Water quality monitoring in Massachusetts and Cape Cod Bays: October - December 1993

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FINAL

WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: OCTOBER - DECEMBER 1993

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EXECUTIVE SUMMARY

This report is the last 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 October, November, and December 1993; each of these surveys included sampling at 21 stations in the nearfield area. The October survey was a combined farfield/nearfield survey that covered 25 additional stations throughout Massachusetts Bay and Cape Cod Bay. In this report, data on physical, chemical, and biological measurements are presented and interrelationships of these measurements are examined. The major results are summarized here.

The main feature observed during this period was the cessation and sedimentation of the fall phytoplankton bloom of the diatom, *Asterionellopsis glacialis*. Chlorophyll concentrations and phytoplankton counts were very high during the October survey (4 to 27 $\mu g\ L^{-1}$ and 2 to 8 million cells L^{-1}, respectively). By the November survey, chlorophyll concentrations had declined to $<2\ \mu g\ L^{-1}$, but the more interesting observation was the short term change observed in chlorophyll in the nearfield. During the farfield survey (October 12 and 13), chlorophyll concentrations were high ($\sim 15\ \mu g\ L^{-1}$) and relatively consistent in the surface layer (<20 m depth) throughout the nearfield. When the nearfield BioProductivity stations were revisited during the nearfield survey, lower chlorophyll concentrations were observed in the upper 20 m (8 $\mu g\ L^{-1}$). This decrease was coincident with a large increase in chlorophyll (from 5 $\mu g\ L^{-1}$ to 10 $\mu g\ L^{-1}$) at depths >20 m. A similar overturn was observed in beam attenuation. Physical parameters and stratification, however, did not appear to change significantly over the 2 to 3 day period. Thus, rather than a consequence of physical mixing, the changes observed in chlorophyll resulted from the cessation and sedimentation of the *A. glacialis* bloom. Due to the paucity of recent and historical data for this region during the month of October, it is unclear if the bloom that was observed in 1993 was an extraordinary or common event.

There was a clear change in the vertical gradients for the chemical parameters in the nearfield over the course of the three surveys. During the October survey, the nearfield surface layer was nutrient depleted and oxygen supersaturated. By the November survey, these waters were nutrient-rich and oxygen undersaturated as a result of bottom waters being mixed into the surface layer. There was progressive mixing of the water column from October to December 1993 in the eastern nearfield, while the western nearfield stations were already well mixed in October.

Clear distinctions were made between Harbor/coastal stations and offshore stations based on a suite of physical, chemical, and biological parameters. An inshore-offshore gradient was observed west to east across the nearfield to varying degrees during each of the fall/early winter surveys.

Besides these general trends, specific findings were as follows (plankton and productivity measurements were made during the combined farfield/nearfield survey only):

- Nutrients – There was a significant change in surface nutrient concentrations over the course of the three surveys. Surface layer nutrients were nearly depleted in October due to high biological demand. In October, nutrient concentrations were higher at near-Harbor stations and in the bottom water at offshore stations. With the onset of winter mixing and the decline in

phytoplankton biomass, nutrient concentrations increased at all stations by November and remained high in December.

- Dissolved oxygen (DO) - With the exception of the Harbor-influenced stations, surface waters were supersaturated with oxygen during the October surveys. High DO concentrations were closely associated with elevated chlorophyll concentrations. At the Harbor-edge stations, DO, as percent saturation, was relatively low and consistent with depth (94-98%). DO reached values as low as 77-82% in the bottom waters of Stellwagen Basin. There was a clear decrease in DO from October to December in both the surface and bottom water.

- Chlorophyll - Besides the main trend of a decline in chlorophyll from a seasonal maximum in October, some spatial variability was noted. On average, lower chlorophyll concentrations were observed at Cape Cod Bay (~5 $\mu g\ L^{-1}$) and near-Harbor (~6 $\mu g\ L^{-1}$) stations compared to Massachusetts Bay (~12 $\mu g\ L^{-1}$) stations during the October survey. During the November and December surveys, chlorophyll concentrations were similar throughout the nearfield ($<2\ \mu g\ L^{-1}$).

- Phytoplankton - There was a strong correlation ($r^2 = 0.816$) between phytoplankton counts and chlorophyll concentrations (extracted samples) during the October survey. This was due to the predominance of a single phytoplankton taxa throughout Massachusetts Bay. Significant changes were seen in the biology of the bays over both the course of the farfield/nearfield survey, and between the October and November surveys. This variability resulted from the dynamics of the *A. glacialis* bloom. The short timescales involved with the changes in biological parameters and the importance of documenting the occurrence of a bay-wide fall bloom necessitate future surveys continue to be scheduled at regular intervals *through* October. It must be kept in mind that the present sampling scheme might miss the peak or decline of the fall bloom in any given year. The importance of this recognition is that year-to-year data comparisons may suggest differences that are simply a matter of precise timing of sampling relative to bloom events. Given the magnitude of the event, more frequent surveys might be warranted.

- Zooplankton - Zooplankton abundance varied significantly over the sampling region, and there was little correlation between zooplankton and phytoplankton abundances. The most abundant zooplankton taxa was *Oithona similis* which has consistently been plentiful in Massachusetts Bay over the course of the 1992 and 1993 monitoring program. *Paracalanus parvus* was most abundant in Cape Cod Bay, while the community at the edge of Boston Harbor was dominated by *Acartia tonsa* and polychaete larvae.

- Metabolism - There was a good correlation ($r^2 = 0.742$) between productivity and integrated chlorophyll. Production rates were generally high and were elevated at the nearfield stations (4-8 $g\ C\ m^{-2}\ d^{-1}$) compared to the coastal and Cape Cod Bay stations (2-3 $g\ C\ m^{-2}\ d^{-1}$).

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: OCTOBER-DECEMBER 1993".

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1.0 INTRODUCTION

This report is the last 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 October, November, and December; each of these surveys included sampling at 21 stations in the nearfield area. The October 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 (October farfield/nearfield survey, November nearfield survey, December nearfield survey).
Section 6.	Discussion of the fall/early winter 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 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 is provided 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 periodic reports (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, 1993). The results of the 1993 surveys conducted from February through September (Table 1-1) were presented in a series of four periodic reports (Kelly *et al.*, 1994a,b; Kelly *et al.*, 1994c,d).

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 were submitted to MWRA for each survey to provide important operational details. The survey reports submitted for the three surveys discussed in this periodic report describe actual survey tracks, samples collected, and other survey details (West, 1993; Bechtold, 1993; Dragos, 1993). The survey plans and reports should be consulted for pertinent information concerning each of the surveys. Data reports on nutrients, plankton, and pelagic metabolism have been submitted to MWRA for the surveys conducted during October, November, and December 1993; these data are included in 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 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), have been conducting surveys similar to those initiated in 1992. The schedule of surveys conducted in 1993 is given in Table 1-1. The survey schedule was designed to match the 1992 schedule. The surveys discussed in this report were conducted during the weeks planned: October 12-16 (W9314), November 3-4 (W9315), and December 1-2 (W9316).

1.4 Summary of Accomplishments: Mid-October to Early December 1993

For the combined farfield/nearfield survey in October (W9314), *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.

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 the nearfield survey was dedicated to high-resolution "tow-yo" profiling with an *in situ* sensor array (as described above, minus irradiance). The towfish was used to obtain the profiles by oscillating from near surface to near bottom as the ship progressed at 4 to 7 kt along the nearfield tracks between the vertical stations. The trackline from survey W9316, for example, is shown in Figure 1-2.

Samples 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 October through December 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

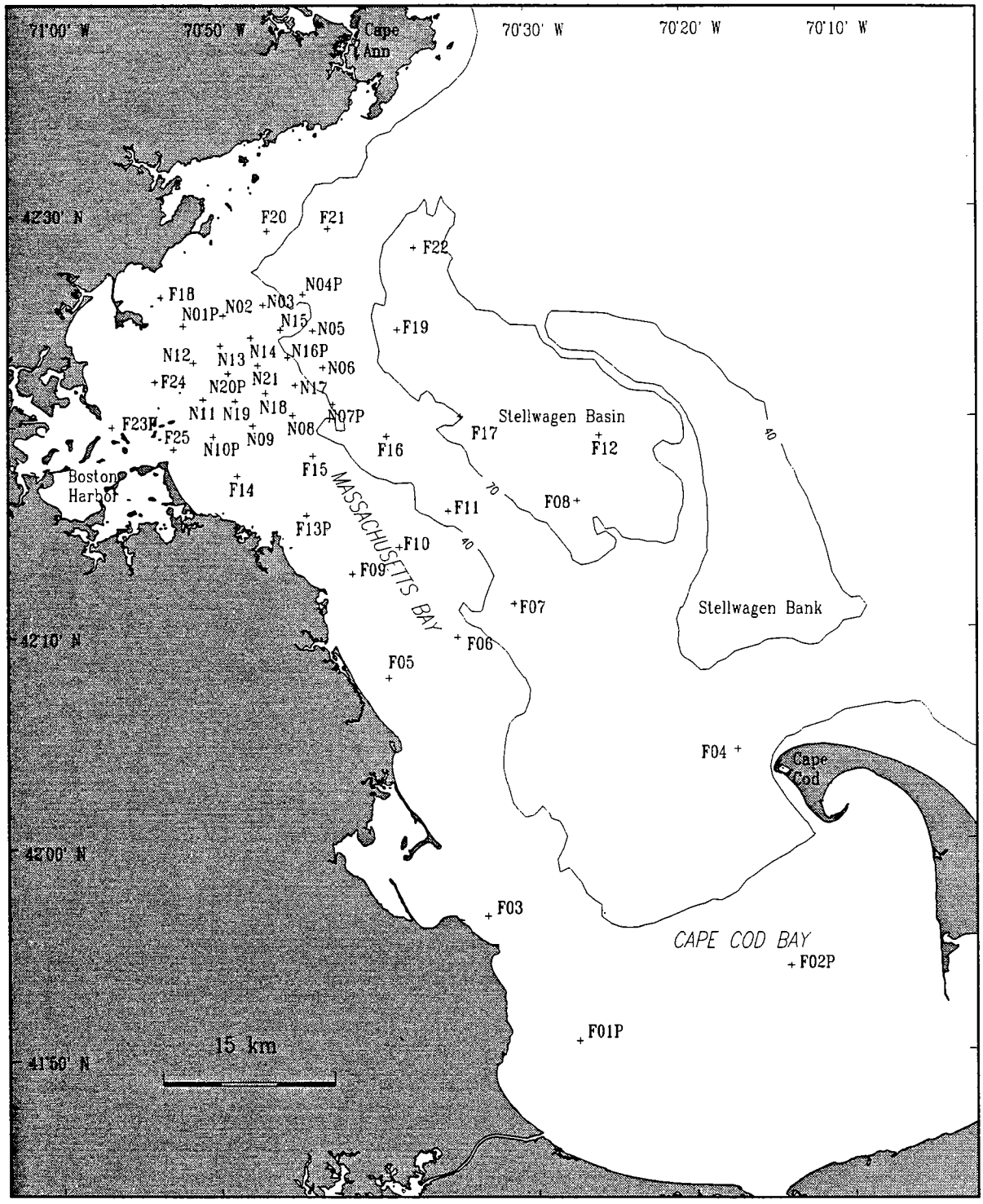

Figure 1-1. **Water quality sampling stations in Massachusetts and Cape Cod Bays. Station codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Depth contours are in meters.**

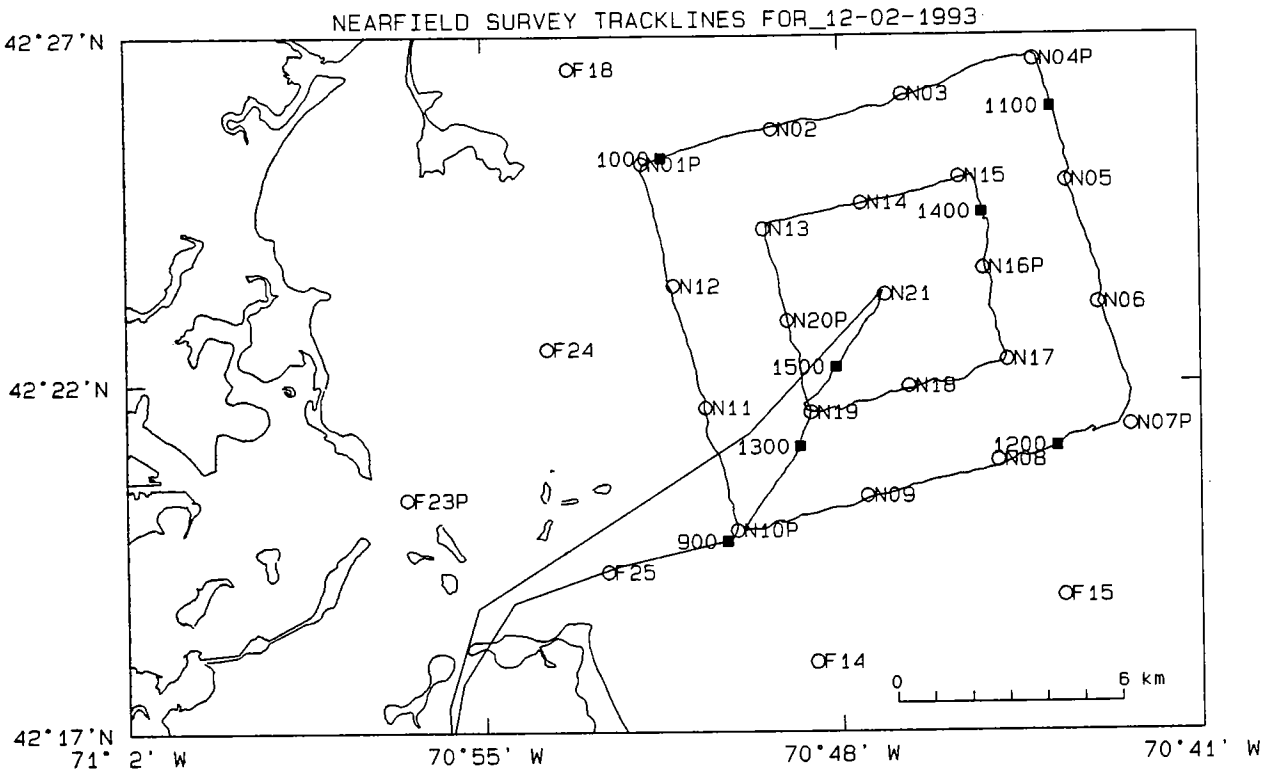

Figure 1-2. **Nearfield survey tracklines for December 2, 1993. Tow-yo operations were conducted clockwise from N10P to N10P, N19 to N19, and N19 to N21. The hour of the day is indicated along the track.**

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 described 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, additional biology/productivity measurements were made at a subset of 10 stations (4 farfield and 6 nearfield); these stations are termed "BioProductivity" stations and are labeled with a "P" (see Figure 1-1). The six "P" stations in the nearfield were 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 the nearfield survey), and lastly as part of the towing track sampled on a second day of the nearfield survey. All planned samples were collected. Principal deviations from the CW/QAPP for each survey are given below; most deviations are reported in the appropriate survey report that is 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 October (W9314):

- No samples were collected for oxygen incubations to determine production or respiration. However, oxygen samples were collected at 21 stations at 3 to 5 depths and were used to calibrate the dissolved oxygen sensors (Appendix A). Production measurements were made using ^{14}C (described below).

- Chlorophyll samples were taken at 15 stations (2 or 3 depths) and were used to calibrate the *in situ* fluorescence sensor (Appendix A). In addition to chlorophyll, a sample for total suspended solids was collected at station F25, as well as at the planned stations.
- Tow-yo sampling (October 16) was completed over the planned nearfield trackline. Due to foggy conditions, the N21–dock transect was canceled to avoid damaging the towfish.

In addition to the procedures described in the CW/QAPP, the following methods were used for the nearfield surveys in November (W9315) and December (W9316):

- Dissolved oxygen samples were collected at 6 BioProductivity stations (5 depths) and were used to calibrate the dissolved oxygen sensor (Appendix A).
- Chlorophyll samples were taken at 4 stations (3 depths) and were used to calibrate the *in situ* fluorescence sensor (Appendix A).

2.1.2 Productivity Measurements

Productivity measurements differed slightly from those described in the CW/QAPP. At the request of 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 $\mu E\ m^{-2}\ sec^{-1}$, with several bottles exposed in the range of 200-600 $\mu E\ m^{-2}\ sec^{-1}$. 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 for 6 h as stated in the CW/QAPP. Respiration data collected in 1992 were reviewed prior to the October 1993 survey. The data review suggested that longer incubations were warranted for significant changes to be measured due to the relatively low respiration rates indicated by the 4- to 6-h incubations in the summer 1992 studies. Results of the respiration calculations are included 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 DIC method used by URI is a "purge-and-trap" method (I.O. Corp., 1984) and was not described in the CW/QAPP. 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 difference between analytical replicates, estimated from samples taken and reported in the first periodic report (Kelly *et al.*, 1994a), averaged less than 1% ($x \pm \sigma$ = 0.47% ± 0.73%, range = 0.08-2.68%, n = 12). The average difference between sample replicates from a GO-FLO bottle was less than 1% ($x \pm \sigma$ = 0.25% ± 0.31%, range = 0.01-0.81%, n = 6).

2.3 Data Analyses

To calculate 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 are 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-bottle 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 data collected on survey W9314.

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 the Platt *et al.* (1980) model to predict net production

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

where

P_B = production (chlorophyll-normalized)

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

$a = \alpha I/P_{SB}$

$b = \beta I/P_{SB}$

α = initial slope of the rise in net production with light increasing from zero irradiance [units of (μgC μgChl^{-1} hr^{-1})/(μE m^{-2} sec^{-1})], calculated from I (light irradiance level, μE m^{-2} sec^{-1}) and P_{SB}.

In the CW/QAPP and in the first periodic report for 1993 (Kelly *et al.*, 1994a), 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. These were expressed as a rate per square meter of surface following the procedure described by Kelly *et al.* (1993c) which is briefly described 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 midday (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 $Z_{0.5\% Io}$, the depth where photosynthetically active radiation equals 0.5% I_o. Estimated rates were expressed per square meter of surface and integrated to $Z_{0.5\% Io}$. 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 midday rates (μg C m^{-2} h^{-1}). Conversion to full day-time rates was made by multiplying by a factor of 7 which recognizes that about 55-60% of the production generally

occurs during the 4-h period (1000-1400 h) when the irradiance is highest (Vollenweider, 1966). Final modeled rates provide an estimate of daytime primary production as g C m^{-2} d^{-1}.

The same procedure was applied to both surface and chlorophyll-maximum samples, each of which yielded independent estimates. For each productivity survey, these estimates are listed in a table that summarizes P-I modeling results (provided in detail in Appendix E).

Table 2-1. Field samples and measurements [cf. Albro *et al.*, 1993]

Parameter	Stations	Sample Volume	Sample Containers	Shipboard Processing/ Preservation
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	14 Biology/ Productivity and 3 Farfield	300 mL	300 mL Glass BOD	Fix per Oudot *et. al.* (1988). Titrate within 24 hours.
Dissolved Organic Carbon	14 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	14 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 hours.
Dissolved Organic Phosphorus	14 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 hours.
Particulate Organic Carbon	14 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	14 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	14 Biology/ Productivity	200 mL	Petri dish	Pass through a filter. Freeze (-5°C)
Chlorophyll *a*/ Phaeopigments	14 Biology/ Productivity	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)	14 Biology/ Productivity	800 mL	1000 mL glass bottle	Preserve with Utermohl's solution.
Phytoplankton (Screened Water)	14 Biology/ Productivity	2000 mL	100 mL Polyethylene bottle	Strain through a 20 μm mesh; wash retained organism into a jar. Fix with Utermohl's solution.
^{14}C Production	2 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	14 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 $\mu E\ m^{-2}\ s^{-1}$
Surface Irradiance	All	---	Floppy disk	1 $\mu E\ m^{-2}\ s^{-1}$
Bottom Depth	All	---	Floppy disk	1 m
Navigational Position	All	---	Floppy disk	0.00017 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 elemental 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 OCTOBER 1993 COMBINED FARFIELD/ NEARFIELD SURVEY (W9314)

3.1 Farfield Survey

3.1.1 Horizontal Distribution of Surface Water Properties

Surface water temperatures in the sampling area of Massachusetts and Cape Cod Bays in mid-October 1993 ranged from 10.0 to 12.2°C (Figure 3-1). The shallow waters of coastal stations near Boston Harbor and along the North Shore exhibited the lowest surface temperatures (10.0 to 10.4°C). Temperatures increased offshore (> 11.0°C), and water at stations in southern Cape Cod Bay was warmer (~12.0°C) than at the Massachusetts Bay stations.

Surface salinity (Figure 3-2) varied over a narrow range (31.3 to 31.9 PSU). Salinities < 31.7 PSU were observed near Boston Harbor and at the southern Cape Cod Bay stations. Central Massachusetts Bay salinities were consistently between 31.7 and 31.8 PSU, increasing to > 31.8 PSU to the north, east, and southeast. Salinities were < 31.8 PSU at the easternmost Massachusetts Bay stations, yielding a pattern showing a band of relatively high salinity between Cape Cod and the North Shore. The gradients in temperature and salinity were small and generally increased with distance offshore.

Beam attenuation suggested a decreasing gradient from the coast (Figure 3-3). Beam attenuations were > 2.0 m^{-1} in both chlorophyll-rich (> 10 $\mu g\ L^{-1}$) and relatively chlorophyll-poor (< 6 $\mu g\ L^{-1}$) coastal waters. Lower beam attenuation values were observed offshore and in Cape Cod Bay. Surface chlorophyll, as measured by fluorescence, was high throughout the sampling region at concentrations ranging from 3.2 to 20.8 $\mu g\ L^{-1}$ (Figure 3-4). The highest values (≥20 $\mu g\ L^{-1}$) were observed at the northern coastal station (F18) and the western nearfield station (N20P) and tended to decrease offshore, while relatively low values were found in Boston Harbor and the southern coastal (F05 and F09) and Cape Cod Bay (F01, F02, and F03) stations. The low chlorophyll fluorescence and high beam attenuation at the Boston Harbor and southern coastal stations are indicative of high turbidity.

Dissolved inorganic nitrogen (DIN) concentrations were < 1.0 μM at all stations except those nearest Boston Harbor (F23P, F24, and F25), where concentrations were > 5.0 μM (Figure 3-5). Excluding those three stations, surface DIN concentrations were higher, on average, in Cape Cod Bay than in Massachusetts Bay (0.5 vs. 0.2 μM). Nitrate (NO_3) followed a pattern similar to DIN and was undetectable at nearly all offshore stations (Figure 3-6). At the stations nearest the Harbor, NO_3 concentrations ranged from 1.3 to 2.3 μM and were lower than the ammonium (NH_4) concentrations (~3.5 μM). Ammonium was a significant fraction of DIN at all stations.

Following a pattern similar to DIN, phosphate (PO_4) concentrations were low (≤ 0.3 μM) throughout Massachusetts and Cape Cod Bays, and higher at the three stations near Boston Harbor (Figure 3-7). Silicate (SiO_4) followed the same general pattern as the other dissolved nutrients and was nearly depleted in the surface waters of Massachusetts Bay (Figure 3-8). Silicate concentrations were slightly higher at the southern offshore and coastal stations and in Cape Cod Bay. In fact, the highest surface SiO_4 concentration (1.4 μM) was observed off the tip of Cape Cod at station F04.

3.1.2 Water Properties Along Selected Vertical Sections

Vertical downcast profile plots for each station are provided in Appendix B and selected transects of stations were used to illustrate some trends (Figure 3-9). Typically, the profiles show that the degree of stratification between the surface and bottom water increased with distance from shore. Coastal stations were well mixed, especially to the south. The gradients in temperature, salinity, and density were small. The thermocline, halocline, and pycnocline were generally located at ~25 m (except at the shallow stations).

The vertical thermal gradient was < 1°C from surface to bottom near the coast and increased to > 3°C at the stations furthest offshore (Figure 3-10a). The coastal waters were well mixed with temperatures > 10°C throughout the water column. Stratification became stronger offshore with the increase in surface temperatures (as shown in Figure 3-1) and the presence of a contiguous mass of cool bottom water.

Vertical sections of salinity depict features similar to those discussed above: generally well mixed in the shallow coastal stations, an increase in stratification offshore, and small vertical and horizontal gradients (31.2 to 32.0 PSU; Figure 3-10b). The freshest water (< 31.3 PSU) was observed at station F23P in Boston Harbor and extended out to station F24. If these two stations are excluded, the vertical and horizontal salinity gradients were < 0.3 PSU over the four transects. Likewise, density gradients were small and σ_T vertical sections were similar to both temperature and salinity for the selected transects (Figure 3-10c).

Chlorophyll fluorescence was extraordinarily high (10 to 20 $\mu g\ L^{-1}$) in the upper 25 m of the northern, Boston-nearfield, and Cohasset transects (Figure 3-11). Slightly lower chlorophyll concentrations (6 to 14 $\mu g\ L^{-1}$) were measured in the surface layer of the Marshfield transect. There was a sharp vertical gradient in chlorophyll associated with the pycnocline at about 25 m. The high concentrations observed at station N20P appear to extend shoreward as a subsurface chlorophyll maximum at station F24. The Harbor signature appears to be reflected in the "low" chlorophyll concentrations at station F23P and the surface waters at station F24, and also the high beam attenuations observed at both stations ($> 2\ m^{-1}$; Figure 3-12). Beam attenuations decreased offshore of the turbid coastal stations and also with depth, yielding a vertical distribution (similar to chlorophyll) with higher measurements in the upper 25 m above the pycnocline.

Above the pycnocline along nearly all the transects, dissolved oxygen (DO), as percent saturation, was greater than 108% (Figure 3-13). Near the Harbor, DO was less than 100%. At stations F06 and F07 along the Marshfield transect, lower DO water appeared nearer the surface. The water was slightly cooler, more saline, and less turbid at these two stations than at the surrounding waters and could be representative of upwelling. These water characteristics could also have developed due to an influx of offshore water from the east, as similar characteristics were observed at station F04 off Cape Cod (Appendix B). DO percent saturation was less than 85% in the bottom waters of Stellwagen Basin. The highest oxygen saturations (> 120%) were associated with the high concentrations of surface chlorophyll measured along the northern transect. High saturations (> 114%) also coincided with the subsurface chlorophyll patch at station N20P.

Nutrients were nearly depleted in the surface waters (upper 20 m) along each of the transects. The vertical profiles of DIN and SiO_4 showed strong gradients at the deeper offshore stations due to a significant increase in nutrient concentrations with depth (Figure 14a and 14b). Surface DIN concentrations increased towards the Harbor along the Boston-nearfield transect, while SiO_4 concentrations remained < 1.0 μM.

3.1.3 Analysis of Water Types

As suggested above, the physical, biological, and geochemical characteristics (Figure 3-15) defined some distinct surface-water regions of the bays. These regions included the Harbor-coastal waters, the nearfield-offshore area in Massachusetts Bay, and Cape Cod Bay (cf. Figure 3-16 for standard station groupings). Vertical gradients of the measured parameters were observed at all stations, except at the shallow coastal and other nearshore stations where the water column was well mixed (Appendix B). The thermocline, halocline, and pycnocline, along with gradients in the biological and geochemical parameters, were consistently between the 20 and 30 m depth range throughout the bays. The vertical water quality variations appeared to be more distinct than the horizontal variations during the October farfield survey.

Although the range in temperature and salinity measurements was narrow (~5°C and ~1 PSU, respectively; Figure 3-15a), physical distinctions could still be made between coastal, offshore, and Cape Cod Bay waters. The coastal waters were generally cooler and less saline than the offshore surface waters, especially near Boston Harbor. Warmer, less saline waters were found in southern Cape Cod Bay. The general trend was a decrease in temperature and an increase in salinity with depth, as evidenced by the strong relationship between these parameters (Figure 3-15a). Coastal waters, however, were well mixed, and profiles of temperature and salinity showed little change with depth (Appendix B).

The lower-salinity surface waters were more turbid. As salinity increased, turbidity generally decreased, though beam attenuation was more variable at the higher salinities. The turbidity and salinity signal clearly differentiate the Harbor from the bays (Appendix C). Most of the variation in the salinity–beam attenuation relationship comes from the nearfield measurements (see Figure 3-28a).

Overall, there was a relatively good relationship between beam attenuation and chlorophyll fluorescence (Figure 3-15a). Despite a high degree of variability, beam attenuation generally increased with increasing chlorophyll concentration. At the northern and offshore stations, the relationship between these two parameters was better and was primarily driven by the vertical changes in each (both decreasing at depth; Appendix B and C). Coastal and Cape Cod Bay stations, however, showed little change in beam attenuation over a very large range of chlorophyll concentrations (Appendix C). Chlorophyll was generally highest in the upper 20 m of water, ranging from 5 to 25 $\mu g\ L^{-1}$ (Figure 3-15b). At the northern, offshore, and Cape Cod Bay stations, a large gradient of decreasing chlorophyll was noted below 30 m (Appendix C).

The DO composite profile shows a clear distinction between the surface layer and deep waters (Figure 3-15b). The water was almost always supersaturated in the upper 20 m but undersaturated at depths greater than 30 m; as a result, the DO gradient between 20 and 30 m was large. At stations F23P, F25, and N10P, surface DO saturations were well below 100%, revealing the effect of water flowing from the Harbor. The other coastal stations showed little variation with depth, which is consistent with the previous discussion of other parameters. There were very good correlations between oxygen saturation and chlorophyll concentration for both the composite and individual profiles (Figure 3-15b and Appendix B and C).

The relationship between DIN and PO_4 was similar in all regions and at all depths (Figure 3-17). The N/P ratio generally followed Redfield proportionality (16N:1P) at detectable levels of DIN but, as discussed previously, the surface waters were nearly depleted of DIN, resulting in a relatively large PO_4 intercept. This pattern, regularly observed in both coastal and open-ocean waters, creates different dissolved N/P ratios depending on the overall level of enrichment. The same general pattern was found for comparisons of NO_3 and PO_4. At coastal and some nearfield stations, however, the comparisons fell below the 16:1 ratio because a significant portion of DIN was comprised of NH_4. In this case, individual nitrogen species (NO_3 and NH_4), rather than DIN, are more useful parameters for distinguishing between coastal and offshore waters.

The surface concentrations of DIN and SiO_4 were nearly depleted at all stations except those influenced by Boston Harbor (cf. Figures 3-5 and 3-8). In comparisons of DIN relative to SiO_4, this was expressed by a convergence of points at the origin (Figure 3-18). The general trend was a 1:1 relationship, but a number of points fell below or well above this ratio. Some nearfield and Cape Cod Bay stations were depleted in DIN relative to SiO_4, while the coastal and nearfield stations mentioned above were replete in DIN relative to SiO_4. When comparisons were made with NO_3, however, the DIN-depleted nearfield and Cape Cod Bay stations remained low relative to SiO_4, and the NH_4-rich nearshore stations were reduced to a 2:1 relationship with SiO_4 (Figure 3-18). The general trend for the NO_3/SiO_4 ratio continued to be a 1:1 relationship. The high NH_4 concentrations at stations influenced by the Harbor allow a distinction to be made with offshore waters based on DIN and SiO_4 comparisons.

Nutrient-salinity plots have been useful in distinguishing water mass character and for inferring dispersion of nutrients. Even over the narrow range of salinities observed in October 1993, there were distinguishable patterns in the nutrient-salinity plots (Figures 3-19 to 3-22). High concentrations of DIN at low salinity (coastal or surface nearfield water), low concentrations of DIN at intermediate salinity (primarily offshore surface water), and high concentrations of DIN at high salinity (generally deep water) is a pattern often observed in 1992 and 1993. Nearfield surface waters generally displayed typical offshore patterns of low DIN vs. salinity (Figure 3-19). At the southwestern nearfield station N10P, there were elevated DIN concentrations throughout the well-mixed water column (i.e. little change in salinity); this was coincident with higher DIN concentrations at the near-Harbor coastal stations (Appendix A).

The high concentrations of DIN in coastal and southwestern nearfield surface waters were primarily due to NH_4, while at all the other stations, the concentrations of NH_4 were low over the range of salinity (Figure 3-20). This relationship was dissimilar to that of the NO_3-salinity plot. NO_3 concentrations were low or not detectable in the coastal and nearfield surface waters, as well as in the surface water from other stations, and were high in the deep offshore waters (Figure 3-20). The DIN pattern, supplemented by the NH_4 and NO_3 plots, illustrates the major distinctions in water types – coastal water with low salinity and high NH_4, and northern, offshore, and Cape Cod Bay transects with DIN-depleted surface water and high NO_3 deep water. Stations in the nearfield displayed a mixture of both water types.

Phosphate vs. salinity trends were similar to the DIN patterns (Figure 3-21). Silicate, however, was more comparable to the pattern observed for NO_3. The low salinity, low NO_3, high NH_4 coastal and nearfield surface water was also low in SiO_4. Using DIN, plus other forms of nitrogen measured at the select group of BioProductivity stations (and special station F25), the coastal stations near Boston Harbor (F23P and F25) are clearly differentiated from the other coastal, nearfield, and Cape Cod Bay BioProductivity stations (Figure 3-22). The coastal F23P and F25 stations have higher concentrations of DIN and dissolved organic nitrogen (DON) (Appendix A).

In summary, a number of distinctions can be made based on the individual parameters, but the main difference is between a well-mixed, coastal water mass and a slightly stratified, offshore water mass. Coastal and some nearfield stations were influenced by flow out of Boston Harbor; this was clearly shown by both the physical and chemical parameters. The nearfield stations exhibited properties found in both coastal and offshore waters. Cape Cod Bay surface waters were generally warmer, fresher, and had slightly higher concentrations of DIN and SiO_4 in comparison to Massachusetts Bay. In general, water above the pycnocline, which was consistently at ~25 m, was depleted of nutrients, supersaturated with oxygen, and high in chlorophyll concentrations.

3.1.4 Distribution of Chlorophyll and Phytoplankton

Extracted chlorophyll data confirmed that chlorophyll concentrations were very high and generally confined to the upper 20 m of the water column (Figure 3-23). Concentrations of chlorophyll in Cape Cod Bay (~5 $\mu g\ L^{-1}$) were lower than at the coastal (5 to 12 $\mu g\ L^{-1}$) and nearfield (4 to 27 $\mu g\ L^{-1}$) stations. The wide range of chlorophyll concentrations in the nearfield may be the result of temporal rather than spatial variations. The nearfield data set is from four stations sampled twice, 2-3 days apart. Fluorescence profiles from each sampling suggest that a major mixing or phytoplankton sinking event took place between October 12 and 15. This will be discussed in more detail in Section 3.2.

There was a very strong relationship between phytoplankton counts and chlorophyll concentrations (Figure 3-24). Phytoplankton counts, ranging from 2 to 8 million cells L^{-1}, corresponded to a coincident increase

in chlorophyll from 5 to 20 $\mu g\ L^{-1}$. The main reason for the strong relationship and the high concentrations of chlorophyll in Massachusetts Bay was a seemingly bay-wide bloom of the diatom, *Asterionellopsis glacialis* (Table 3-1a and 3-1b). The wide range of phytoplankton counts at chlorophyll concentrations of ~5 $\mu g\ L^{-1}$ was due to the Harbor (F23P), where *A. glacialis* was present, as well as Cape Cod Bay (F01P and F02P) stations, where the *A. glacialis* bloom was not detected. *A. glacialis* was the dominant phytoplankton throughout Massachusetts Bay and, along with other diatoms (*Leptocylindrus minimus* and *Skeletonema costatum*) and the microflagellates, accounted for nearly all of the phytoplankton. This was true for both the surface and mid-depth "chlorophyll maximum" samples (Figure 3-25a and 3-25b). Phytoplankton counts were significantly lower at F23P, the Boston Harbor station, and were apparently lower in Cape Cod Bay than in Massachusetts Bay (Figure 3-25). *L. minimus* was the dominant species in Cape Cod Bay.

Plankton counts were relatively high in the 20-μm-screened samples, and *Ceratium fusus* was the dominant species (often >1000 cells L^{-1}) throughout both bays at the surface and chlorophyll maximum (Table 3-2a and 3-2b). Tintinnids numbered in the 100s of cells L^{-1} at most stations and were dominant in the 20-μm size class at the Boston Harbor station. Dinoflagellate species and individual abundances were significantly lower at station F23P in comparison to the other stations.

3.1.5 Distribution of Zooplankton

Total numbers of zooplankton varied about seven-fold across the stations (Figure 3-26). The counts at station F23P were low, as they were for phytoplankton, but the lowest zooplankton counts were at the southwestern nearfield station N10P where the phytoplankton counts were ~8 million cells L^{-1}. Counts of phytoplankton and zooplankton were not well correlated over the stations (cf. Figure 3-25 and 3-26). Zooplankton were most plentiful at the central nearfield stations and bivalve veliger (category "other" in Figure 3-26) were numerically dominant ($>90,000$ individuals m^{-3} at N16P and 40,000 individuals m^{-3} at N20P). At the other stations, copepods and their nauplii constituted most of the zooplankton counted. The dominant copepod species were *Oithona similis* and *Paracalanus parvus; O. similis* was slightly more plentiful in Massachusetts Bay and *P. parvus* was more abundant in Cape Cod Bay. Several types of

zooplankton distinguished Boston Harbor from the bays, a trend already noted above for some of the other parameters. In addition to the ubiquitous copepod nauplii, the Harbor was dominated by polychaete larvae and *Acartia tonsa*, neither of which were plentiful in the bays.

3.1.6 ^{14}C Production Measurements

The P-I incubations were used, in conjunction with light and fluorescence profiles, to estimate integrated daily ^{14}C production at each BioProductivity station. In most cases, the P-I data were fit by the negative exponential model (Webb *et al.*, 1974). The three cases fit by the inhibition model (Platt *et al.*, 1980) occurred with chlorophyll maximum samples, but did not show strong suppression of rates at the higher irradiances (>800 $\mu E\ m^{-2}\ sec^{-1}$). Maximum production rates were achieved at irradiances between 200 to 600 $\mu E\ m^{-2}\ sec^{-1}$. All P-I data and curve-fitting results are included in Appendix E.

Estimated production rates were expressed per square meter after integrating to the depth of the 0.5% isolume ($Z_{0.5\%Io}$). Production rates were high throughout the region and were elevated at the nearfield stations (4-8 g C $m^{-2}\ d^{-1}$) compared to the coastal and Cape Cod Bay stations (2-3 g C $m^{-2}\ d^{-1}$; Table 3-3). The high production rates coincided with high chlorophyll concentrations, and there was a strong correlation between productivity and integrated chlorophyll (see Figure 6-6).

The P-I incubations were run using surface and subsurface (chlorophyll maximum) water samples. The integrated production estimates were similar for each of the sample depths (Table 3-3). The largest difference between surface and chlorophyll maximum production estimates was observed at station N07P. This is illustrated in Figure 3-27 showing the productivity estimates and chlorophyll concentrations (as measured by fluorescence) for station N07P. The primary reason for the difference at this station was that the chlorophyll maximum sample was quite shallow and thus the phytoplankton were not light inhibited during incubations. This resulted in elevated production rates for the subsurface samples at higher light intensities. Due to the moderate surface irradiance and the generally uniform, chlorophyll-rich surface layer, there was little difference between surface and chlorophyll maximum production estimates, and light

inhibition was negligible during the P-I incubations. *In situ* conditions, however, may have been light limiting at the subsurface depths of the chlorophyll maximum.

3.2 Nearfield Survey

3.2.1 Distribution of Water Properties from Vertical Profiling

On October 15, vertical profiling was performed at 21 nearfield stations and at the Harbor-edge station (F23P), repeating 6 BioProductivity stations sampled two to three days earlier as a part of the farfield survey. Scatter plots for continuous profile data are shown in Figures 3-28a and 3-28b; note that nearfield data are from a subset of the stations shown in Figure 3-15. Comparison of Figures 3-28a and 3-28b with Figures 3-15a and 3-15b illustrates that much of the variation in the measured parameters was from the nearfield stations. There was, however, less variability in the temperature-salinity relationship in the nearfield, despite the Harbor influence of low salinity and cool (~10°C) water at station N10P. There was an increase in water column stratification from the western nearfield stations (generally well mixed) to the offshore nearfield stations (strong pycnocline between 20 and 25 m). A large gradient in DO saturation was associated with the layering — supersaturated in the upper 20 m and undersaturated below 30 m (Figure 3-28b).

In the nearfield, chlorophyll concentrations were high and variable, ranging from ~2 to 25 $\mu g\ L^{-1}$ (Figure 3-28b). Part of this variation, especially the high concentrations in both surface and bottom waters, can be explained by temporal changes in chlorophyll. The BioProductivity stations were sampled first on October 12 or 13 and then again on October 15. During this time, significant changes occurred in the vertical profiles of both chlorophyll and beam attenuation (Figure 3-29a and 29b). The changes observed at stations N01P and N20P are representative of the changes at all BioProductivity nearfield stations. Over the three-day period, there was a slight decrease in stratification at station N20P, while the water column appeared to remain well mixed at station N01P during this period. The small decrease in stratification at

station N20P and the consistently well-mixed water column at station N01P suggest that increased mixing was not the primary cause of the observed changes in chlorophyll concentration and beam attenuation. Instead, the data suggest that the phytoplankton "bloom" (*A. glacialis*) collapsed and sank out of the surface layer.

Graphics described above in Section 3.1.3 illustrate the patterns of nearfield nutrients relative to salinity and suggest inshore-offshore gradients, as well as patterns of nutrients with increasing salinity. Nutrient concentrations as a function of depth are presented in Figure 3-30. Other regions from the farfield survey are shown for reference. In general, nutrients were depleted in the surface waters of the nearfield and increased with depth below the pycnocline. Surface DIN concentrations were similar to coastal waters for some of the western nearfield stations due to elevated concentrations of both NO_3 and NH_4 (Figure 3-30b). Phosphate profiles were similar to DIN, except PO_4 was not as depleted in the surface waters (Figure 3-30c). A sharp vertical gradient was noted for SiO_4, which was depleted in the upper 15 m in nearfield waters. This feature must have been related to the diatom growth and contributed to its cessation.

3.2.2 Distribution of Water Properties from Towing

The horizontal tow-yo profiling took place on October 16, the day after nearfield vertical profiling. The sequence of sampling followed the clockwise pattern shown in Figure 1-2. Results are shown as vertical sections, contoured with depth and distance, across tracks of the outer and inner "boxes" of the same stations sampled by vertical profiling (Figures 3-31, 3-32, and 3-33).

Temperature contours from the tow-yo profiling continued to show the offshore trends – warming of surface water and increased stratification – that had been observed during the farfield survey (Figure 3-31). The thermocline at the more stratified, offshore (eastern) stations was at a depth of ~20 m. At the northern stations, the well-mixed, cool inshore water extended further offshore. The density structure in the nearfield followed temperature contours very closely (Figure 3-32). Low σ_T values characterized the inshore waters which appeared to be well mixed. Because of cooler temperatures, the density of inshore surface waters was generally higher than offshore; density was highest, however, in the cool, bottom

waters to the southeast of the nearfield. The water column appeared to be stratified at all but the most western transect stations. Density stratification increased to the east where the surface waters were warm and the bottom waters were cool (Appendix B).

The contours of chlorophyll fluorescence obtained from towing are particularly striking when compared to the vertical profile data from October 12 and 13 (Figure 3-33 compared to Figure 3-11). During the earlier samplings, chlorophyll concentrations were >10 $\mu g\ L^{-1}$ in the upper 20 m throughout the nearfield (Appendix B). On October 16, the nearfield data indicated that <5 $\mu g\ L^{-1}$ chlorophyll was present in surface waters and that patches with >15 $\mu g\ L^{-1}$ chlorophyll were observed in bottom waters. It appeared as though the chlorophyll (phytoplankton) had sunk or had been mixed down and out of the surface layer over a 2- to 3-day period. However, the physical parameters, which indicated that the water column was still stratified over much of the nearfield area, support the concept of sedimentation.

3.2.3 Water Types and Analysis of Small-Scale Variability

The farfield survey indicated that, for the physical and chemical parameters, general inshore-offshore trends could be detected; these trends were also noted during the nearfield survey. The water column at the western stations was well mixed and influenced slightly by the flow of fresher, higher nutrient water from the Harbor. At the eastern stations, the water column was stratified and water quality was more characteristic of offshore waters (i.e., more saline, warmer, and nutrient-depleted). Over the five-day sampling period, the physical and chemical parameters were consistent and there was little region-wide change in the water column stratification. Nutrients remained depleted in the surface waters and replete at depths below the pycnocline.

The most interesting aspect of the October survey was the observed cessation and sedimentation of the *A. glacialis* bloom. This is dramatically evident in the comparison of profiles taken at BioProductivity stations over a period of 2 to 3 days (Figure 3-29; Appendix B). As mentioned above, there was very little change in the temperature, salinity, and σ_T profiles, indicating negligible mixing. However, both the vertical and horizontal (tow-yo) profiles showed a shift of high chlorophyll and turbidity from the surface

water to the bottom water. This shift probably resulted from sedimentation of the *A. glacialis* bloom. This is corroborated by phytoplankton counts showing a significant decrease in *A. glacialis* in the surface water at station N10P from October 12 (5.8 million cells L^{-1}) to October 15 (3.4 million cells L^{-1}) (Appendix F).

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

SPECIES	COASTAL STATIONS		NEARFIELD STATIONS						CAPE COD BAY STATIONS	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
ASTERIONELLOPSIS GLACIALIS	1.239 (1)	4.835 (1)	4.800 (1)	4.674 (1)	1.476 (1)	5.775 (1)	2.766 (1)	6.505 (1)		0.853 (2)
MICROFLAGELLATES	0.500 (2)	0.626 (2)	0.359 (2)	0.765 (2)	0.853 (3)	0.874 (2)	0.449 (3)	0.645 (2)	0.688 (2)	0.365 (4)
SKELETONEMA COSTATUM	0.197 (3)	0.580 (3)	0.092 (5)	0.252 (3)	0.394 (4)	0.251 (3)	0.178 (5)	0.260 (3)	0.265 (3)	0.426 (3)
LEPTOCYLINDRUS DANICUS			0.137 (3)			0.231 (4)	0.822 (2)	0.192 (4)		
CRYPTOMONADS	0.042 (5)					0.131 (5)			0.100 (4)	
RHIZOSOLENIA DELICATULA	0.046 (4)	0.276 (5)	0.114 (4)	0.153 (5)	0.230 (5)		0.234 (4)	0.183 (5)	0.093 (5)	0.074 (5)
LEPTOCYLINDRUS MINIMUS		0.396 (4)		0.189 (4)	1.030 (2)				2.538 (1)	1.137 (1)

Units are millions of cells/L.
Rank of taxa abundance given in ( ).

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

SPECIES	COASTAL STATIONS		NEARFIELD STATIONS						CAPE COD BAY STATIONS	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
ASTERIONELLOPSIS GLACIALIS	1.629 (1)	3.783 (1)	6.072 (1)	3.669 (1)	1.669 (1)	5.249 (1)	5.133 (1)	6.398 (1)		0.808 (2)
MICROFLAGELLATES	0.556 (2)	0.56 (3)	0.535 (2)	0.663 (2)	0.939 (3)	0.613 (2)	0.645 (2)	0.475 (2)	0.656 (2)	0.272 (4)
CRYPTOMONADS	0.053 (3)								0.116 (4)	
SKELETONEMA COSTATUM	0.036 (4)	0.701 (2)		0.149 (4)	0.499 (4)	0.581 (3)	0.37 (3)	0.308 (3)	0.362 (3)	0.309 (3)
RHIZOSOLENIA DELICATULA	0.027 (5)	0.113 (5)	0.126 (4)	0.19 (3)	0.188 (5)	0.148 (5)	0.133 (4)		0.089 (5)	0.183 (5)
LEPTOCYLINDRUS DANICUS			0.22 (3)			0.18 (4)	0.123 (5)	0.211 (4)		
LEPTOCYLINDRUS MINIMUS		0.241 (4)	0.115 (5)	0.124 (5)	0.968 (2)			0.097 (5)	2.472 (1)	1.585 (1)

Units are millions of cells/L.
Rank of taxa abundance given in ( ).

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

SPECIES		CAPE COD BAY STATIONS		COASTAL STATIONS		NEARFIELD STATIONS					
	STATION	F01P	F02P	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P
	SAMPLE ID	W93140392	W93140376	W93140273	W93140475	W93140229	W93140241	W93140257	W93140061	W93140045	W93140031
	DATE	Oct. 14	Oct. 14	Oct. 13	Oct. 15	Oct. 13	Oct. 13	Oct. 13	Oct. 12	Oct. 12	Oct. 12
ALEXANDRIUM TAMARENSE		0	0	0	0	0	3	0	0	0	0
ALORICATE CILIATES		13	13	15	8	0	13	13	13	15	3
AMPHIDINIUM SPP.		18	8	0	0	0	0	5	0	0	0
CERATIUM FUSUS		2267	2242	643	18	370	1759	2062	393	1919	983
CERATIUM LINEATUM		5	18	5	0	8	20	10	5	15	15
CERATIUM LONGIPES		23	50	13	0	25	65	50	18	60	60
CERATIUM MACROCEROS		5	13	0	0	5	8	8	3	3	0
CERATIUM TRIPOS		566	708	148	3	33	480	591	88	473	135
DICTYOCHA FIBULA		8	10	0	0	0	0	3	0	0	0
DICTYOCHA SPECULUM		8	8	0	0	0	3	3	0	3	5
DINOPHYSIS ACUMINATA		0	0	3	0	0	3	5	0	0	0
DINOPHYSIS CAUDATA		3	28	5	0	0	13	8	0	3	13
DINOPHYSIS NORVEGICA		18	23	38	5	18	35	30	8	28	63
DIPLOPSALIS SPP.		3	13	23	8	8	58	23	28	60	15
GONYAULAX SPINIFERA		35	63	65	0	0	30	65	0	0	20
GYMNODINIUM SPP.		5	13	3	0	0	3	18	3	0	0
GYRODINIUM SPIRALE		3	0	8	13	3	15	0	8	8	0
GYRODINIUM SPP.		0	3	0	0	0	0	0	0	0	0
MERISMOPEDIA COLONY		0	0	0	0	10	0	0	0	0	0
MERISMOPEDIA SPP. COLONY		0	0	10	0	0	0	0	0	0	0
MESODINIUM RUBRUM		0	0	5	0	3	0	5	3	0	0
PROROCENTRUM MICANS		18	28	18	0	15	33	30	8	43	35
PROROCENTRUM TRIESTINUM		0	0	0	0	0	0	3	0	0	0
PROTOPERIDINIUM (CF) BREVIPES		0	0	0	0	3	0	0	13	0	0
PROTOPERIDINIUM BIPES		0	0	0	0	0	0	3	0	0	5
PROTOPERIDINIUM BREVE		8	0	0	3	0	0	0	0	25	8
PROTOPERIDINIUM DEPRESSUM		13	15	25	0	8	53	28	5	18	28
PROTOPERIDINIUM PELLUCIDUM		13	48	13	0	5	28	23	5	28	8
PROTOPERIDINIUM PENTAGONUM		0	0	0	0	0	0	0	3	0	0
PROTOPERIDINIUM SPP.		43	133	73	35	30	105	143	35	193	180
SCRIPPSIELLA TROCHOIDEA		35	93	230	20	165	188	180	163	168	340
TINTINNIDS		200	238	148	796	73	200	238	80	108	240
UNID. ATHECATE DINOFLAGELLATE		10	3	0	0	0	28	25	10	5	15
UNID. THECATE DINOFLAGELLATES		8	18	5	0	3	3	5	20	3	50

Values are Cells/L

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

SPECIES		CAPE COD BAY STATIONS		COASTAL STATIONS		NEARFIELD STATIONS					
	STATION	F01P	F02P	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P
	SAMPLE ID	W93140391	W93140374	W93140272	W93140473	W93140227	W93140240	W93140256	W93140059	W93140043	W93140029
	DATE	Oct. 14	Oct. 14	Oct. 13	Oct. 15	Oct. 13	Oct. 13	Oct. 13	Oct. 12	Oct. 12	Oct. 12
ALORICATE CILIATES		8	10	15	13	0	13	8	18	0	18
AMPHIDINIUM SPP.		8	5	0	0	0	3	3	0	0	6
CERATIUM FURCA		3	8	0	0	0	0	0	0	0	0
CERATIUM FUSUS		2720	2172	616	45	475	1522	1689	818	1644	1682
CERATIUM LINEATUM		5	3	5	0	8	10	18	13	15	6
CERATIUM LONGIPES		35	75	25	3	48	83	53	28	48	18
CERATIUM MACROCEROS		13	5	0	0	0	0	5	0	0	6
CERATIUM TRIPOS		623	516	150	8	90	350	440	128	40	147
DICTYOCHA FIBULA		10	15	0	0	0	0	0	0	0	0
DICTYOCHA SPECULUM		13	3	0	0	8	3	8	0	13	0
DINOPHYSIS ACUMINATA		8	0	0	0	5	0	0	0	0	0
DINOPHYSIS CAUDATA		0	23	0	0	3	18	0	8	8	12
DINOPHYSIS NORVEGICA		5	25	33	5	45	58	20	23	55	100
DIPLOPSALIS SPP.		0	18	13	0	13	45	25	40	15	6
EBRIA TRIPARTITIA		8	0	0	0	3	0	0	0	0	6
GONYAULAX DIACANTHA		0	0	0	0	10	0	0	0	0	0
GONYAULAX SPINIFERA		65	68	25	0	0	8	35	0	0	0
GYMNODINIUM SPP.		3	3	10	0	5	10	15	0	0	0
GYRODINIUM SPIRALE		0	0	5	28	8	8	0	8	8	6
GYRODINIUM SPP.		0	3	0	0	3	3	0	0	0	0
HETEROSIGMA AKASHIWO		0	0	0	0	0	0	0	0	3	0
MESODINIUM RUBRUM		0	0	5	0	0	3	3	0	0	0
PROROCENTRUM MICANS		15	25	23	5	30	25	13	25	8	12
PROTOPERIDINIUM (CF) BREVIPES		0	0	0	0	0	0	0	0	0	18
PROTOPERIDINIUM BIPES		0	0	0	0	0	0	0	3	3	23
PROTOPERIDINIUM BREVE		3	0	5	0	0	0	0	5	8	0
PROTOPERIDINIUM DEPRESSUM		8	48	28	0	15	20	28	23	10	23
PROTOPERIDINIUM PELLUCIDUM		18	53	18	0	5	28	18	20	5	12
PROTOPERIDINIUM SPP.		50	40	85	20	65	100	128	220	185	199
SCRIPPSIELLA TROCHOIDEA		68	115	278	18	308	175	193	203	88	100
TINTINNIDS		273	210	288	1394	190	170	185	248	193	346
UNID. ATHECATE DINOFLAGELLATE		3	5	5	0	8	23	8	5	8	35
UNID. THECATE DINOFLAGELLATES		0	13	0	0	10	3	0	3	5	6

Values are Cells/L

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

	COASTAL STATIONS				NEARFIELD STATIONS												CAPE COD BAY STATIONS			
	F23P[6]		F13P		N01P		N04P		N07P		N10P		N16P		N20P		F01P		F02P	
Water depth (m)	25		26		31		52		49		25		43.5		33		28		32	
$Z_{(0.5\%Io)}$ (m)	21.5		11.5		24.5		16		20.5		12.5		20.5		15		20.5		21	
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 $m^{-2}d^{-1}$)	2129	2929	2384	2895	7973	7535	4308	4227	4715	6354	4555	5008	5356	5875	3795	4743	2324	2002	2661	2194
Model[2]	W	P	W	P	W	P	W	W	W	W	W	W	W	W	W	W	W	W	W	W
P_{SB} or P_{MAX}[3]	7.82	9.41	5.53	8.63	5.53	7.04	5.51	5.54	5.28	7.11	7.46	8.21	6.20	7.26	3.31	5.54	4.47	3.70	4.46	3.41
α[4]	0.042	0.072	0.053	0.057	0.078	0.050	0.063	0.059	0.063	0.085	0.057	0.063	0.074	0.072	0.053	0.040	0.047	0.043	0.043	0.040
β[5]	-	0.001	-	0.003	-	0.001	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[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 at station F23P (20.5 m).

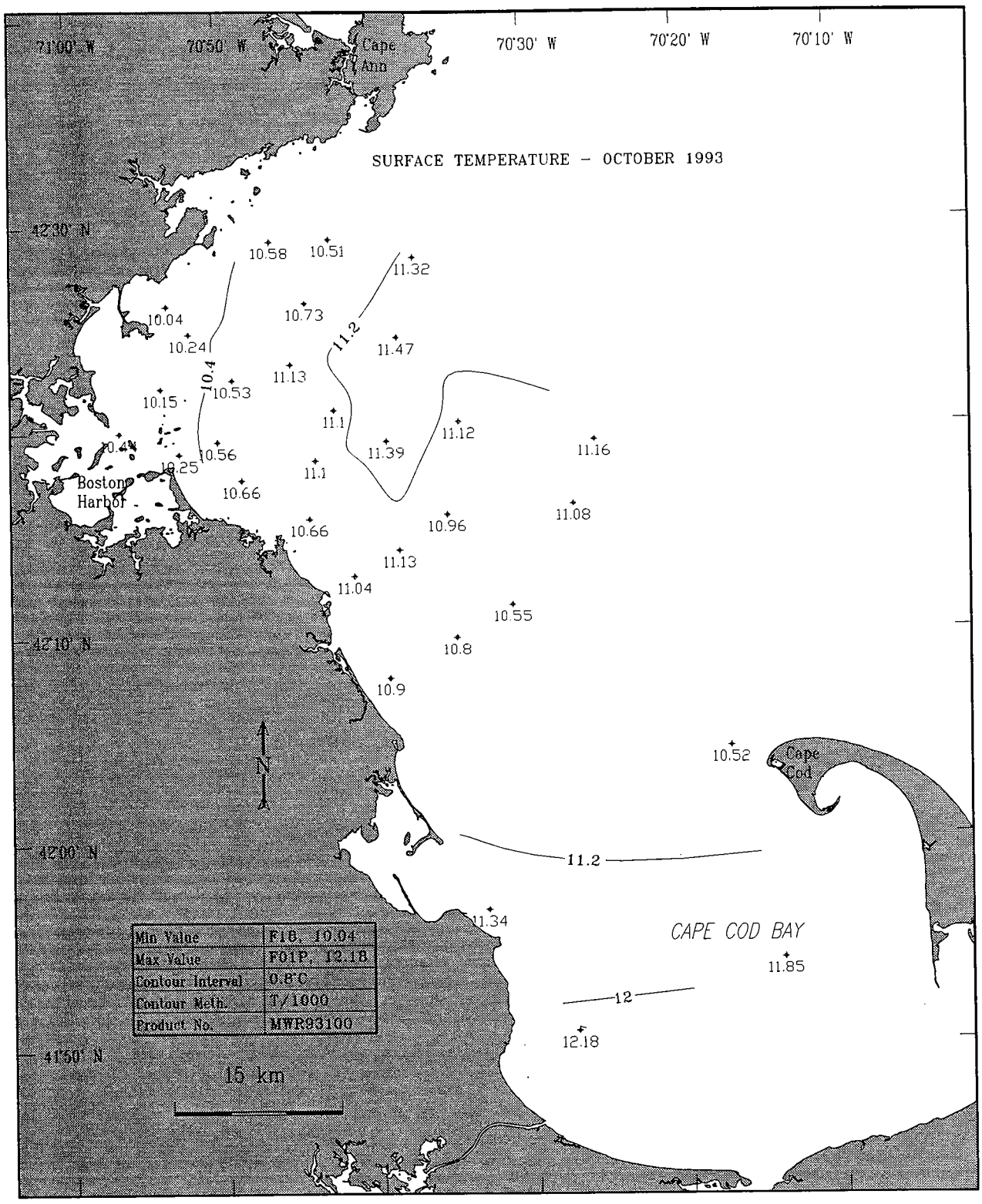


Figure 3-1. **Surface temperature (°C) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

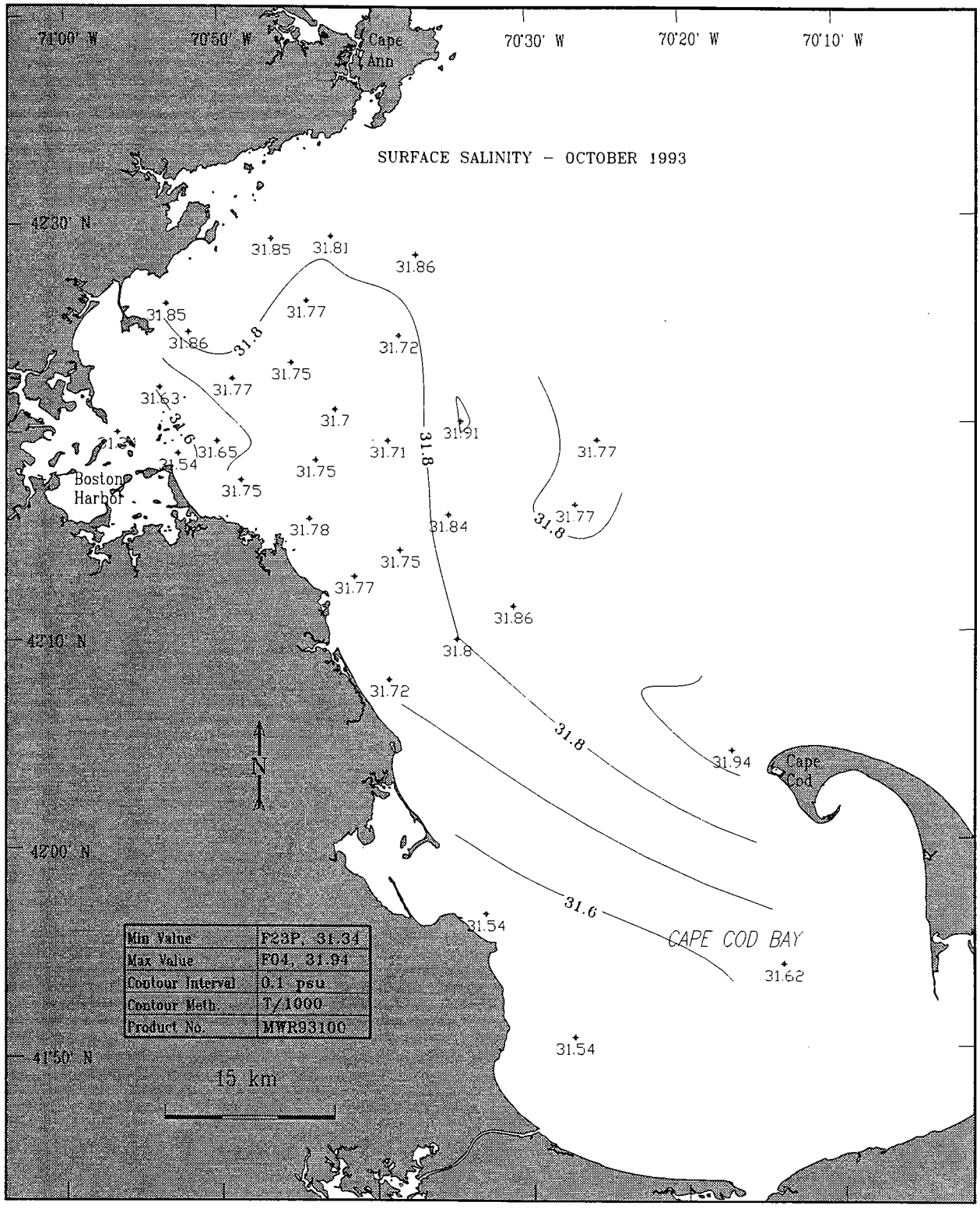


Figure 3-2. **Surface salinity (PSU) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

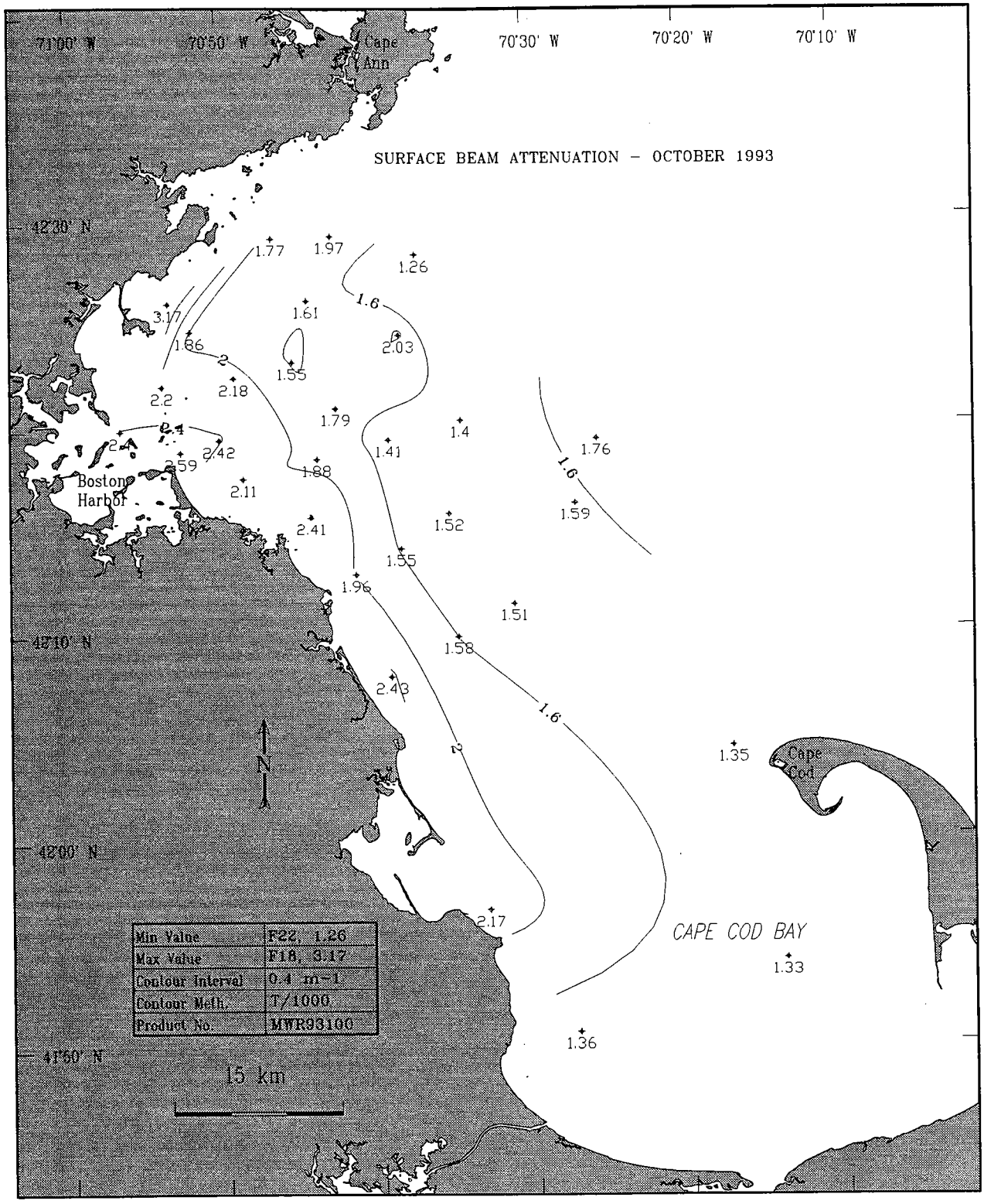


Figure 3-3. **Surface beam attenuation (m^{-1}) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

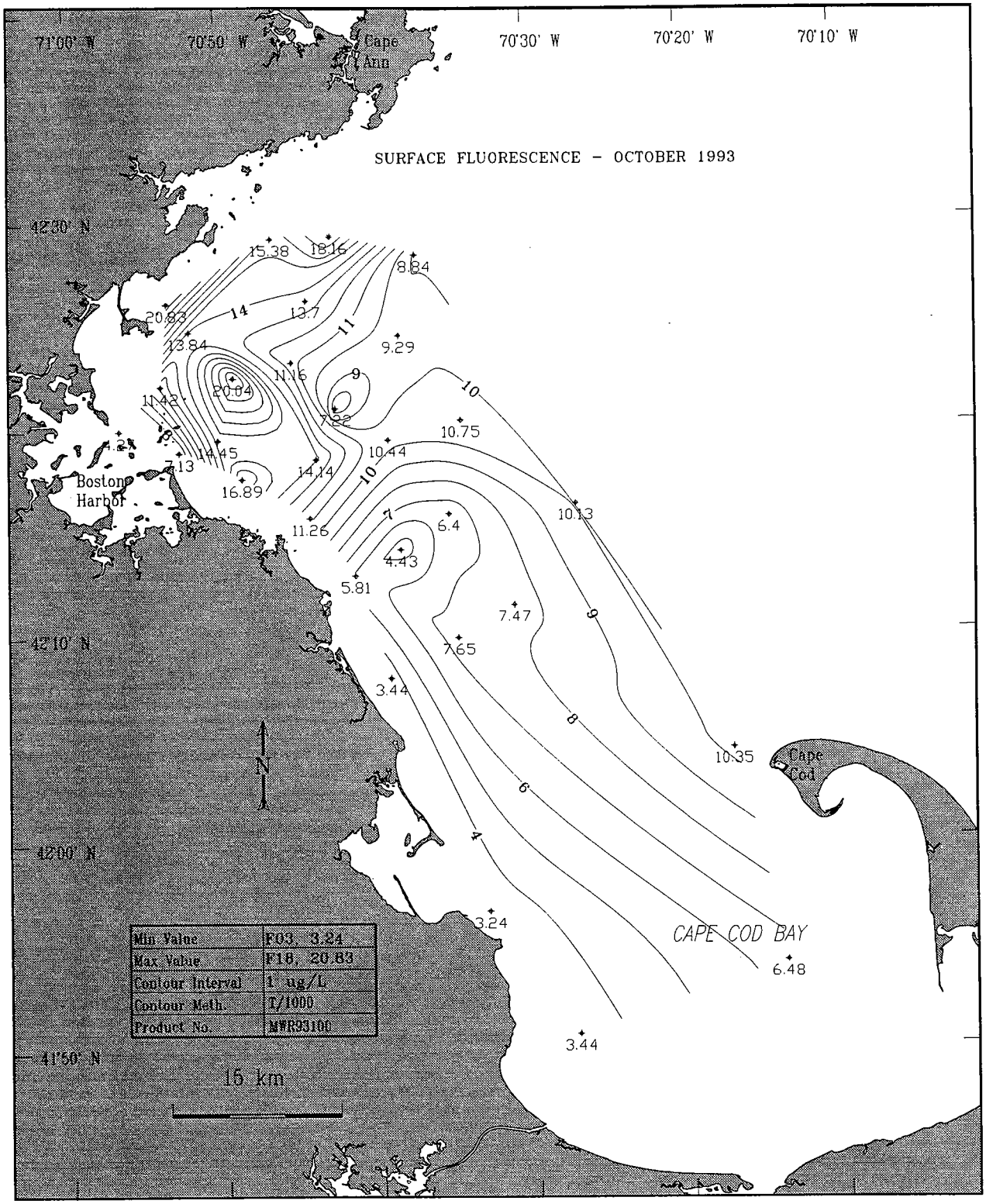


Figure 3-4. **Surface *in situ* fluorescence (as μg Chl L^{-1}) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A). No data were available for station F12.**

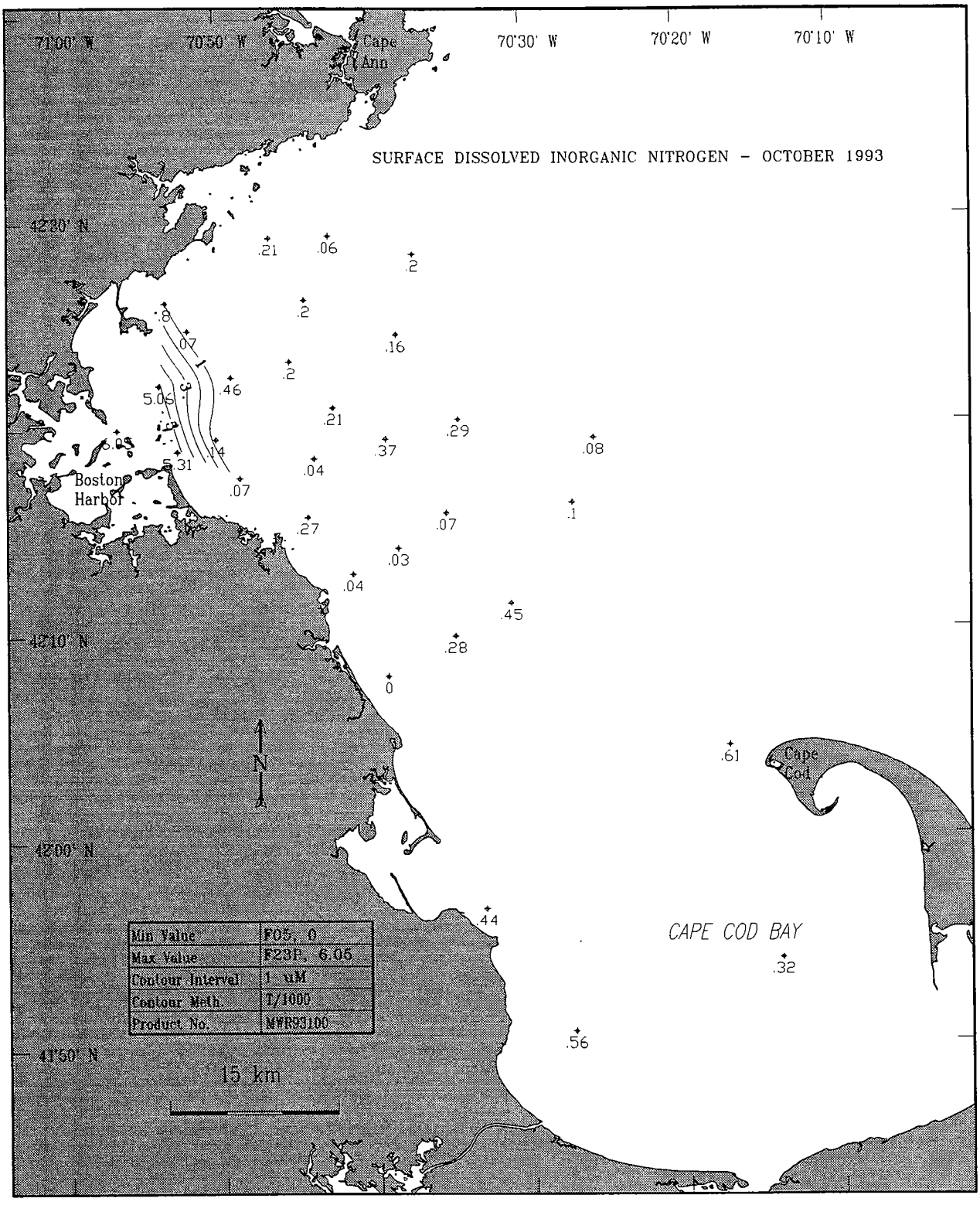


Figure 3-5. **Surface dissolved inorganic nitrogen (DIN, μM) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

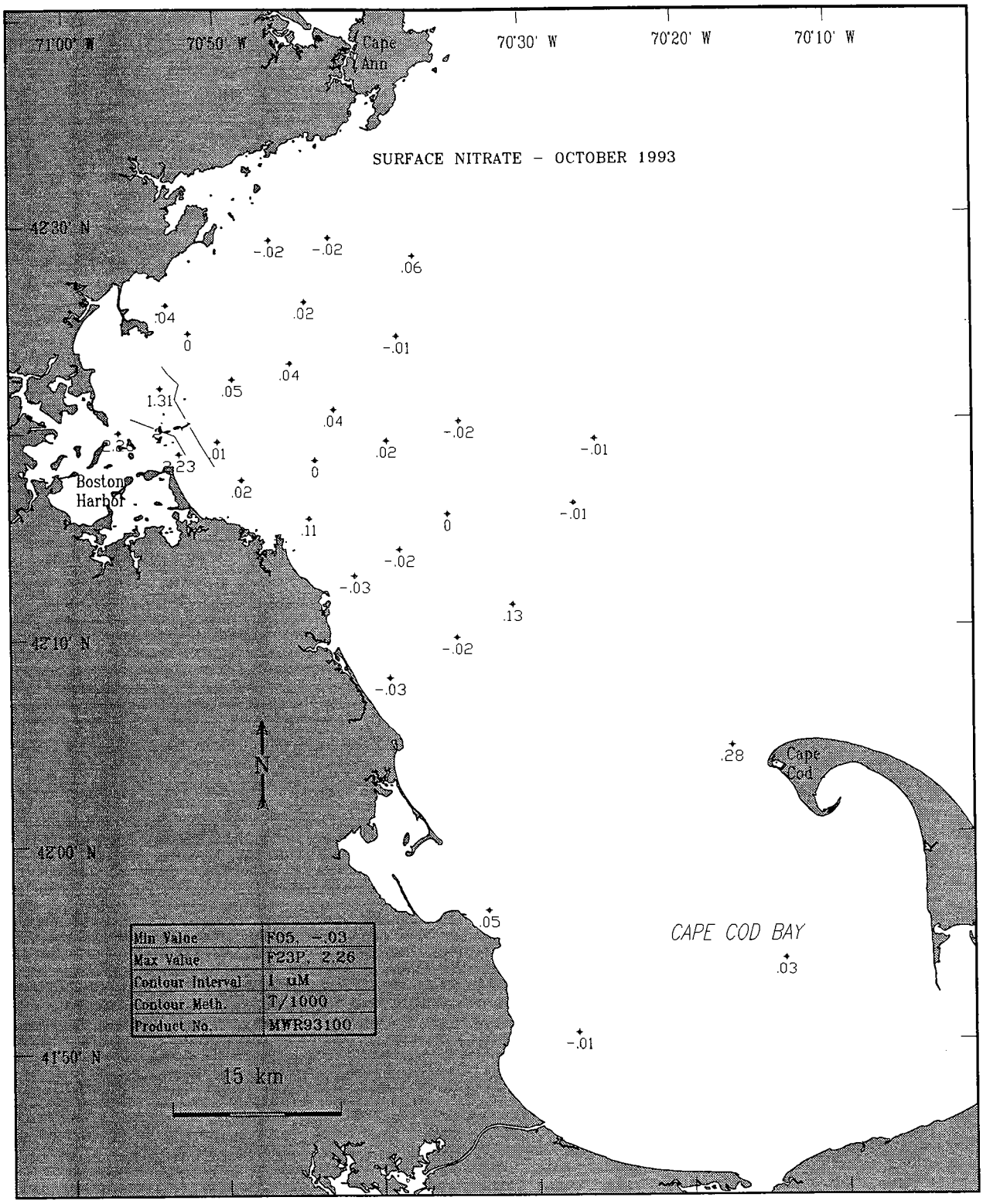


Figure 3-6. **Surface nitrate (NO_3, μM) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

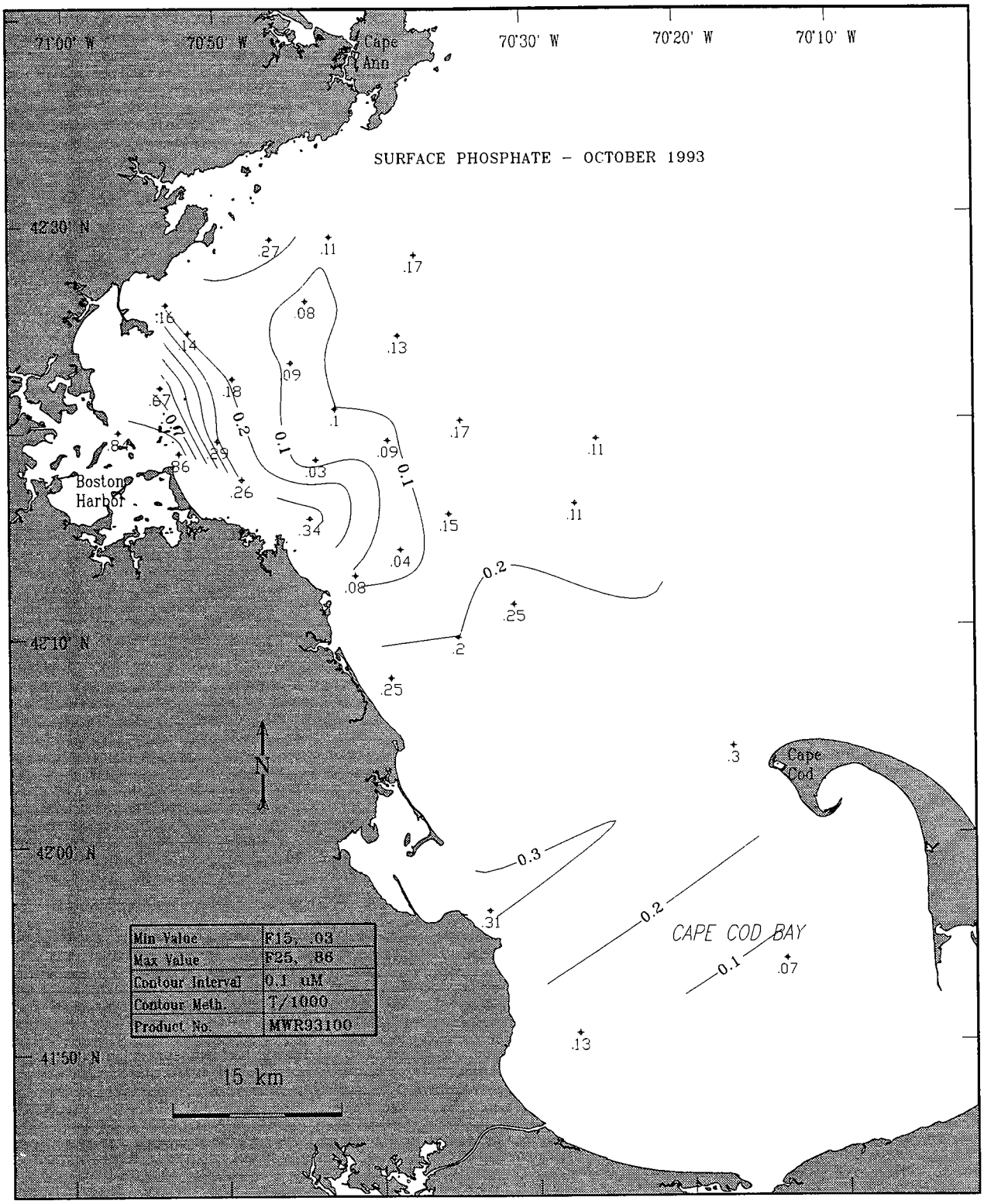


Figure 3-7. **Surface phosphate (PO_4, μM) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

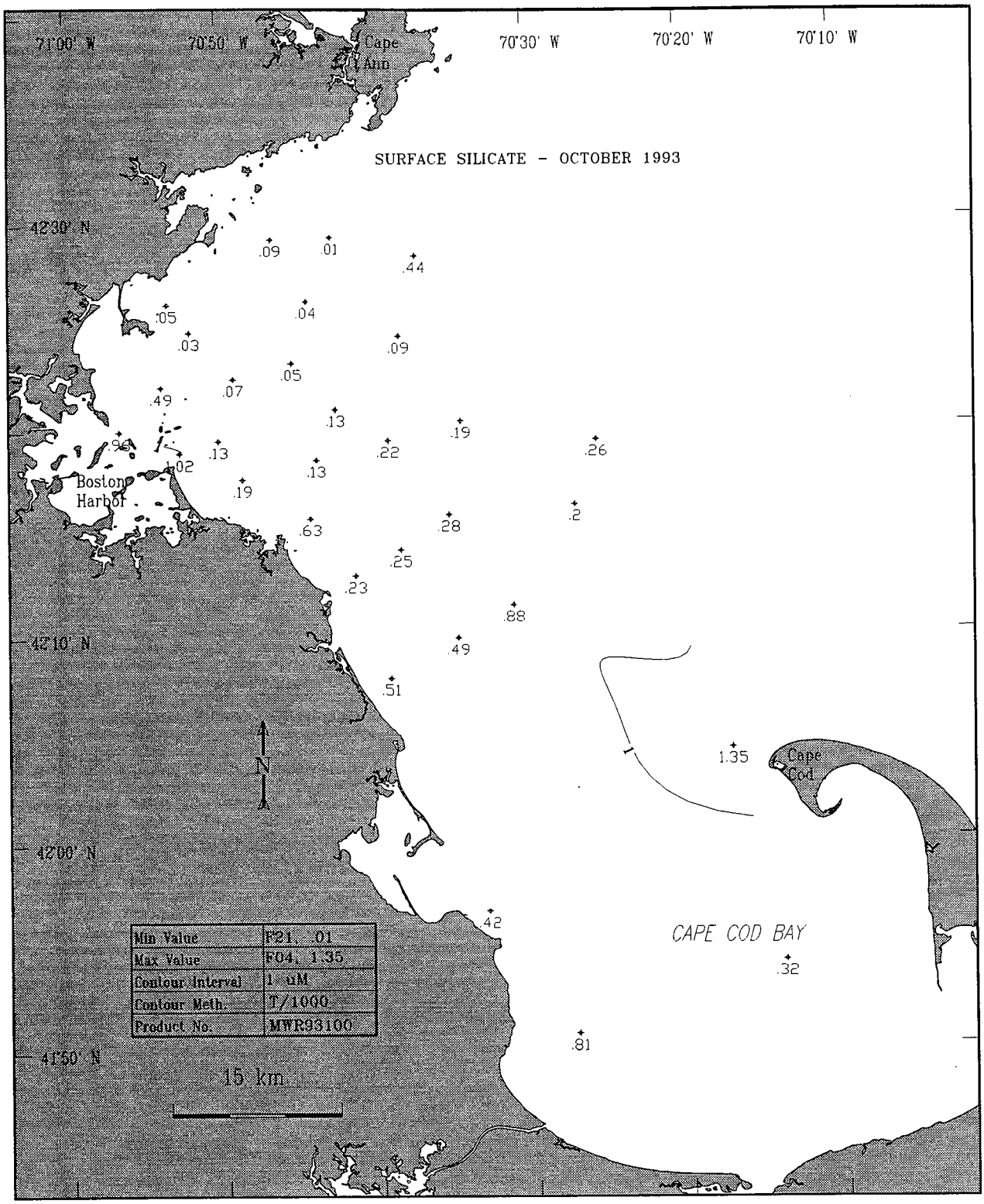


Figure 3-8. **Surface silicate (SiO_4, μM) in the study area in October 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

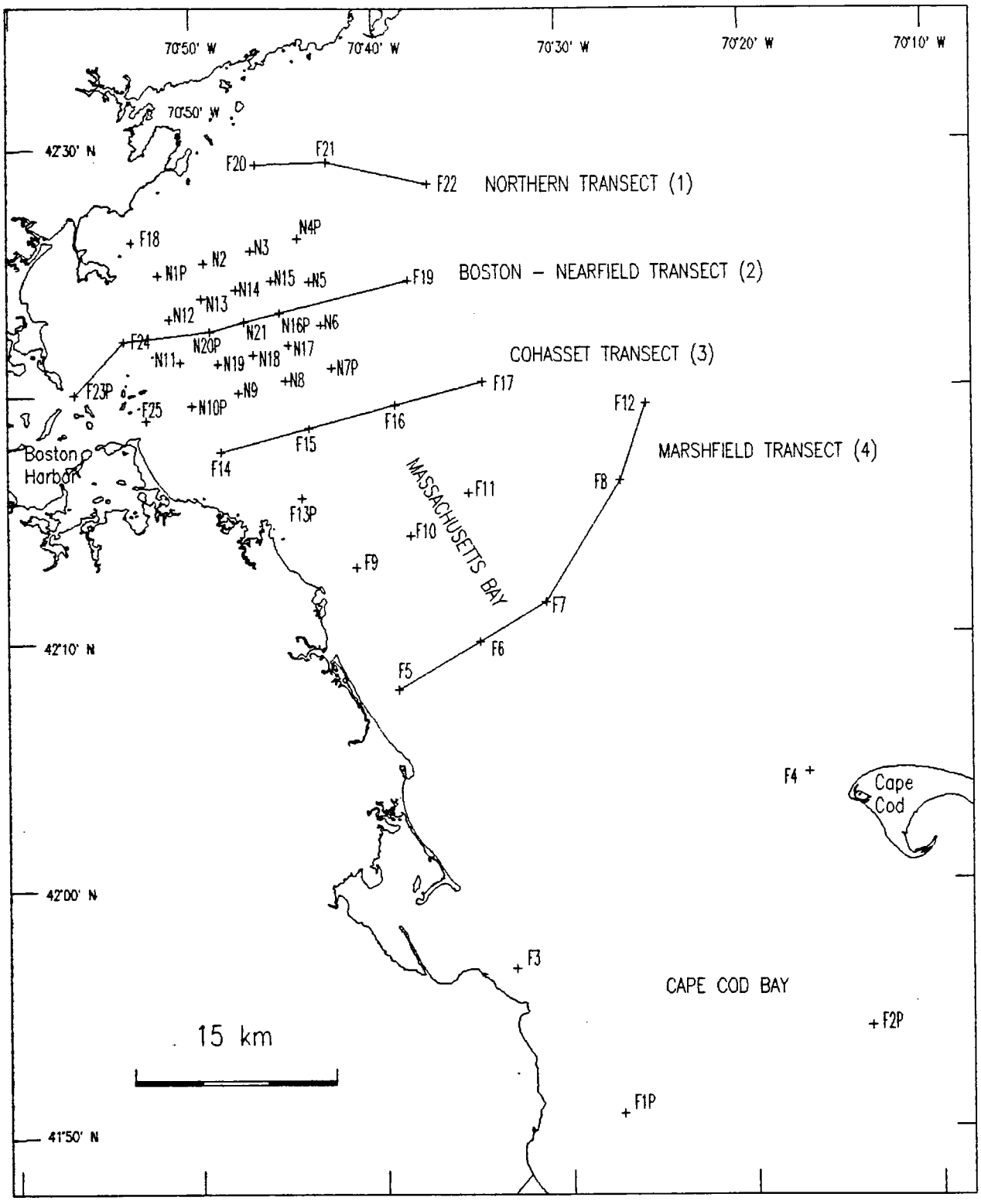


Figure 3-9. **Map showing position of four standard transects for which vertical contour plots were produced in following Figures 3-10 to 3-14.**

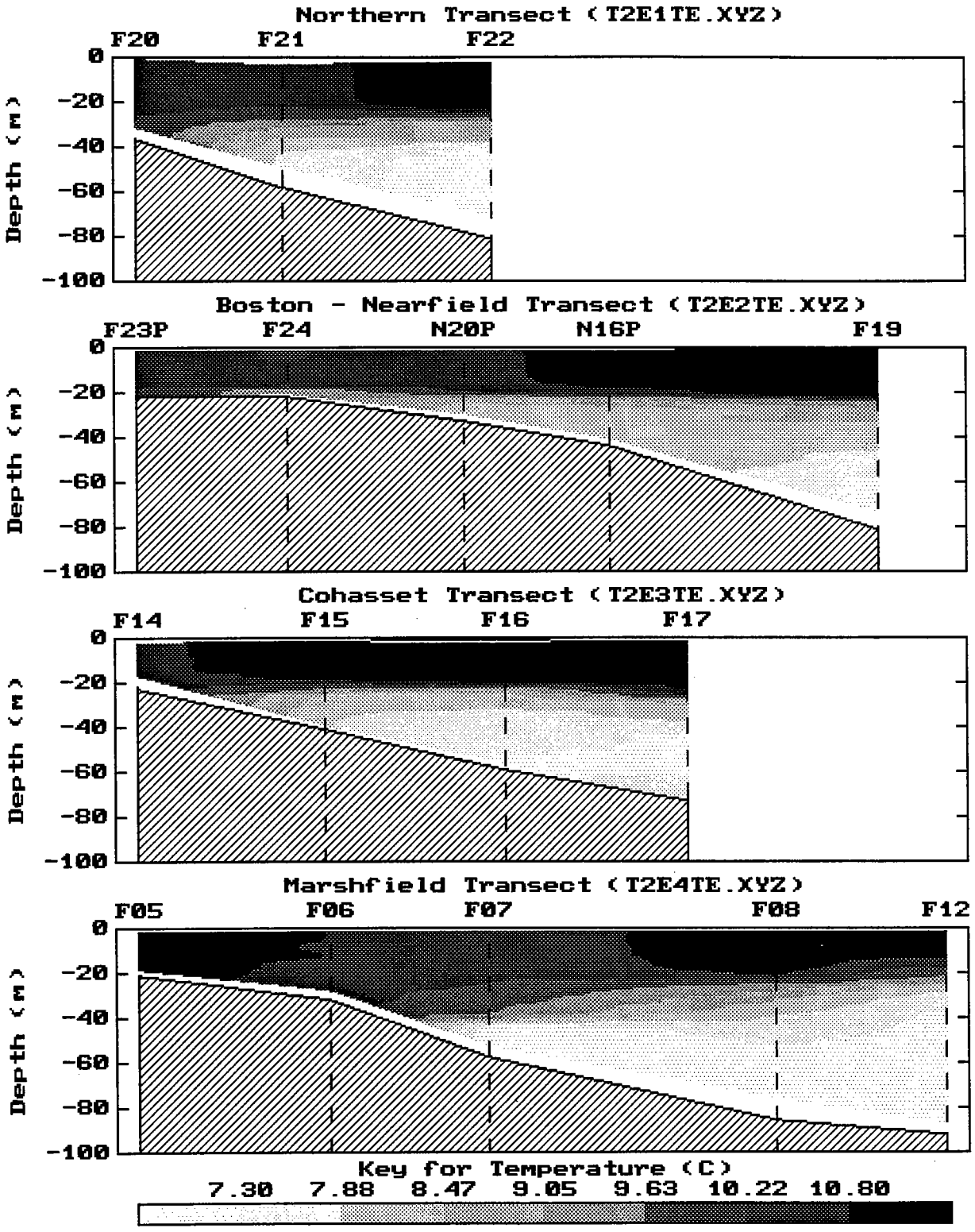


Figure 3-10a. Vertical section contours of temperature in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

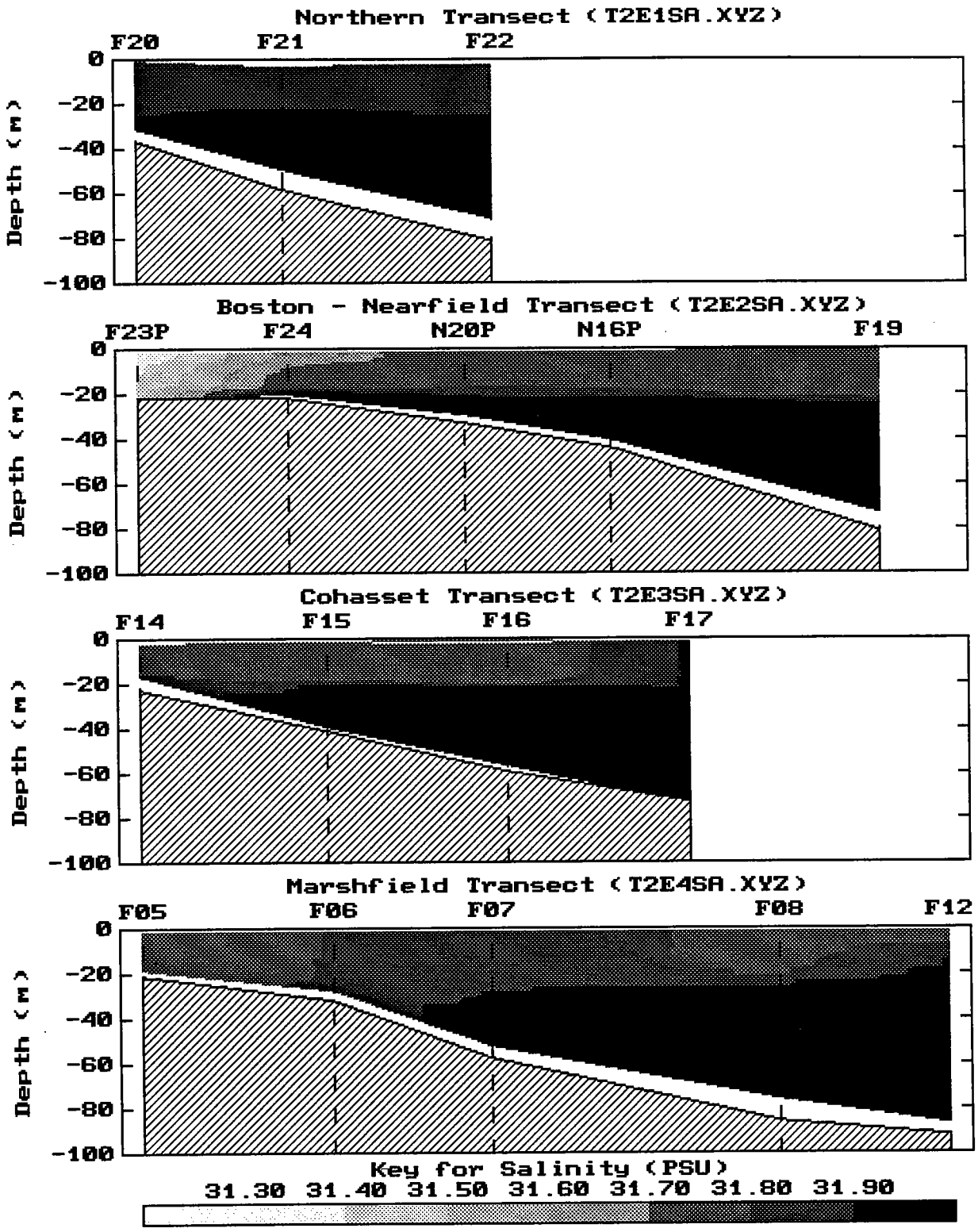


Figure 3-10b. Vertical section contours of salinity in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

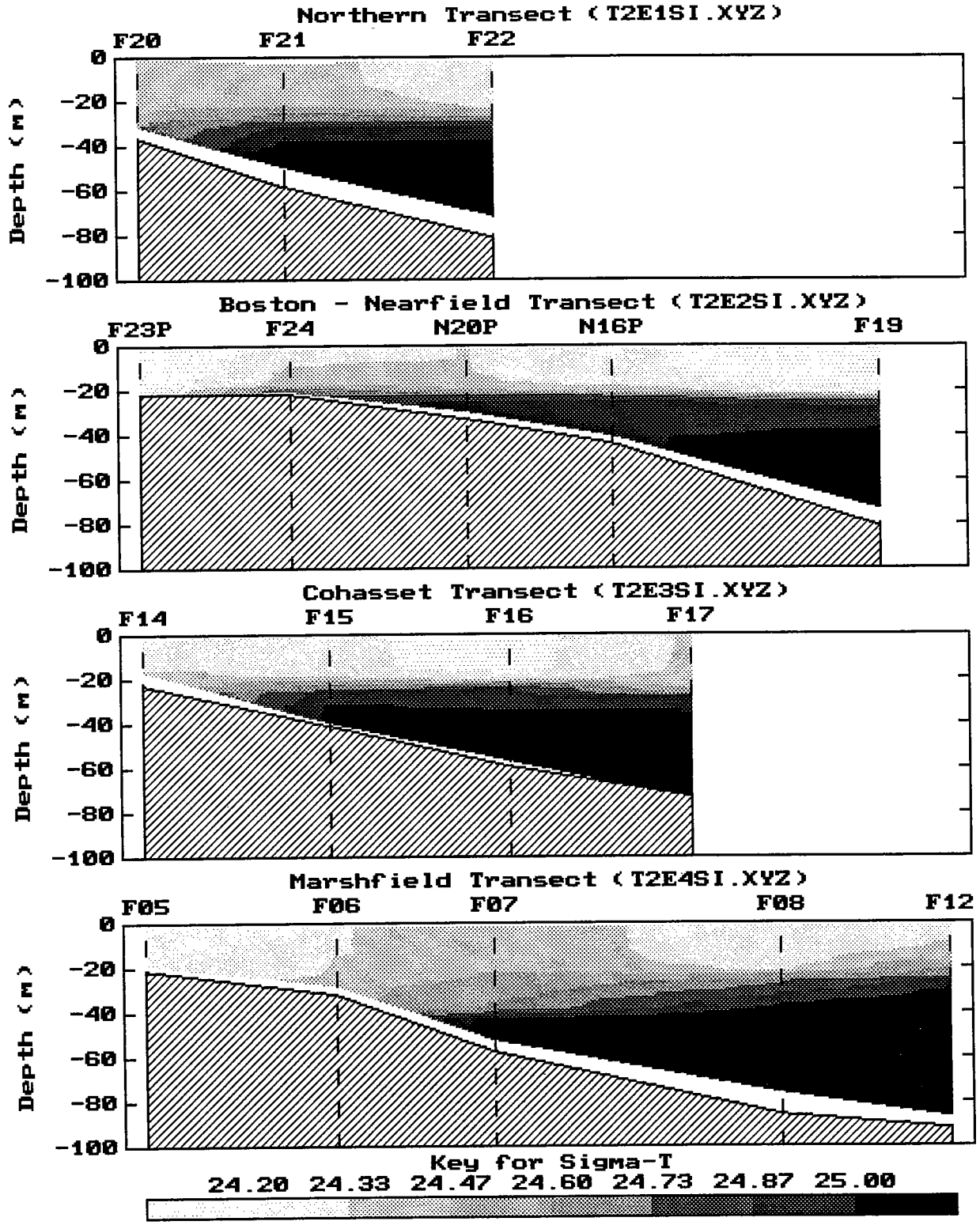


Figure 3-10c. Vertical section contours of density (σ_T) in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

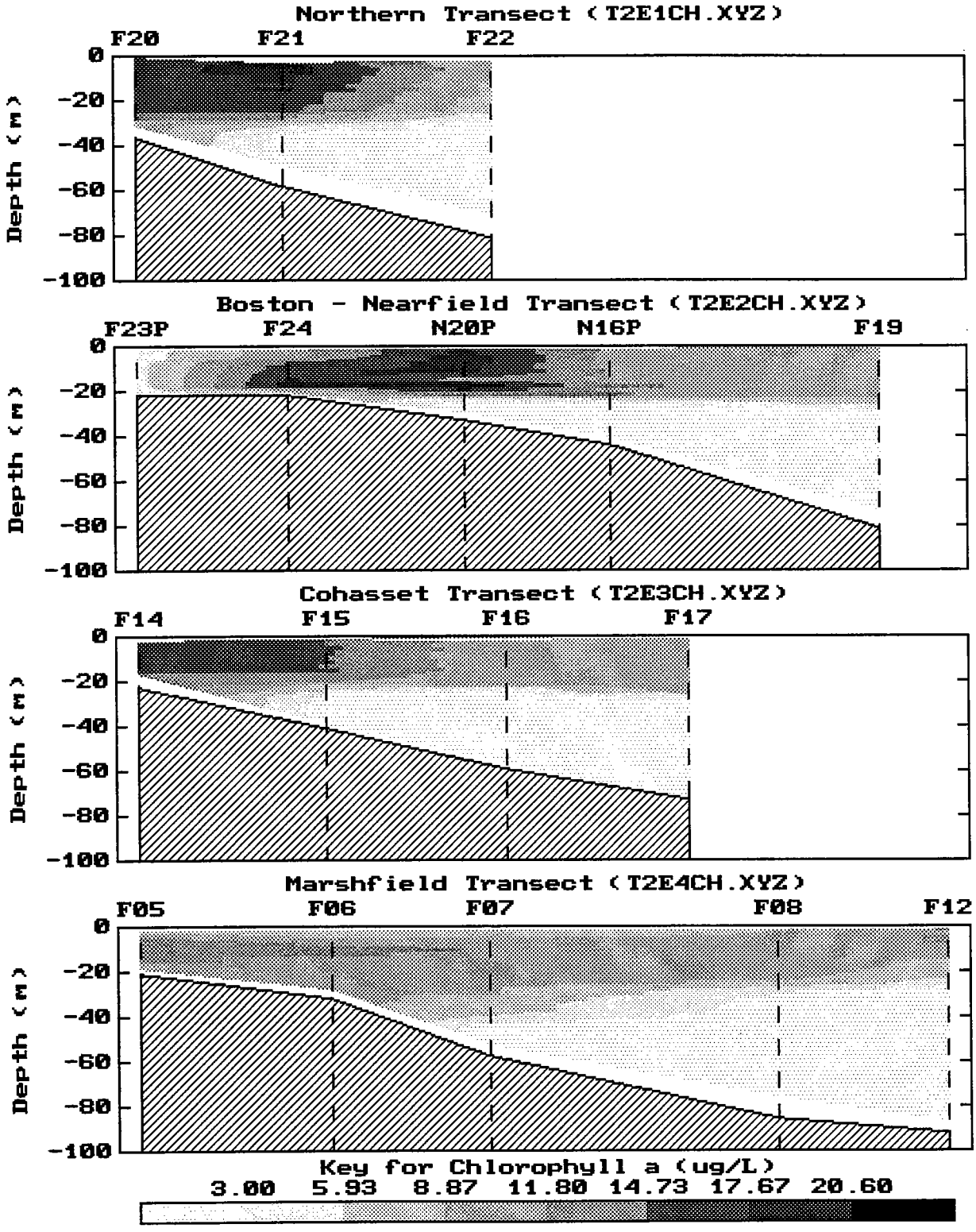


Figure 3-11. Vertical section contours of fluorescence (as μg Chl L^{-1}) in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

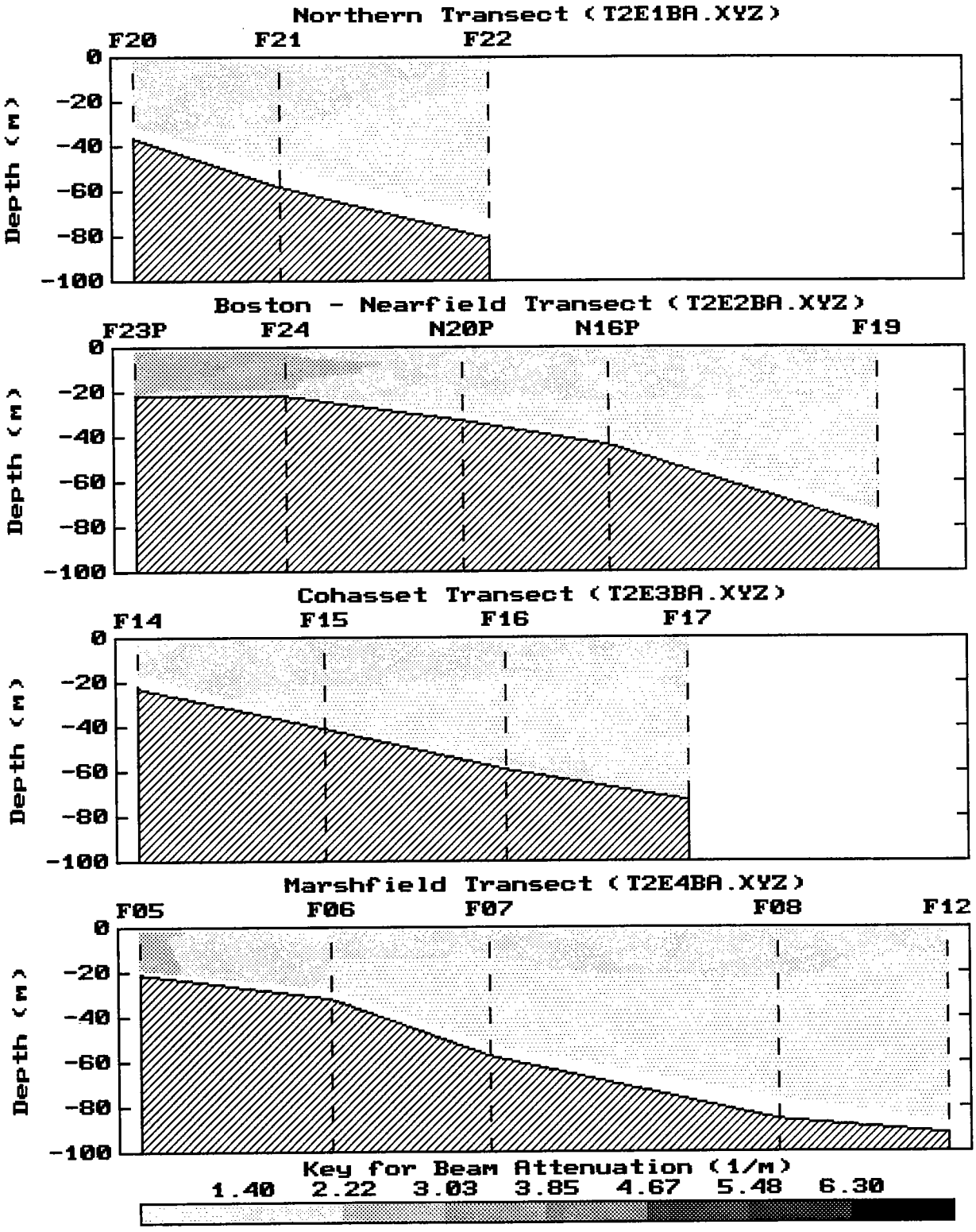


Figure 3-12. Vertical section contours of beam attenuation in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

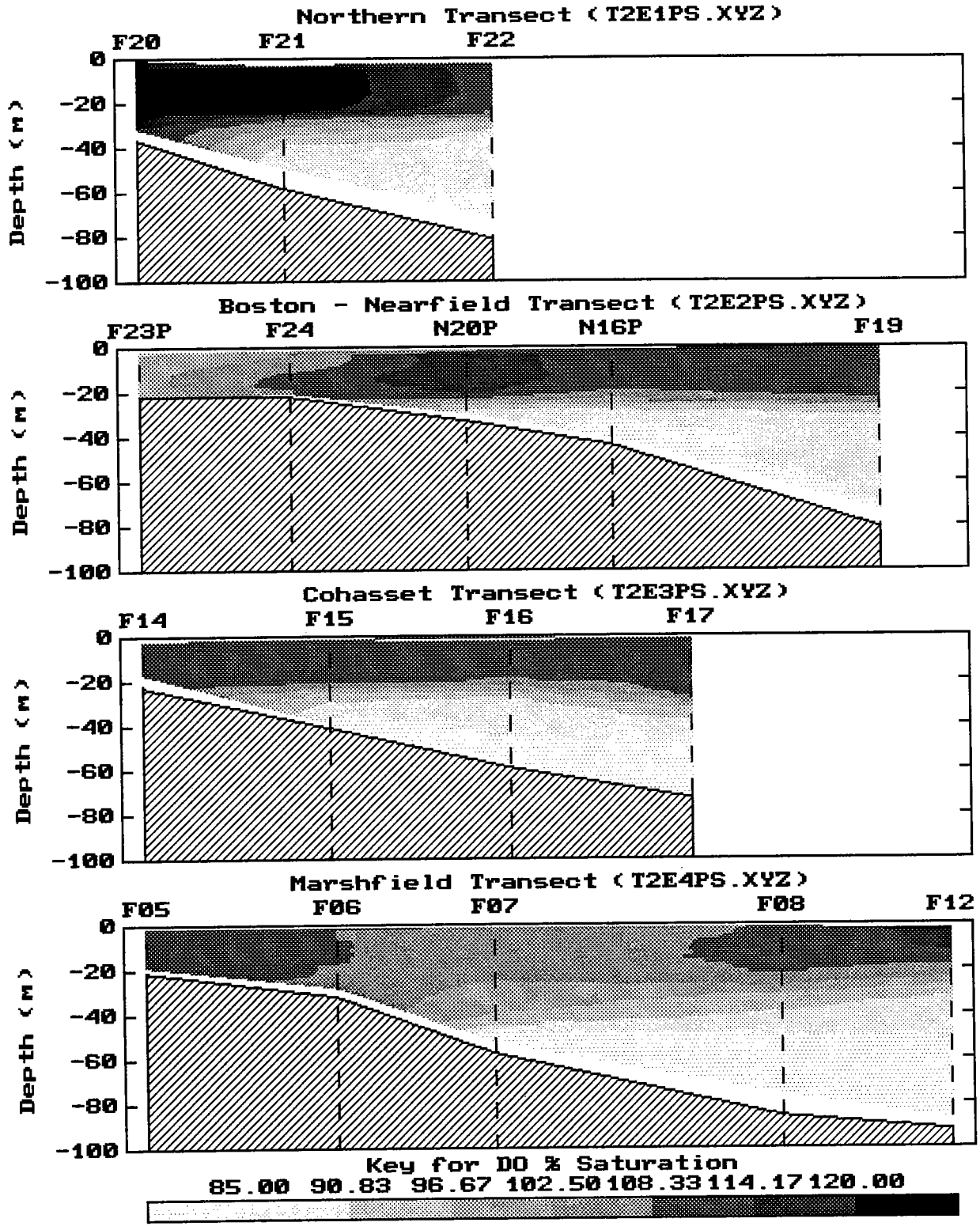


Figure 3-13. Vertical section contours of dissolved oxygen (% saturation) in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

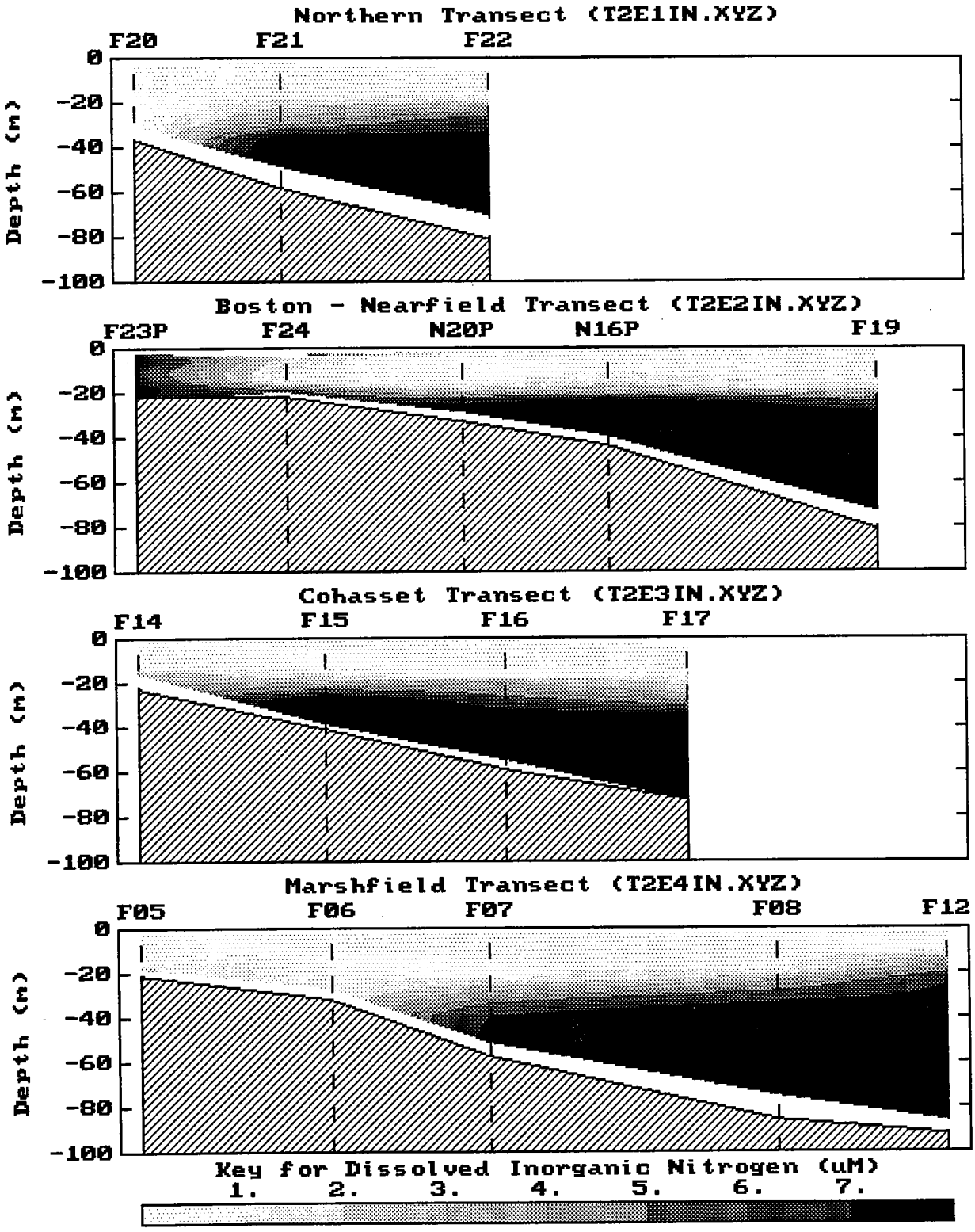


Figure 3-14a. Vertical section contours of dissolved inorganic nitrogen (DIN, μM) in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from discrete bottle samples (Appendix A).

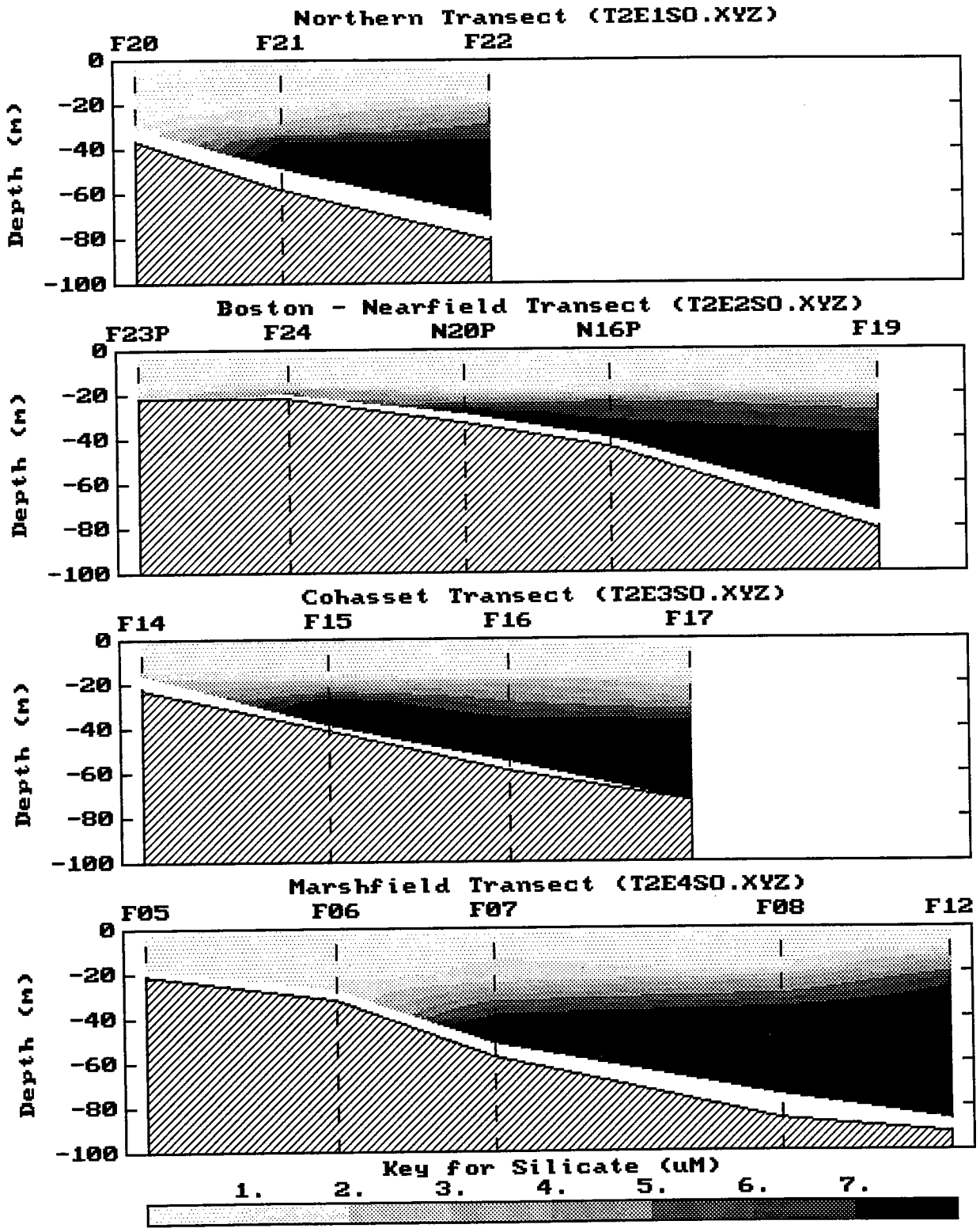


Figure 3-14b. Vertical section contours of silicate (SiO_4, μM) in October 1993 for standard transects (see Figure 3-9). The data used to produce contours are from discrete bottle samples (Appendix A).

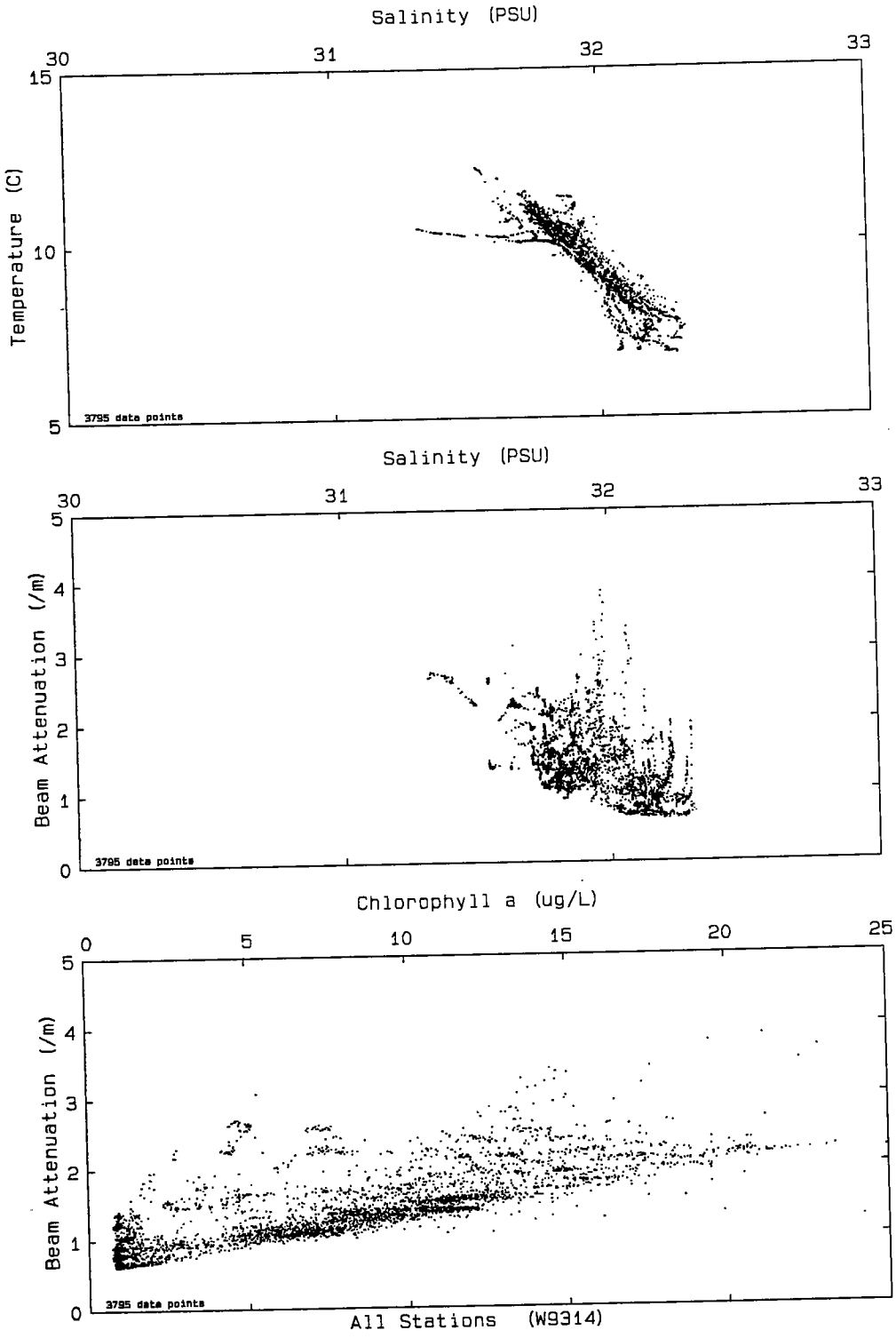


Figure 3-15a. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all farfield and nearfield stations occupied in October 1993. Individual station casts that were used to produce this composite are in Appendix B. Regional plots are in Appendix C. Chlorophyll is estimated from *in situ* fluorescence.

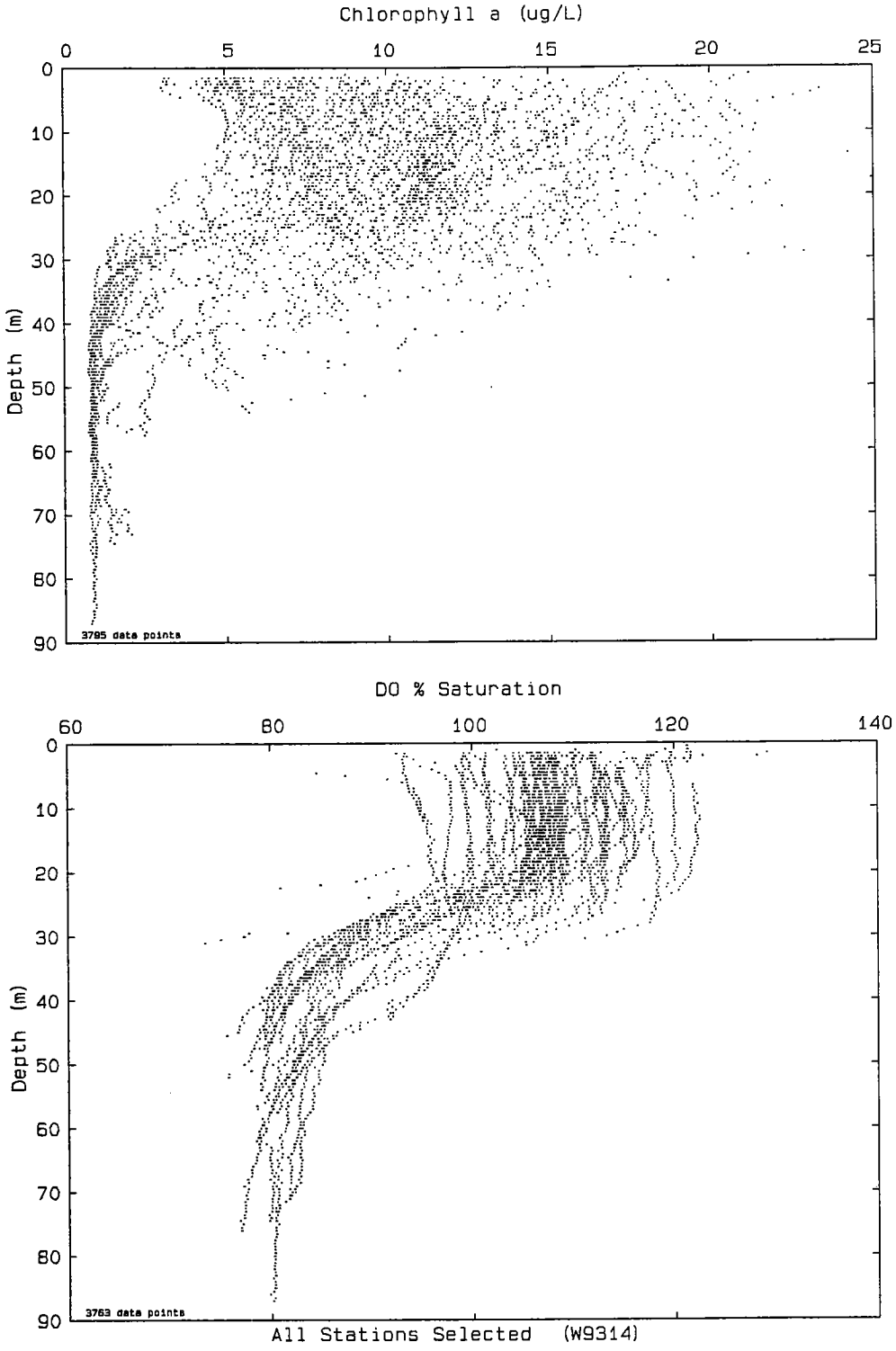


Figure 3-15b. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all farfield and nearfield stations occupied in October 1993. Individual station casts that were used to produce this composite are in Appendix B. Regional plots are in Appendix C. Chlorophyll is estimated from *in situ* fluorescence.

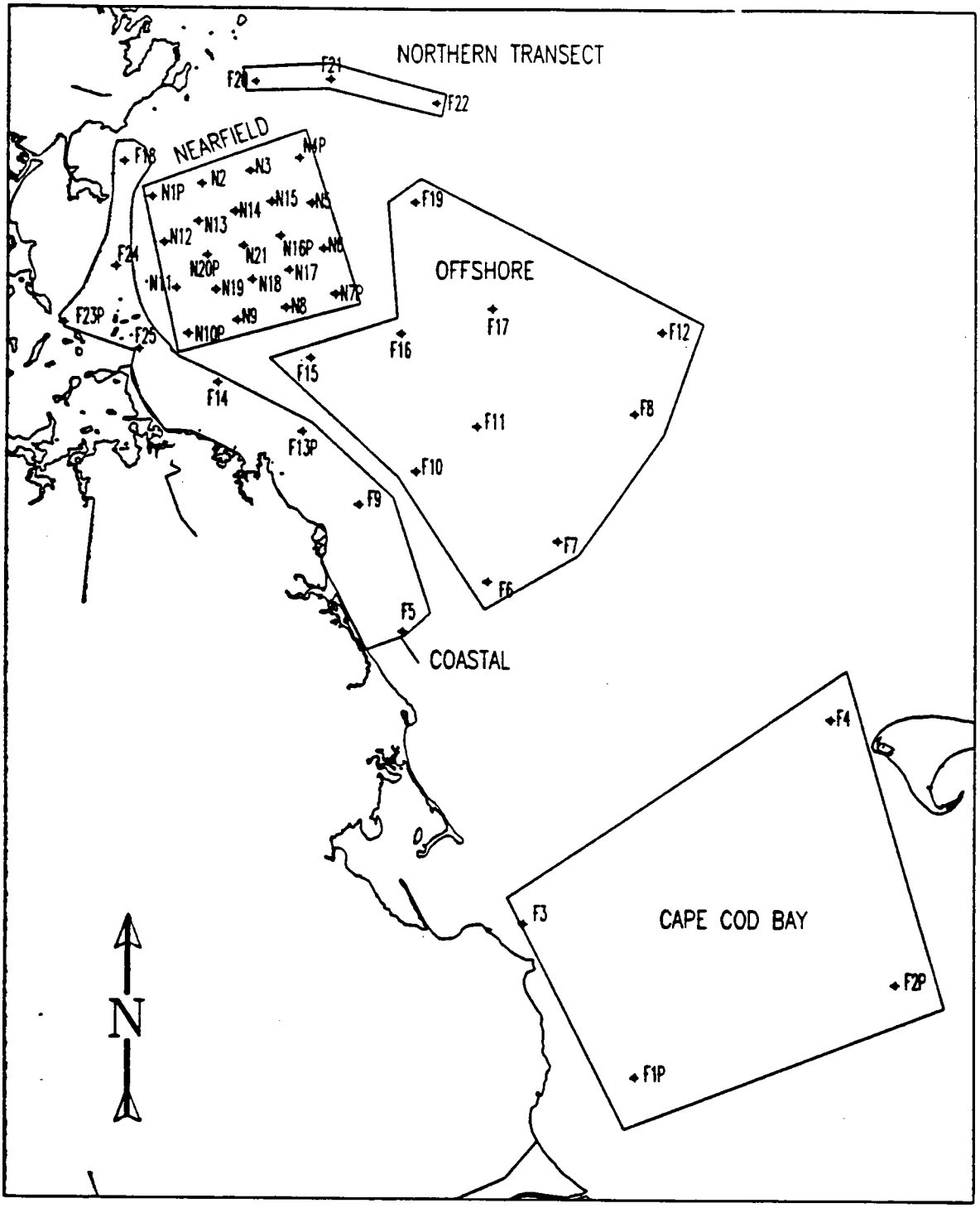


Figure 3-16. **Map to show station groups designated in Figures 3-17 through 3-22. Massachusetts Bay stations were separated into four groups based on water depth and geographic position; Cape Cod Bay has four stations.**

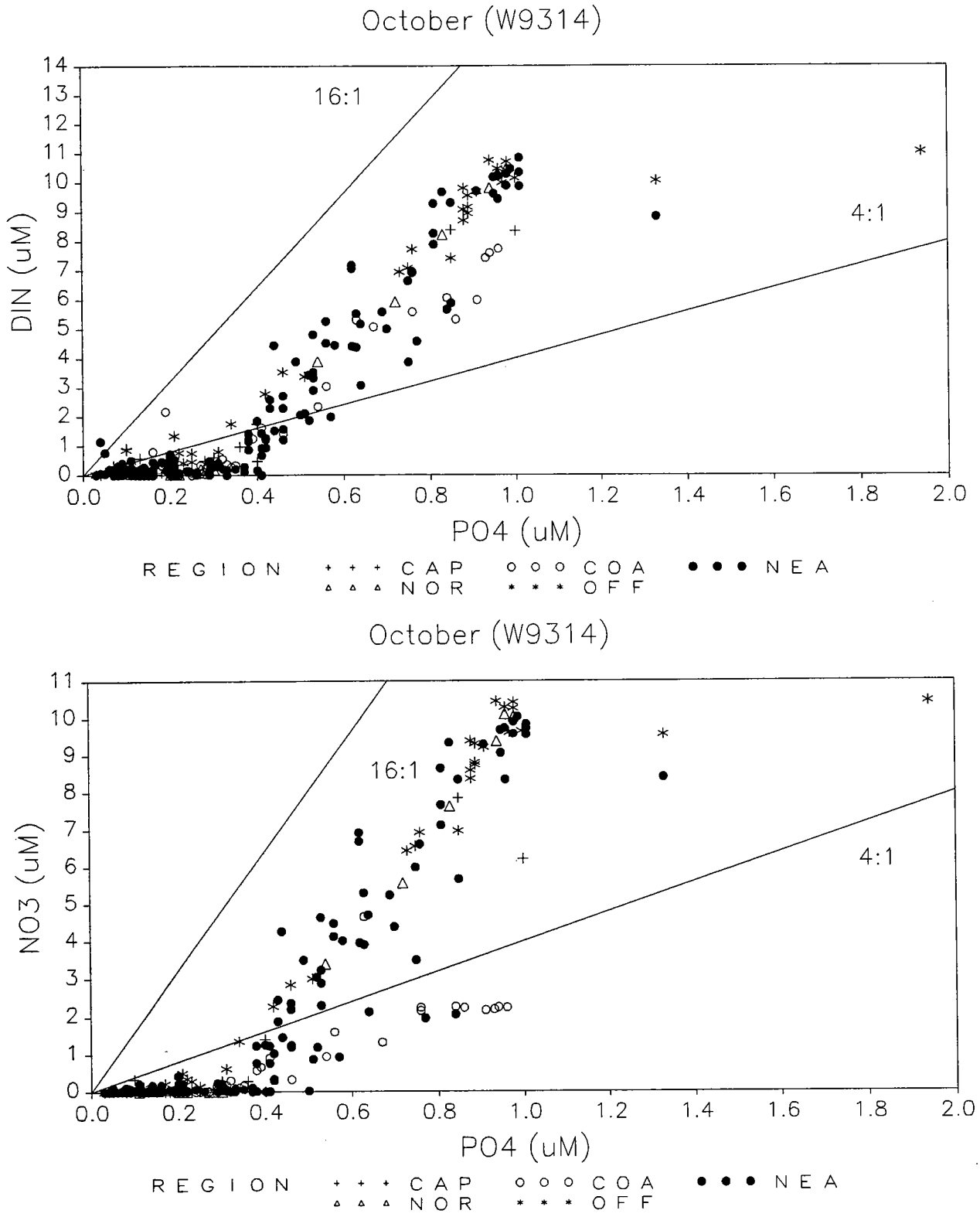


Figure 3-17. **Scatter plots of nitrogen forms vs. phosphate during October 1993. All stations and depths are included. Lines show constant proportions of nitrogen relative to phosphorous. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.**

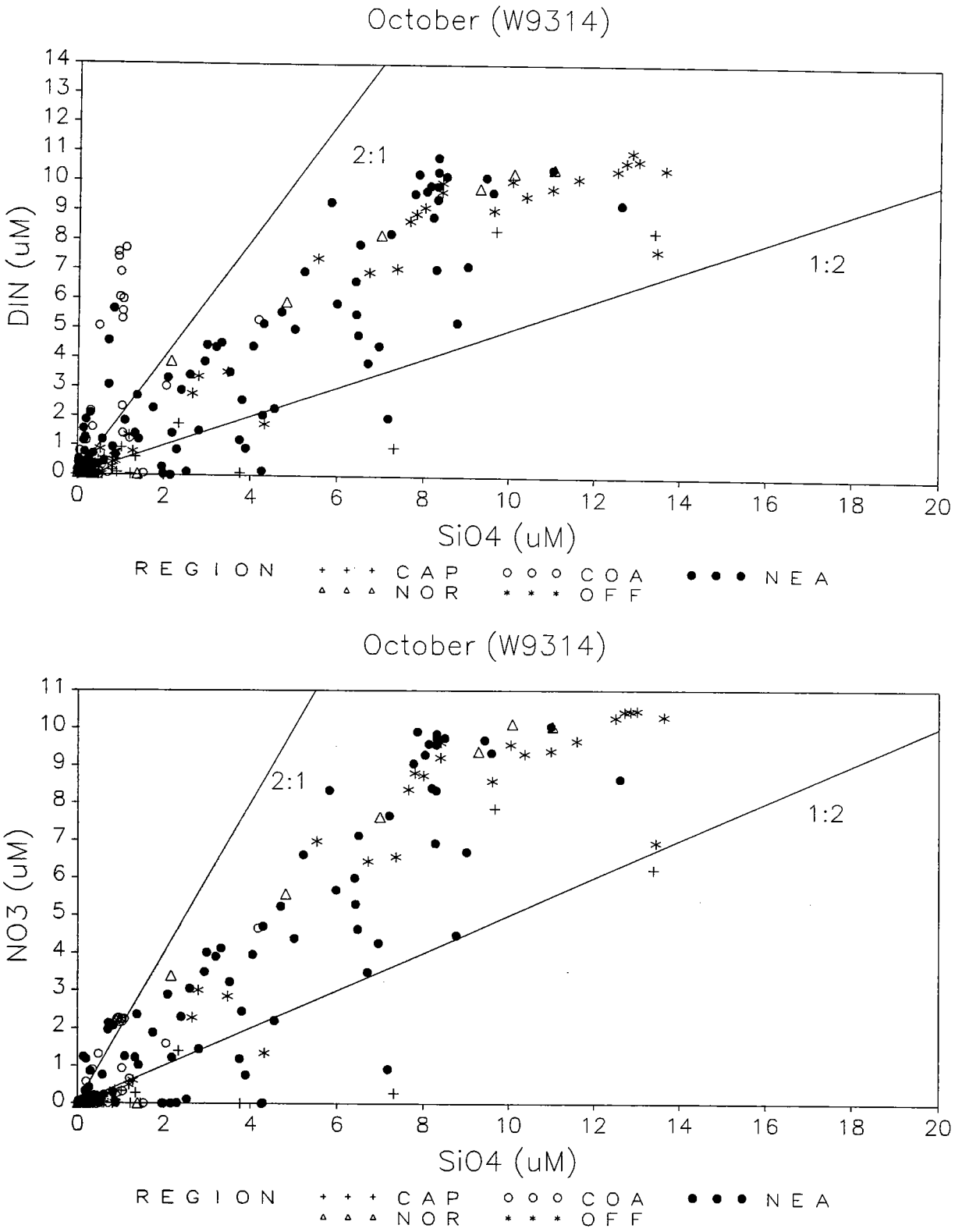


Figure 3-18. **Scatter plots of nitrogen vs. silicate during October 1993. All stations and depths are included. Lines show constant proportions of nitrogen relative to silicate. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.**

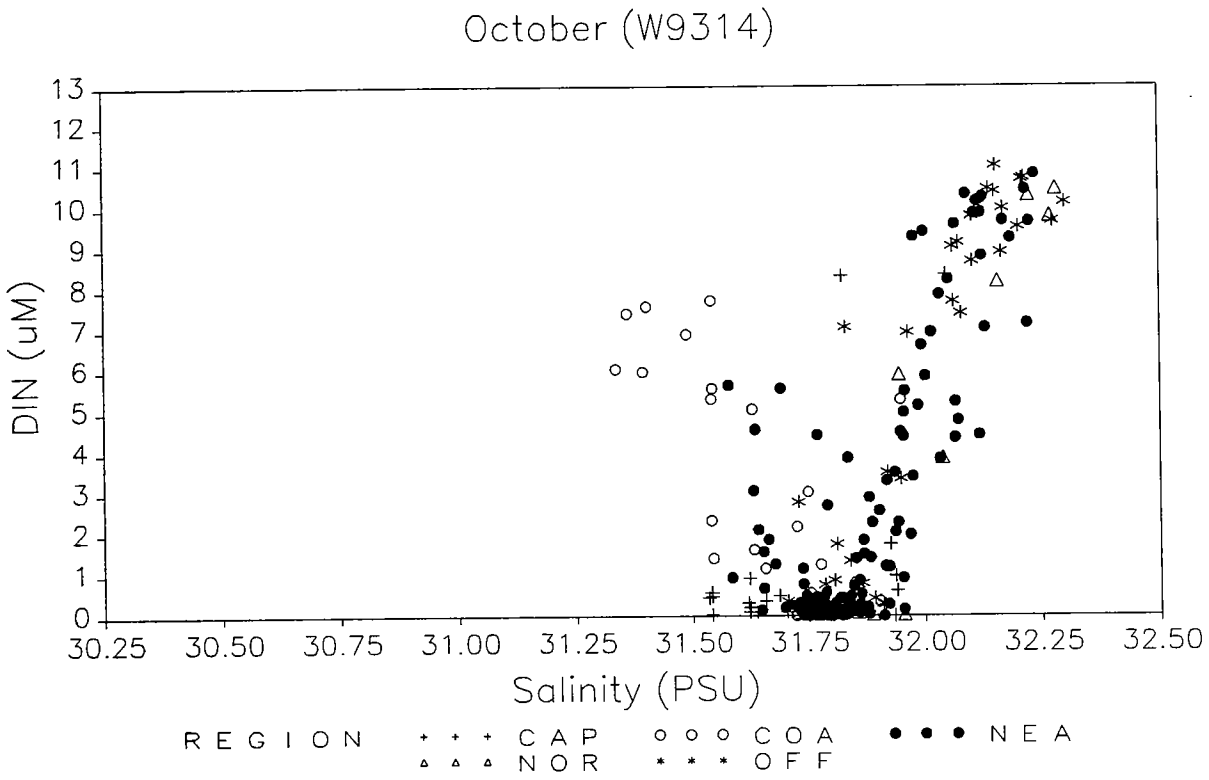


Figure 3-19. **Dissolved inorganic nitrogen vs. salinity in October 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.**

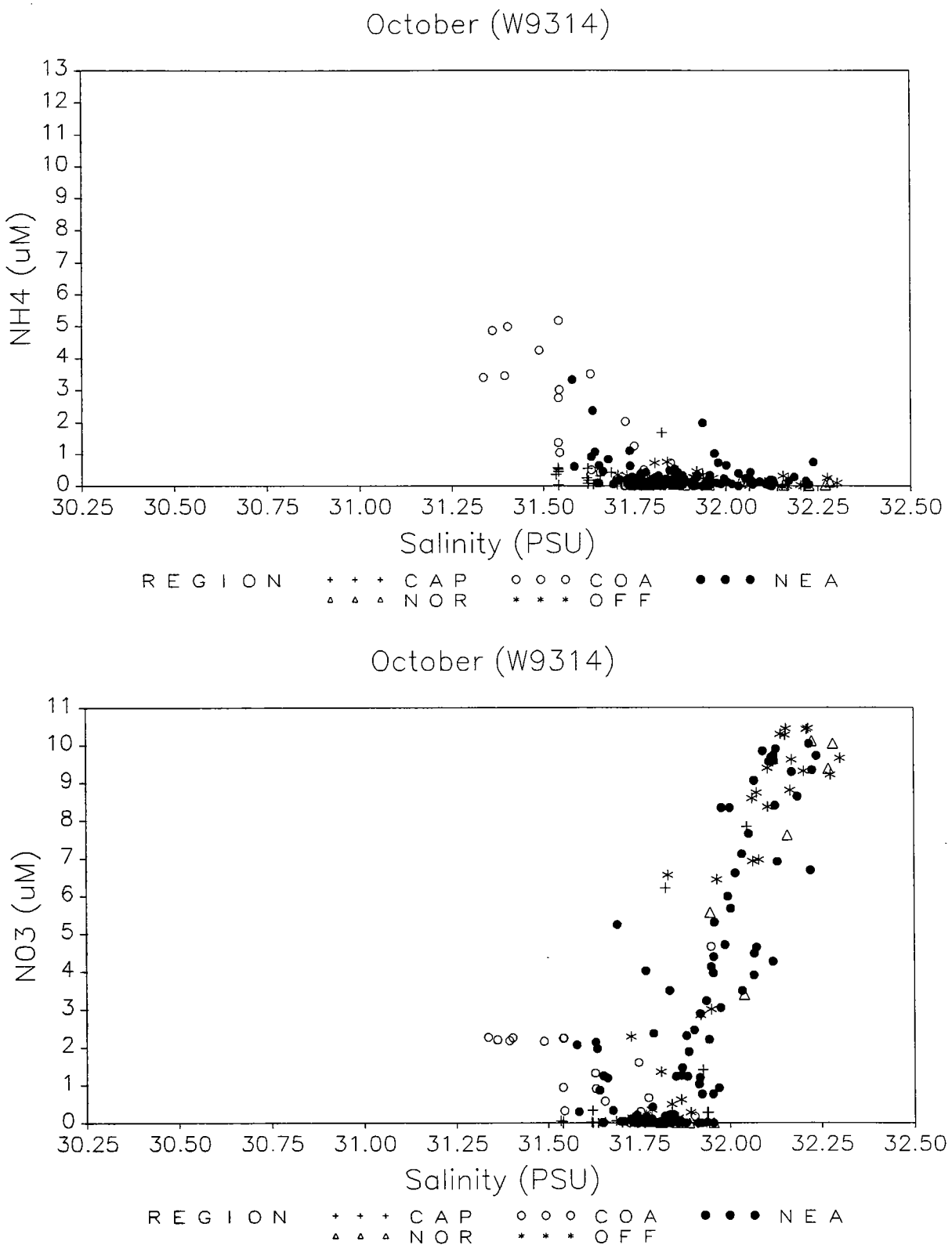


Figure 3-20. Ammonia and nitrate vs. salinity in October 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

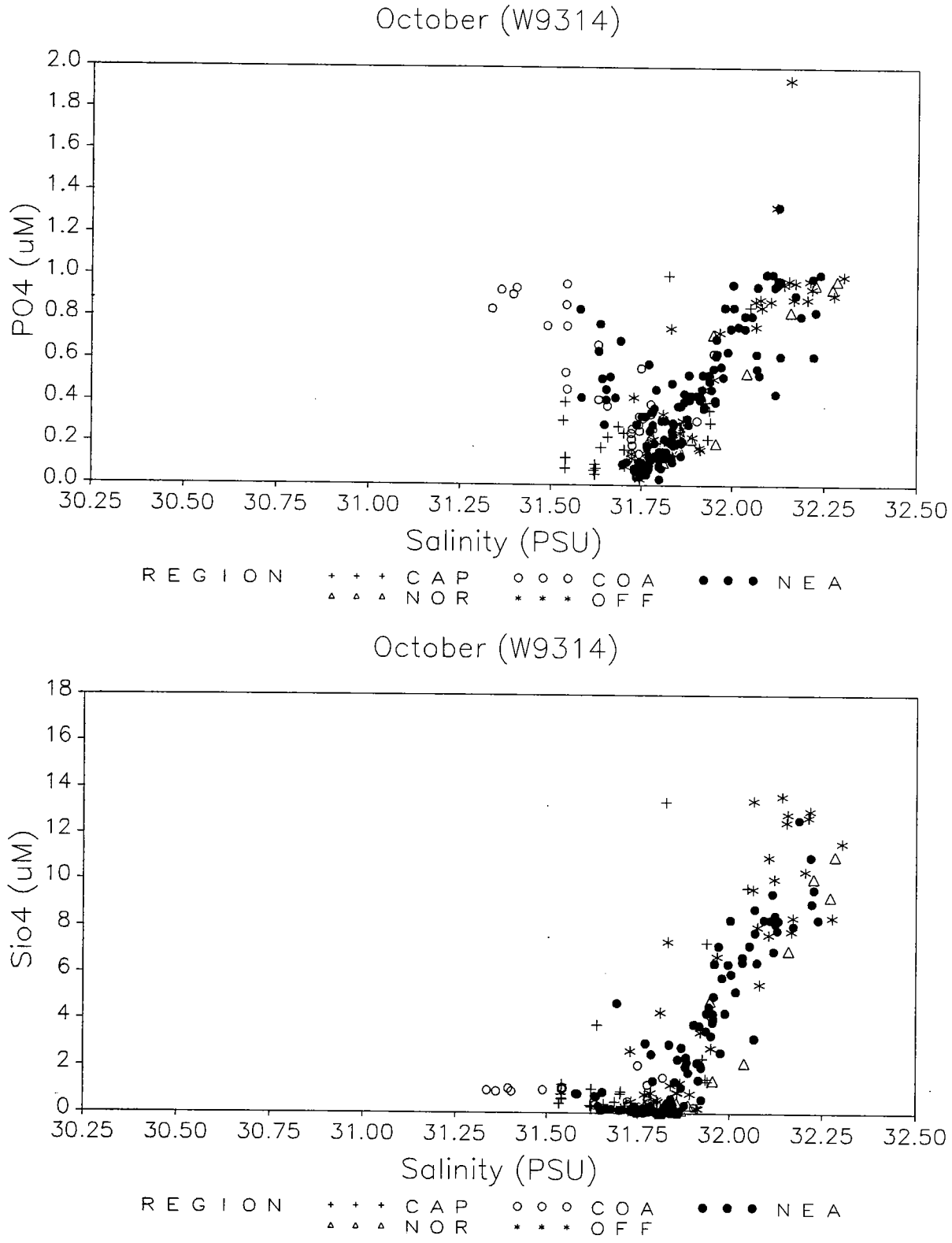
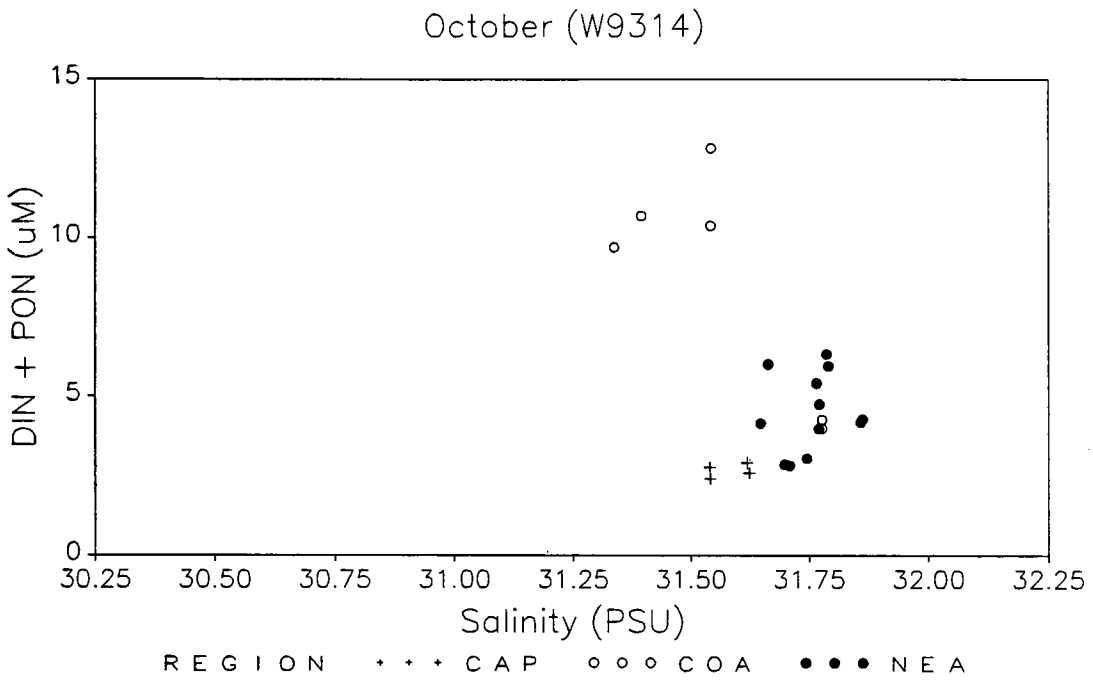


Figure 3-21. Phosphate and silicate vs. salinity in October 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.



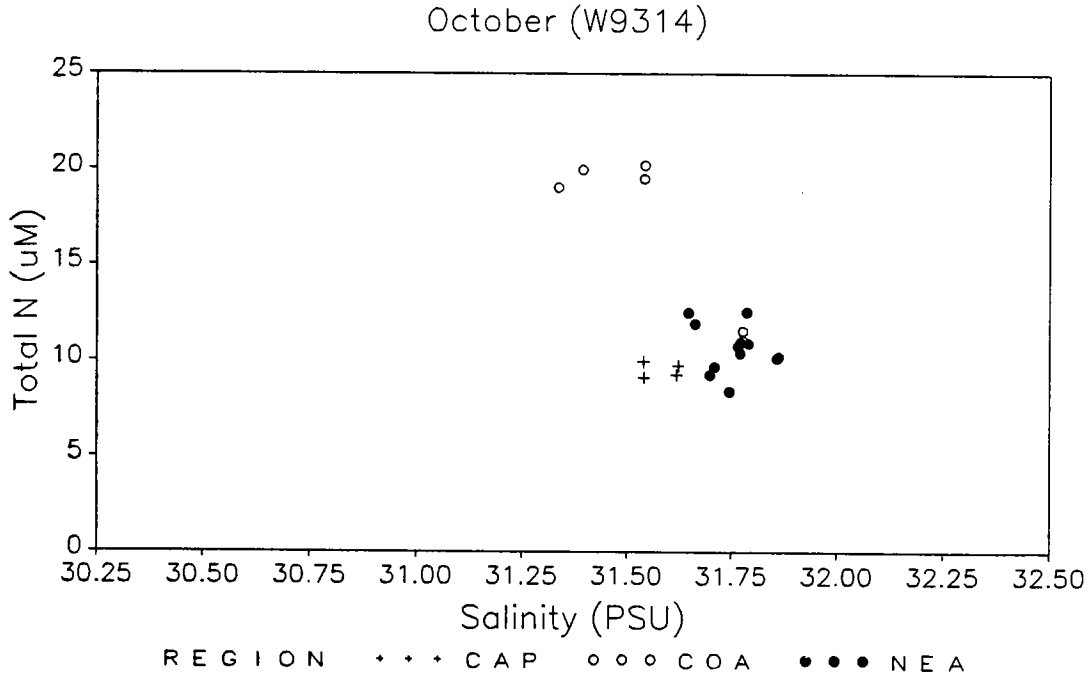


Figure 3-22. **Nitrogen forms vs. salinity in October 1993. Data are from BioProductivity stations and special station F25. The station groups are coded as given in Figure 3-16; there are no BioProductivity stations in the offshore or northern transect groups. Data are given in Appendix A. Dissolved 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.**

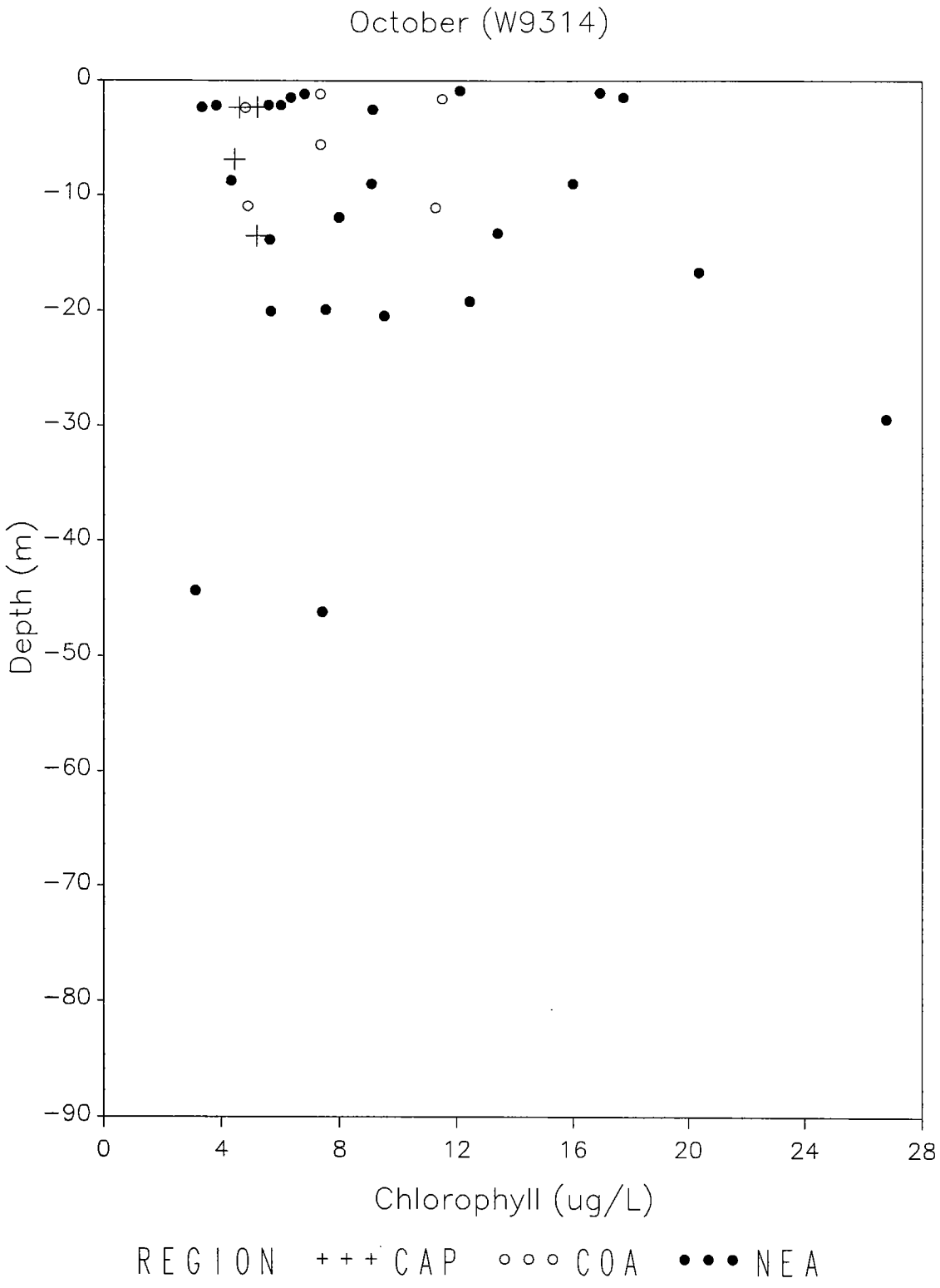


Figure 3-23. **Chlorophyll (extracted samples) at BioProductivity stations and special station F25 as a function of depth in October 1993. Data are from farfield (n=22) and nearfield (n=12) surveys. The regions correspond to three of the groups of stations shown in Figure 3-16.**

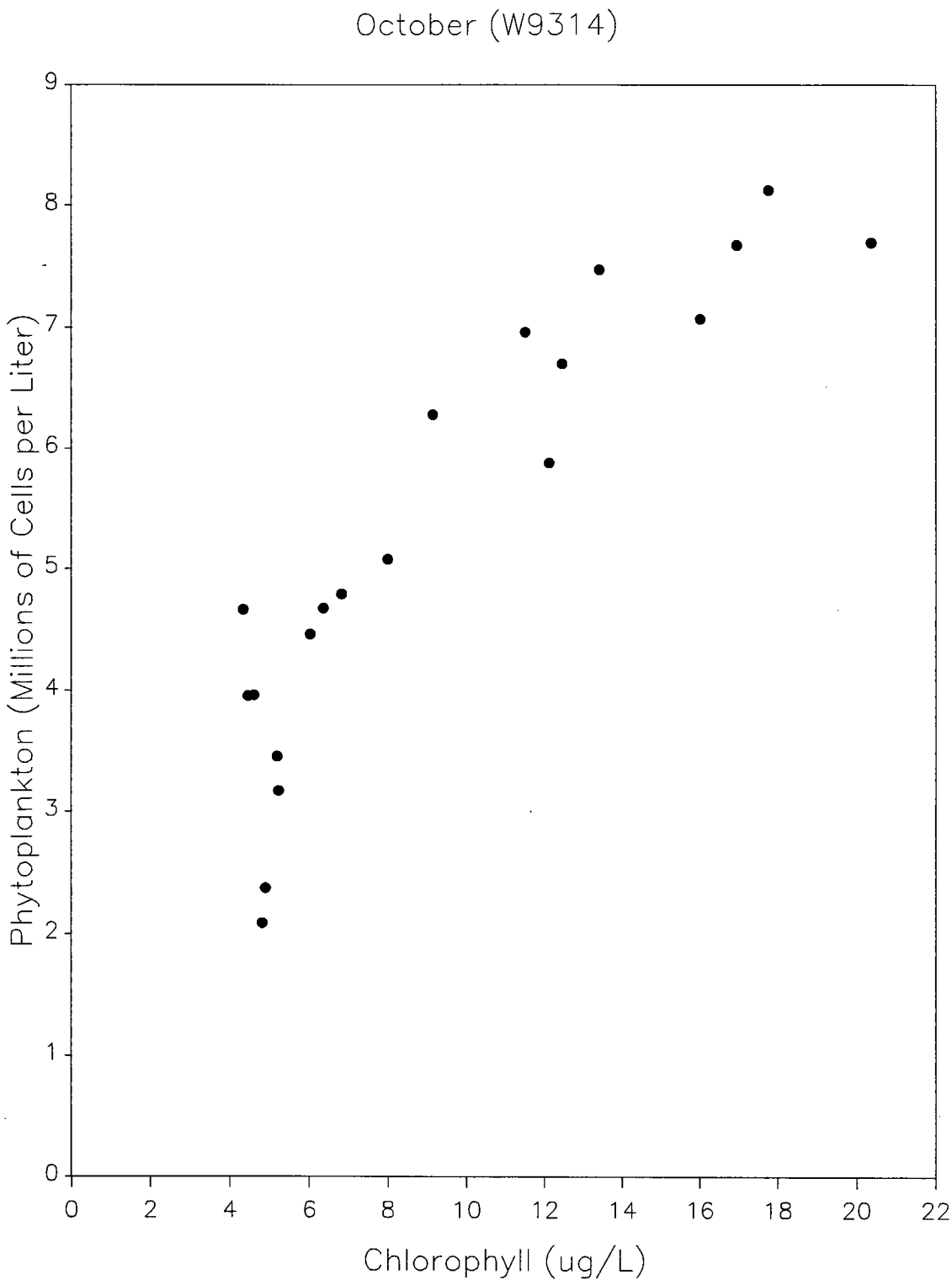


Figure 3-24. **Total phytoplankton abundance vs. chlorophyll (extracted samples) at BioProductivity stations in October 1993. Station N10P surface was analyzed for both farfield and nearfield surveys. Data are given in Appendices A and F.**

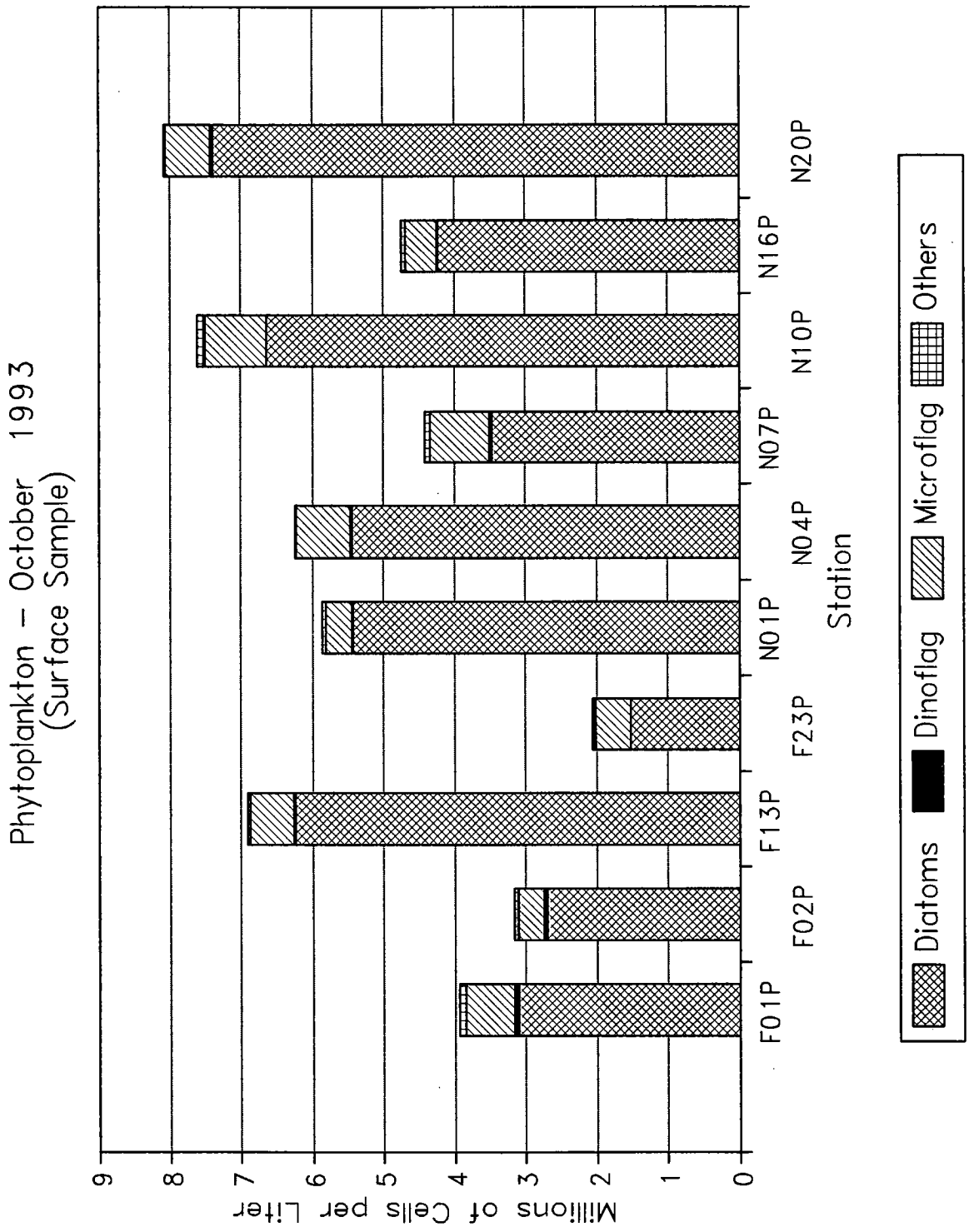


Figure 3-25a. Total phytoplankton abundance, by taxonomic groups, at the surface of BioProductivity stations in October 1993. Data are given in Appendix F.

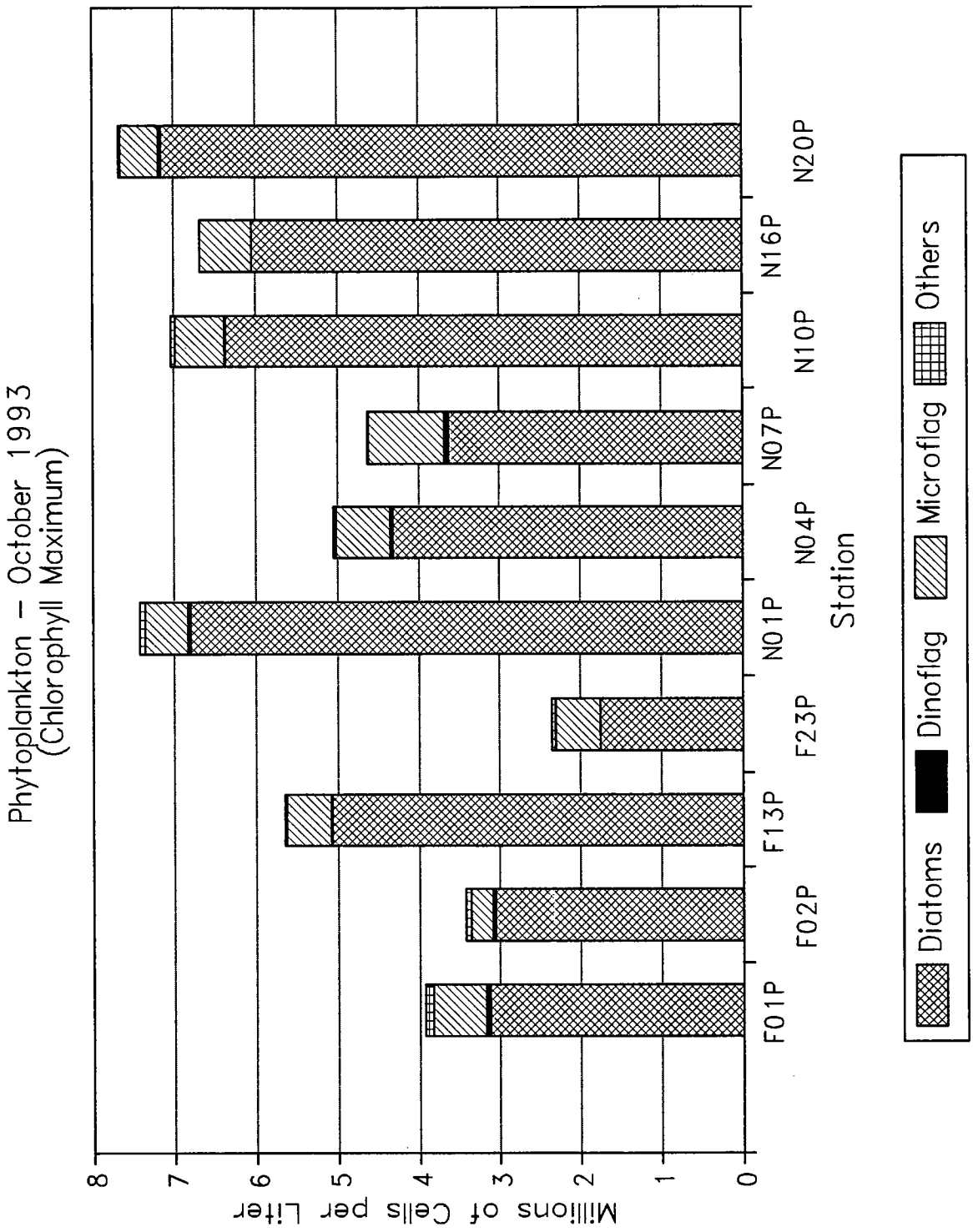


Figure 3-25b. Total phytoplankton abundance, by taxonomic groups, at the chlorophyll maximum of BioProductivity stations in October 1993. Data are given in Appendix F.

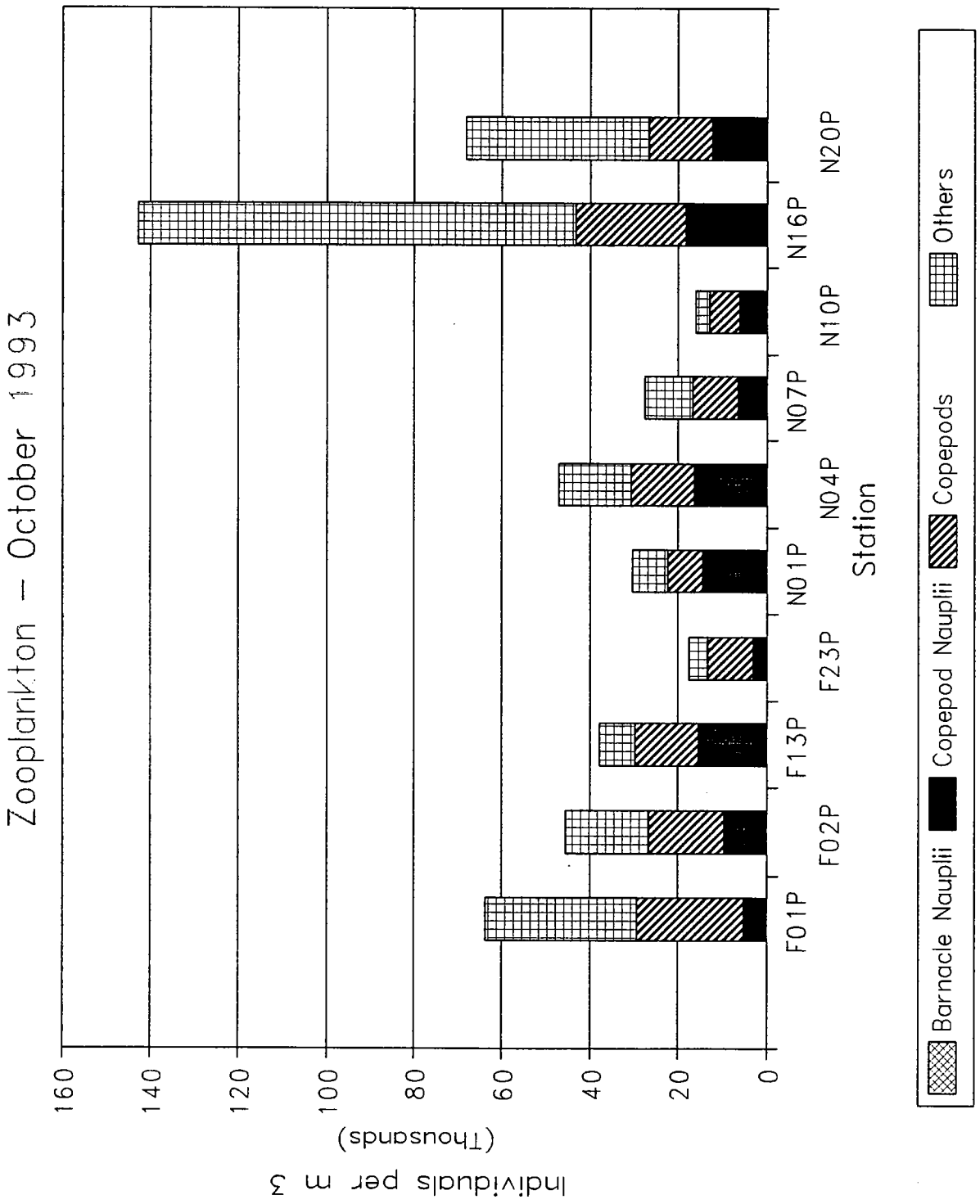


Figure 3-26. Zooplankton abundance, by groups, at BioProductivity stations in October 1993. Data are given in Appendix G.

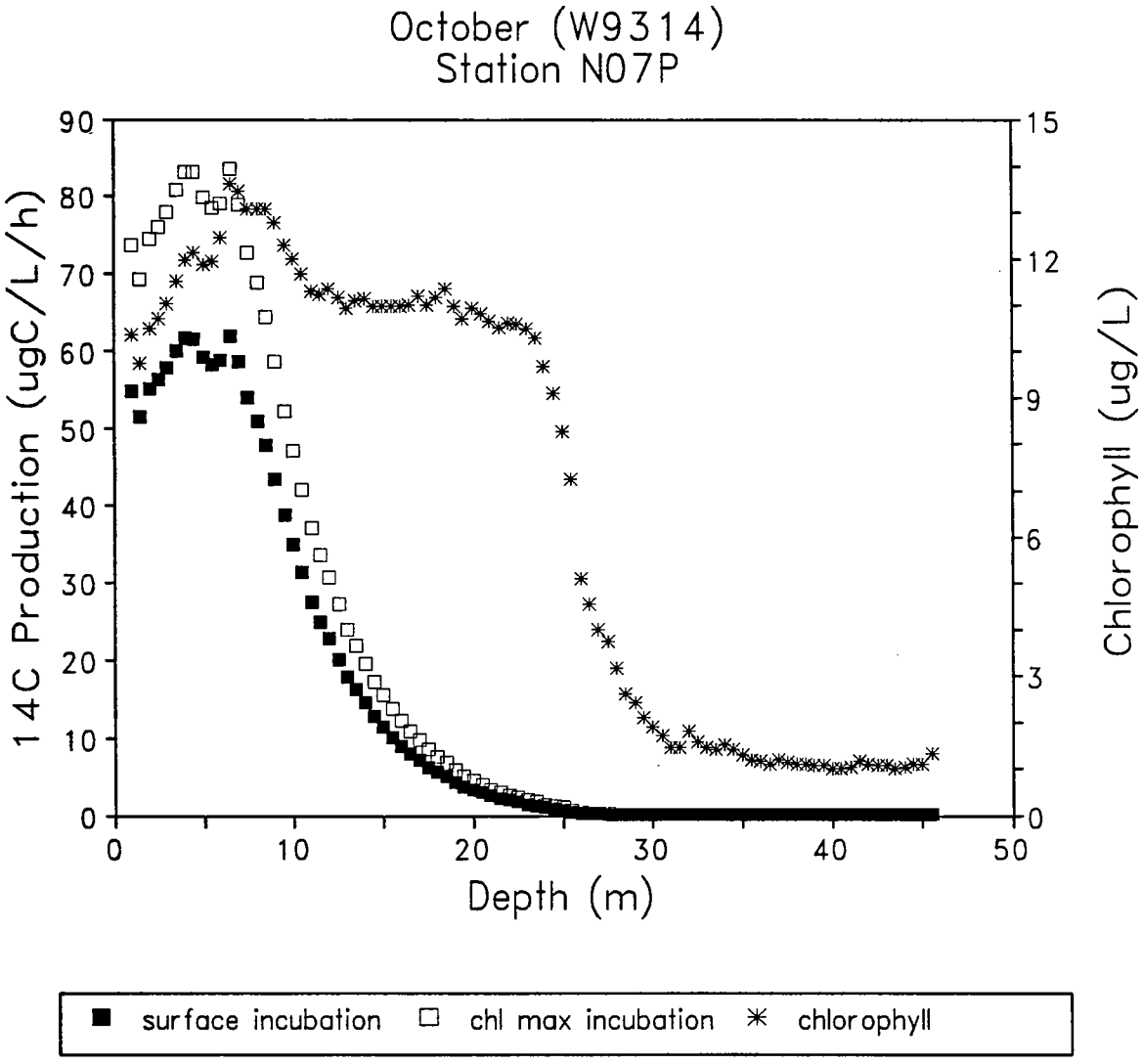


Figure 3-27. **Estimated ^{14}C production and chlorophyll vs. depth at station N07P in October 1993. Production was calculated using the Webb *et al.* (1974) model for surface and chlorophyll maximum water samples, see Appendix E.**

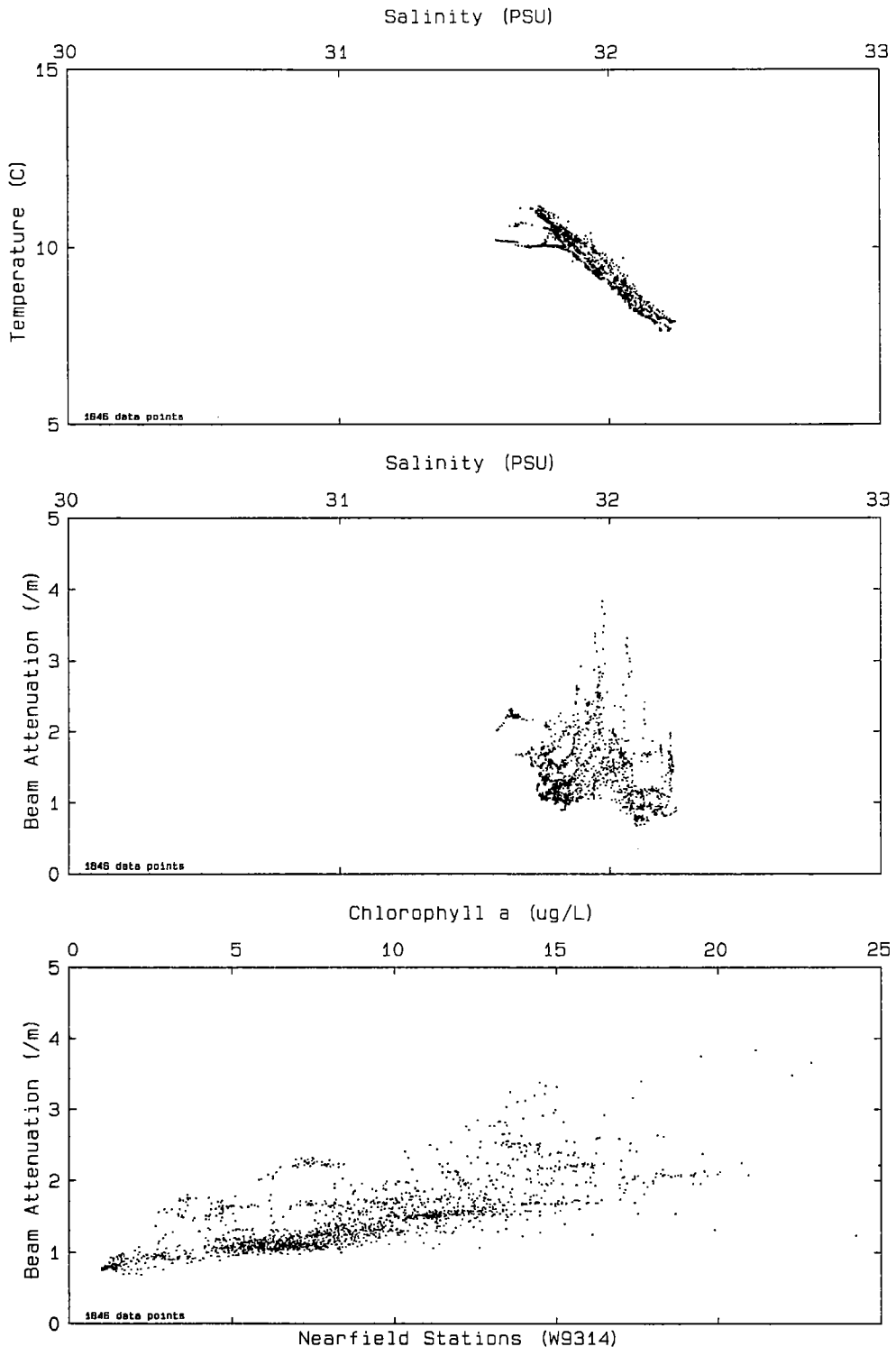


Figure 3-28a. Scatter plots for nearfield stations in October 1993. Compare to Figure 3-15.

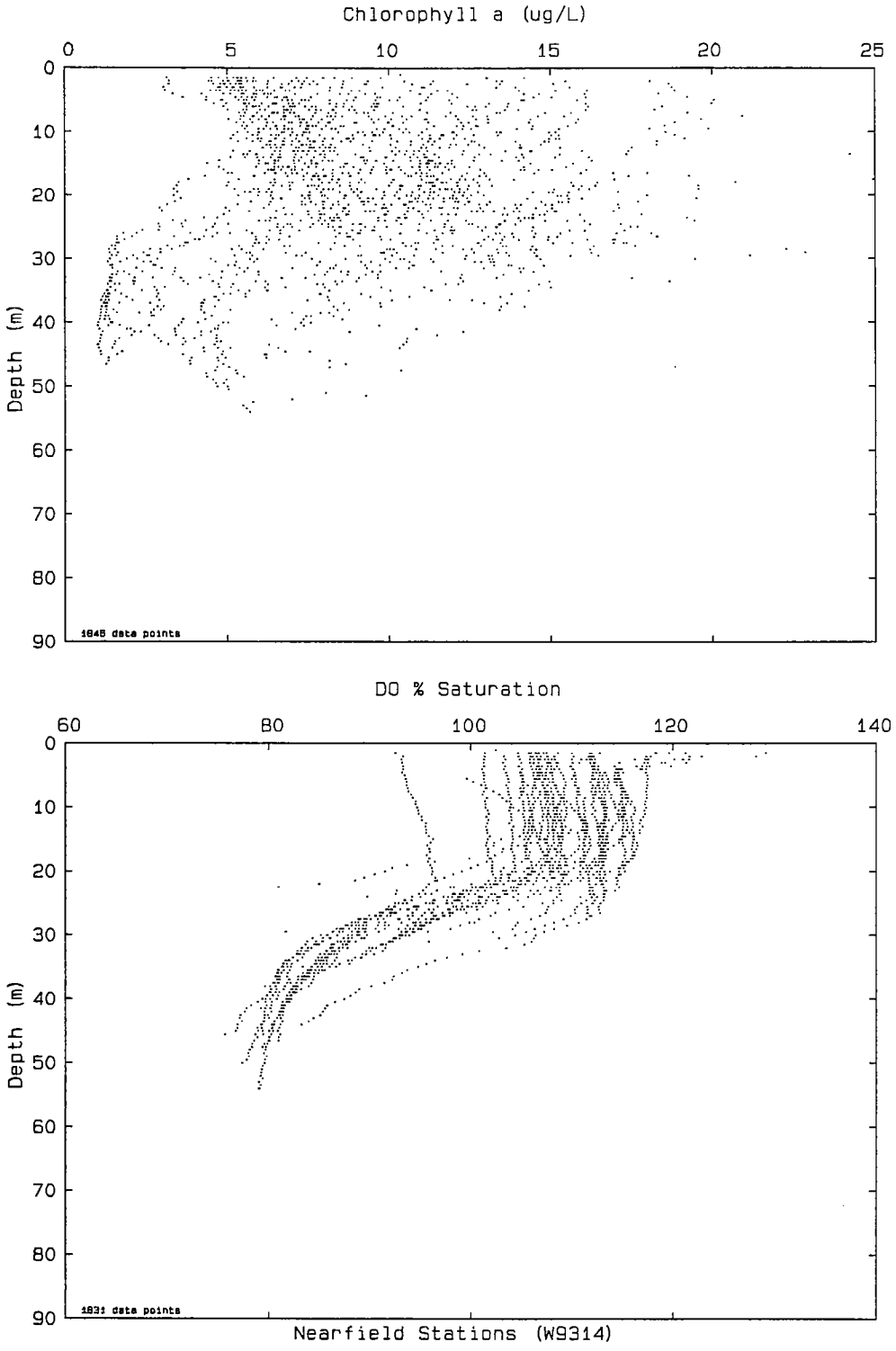
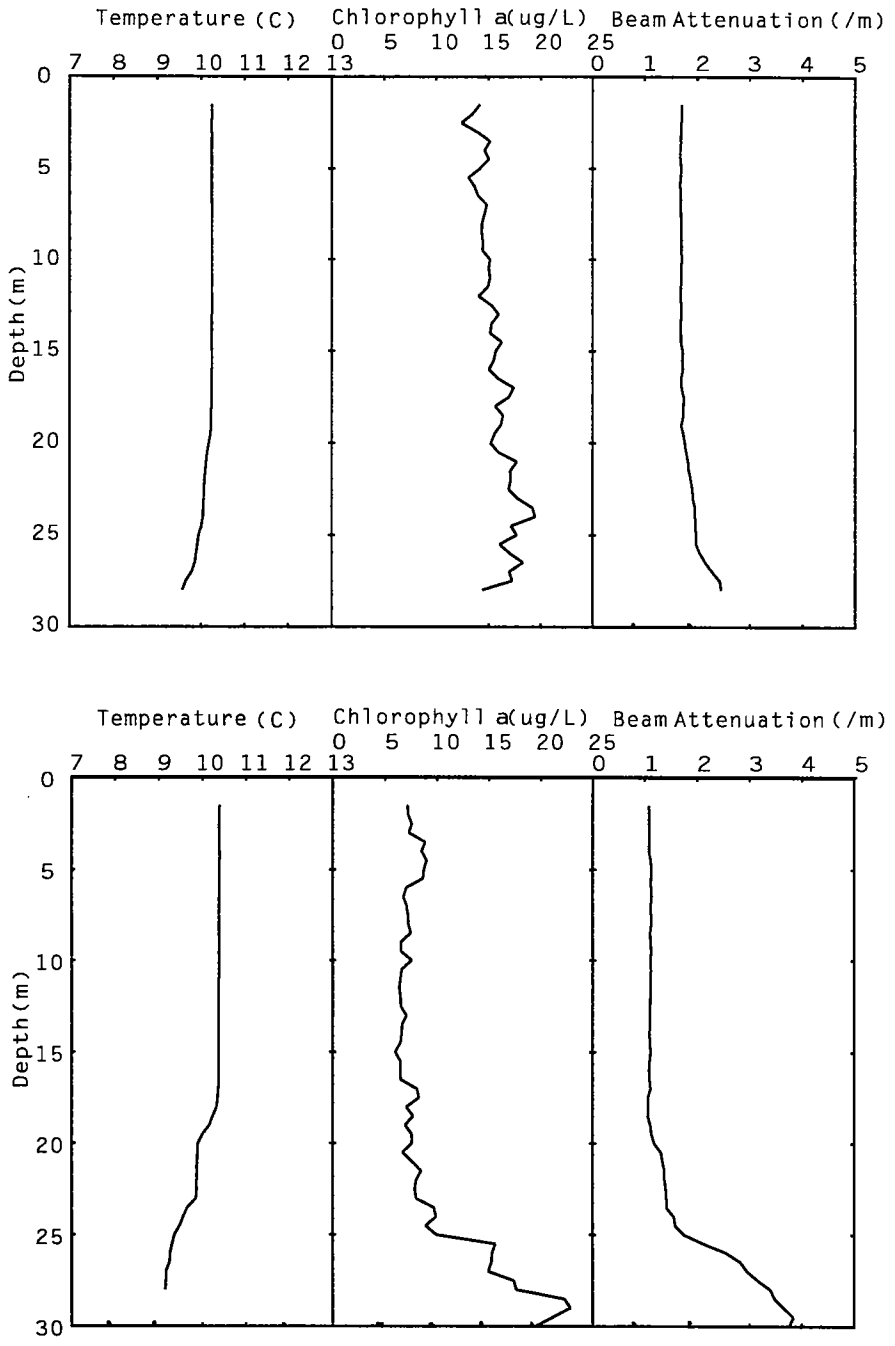


Figure 3-28b. Scatter plots for nearfield stations in October 1993. Compare to Figure 3-15.



N01P

Figure 3-29a. Temperature, chlorophyll, and beam attenuation profiles for October 13 (top panel) and 15 (bottom panel) 1993 at station N01P. Data are from the downcast (complete profile set presented in Appendix B).

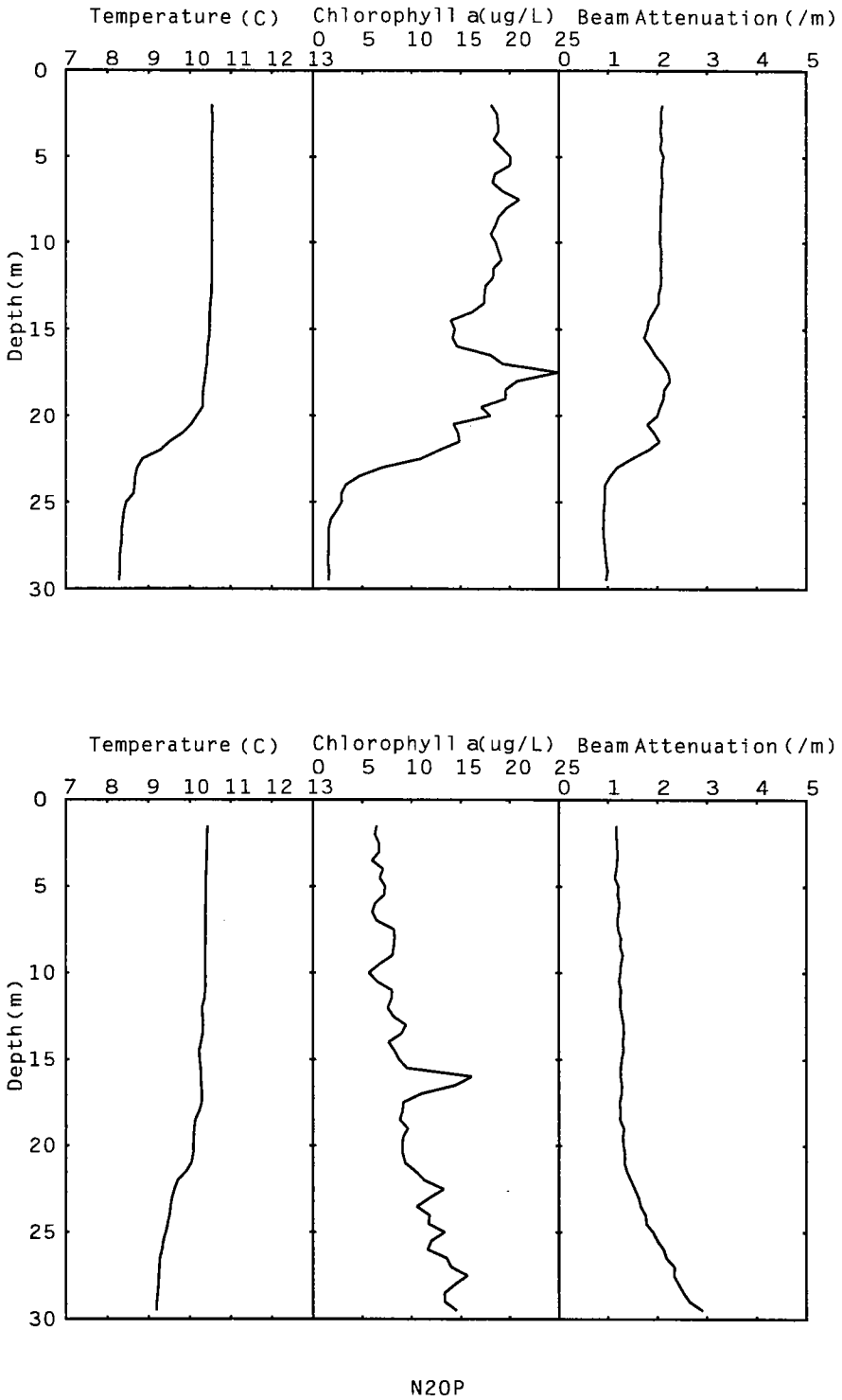


Figure 3-29b. Temperature, chlorophyll, and beam attenuation profiles for October 12 (top panel) and 15 (bottom panel) 1993 at station N20P . Data are from the downcast (complete profile set presented in Appendix B).

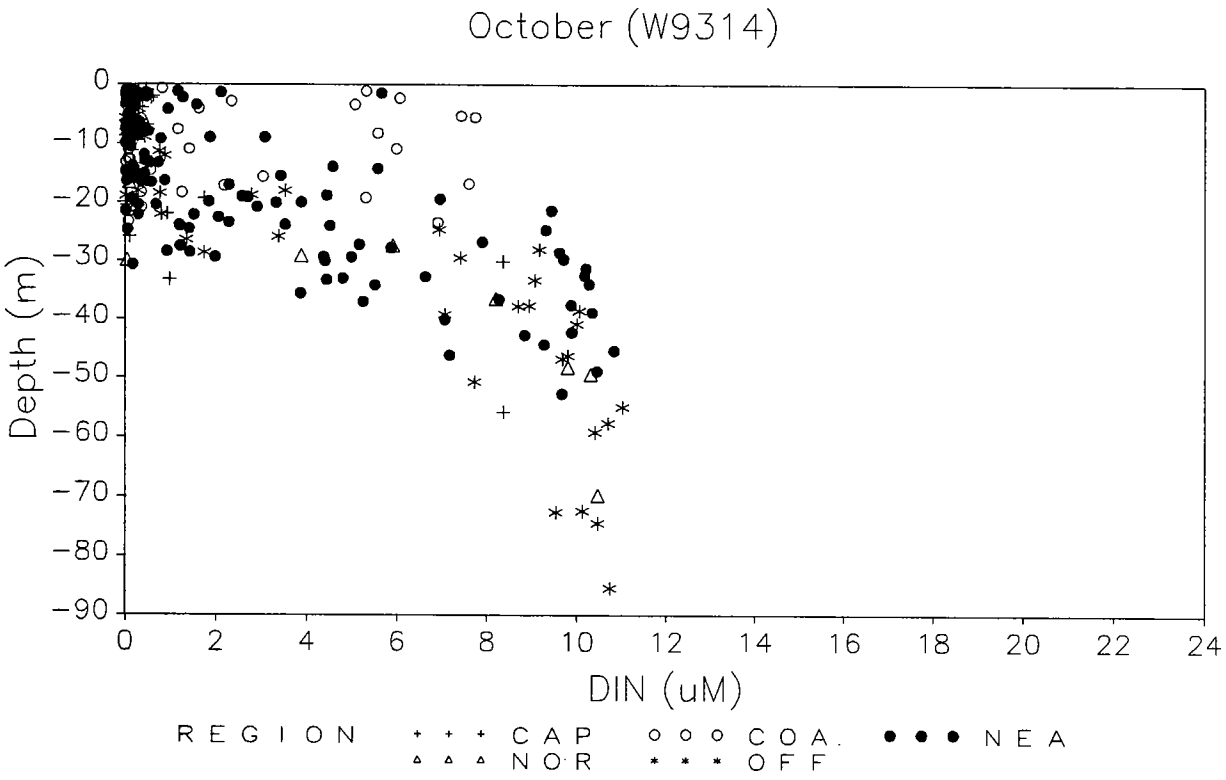
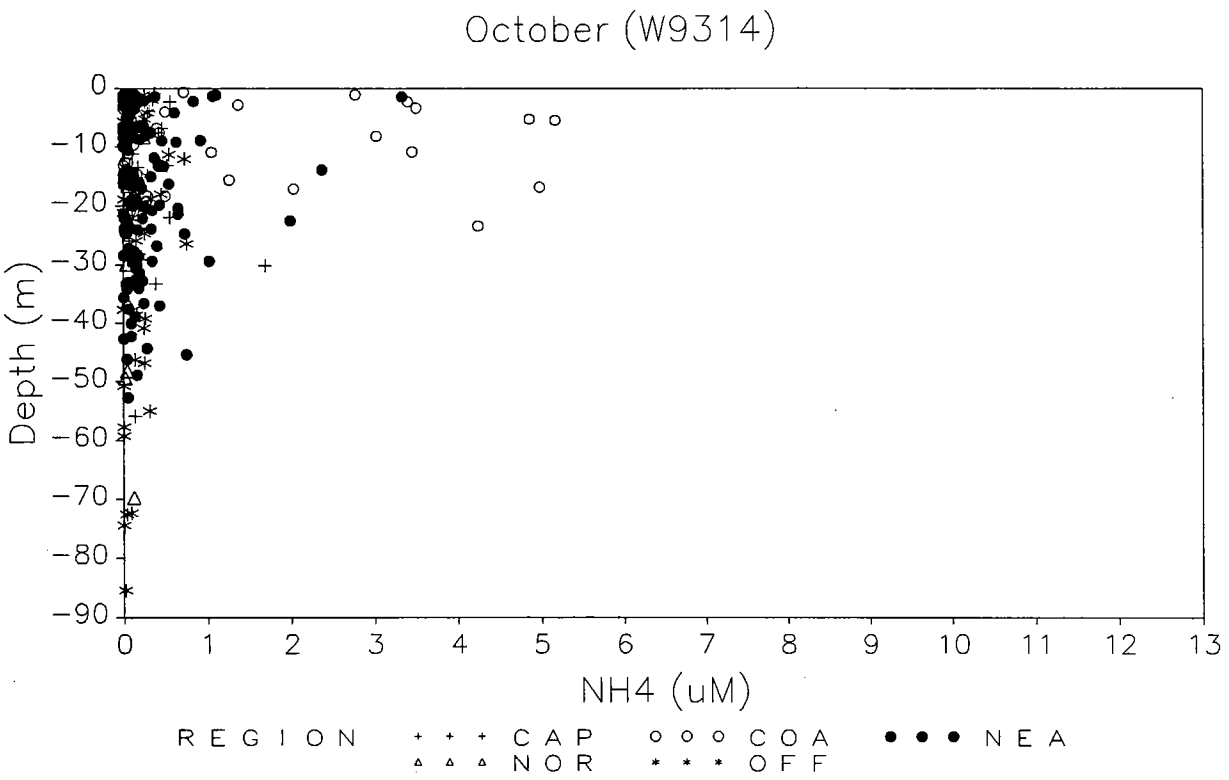


Figure 3-30a. DIN vs. depth in October 1993. The regions correspond to the groups of stations shown in Figure 3-16.



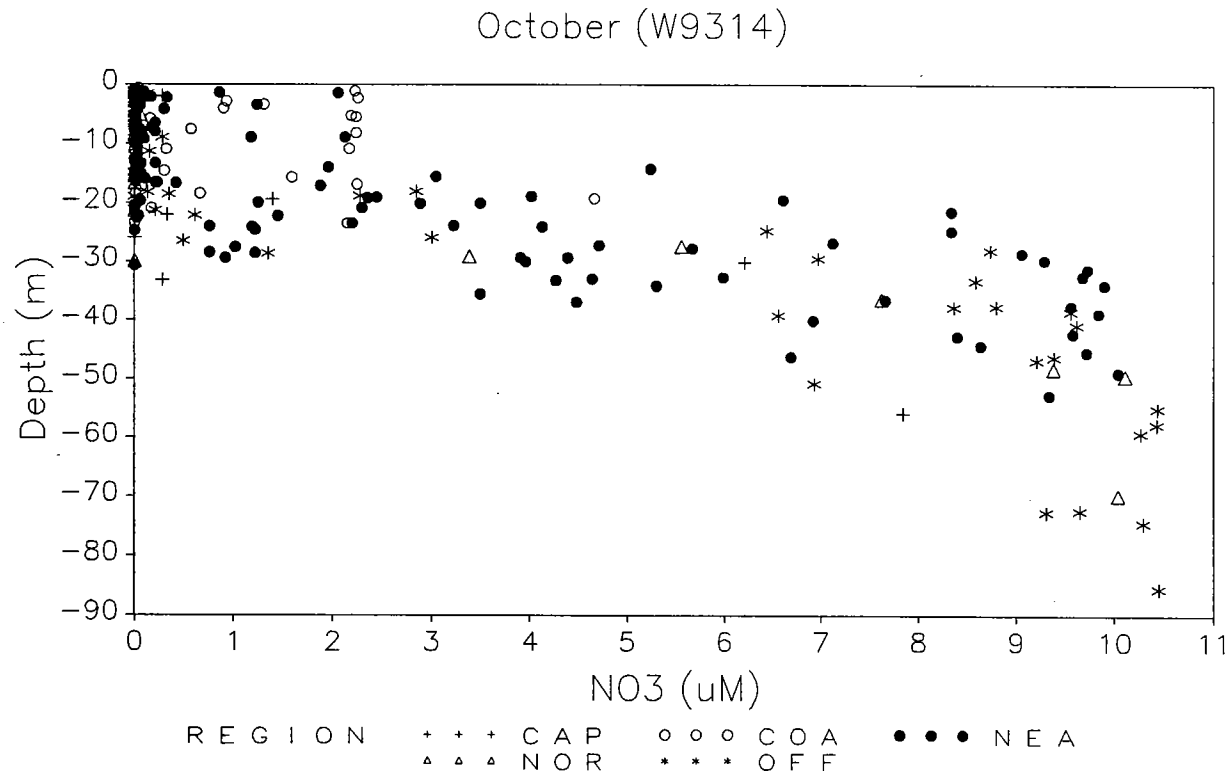


Figure 3-30b. NH_4 and NO_3 vs. depth in October 1993. The regions correspond to the groups of stations shown in Figure 3-16.

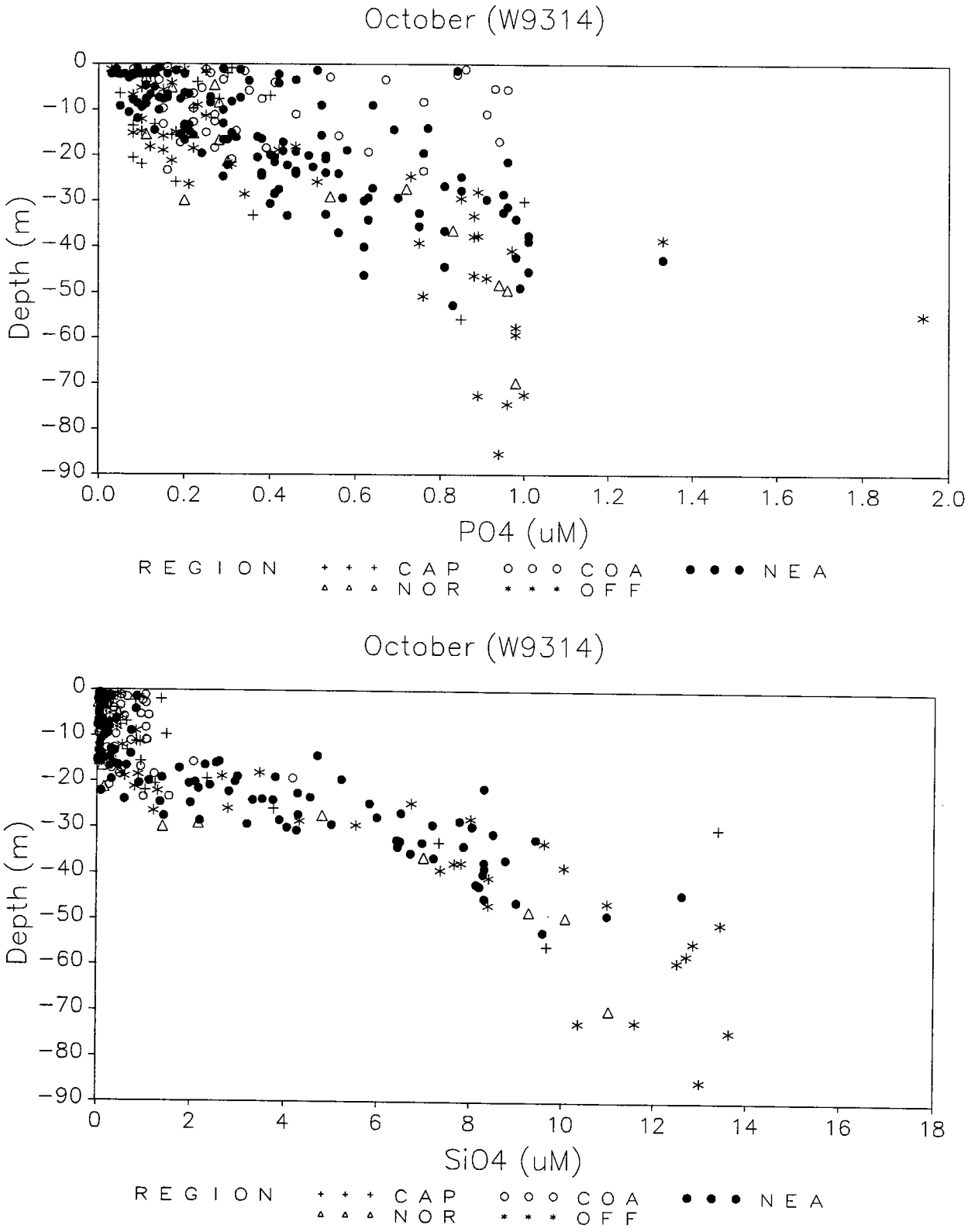


Figure 3-30c. **PO_4 and SiO_4 vs. depth in October 1993. The regions correspond to the groups of stations shown in Figure 3-16.**

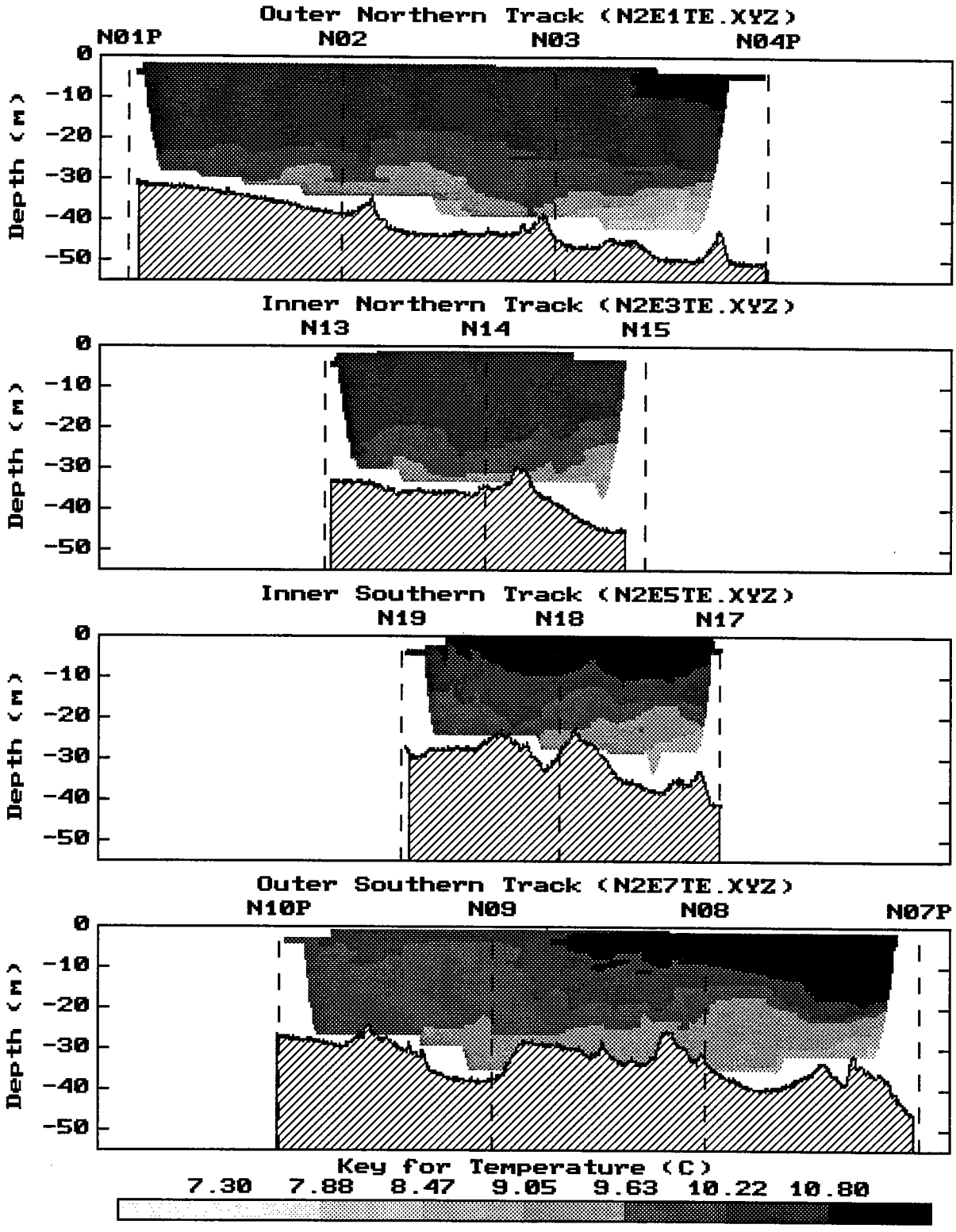


Figure 3-31a. Vertical section contours of temperature (°C) generated for tow-yo profiling conducted in October 1993. The view is towards the North.

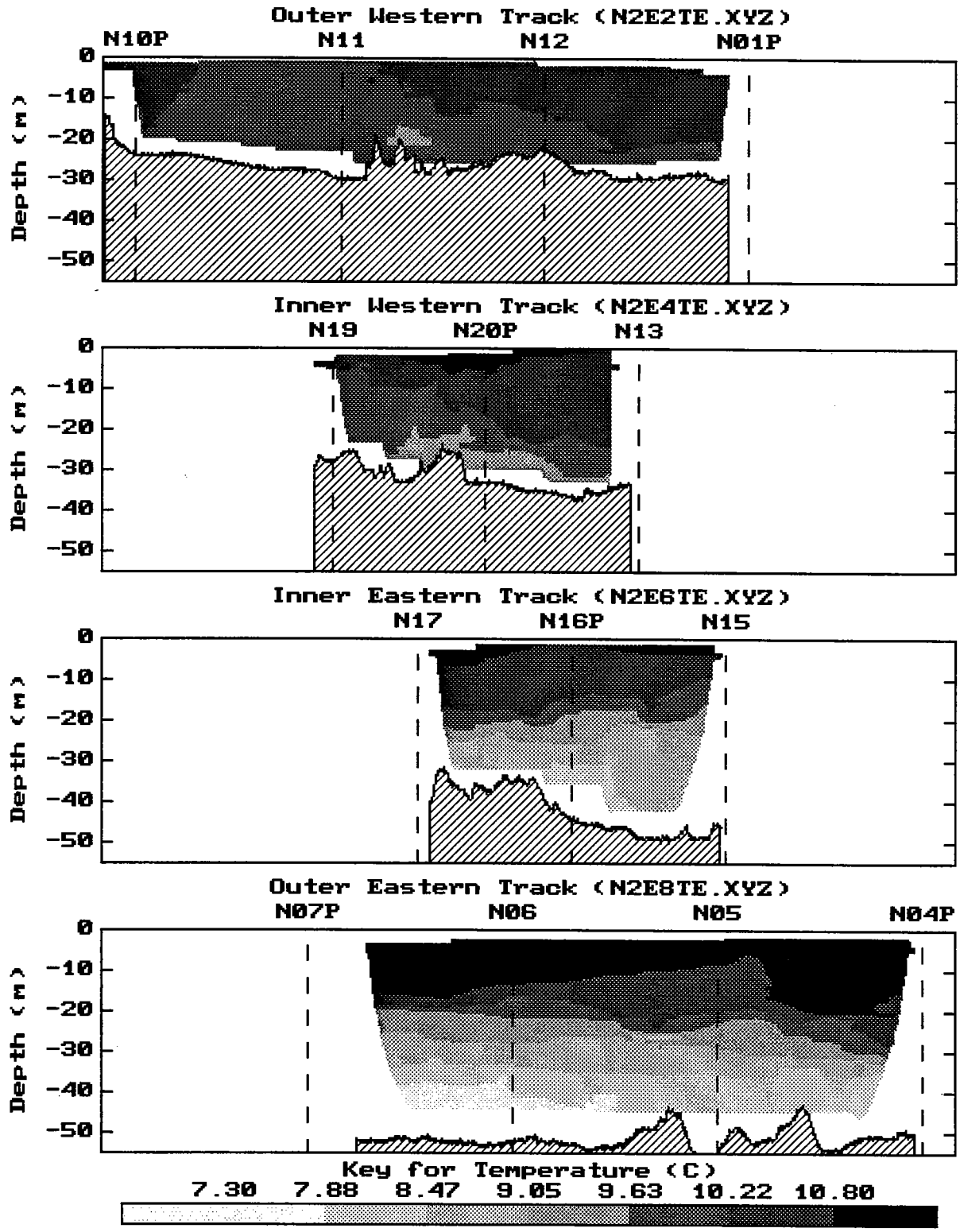


Figure 3-31b. Vertical section contours of temperature (°C) generated for tow-yo profiling conducted in October 1993. The view is towards Boston Harbor.

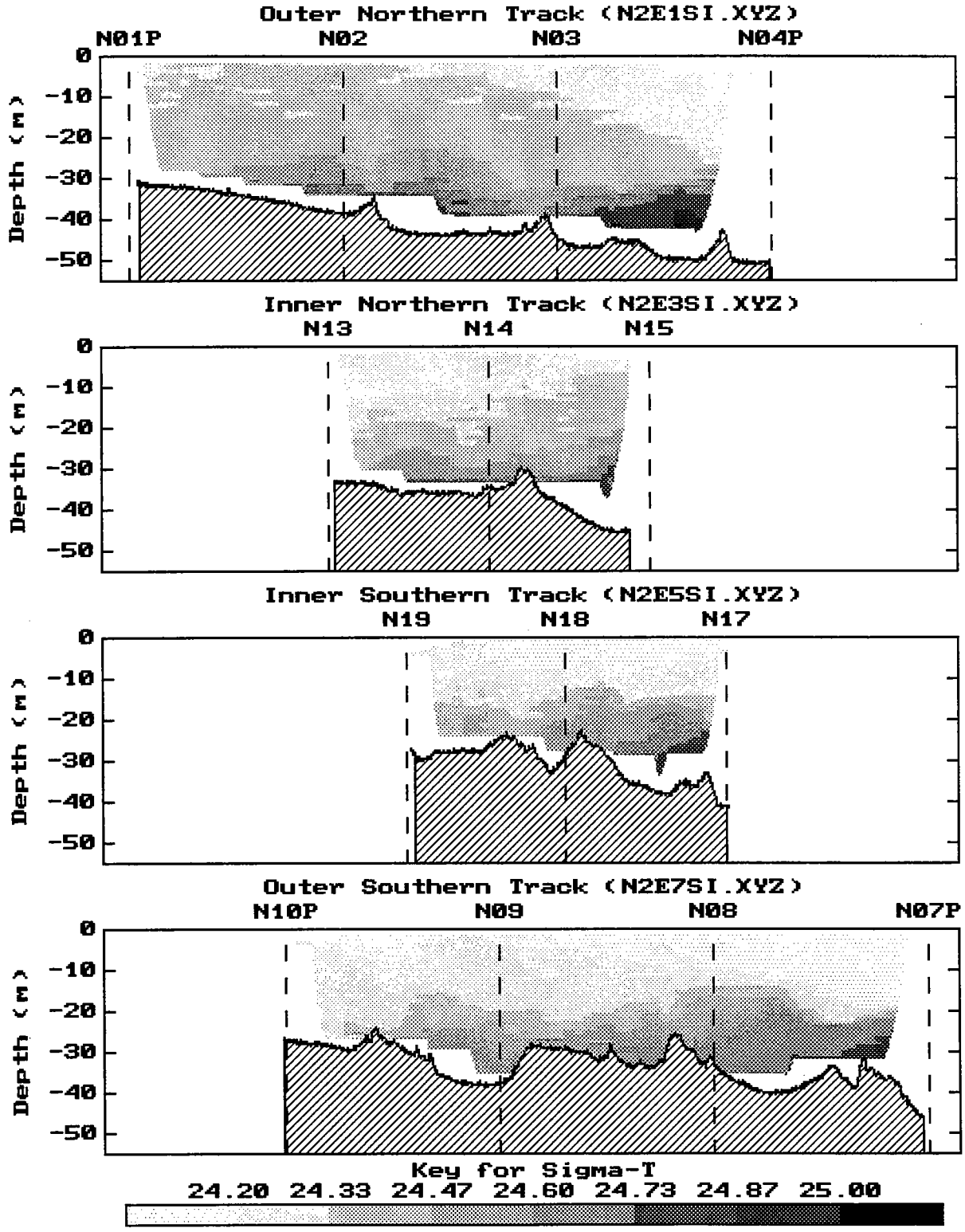


Figure 3-32a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in October 1993. The view is towards the North.

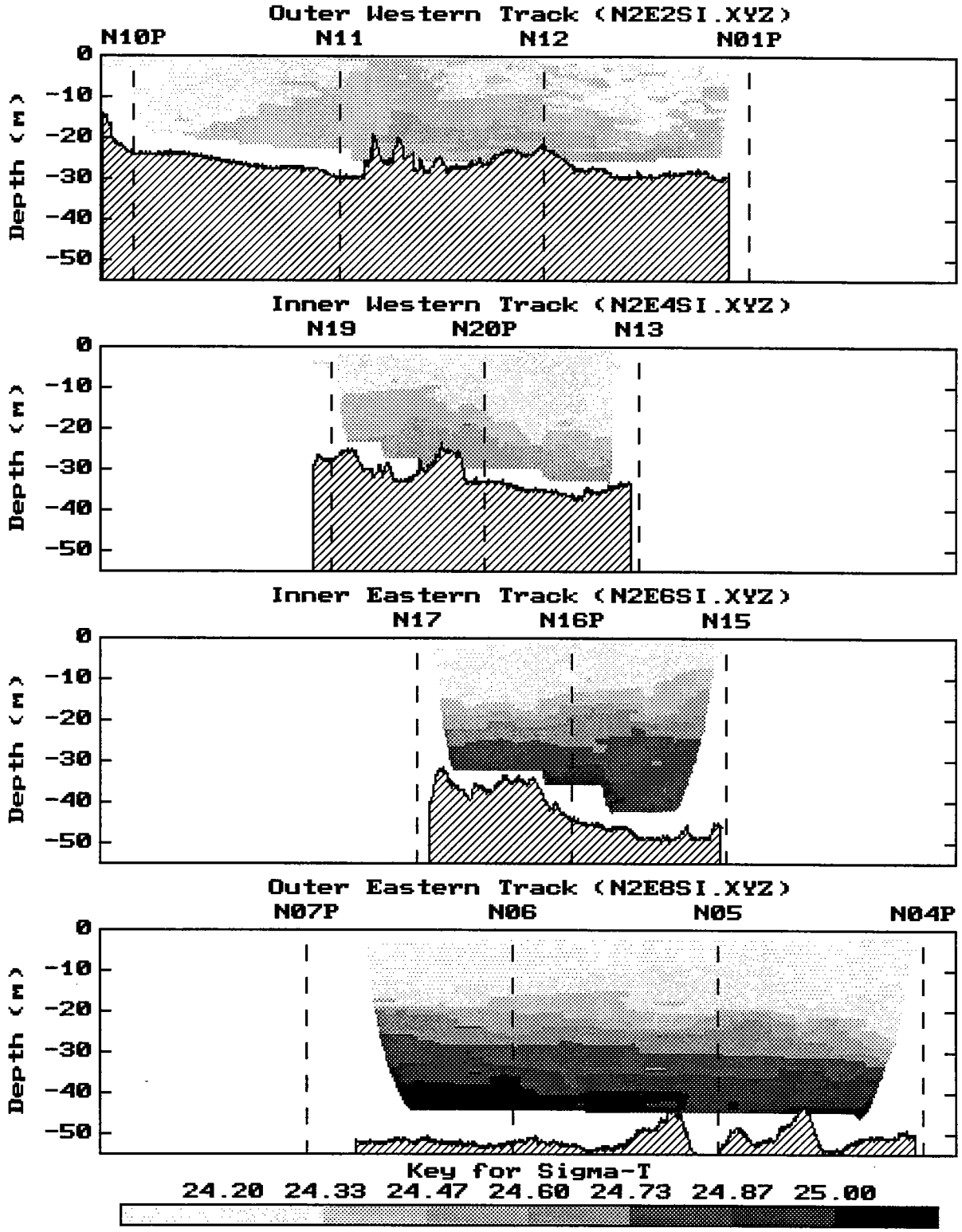


Figure 3-32b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in October 1993. The view is towards Boston Harbor.

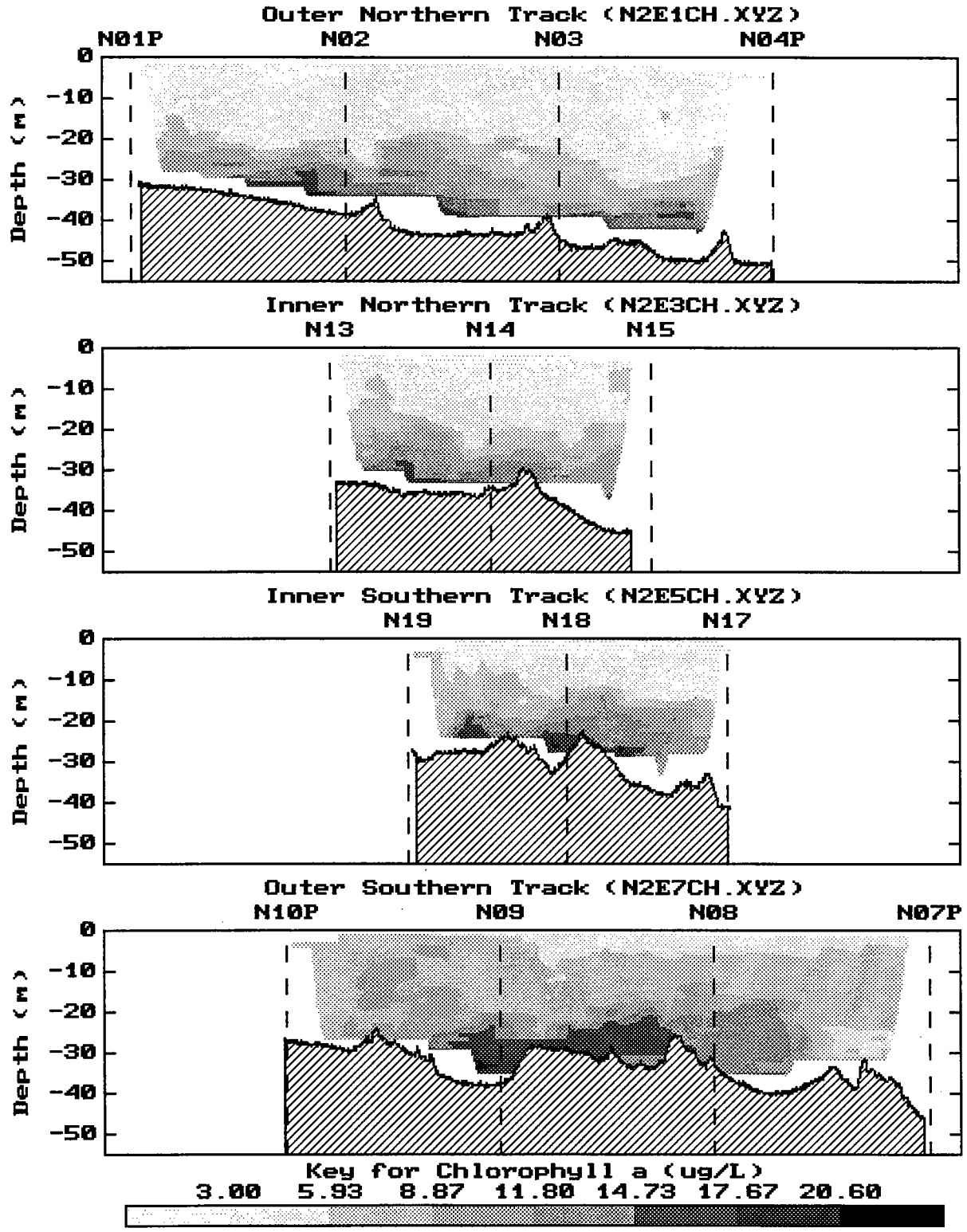


Figure 3-33a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in October 1993. The view is towards the North.

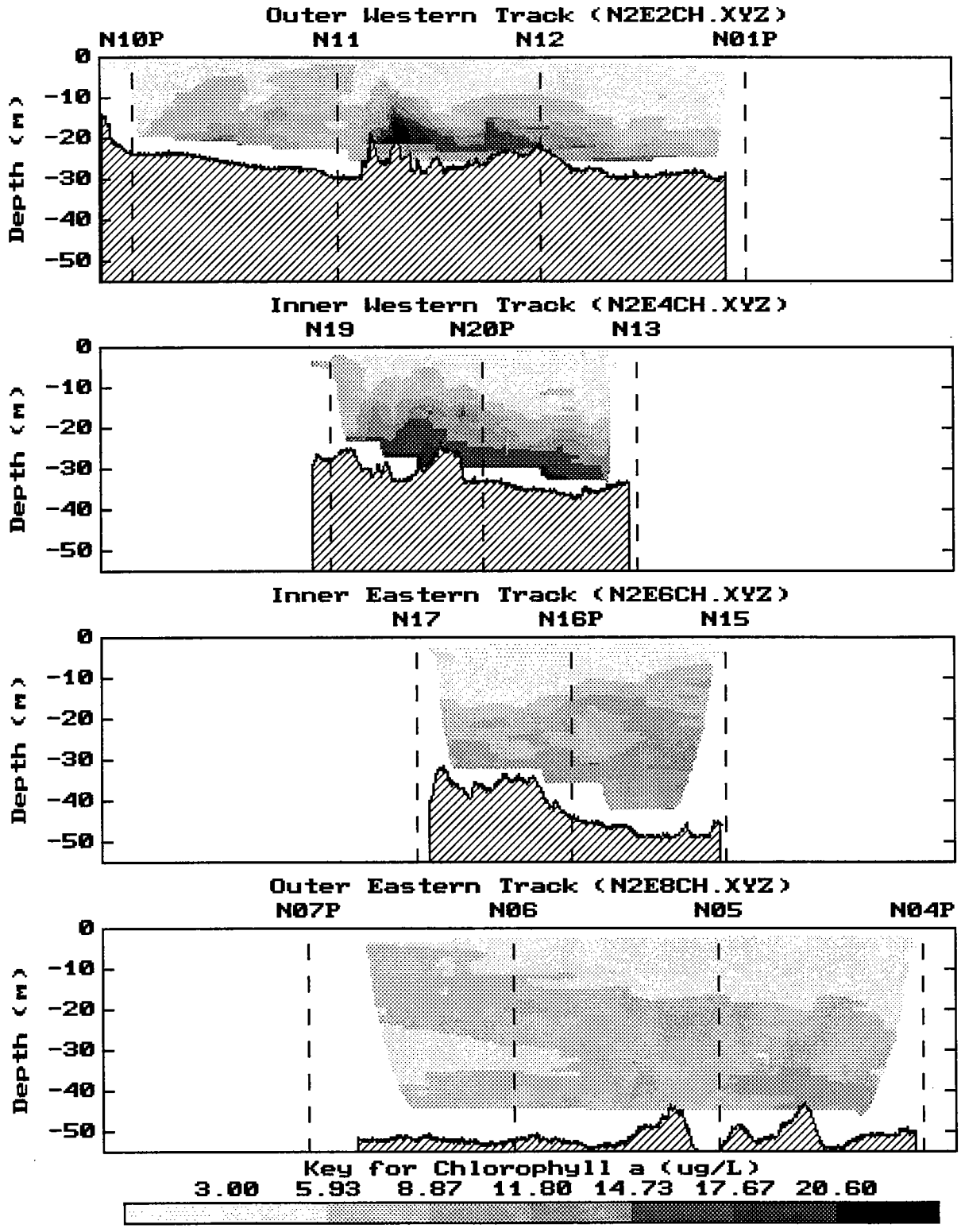


Figure 3-33b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in October 1993. The view is towards Boston Harbor.

4.0 RESULTS OF NOVEMBER 1993 NEARFIELD SURVEY (W9315)

4.1 Distribution of Water Properties from Vertical Profiling

Vertical profiling and water sampling were conducted on November 3; sampling at all 21 nearfield stations was completed and individual station profiles can be found in Appendix B. The nearfield was well mixed with temperatures of 9 to 10°C and salinities of approximately 32 PSU. The temperature and salinity profiles showed little vertical structure (Appendix B). Slight stratification occurred in the deep waters of only the most eastern stations. Cooler, fresher surface waters were found at the near-Harbor stations (N10P and N11), but the general trend was for small increases in salinity and small decreases in temperature with depth (Figure 4-1a).

Beam attenuation and chlorophyll fluorescence were less variable and much lower than the measurements taken in October. Generally, beam attenuation was low (< 1.0 m^{-1}) and did not vary with salinity or depth (Appendix B). The pattern observed in the beam attenuation vs. salinity plot resulted from higher beam attenuations in the fresher surface waters at the Harbor-influenced stations, and a combination of higher beam attenuations in both surface and deep waters at the eastern stations (Figure 4-1a). Due to narrow ranges and low values, the beam attenuation vs. chlorophyll plot yields little information, except that there had been considerable change in the water column since October. Chlorophyll concentrations were low (< 2 μg L^{-1}) and decreased with depth (Figure 4-1b). Concentrations of DO, as percent saturation, were generally consistent throughout the nearfield (Figure 4-1b; ~100%). Once again, deviations were observed at stations near the Harbor (undersaturated surface to bottom) and at the stations on the seaward side of the nearfield (undersaturated at depths > 40 m).

Nutrient concentrations were high throughout the water column. DIN concentrations were > 2 μM at all stations and depths (Figure 4-2a). High concentrations of surface DIN were due to high concentrations of NH_4 at the near-Harbor stations, while high concentrations of DIN below 40 m resulted from NO_3-rich bottom waters at the offshore stations (Figure 4-2b). Phosphate and SiO_4 profiles were similar to DIN,

and concentrations were >0.5 and 3 μM, respectively (Figure 4-2c). In comparison to the October survey, the surface waters were replete in nutrients and the water column had become characteristically well mixed with respect to nutrients.

Even though whole scale changes in nutrient concentrations in the water column had taken place since the October survey, changes in the salinity-nutrient relationships were minimal (Figure 4-3). The decrease in DIN vs. salinity was driven by depth-related changes in NH_4 at the Harbor-influenced stations (Figures 4-3a and 4-3b). The general pattern was an increase in DIN concentrations at higher salinity, resulting from higher NO_3 concentrations in the bottom waters of the offshore stations. Similar patterns were observed for both PO_4 and SiO_4 vs. salinity during the November survey (Figure 4-3c). The outflow from Boston Harbor contributed to elevated concentrations of DIN (as NH_4), PO_4, and SiO_4 in the surface waters at stations N10P and N11; at other locations there was a strong nutrient-depth relationship evident in the nutrient-salinity plots.

4.2 Distribution of Water Properties from Towing

Tow-yo sampling was performed over all tracks of the nearfield outer and inner boxes (Figure 1-2) the day after vertical profiling was conducted. The temperature results are presented in Figures 4-4a and 4-4b. As discussed above, the water column was well mixed and there was no apparent temperature stratification or horizontal variation across the nearfield. Slightly cooler water flowing out of the Harbor was observed at station N10P, while somewhat warmer water was present to the southeast.

Plots of density (σ_T) with depth and distance were very similar to temperature plots (Figures 4-5a and 4-5b). Density was relatively consistent throughout the nearfield. Slightly less dense water was observed along the southern transect and near the Harbor. The water column appeared to be well mixed with respect to density but, at the northeast stations, a slight increase in density was evident in the deep bottom waters.

Chlorophyll concentrations were <2 μg in the nearfield and there were no apparent changes in concentration with depth (Figures 4-6a and 4-6b). The towed sampling results clearly illustrate the distinction between the October and November surveys. Winter conditions (a well-mixed, nutrient-replete, and chlorophyll-poor water column) had been established less than three weeks after the cessation of the fall bloom.

4.3 Water Types and Analysis of Small-Scale Variability

Based on the data collected, the tidal cycle apparently had little or no effect on water properties, although the outflow of water from Boston Harbor could be physically and chemically distinguished at stations N10P and N11. Both the vertical and horizontal profiles indicated the onset of winter conditions in the nearfield. The water column was well mixed, nutrient replete, and low in chlorophyll.

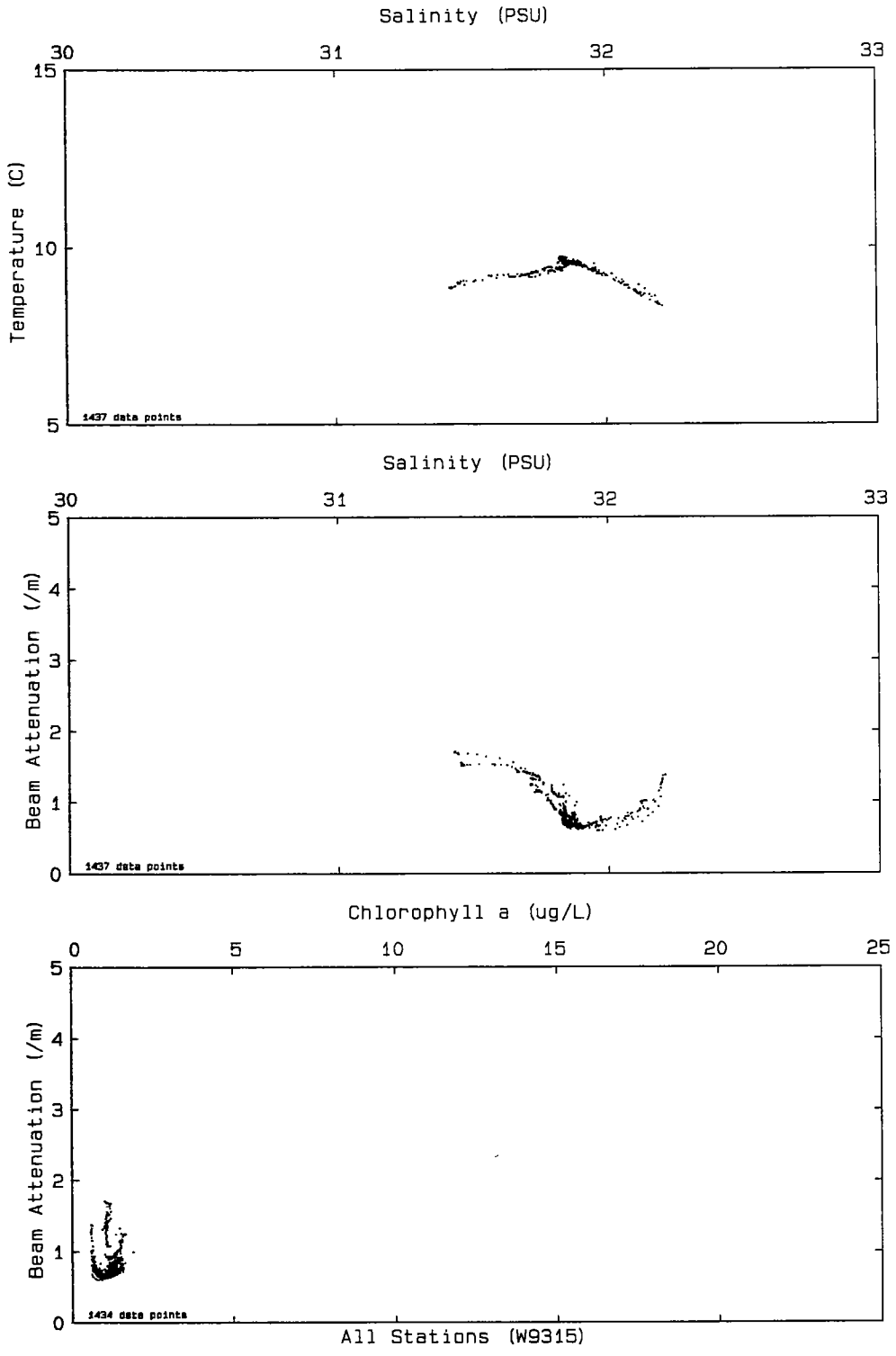


Figure 4-1a. **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in November 1993. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.**

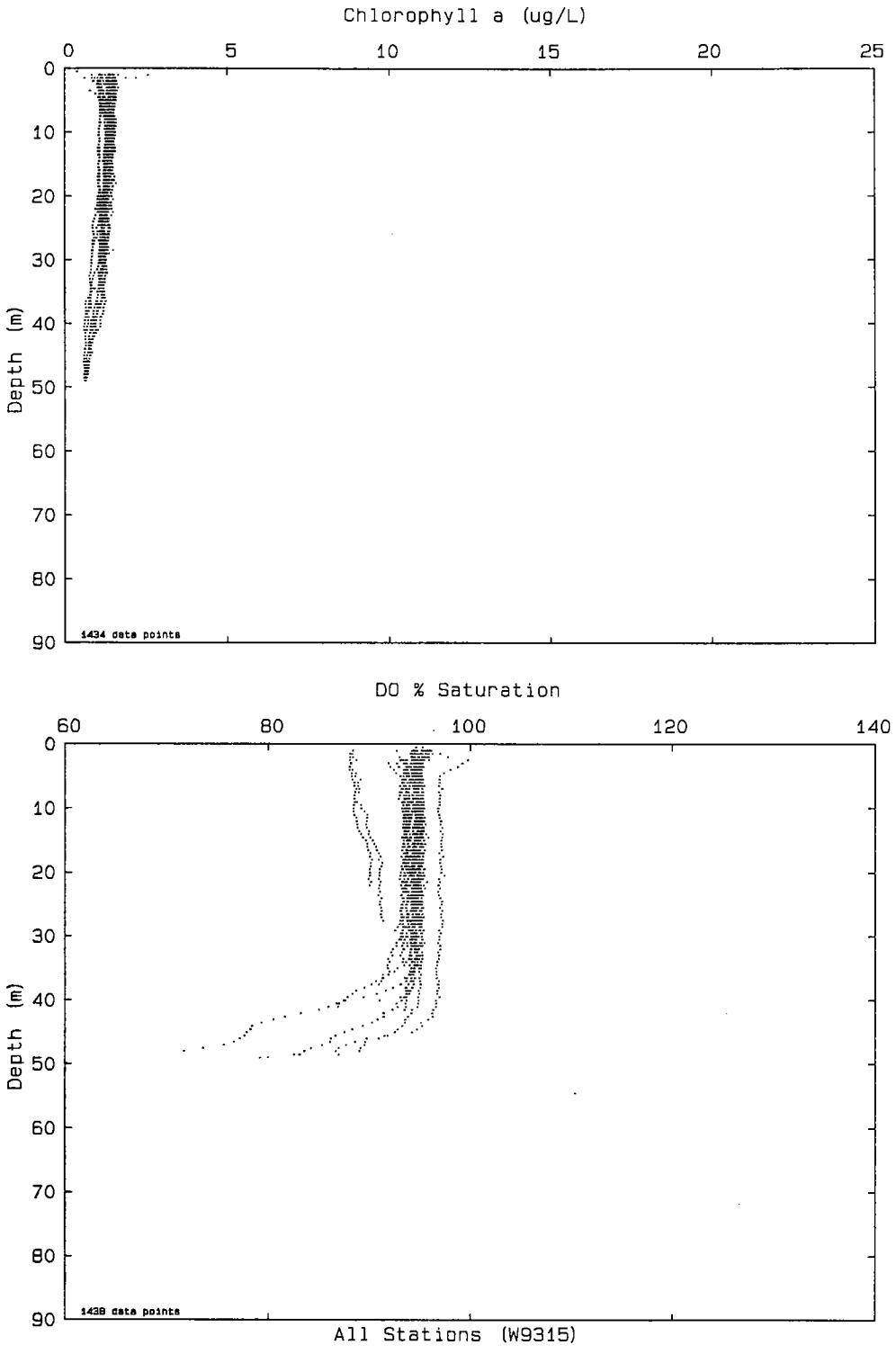


Figure 4-1b. **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in November 1993. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.**

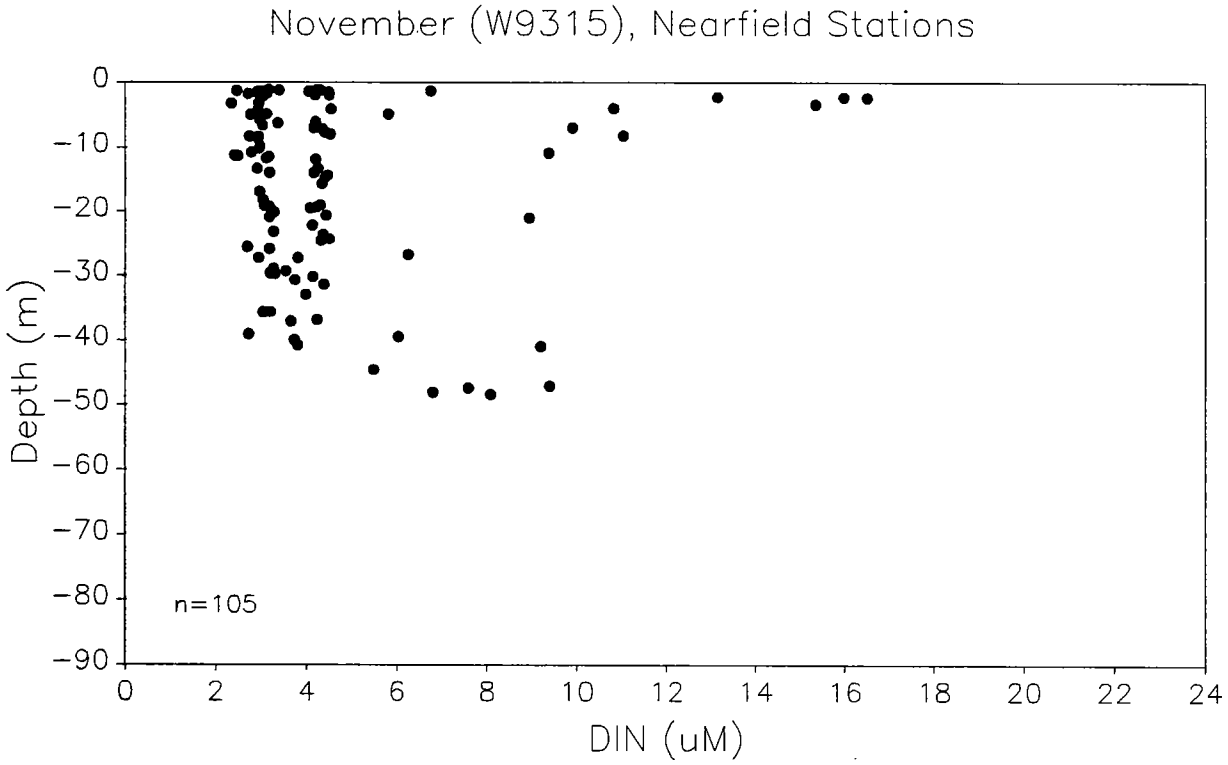
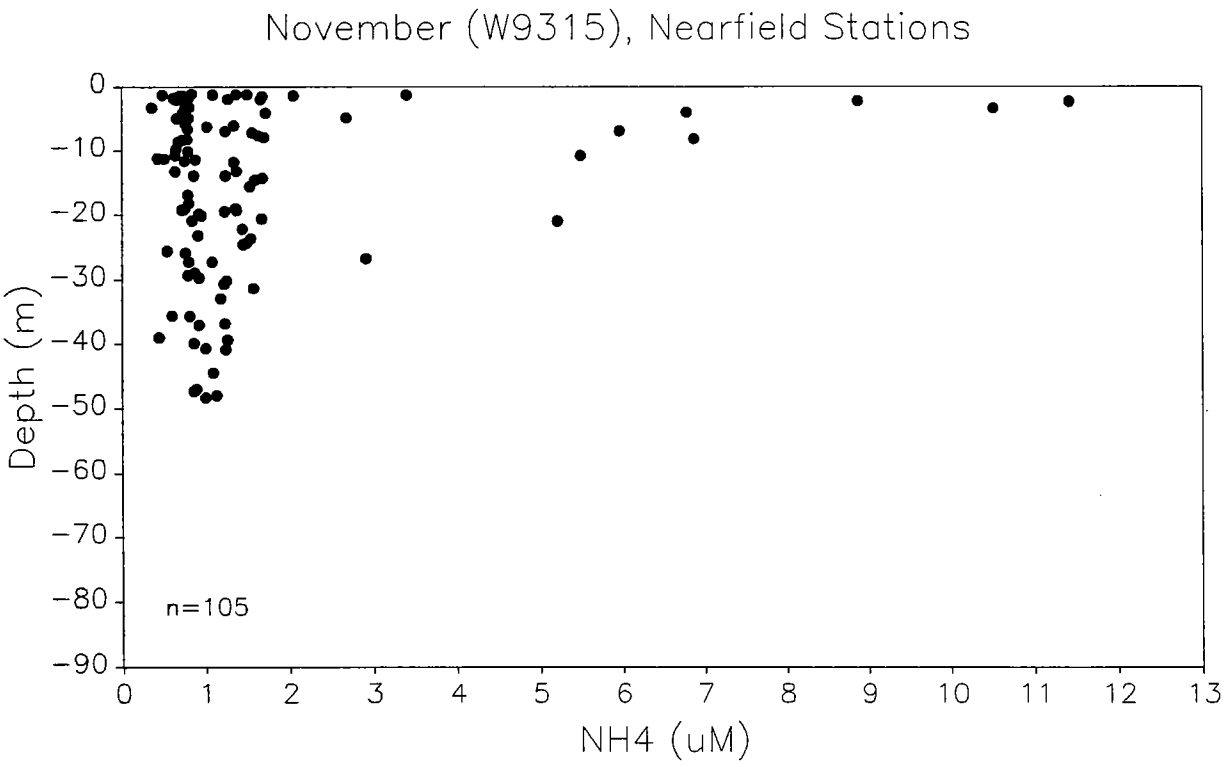


Figure 4-2a. DIN vs. depth in November 1993.



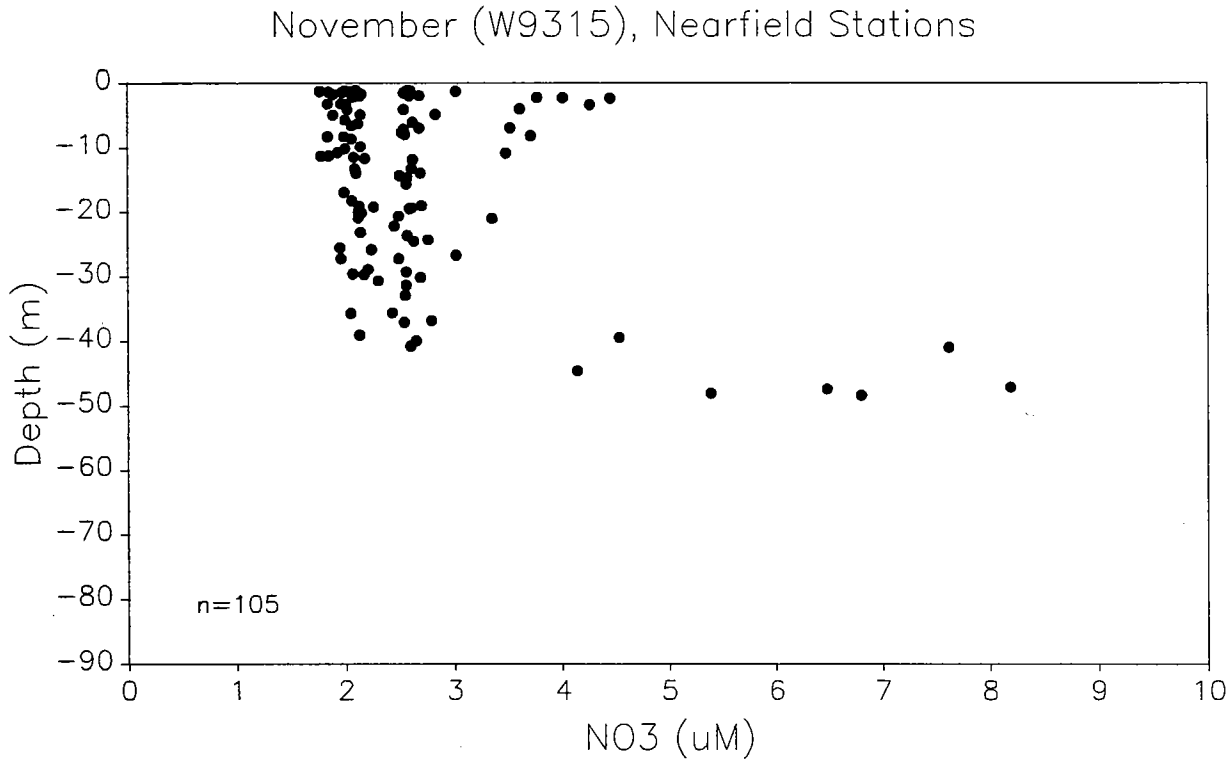


Figure 4-2b. NH_4 and NO_3 vs. depth in November 1993.

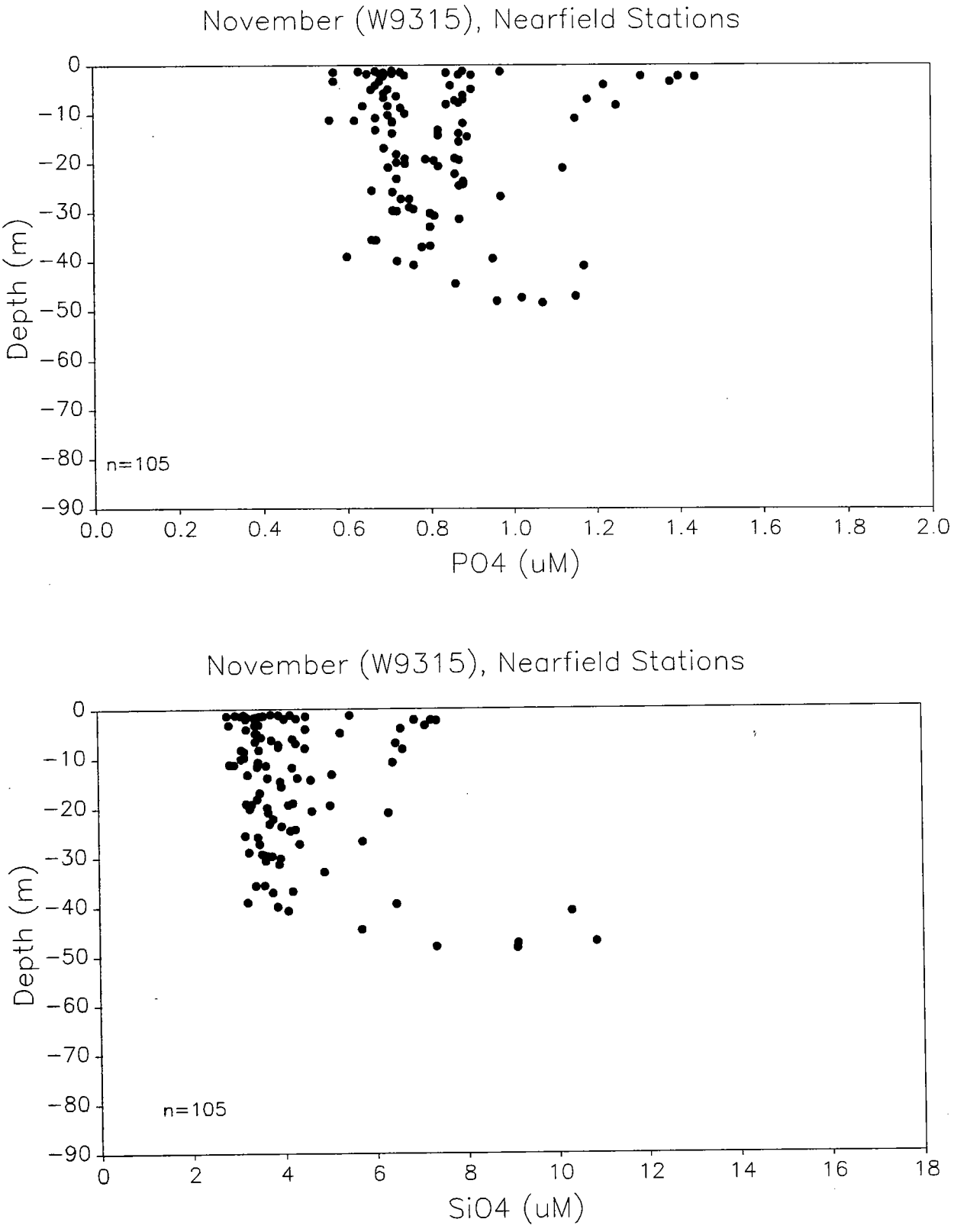


Figure 4-2c. PO_4 and SiO_4 vs. depth in November 1993.

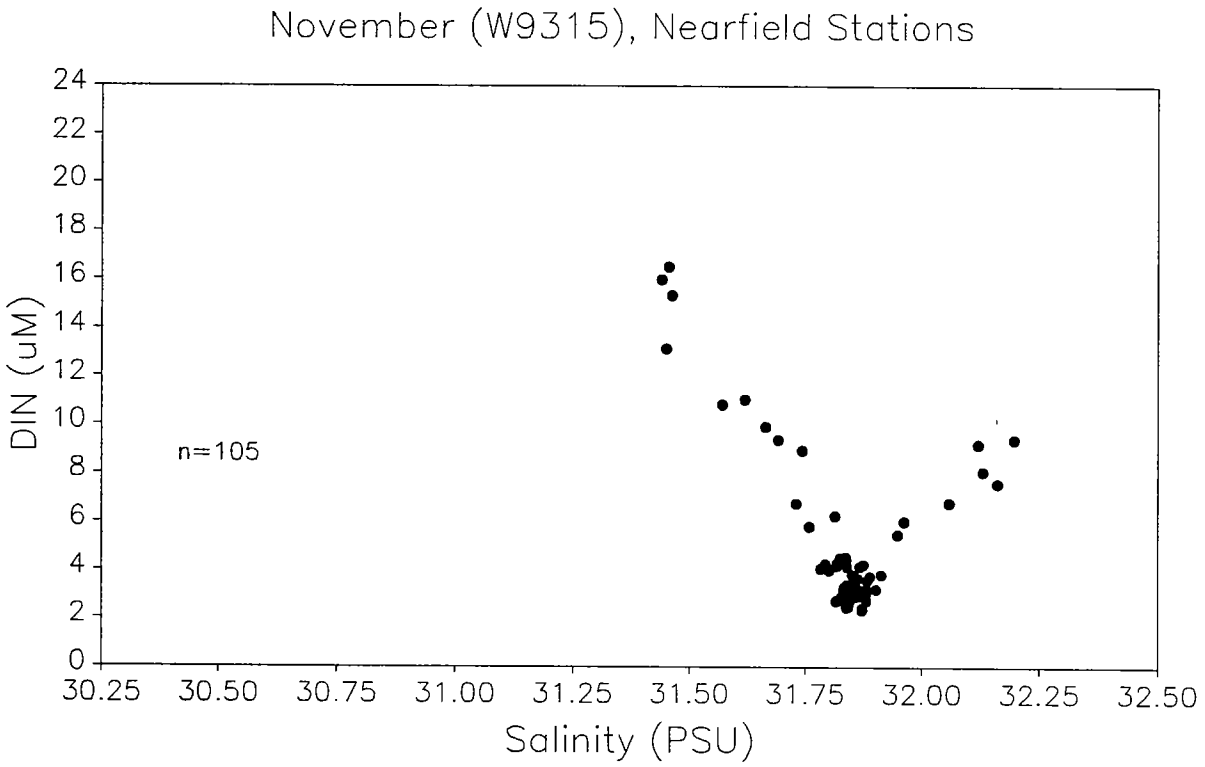


Figure 4-3a. DIN vs. salinity in November 1993.

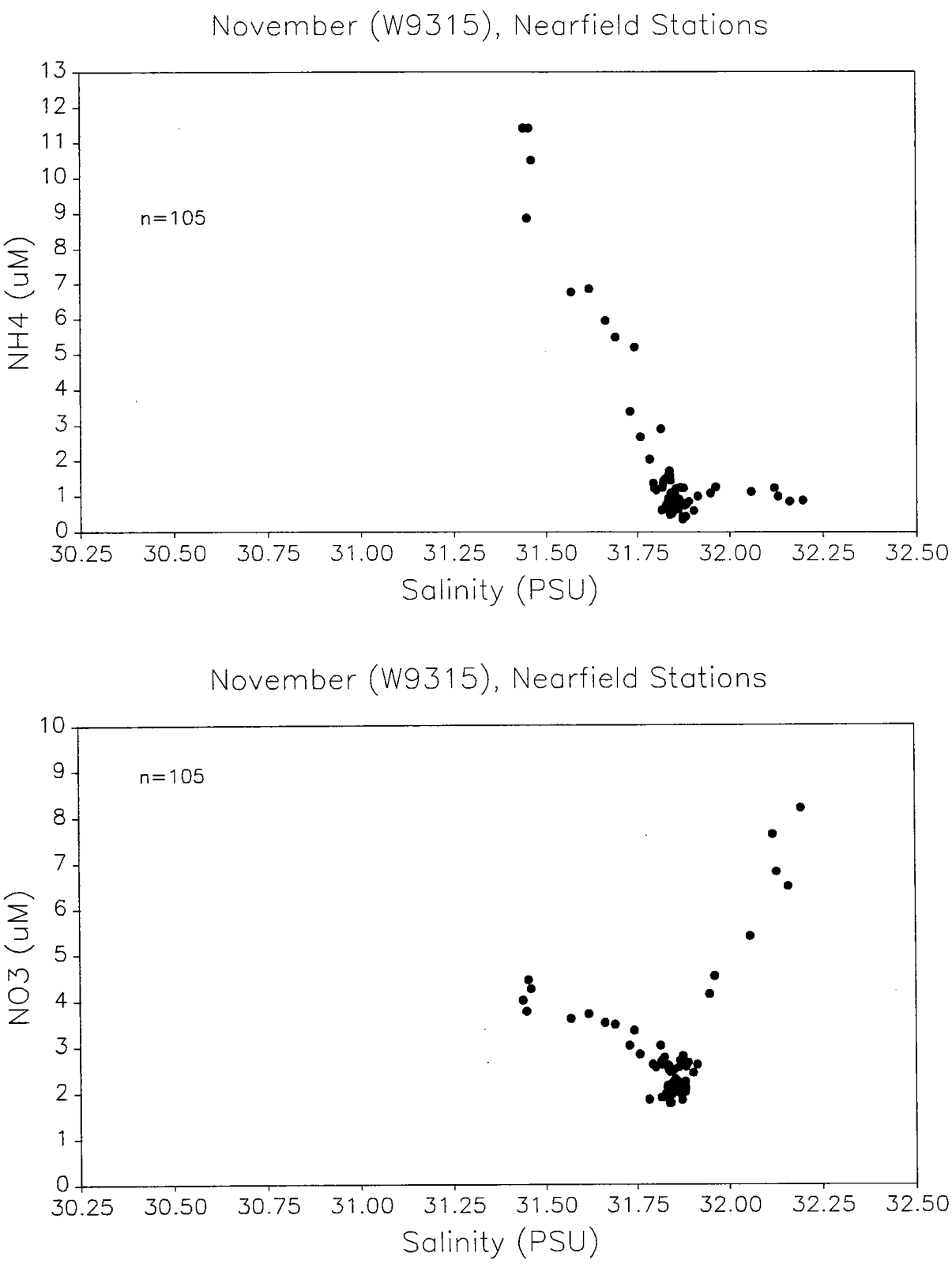
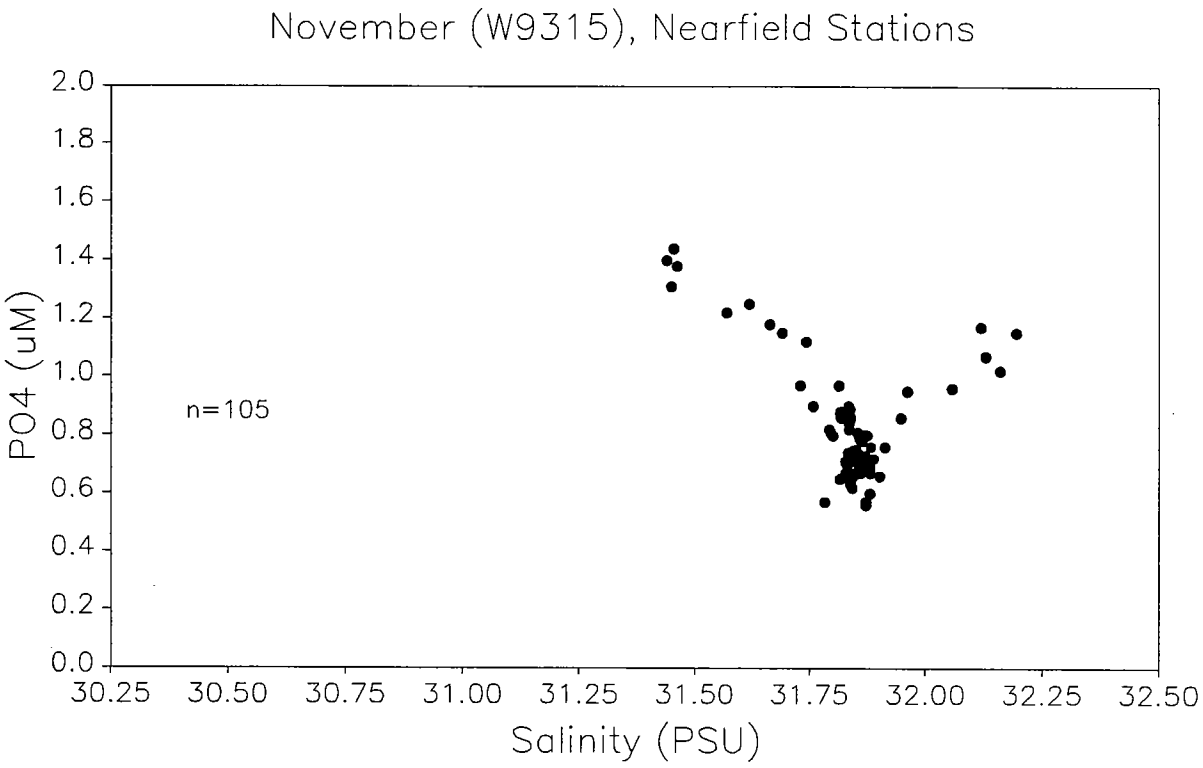


Figure 4-3b. NH_4 and NO_3 vs. salinity in November 1993.



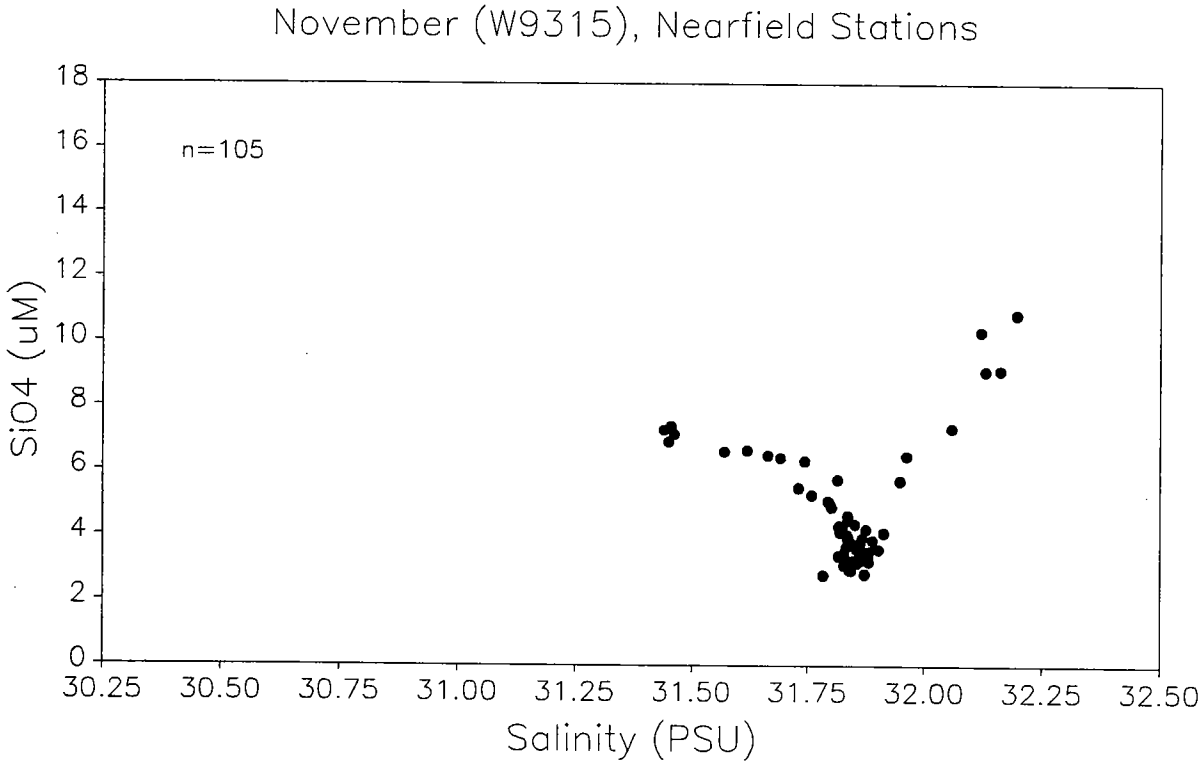


Figure 4-3c. PO_4 and SiO_4 vs. salinity in November 1993.

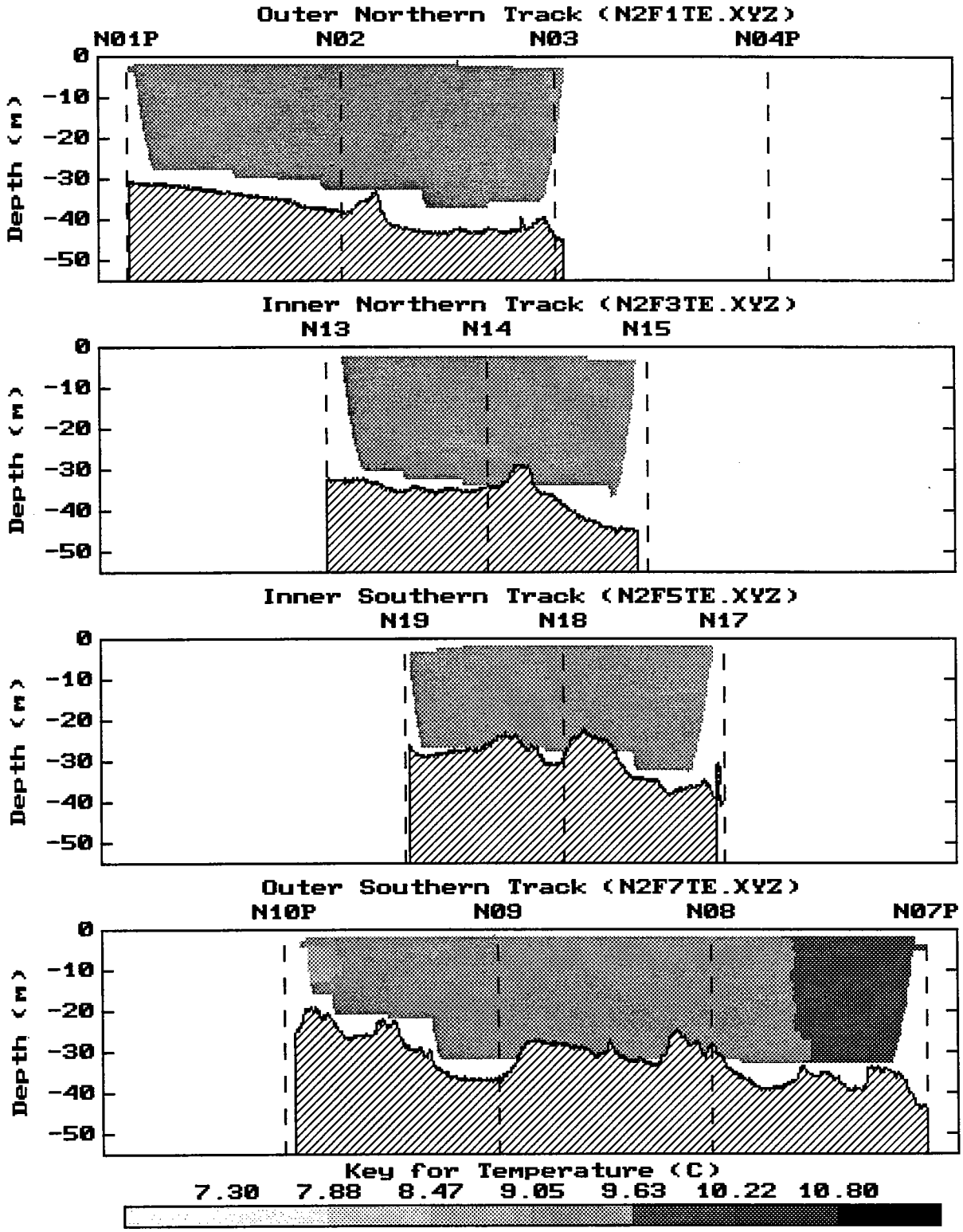


Figure 4-4a. Vertical section contours of temperature (°C) generated for tow-yo profiling conducted in November 1993. The view is towards the North.

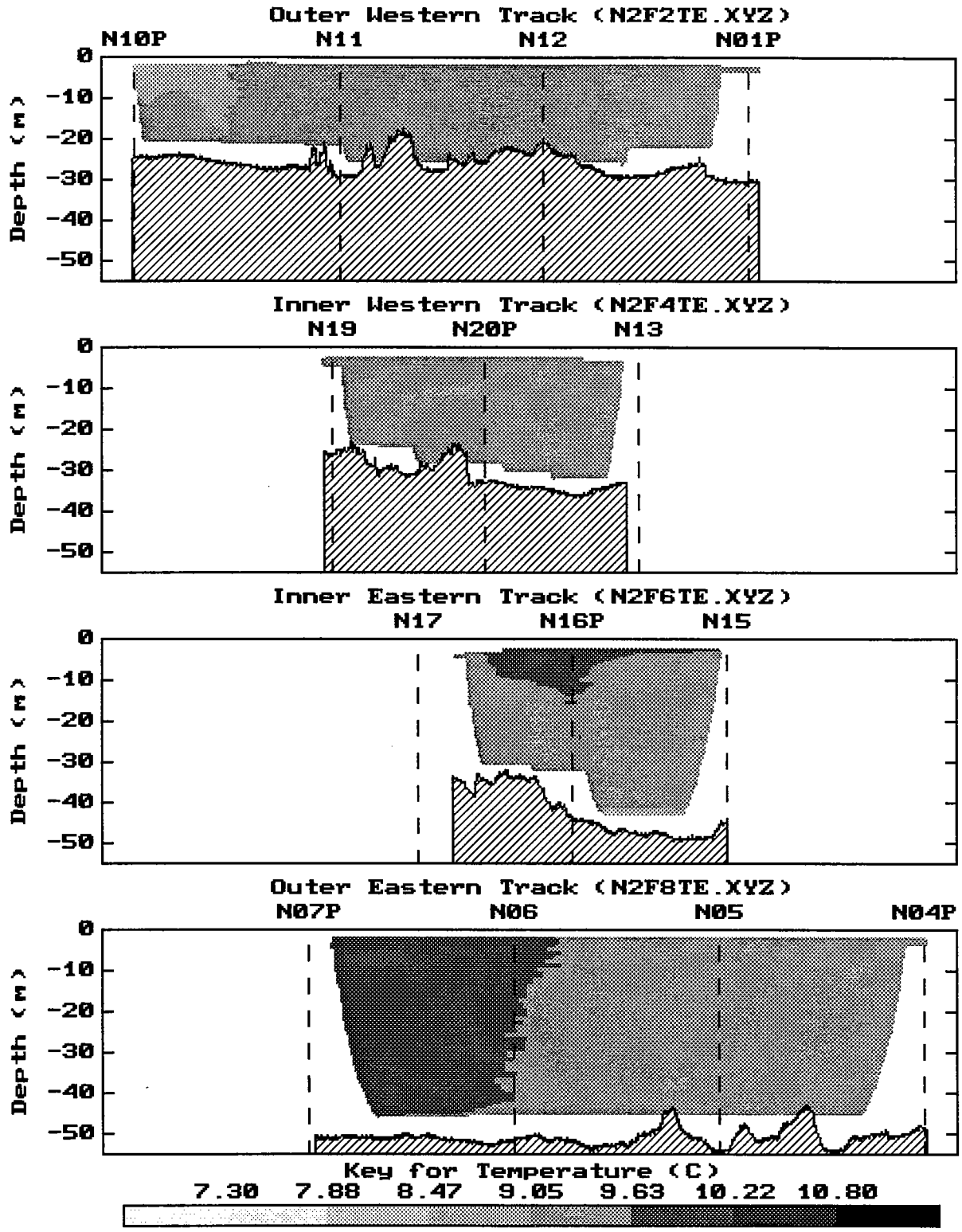


Figure 4-4b. Vertical section contours of temperature (°C) generated for tow-yo profiling conducted in November 1993. The view is towards Boston Harbor.

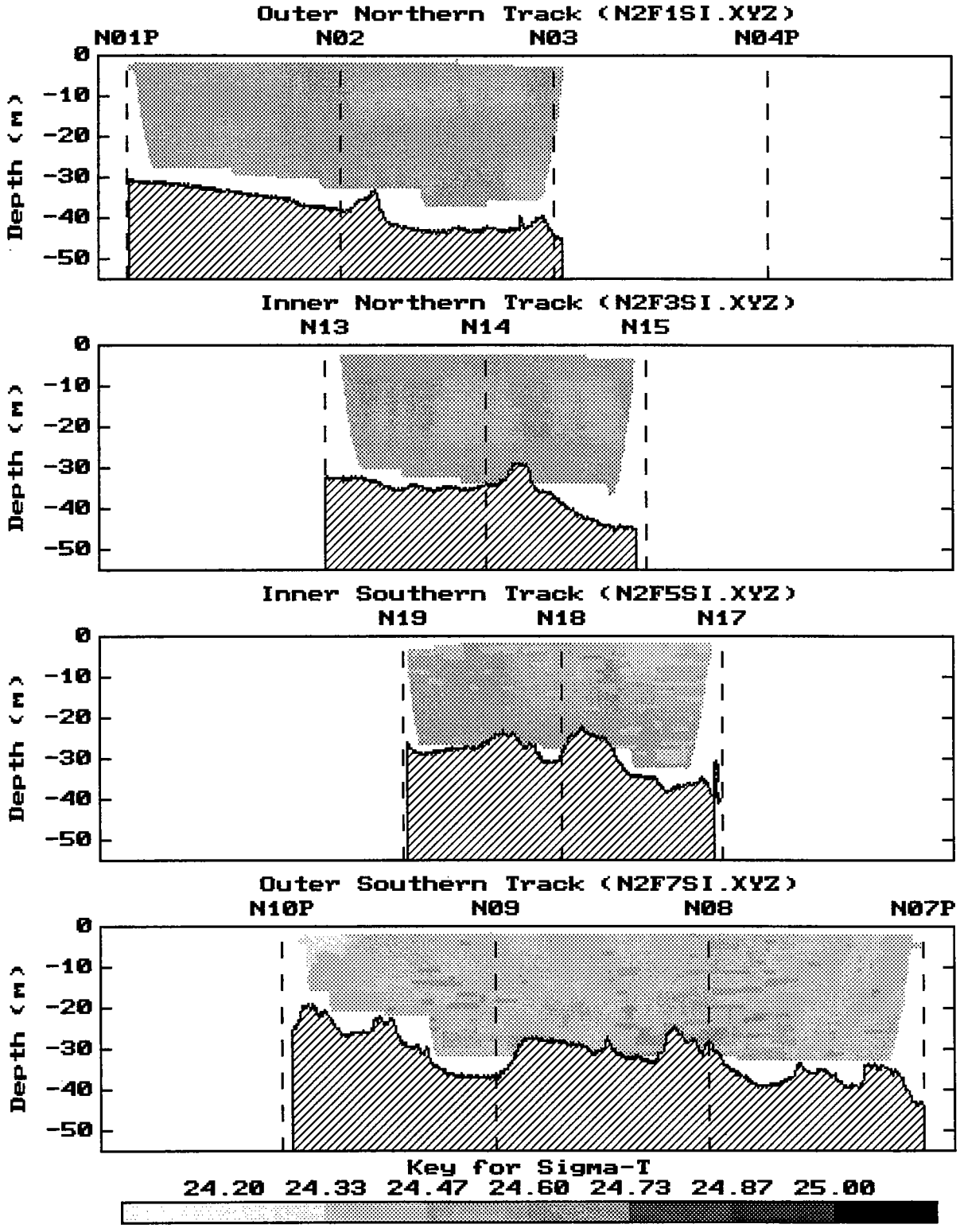


Figure 4-5a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in November 1993. The view is towards the North.

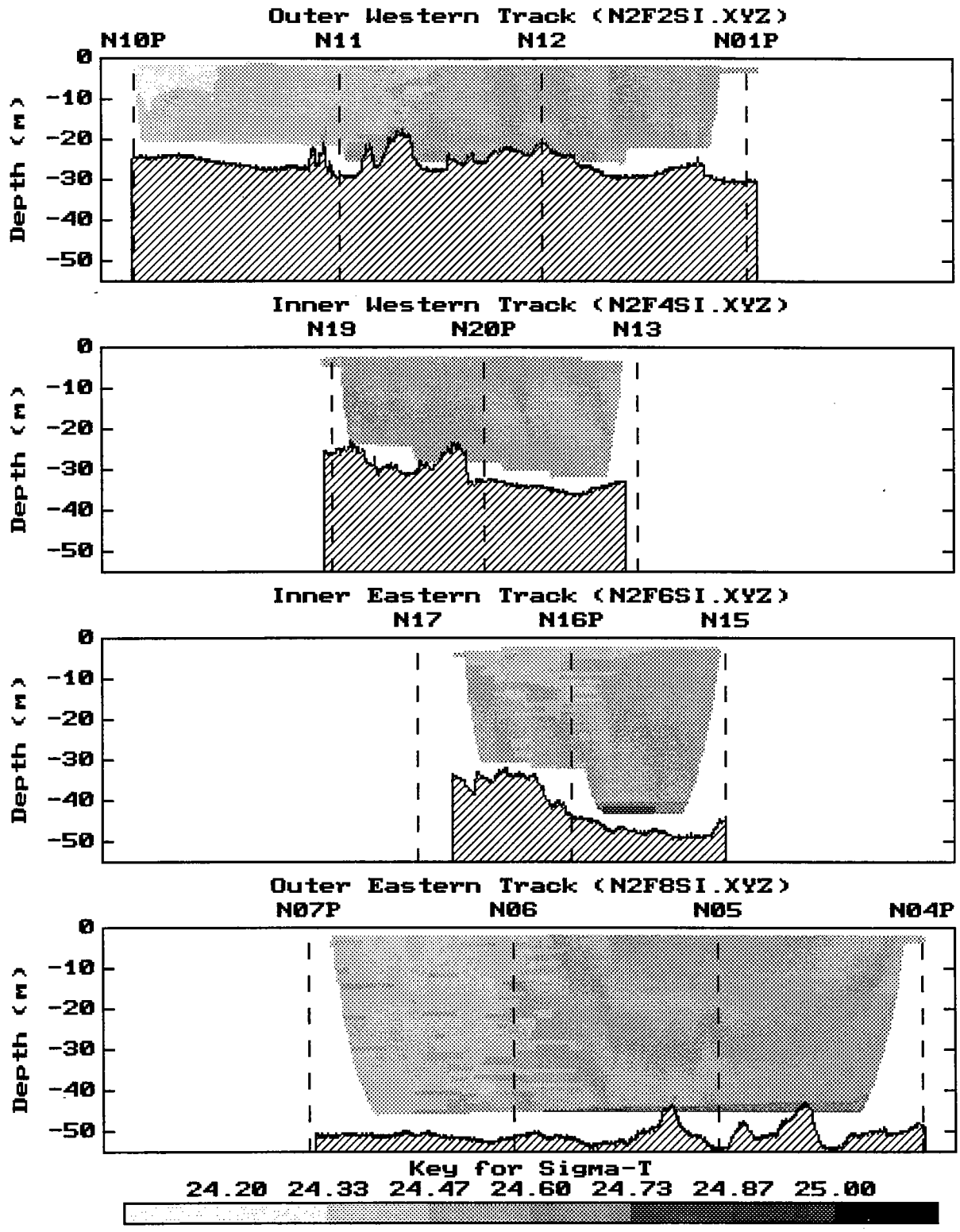


Figure 4-5b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in November 1993. The view is towards Boston Harbor.

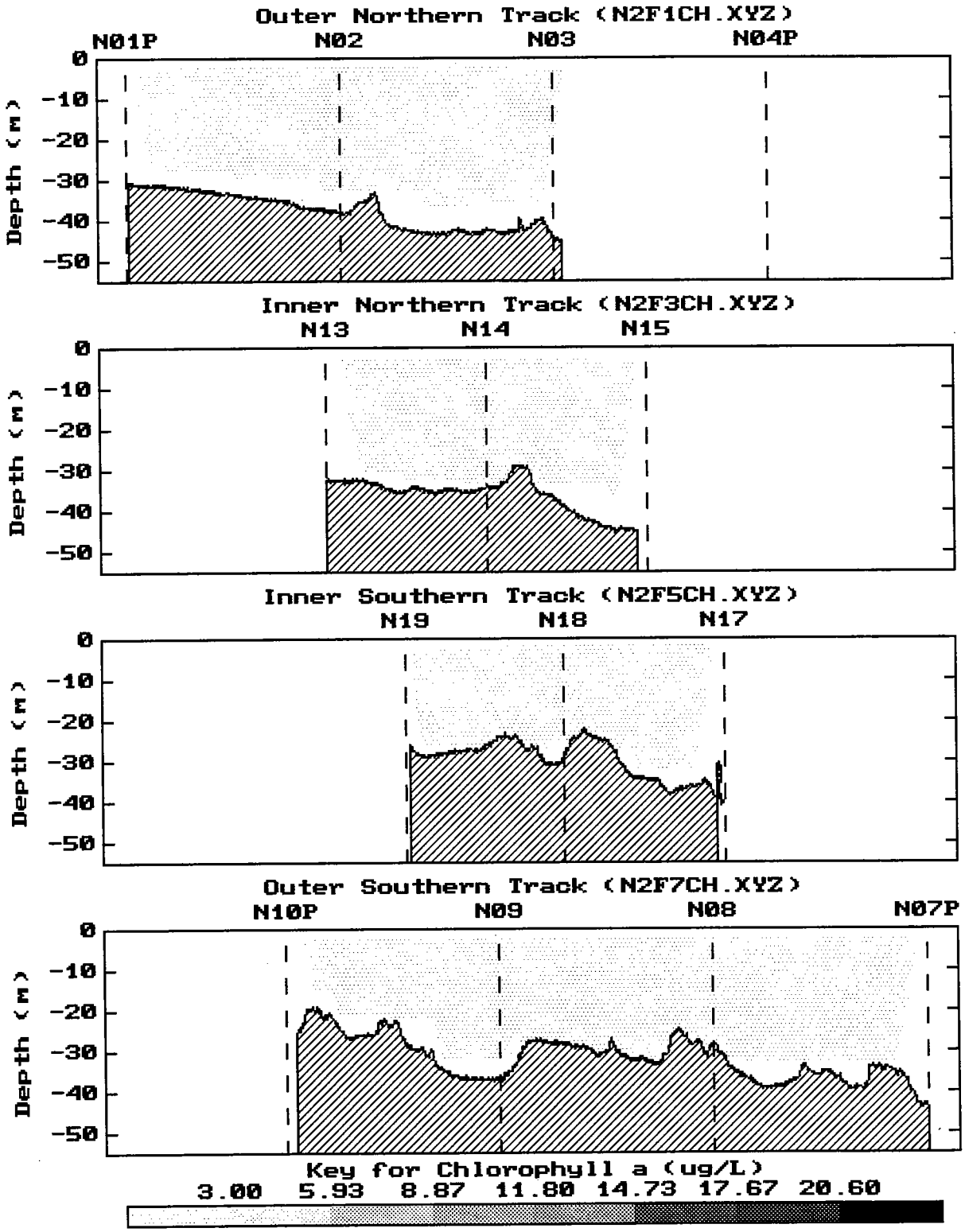


Figure 4-6a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in November 1993. The view is towards the North.

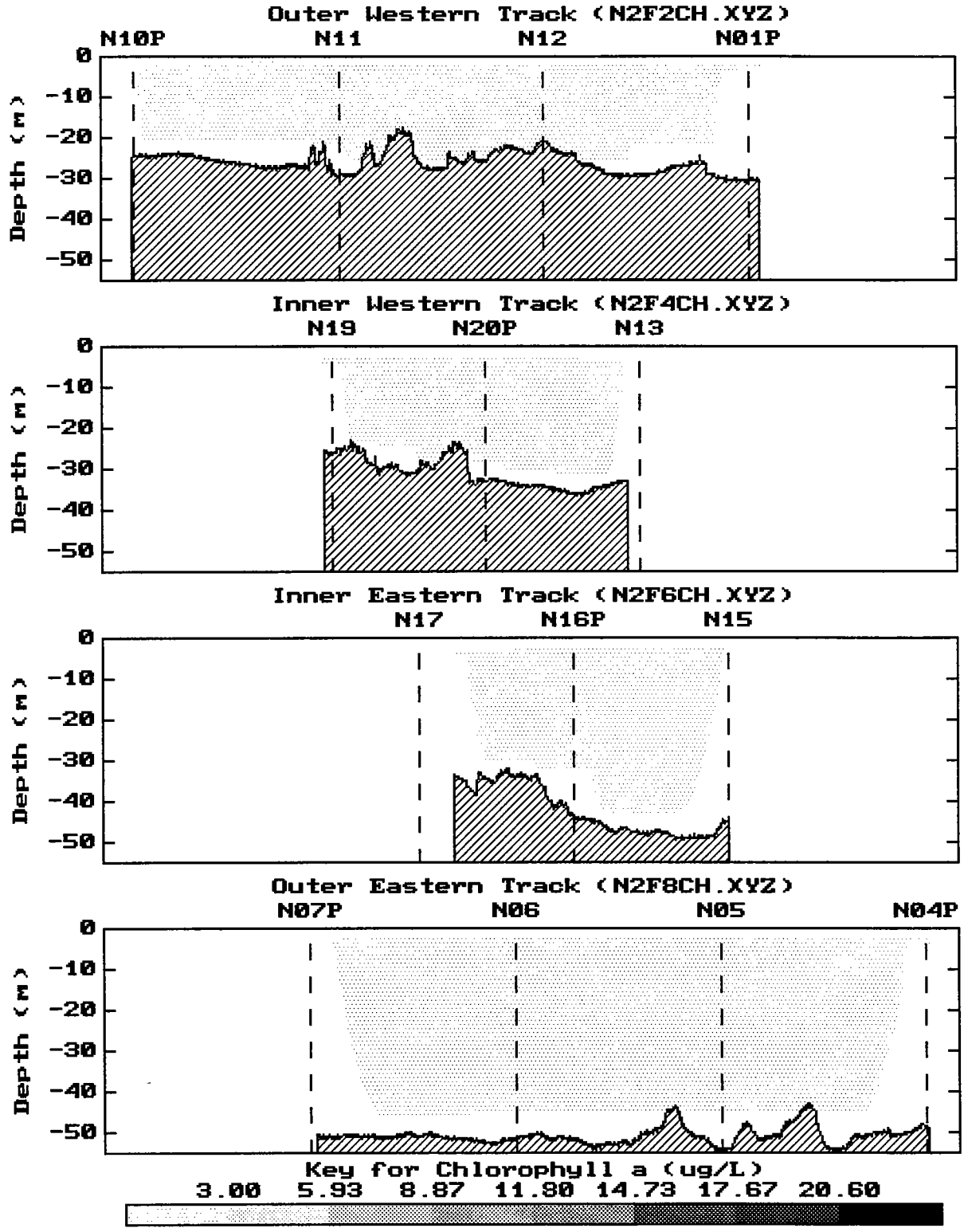


Figure 4-6b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in November 1993. The view is towards Boston Harbor.

5.0 RESULTS OF DECEMBER 1993 NEARFIELD SURVEY (W9316)

5.1 Distribution of Water Properties from Vertical Profiling

Vertical profiling and water sampling occurred on December 1, 1993 at all 21 nearfield stations. Bottle data and profile plots are provided in Appendix A and B, respectively. Overall, December water temperatures were approximately 8°C with salinities of 32.0 $\pm$ 0.2 PSU (Figure 5-1a). Due to the influence of the Harbor, the water was slightly cooler and fresher at station N10P. Otherwise, there was relatively little change, at stations or regionally, in the temperature and salinity profiles (Appendix B). Surface temperatures continued to decrease and were about 2°C cooler than temperatures observed in November.

Compared to November, beam attenuation-salinity patterns were more variable during this survey (Figure 5-1a). Turbidity was high in the bottom waters at the offshore stations (N04P, N05, N06, and N07P) and slightly elevated in the surface water at station N10P. Anomalously high turbidity was measured in the deep water at station N13. Beam attenuation did not correspond well to salinity or chlorophyll (Figure 5-1a) and generally showed little variation through the water column. Chlorophyll concentrations were $< 2\ \mu g\ L^{-1}$, decreased with depth, and were relatively similar throughout the nearfield (Figure 5-1b).

There was a clear progression in DO percent saturation from October (supersaturated) to December (undersaturated). With the exception of surface water at offshore station N06, the water column throughout the nearfield was undersaturated (Figure 5-1b). There was a distinct decrease in DO in the bottom waters (below 30 to 40 m) at stations N02 to N07, N15, and N16; this decrease coincided with cooler, more dense water.

Nutrient concentrations continued to increase relative to the previous two surveys and were consistently high at the depths sampled (Figure 5-2). DIN concentrations increased from 3 to 4 μM in November to 4 to 12 μM in December; higher concentrations were found at station N10P (Figure 5-2a). The high DIN

concentrations in the near-surface waters at station N10P were again due to the NH_4-rich outflow from Boston Harbor (Figure 5-2b). A significant portion of the DIN increase was due to NO_3 concentrations which were >4 μM at all stations (Figure 5-2b). Similarly, PO_4 and SiO_4 concentrations were high throughout the water column, averaging about 1.0 μM and 10.0 μM, respectively.

Nutrient-salinity plots generally showed the same patterns observed in November although overall nutrient concentrations were higher (Figure 5-3). DIN concentrations were high at both low and high salinities. The decrease in DIN concentrations with depth (i.e., increased salinity) was driven by a large decrease in NH_4 in conjunction with consistent NO_3 concentrations over the water column at many of the nearfield stations (Figure 5-3a and 5-3b; Appendix A). At the eastern nearfield stations, NH_4 concentrations were low (<1 μM) and DIN concentrations (as NO_3) increased with depth from the surface to the deep, more saline waters.

The PO_4-salinity plot was similar to the DIN plot and PO_4 concentrations were relatively consistent over depth at each station (Figure 5-3c and Appendix A). Silicate concentrations, which were >10 μM except in the upper water column at the eastern nearfield stations, varied with salinity in the same manner as NO_3.

The water column was well mixed during the December survey. The presence of a bottom water layer was only observed at the offshore nearfield stations and then only at depths >30 m. Nutrient concentrations were higher in water at the western nearfield stations and may have resulted from stronger mixing with the bottom waters, upwelling, or Harbor/coastal influences.

5.2 Distribution of Water Properties from Towing

Tow-yo sampling was performed over all tracks of the nearfield outer and inner boxes (Figure 1-2) on December 2. The temperature data are presented in Figures 5-4a and 5-4b. As mentioned above, water temperatures at the nearfield stations in December were about 2°C cooler than in November. Temperatures were slightly cooler to the north and west; coolest temperatures (<7.3°C) were measured in

the surface waters of the outer western transect. Because surface-to-bottom temperature differences were often much $<0.5°C$, no distinct vertical thermal gradients were observed.

The well-mixed character of the nearfield water column was also evident in plots of σ_T (Figures 5-5a and 5-5b). Because of the lower temperatures, the water was generally more dense than it had been in November. Lower density water was observed at stations N10P and N11, and may have been due to mixing with Harbor/coastal waters. The presence of heavy (more dense) bottom waters was evident at the deeper, offshore stations. There was not, however, a distinct pycnocline in the nearfield region.

The plots of chlorophyll were identical to the November survey plots. Chlorophyll concentrations were <2 $\mu g\ L^{-1}$ (see above) and thus showed no apparent change with depth in Figures 5-6a and 5-6b. The towed sampling results of the December survey indicated a continuation in the development of winter conditions in the water column. Winter conditions (i.e., well-mixed, nutrient-replete, and chlorophyll-poor water column) became well-established during the month following the November survey.

5.3 Water Types and Analysis of Small-Scale Variability

Both the vertical and horizontal profiles indicated that the nearfield was generally well mixed in relation to all of the parameters measured. The signature of Harbor water continued to be apparent at stations N10P and N11, and, at the deeper offshore stations, the bottom and surface waters were still distinct. There were no discernable effects of the tides on water quality measurements, perhaps because station N10P (the nearfield station most often effected by the tidal cycle) was sampled at similar tidal stages.

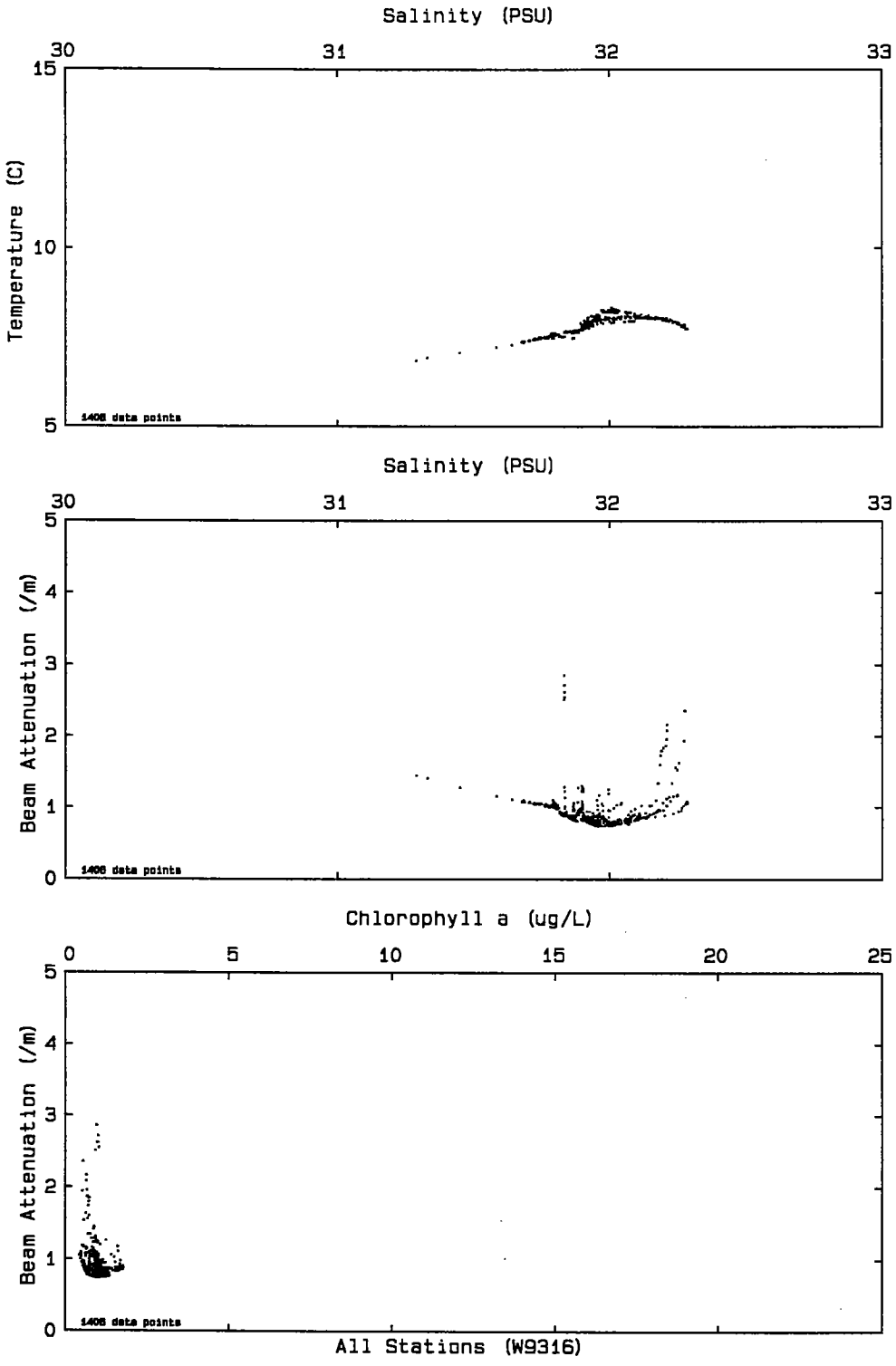


Figure 5-1a. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in December 1993. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.

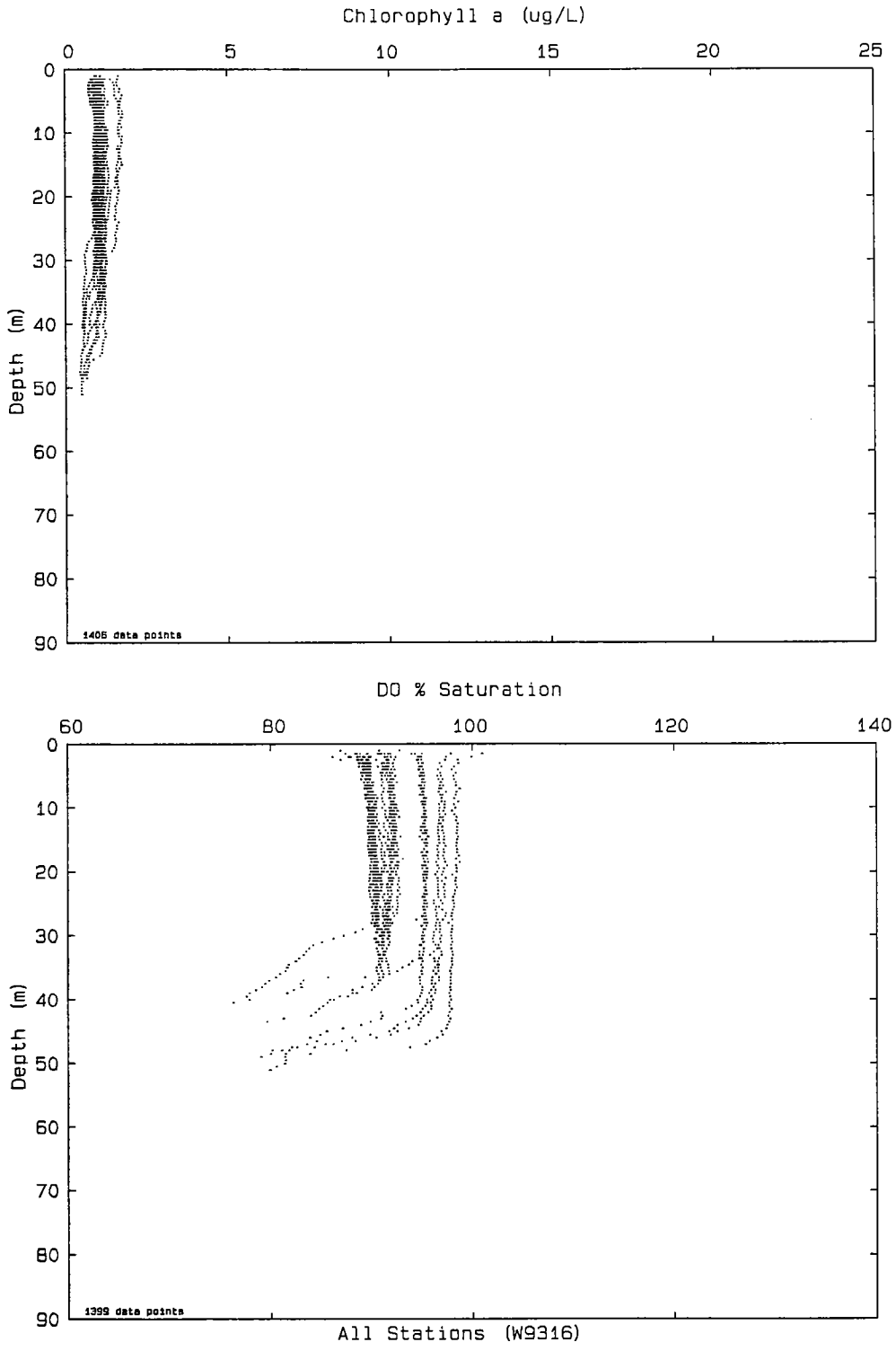


Figure 5-1b. **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in December 1993. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll is estimated from *in situ* fluorescence.**

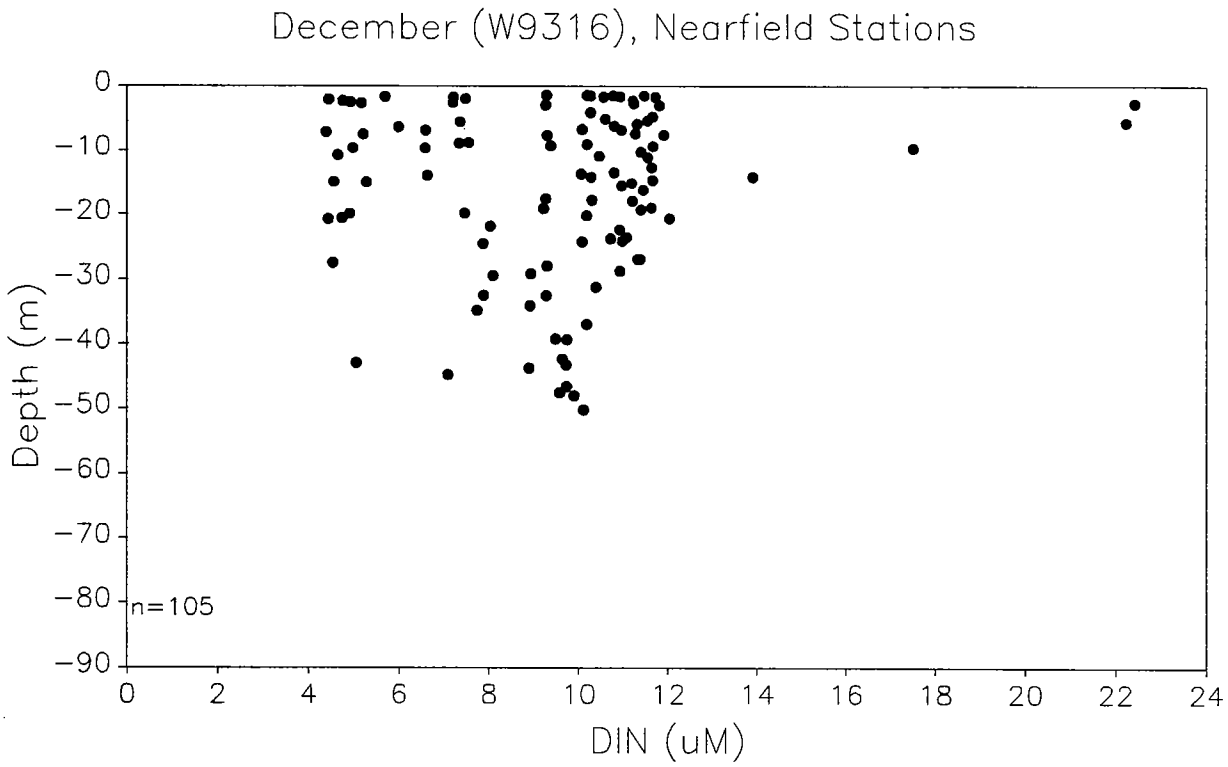


Figure 5-2a. DIN vs. depth in December 1993.

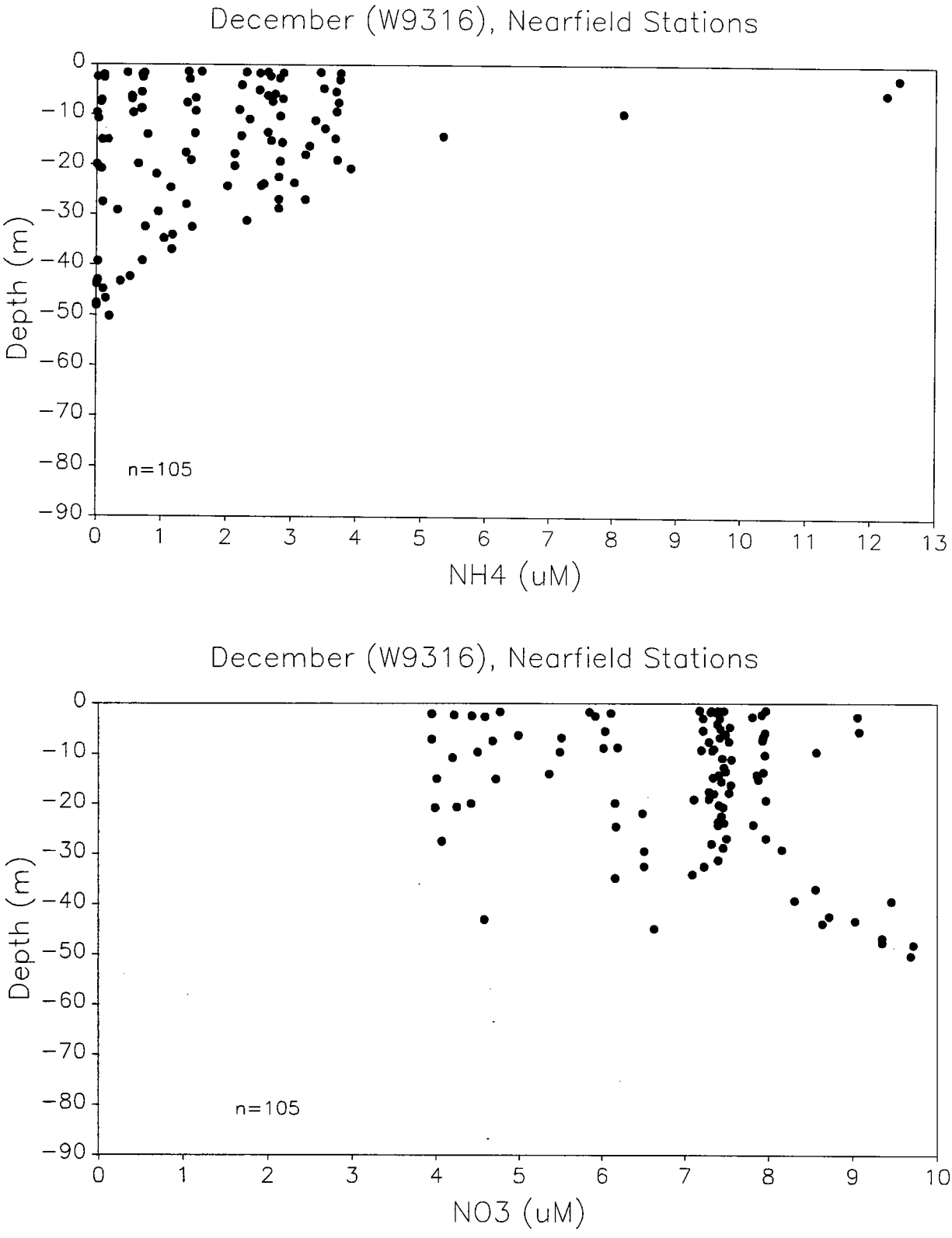


Figure 5-2b. NH_4 and NO_3 vs. depth in December 1993.

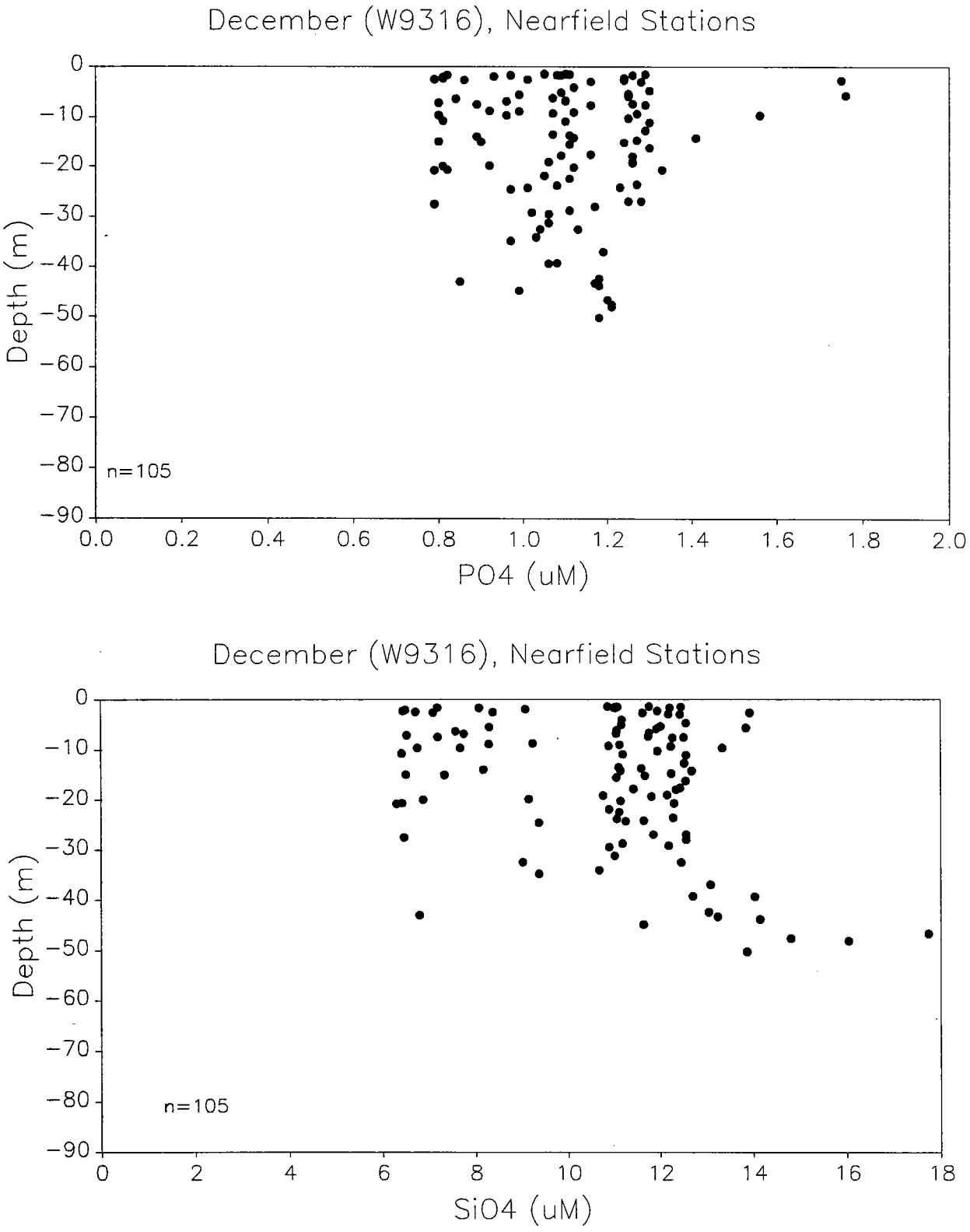


Figure 5-2c. PO_4 and SiO_4 vs. depth in December 1993.

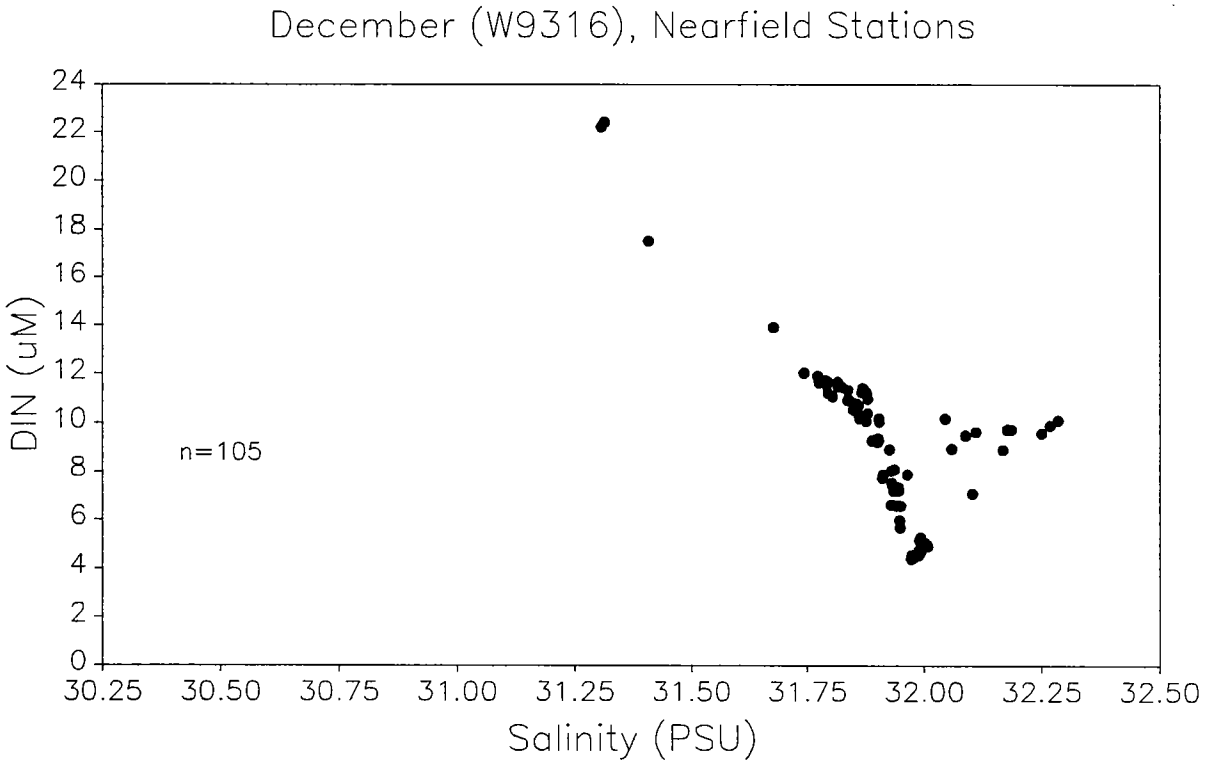


Figure 5-3a. DIN vs. salinity in December 1993.

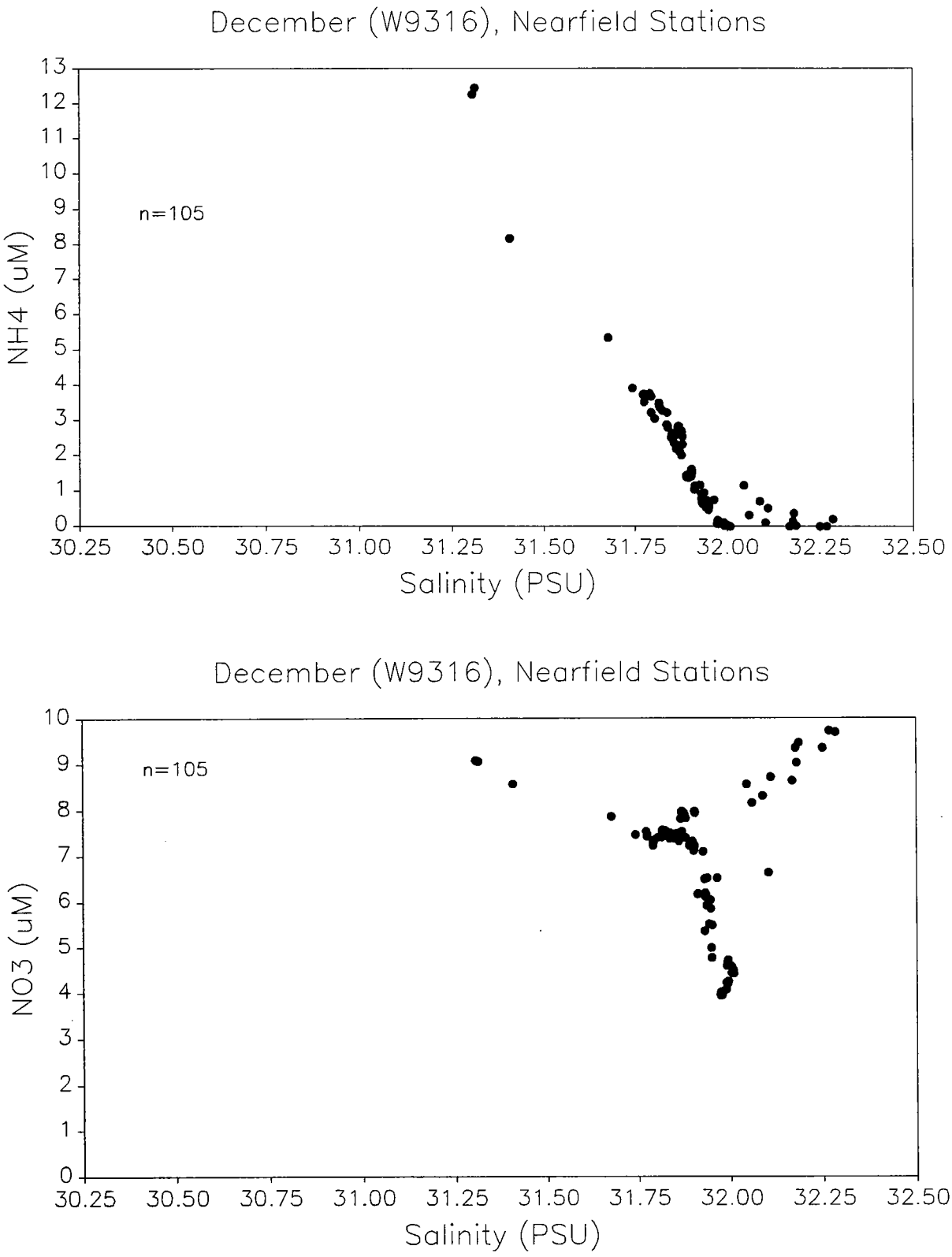
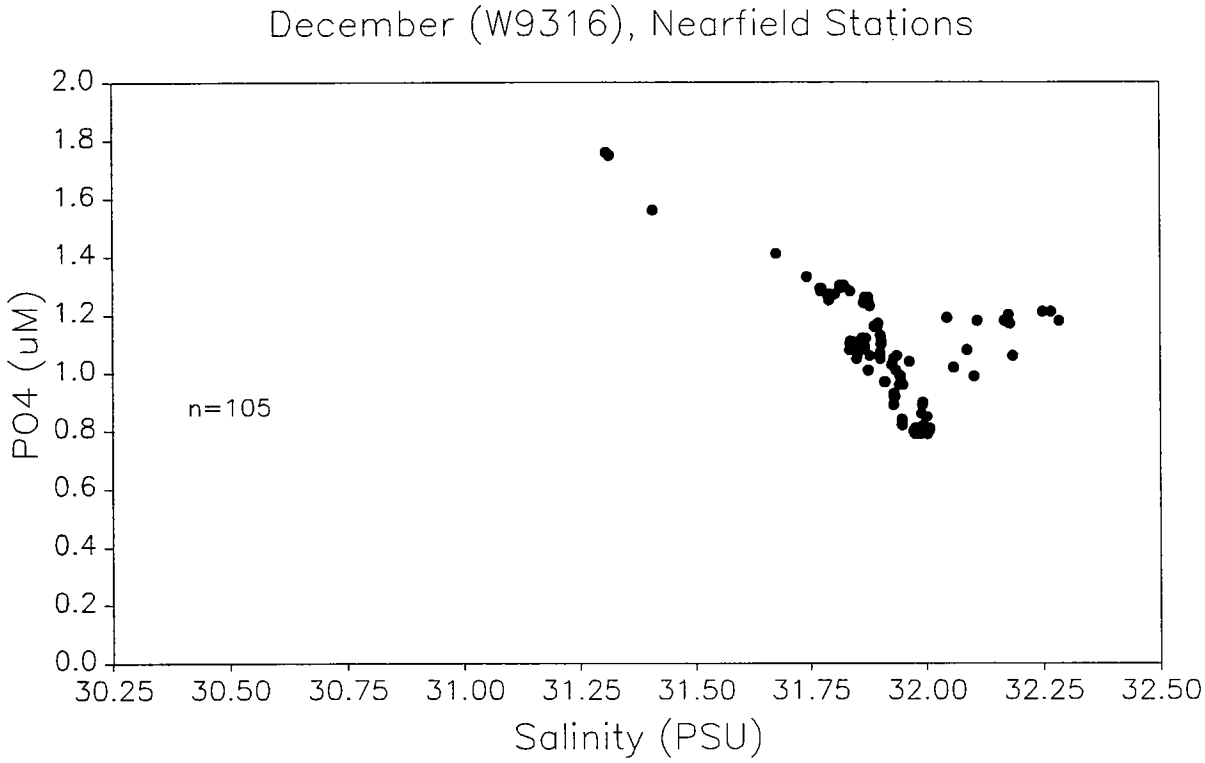


Figure 5-3b. NH_4 and NO_3 vs. salinity in December 1993.



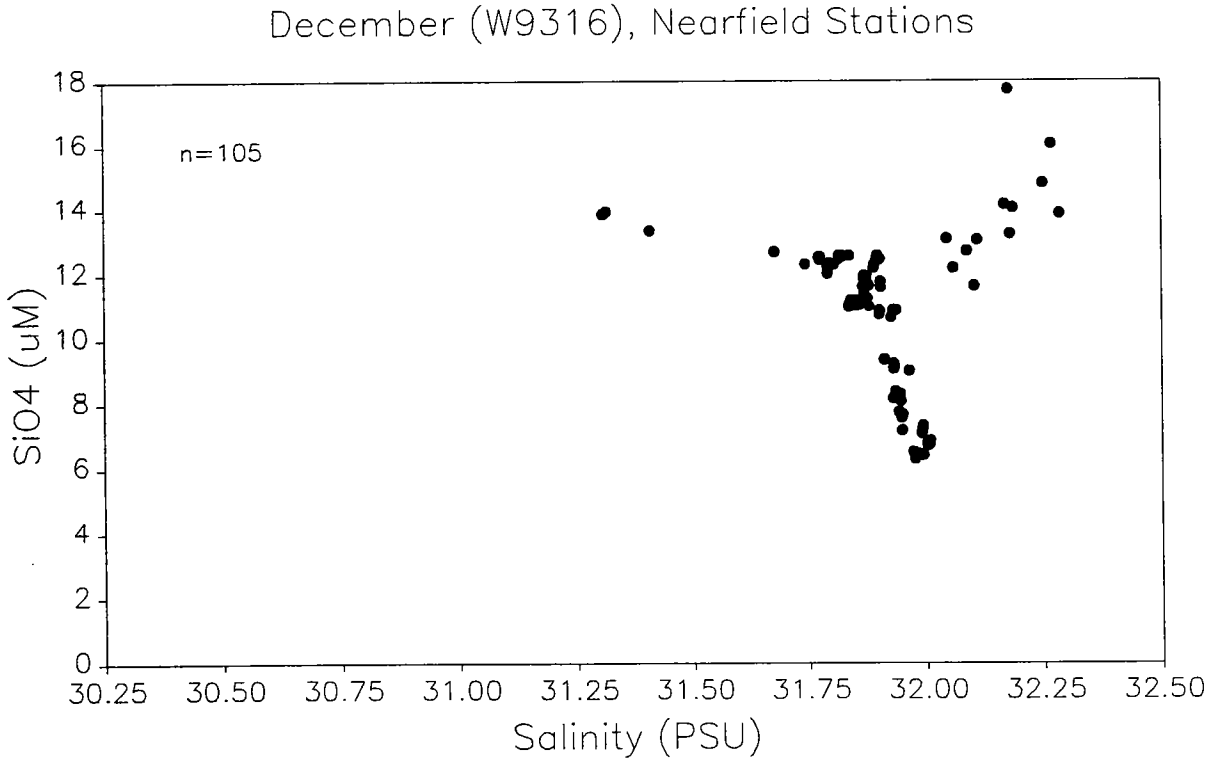


Figure 5-3c. PO_4 and SiO_4 vs. salinity in December 1993.

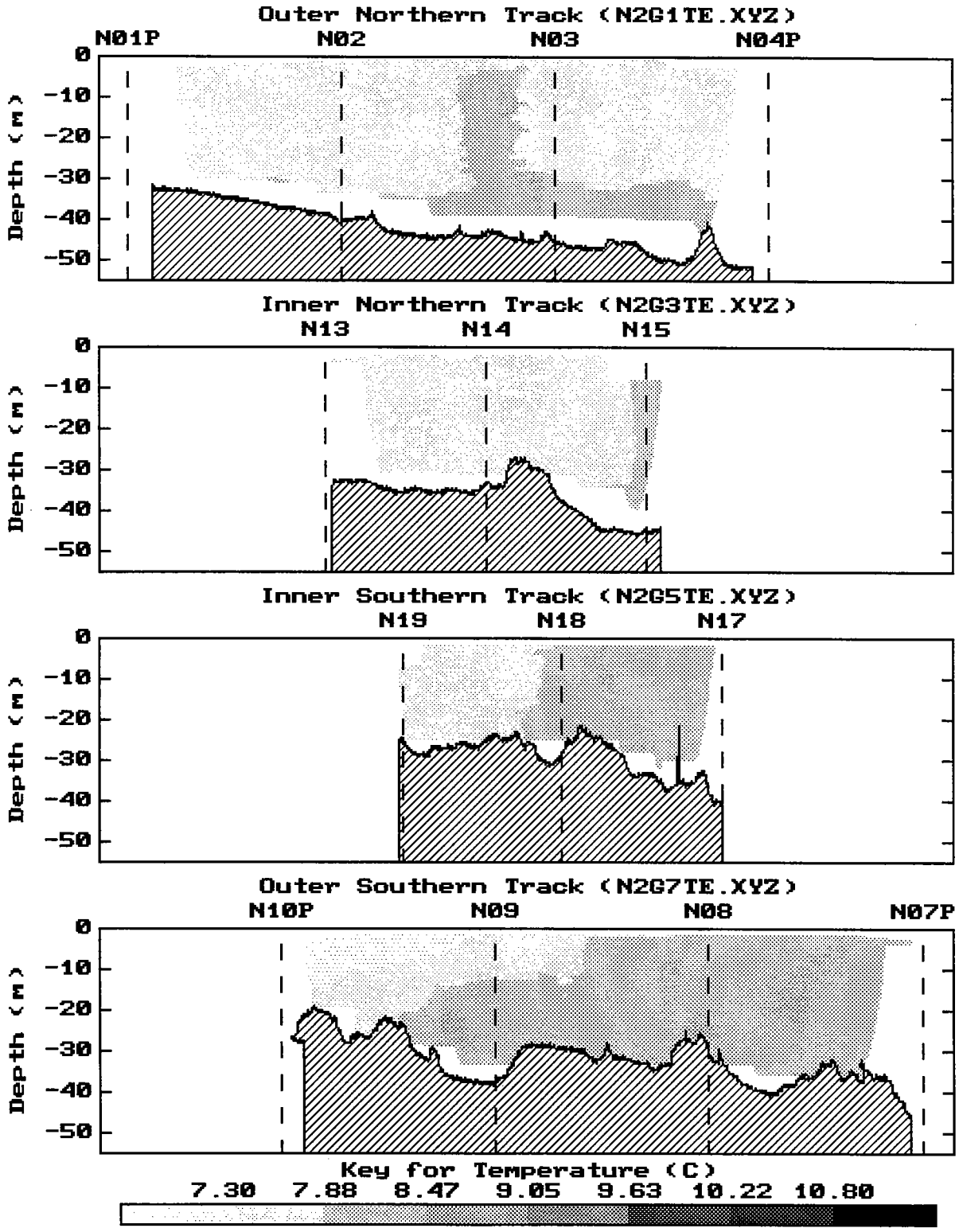


Figure 5-4a. Vertical section contours of temperature (°C) generated for tow-yo profiling conducted in December 1993. The view is towards the North.

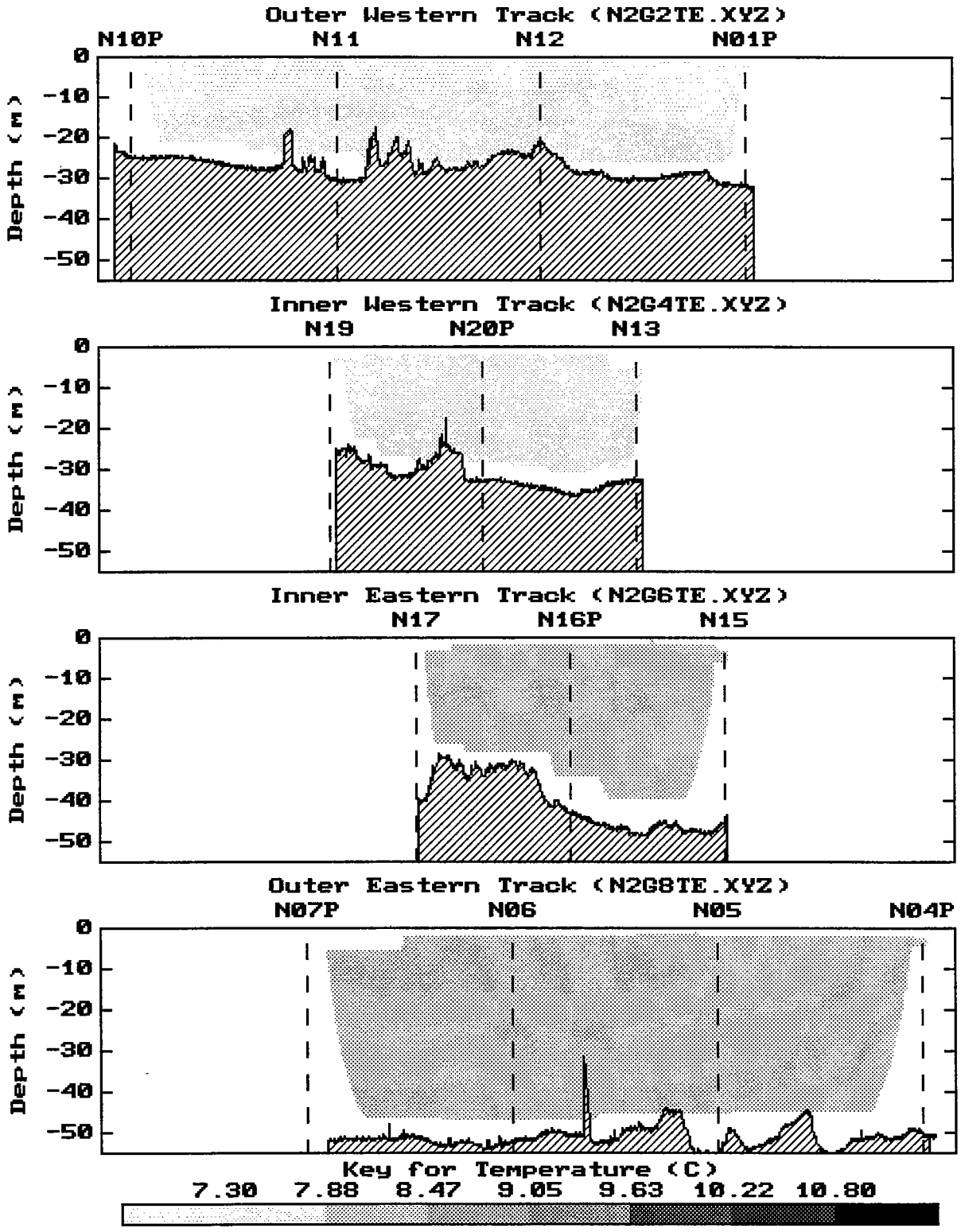


Figure 5-4b. Vertical section contours of temperature (°C) generated for tow-yo profiling conducted in December 1993. The view is towards Boston Harbor.

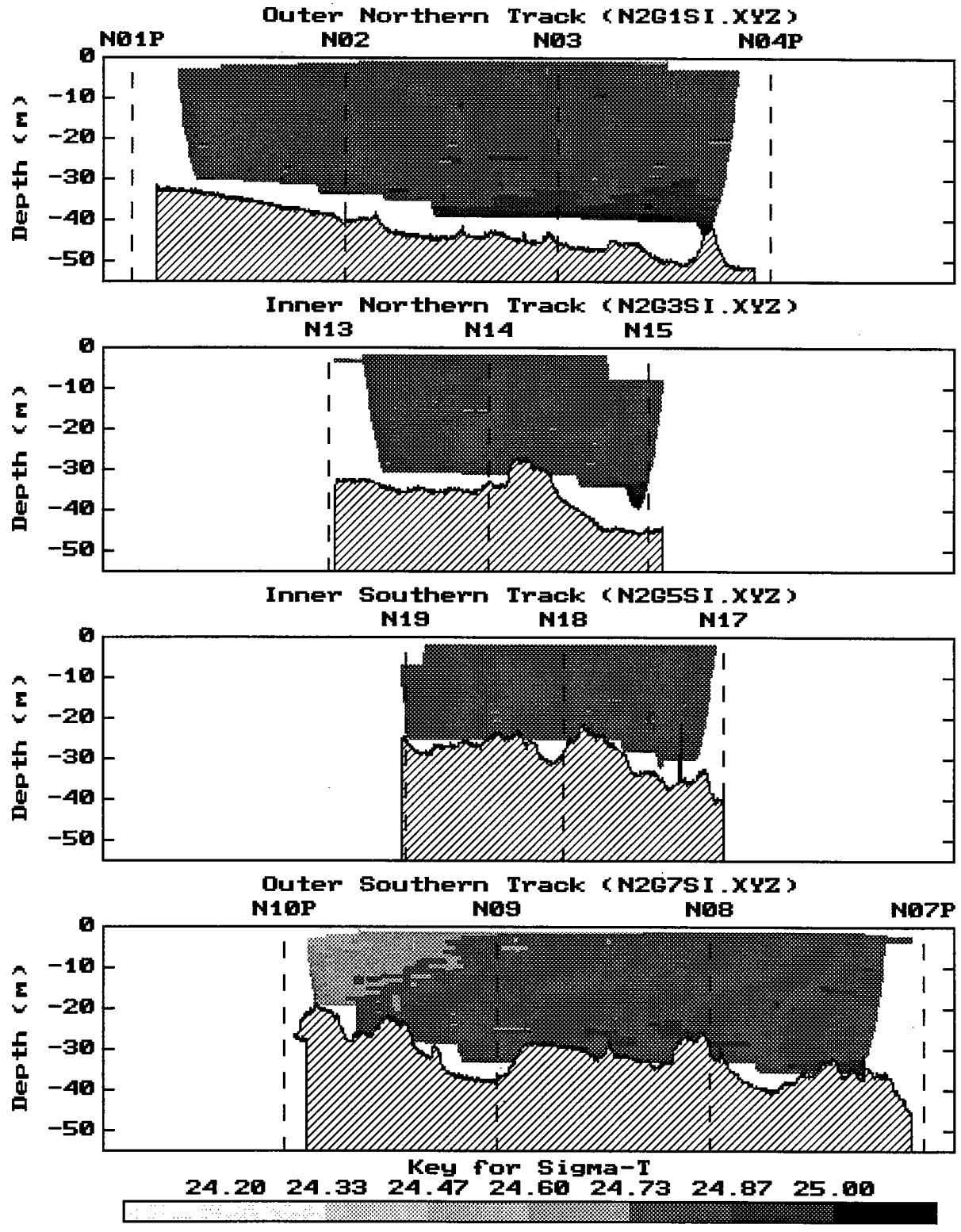


Figure 5-5a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in December 1993. The view is towards the North.

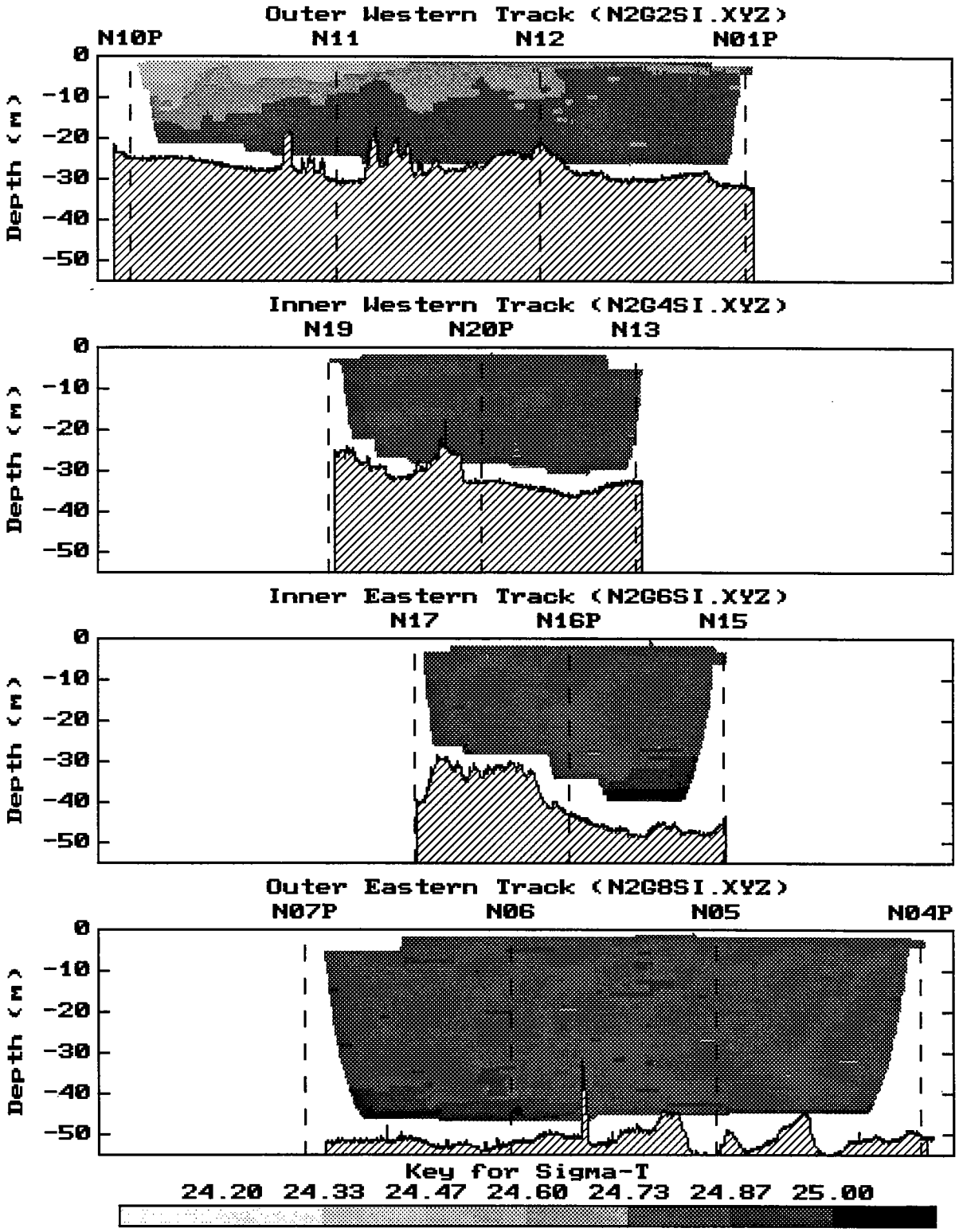


Figure 5-5b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in December 1993. The view is towards Boston Harbor.

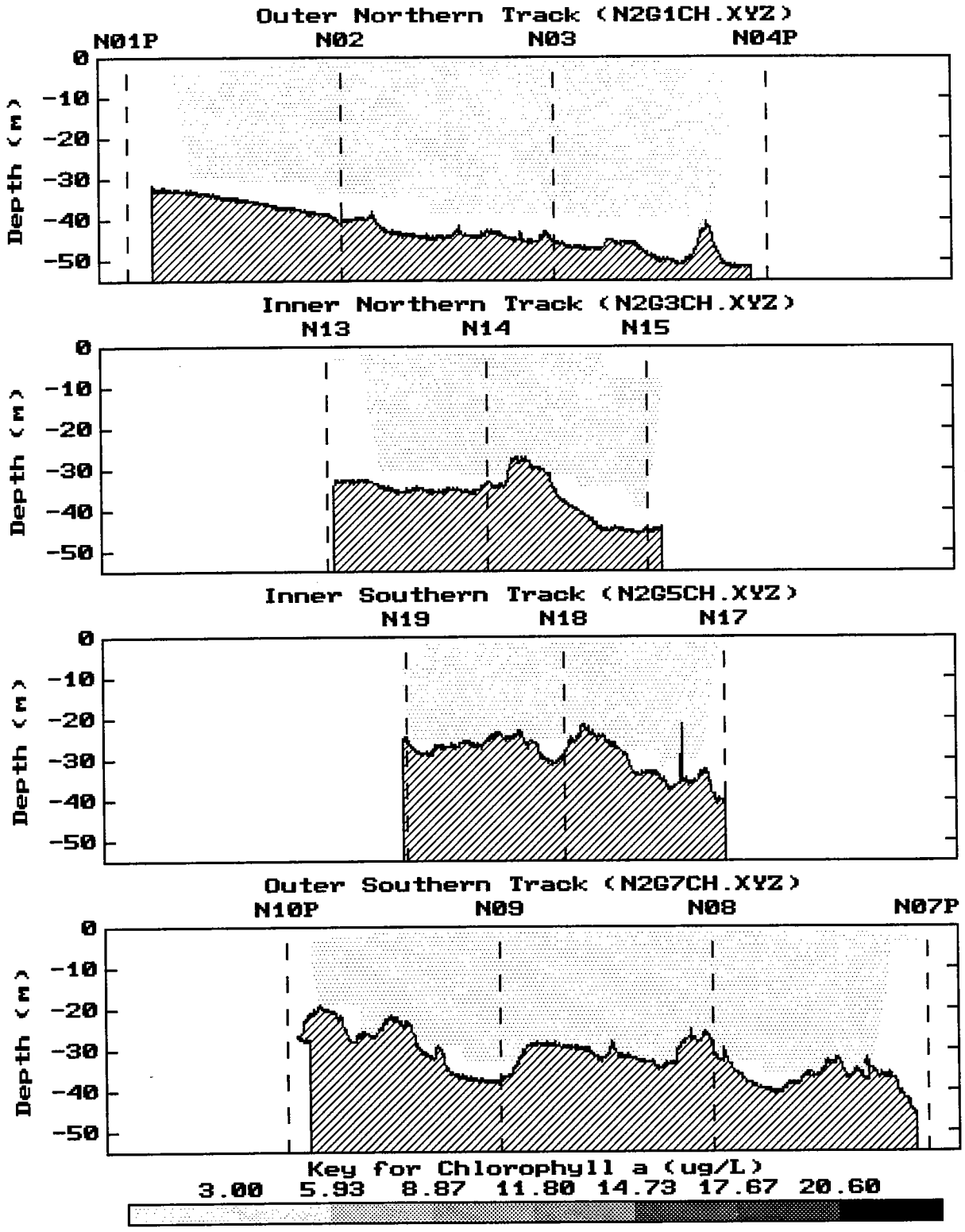


Figure 5-6a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in December 1993. The view is towards the North.

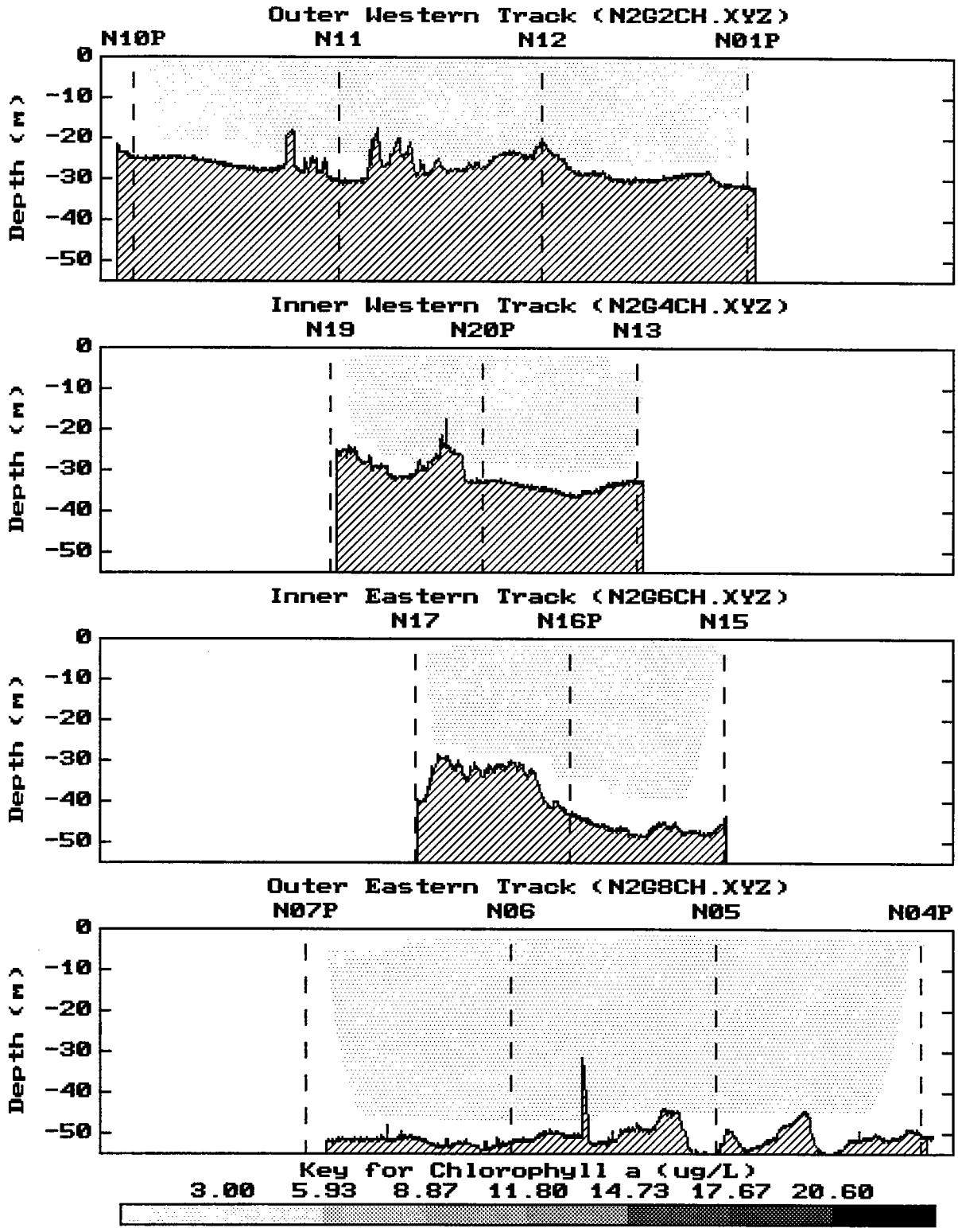


Figure 5-6b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in December 1993. The view is towards Boston Harbor.

6.0 DISCUSSION OF THE FALL/EARLY WINTER PERIOD OF SURVEYS

6.1 Water Properties

6.1.1 Variability at the Regional Scale

Regional scale sampling took place during the October farfield survey. In general, the range of the physical and chemical parameters was small and thus appeared to be relatively consistent throughout the region. The main trends for the parameters measured were inshore-offshore variations with distinct, yet usually small, differences between coastal-Harbor, nearfield-offshore Massachusetts Bay, and Cape Cod Bay waters. Surface temperature and salinity increased with distance from shore in Massachusetts Bay, while warmer less saline waters were found in Cape Cod Bay.

The most striking differences were observed at the stations near Boston Harbor (F23P, F24, and F25). The water at these stations was cooler, fresher, and much higher in nutrient concentrations than the water at nearby western nearfield and coastal stations. The near-Harbor and other shallow stations exhibited a well-mixed water column which was in contrast to the vertical stratification observed at the stations further offshore. At the offshore stations, a consistent pycnocline was located at ~25 m, separating the warm nutrient-depleted surface layer from the cool nutrient-rich bottom waters. The stratification of the water column due to vertical gradients in temperature, salinity, and density increased with distance from shore.

Surface chlorophyll concentrations were high throughout the bays, ranging from 3 to 20 $\mu g\ L^{-1}$. The highest concentrations, along with the most NO_3- and SiO_4-depleted surface waters, were observed to the northwest of the nearfield. Chlorophyll concentrations $> 10\ \mu g\ L^{-1}$ were found throughout most of Massachusetts Bay, while lower concentrations were present in Boston Harbor, southern Massachusetts Bay, and Cape Cod Bay (except station F04). On average, higher DIN and SiO_4 concentrations were measured in the surface water in Cape Cod Bay than in Massachusetts Bay.

6.1.2 Variability in the Nearfield

In the nearfield, major changes in water quality characteristics occurred between mid-October and early December. In fact, during the October farfield and nearfield surveys, over the period of a few days, significant changes occurred in chlorophyll concentrations and in beam attenuation. During the October surveys, the cessation of a diatom bloom was observed both before and after sedimentation. In the ensuing weeks, the nearfield waters that had been nutrient depleted, oxygen supersaturated, and chlorophyll rich became well mixed, nutrient replete, oxygen undersaturated, and chlorophyll poor. This change, between mid-October and early November, represents the onset of winter mixing which continued into December.

Spatial variability was apparent during all three surveys in the nearfield. The inshore-offshore trends, evident during the farfield survey, were also observed in the nearfield. At the western nearfield stations, a Harbor/coastal signature of cooler, fresher water and higher nutrient concentrations was normally apparent. This nearshore water also was well mixed, while the more offshore nearfield stations continued to be stratified, though the thermal and density gradients decreased from October to December.

6.1.3 Coherence of Nearfield and Farfield Station Properties

The trends observed during the October surveys were generally inshore-offshore, and thus the nearfield was generally in the transition zone for many of the parameters measured. As discussed above, the western nearfield consistently displayed Harbor/coastal water quality characteristics and the eastern nearfield stations were similar to the offshore waters. The diatom bloom was apparently focused in the northwestern portion of the nearfield, but chlorophyll concentrations were consistently high throughout most of Massachusetts Bay.

6.1.4 Special Features: Comparison of 1993 with 1992

The nearfield surface temperatures decreased during the fall/early winter surveys in both years, but the temperatures were about 2°C cooler in October 1993 (~10°C) than in October 1992 (~12°C; Figure 6-1). Water temperatures in November and December were comparable during both years. Seasonal cooling began sooner in 1993 but, by November, the winter trends were similar. The cooler water in October 1993 may have been due to an increase in mixing which is consistent with the vertical profiles of salinity and σ_T.

Bottom water DO concentrations increased from late September to mid-October in 1993 (Figure 6-2). This increase was due to a combination of decreased temperature, increased vertical mixing, and the diatom bloom that was observed in October. The wide range of DO concentrations noted in October continued through December and there was no significant change in the concentrations over that time period, although increased mixing and cooler temperatures were observed after October. This suggests that the higher DO concentrations measured in October resulted primarily from the fall diatom bloom. The main differences between 1993 and 1992 were the elevated DO concentrations observed in October 1993 and the variability associated with DO concentrations over the three-month period in 1993. The DO changes in 1992 appeared to be more closely related to decreases in temperature than they were in 1993.

6.2 Water Column Nutrient Dynamics

6.2.1 Vertical Structure and Initiation of Seasonal Mixing

Vertical profiles of temperature, salinity, and density are indicators of water column stratification and/or mixing. As discussed previously, stratification intensified with distance from shore and diminished over the period of the three surveys. The breakdown of seasonal stratification had already been initiated by the October survey, although mild stratification at the eastern nearfield stations persisted through the December survey.

During the October survey, nutrient concentrations were low throughout the bays, and both NO_3 and SiO_4 were depleted in the nearfield surface water. Higher nutrient concentrations were present near Boston Harbor and below the pycnocline (~25 m). The physical parameters suggest that the coastal and western nearfield stations were well mixed, yet nutrient concentrations were depleted at these stations as a result of the phytoplankton bloom. With the cessation of the bloom and increased mixing, nutrient concentrations increased substantially by early November and concentrations were even higher in December.

6.2.2 Inshore-offshore Gradients

During each of the three surveys, inshore-offshore gradients were detected for physical and chemical parameters that were measured. The gradients were strongest in October and also in the vicinity of Boston Harbor. During the October farfield survey, nutrients were depleted at all locations except near the Harbor where the water was cooler and fresher. The Harbor influence was observed at nearby coastal and nearfield stations. There were no Harbor-edge stations during the November and December nearfield surveys, but the signature of Harbor/coastal waters (cooler, fresher, and rich in NH_4) was apparent at stations N10P and N11. The inshore-offshore gradients were most noticeable with the surface water nutrient data, especially for NH_4, during the fall/winter surveys (Appendix A).
There was a significant inshore-offshore gradient in stratification and, with increased stratification, there was an increase in the vertical nutrient gradient. This gradient of lower surface and higher bottom water nutrient concentrations, in conjunction with the Harbor/coastal influence of nutrient-rich water, was responsible for the surface nutrient gradient observed in November and December.

6.2.3 Special Features: Comparison of 1993 with 1992

On average, DIN concentrations in the surface 20 m decreased from late September to mid-October of 1993 and the October 1993 concentrations were slightly lower than in October 1992 (Figure 6-3). Figure 6-3, however, belies the fact that the nutrient regimes in October 1993 and 1992 were strikingly different. As shown in Section 3.1, nutrients were nearly depleted over most of the sampling area in October 1993,

while in October 1992 nutrient concentrations were high and only NO_3 appeared to be depleted in the more offshore surface waters (Kelly *et al.*, 1993b). Silicate concentrations, which were depleted in the nearfield in 1993, had been present at concentrations ranging from 2 to 8 μM throughout the bays in October 1992. In contrast, November nutrient concentrations were much higher in 1993 than in 1992. DIN concentrations were >2 μM at all stations in November 1993 (2 to 16 μM), while DIN was depleted in the upper 20 m at some stations in November 1992 (0 to 7 μM; Figure 6-3). However, in December of both years, DIN concentrations were similar with the exception of high ($\tilde{}$22 μM) values at station N10P in 1993.

The variability in the concentration of nutrients was due to both physical and biological annual variations. The low nutrient concentrations measured in October 1993 were the result of a massive, bay-wide diatom bloom. The 1992 survey data suggest that the fall bloom occurred previous to the October survey, and that the breakdown of stratification and the onset of winter mixing was well underway by that survey. This also seems to indicate that the water column turned over more quickly in 1993 — during the interim between the October and November surveys — while the breakdown of stratification started earlier but took longer in 1992.

6.3 Biology in Relation to Water Properties and Nutrient Dynamics

6.3.1 Phytoplankton-Zooplankton Relationships

In October, there was a strong relationship between phytoplankton counts and extracted chlorophyll concentrations (see Figure 3-24). This was primarily due to the presence of a dominant phytoplankter throughout Massachusetts Bay. The only points on the figure that seem to fall far off the relationship were from station F23P at the edge of the Harbor. Zooplankton counts, however, showed no correlation with chlorophyll and varied by an order of magnitude over the stations sampled (~15,000 to 150,000 individuals m^{-3}; Figure 6-4). This large variation showed no relationship to changes in phytoplankton, as zooplankton counts were low at stations with both low (F23P; ~2 million cells L^{-1}) and high (N10P; ~8 million cells L^{-1}) phytoplankton counts. This is surprising given that high chlorophyll concentrations had been observed

since August and that the zooplankton community should have had time to respond to the abundant phytoplankton. A number of factors may have led to the formation of this community structure: (1) onset of cooler water temperatures, (2) the zooplankton's aversion to *A. glacialis*, (3) the lack of a significant spring bloom affecting zooplankton "seed" stocks, and/or (4) the bloom was a short-term event and zooplankton had not yet responded. Shorter time intervals for sampling and grazing experiments would be needed to more fully understand zooplankton-phytoplankton interactions.

6.3.2 Plankton Species and Water Properties

Chlorophyll concentrations were high at all the BioProductivity stations in October, yet there were discernable differences between Massachusetts Bay, Cape Cod Bay, and stations F23P and F25 at the edge of Boston Harbor. Chlorophyll in extracted samples ranged between 5 and 20 $\mu g\ L^{-1}$ in Massachusetts Bay, with concentrations decreasing offshore. Lower chlorophyll concentrations were found at the Cape Cod (~5 $\mu g\ L^{-1}$) and Harbor-edge stations (~6 $\mu g\ L^{-1}$). There was relatively little change in plankton species composition over the sampling region, but the changes that were detected were sufficient to differentiate between the bays. Massachusetts Bay was dominated by a bloom of *A. glacialis*; the most abundant copepod in the bay was *O. similis*. Although both of these species were also plentiful, the most numerous plankton in Cape Cod Bay consisted of the diatom *L. minimus* and the copepod *P. parvus*. High counts of *C. fusus* were found in the 20-μm-screened samples in both bays, but this species made only a token appearance at the Harbor-edge station F23P (no plankton samples were taken at F25). At station F23P, the 20-μm-screened samples were dominated by tintinnids, while *A. glacialis* and *A. tonsa* were the most abundant phytoplankton and zooplankton species present.

Results of the near-surface 20-μm-screened plankton taxonomy at station N10P between October and December are shown in Table 6-1. The abundance of larger organisms was low (< 500 cells L^{-1}) in comparison to the counts of whole water phytoplankton during the October survey. A comparison of samples taken from station N10P on October 12 (Table 3-2) and October 15 indicates that there was a significant decrease in the abundance of *C. fusus*. This may have been related to the cessation of the *A.*

glacialis bloom and could explain why the *C. fusus* counts were so much lower at station F23P (also sampled October 15).

6.3.3 Chlorophyll Biomass and the Distribution of Nutrients and DO

A strong inverse relationship between chlorophyll biomass and nutrient concentrations was noted during the October farfield survey. Chlorophyll concentrations were high throughout the bays, while nutrients were nearly depleted at all but the Harbor-edge stations. During this time period, biological utilization governed the distribution of nutrients, rather than the reverse which is often the case (i.e., chlorophyll maximum at the pycnocline). The depletion of nutrients (especially SiO_4), in turn, contributed to the cessation of the diatom bloom.

As illustrated in Figure 6-5, extracted chlorophyll and total nitrogen (TN) were positively related in October 1993. In this figure, the outlying points represent samples taken near the Harbor (stations F23P and F25), and the higher TN concentrations were due to elevated NH_4 and dissolved organic nitrogen concentrations. The TN-chlorophyll relationship, though tenuous, was driven by the increase in chlorophyll (i.e., phytoplankton particulate nitrogen) since total dissolved nitrogen concentrations were relatively consistent at the non-Harbor BioProductivity stations (Appendix A).

Oxygen percent saturation was correlated with chlorophyll in the surface waters during the October survey. The high chlorophyll concentrations observed at many nearfield and northern transect stations were coincident with oxygen saturation $>110\%$. Both chlorophyll and DO concentrations were elevated above the pycnocline in October, and decreased over the course of the November and December surveys.

6.3.4 Metabolism and Environment

As indicated in Figure 6-6, there was a strong relationship between integrated chlorophyll (as measured by fluorescence) and primary productivity for both surface and subsurface phytoplankton populations. Given

the moderate surface light intensities (i.e., low inhibition) and uniformly chlorophyll-rich surface layer (includes chlorophyll maximum), little difference was expected between the surface and subsurface phytoplankton assemblages. Both production rates and chlorophyll concentrations were higher in central Massachusetts Bay compared to the coastal and Cape Cod Bay BioProductivity stations.

6.3.5 Special Features: Comparison of 1993 with 1992

Chlorophyll concentrations measured during the October 1993 survey were generally comparable to those measured at the end of September, but were somewhat higher at the "chlorophyll-poor" stations. However, counts of phytoplankton species indicate that there was a distinct change in community structure from late September (mixed phytoplankton community) to mid-October (domination by the small diatom, *A. glacialis*). This shift in the phytoplankton community coincided with, and perhaps contributed to, a general decrease in zooplankton abundances. A diverse community of phytoplankton was also observed during the late August and October 1992 surveys. Unfortunately, however, taxonomic data were collected only at station N10P on the September 1992 survey, the time at which seasonally-high chlorophyll concentrations were observed. With only one station in early September and no surveys until mid-October in 1992, it is not possible to broadly assess if and and when a change in plankton community structure may have occurred during the full bloom of 1992.

There were striking differences between the 1993 and 1992 October surveys, and the seasonal trends in chlorophyll (Figure 6-7). Chlorophyll concentrations in October 1993 (3 to 20 $\mu g\ L^{-1}$) were much higher than in October 1992 (1 to 6 $\mu g\ L^{-1}$). Similar late summer increases in chlorophyll were apparent during both years, yet this trend continued into the middle of October in 1993 and only to early September in 1992. There is, however, a data gap encompassing more than one month in the 1992 data set. The October and November 1993 data emphasize that the phytoplankton community of Massachusetts Bay can change very rapidly over periods of a few days (sedimentation of bloom) to a few weeks (chlorophyll concentrations reduced from $>20\ \mu g\ L^{-1}$ to $<2\ \mu g\ L^{-1}$); therefore, the "fall bloom" may not have been observed in 1992 due to the timing of the surveys. The historical data, as summarized by Cura (1991),

suggest that the fall bloom usually occurs in September but, due to the paucity of data for October, it is unclear whether the *A. glacialis* bloom observed in 1993 was an extraordinary or common event.

6.4 Summary and Recommendations

During each of the three surveys, physical parameters varied little, although different degrees of stratification were observed. With the onset of winter mixing, temperature and the extent of water column stratification decreased between October and December. The most significant changes were in the biology of the bays over both the course of the farfield/nearfield survey, and between the October and November surveys. This variability resulted from the dynamics of the *A. glacialis* bloom. The short timescales involved with the changes in biological parameters and the importance of documenting the occurrence of a bay-wide fall bloom necessitate future surveys to be scheduled at regular intervals *through* October. Implementing this recommendation should increase the likelihood of documenting the fall bloom and will be helpful in understanding the biological dynamics during the destabilization of seasonal stratification.

Table 6-1. Abundance of all identified phytoplankton taxa in near-surface screened (20um) samples at station N10P collected in October, November, and December 1993.

SPECIES	STATION	N10P	N10P	N10P
	SAMPLE	W93140494	W93150026	W93160027
	DATE	Oct. 15	Nov. 03	Dec. 01
ALEXANDRIUM TAMARENSE		0	0	0
ALORICATE CILIATES		13	0	3
AMPHIDINIUM SPP.		0	0	0
CERATIUM FUSUS		35	205	178
CERATIUM LINEATUM		0	0	0
CERATIUM LONGIPES		3	5	5
CERATIUM MACROCEROS		0	0	8
CERATIUM TRIPOS		15	33	28
DICTYOCHA FIBULA		0	0	3
DICTYOCHA SPECULUM		0	3	3
DINOPHYSIS ACUMINATA		0	0	0
DINOPHYSIS CAUDATA		0	0	3
DINOPHYSIS NORVEGICA		3	0	0
DIPLOPSALIS SPP.		5	5	3
GONYAULAX SPINIFERA		5	0	0
GYMNODINIUM SPP.		0	0	0
GYRODINIUM SPIRALE		10	0	0
GYRODINIUM SPP.		0	0	0
MERISMOPEDIA COLONY		0	0	0
MERISMOPEDIA SPP. COLONY		0	0	0
MESODINIUM RUBRUM		0	0	0
PROROCENTRUM MICANS		5	3	0
PROROCENTRUM TRIESTINUM		0	0	0
PROTOPERIDINIUM (CF) BREVIPES		0	0	0
PROTOPERIDINIUM BIPES		0	0	0
PROTOPERIDINIUM BREVE		0	0	0
PROTOPERIDINIUM DEPRESSUM		5	8	0
PROTOPERIDINIUM PELLUCIDUM		0	0	0
PROTOPERIDINIUM PENTAGONUM		0	0	0
PROTOPERIDINIUM SPP.		20	5	0
SCRIPPSIELLA TROCHOIDEA		15	3	0
TINTINNIDS		393	55	18
UNID. ATHECATE DINOFLAGELLATE		0	0	0
UNID. THECATE DINOFLAGELLATES		0	3	0

Values are cells/L

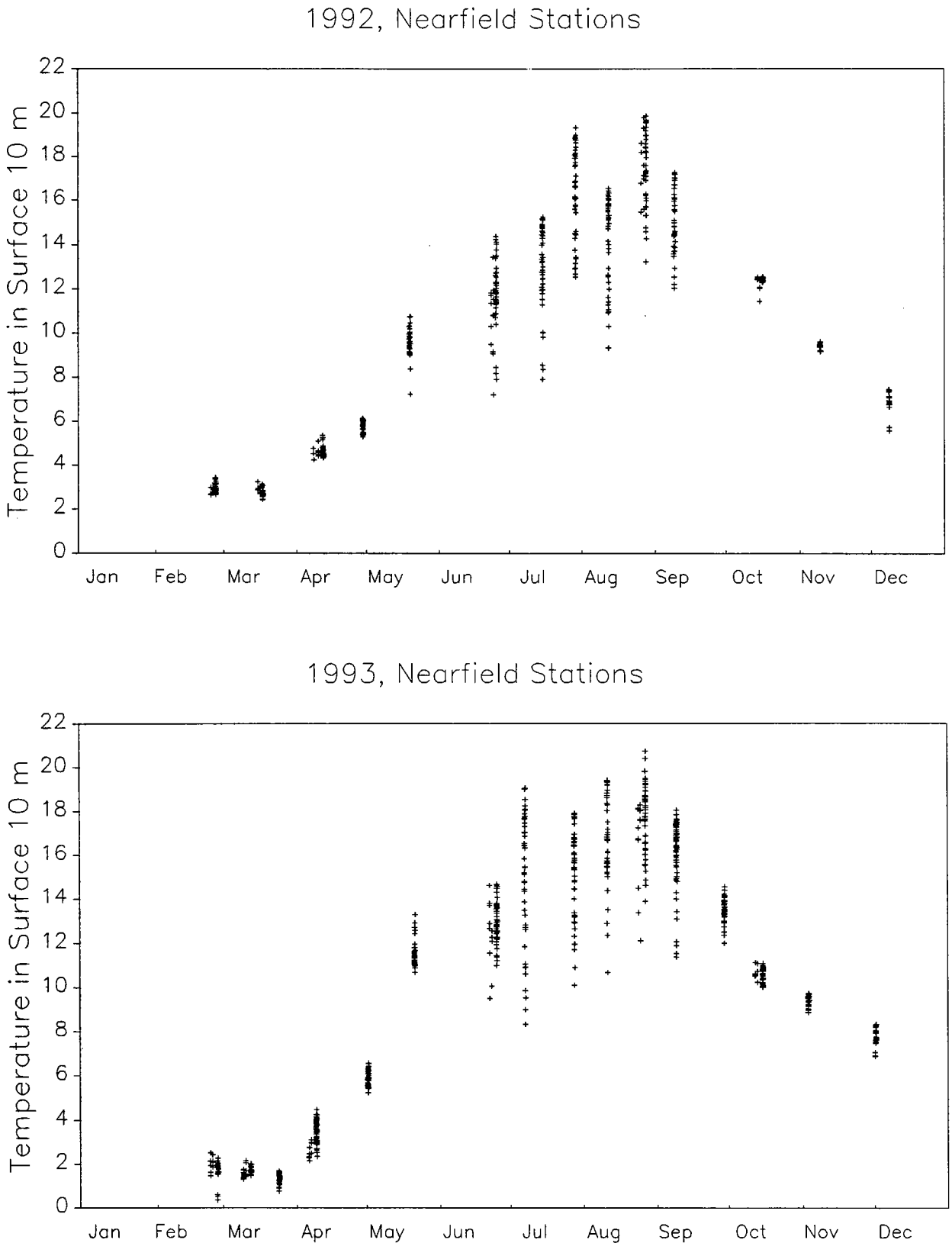


Figure 6-1. Comparison of the nearfield region in 1993 to the annual cycle of 1992: temperature (°C).

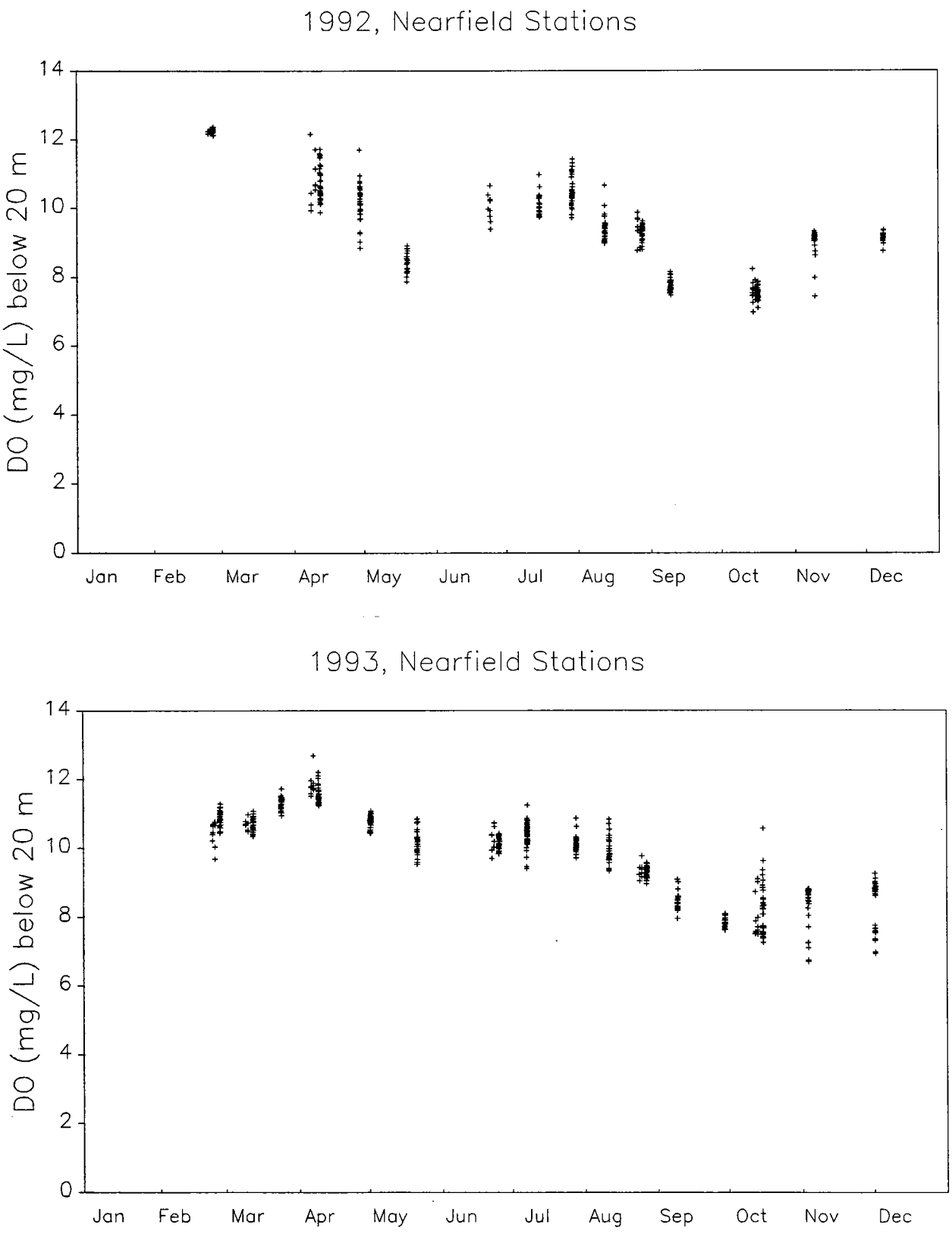


Figure 6-2. Comparison of the nearfield region in 1993 to the annual cycle of 1992: dissolved oxygen (mg/L).

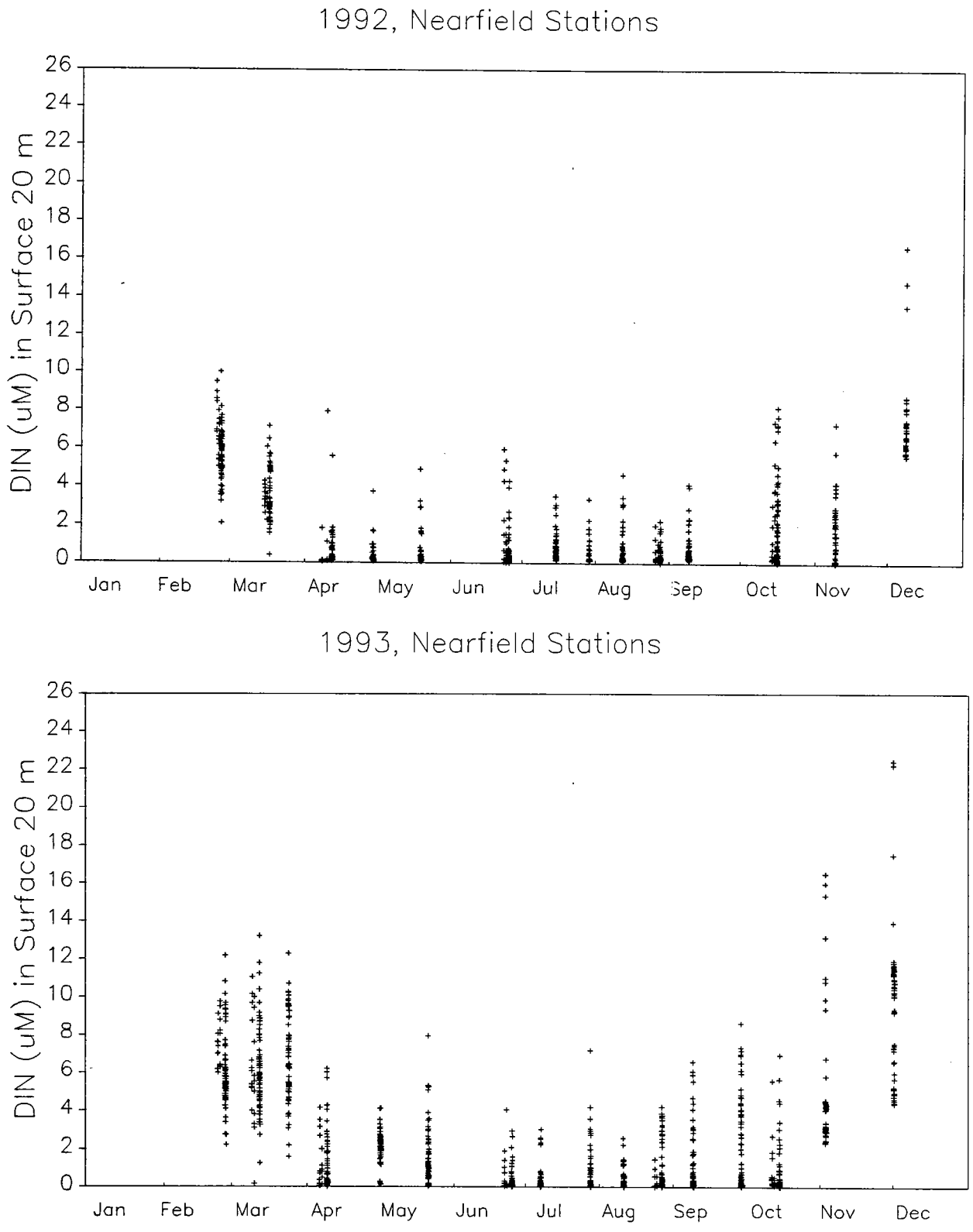


Figure 6-3. **Comparison of the nearfield region in 1993 to the annual cycle of 1992: dissolved inorganic nitrogen (μM).**

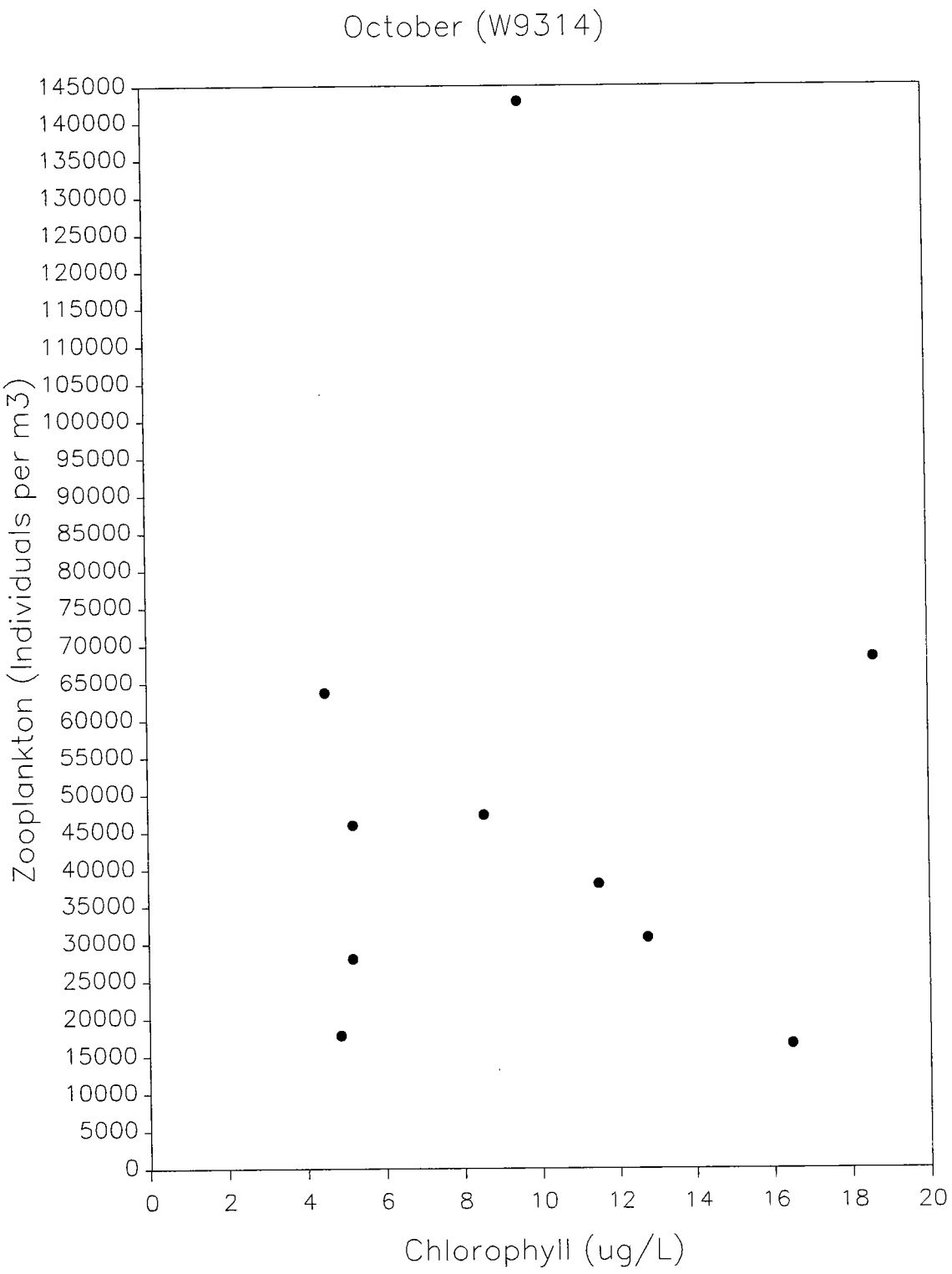


Figure 6-4. **Zooplankton abundance compared to the average chlorophyll concentration (extracted samples; n=2 depths) for October 1993.**

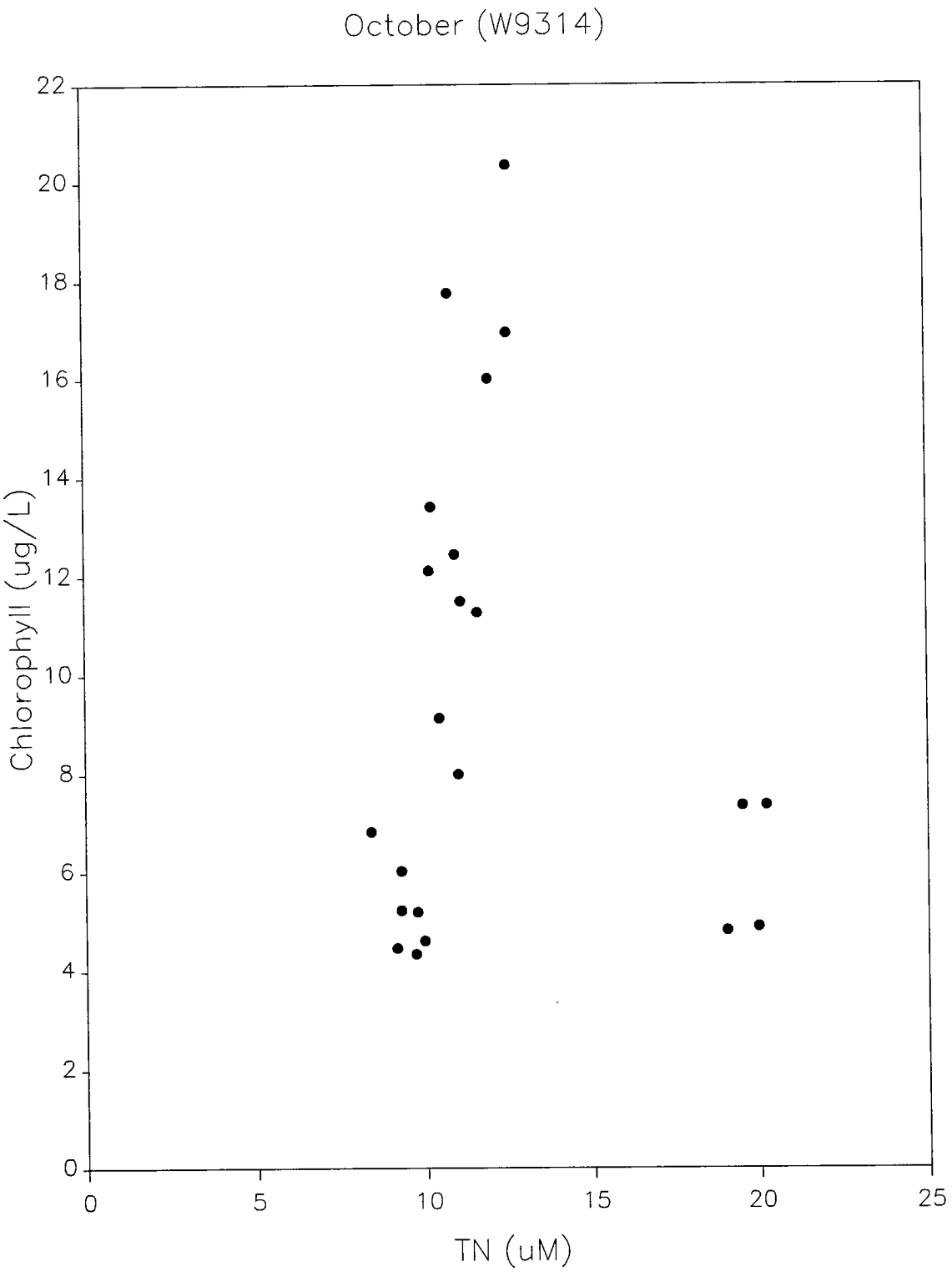


Figure 6-5. Chlorophyll and total nitrogen in samples from October 1993.

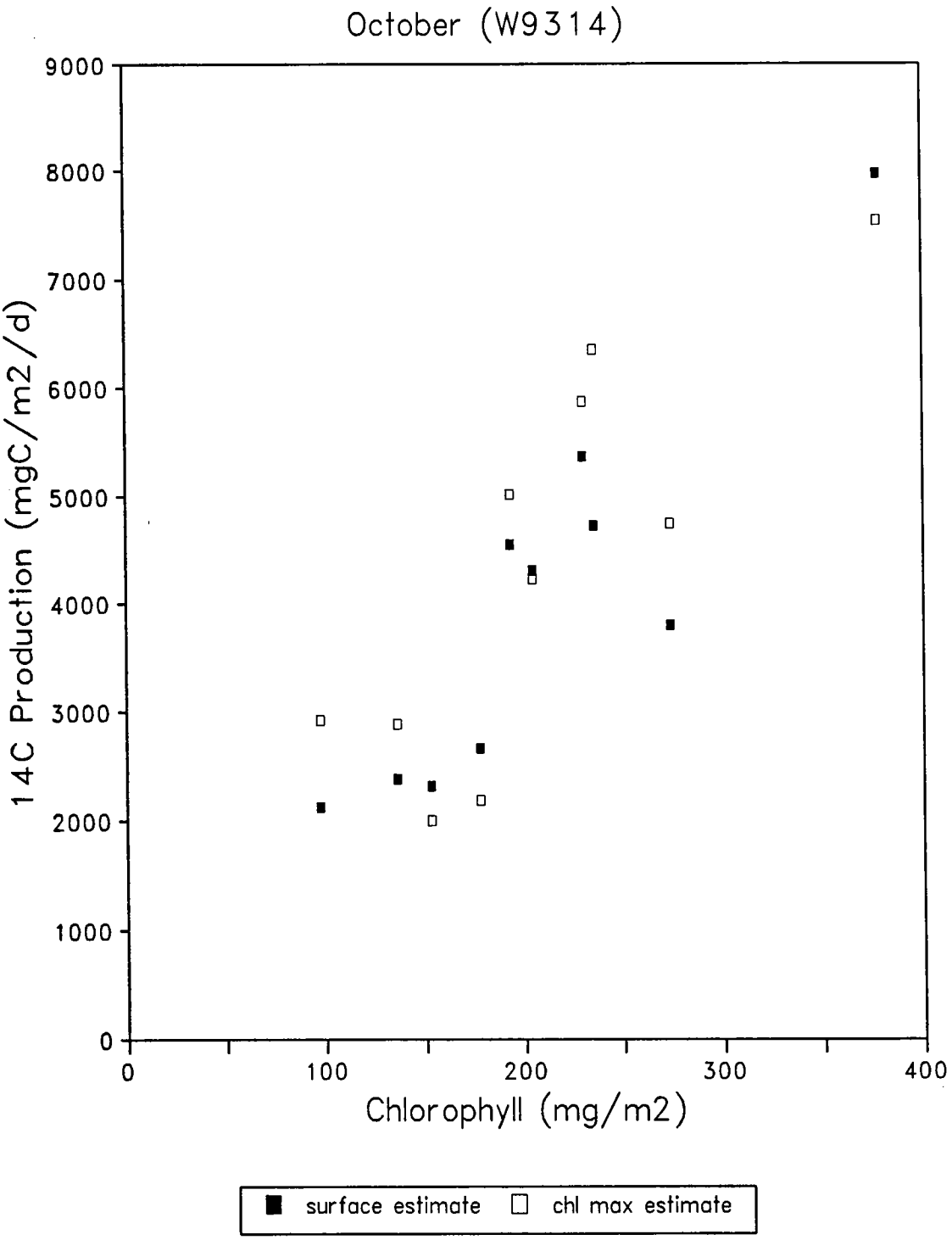


Figure 6-6. **^{14}C production compared to integrated chlorophyll in samples from October 1993. Production and integrated chlorophyll calculated over the photic zone ($Z_{0.5\%Io}$).**

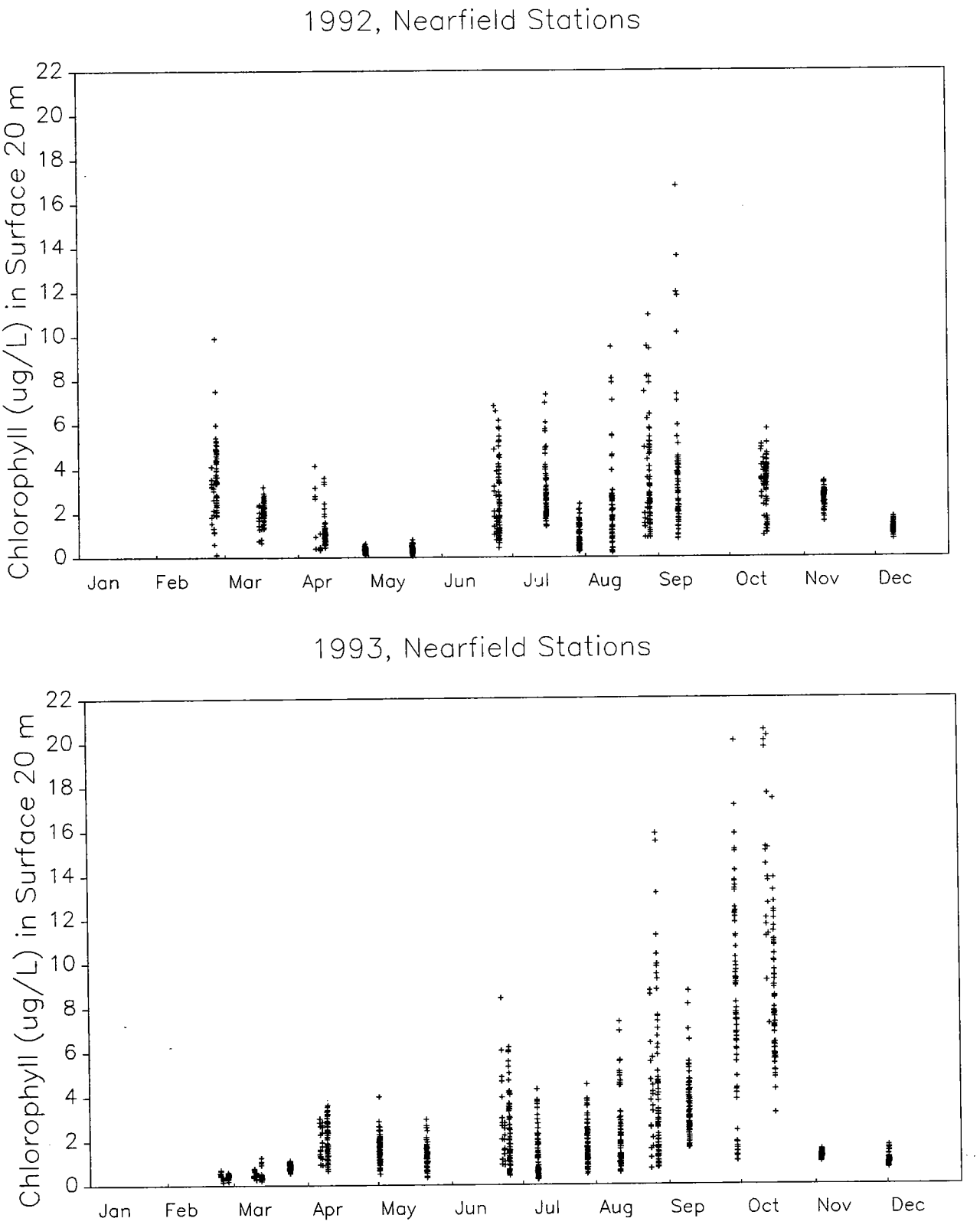


Figure 6-7. Comparison of the nearfield region in 1993 to the annual cycle of 1992: chlorophyll (μg/L). Chlorophyll is estimated from *in situ* fluorescence.

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