctions were observable. There was a shore-to-sea gradient in the degree of stratification. All stations within 5-10 km from shore from Cohasset south to stations F03 and F01P in western Cape Cod Bay were well-mixed, a feature which likely relates to mixing by wind. In contrast, shallow stations north of Boston (F18, F20) were stratified. In this respect, there was a small difference between northern and southern areas within Massachusetts Bay. There was a slight temperature and salinity difference between inshore and offshore waters, the former often being a bit cooler and marginally fresher. The gradient, in physical parameters, from the Harbor to the nearfield and southward along the coast was detectable, but slight.

Cape Cod Bay and Massachusetts Bay were not particularly distinct from each other, but there was a noticeable difference from west to east across Cape Cod Bay that in part paralleled the general shore-to-sea gradation described above. For example, surface water at station F02P at the eastern side of Cape Cod Bay was warm, quite fresh, and had a deep pycnocline (about 20-25 m in about 30 m of water) with a turbid bottom layer (see Appendix B). Station F04 was similar to station F02P in deepwater aspects, although it had a separate, cooler, near-surface layer and therefore an additional pycnocline at about 10 m depth. Thus, there were clear differences in the physical regimes of the west and east sides of Cape Cod Bays, both west-side stations being mixed and both east-side stations being strongly stratified. This cross-Cape Cod Bay distinction during the summer season has been observed previously in MWRA and Massachusetts Bay monitoring programs.

Overall, the main distinction in the Bay system, as expected during this season, was in the vertical dimension. Variations in the definition and degree of layering at a given location, minor exceptions noted above, were essentially more local than regional. Sub-pycnocline bottom waters at a given depth were very similar in physical parameters, independent of geographic location.

6-1

6.1.2 Variability in the Nearfield

In terms of physical parameters, the geographical variation across the nearfield was slight during the entire period from June to July. As for the whole Bay, slight variations from west to east in the depth and definition of vertical layering were observed, but the main geographical variation was in chlorophyll (see below).

There were some short-term local variations noted at specific stations during the course of the June survey. Overall, however, from June through July stratification remained strong, fairly uniform across the field, and fairly constant over time. There was no strong evidence of a field-level perturbation of the thermal stratification.

6.1.3 Coherence of Nearfield and Farfield Station Properties

Variation across the nearfield was nearly as large as the variability across all stations in the Bays. This does not argue that the nearfield was particularly variable; conversely, total variation in physical parameters was small.

The western side of the nearfield obviously was influenced by inshore processes more than the eastern side. However, with respect to temperature and salinity, a weak signal of an inshore water source from the Harbor was occasionally apparent on this western side of the nearfield (cf. Figure 3-1). High-resolution studies (cf. Kelly and Albro, 1994) were effective in resolving the time-space coherence in water mass properties and inferring dynamical interactions between adjacent farfield and nearfield areas for this period, even when the range of physical parameters was relatively small.

6.1.4 Special Features: Comparison of 1993 with 1992

Figure 6-1 compares the annual temperature cycle in surface water observed at nearfield stations during 1992 with data for 1993 through July. The two years are comparable, although higher temperatures were reached earlier in 1993 and perhaps stabilized at the characteristic summer

temperature regime more strongly than in 1992. For example, on average, June-July 1992 saw a linear, progressive increase of about 6 °C or more from May to late July, whereas the difference from May to late July 1993 was somewhat less and the two surveys in July revealed very similar temperatures.

A striking feature of Figure 6-1 is that the data for early July 1993 have a particularly wide range. Although there was some variation inshore to offshore at this time, the pronounced vertical layering accounts for much of the large range, which also arises from the choice of a 10 m interval for summarizing the data. The pycnocline everywhere was shallow (5-10 m) and sharp, so several meters up or down at a station for the position of a bottle sampling means a variation of several degrees (cf. Appendices A and B). Given some local variation in the pycnocline and variations in the position of bottles at each station, vertical temperature variability becomes portrayed as regional variability in Figure 6-1. This is true in general for summer, where the range in temperature become much wider than during unstratified periods.

Figure 6-2 shows DO in bottom waters of the nearfield during 1992 and to date in 1993. The DO in the bottom layer was similar throughout the field, as evidenced by the constrained range of values during any survey, even in the summer.

DO during the winter-spring periods of the two years was quite different (see also Kelly et al., 1993d,e). After this, a striking pattern for bottom-water DO is that there was a depression of DO in May of each year, following the onset of stratification. Thereafter, there appeared a stabilization or slight rise in DO concentrations in spite of increasing bottom water temperatures. The rise in early summer was more pronounced in 1992 than 1993, which might relate in part to differences in intensity and timing of the spring bloom in each year. Interannual differences in mid water chlorophyll and associated production of mid water DO may have contributed to this early summer variability (see also below). Physical factors such as overturn of the water column or advection of bottom water into the nearfield, could also create DO stabilization or rise during the early summer period. Advection seems an unlikely principal factor in 1993 given the similarity in physical and

geochemical characteristics of bottom water described for the suite of surveys. An overturn driven by a vertical mixing event is difficult to address without any profile data between mid May and late June.

6.2 Water Column Nutrient Dynamics

6.2.1 Seasonal Stratification

During June and July, stratification, other than at shallow western-edge coastal stations, was strong and quite consistent over time. This uniformity lead to the main observation of nutrient concentrations with depth — low or depleted levels in the surface layer (Figure 6-3) and a progressive increase with increasing depth below the thermocline/pycnocline that was essentially independent of geographic location. Concomitantly, only a slight change in bottom-water nutrient concentrations in the nearfield was noted from June through July.

6.2.2 Inshore-offshore Gradients

For dissolved inorganic nutrients, the gradient from Boston Harbor was small, repeating the general trend observed in 1992 (Kelly, 1994). Instead of nutrients or physical variables, the principal observable gradients from the Harbor at this time of year are in turbidity and chlorophyll. In this regard, it was interesting to note a similar pattern several kilometers off Salem Harbor (station F20) in June — locally higher chlorophyll and turbidity without concomitant enrichment in dissolved nutrients.

The broad scale difference from shore-to-sea with respect to stratification, i.e. well-mixed at shallow western-edge stations vs. stratified offshore conditions, did not appear to create differences in nutrient concentrations at the surface (cf. Figure 3-5 to 3-8). However, it did lead to reduced nutrient concentrations at depth in the mixed water columns relative to stratified conditions (Appendix A).

The data did not provide evidence of an influence on surface nutrients in the nearfield from an offshore or northerly direction. However, in June there was a deepening of the pycnocline towards

the northeast corner of the nearfield, which could suggest a slightly different pool of surface water there. At depth, because nutrients were generally higher, there was potential to influence nutrient concentrations in the nearfield if deeper offshore water intruded. Given the strong vertical layering, diffusive and advective communication of bottom waters should in theory be faster and/or require less energy to happen horizontally, along σ_T surfaces. Due to the similarity of nutrient concentrations at depths below the pycnocline, however, there was little gradient to induce a strong diffusive flux. The extent of any advective communication is unknown and would be hard to detect given the relative constancy of conditions in each layer. The stability in bottom water nutrients in the nearfield over this period and the fact there was little change in overall water quality characteristics supports the argument that advective exchange rates with offshore waters were slow during stratification, as expected from previous and ongoing physical oceanographic studies.

6.2.3 Special Features: Comparison of 1993 with 1992

The means and ranges for DIN concentrations during June and July were similar in 1992 and 1993 and values were low during all surveys (Figure 6-3). For bottom waters of the nearfield in 1992, an apparent disruption caused significant variability in the vertical nutrient distribution in late July (Kelly *et al.*, 1993a), although the vertical pattern was "reorganized" and variability diminished by early August. In comparison, in 1993, a strong consistent pattern was observed and no disruption was identified from the data in hand. These interannual differences are most likely due to climatological differences between the years, but this possibility can only be examined anecdotally.

6.3 Biology in Relation to Water Properties and Nutrient Dynamics

6.3.1 Phytoplankton-Zooplankton Relationships

There was a strong relationship between total phytoplankton cell counts and chlorophyll across stations in Massachusetts and Cape Cod Bays (Figure 6-4) with the one exception described in Section 3. This may provide ancillary evidence of the relative similarity of the overall phytoplankton community composition through the Bays at this time. Interestingly, total zooplankton abundance (not

measured at the anomalous high point in Figure 6-4) and chlorophyll did not relate well (Figure 6-5). Total zooplankton abundance was high at three of the four principal locations having high chlorophyll (stations F23P, N10P, and N20P), but the highest numbers were found at an offshore station (N16P) having a lower average chlorophyll concentration — thus, the lack of a strong pattern.

Perhaps a focus on certain groups or taxa would reveal stronger overall patterns. Total numbers do not reflect differences in grazing rates, energetics, development times, and therefore responsiveness of zooplankton to chlorophyll concentration variability, much less the quality and preferability of different phytoplankton as food. So, the lack of a general relationship should not be construed as a lack of strong coupling between phytoplankton and zooplankton communities. On inspection of the taxa, a geographic trend was that *Acartia* was found at the sites with higher chlorophyll (Section 3). The *Acartia* trend may well be more a reflection of the origin and history of the water mass than a responsiveness to growth of chlorophyll. Accordingly, simple interpretations of zooplankton-phytoplankton linkages are very difficult without more data suited to time trend analyses of areas or discrete water masses.

6.3.2 Plankton Species and Water Properties

There were few striking geographic distinctions in dominant species composition in whole-water or 20-μm screened samples taken in the Bays during June. Diatoms, microflagellates, and cryptomonads regularly dominated the community and a number of dinoflagellates were present in low numbers. Although a small gradient in nutrients was apparent from the Harbor, the station with highest nutrients (F23P) did not have an anomalous phytoplankton community. In the zone of stations from the Harbor eastward and southward that had higher chlorophyll, the phytoplankton community was quite similar to that observed in adjacent stations both north and further east. Many studies of nutrient enrichment find stimulation of certain species from the mix of those present, but without a major shift in community composition; perhaps the observations in June reflect just such a response.

At station N10P there are data for phytoplankton at the surface for each farfield and nearfield survey, that are useful for looking at time trends during the period (Table 6-1). This station usually captures

much of the flavor of water quality in outer Boston Harbor, as it receives tidal export through the southern Harbor exit. Throughout the period, the water was dominated by diatoms, principally *Leptocylindrus danicus* or *Skeletonema costatum*, either of which approached or exceeded 1 million cells per liter at surveys during the period. Fluctuations in total cells mainly reflect variations in these two species. Other diatoms were also dominants: several *Chaetoceros* species and *Rhizosolenia delicatula*, a species which may often be a dominant in autumn (Kelly *et al.*, 1993c). Time trends in screened samples at station N10P show a continual, stable, but low-level presence of several dinoflagellates and tintinnids (Table 6-2). Principal taxa include several species of *Ceratium* (especially *C. longipes*), *Dinophysis* and *Protoperidinium*.

Given the diatom dominance and variability, it is reasonable to presume that the time variability (survey to survey) for silicate in surface waters of the nearfield, may be related. The variability was small, but was not noted in DIN. Obviously the selective nutrient shift was not large enough to engender a strong dinoflagellate response during the period. Although a speculative notion, it seems reasonable to presume that phytoplankton were controlling dissolved nutrient variability in near-Harbor and nearfield surface waters at this time, rather than the converse, that variability in dissolved nutrient concentrations or ratios were controlling the phytoplankton.

6.3.3 Chlorophyll Biomass, Nutrients, and DO

There was little pattern between DIN and chlorophyll, but the relation between Total Nitrogen (TN) and chlorophyll was strong (Figure 6-6). Excepting the two points with high TN (about 20 μM), the slope suggests a rise of about 1 μg Chl L^{-1} for a 1 μM rise in TN. This has been a consistent, and on average, expected relationship (Kelly, 1991 and 1994), which should appear even when DIN is virtually depleted, because then the available nitrogen is tied up in organic forms. Highest TN samples were from station F23P at the Harbor's edge (Appendix A) and were associated with intermediate, rather than the highest, concentrations of chlorophyll. This, too, is a consistent observation for this location (Kelly, 1991; Kelly, 1994; Kelly and Albro, 1994).

Besides the correlation between TN and chlorophyll, other evidence strongly supports the notion that the level of phytoplankton biomass is broadly and directly controlled by nutrient sources. The west side of the nearfield, which receives nutrients principally by surface export from the Harbor, had consistently high chlorophyll concentrations measured *within the surface layer*. In contrast on the east side of the nearfield, the nutrient export from Boston Harbor has become more diluted and the principal nutrient source must shift to exchange across the pycnocline. There is a vertical, diffusive flux due to the vertical gradient of nutrients between bottom waters and the surface layer (see Kelly, 1994). Not surprisingly then, the highest chlorophyll in this more offshore region was regularly found at depth, usually within the pycnocline. To an extent, chlorophyll concentrations and distribution may indicate the direction of flux of the strongest nutrient source in a location. If so, abrupt shifts in chlorophyll layering from inshore to offshore may be one of the prime indicators of the geographic limits of Harbor-origin waters' influence within the nearfield. When physical water characteristics (like T-S variation) are in a very narrow range — a usual occurrence in surface waters in summer — chlorophyll seems the strongest signal for monitoring nutrient availability and fluxes.

DO, as % saturation, seemed to follow the chlorophyll distribution. Interestingly, though, the concordance was that *higher* DO was found at the position of maximum chlorophyll concentrations and thus appeared as a layer at intermediate depth in some offshore waters. This data is evidence for a strong link between nutrient sources and primary production, a topic discussed shortly, as well as nutrient sources and chlorophyll. It was noted that near the Harbor (station F23P), where nutrients were high, both production and respiration measurements recorded relatively high rates. Even though not stratified, station F23P was the anomalous location where a relatively low % DO saturation was found in June (cf. Figure 3-13).

6.3.4 Metabolism and Environment

As detailed in Section 3, average chlorophyll and integrated production rates were strongly correlated. However, rates based on samples from the surface and chlorophyll maximum differed sharply, as shown in Figure 6-7. In the figure, each rate for a station is plotted relative to the integrated water column chlorophyll (to the 0.5% isolume). To obtain a best estimate of the rate, some averaging

scheme may be appropriate, although a good approach would be to incubate samples over more depths to achieve a more faithful depth-integration scheme that incorporates P-I differences associated with populations residing at different depths. Regardless, the patterns of production with chlorophyll (either using average concentration [Figure 3-27b] or photic-zone mass [Figure 6-7]) are quite strong. Kelly (1993) demonstrated, following Cole and Cloern (1987) and in part using these June 1993 data, that biomass in the nearfield was closely correlated to production, particularly if one accounts for the depth of the photic zone.

During the summer, biomass is a main determinant of metabolism, not only on the basis of integrated water column production rates, but also in terms of the vertical distribution of production. Modeling indicated that vertical production rate profiles (from either sample incubation) paralleled the vertical chlorophyll concentration profile (e.g. Figure 3-27). Rates were generally high in surface layers and usually peaked at the chlorophyll maximum, which usually was within the top 3-13 m of the water column and in all cases except one was well above the 0.5 or 1 % isolume (Appendix B). The exception was station F02P, where a very deep chlorophyll maximum was noted near the 0.5% isolume; highest production rates at F02P were found near the surface. In general, a supersaturated DO surface layer, and perhaps a mid-depth DO peak associated with the subsurface chlorophyll maximum, could be expected from the P-I incubations and modeled rates, and indeed this is what profiles suggested.

Respiration should increase where chlorophyll and production are high, barring differences in temperature. Not all respiration rates were significant and in particular the bottom water rates cannot be assessed reliably with the data. There were, however, some overall expected trends; a greater proportion of significant rates were observed near the surface and higher rates were found at locations with highest chlorophyll. Thus, to an extent, the linkage between nutrient sources, chlorophyll, and metabolism (production and respiration) seems supported by these data.

Interestingly, the concordance between DO saturation, nutrients, and production is not the prime relationship of concern with nutrient enrichment. Rather, the concern is an expectation that stratified waters underlying highly productive surface layers may experience lowered DO. Note that bottom

water respiration rates were hardest to detect and, by logic, must have been low (Appendix E). In spite of the regularly higher chlorophyll on the western side of the field, there is a limited range in the bottom-water DO across the whole nearfield (Figure 6-2) and, at best, very weak, across-field trends in bottom-water % DO saturation (Appendix A). Therefore, the bottom waters must either 1) not receive much of the organic matter from the productive layer, or 2) if they do, the receipt and/or subsequent respiration is not expressed in the water column as a localized phenomenon. Local "hot-spots" for sediment metabolism could exist because of the heterogeneous bottom and limited depositional area in the nearfield (Knebel, 1992; Giblin *et al.*, 1994). But if all respiration rates (in sediments or the bottom water layer) are low, tidal motion may effectively mix the bottom waters (at least a few meters off the bottom) to relative homogeneity, and produce the observed results. Kelly (1994) further summarized what is understood of the carbon and oxygen dynamics in the nearfield area.

Given the strong stratification, a fairly consistent and uniform field, and substantial production rates, it seemed a good instance to examine if modeled and measured metabolism trends over depth could be assessed by a different approach — observing free-water changes *in situ*. In the following approach, the field is treated as a homogeneous unit. Sampling for the June nearfield survey progressed from station N10P clockwise around the outer box of stations, spiraling in to the inner box from station N09 to N19 and then from N18 to N21 (Albro, 1993a). Since sampling occurred from near dawn to mid-afternoon, one can ask if trends in DO during the daytime can be seen that would reflect measured and modeled metabolism trends.

Results are shown in Figure 6-8. The top three strata — with 0-4 m being chosen to include only the surfacemost bottle-depth sample from each of the twenty-one stations — covered the depth to 15 m. This was deep enough to include the chlorophyll maximum at stations on both the east and west sides of the field (Figure 6-8a). The bottom three strata cover the lower pycnocline to about 3-5 m off the bottom at each station (Figure 6-8b). There is some variability from point to point, which is expected due to differences in chlorophyll across the stations and we were not sampling the same discrete small parcel of water. Nevertheless, Figure 6-8 shows coherent trends over time, as summarized in Table 6-3. Significant increases over the day, which could indicate net production, were only seen in the

top three strata. P-I modeling shows a similar result. The 0-4 m layer, is exposed to the atmosphere and might have changes that are due to diffusion, but given that even the earliest samples of the day were slight supersaturated, a true increase due to production would be underestimated if anything. In contrast to the surface layers, all bottom strata had no change over the day. No detectable production or respiration is therefore suggested for these bottom waters.

The trends, besides confirming the basic pattern for production over depth, also may suggest an overall metabolism similar to that measured in bottle P-I incubations. For example, the slopes of increase are about 0.5 to 0.9 % DO saturation per h. Using the approximate saturation values for the mean temperature and salinity in each strata (about 8.7 to 9.2 mg L^{-1}) and the slopes in Table 6-3, the calculated rates implied for the three strata are 0.045 to 0.083 mg O_2 L^{-1} h^{-1}, or about 0.063 mg O_2 L^{-1} h^{-1} on average. Converting to an areal basis for the 15 m layer, the integrated rate is 945 mg O_2 m^{-2} h^{-1}. Using standard conversions to convert hourly to daily rates, and assuming a Photosynthetic Quotient (PQ) range of 1 to 1.25 (Kelly et al., 1993c and Section 2, Methods), the result is a production estimate, uncorrected for diffusion, of 2.5 to 3.2 g C m^{-2} d^{-1}. For comparison, the six nearfield stations, measured just days before on the farfield survey had an average of 2.4 g C m^{-2} d^{-1}, based on ^{14}C incubations at both depths, or 3.1 g C m^{-2} d^{-1} based only on surface ^{14}C incubations (refer to Table 3-3). The comparability is remarkable and should be provocative, especially to those who expected diurnal DO changes not to be easily detectable.

That no changes occurred in bottom water, where respiration rates have been very difficult to detect in 8-10 h incubations, offers confirmation of the bottle measurements and depth trends. It is interesting to note that the surface layer respiration rates that were significant were on the order of 0.007 to 0.03 mg O_2 L^{-1} h^{-1} (Appendix E). Respiration applies over 24 hrs, so as a daily rate an average (using 0.02 mg O_2 L^{-1} h^{-1}) in the surface might be as high as about 0.48 mg O_2 L^{-1}. Over the 15 m layer, assuming a Respiratory Quotient (RQ) of 1 this converts to 2.7 g C m^{-2} d^{-1}. To directly compare this with production, we would have to know if ^{14}C production rates measured net or gross production and ^{14}C production can measure anywhere between the two. Nonetheless, initial interpretations of these calculations suggests that the majority of the day's production has the potential to be consumed within the surface layer and not passed to the bottom. This suggestion too may be

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found provocative and certainly needs more evidence to be accepted. The concept is significant, however, for understanding the present relationship between surface and bottom waters with respect to oxygen dynamics.

At a minimum, this example suggests that the system is sometimes productive enough to produce diurnal changes that are detectable via monitoring of free-water DO and water quality. Perhaps more importantly, the promise of the approach indicates that the nearfield, at some periods and for some analyses, may be considered as a homogeneous unit that is sampled repeatedly. The ultimate importance of this may be to free us from performing countless statistical tests on a station-by-station basis. Given the dynamics of the field, the station-by-station statistical approach will suffer power from inherent small-scale variability. Due to tidal "aliasing" and other attendant concerns, the station-by-station water motion probably amounts to testing features at fine scales that are often ephemeral and not ecologically meaningful.

6.3.5 Special Features: Comparison of 1993 with 1992

For the nearfield, Figure 6-9 show surface layer trends for chlorophyll concentrations in 1992 and 1993. Early in the season, 1993 had been much different from 1992. In June and early July 1992, concentrations were slightly higher on average than in 1993, whereas late July 1992 was slightly lower on average than 1993. While there may have been slight differences in time progressions for this season across the two years, the main message from the comparison is relative similarity. The range for both years during the period was about 0.5 to 6 μg L^{-1} for all but a few points.

Baywide, a main difference between the two years was that in June 1992 an explosive growth of *Ceratium longipes* was documented as a subsurface layer (10^5 cells L^{-1}) in Cape Cod Bay (Kelly *et al.* 1993a). *Ceratium longipes* and other *Ceratium* species were present throughout both Bays in 1992 in the range 10^1 to 10^3 cells L^{-1}. In 1993 the genus was routinely present in the range 10^2 to 10^3 cells L^{-1}, and reached 10^4 cells L^{-1} at the subsurface chlorophyll maximum at stations N01P and N16P. One cannot be certain, but the development of the bloom in Cape Cod Bay in 1992 may have been

due to a special sequence of events including the chronology and intensity of the winter-spring bloom and its biogeochemical influence on water quality (Kelly *et al.*, 1993a and Kelly *et al.*, 1993c).

6.4 Summary and Recommendations

The main feature of the season, driving most of the water quality trends was a strong, consistent vertical stratification everywhere except shallow coastal stations. In part because of the stratification, the biological, chemical, and physical changes over time during the early part of the summer were not very remarkable. Trends for the most part were similar to those during the same period in 1992.

Production rates were high and the example of diurnal changes in the nearfield was provocative. Free-water change studies might be designed to supplement bottle metabolism measurements and confirm processes at the scale of ecological concern. As a data analyses recommendation, the example suggests the water column of the whole field, or portions of it (east vs. west), be considered as the suitable unit for statistical testing purposes.

Bottle respiration measurements, although incubation times were extended from 1992 studies, were still unable to consistently detect a significant change and may not estimate rates very well. A new strategy of time series measurements will be instituted for 1994. If oxygen dynamics and process-level understanding of carbon budgets is to remain part of the goal of monitoring, good estimates of respiration throughout the water column are a critical need.

Table 6-1. Abundance of top five dominant phytoplankton taxa in near-surface whole-water samples at station N10P collected in June and July 1993.

Date	22-June	25-June	07-July	28-July
CHAETOCEROS COMPRESSUS				0.082 (3)
CHAETOCEROS SPP. (<10UM)	0.086 (5)			0.054 (4)
CRYPTOMONADS		0.131 (5)	0.065 (4)	0.041 (5)
LEPTOCYLINDRUS DANICUS	1.080 (1)	3.647 (1)	0.663 (1)	
MICROFLAGELLATES	0.642 (2)	0.225 (3)	0.514 (2)	0.286 (2)
RHIZOSOLENIA DELICATULA		0.188 (4)	0.189 (3)	
SKELETONEMA COSTATUM	0.273 (3)	0.526 (2)		1.576 (1)
THALASSIOSIRA SPP.	0.102 (4)			
UNIDENTIFIED NAKED DINOFLAGELLATE			0.023 (5)	

Units are 10^6 cells L^{-1}

Table 6-2. Abundance of all identified phytoplankton taxa in near-surface screened (20um) samples at station N10P collected in June and July 1993.

| SPECIES	STATION	N10P	N10P	N10P	N10P
	SAMPLE	W93070097	W93070544	W93080034	W93090029
	DATE	22-Jun-93	25-Jun-93	07-Jul-93	28-Jul-93
ALEXANDRIUM TAMARENSE		0	0	0	0
ALORICATE CILIATES		38	123	8	0
CERATIUM FUSUS		78	205	323	200
CERATIUM LINEATUM		8	98	18	20
CERATIUM LONGIPES		1331	1509	425	455
CERATIUM MACROCEROS		0	0	0	0
CERATIUM TRIPOS		5	20	25	20
DICTYOCHA SPECULUM		5	0	0	0
DINOPHYSIS NORVEGICA		153	233	123	248
DINOPHYSIS OVUM		25	20	0	15
DINOPHYSIS SPP.		0	0	0	0
DISSODINIUM SPP.		0	0	0	8
GONYAULAX SPINIFERA		0	0	0	0
GONYAULAX SPP.		0	0	3	0
GYMNODINIUM SPP.		5	0	0	0
GYRODINIUM SPIRALE		10	18	0	3
GYRODINIUM SPP.		5	0	0	0
HETEROCAPSA TRIQUETRA		8	3	0	0
KATODINIUM SPP.		0	0	0	0
MESODINIUM RUBRUM		5	10	0	10
PROROCENTRUM MICANS		3	0	0	0
PROROCENTRUM MINIMUM		0	0	0	0
PROTOPERIDINIUM (CF) BREVIPES		8	0	0	0
PROTOPERIDINIUM BIPES		0	5	70	3
PROTOPERIDINIUM BREVE		20	15	35	0
PROTOPERIDINIUM DEPRESSUM		18	25	8	33
PROTOPERIDINIUM PELLUCIDUM		8	55	130	28
PROTOPERIDINIUM PENTAGONUM		0	0	0	13
PROTOPERIDINIUM SPP.		75	13	173	63
SCRIPPSIELLA TROCHOIDEA		0	0	0	0
TINTINNIDS		238	460	388	548
UNID. ATHECATE DINOFLAGELLATE		18	3	0	0
UNID. THECATE DINOFLAGELLATES		35	43	70	50

Values are cells/L

Table 6-3. Regression statistics for Diurnal DO changes in the nearfield on June 25, 1993.

Depth Strata (m)	R^2	P_r	Slope[1] (± stnd error)	Intercept[2] (± stnd error)
0-4	0.50	>0.0003	0.7 (± 0.2)	106 ± 2
4-10	0.35	>0.005	0.5 (± 0.2)	107 ± 2
10-15	0.44	>0.02	0.9 (± 0.3)	101 ± 3
15-20	0.007	ns	ns	107 ± 2
20-30	0.02	ns	ns	104 ± 3
>30	0.005	ns	ns	100 ± 1

[1] Units for slope are % saturation per hour.
[2] All intercepts were significant even if slope was not.

1992, Nearfield Stations
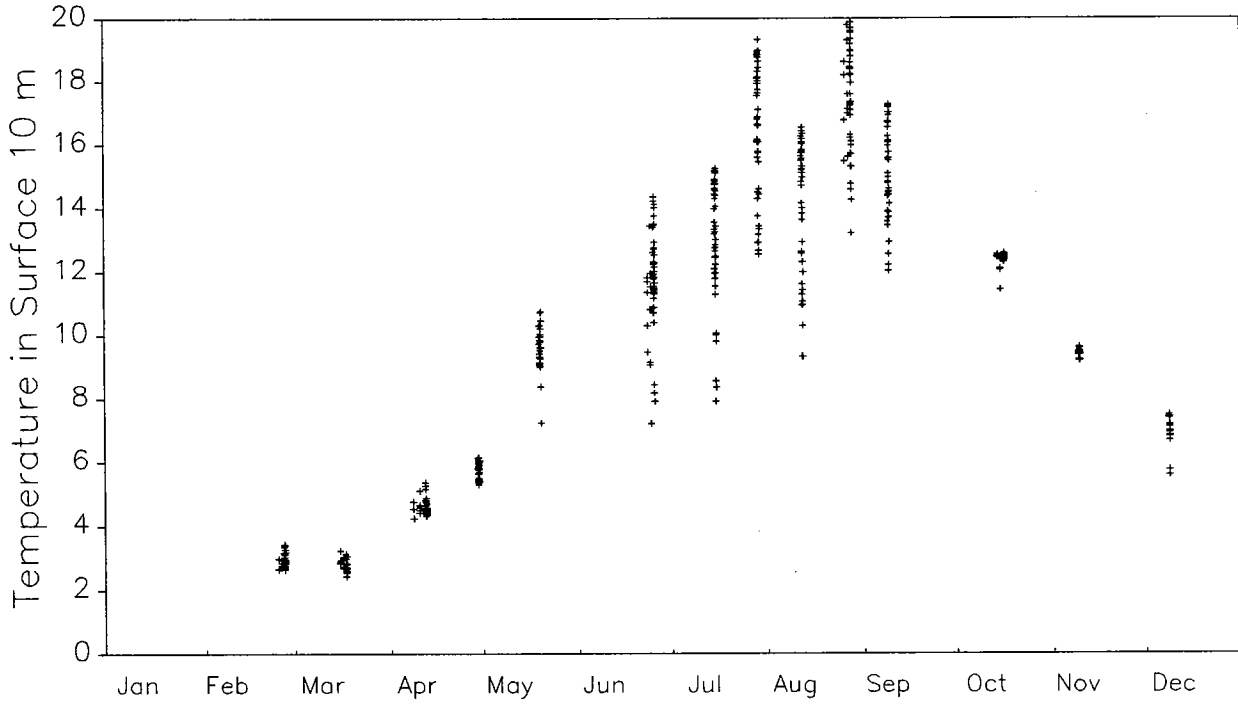
1993, Nearfield Stations
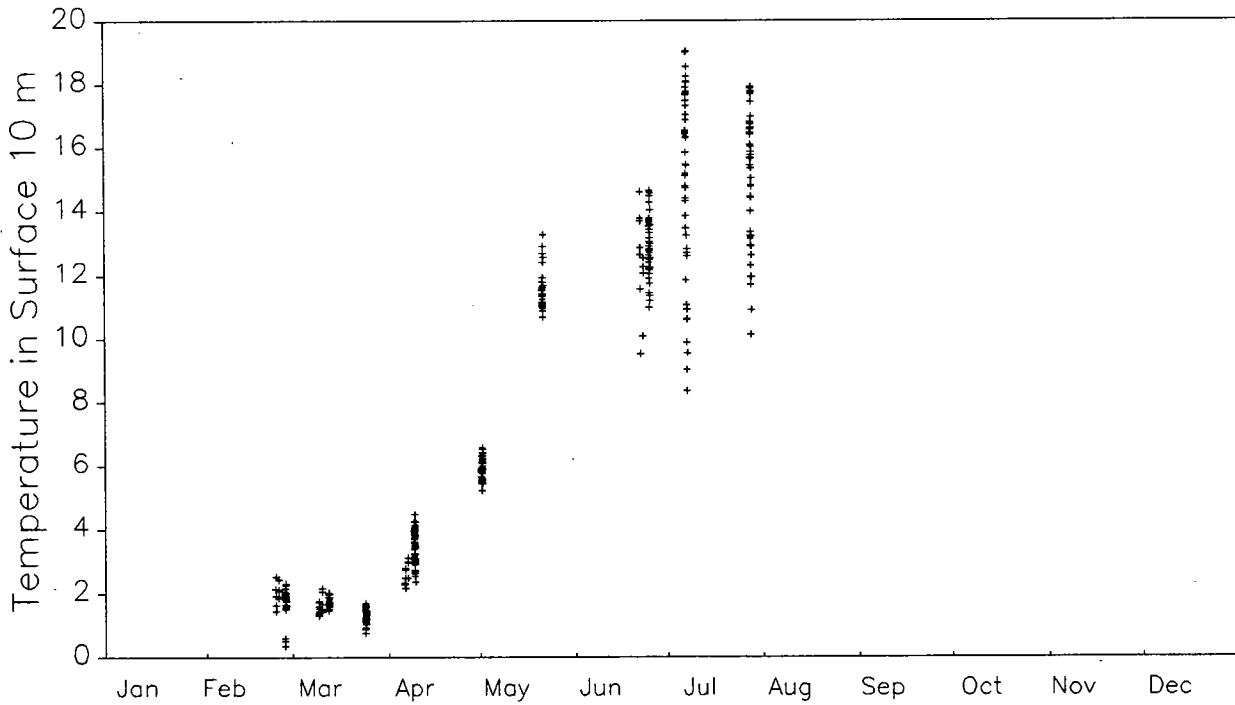
Figure 6-1. Comparison of the nearfield region in 1993 to the annual cycle of 1992: temperature (°C).
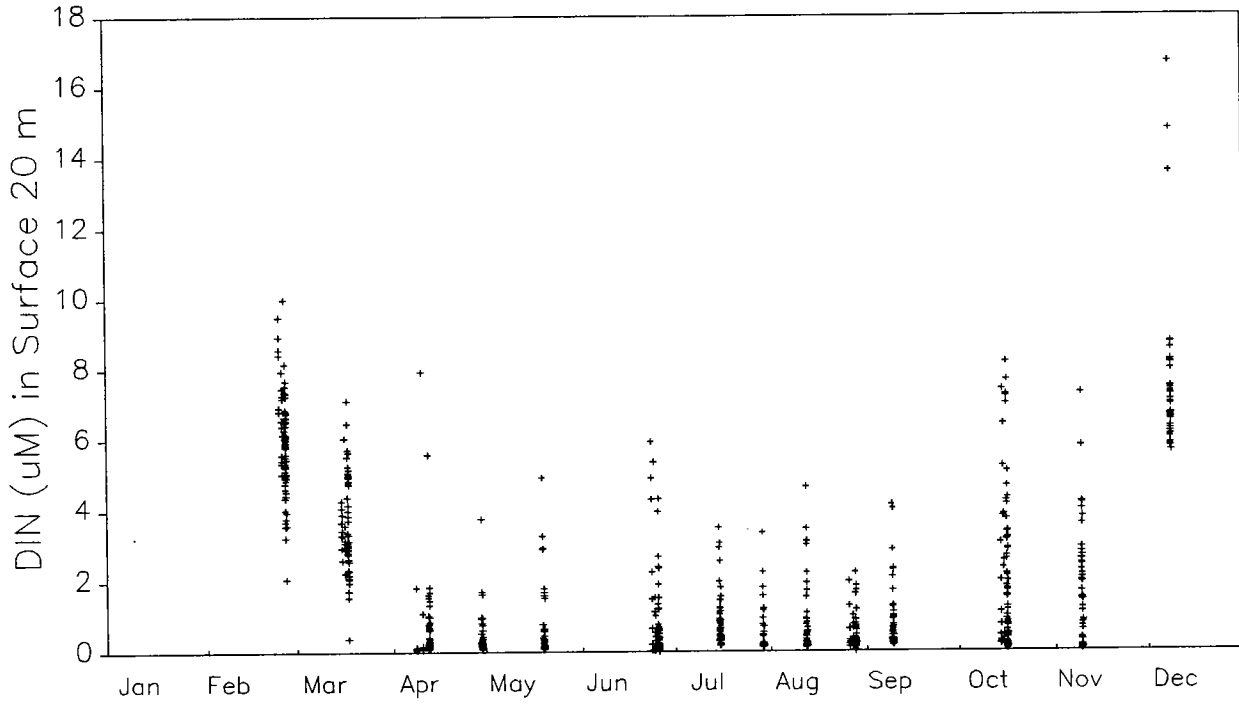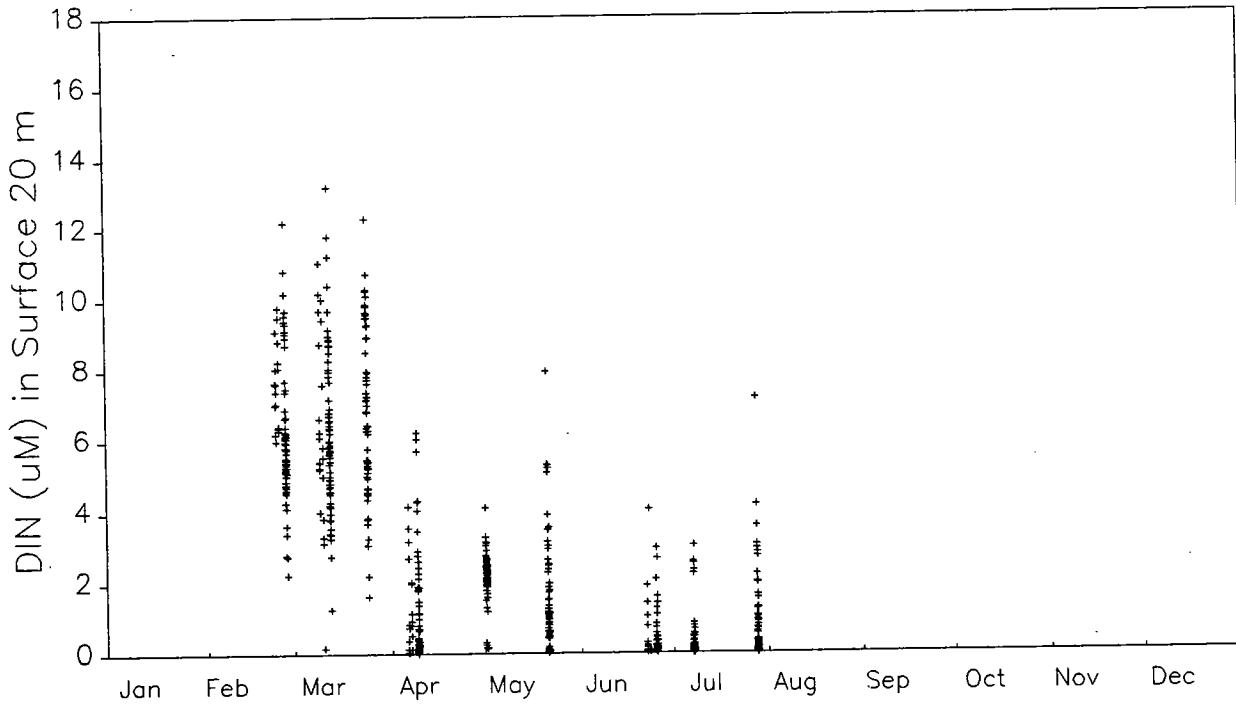
1992, Nearfield Stations
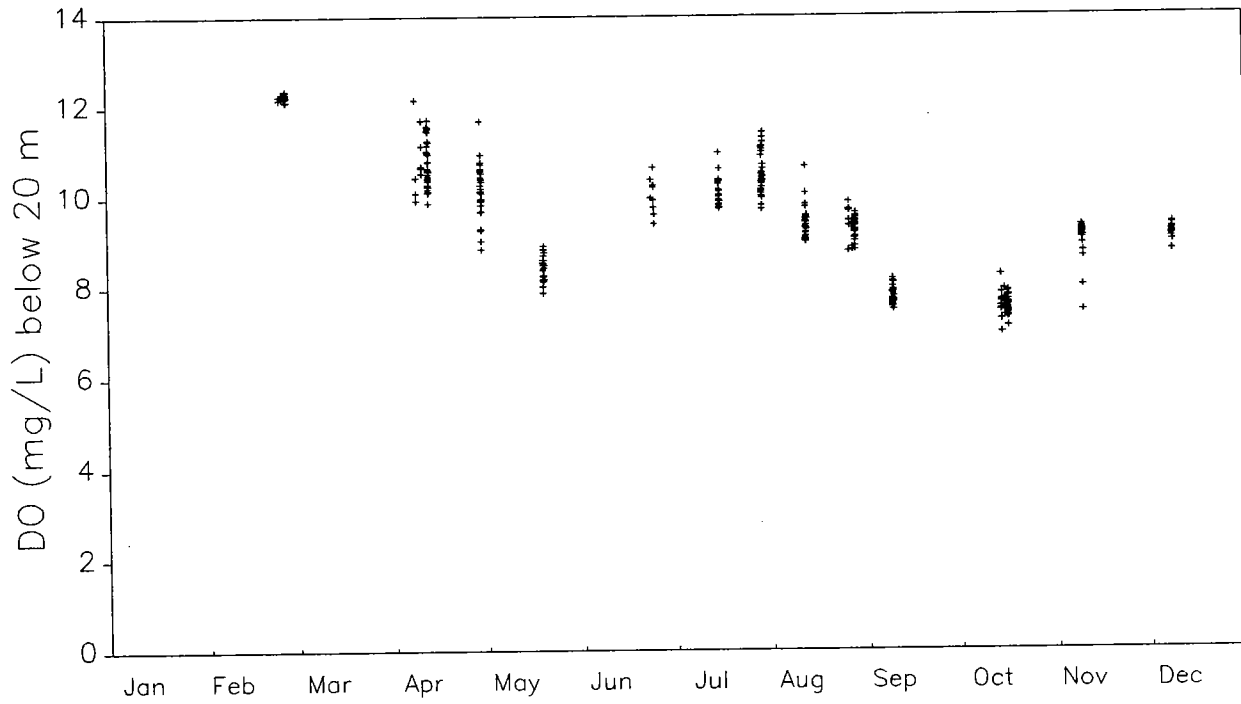
1993, Nearfield Stations
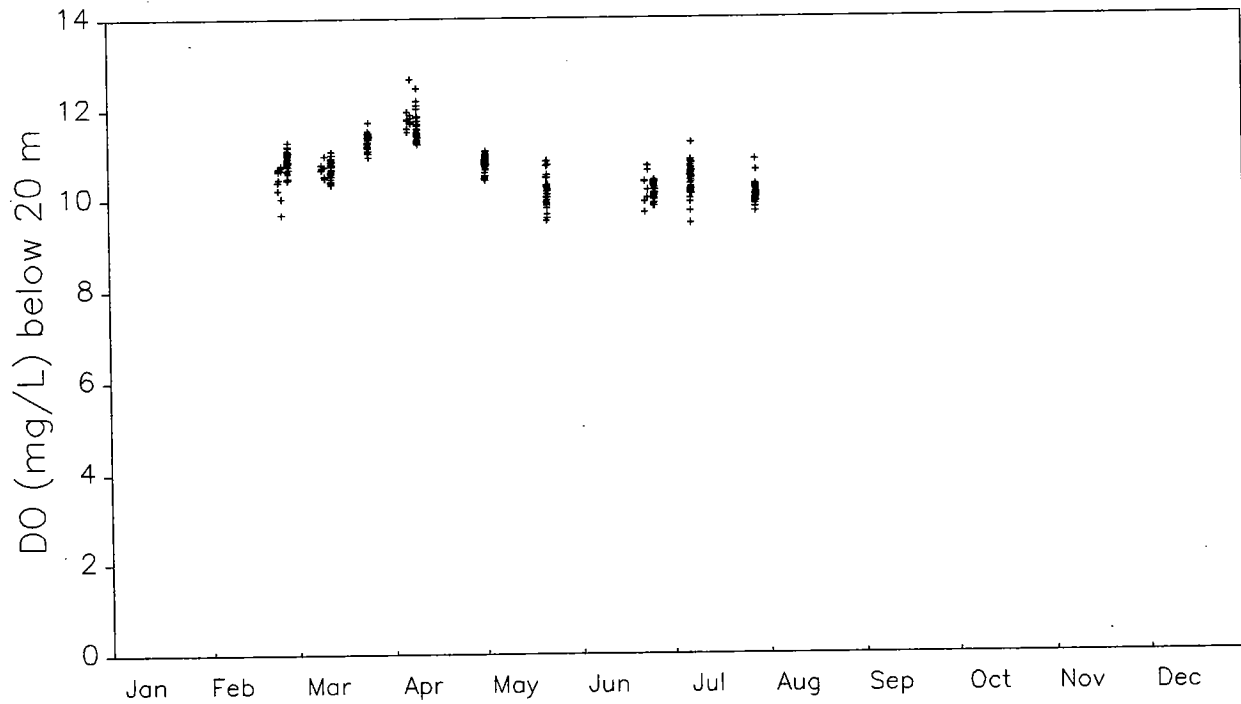
Figure 6-2. Comparison of the nearfield region in 1993 to the annual cycle of 1992: dissolved oxygen (mg/L).

Figure 6-3.   Comparison of the nearfield region in 1993 to the annual cycle of 1992: dissolved inorganic nitrogen (μm).
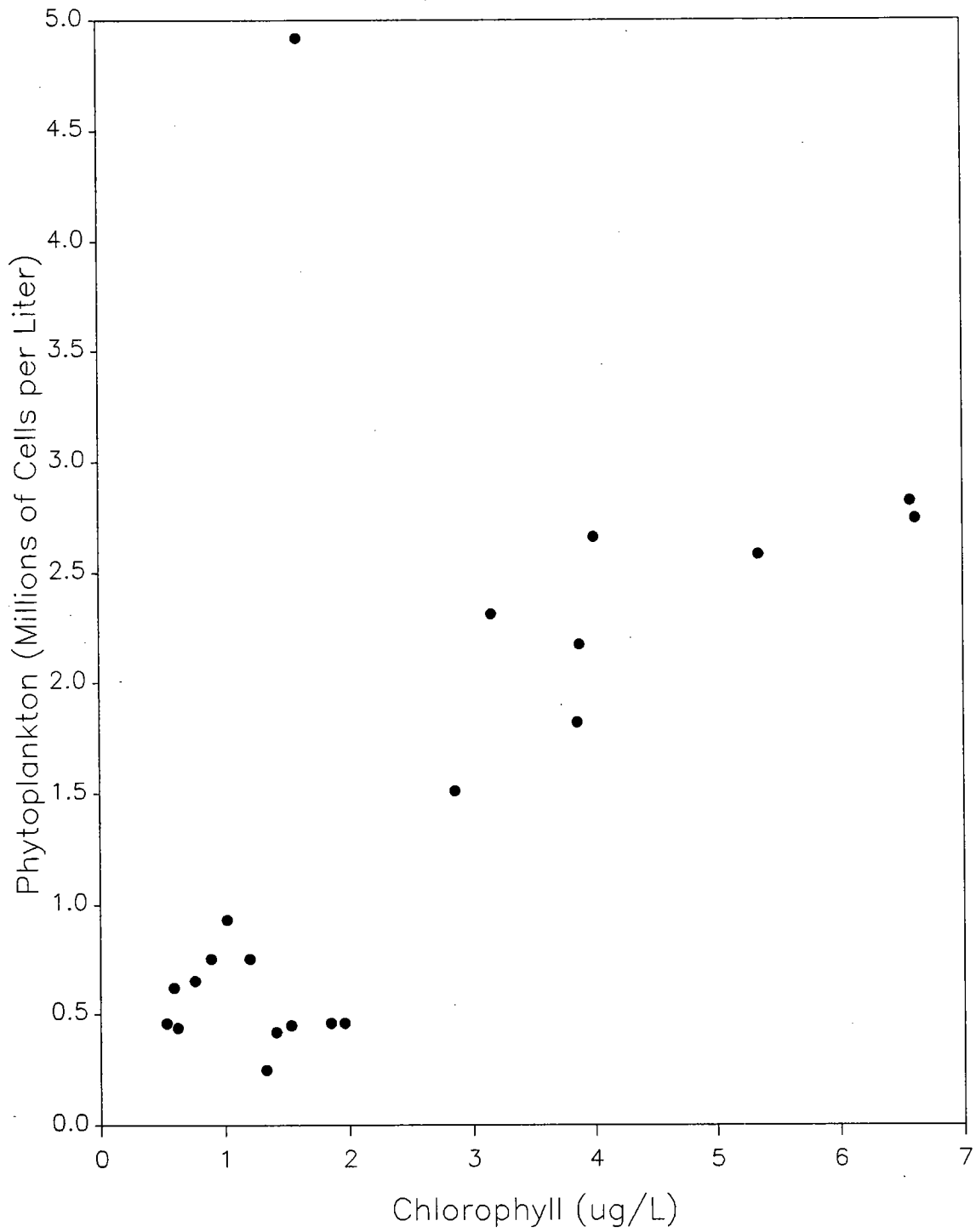
Figure 6-4. Phytoplankton abundance compared to chlorophyll (extracted) concentrations in samples from June 1993.
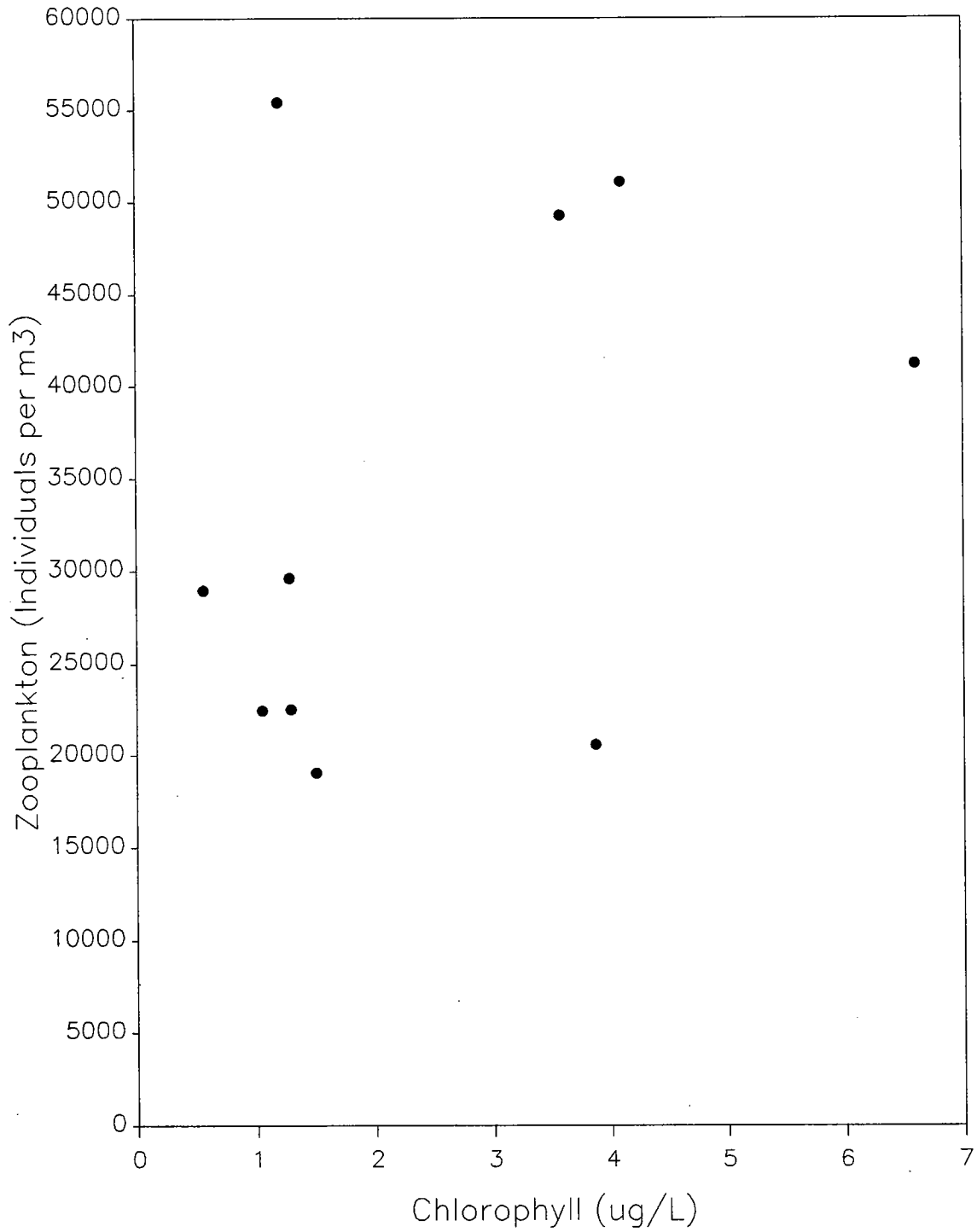
Figure 6-5. Zooplankton abundance compared to the average chlorophyll (extracted) concentration (n=2 depths) in the water column in June 1993.
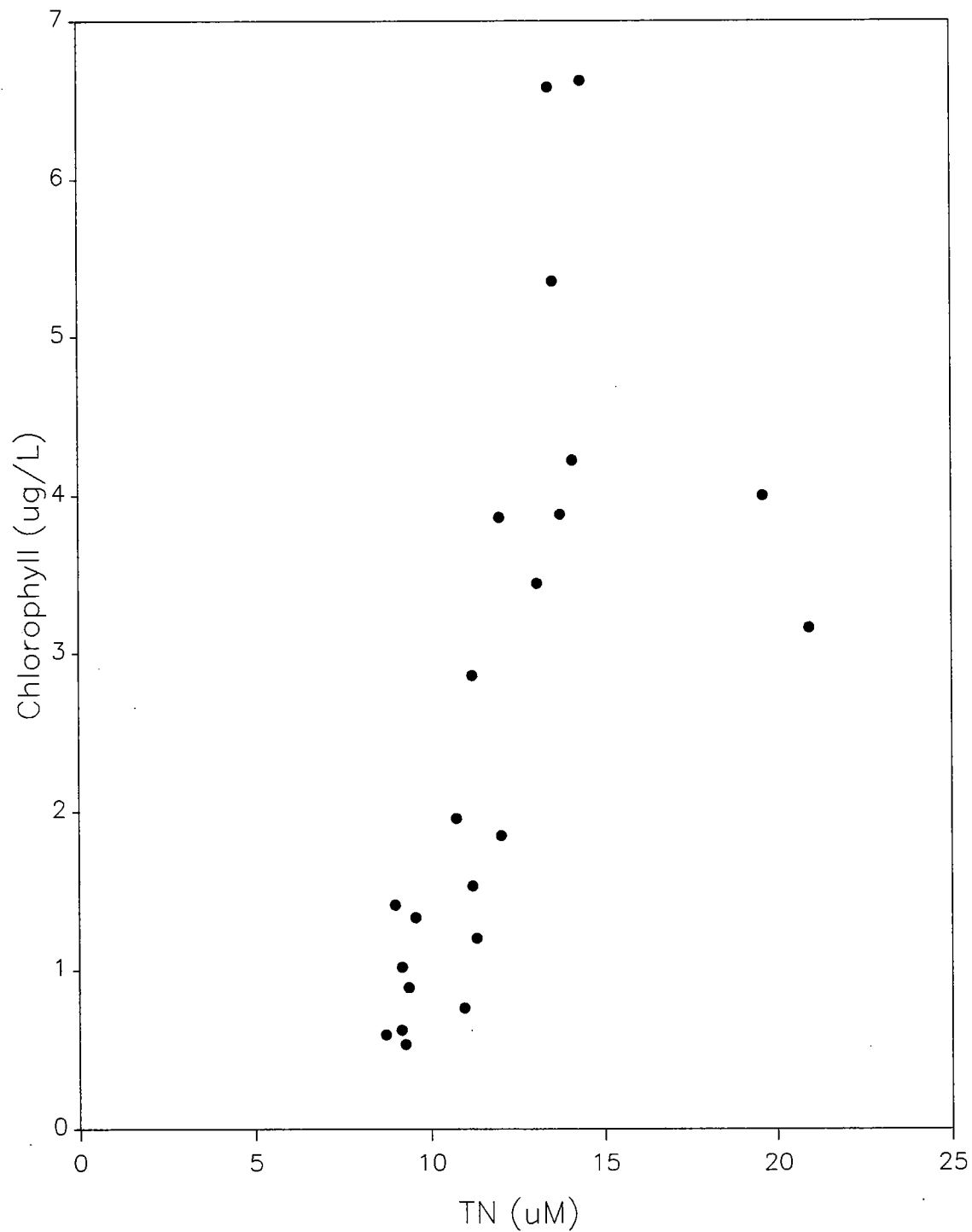
Figure 6-6. Chlorophyll and total nitrogen (extracted) concentrations in samples from June 1993.
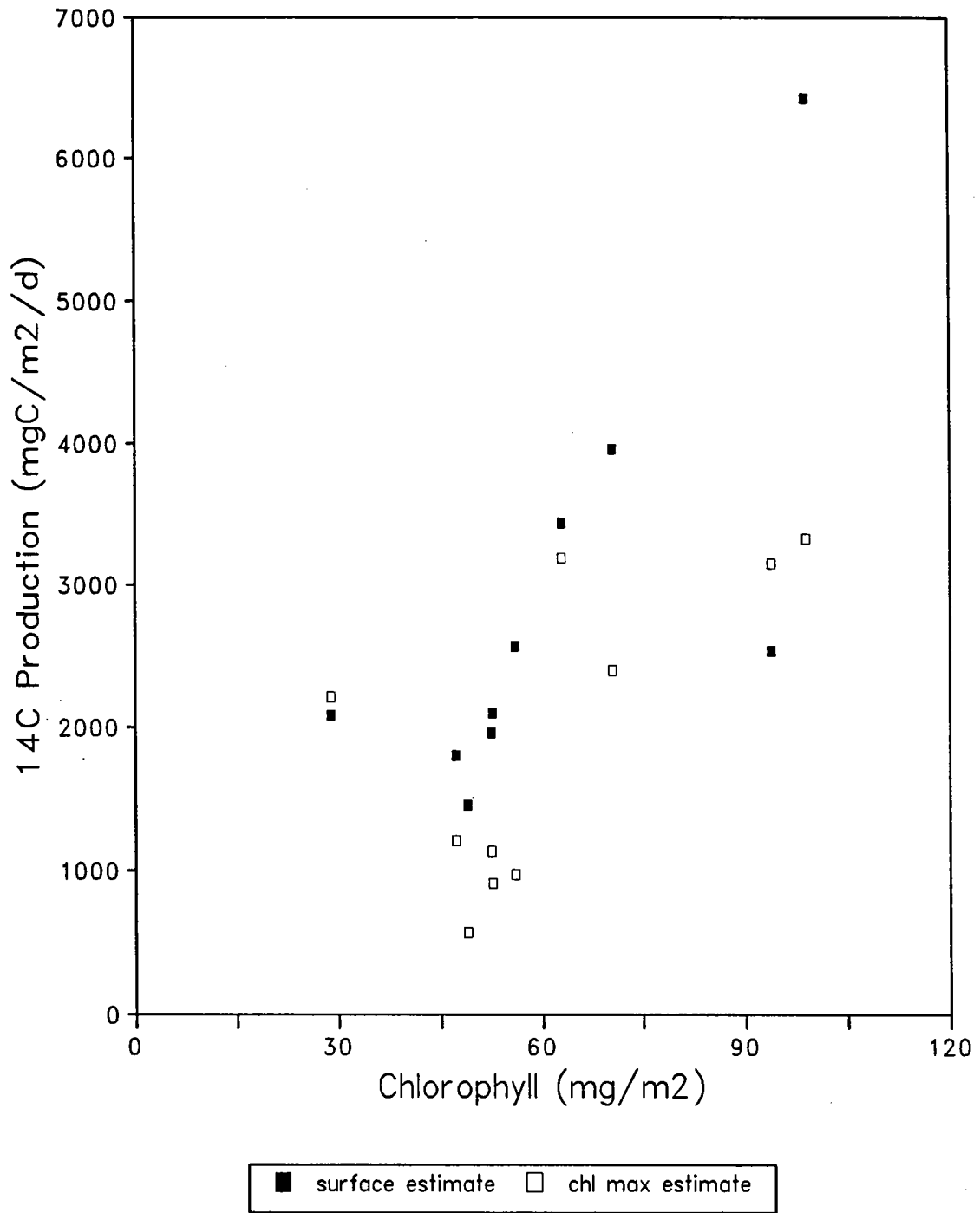
Figure 6-7. Integrated water column production (mean of surface and chl max incubations) relative to integrated chlorophyll in the photic zone. Chlorophyll is estimated from *in situ* fluorescence.
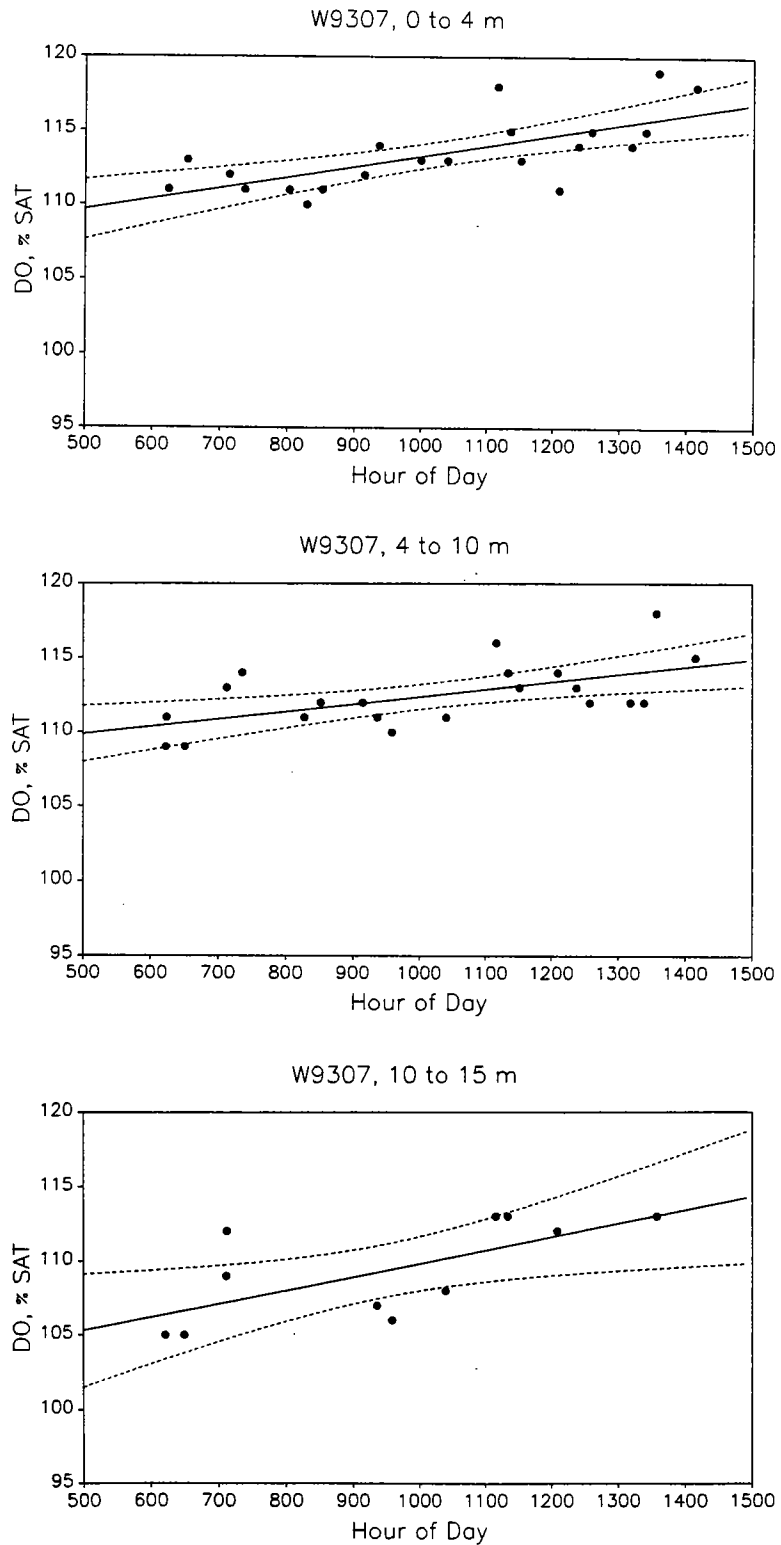
Figure 6-8a. Diurnal changes in DO in the nearfield (June 25, 1993) by depth strata within the surface 0-15 m. Solid and dotted lines show linear regression model ±95% confidence intervals. All slopes were significant from 0.
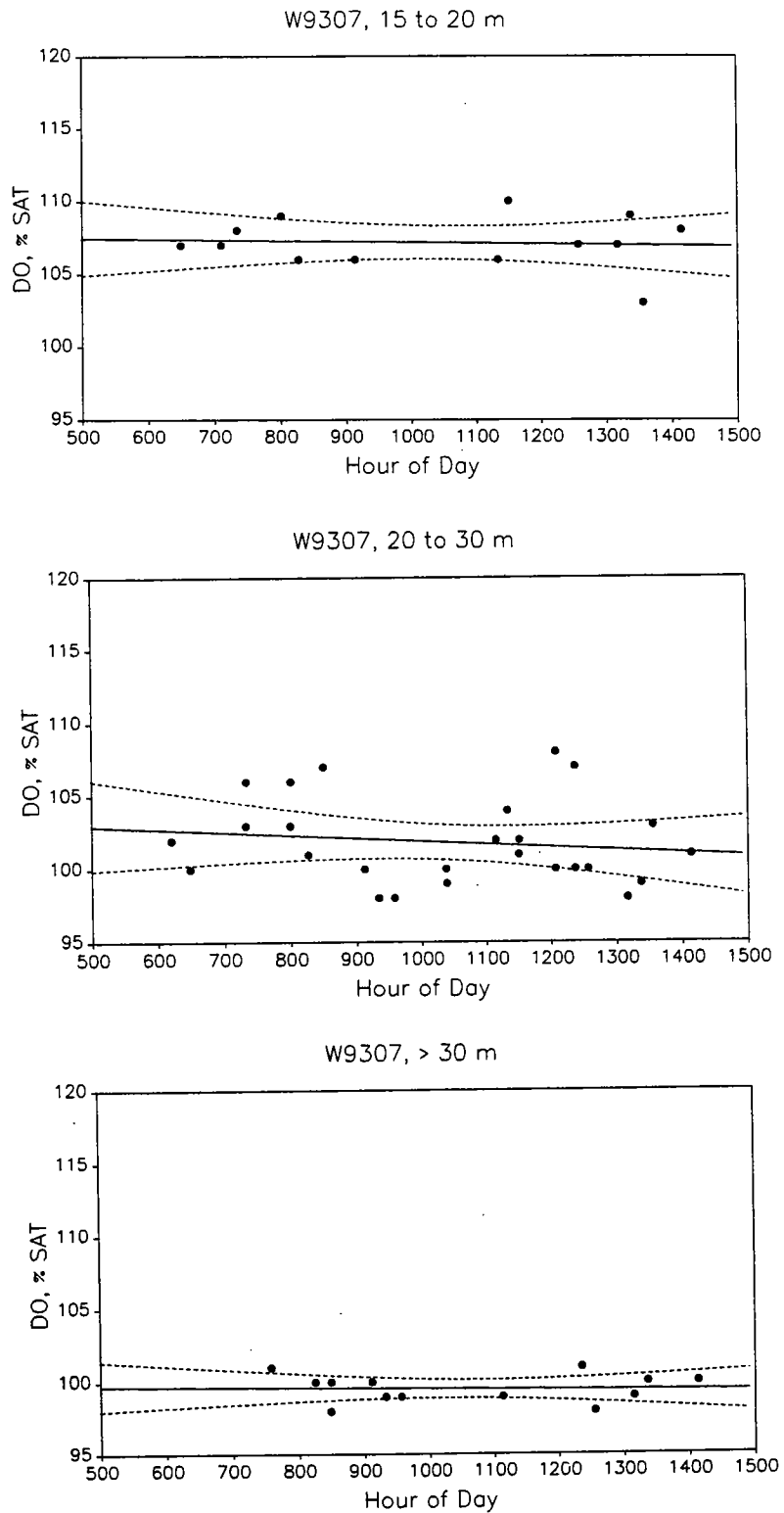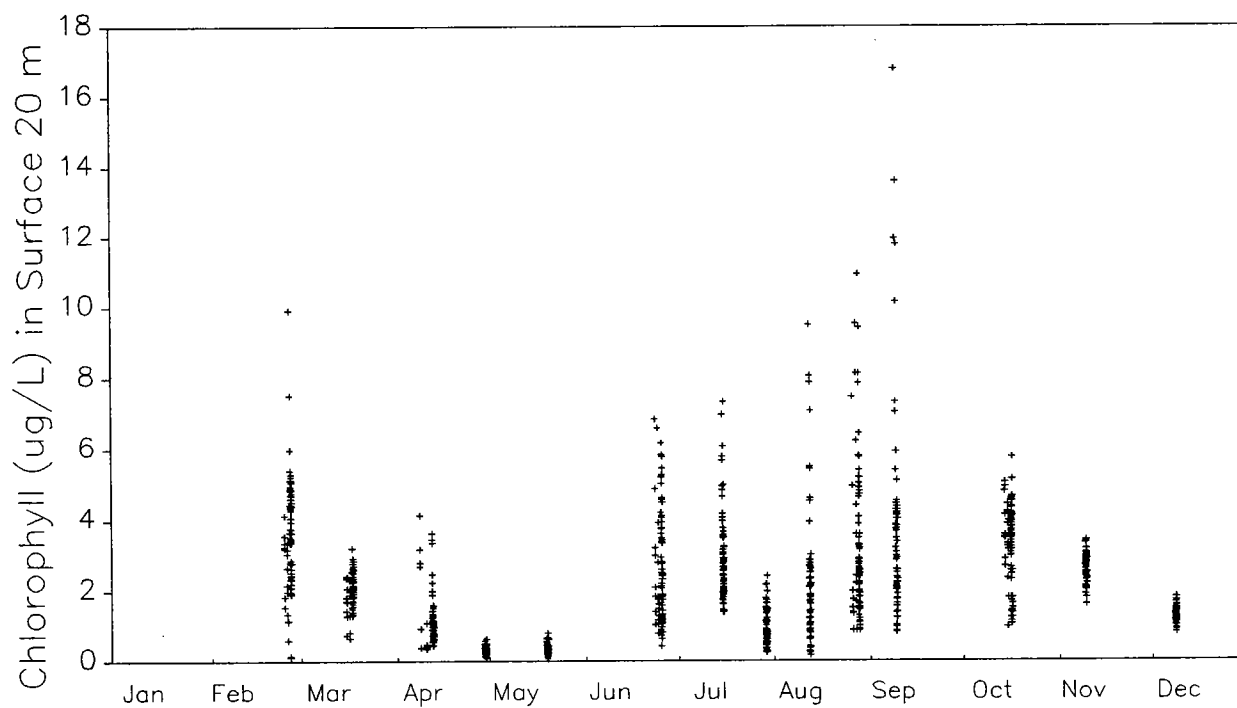
Figure 6-8b. Diurnal changes in DO in the nearfield (June 25, 1993) by depth strata within the bottom waters. Solid and dotted lines show linear regression model ±95% confidence intervals. No slopes were significant from 0.

1992, Nearfield Stations

1993, Nearfield Stations

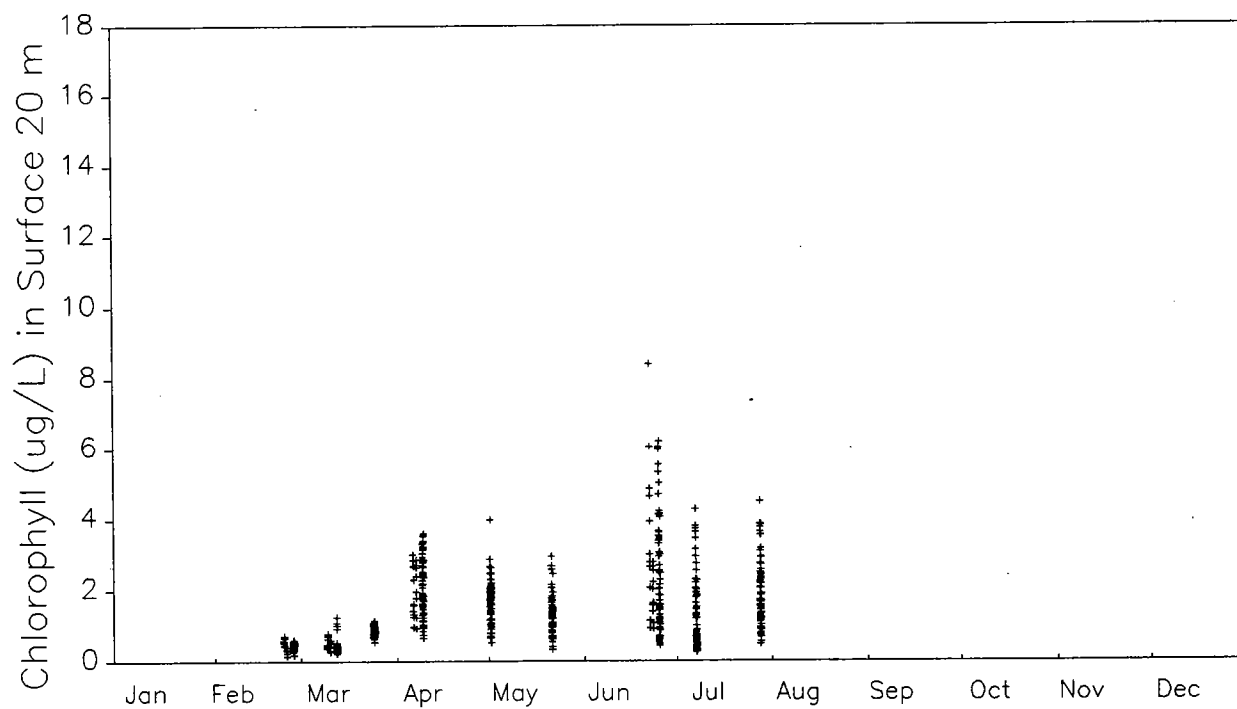**Figure 6-9.** Comparison of the nearfield region in 1993 to the annual cycle of 1992: chlorophyll (µg/L). Chlorophyll is estimated from *in situ* fluorescence.

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