Water quality monitoring in Massachusetts and Cape Cod Bays: April and May 1993.

Massachusetts Water Resources Authority

Environmental Quality Department
Technical Report Series No. 94-3

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FINAL REPORT

WATER QUALITY MONITORING
IN
MASSACHUSETTS AND CAPE COD BAYS:
APRIL AND MAY 1993

by

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EXECUTIVE SUMMARY

This report is the second 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 April and May 1993; each of these surveys included sampling at 21 stations in the nearfield area. The early April 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 the early April combined survey was the presence of a cell of cool, saline water located in the nearfield region and extending to the southeast. This water mass was weakly stratified and depleted in nutrients relative to the surrounding waters. To the west, the coastal surface-water mass was warmer, fresher, and highly enriched with nutrients, while to the north and east, the offshore surface waters were warmer, less saline (though not as fresh as the coastal waters), and had intermediate nutrient concentrations. The development of the surface lens in the coastal and offshore regions resulted from spring runoff and coastal outflows from Boston Harbor and rivers to the North. The nearfield cell of cool, saline water results from the mixing of coastal and/or offshore surface waters with the offshore bottom waters. However, the nearfield nutrient regime did not result from the physical mixing of these water masses, but rather, resulted from biological utilization. It is suggested that in early April nitrogen advected into the nearfield region was being actively removed from the water column.

Another feature observed during this period of surveys was the seasonal development of strong thermal and density stratification in the nearfield region. As mentioned above, the region was influenced by less saline water from coastal and northeastern offshore sources that resulted in mild stratification due to the vertical gradients in salinity, but generally stratification was weak in early April. These conditions persisted into May. A period of rapid surface warming over a three week period led to the development of the well-defined stratification observed in late May. Thermal distribution, rather than salinity variations with depth, primarily regulated the seasonal development of stratification in the nearfield region in May.

Several key monitoring parameters - nutrients, dissolved oxygen (DO), chlorophyll, and phytoplankton (at the surface of station N10P) - were measured on each of the three surveys. Other key parameters - phytoplankton, zooplankton, and water column metabolism (production) - were only measured at the 10 "BioProductivity" stations during the farfield survey in early April. Specific findings for each of the key parameters during the April-May 1993 period are summarized as follows:

- Nutrients - There were strong inshore-offshore gradients in surface nutrient concentrations in early April. These gradients were most evident near the Harbor and were observed for all of the nutrients measured - nitrogen forms, phosphate, and silicate. There was a strong relationship between nutrient concentrations and salinity. Both low salinity surface waters and high salinity bottom waters had high nutrient concentrations. Nitrate was nearly depleted throughout the water column at most of the nearfield stations. Surface concentrations of phosphate and silicate were low but did not achieve the same level of depletion as nitrate and both increased with depth (to

~0.5 and ~5 μM, respectively). By early May, because of an increase in surface nutrient concentrations, the inshore-offshore nutrient gradient in the nearfield was no longer very well defined.

- Dissolved oxygen (DO) - Surface waters were supersaturated with oxygen during this period of surveys. There was a decrease in DO, as percent saturation, with depth during each of the surveys, but saturations were only slightly below 100% even in the deep waters in Stellwagen Basin. In early April, peak oxygen values (~120%) were observed near the approximate depth of the chlorophyll maximum.

- Chlorophyll - In the nearfield, there was a decrease in chlorophyll concentrations from early April to late May. This was concomitant with a change from a mottled distribution of chlorophyll closely associated with the pycnocline in early April to a more uniform distribution of chlorophyll generally highest in the surface layer by late May. During the early April survey, it was noted that for several nearfield stations the subsurface chlorophyll maximum decreased over time. This, in conjunction with the presence of high concentrations of chlorophyll near the pycnocline and depletion of DIN in the surface layer, may have signaled the beginning of the cessation of the spring bloom in Massachusetts Bay.

- Phytoplankton - Despite the distinct water quality differences across regions of Massachusetts Bay that were observed during the early April survey, the plankton community composition was generally quite homogeneous. Several diatoms and copepods were consistently the dominant species. Diatoms, *Chaetoceros* spp. and *Thalassiosira* (cf.) *gravida/rotula*, were numerically dominant at all stations except the Harbor-edge station, F23P. The dominant taxa also included microflagellates and cryptomonads, which were the most abundant taxa at station F23P. In the screened (>20 μm) samples, the assortment of taxa and individual counts were similar between Massachusetts and Cape Cod Bays. At station N10P, the surface whole-water phytoplankton samples continued to be dominated by diatoms into early May. By the late May survey, however, the dinoflagellate *Heterocapsa triquetra* was the dominant species, along with microflagellates and cryptomonads. As the winter-spring diatom bloom ended and seasonal stratification developed, the phytoplankton community at station N10P changed to a mixed-flagellate, reduced diatom community that is typical of summer stratified conditions. By the early May survey, a similar increase in dinoflagellates was observed in the screened phytoplankton samples. Seasonal changes in the phytoplankton community were more distinct than regional differences during the winter-spring bloom.

- Zooplankton - Zooplankton abundance ranged from about 5,000 to 30,000 individuals m^{-3} and was dominated by copepods and their nauplii. As with phytoplankton, the zooplankton community was generally quite similar throughout the Bays. *Oithona similis* was the dominant copepod. *Oikiopleura dioica*, an appendicularian, was also abundant at most stations. Stations N16P and N20P, located in the middle of the nearfield, had a slightly different zooplankton community. The highest abundances of *O. dioica* were observed at these stations and *Acartia hudsonica*, which was found at all the other stations, was not present. The differences observed in the zooplankton community correspond with the variations in physical, chemical, and biological parameters noted previously for this region. Total zooplankton counts were generally correlated with chlorophyll concentrations and phytoplankton counts.

- Metabolism - Estimated production rates were significantly higher in Massachusetts Bay (~3 gC m^{-2} d^{-1}) compared to Cape Cod Bay (~1.5 gC m^{-2} d^{-1}). At each station, production estimates varied by up to a factor of 4 between calculations made using the P-I curve for surface vs. chlorophyll maximum incubations. There was no consistent trend toward higher production estimates based on either incubation. Primary production rates and chlorophyll concentrations were not closely correlated (r^2=0.163). There were no obvious production-water quality associations.

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: APRIL AND MAY 1993".

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1.0 INTRODUCTION

This report is the second 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 April and May of 1993; each of these surveys included sampling at twenty-one stations in the nearfield area. The early April 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 (early April farfield/nearfield survey, late April/early May nearfield survey, late May nearfield survey).
Section 6.	Discussion of the late spring period of surveys.

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

1.1 Background

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

To help establish the present conditions with respect to water properties, nutrients, and other important parameters of eutrophication, the MWRA contracted with Battelle Ocean Sciences to conduct baseline water-quality surveys throughout Massachusetts Bay during 1992 to 1994. Results of the 1992 surveys were presented in a series of three reports similar to this report (Kelly *et al.*, 1992; Kelly *et al.*, 1993a,b), summarized in an annual report (Kelly *et al.*, 1993c), and used to examine nutrient issues related to the offshore outfall (Kelly, 1994). The first periodic water column report for 1993 covered surveys conducted during February and March (Kelly *et al.*, 1993d).

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

1.2 Survey Objectives

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

Physical Oceanography

- Obtain high-resolution measurements of water properties throughout Massachusetts Bay.
- Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in water properties, and to provide supporting data to help interpret biological and chemical data.
- Use high-resolution, near-synoptic, water-property measurements along transects within the nearfield area for analysis of smaller-scale spatial (kilometers) and temporal

(semi-monthly) variability in water properties, and develop a three-dimensional picture of water properties near the future outfall.

Nutrients

- Obtain nutrient measurements in water that is representative of Massachusetts and Cape Cod Bays.
- Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in nutrient concentrations and to provide supporting data to help to interpret biological data.
- Use vertical-profile data along transects of closely-spaced stations within the nearfield area for analysis of smaller-scale spatial (kilometers) and temporal (semi-monthly) variability in nutrient concentrations, and develop a three-dimensional understanding of the nutrient field near the future outfall.

Plankton

- Obtain high-quality identification and enumeration of phytoplankton and zooplankton in water that is representative of Massachusetts and Cape Cod Bays.
- Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in plankton distribution.

Water Column Respiration and Production

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

General

- Evaluate the utility of various measurements to detect change or to help to explain observed change.
- Provide data to help modify the monitoring program to allow a more efficient means of attaining monitoring objectives.
- Use the data appropriately to describe the water-quality conditions (over space and time) in Massachusetts and Cape Cod Bays.

1.3 Survey Schedule for 1993 Baseline Water Quality Monitoring Program

Throughout 1993 and 1994, Battelle and its subcontractors, the University of Rhode Island (URI) and the University of Massachusetts at Dartmouth (UMD), are conducting surveys similar to those initiated in 1992. The schedule of surveys in 1993 is given in Table 1-1. The survey schedule was designed to match the schedule conducted in 1992. The surveys discussed in this report were conducted during the weeks planned: April 6-10 (Survey W9304), April 29 - May 1 (Survey W9305), and May 20-21 (W9306).

1.4 Summary of Accomplishments: Early April to Late May 1993

For the combined farfield/nearfield survey in early April (W9304), *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 a nearfield survey was dedicated to high-resolution "tow-yo" profiling. A towfish containing *in situ* sensors (as above, minus irradiance) was performed along nearfield tracks set between the vertical stations with the towfish oscillating from near surface to near bottom as the ship progressed at 4 to 7 kt. An example trackline from survey W9306 is provided in Figure 1-2.

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

Table 1-1. Schedule of water quality surveys for calendar year 1993. This report provides data from the surveys conducted from April through May 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

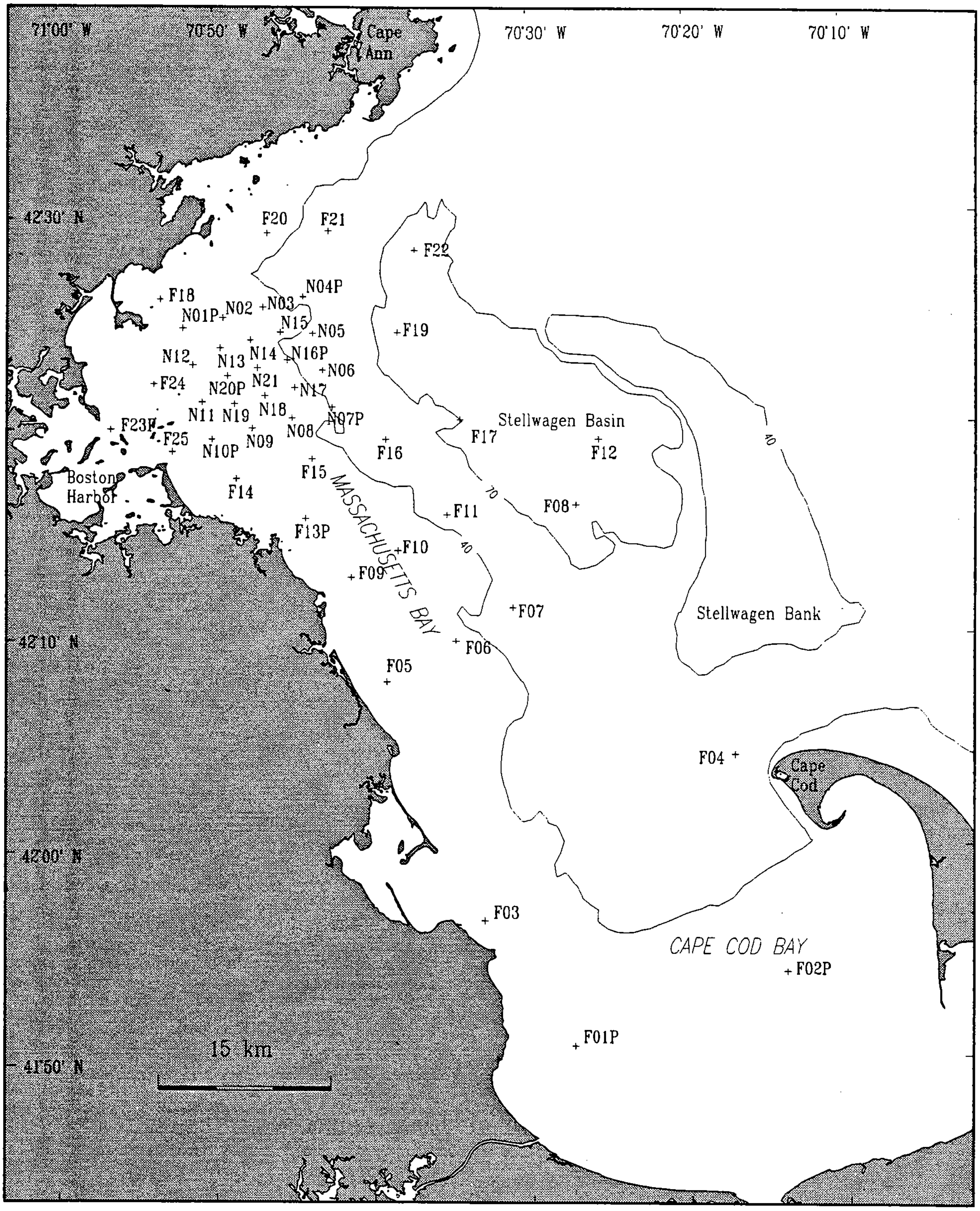


Figure 1-1. Water quality sampling stations in Massachusetts and Cape Cod Bays. Station codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Depth contours are in meters.

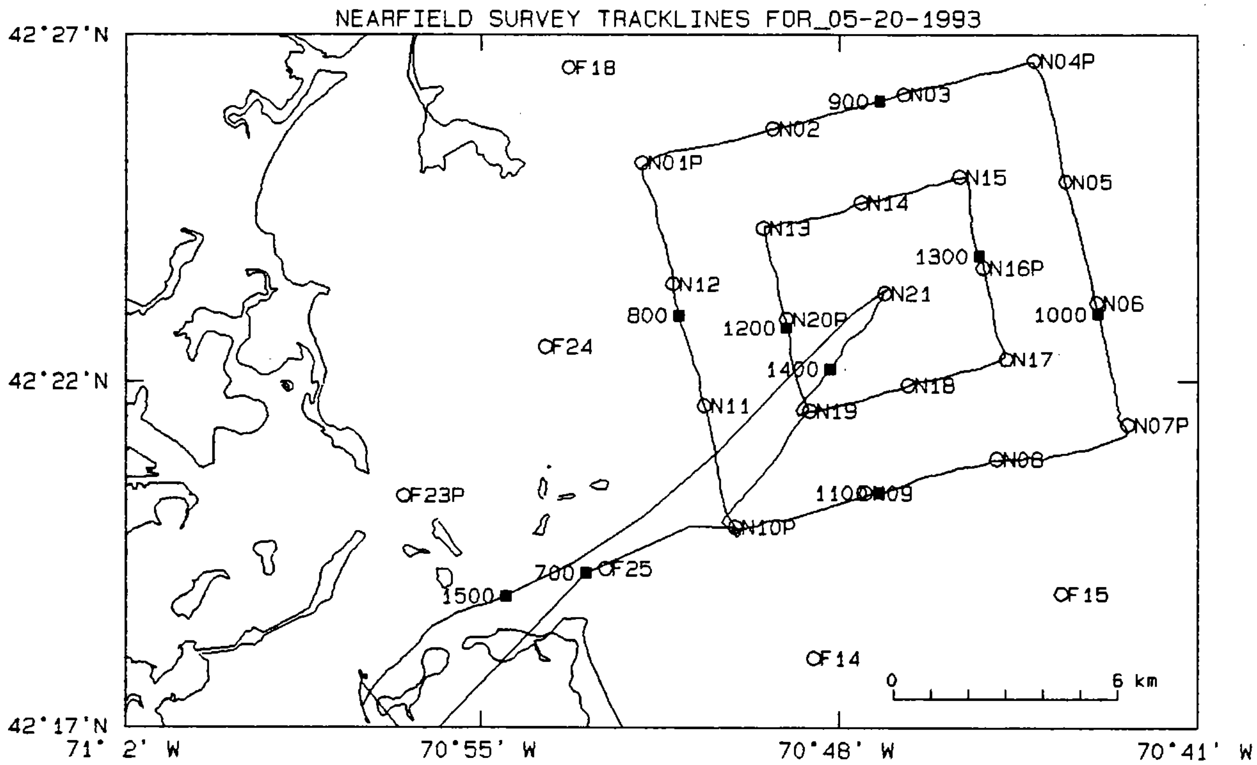


Figure 1-2. Nearfield survey tracklines for May 20, 1993. Tow-yo operations were conducted clockwise from N10P to N10P, N19 to N19, and N19 to N21. The hour of the day is indicated (700-1500) along the track.

2.0 METHODS

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

2.1 Field Procedures

2.1.1 Hydrographic and Water Sampling Stations

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

In addition to the procedures described in the CW/QAPP, the following methods were used for the combined farfield/nearfield survey in early April (W9304):

- 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). Total suspended solids, in addition to chlorophyll, was sampled at station F25, as well as at planned stations.
- Nutrient samples for stations F17 and F19 were improperly labeled and their location could not be validated as to location. Thus, values are not reported.

In addition to the procedures described in the CW/QAPP, the following methods were used for the nearfield survey in late April/early May (W9305):

- Tow-yo sampling (April 29) was completed over only 70% of the planned trackline. The interruption was caused by a sudden malfunction of the CTD.
- Dissolved oxygen samples were collected at six "P" stations at five depths and were used to calibrate the dissolved oxygen sensor (Appendix A).

In addition to procedures described in the CW/QAPP, the following methods were used for the nearfield survey in late May (W9306):

- Only 20 of 21 stations (no station N18) were sampled on the vertical profiling day. No near-bottom nutrient samples were obtained at stations N10P and N06.
- Dissolved oxygen samples were collected at six "P" stations at four or five depths and at mid-depth at station N17, and used to calibrate the dissolved oxygen sensor (Appendix A).

2.1.2 Productivity Measurements

Productivity measurements differ slightly from those described in the CW/QAPP. First, at the request of the MWRA and 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).

2.2 Laboratory Procedures

Table 2-3 summarizes laboratory methods for chemistry and biology samples as detailed in the CW/QAPP. The dissolved inorganic carbon (DIC) method was not described in the CW/QAPP. The

DIC analysis used by URI is a "purge-and-trap" method (I.O. Corp., 1984). Samples are collected in a 40-mL screw-cap VOC vial with a septum. The bottle is filled and overflown, the sample is then "killed" with mercury chloride, and the bottle is sealed. In the laboratory, the vial is placed in a total carbon analyzer where the vial septum is pierced. A sample is then withdrawn, acidified, bubbled with nitrogen (N_2) and the carbon dioxide (CO_2) in the gas stream is caught on a molecular sieve. The sieve is heated to 200°C, releasing the CO_2 into a new stream of N_2, the carrier gas that transports the CO_2 to an IR detector where the CO_2 content is measured.

The difference between analytical replicates, estimated from samples taken and reported in the first periodic report (Kelly *et al.*, 1993d), averaged less than 1% ($\bar{x} \pm \sigma$ = 0.47% ± 0.73%, range = 0.08-2.68%, n = 12). The average difference between sample replicates from a GO-FLO bottle was less than 1% ($\bar{x} \pm \sigma$ = 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). Suspect values were determined by statistical testing rather than by professional judgement, as in the first periodic report (Kelly *et al.*, 1993d).

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

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

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

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

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

X_3 and *X_1* are calculated for each set of three dark bottles replicates. When *X_3* or *X_1* exceeds the tabled value of 0.941 for n=3, the outlier is rejected and not used in calculations. Appendix E provides results of testing for survey W9304.

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

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

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

P_B = production (chlorophyll-normalized) and

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

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

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

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

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

P_{max} = light saturated maximal productivity

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

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

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

Volumetric production rates, chlorophyll-normalized P-I curves, and model coefficients (Appendix E), were used to calculate integrated water column rates of production. 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_0. 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 [from 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	10 Biology/ Productivity and 3 Nearfield	300 mL	300 mL glass BOD	Fix per Oudot *et al.* (1988). Titrate within 24 h.
Dissolved Organic Carbon	10 Biology/ Productivity and F25	50 mL	100 mL amber glass bottle	Pass through a pre-ashed glass fiber filter. Fix with 0.5 mL of phosphoric acid.
Dissolved Organic Nitrogen	10 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 h.
Dissolved Organic Phosphorus	10 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 h.
Particulate Organic Carbon	10 Biology/ Productivity and F25	50 mL	Whatman GF/F glass fiber filter	Pass through a pre-ashed glass fiber filter. Freeze (-5 °C).
Particulate Organic Nitrogen	10 Biology/ Productivity and F25	50 mL	Whatman GF/F glass fiber filter	Pass through a pre-ashed glass fiber filter. Freeze (-5 °C).
Total Suspended Solids	10 Biology/ Productivity and 3 Nearfield	200 mL	Petri dish	Pass through a filter. Freeze (-5 °C)
Chlorophyll *a*/ Phaeopigments	10 Biology/ Productivity and 3 Nearfield	2 x 10 mL	Whatman GF/F glass fiber filter	Pass through filter. Fix with 1% $MgCO_3$ solution, wrap in foil, store over desiccant, and refrigerate.
Phytoplankton (Whole Water)	10 Biology/ Productivity	800 mL	1000 mL glass bottle	Preserve with Utermohl's solution.
Phytoplankton (Screened Water)	10 Biology/ Productivity	2000 mL	100 mL polyethylene bottle	Strain through a 20-µm mesh; wash retained organisms into a jar. Fix with Utermohl's solution.
^{14}C Production	10 Biology/ Productivity	300 mL	300 mL glass BOD	Inoculate with 2.5 µCi of $Na_2{}^{14}CO_3$ and incubate.
Following sample is collected with a vertically towed net				
Zooplankton	10 Biology/ Productivity	800 mL	1000 mL glass bottle	Wash into jar. Fix with a 5-10% formalin solution.
The following measurements are collected by the Battelle Ocean Sampling System				**Precision**
Conductivity	All	---	Floppy disk	0.01 mS/cm
Temperature	All	---	Floppy disk	0.001 °C
Pressure	All	---	Floppy disk	0.01 decibars
Dissolved Oxygen	All	---	Floppy disk	0.05 mg/L
Chlorophyll *a* Fluorescence	All	---	Floppy disk	0.01 µg/L
Transmissometry	All	---	Floppy disk	0.01 m^{-1}
In situ Irradiance	All	---	Floppy disk	1 µE m^{-2} s^{-1}
Surface Irradiance	All	---	Floppy disk	1 µE m^{-2} s^{-1}
Bottom Depth	All	---	Floppy disk	1 m
Navigational Position	All	---	Floppy disk	0.000017 deg

Table 2-2. Water samples to be collected from Niskin or GO-FLO bottles [from Albro et al., *1993].*

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

Notes:

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

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

Parameter	*Units*	*Method*	*Reference*[1]	*Maximum Holding Time*	*Preservation*
Dissolved Ammonia	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Nitrate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Nitrite	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Phosphate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Silicate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Oxygen	mg L^{-1}	Autotitrator	Oudot *et al.* (1988)	24 h	dark/cool
Dissolved Organic Carbon	μM	O.I. Model 700 TOC Analyzer	Menzel and Vaccaro (1964)	3 mo.	Fix with 0.5 mL of phosphoric acid.
Dissolved Organic Nitrogen	μM	Technicon II AutoAnalyzer	Valderrama (1981)	3 mo.	Add reagents immediately, heat to 100°C within 8 hours.
Dissolved Organic Phosphorus	μM	Technicon II AutoAnalyzer	Valderrama (1981)	3 mo.	Add reagents immediately, heat to 100°C within 8 hours.
Particulate Organic Carbon	μM	Carlo Erba Model 1106 CHN elmental analyzer	Lambert and Oviatt (1986)	3 mo.	Dry over desiccant.
Particulate Organic Nitrogen	μM	Carlo Erba Model 1106 CHN 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 EARLY APRIL 1993 COMBINED FARFIELD/NEARFIELD SURVEY (W9304)

3.1 Farfield Survey

3.1.1 Horizontal Distribution of Surface Water Properties

Surface water temperatures at sampling stations throughout Massachusetts and Cape Cod Bays in early April 1993 ranged from about 2.2 to 4.2 °C (Figure 3-1). Many shallow-water locations near the coast had surface temperatures at the higher end of this range (above 3.6 °C). The northeast Massachusetts Bay stations were roughly the same temperature as Cape Cod Bay stations (about 3.4 to 3.6 °C). The most interesting feature was a cell of colder water (< 3.0 °C) centered in the nearfield region, but stretching from west to east across much of Massachusetts Bay.

The distribution of salinity in surface waters (Figure 3-2) exhibited a pattern generally similar to the temperature distribution (Figure 3-1). For example, a group of coastal stations running south from Boston Harbor were all lower in salinity (< 30 PSU). The fresher water was observed at or near the edge of Boston Harbor (stations F23P, F24, F25). There was a strong gradient of increasing salinity from the Boston Harbor area across the nearfield region in western Massachusetts Bay, but also a cell of higher salinity stretching from the nearfield to the east over Stellwagen Basin. To the north, a tongue of lower salinity (< 30 PSU) surface water was evident, with fresher water apparently intruding down the axis of Stellwagen Basin and perhaps across the northeast edge of the nearfield (station N04P). The salinity in Cape Cod Bay was generally higher than coastal waters but lower than offshore waters of mid-Massachusetts Bay.

Beam attenuation suggested a decreasing gradient from shore and more turbid waters close to the coast south of Boston (Figure 3-3). Lowest values were observed where salinity was high, in open deeper waters of Massachusetts Bay. Chlorophyll fluorescence in surface water ranged from about 0.4 to 2.7 μg L^{-1} (Figure 3-4), with the highest reading made at the northwest corner of the nearfield (station N01P). The fluorescence pattern was generally similar to the distribution of beam attenuation — the main feature being that near-coastal values (although patchy) were graded to lower values offshore. Surface fluorescence at station F02P in Cape Cod Bay was similar to that at the coastal group of stations.

The trend, from shore to sea, for dissolved inorganic nitrogen (DIN) was striking (Figure 3-5). The highest concentrations were found at the edge of Boston Harbor and extended to the western edge of the nearfield as well as southward down the coast. This spatial pattern resembled temperature, salinity, beam attenuation, and chlorophyll patterns. Lowest DIN values (< 1 μM) were measured in the colder, more saline cell within the nearfield and stretching offshore to the southeast. DIN concentrations at northeastern stations were intermediate (1-2 μM). Relatively high values (2-5 μM) were noted at the eastern side of Cape Cod Bay (stations F02P and F04).

Interestingly, at station F02P most of the DIN was nitrate (NO_3) (Figure 3-6). In contrast, nitrate was undetectable in surface waters of many offshore stations (Figure 3-6) in Massachusetts and Cape Cod Bays, other than along the coast. Ammonia (NH_4) was a significant fraction of the DIN at most coastal stations and comprised virtually all of the DIN at the northeast Massachusetts Bay stations (F21 and F22).

Phosphate (PO_4) concentrations, like DIN, were slightly higher near the Harbor, low in the nearfield, and intermediate in northeastern Massachusetts Bay and in Cape Cod Bay (Figure 3-7). Silicate (SiO_4) generally followed this trend also, but concentrations were higher (5-6 μM) in northeast Massachusetts Bay than at the surface of any Cape Cod Bay stations (3-5 μM) (Figure 3-8).

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 most stations were slightly stratified, with fresher and warmer water in a shallow surface layer. The sharpness and depth range of the thermocline, halocline, and pycnocline varied across stations. On inspection, it was noted that stratification was generally less developed at Cape Cod Bay stations than at most stations in Massachusetts Bay.

Throughout the bays, the vertical thermal gradients were rather small (1-3 °C); this is evident in the transect sections of temperature shown in Figure 3-10a. The main feature suggested by this series is the presence of a cooler mass of water throughout the bottom water in most areas; however, in the middle of the nearfield and just southeast (F15-F16 of Cohasset transect) this cool bottom water extended much closer to the surface. A cool surface cell has already been suggested in this area (Figure 3-1).

Salinity sections (Figure 3-10b) show more surface layering across the northern transect, radiating outward in surface waters from Boston Harbor and along the coast as far as the Marshfield transect. Note that the middle of the nearfield (N20P-N16P), just south (F15-F16), and further southeast (F07-F08) is where more saline waters are found at the surface, apparently segregating a fresher surface lens inshore from a separate fresher, surface layer in deeper offshore water. With the small temperature range, salinity is influential in determining density stratification and the density sections look remarkably similar to salinity (Figure 3-10c).

With the exception of the Harbor station (F23P), a subsurface maximum was generally observed for chlorophyll fluorescence (Figure 3-11). Comparison of density sections (Figure 3-10c) with chlorophyll suggests that highest chlorophyll accumulations were found at sharp density interfaces near the top of the bottom water layer. The locations of highest subsurface chlorophyll concentration were at stations with water depths greater than 30 m. The middle of the nearfield was one of these regions; note that across the stations N20P-N16P-F19 of the Boston—nearfield transect, the depth of the chlorophyll maximum seemed to follow density contours. Beam attenuation did not show patterns similar to fluorescence and also showed less patchiness (Figure 3-12). However, the trend of higher beam attenuation at coastal and near-Harbor stations was strongly evident.

Dissolved oxygen (DO), as percent of saturation, was not less than 95% in the deepest bottom waters of Stellwagen Basin (F08 and F12) (Figure 3-13). Surface waters appeared to be greater than 105% saturated with oxygen, except at the edge of the Harbor. With that exception, it is striking that the highest oxygen saturation (>110%) was found where a relatively intense subsurface chlorophyll maximum had been detected (cf. Figure 3-11) and thus, for the most part, above a sharp, but shallow, pycnocline.

With the exception of lighter (less dense) Boston Harbor water near the surface (F23P-F24), and along the coast to the south (F14 and F05), the surface waters were low in DIN (Figure 3-14a). Silicate also showed higher values near the Harbor, but was quite low in offshore surface waters having high surface layer DO concentrations and peaks of subsurface chlorophyll. DIN and silicate were still relatively high in deeper offshore bottom waters (Figure 3-14b).

3.1.3 Analysis of Water Types

As suggested above, there were some distinct surface-water regions of the bays, judged by physical, biological, and geochemical parameters (Figure 3-15). These distinctive regions included the Harbor-coastal waters, the nearfield-offshore area, the northeast transect in Massachusetts Bay, and eastern Cape Cod Bay (cf. Figure 3-16 for standard station groupings). In addition to surface waters, the deeper offshore locations (especially greater than 30 m) were beginning to show the normal seasonal physical stratification that includes a surface layer of nutrient-depleted water with nutrient concentrations increasing with depth. Thus, there were both identifiable horizontal and vertical water quality distinctions in early April.

Some physical distinctions were evident in spite of small ranges in parameter values. For example, the range of temperature throughout the depths measured in the Bays was only a few degrees Celsius (Figure 3-15a) and most temperature profiles were quite similar at similar salinity. In general, the most saline waters (> 32 PSU) were found at greatest depths and these were also the coldest waters, illustrated by the general convergence of points at higher salinity in Figure 3-15a. Cape Cod Bay stations had little vertical variability in temperature and salinity (Appendix C) and, as discussed above, showed weakest stratification. For Massachusetts Bay stations, some divergence in the temperature-salinity relationship was noted at lower salinity, creating some of the distinctive features of the surface water masses; but, as shown above, the shallower waters or surface waters of lower salinity were warmer. The data suggest, in part, a nearshore warming and freshening due to spring runoff and coastal outflows (Boston Harbor). Additionally, rivers from the North helped initiate the slight stratification in the northeast-offshore area of Massachusetts Bay noted in early April.

Generally, the lower salinity water often carried higher turbidity as measured by beam attenuation (Figure 3-15a). High beam attenuations ($>3\ \mathrm{m^{-1}}$) were observed at station F22 (see Appendix B) and were the result of sampling the near-bottom nepheloid layer. Except for station F22, beam attenuation above a salinity of 31 PSU showed very little variation. Excluding the area around Boston Harbor, this parameter was not useful in characterizing water masses.

The relationship between beam attenuation and chlorophyll was poor in early April (Figure 3-15a). Beam attenuation increased slightly with chlorophyll in some cases (e.g., around the edge of Boston Harbor), but viewed in total, locations having chlorophyll above 1-2 μg L^{-1} did not show a concomitant rise in beam attenuation. (Figure 3-15a). At many stations, the overall vertical feature was low chlorophyll concentrations (0.5 to 1.5 μg L^{-1} mostly) at the surface. Peak concentrations were most commonly observed in mid-waters between 5 and 25 m (Figure 3-15b). The highest mid-water concentrations (> 3 μg L^{-1}) were found, not in Cape Cod Bay as observed earlier in the year, but at some coastal and offshore stations in Massachusetts Bay. Fluorescence readings at many offshore Massachusetts Bay, as well as northern transect stations, were above 1.5 μg L^{-1} from 25 to 60 m and thus were often higher than readings in surface waters (Figure 3-15b and Appendix C).

The DO composite of all station profiles generally suggests a strong trend of decreasing saturation with depth (Figure 3-15b). Values near 110-120% saturation were common near the surface; deep bottom waters were near or slightly below 100% saturation. Some station profiles suggested peak oxygen values in mid-waters at the approximate depths where high chlorophyll accumulations were measured, and slightly lower saturation at the surface and below this depth (Appendix B, C). The location not confirming to this pattern was the shallow coastal area north and south of the Boston Harbor mouths, where stations each showed a more uniform vertical profile, supersaturated, and usually in the range of 100-110% saturation (Appendix C).

The relationship between DIN and phosphate was highly constrained and similar in all regions and at all depths, with the exception of the coastal stations (Figure 3-16). Figure 3-17 shows the N/P trend generally following a Redfield proportionality (16N:1P), but with an intercept — i.e., detectable P at virtually undetectable N. This pattern, regularly observed in the bays, creates different dissolved N/P ratios depending on the overall level of enrichment. Many samples from the coastal stations exhibited relatively higher N at a given P concentration and these samples, thus, lie above the main trend of data points shown in Figure 3-17. A few nearfield stations, which receive some of the coastal water from Boston Harbor, are included in this nitrogen enriched group. It was noted that NO_3 alone, as well as DIN, was an indicator that discriminated many of the coastal samples (Figure 3-17). Also, with respect to the NO_3/PO_4 pattern, most nearfield, as well as some offshore points, fell below Cape Cod Bay points because ammonium was a substantial fraction of the DIN found offshore and particularly in the nearfield (as discussed previously).

The pattern for DIN relative to silicate offered slightly different insight into the water quality conditions in different regions of the bays (Figure 3-18). As with phosphate, silicate was still present when DIN has been essentially removed. Samples from coastal stations, although having elevated concentrations of both nutrients, fell roughly on the same trend line (e.g., approximately 1 atom of N to 1 atom of Si) as most nearfield samples, which were additionally similar to Cape Cod Bay samples. At a few offshore stations, northern transect stations, and nearfield stations (principally the near-bottom waters, see Appendix A), relatively high silicate was detected for a given nitrogen concentration; thus, these stations fall at or below a N/Si ratio of 1:2 (Figure 3-18). Distinctions are less clear if only nitrate vs. silicate is examined (Figure 3-18), but it is apparent that silicate was detectable (over a broad range in concentrations) at virtually undetectable nitrate concentrations at many nearfield stations.

Nutrient-salinity plots have been useful in distinguishing water mass character and for inferring dispersion of nutrients. Plots of these relationships are presented in Figures 3-19 to 3-22. DIN vs. salinity repeats an often-observed pattern of high DIN at low salinity (generally coastal or surface nearfield water), low DIN at intermediate salinity and high DIN at the highest salinity (generally deep water). Coastal-type surface water and offshore-type deep water are found in the nearfield, in addition to an intermediate salinity—low DIN condition that is unique to the nearfield and is clearly not just a mixing of the coastal- and offshore-type waters. Note that low salinity northern transect water is lower in DIN concentrations than coastal water and Cape Cod Bay water, and that northern transect high salinity water is relatively high in DIN. NH_4 was present in significant concentrations ($>1\ \mu M$) at portions of all regions and depths, and thus lacks a strong pattern with salinity (Figure 3-20). The pattern of nitrate serves to illustrate the major distinctions — coastal water with low salinity and high nitrate, Cape Cod Bay and northern transect water with high salinity and high nitrate compared to the other offshore stations, and the main body of water in the nearfield having intermediate salinity but depleted nitrate.

Both phosphate and silicate show striking overall trends with salinity that are similar to DIN (Figure 3-21). The regional differences in these nutrients, relative to DIN, have been described above. Using DIN, plus other forms of nitrogen measured at the select group of BioProductivity stations (and special station F25), strong patterns with salinity are evident, suggesting some mixing of water and nutrients into the nearfield (Figure 3-22). A slight curvature, at intermediate salinity (about 30 to 31.5 PSU, especially with Total N), from an otherwise linear relationship, could suggest an active nitrogen sink (settling from surface waters) within the nearfield region at this time. Total nitrogen concentrations of the Cape Cod Bay samples were in the range of total nitrogen concentrations measured in the coastal and nearfield samples in spite of a more prolonged chlorophyll bloom that started earlier in the year in Cape Cod Bay (Kelly *et al.*, 1993d).

In summary, a number of regional water mass distinctions were evident in surface waters in early April. One major feature isolating regional water masses was the presence of a cell of cool, low nutrient water having weakly defined vertical stratification. This cell of cool water was located in the nearfield (and extending to the southeast) between a coastal water mass and an offshore water mass. Coastal waters and deep bottom waters generally were highly enriched with nutrients. Relative nitrogen enrichment at the edge of the Harbor was clearly detected and the data hint that nitrogen flowing from the Harbor to nearfield region was being actively removed from the water column in early April.

3.1.4 Distribution of Chlorophyll and Phytoplankton

Evaluation of extracted chlorophyll samples reinforced some of the impressions of the basic regional patterns described above, but also suggested some slight modifications. As with fluorescence, peak values were seen from 10-25 m at several nearfield stations, and Cape Cod Bay had intermediate values (Figure 3-23). Coastal stations, including the edge of the Harbor, were slightly lower in chlorophyll than suggested by calibrated fluorescence readings. Samples from these stations were indeed low in chlorophyll concentration relative to the general trend for fluorescence (Appendix A); the reason is unknown. However, the chlorophyll-fluorescence pattern did not show a systematic trend, identifiable by either geographic location or water depth, to warrant use of separate calibration algorithms. Nevertheless, it is noted that chlorophyll concentrations extrapolated from fluorescence at some Harbor edge and nearfield stations may be overestimates. Consequently, the trend of decreasing surface chlorophyll from the Harbor (e.g., Figure 3-4) may be overstated and the trend of increasing subsurface peak chlorophyll concentrations from the Harbor across the nearfield (e.g., Figure 3-11) may be understated.

Phytoplankton counts were not particularly high anywhere and did not exceed 1 million cells per liter in any samples. As for chlorophyll, slightly higher counts were measured in most subsurface chlorophyll-maximum samples (Figure 3-24). There was some variability in the relation between chlorophyll and phytoplankton counts (Figure 3-24). Further inspection did not suggest any clear geographic groupings of these data.

The overall community composition for surface samples is indicated in Figure 3-25. Diatoms were numerically dominant; they comprised the majority of the total counts at all stations except F23P. At this Harbor-edge location, there were, both relatively and absolutely, more microflagellates, more cryptomonads (category "other" in Figure 3-25), and fewer dinoflagellates than at other stations.

At each station, the surface and mid-water "chlorophyll maximum" samples for whole-water phytoplankton taxonomic analyses suggested a similar community existing throughout the water column (cf. Tables 3-1a and 3-1b). In addition to the microflagellate and cryptomonad groups, the dominant taxa at all locations were diatoms — primarily a collection of several *Chaetoceros* species and *Thalassiosira* (cf.) *gravida/rotula*.

Counts of the most abundant diatom species were 10^5 cells L^{-1}, whereas the dinoflagellate species counted in 20 μm-screened samples were approximately 10,000 times lower and in the range of 10^0 to 10^2 cells L^{-1} (Tables 3-2a and 3-2b). Based on the screened samples, the number of dinoflagellate species and individual taxa counts were lower at station F23P than at other stations, supporting the observations made on whole-water samples (e.g., Figure 3-25). Additionally, note that the array of taxa and their individual abundances at the two Cape Cod Bay stations were very similar to many sites in the nearfield. Finally, a species (*Alexandrium tamarense*) associated with paralytic shellfish poisoning, was found in only one early April sample — the surface water of station F02P in eastern Cape Cod Bay.

3.1.5 Distribution of Zooplankton

Total numbers of zooplankton varied about six-fold across the stations (Figure 3-26). Similar to phytoplankton, lowest counts were obtained at station F23P; excluding the sample from this station, the variation was less than three-fold. Copepods and their nauplii constituted most of the zooplankton counted at all stations. At two locations (F02P and N16P), a substantial fraction of the total count was due to barnacle nauplii. Total zooplankton and phytoplankton counts were generally correlated over the stations (cf. Figure 3-25 and 3-26 and also Section 6).

The appendicularian, *Oikiopleura dioica* (category "other" in Figure 3-26), was abundant at most stations. The dominant copepod was *Oithona similis*. Other relatively abundant and virtually cosmopolitan forms were *Calanus finmarchicus*, *Microsetella norvegica*, and *Paracalanus parvus*.

Few striking geographic distinctions could be determined for copepod species. However, it was interesting that *Acartia hudsonica* was found at all stations, except N20P and N16P and the zooplankton community may have been slightly different in this area. The common features of stations N20P and N16P, other than their relative proximity, include their location in the center of the surface cold cell in Massachusetts Bay (Figure 3-1), their location at a physical transition point (see Figure 3-10c), and peak chlorophyll concentrations at the base of the pycnocline. The highest baywide abundances of *Oikiopleura dioica* were also found at stations N20P and N16P. Even so, considering the range of nutrient concentrations, temperature and salinity, as well as chlorophyll concentrations across this and other regions (cf. Section 3.1.3), any biological distinctions are indeed subtle and the zooplankton community, in general, was fairly well-mixed over the bays.

3.1.6 ^{14}C Production Measurements

Using the P-I incubations, and light and fluorescence profiles at each station, modeling was performed to estimate integrated daily ^{14}C production (see Section 2). All P-I data and curve-fitting results are given in Appendix E. In general, the goodness-of-fit for P-I modeling was excellent; example curves are shown in Figure 3-27. Estimated areal production rates, as for other 1993 surveys (Kelly *et al.*, 1993d), were expressed per square meter of surface after integration to the depth of the 0.5% isolume ($Z_{0.5\%Io}$).

The depth of $Z_{0.5\%Io}$ is provided for the Bioproductivity stations in Table 3-3. This depth varied from about 10 m at the edge of the Harbor to greater than 30 m at the eastern side of the nearfield (N16P and N07P).

Table 3-3 also presents production as calculated from incubations of either the surface water sample or the chlorophyll-maximum sample taken at each station. At some locations these estimates were similar, but at others the variation was very large; the variation is wholly due to different P-I curves because the same light and chlorophyll fluorescence profiles are used for a given station. The production estimates, across stations, range from a low of 0.9 mg C m^{-2} d^{-1} to almost 4.9 mg C m^{-2} d^{-1} (Table 3-3). On average, the rates for Massachusetts Bay stations were higher than they had been in either February or March, whereas Cape Cod Bay peak rates seemed to occur in February (Kelly *et al.,* 1993d).

To an extent, integrated rates are a function of chlorophyll in the water column, but differences in the depth of $Z_{0.5\%Io}$, as well as other factors are involved. For example, Figure 3-27 shows P-I curves for station F23P and F01P, which are slightly different, especially in the maximum levels attained at light saturation. The maximum chlorophyll-normalized rate, as well as the average chlorophyll concentration in the euphotic zone, was higher at F23P, but the integrated water-column rates are comparable (Table 3-3) because the euphotic zone was more than twice as deep at station F01P and the total euphotic zone chlorophyll mass was roughly comparable at the two stations.

3.2 Nearfield Survey

3.2.1 Distribution of Water Properties from Vertical Profiling

Vertical profiling was performed at 21 stations in the nearfield on April 9, repeating all 6 "P" 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 a subset of those stations shown in Figure 3-15. Comparison of Figures 3-28a and 3-28b with Figures 3-15a and 3-15b illustrates that the ranges for measured parameters are narrower for the group of nearfield stations than for the group of combined nearfield and farfield stations (Figures 3-15a and 3-15b). Characteristic of nearfield station profiles was a mild stratification, with a pycnocline between 5 and

25 m, the specific depth of which varied by station. The variation in near-surface temperatures and surface salinity was only about two degrees and about 2 PSU, respectively (Figure 3-28a).

Also characteristic was a mid-water chlorophyll maximum in the pycnocline, with chlorophyll slightly lower in the surfacemost layer (Figure 3-28b). In general, DO concentrations (expressed as % saturation) were higher in the upper water column and decreased below the pycnocline, but all concentrations were above 100% saturation.

Previous graphics (Section 3.1.3) describe 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 3-29. Other regions from the farfield survey also are shown for reference. For DIN, the majority of nearfield stations showed a depletion in the near-surface layer and concentrations increasing with depth below about 10-15 m. Some nearfield surface water DIN concentrations were similar to those at coastal stations located just to the west. DIN vertical patterns in the nearfield were generally similar to those in the offshore and northern transect regions. In comparison, Cape Cod Bay stations were less depleted in surface DIN (Figure 3-29a).

In general, the description of DIN patterns over depth and region also applies to NH_4 (Figure 3-29b). In contrast, a poorly defined vertical pattern was observed for nitrate because the concentrations were near zero throughout the water column. Nitrate was as high as 4 μM in NO_3 in a few nearfield samples, but all were within the range of concentrations for other regions (Figure 3-29b). Phosphate concentrations generally increased by about 0.5 μM with depth. A sharper increase in concentration from the pycnocline to the bottom is evident for most of the nearfield stations (Figure 3-29c). Silicate depth profiles resembled DIN, but without the level of depletion in surface waters. In the nearfield, the range of surface silicate concentrations (2-5 μM) was similar to Cape Cod Bay stations.

3.2.2 Distribution of Water Properties from Towing

The horizontal tow-yo profiling took place on April 10, the day after vertical profiling. The sequence of sampling followed the same counterclockwise 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" towed across the same stations sampled by vertical profiling (Figures 3-30, 3-31, and 3-32).

Temperature patterns, as observed in the farfield survey, continued to show a cooler surface water mass in the middle of the nearfield. Slightly warmer water was noted along the northern and eastern (offshore) edges, as well as the southwest corner near station N10P (Figures 3-30a,b). A layer of cold water (<2 °C) was apparent below about 30 m in the southeast corner around stations N06, N07P, and N08.

Water column density structure is shown in Figures 3-31a,b. In spring, salinity often has a strong influence on density. Density stratification and layering, in part due to fresher waters, are evident along several towing tracks. There was shoaling offshore from the coast at the southwest corner (N10P) as well as a surface lens along the north and northeast corners of the nearfield. Similar to the results of the farfield survey (only the "P" stations) conducted three to four days earlier (Section 3.1), the middle of the nearfield had weaker surface-water stratification.

The contours for fluorescence (as chlorophyll) reveal a high degree of patchiness (Figure 3-32b). The more spatially extensive patches of high chlorophyll concentrations (>2.75 μg/L) coincide strongly with the pycnocline, often its lower edge, and follow some of it's apparent undulation over space. For example, the density stratification along inner eastern track from station N17 to station N15 follows a variable bathymetry (Figure 3-31b). This pattern is also evident for fluorescence (Figure 3-32b); one of the larger and more intense patches of fluorescence was found in this subsurface layer. A similar observation was noted at the outer eastern track. Interestingly, the higher subsurface accumulations of chlorophyll were in the middle of the field and extended to the southeast, the general area encompassed by the cooler, more saline cell observed during the period of the farfield/ nearfield surveys.

3.2.3 Water Types and Analysis of Small-Scale Variability

As was evident from the farfield sampling, the spatial variation evident from the nearfield towing data showed the presence of an offshore lens of surface water as well as some probable surface outflow from inshore. In general, because of this, there was a slight sea-to-shore gradient; but sandwiched between these two masses was a less stratified parcel of water in the nearfield that generally persisted during the five-day sampling period.

Most notable was the high degree of biological variability over short spatial scales, as evidenced by the mottled distribution of chlorophyll (Figure 3-32b), compared to the more uniform distribution of physical variables. Nevertheless, there was some obvious coupling between physical and biological features. For example, on average, chlorophyll concentrations were higher throughout the middle nearfield zone where more physically mixed conditions were prevalent. Additionally, it was striking that chlorophyll accumulated along certain pycnal surfaces (about $\sigma_T = 24.8$) near the base of the pycnocline and usually near the bottom of the euphotic zone (Table 3-3).

In terms of small-scale temporal variability, two short time scales can be addressed with the data: changes within a day that relate to tidal dynamics and changes over several days.

With respect to tidal dynamics, there were only small differences in water properties at different stages of the tide. The southwest corner (station N10P) was visited shortly after low tide and the tide was beginning to flood as the track from N10P to N01P was sampled ("outer western track" in Figures 3-30 to 3-32). In contrast, as the outer box was completed with the return to station N10P along the "outer southern track" (station N07P to N10P), the tide was approaching high and it was shortly after maximum flood tidal currents. However, at both times, a warmer surface lens of water was apparent at N10P (Figures 3-30, 3-31). The density contours between N10P and N11 may suggest the breaking off of parcels of Harbor outflow water as the tide turned, but little other influence of tidal cycle can be directly suggested from the data. It may be that much of the tidally-pulsed flow from the Harbor was being directed southeastward from the area of N11-N10P-N19 at this time, perhaps constrained somewhat by the water mass in the middle of the field (cf. Figures 3-1 and 3-2). Such a constraint would reinforce the strong stratification (even at high tide) seen between N10P and N09 (Figure 3-31a) and be consistent with the apparent coastal current flow further south along the coast (Figure 3-10c).

With respect to changes over several days, the following comments can be made from inspection of Appendix B over the course of repeated vertical sampling at "P" stations. There appeared to be some surface warming at all six "P" stations of the nearfield. The deeper stations, N04P, N16P, and

N20P, also experienced an apparent increase in surface salinity, especially N20P, possibly indicating some daily or progressive excursion of the mid-nearfield water mass and of the northeast surface lens. These changes had minor effects on the degree of stratification. Finally, it was noted for several stations (especially N07P and N16P) that the subsurface chlorophyll maximum seemed to decrease over time. This, along with the presence of high concentrations of chlorophyll along certain deep isopycnal layers near the base of the euphotic zone and depletion of DIN in the surface layer, may have signaled the beginning of the cessation (and sedimentation) of the spring bloom in Massachusetts Bay in 1993.

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

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	**F13P**	**N01P**	**N04P**	**N07P**	**N10P**	**N16P**	**N20P**	**F01P**	**F02P**
	Apr 06	Apr 07	Apr 07	Apr 07	Apr 07	Apr 06	Apr 06	Apr 06	Apr 08	Apr 08
Chaetoceros compressus					0.02 (5)					
Chaetoceros debilis	0.013 (4)	0.021 (4)	0.091 (3)	0.095 (2)	0.182 (1)	0.053 (4)	0.176 (2)	0.075 (3)	0.069 (3)	0.163 (1)
Chaetoceros socialis	0.012 (5)	0.077 (3)	0.134 (2)	0.088 (3)	0.139 (2)	0.074 (3)	0.074 (4)		0.119 (1)	0.101 (3)
Chaetoceros spp. (10-20 μm)		0.019 (5)	0.031 (5)				0.071 (5)	0.043 (4)		
Cryptomonads	0.115 (2)			0.017 (5)	0.026 (4)	0.031 (5)		0.036 (5)	0.046 (5)	0.038 (5)
Microflagellates	0.16 (1)	0.095 (2)	0.087 (4)	0.069 (4)	0.092 (3)	0.10 (2)	0.105 (3)	0.085 (2)	0.114 (2)	0.06 (4)
Thalassiosira (cf.) *gravida/rotula*	0.096 (3)	0.14 (1)	0.199 (1)	0.11 (1)	0.139 (2)	0.163 (1)	0.211 (1)	0.139 (1)	0.067 (4)	0.159 (2)

Units are millions of cells L^{-1}

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

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr 06	Apr 07	Apr 07	Apr 07	Apr 07	Apr 06	Apr 06	Apr 06	Apr 08	Apr 08
Chaetoceros debilis		0.124 (2)	0.074 (4)	0.234 (2)	0.103 (3)	0.142 (3)	0.098 (2)	0.16 (2)	0.077 (3)	0.173 (1)
Chaetoceros socialis	0.025 (5)	0.092 (4)	0.168 (1)	0.104 (3)	0.177 (1)	0.094 (4)	0.031 (5)	0.053 (5)	0.077 (3)	0.129 (3)
Chaetoceros spp. (10-20 μm)	0.034 (4)	0.041 (5)	0.032 (5)	0.044 (5)		0.055 (5)	0.06 (3)	0.06 (3)		
Cryptomonads	0.117 (2)	0.041 (5)							0.057 (5)	0.042 (5)
Cyanophyceae (nostoc-like 4μm dia)					0.079 (4)					
Microflagellates	0.22 (1)	0.11 (3)	0.098 (3)	0.046 (4)	0.068 (5)	0.152 (2)	0.052 (4)	0.06 (3)	0.113 (1)	0.136 (2)
Thalassiosira (cf.) *gravida/rotula*	0.078 (3)	0.198 (1)	0.165 (2)	0.262 (1)	0.132 (2)	0.195 (1)	0.162 (1)	0.268 (1)	0.096 (2)	0.122 (4)

Units are millions of cells L^{-1}

Table 3-2a. Abundance of all identified taxa in screened (20um) samples collected near the surface in early April 1993.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr 06	Apr 07	Apr 07	Apr 07	Apr 07	Apr 06	Apr 06	Apr 06	Apr 08	Apr 08
ALEXANDRIUM TAMARENSE										3
ALORICATE CILIATES	38	10	20	48	28	10	5	20	20	43
CERATIUM FUSUS			3		5	5	15			
CERATIUM LINEATUM			5	3		3				3
CERATIUM LONGIPES		3	18	33	15	30	43	20	15	18
CERATIUM TRIPOS					3		3		3	3
DICTYOCHA SPECULUM			10	3	8	3	8	15	18	3
DINOPHYSIS ACUMINATA				8						
DINOPHYSIS NORVEGICA	3	8	13	3	5	8	5	8	8	35
DINOPHYSIS OVUM			18	10	3	8		3	5	5
DINOPHYSIS SPP.				3						
EUTREPTIA SPP.										3
GYMNODINIUM SPP.		3						3	3	
GYRODINIUM SPIRALE	8	13	8	13	25	13	13	5	5	55
GYRODINIUM SPP.		3	3	3	5		3	5	5	5
HETEROCAPSA TRIQUETRA		3	5	18		5	5		3	
KATODINIUM SPP.	10	23	10	5	28	13	13	5	3	5
MERISMOPEDIA SPP. COLONY						20				

Units are cells L^{-1}

Table 3-2a. Continued.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr 06	Apr 07	Apr 07	Apr 07	Apr 07	Apr 06	Apr 06	Apr 06	Apr 08	Apr 08
MESODINIUM RUBRUM	3	8	18	10	5	18	13	20	8	43
PROTOPERIDINIUM (CF) BREVIPES		8	10	8		3	23	3	18	3
PROTOPERIDINIUM BIPES			3						3	3
PROTOPERIDINIUM BREVE			20	10	3	3			3	5
PROTOPERIDINIUM DENTICULATUM			20	5	5	13	40	28	5	10
PROTOPERIDINIUM DEPRESSUM			3		5	3	5			
PROTOPERIDINIUM PELLUCIDUM		3	8	13		15	8	5	8	13
PROTOPERIDINIUM SPP.	10	23	48	35	18	23	18	8	25	50
PROTOPERIDINIUM STEINII	3									
SCRIPPSIELLA TROCHOIDEA										3
TINTINNIDS	75	8	63	70	13	35	48	50	10	135
UNID. ATHECATE DINOFLAGELLATE	5	8		10	25		3	3	10	18
UNID. THECATE DINOFLAGELLATES	3		8	23	15	20	18	18	3	3

Units are cells L^{-1}

Table 3-2b. Abundance of all identified taxa in screened (20um) samples collected near the chlorophyll maximum in early April 1993.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr 06	Apr 07	Apr 07	Apr 07	Apr 07	Apr 06	Apr 06	Apr 06	Apr 08	Apr 08
ALORICATE CILIATES	23	115	38	40	20	13	15	3	28	118
CERATIUM FUSUS		3	3	10		5	10	8	5	
CERATIUM LINEATUM				5		3		3		3
CERATIUM LONGIPES	5	20	10	48	30	15	20	38	38	15
CERATIUM TRIPOS		3	3	5						
DICTYOCHA SPECULUM	5	3	3			3	5		5	3
DINOPHYSIS ACUMINATA				3		3				
DINOPHYSIS NORVEGICA	3	13	8	8	5	15	28	5	20	10
DINOPHYSIS OVUM		5	15	5		3	13	3	3	
GYMNODINIUM SPP.		3	3							
GYRODINIUM SPIRALE	18	38	23	30	15	38	33	13	18	60
GYRODINIUM SPP.					5	5			5	10
HETEROCAPSA TRIQUETRA		5	5		3				3	5
KATODINIUM SPP.		10	28	30	15	28	40	13	15	5

Units are cells L^{-1}

Table 3-2b. Continued.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr 06	Apr 07	Apr 07	Apr 07	Apr 07	Apr 06	Apr 06	Apr 06	Apr 08	Apr 08
MESODINIUM RUBRUM	3	133	23	5			10		10	33
PROTOPERIDINIUM (CF) BREVIPES		3		15		8	15		5	
PROTOPERIDINIUM BIPES				3						3
PROTOPERIDINIUM BREVE			5	18	3	3			8	5
PROTOPERIDINIUM DENTICULATUM		35	20	35	30	30	53	25	10	13
PROTOPERIDINIUM DEPRESSUM	3		15		3		5	8		5
PROTOPERIDINIUM PELLUCIDUM	3		5	13	8	10	5	3	20	3
PROTOPERIDINIUM SPP.	5	50	20	53	23	18	63	20	23	63
PROTOPERIDINIUM STEINII	3									
TINTINNIDS	80	28	53	85	8	73	43	15	35	115
UNID. ATHECATE DINOFLAGELLATE		3		23	15			3	25	23
UNID. THECATE DINOFLAGELLATES	10	5	13	23	13	15				5

Units are cells L^{-1}

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

	Coastal Stations				Nearfield Stations												Cape Cod Bay Stations			
	F23P		F13P		N01P[6]		N04P		N07P		N10P		N16P		N20P		F01P[6]		F02P	
Water depth (m)	25		28.5		30		48.5		46.5		22.5		41		34		27		32	
$Z_{(0.5\%Io)}$ (m)	9.5		21.5		28.5		18.5		33		21.5		32.5		18.5		27		23.5	
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 $m^{-2}d^{-1}$)	1677	1377	4756	3811	3366	4416	3746	1973	3098	5302	2756	2128	988	3283	2149	2234	1035	1311	2313	1540
Model[2]	W	W	W	W	W	W	W	W	P	W	W	W	W	W	W	P	W	W	W	W
P_{SB} or P_{MAX}[3]	16.10	12.69	41.83	28.96	13.21	16.18	27.22	12.50	16.83	28.03	17.15	13.56	10.90	15.23	12.36	12.52	8.57	9.63	13.97	8.71
α[4]	0.099	0.088	0.233	0.228	0.087	0.141	0.199	0.133	0.107	0.194	0.129	0.094	0.010	0.098	0.081	0.088	0.043	0.065	0.085	0.065
β[5]	-	-	-	-	-	-	-	-	0.002	-	-	-	-	-	-	0.002	-	-	-	-

[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 depths at stations N01P (22.5 m) and F01P (26.5 m).

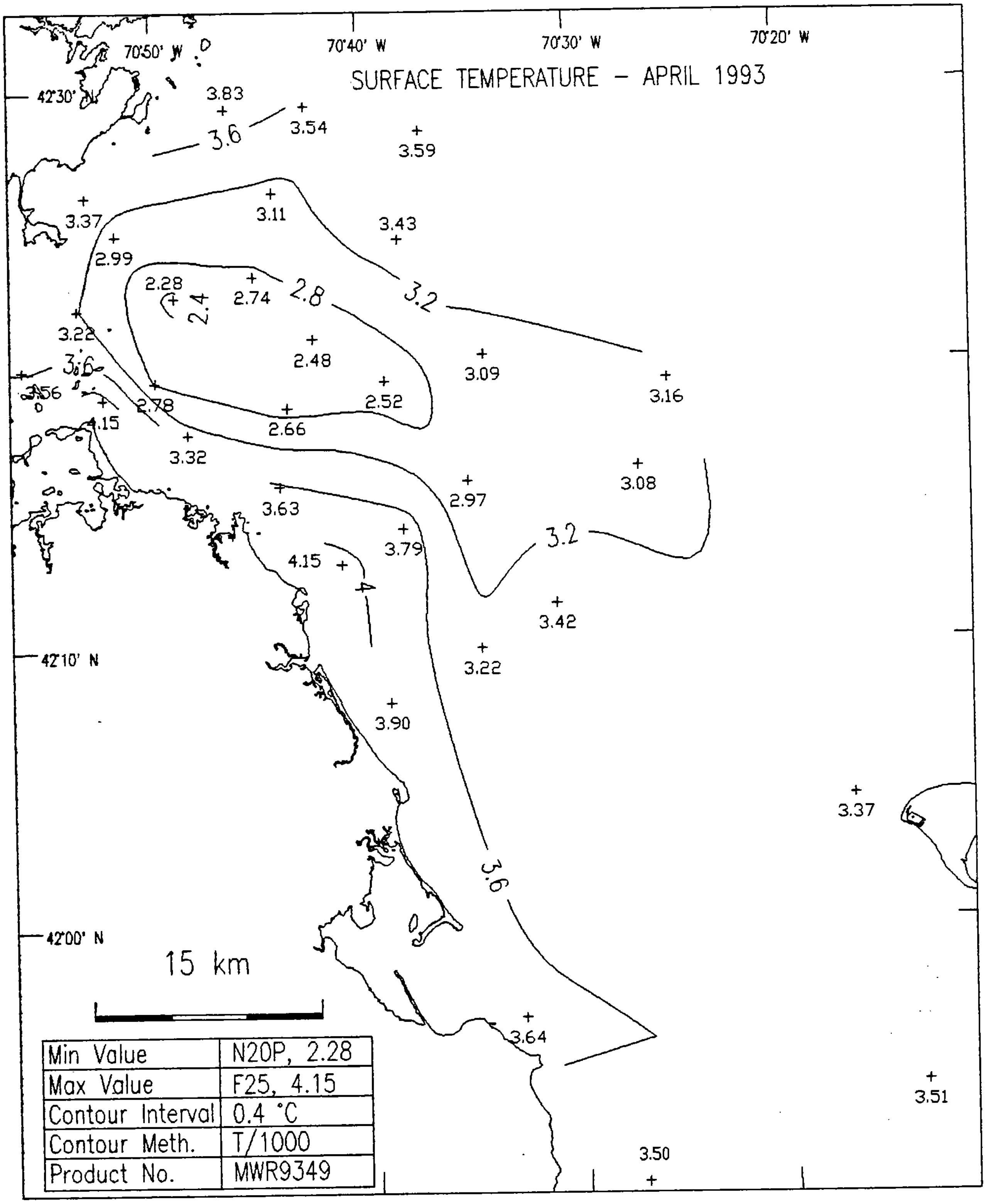


Figure 3-1. Surface temperature (°C) in the study area in early April 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).

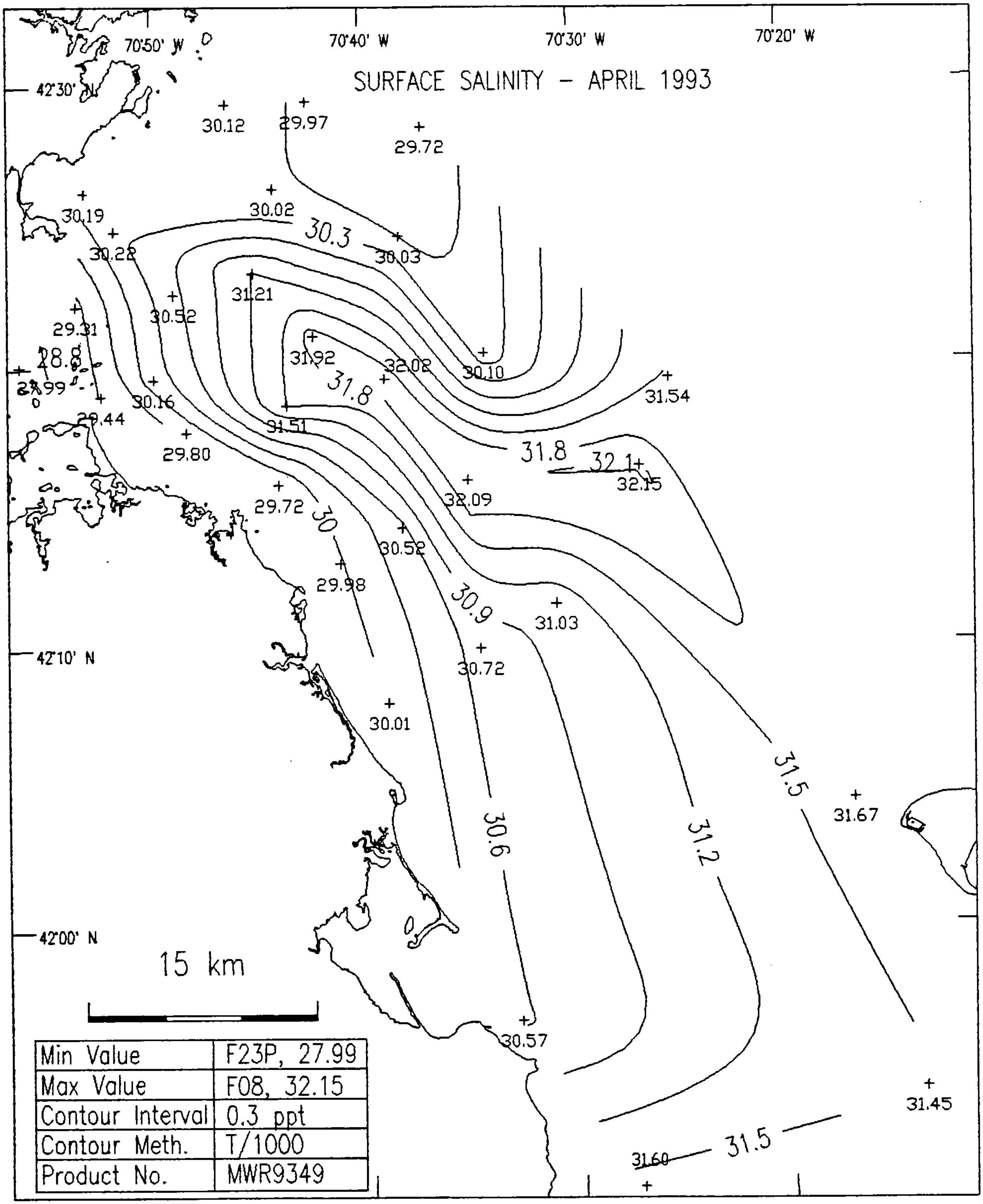


Figure 3-2. **Surface salinity (PSU) in the study area in early April 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

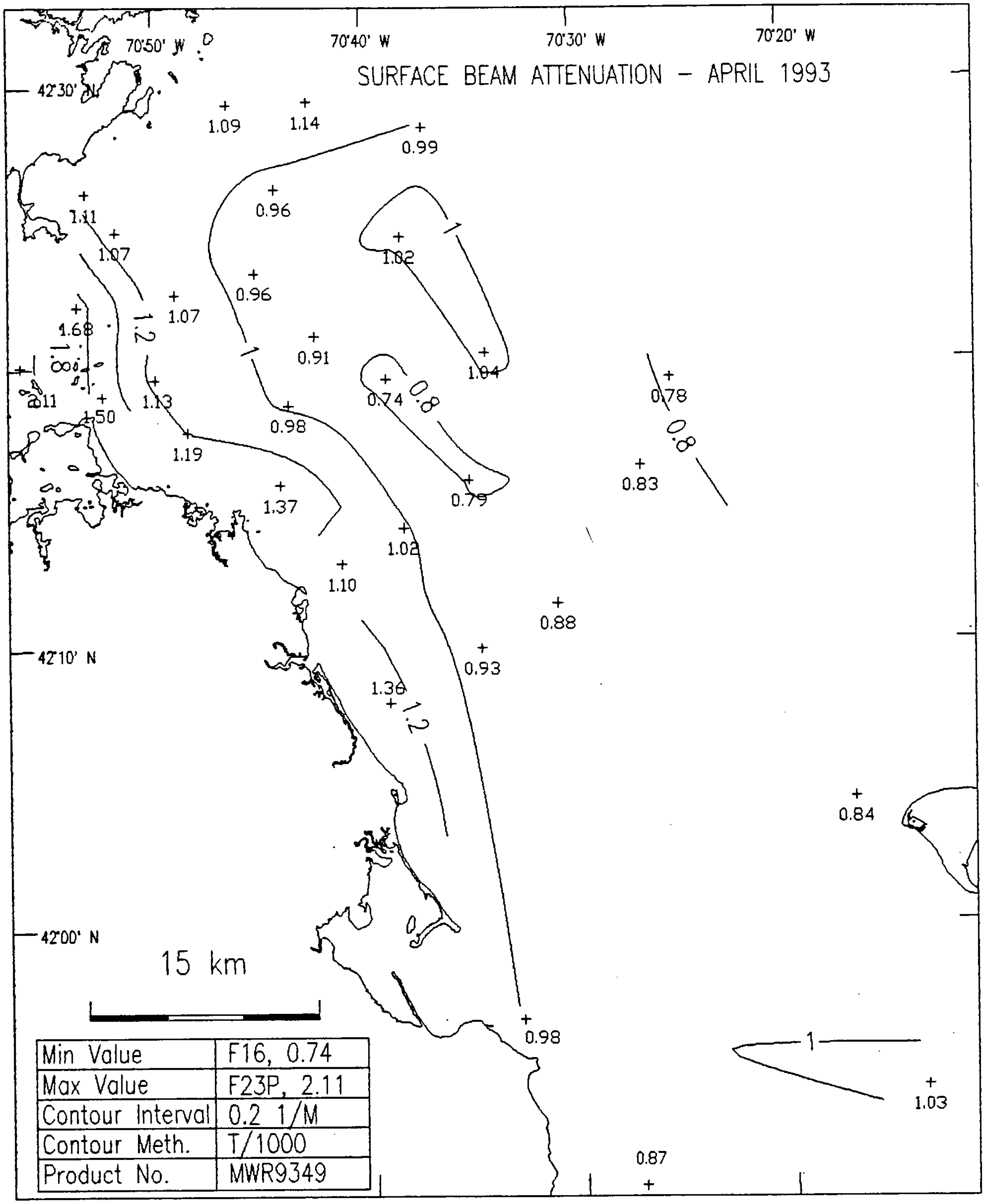


Figure 3-3. Surface beam attenuation (m^{-1}) in the study area in early April 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).

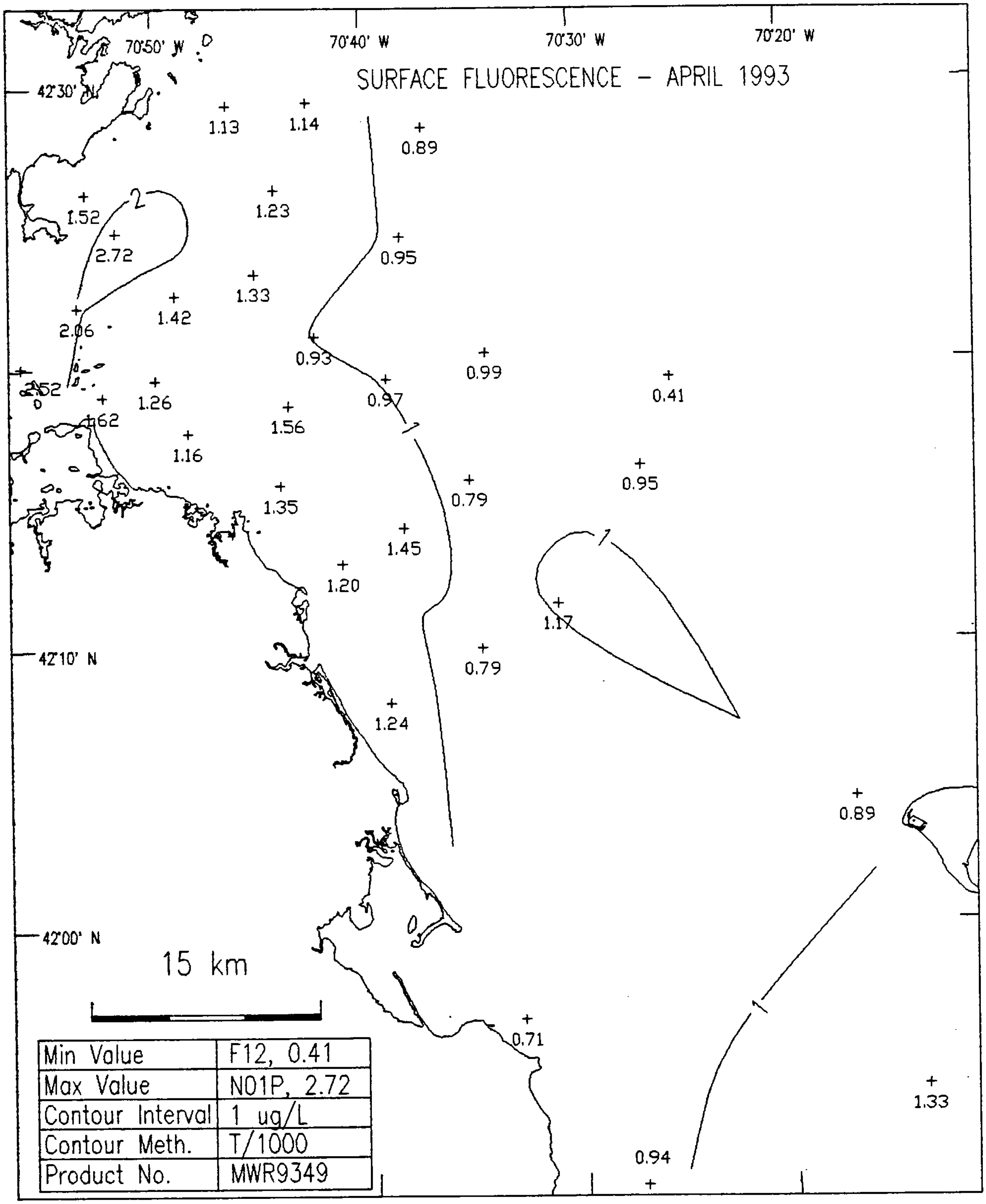


Figure 3-4. **Surface *in situ* fluorescence (as μg Chl L^{-1}) in the study area in early April 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A).**

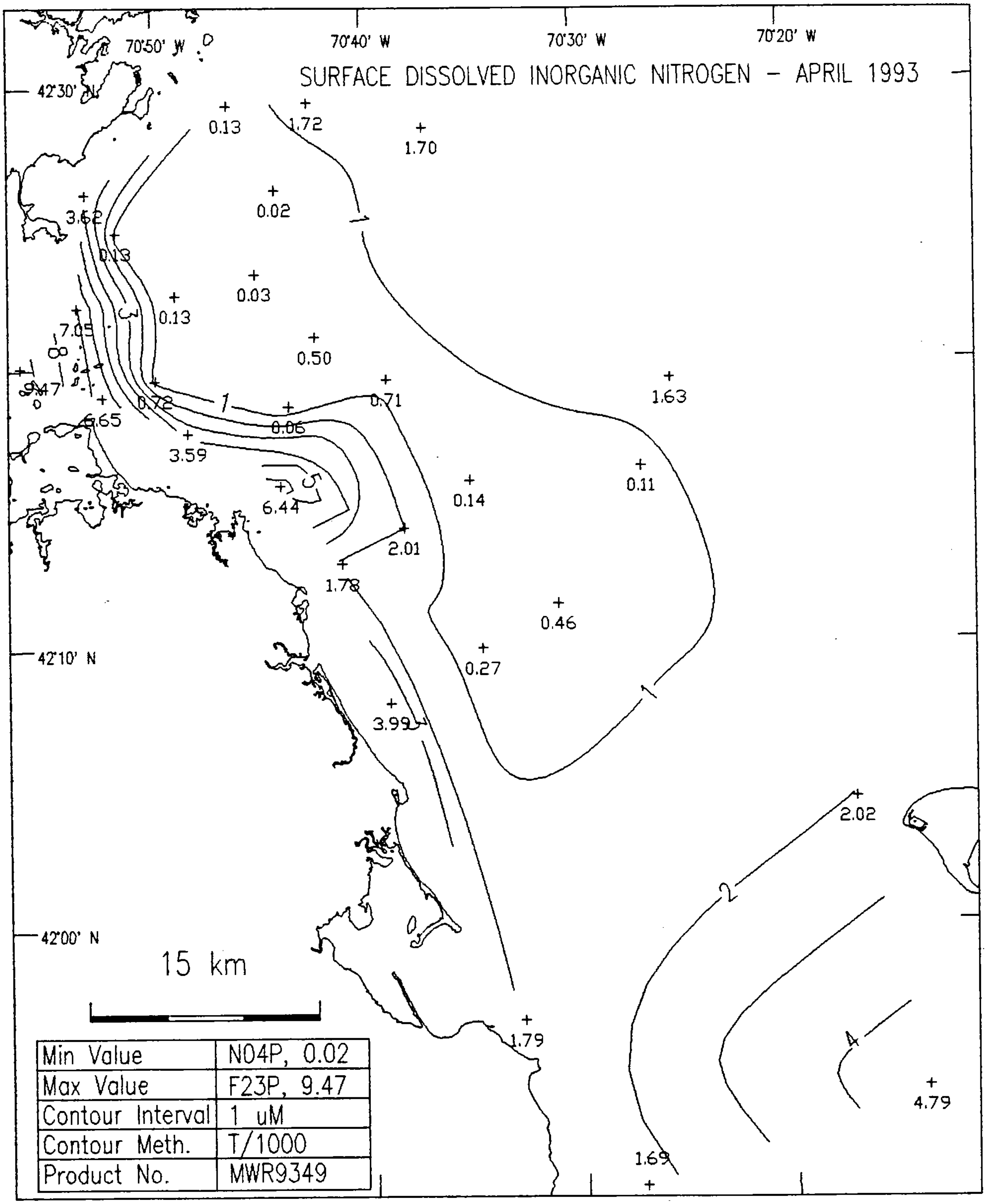
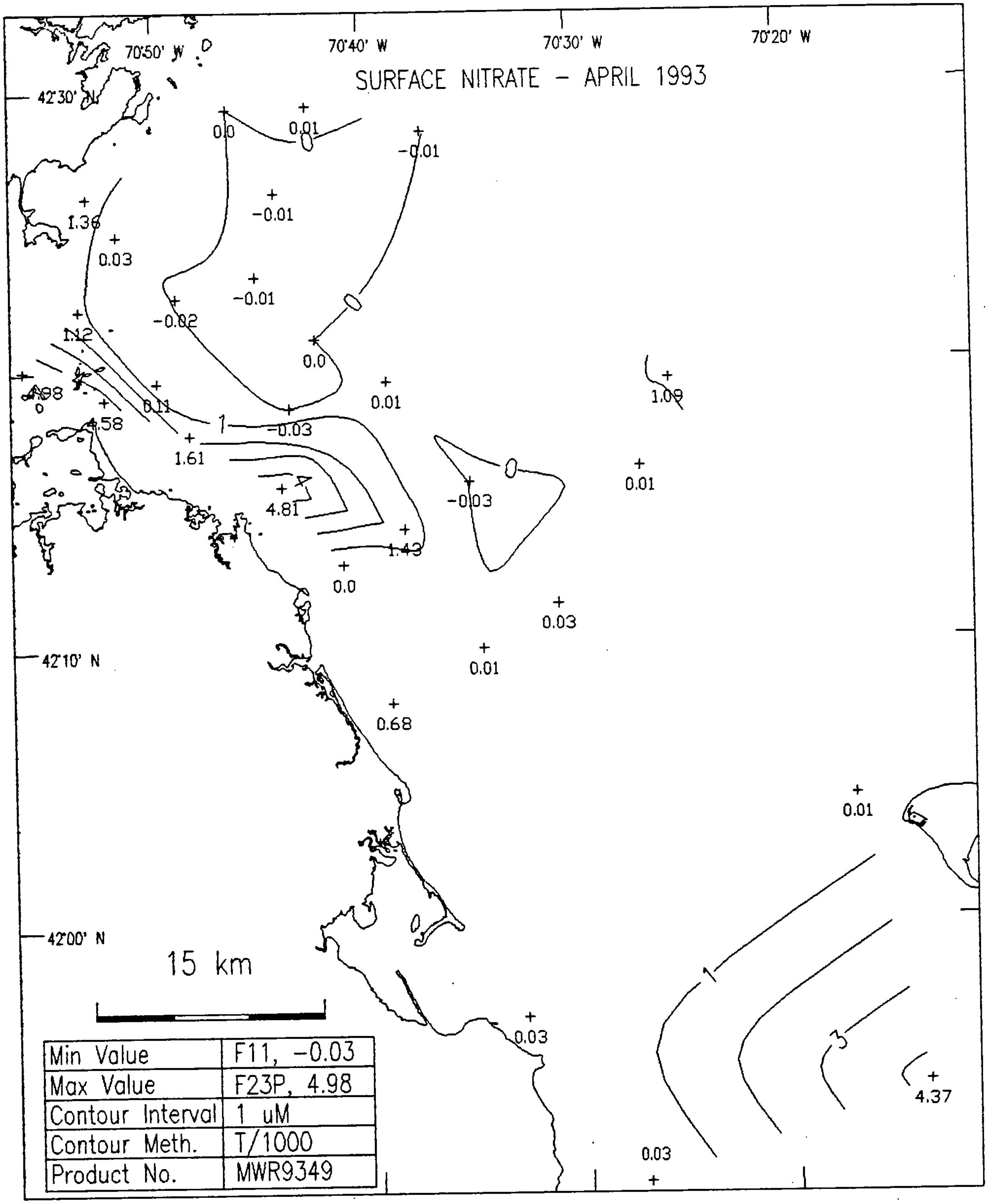


Figure 3-5. Surface dissolved inorganic nitrogen (DIN, μM) in the study area in early April 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A). No data were available for stations F17 and F19. At station N04P, only nitrate and nitrite are included in the DIN measurement because ammonia was not determined.



Min Value	F11, -0.03
Max Value	F23P, 4.98
Contour Interval	1 uM
Contour Meth.	T/1000
Product No.	MWR9349

Figure 3-6. **Surface nitrate (NO_3, μM) in the study area in early April 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 stations F17 and F19.**

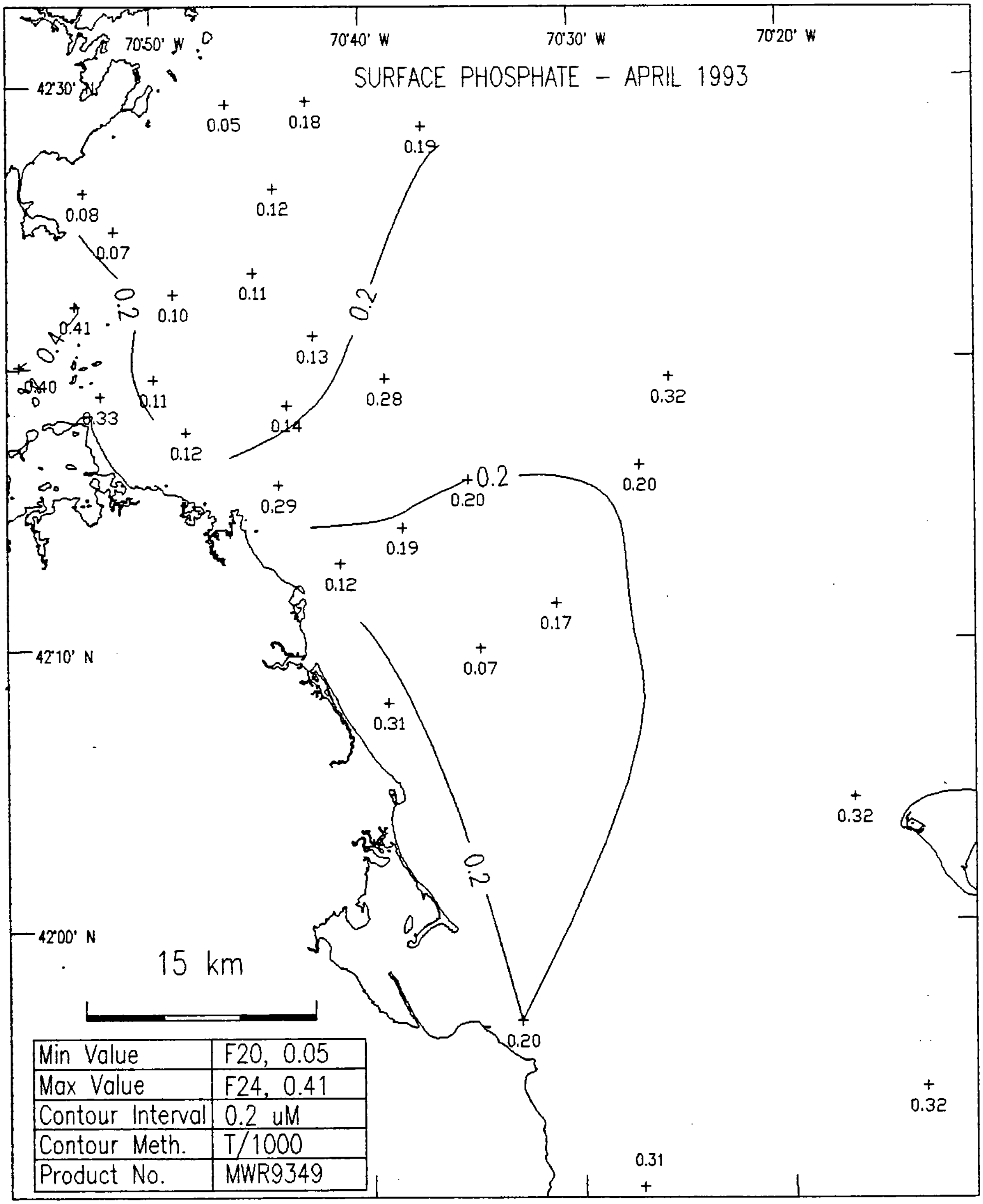
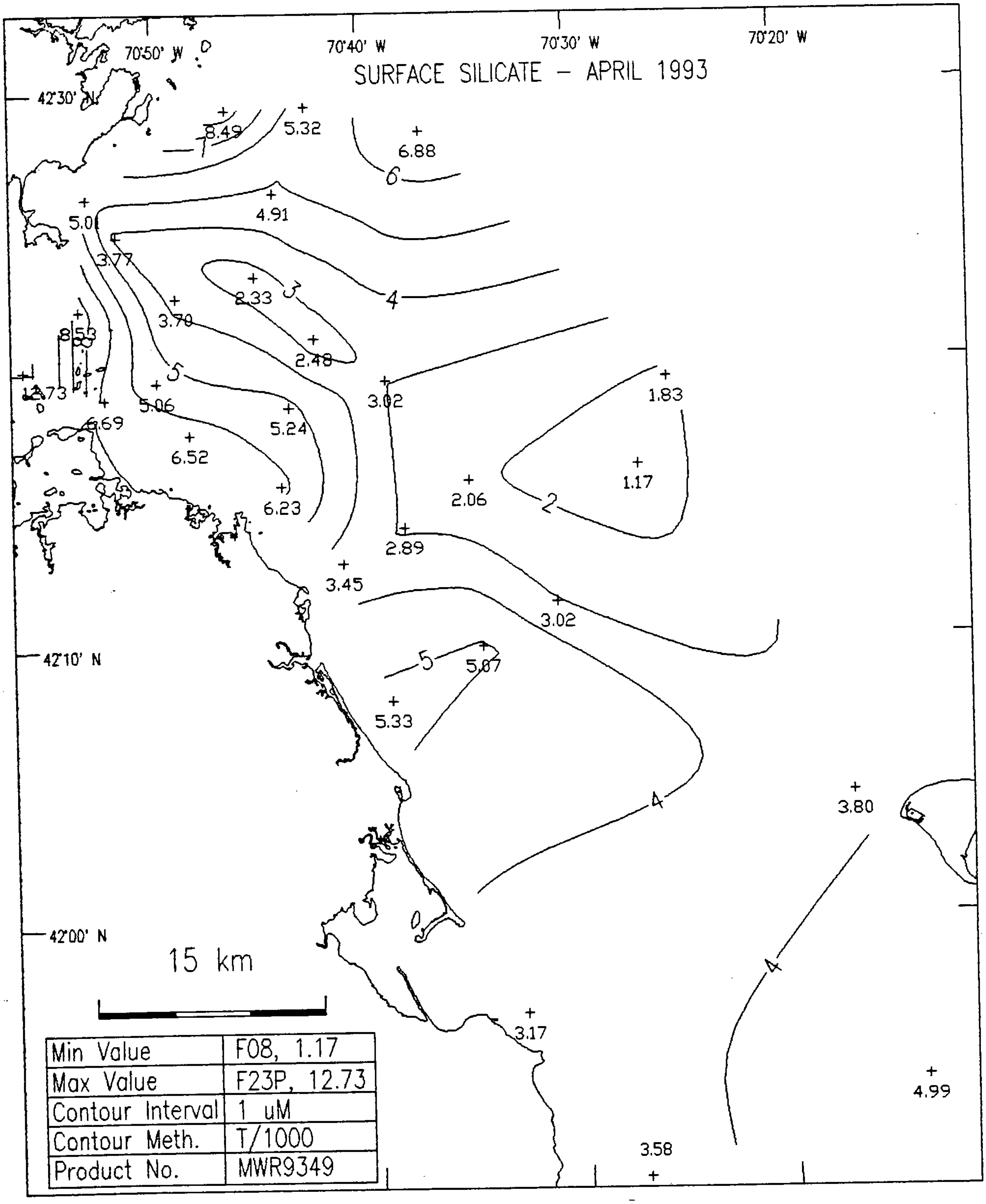


Figure 3-7. **Surface phosphate (PO_4, μM) in the study area in early April 1993. Data are from the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid (Appendix A). No data were available for stations F17 and F19.**



Min Value	F08, 1.17
Max Value	F23P, 12.73
Contour Interval	1 uM
Contour Meth.	T/1000
Product No.	MWR9349

Figure 3-8. Surface silicate (SiO_4, μM) in the study area in early April 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 stations F17 and F19.

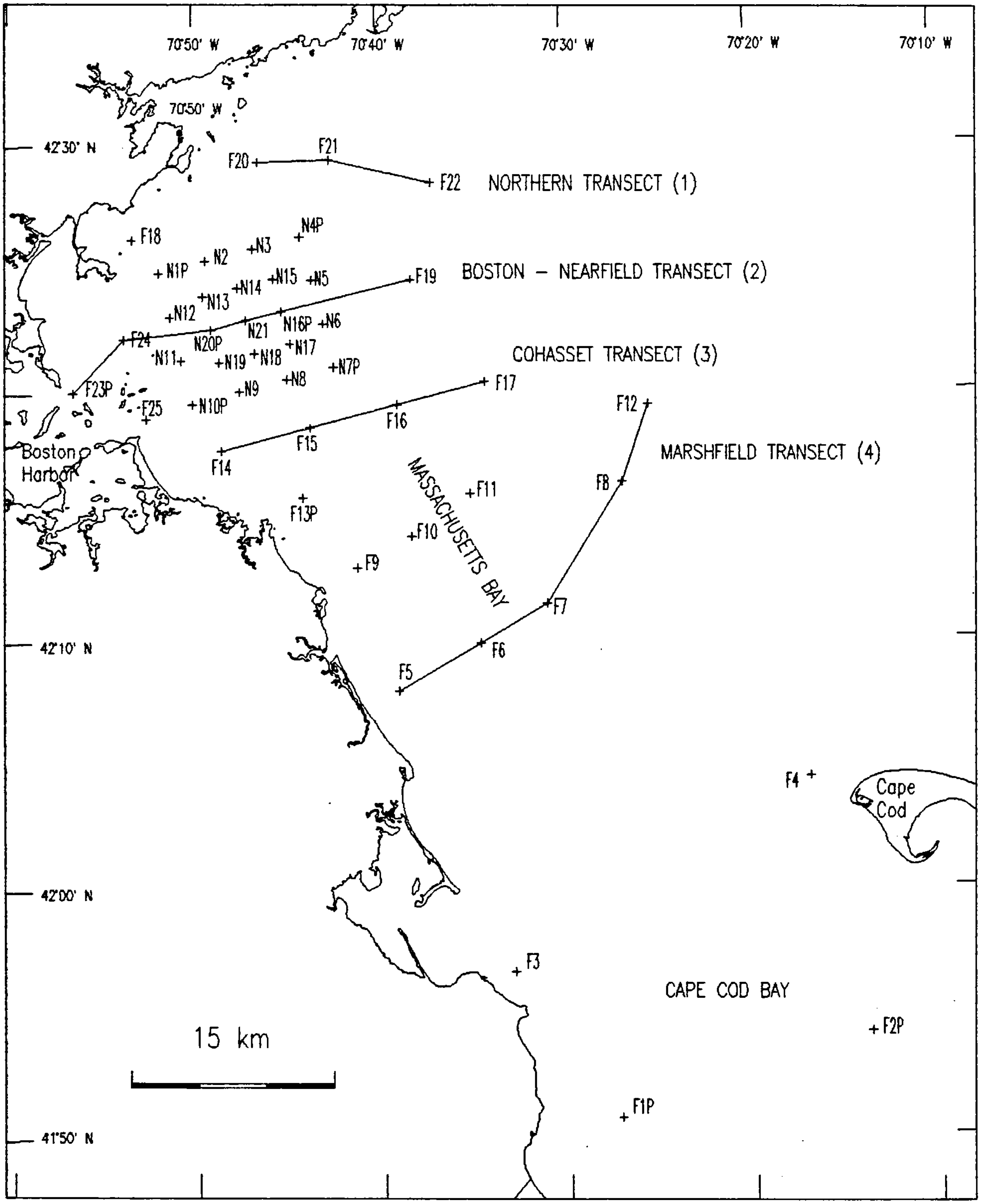


Figure 3-9. Map showing position of four standard transects for which vertical contour plots were produced in following Figures 3-10 to 3-14.

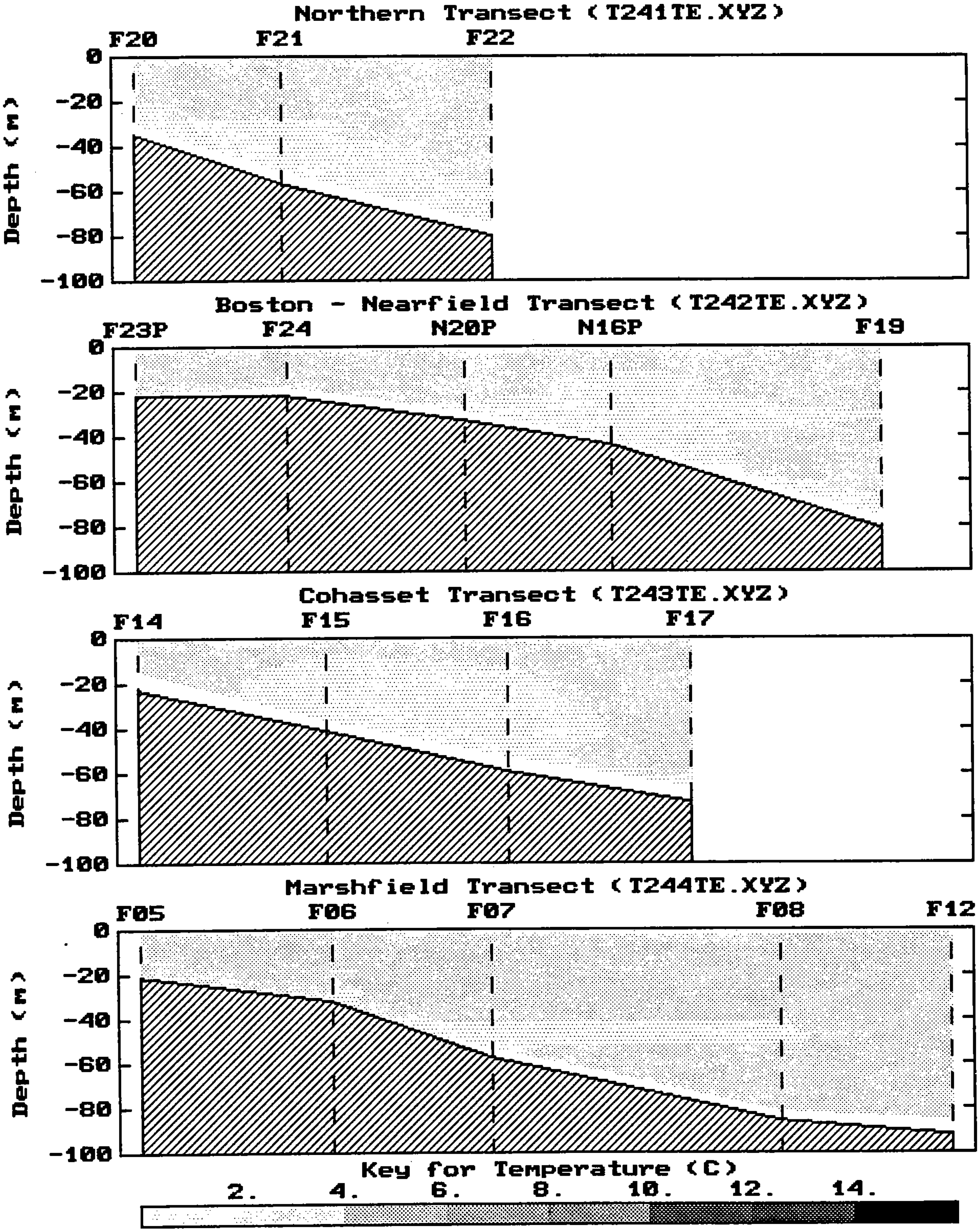


Figure 3-10a. Vertical section contours of temperature in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

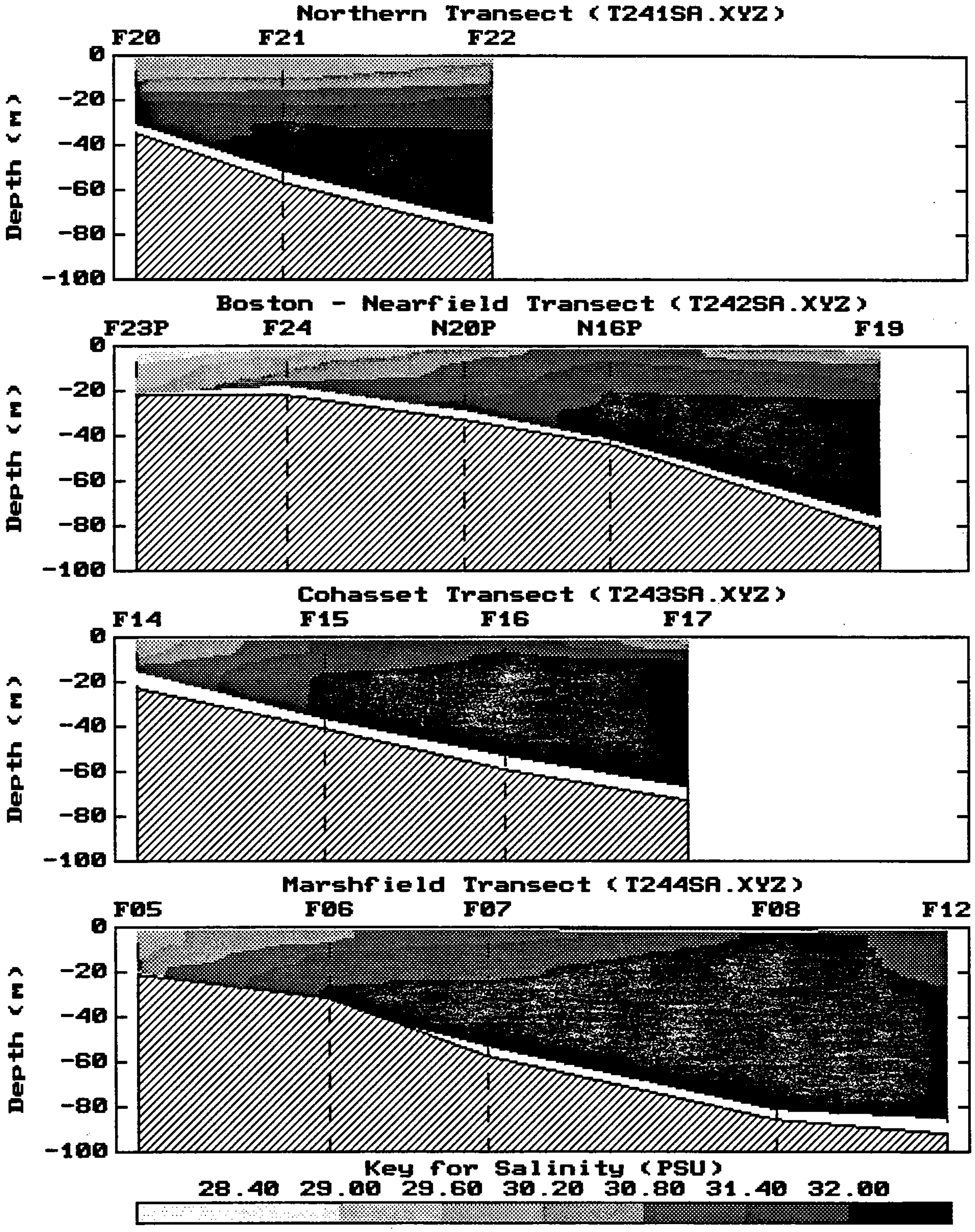


Figure 3-10b. Vertical section contours of salinity in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

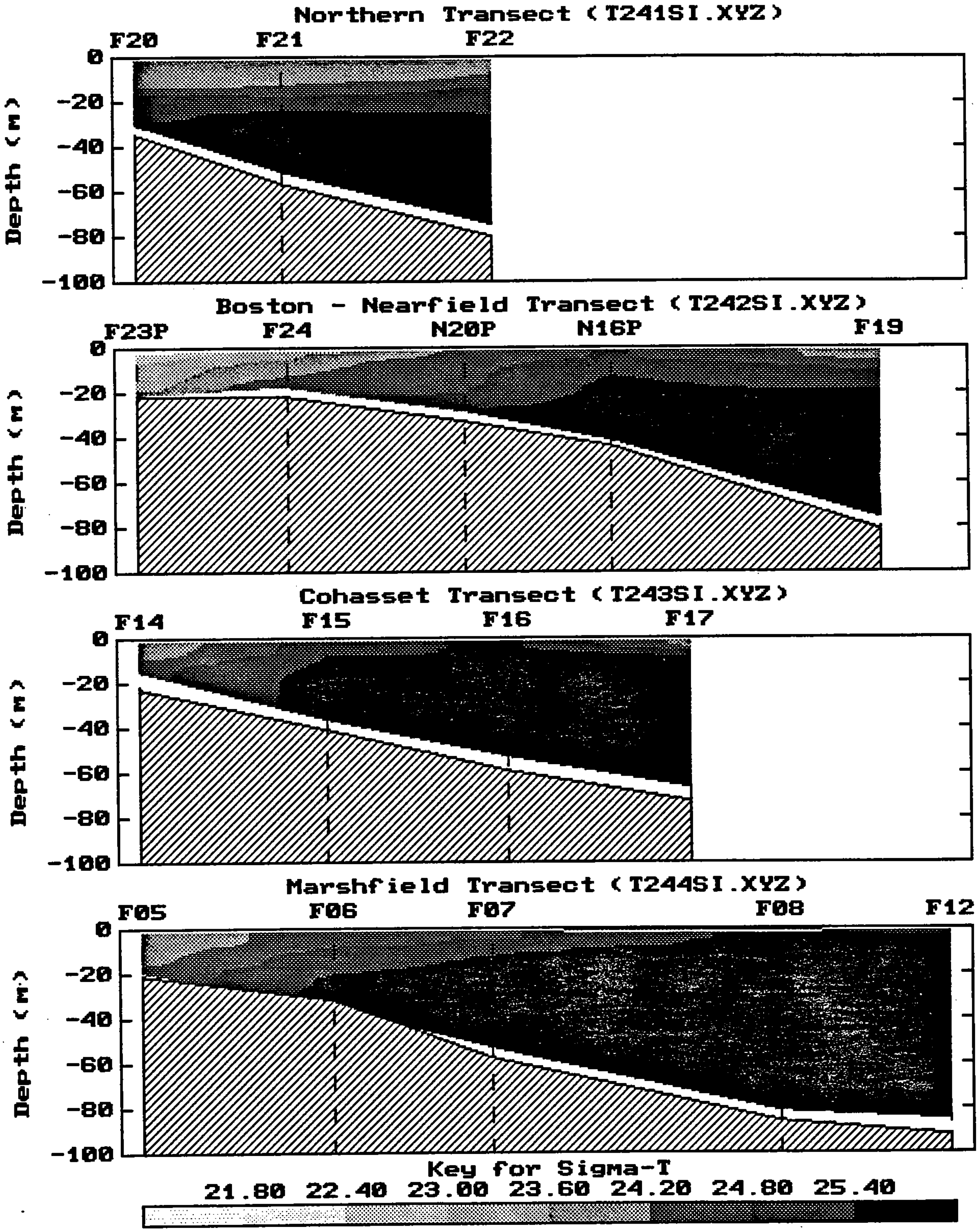


Figure 3-10c. Vertical section contours of density (σ_T) in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

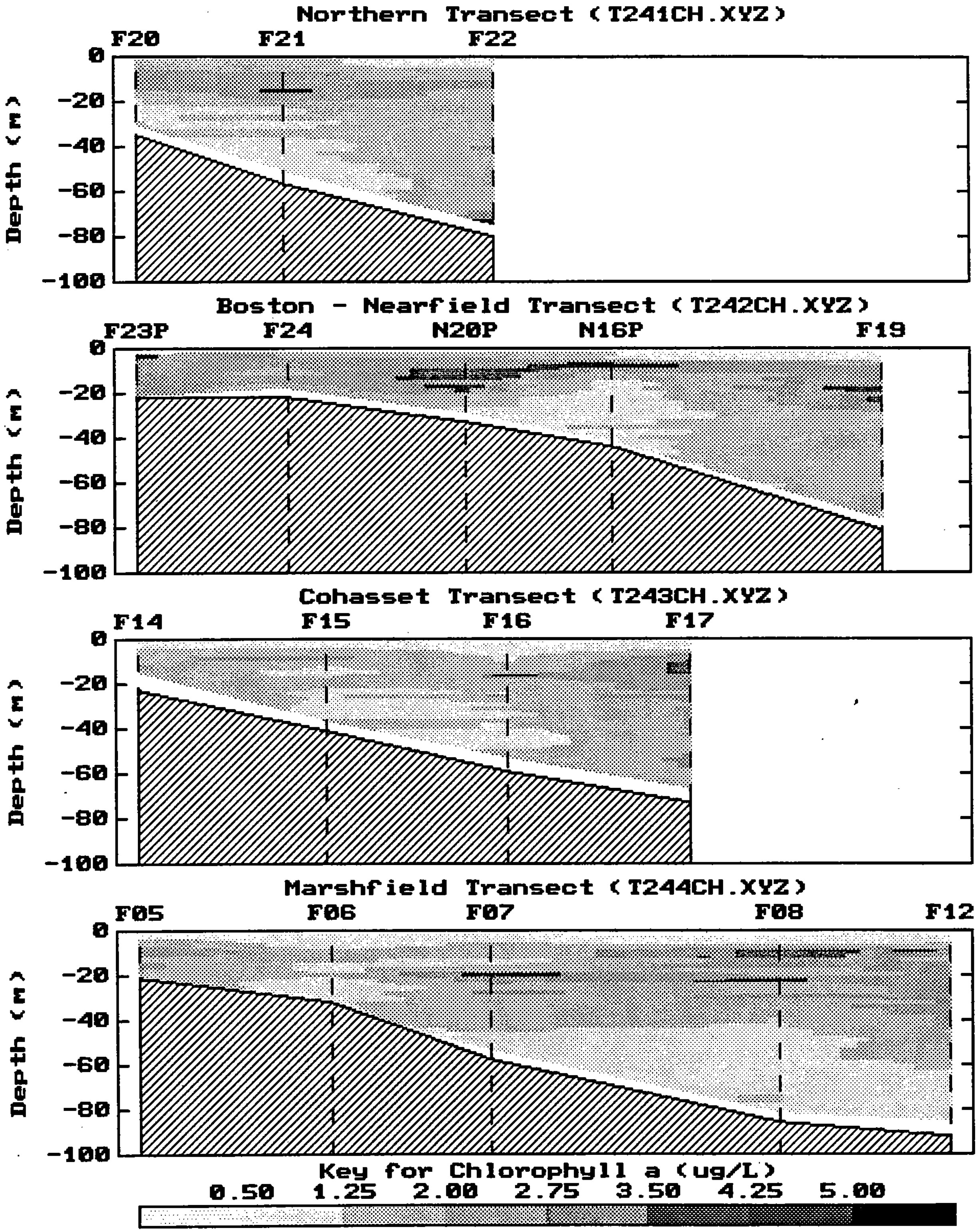


Figure 3-11. Vertical section contours of fluorescence (as μg Chl L^{-1}) in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

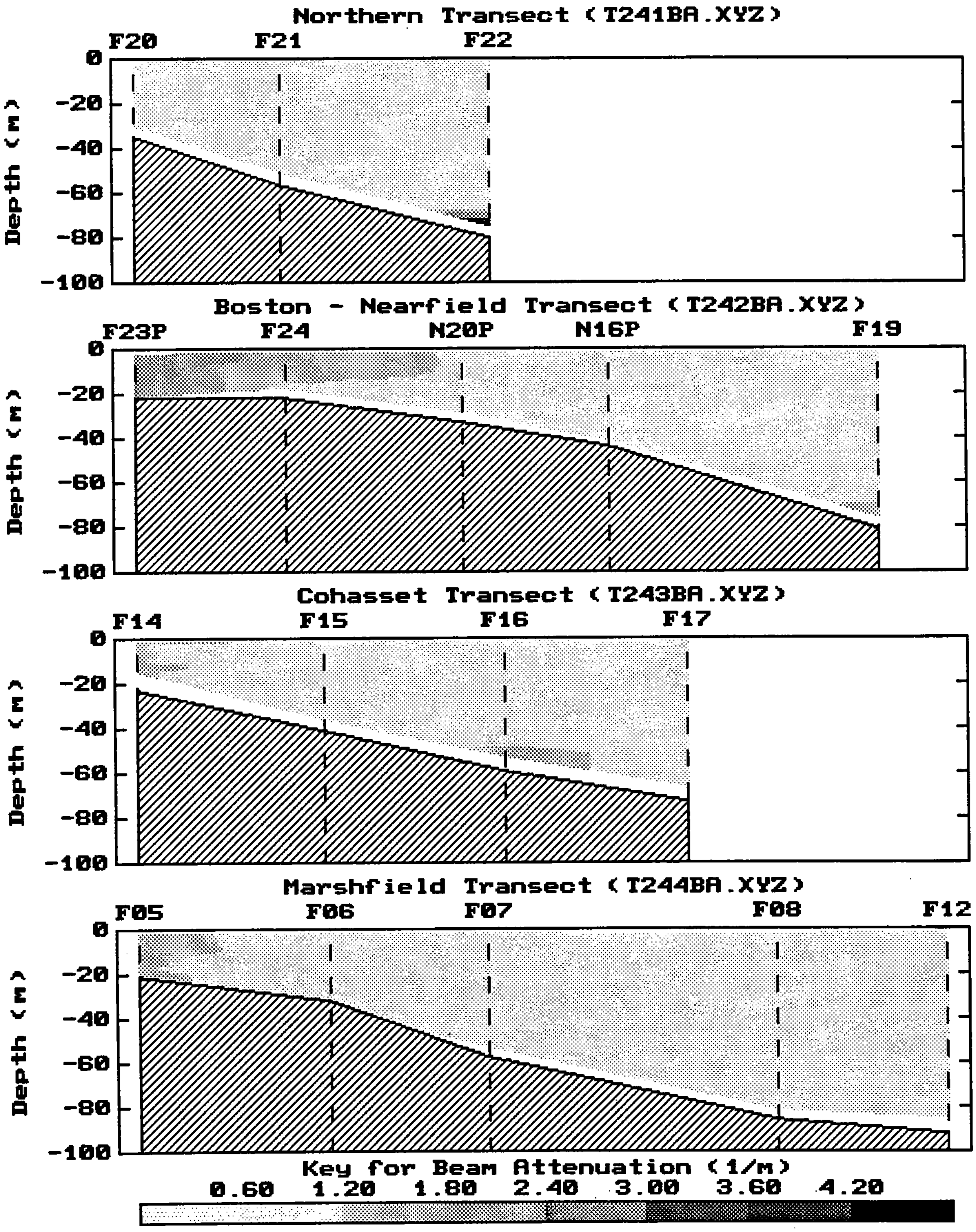


Figure 3-12. Vertical section contours of beam attenuation in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

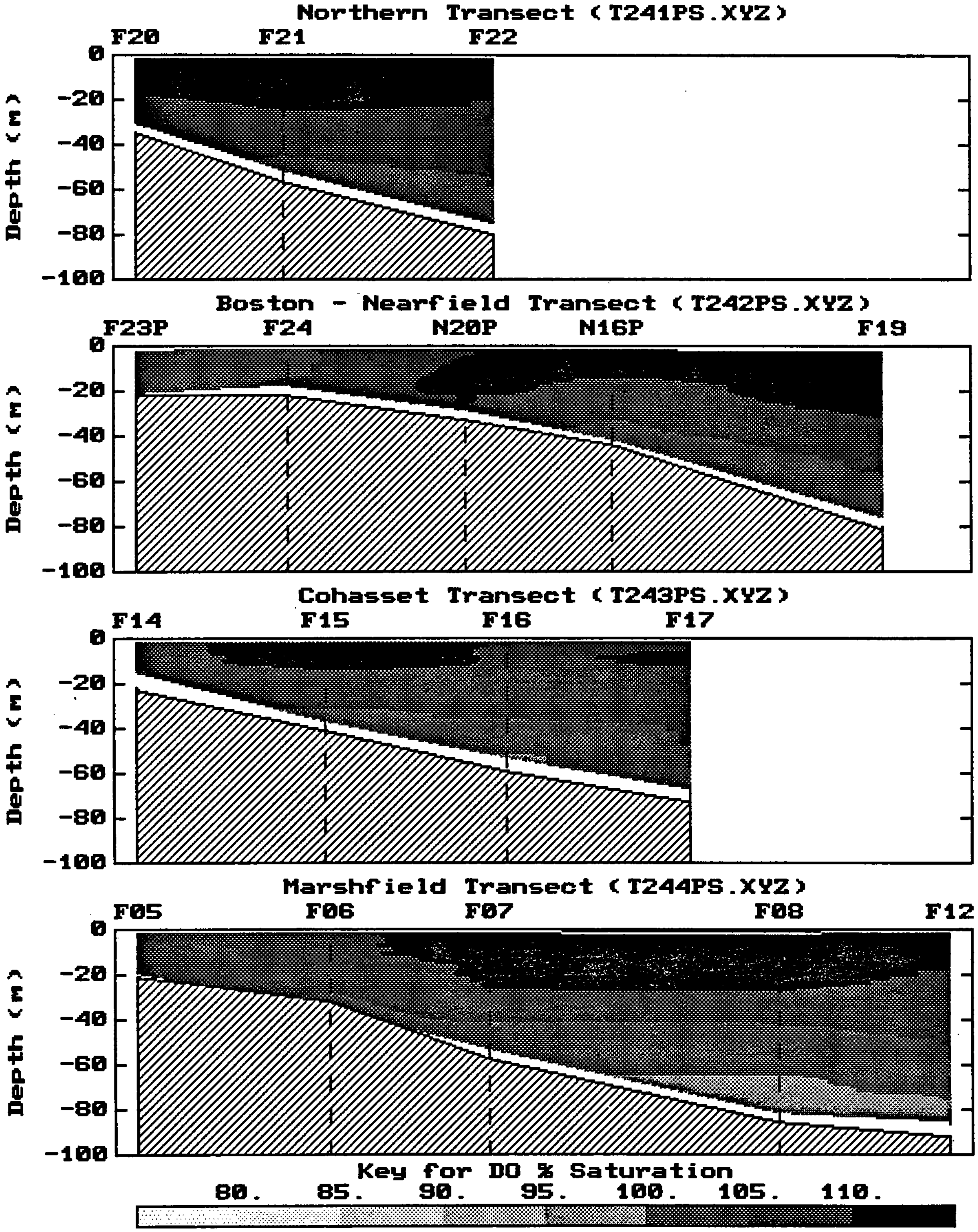


Figure 3-13. Vertical section contours of dissolved oxygen (% saturation) in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

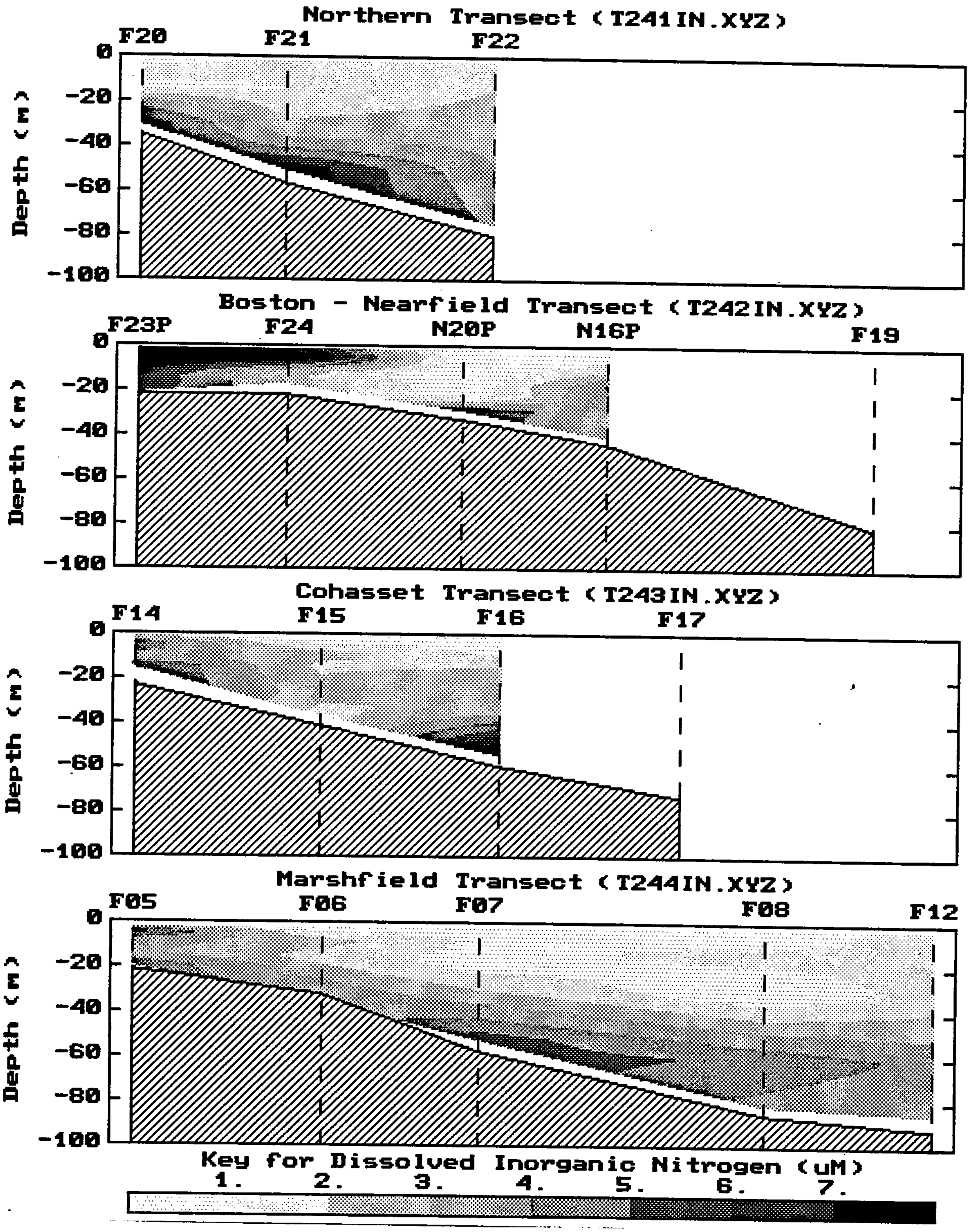


Figure 3-14a. Vertical section contours of dissolved inorganic nitrogen (DIN, μM) in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from discrete bottle samples (Appendix A).

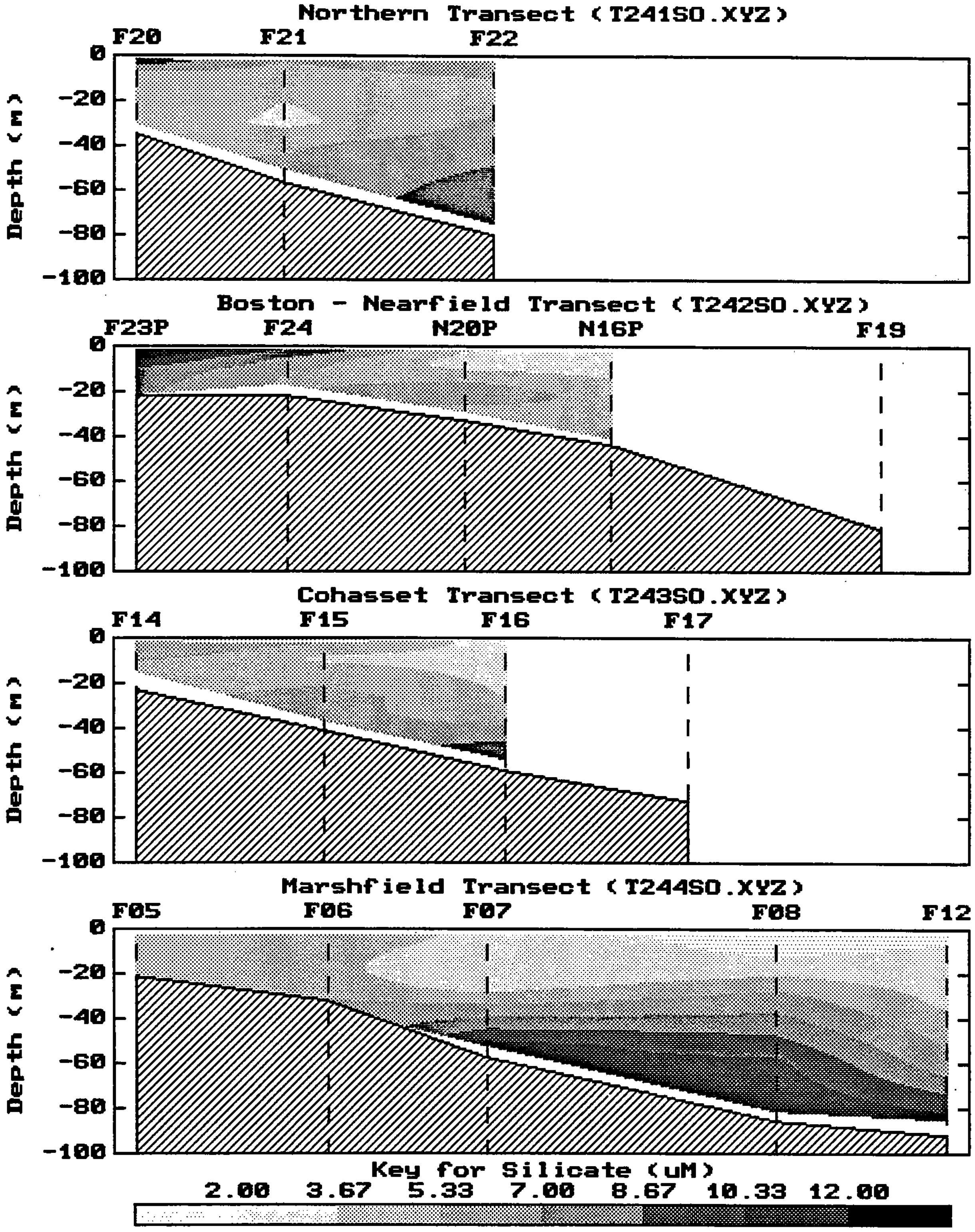


Figure 3-14b. Vertical section contours of silicate (SiO_4, μM) in early April 1993 for standard transects (see Figure 3-9). The data used to produce contours are from discrete bottle samples (Appendix A).

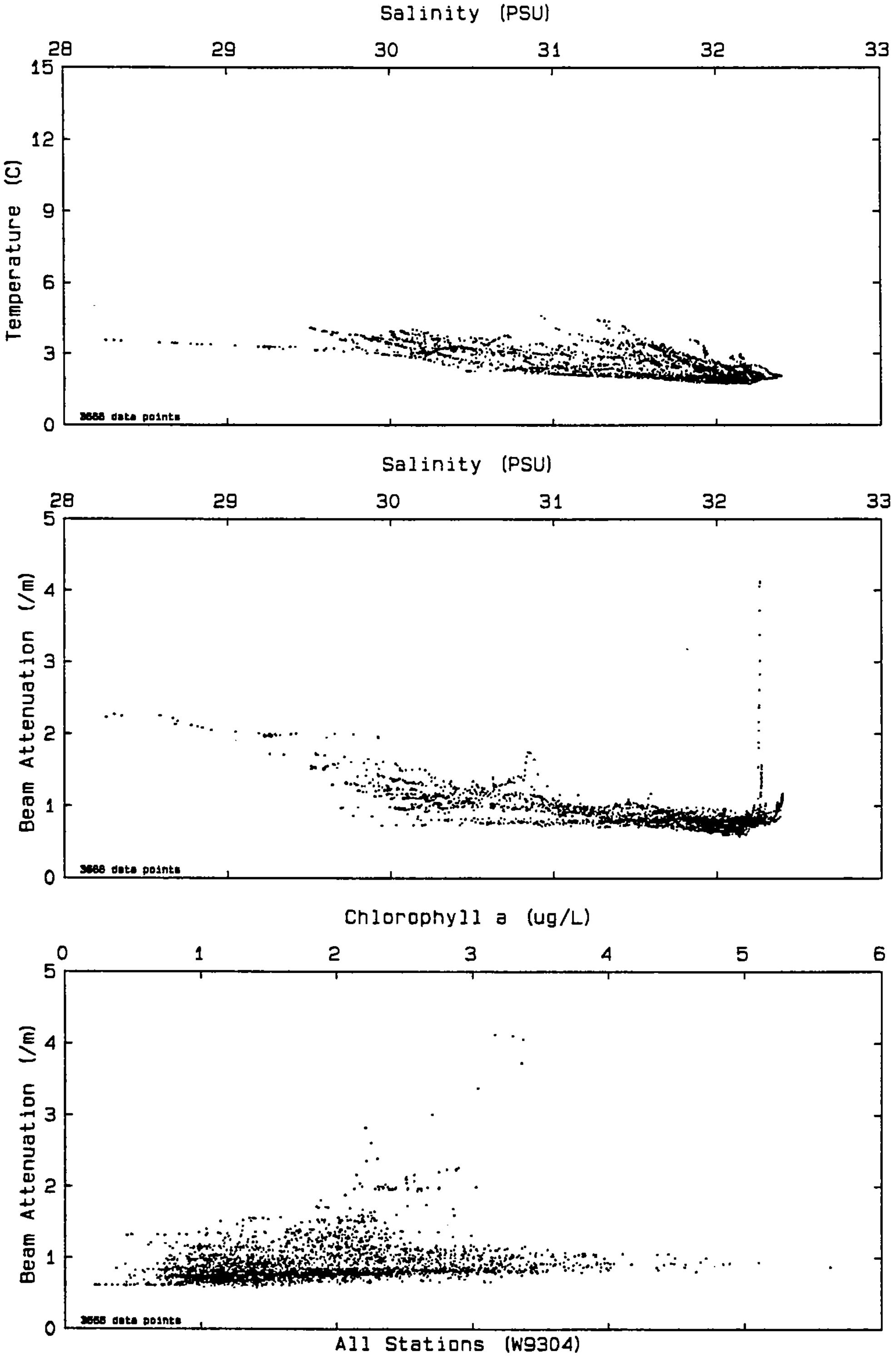


Figure 3-15a. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in early April 1993. Regional plots are in Appendix C.

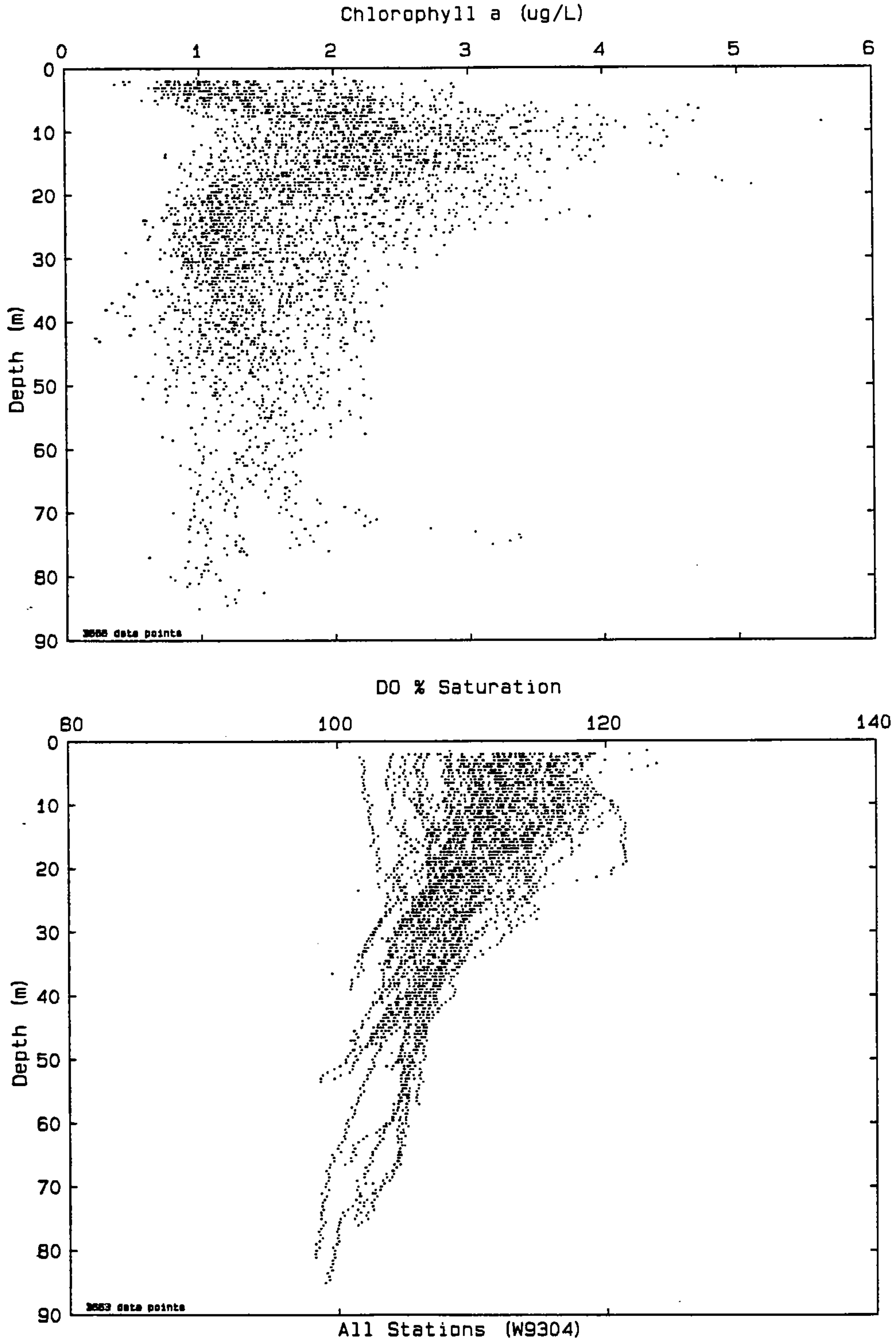


Figure 3-15b. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in early April 1993. Regional plots are in Appendix C.

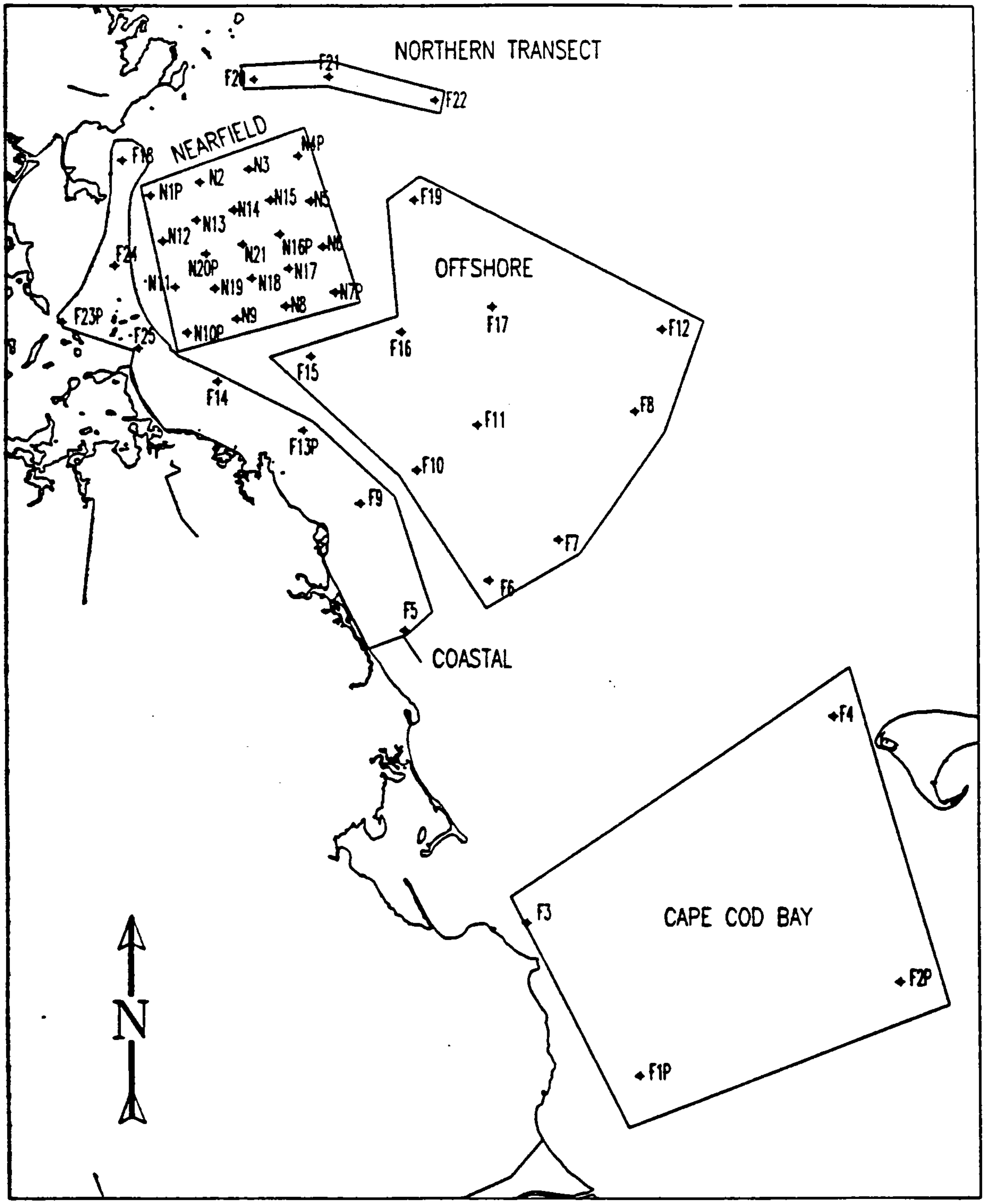


Figure 3-16. Map to show station groups designated in Figures 3-17 through 3-22. Massachusetts Bay stations were separated into four groups based on water depth and geographic position; Cape Cod Bay has four stations.

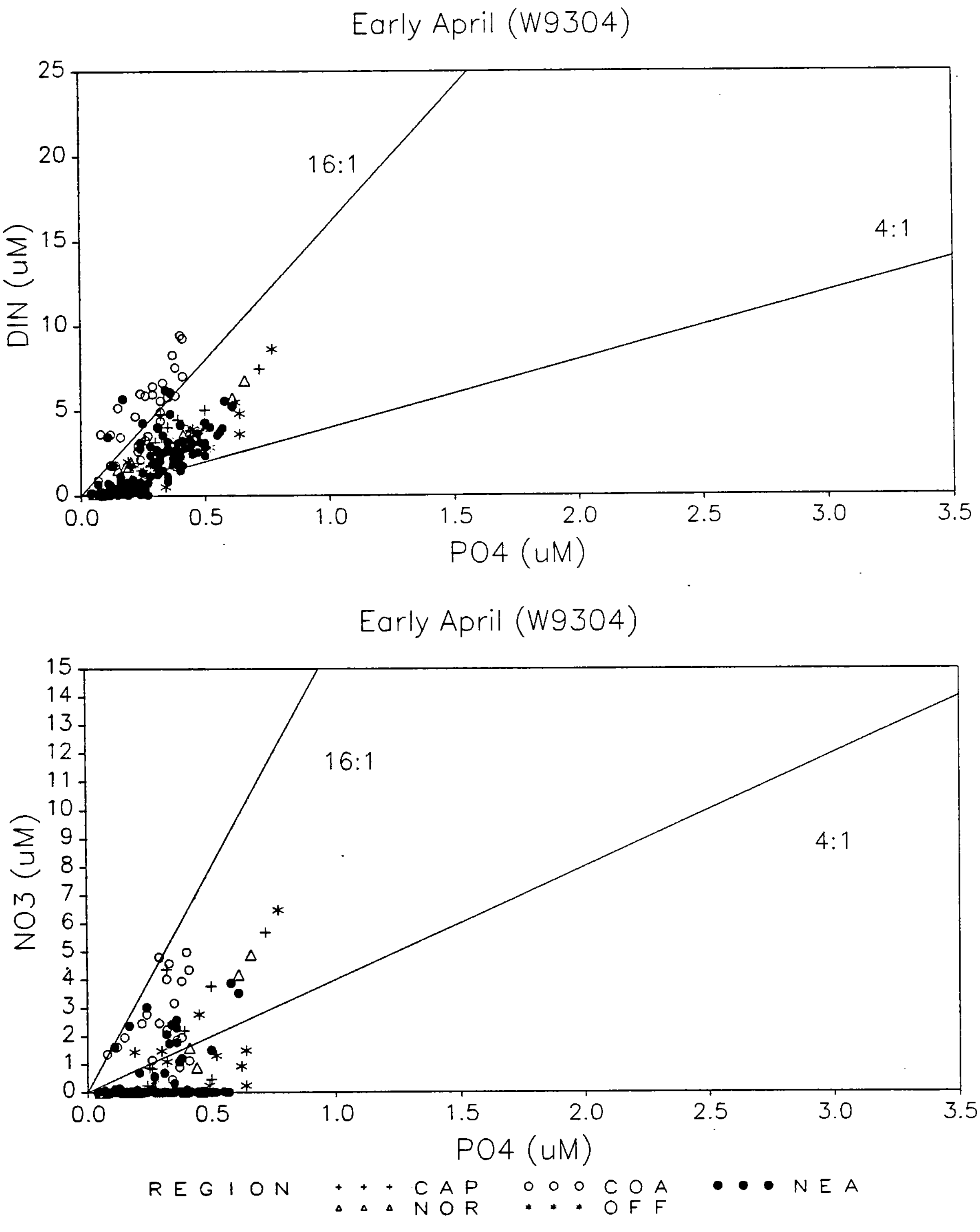


Figure 3-17. Scatter plots of nitrogen forms vs. phosphate during early April 1993. All stations and depths are included. Lines show constant proportions of nitrogen relative to phosphate. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

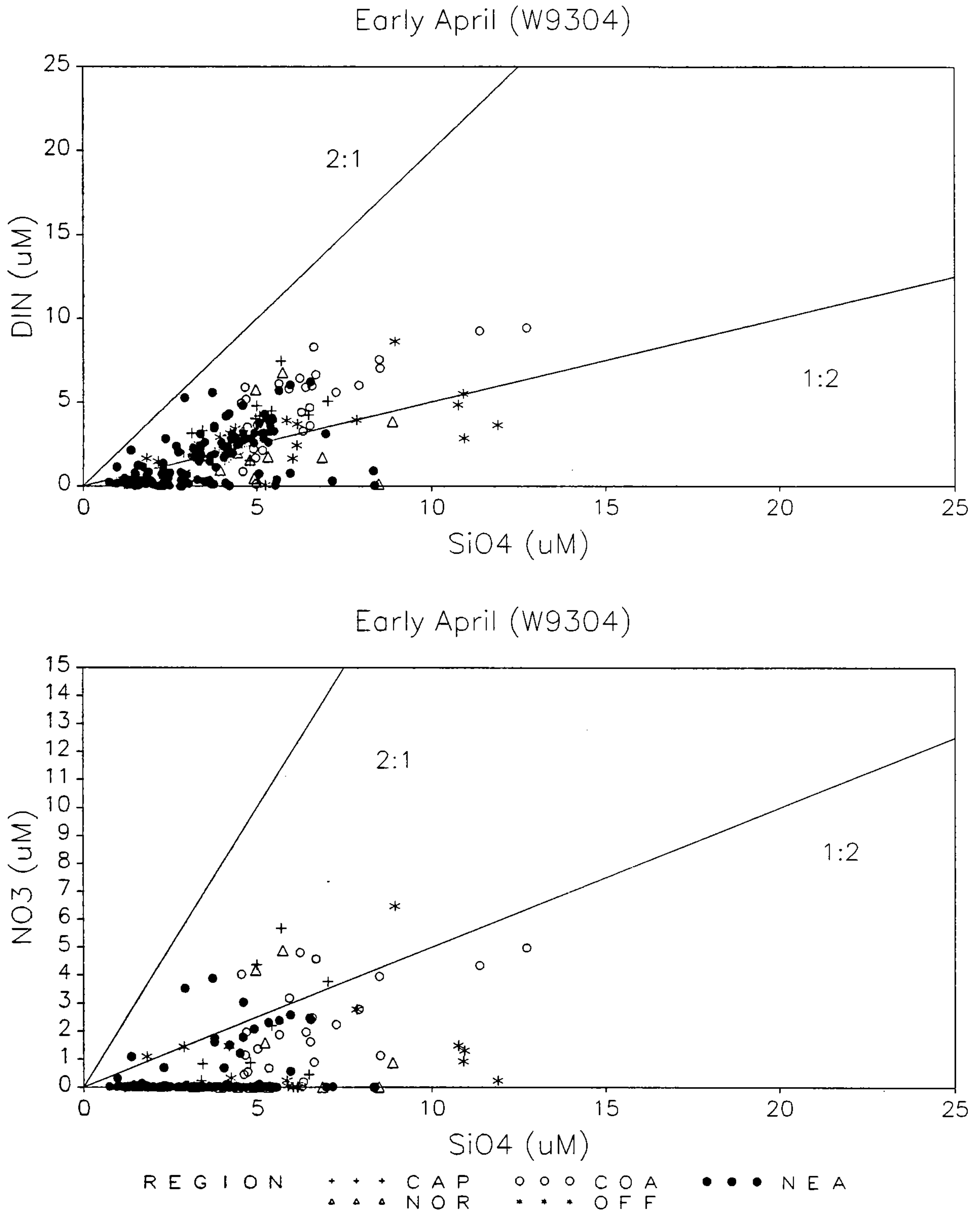


Figure 3-18. Scatter plots of nitrogen forms vs. silicate during early April 1993. All stations and depths are included. Lines show constant proportions of nitrogen relative to silicate. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

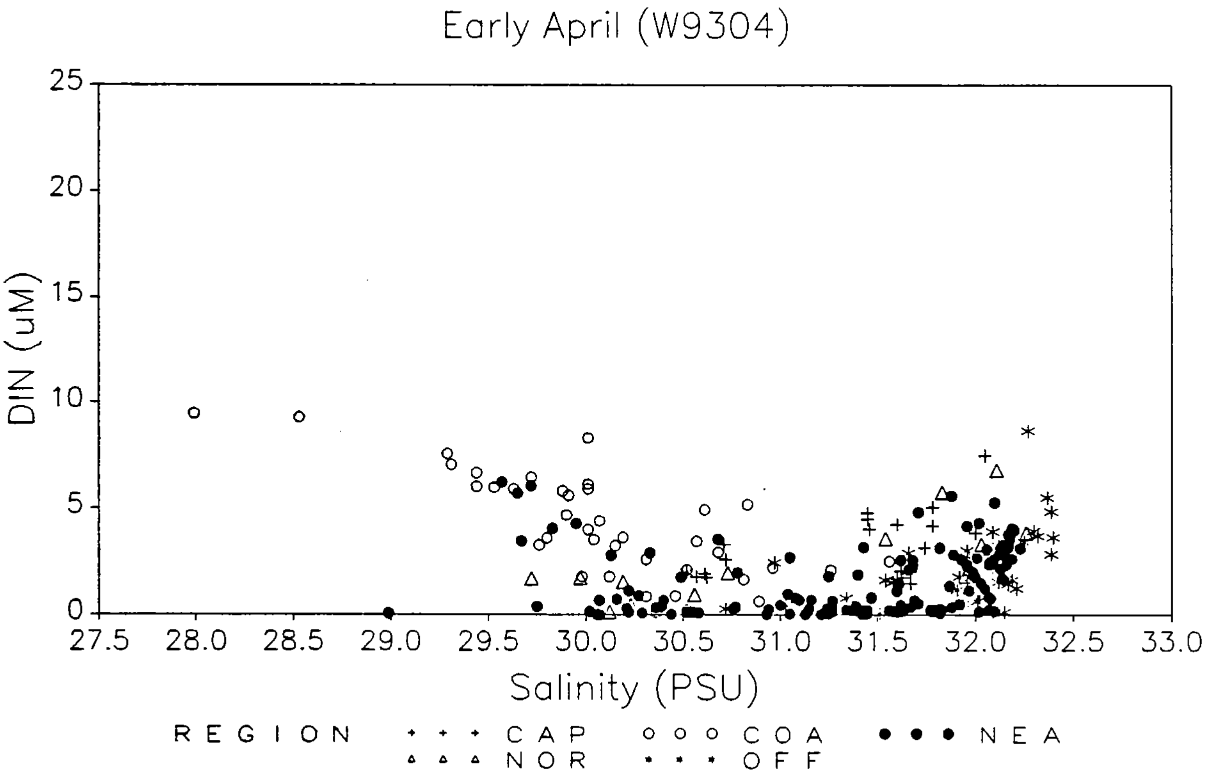


Figure 3-19. Dissolved inorganic nitrogen vs. salinity in early April 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

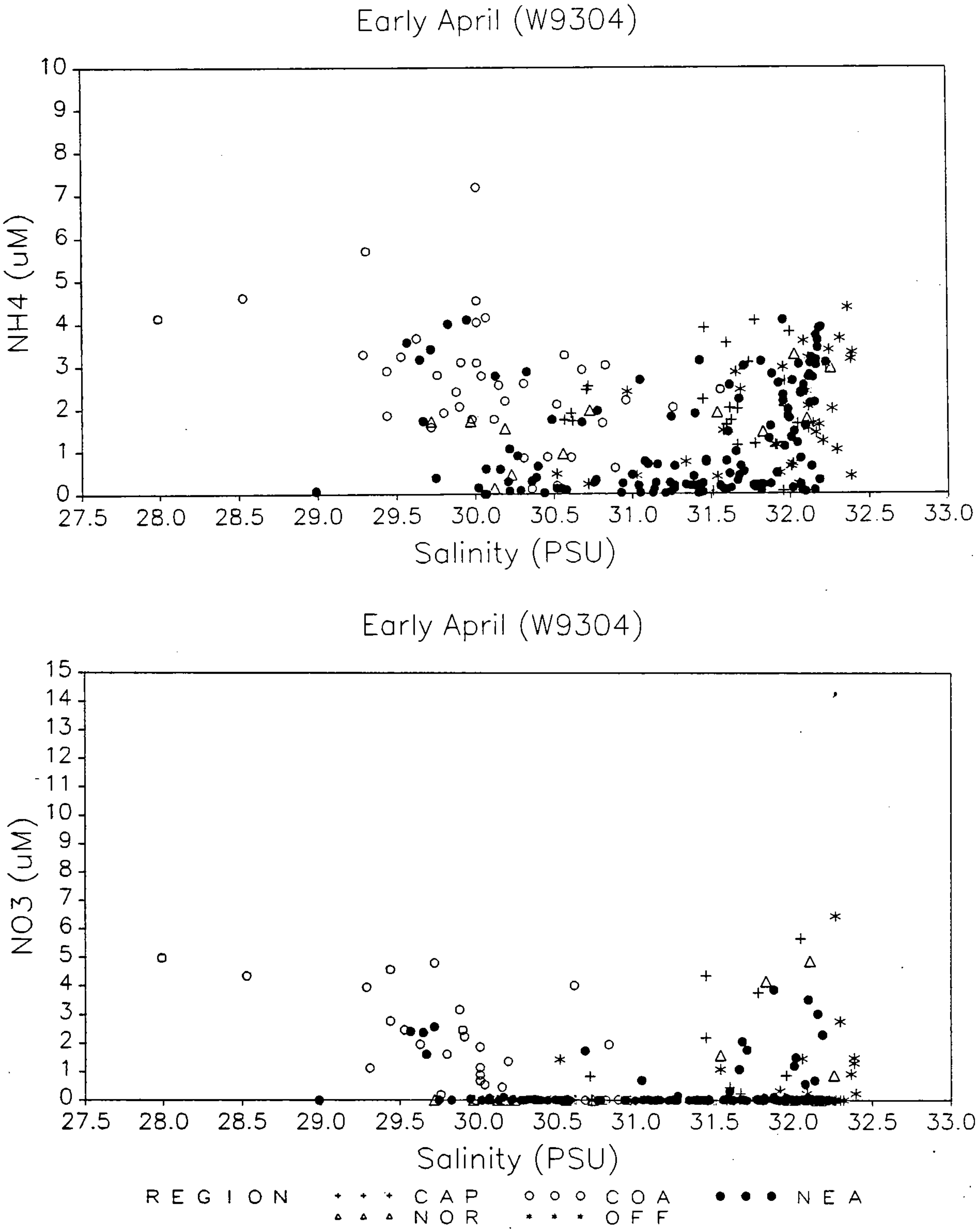


Figure 3-20. **Ammonia and nitrate vs. salinity in early April 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.**

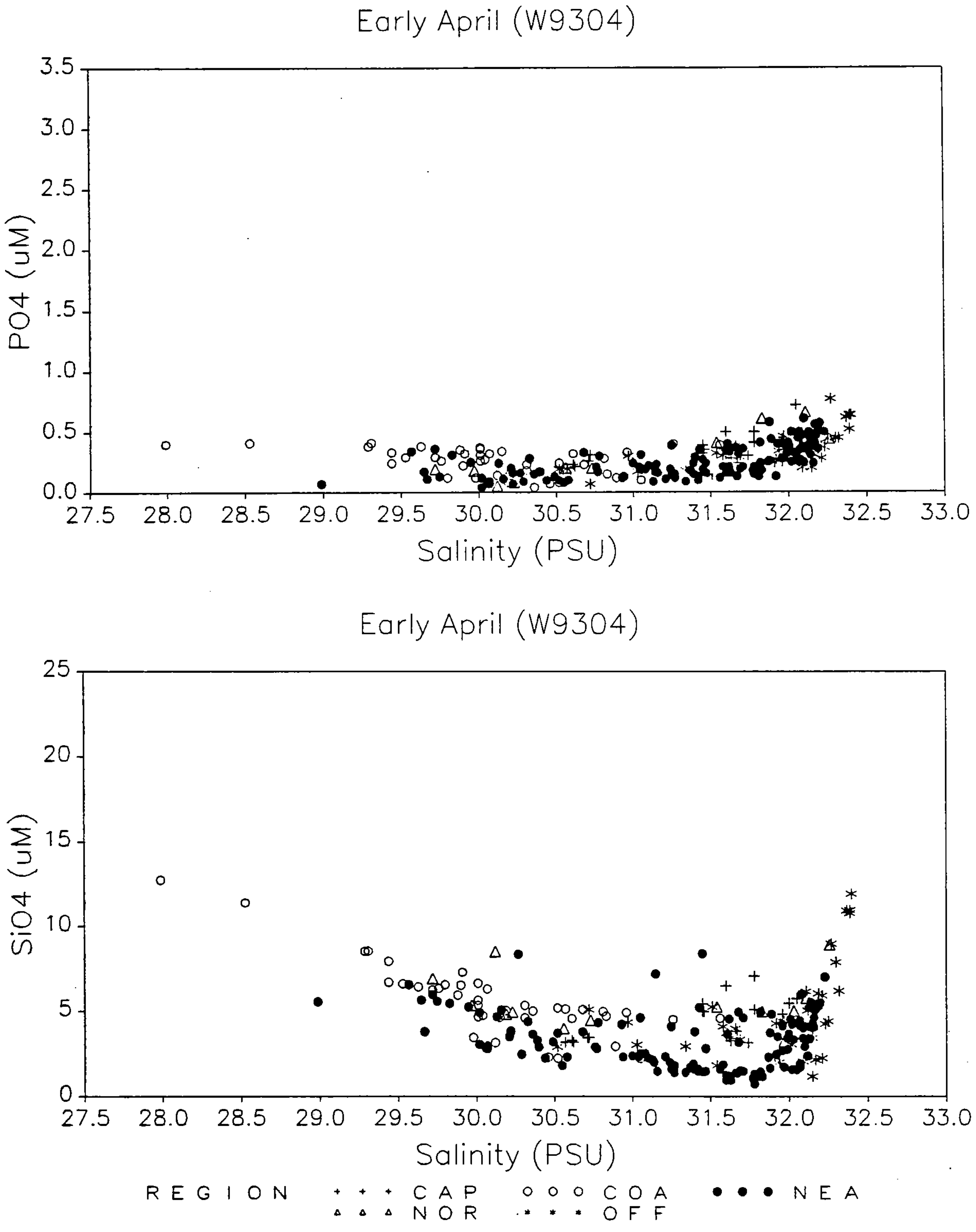


Figure 3-21. Phosphate and silicate vs. salinity in early April 1993. All stations and depths are included. Data are given in Appendix A. The regions correspond to the groups of stations shown in Figure 3-16.

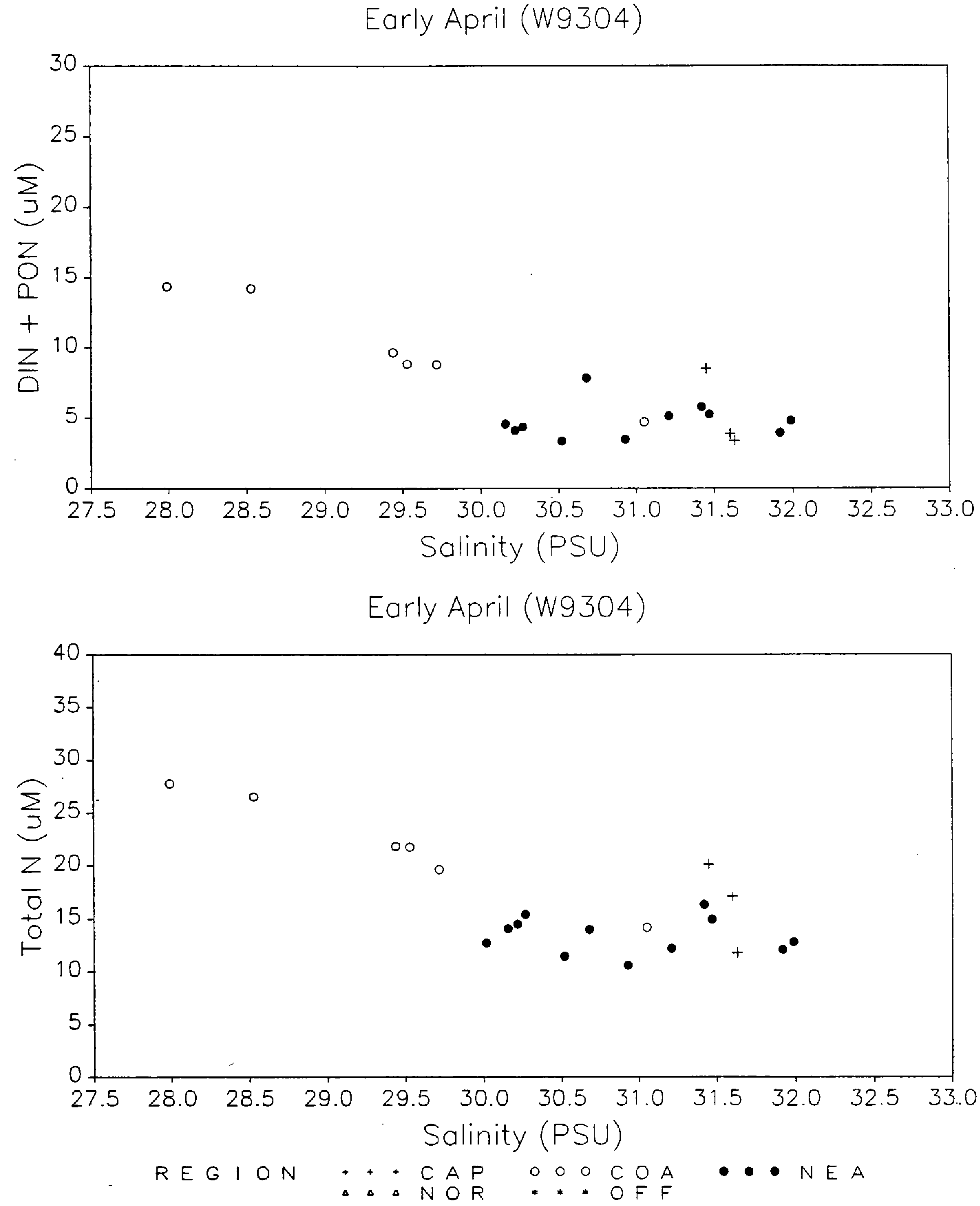


Figure 3-22. Nitrogen forms vs. salinity in early April 1993. Data are from BioProductivity stations and special station F25. The station groups are coded as given in Figure 3-16; there are no BioProductivity stations in the offshore or northern transect groups. Data are given in Appendix A. Dissolved inorganic nitrogen = DIN, particulate organic nitrogen = PON, and total nitrogen (TN) = total dissolved nitrogen (TDN) + PON.

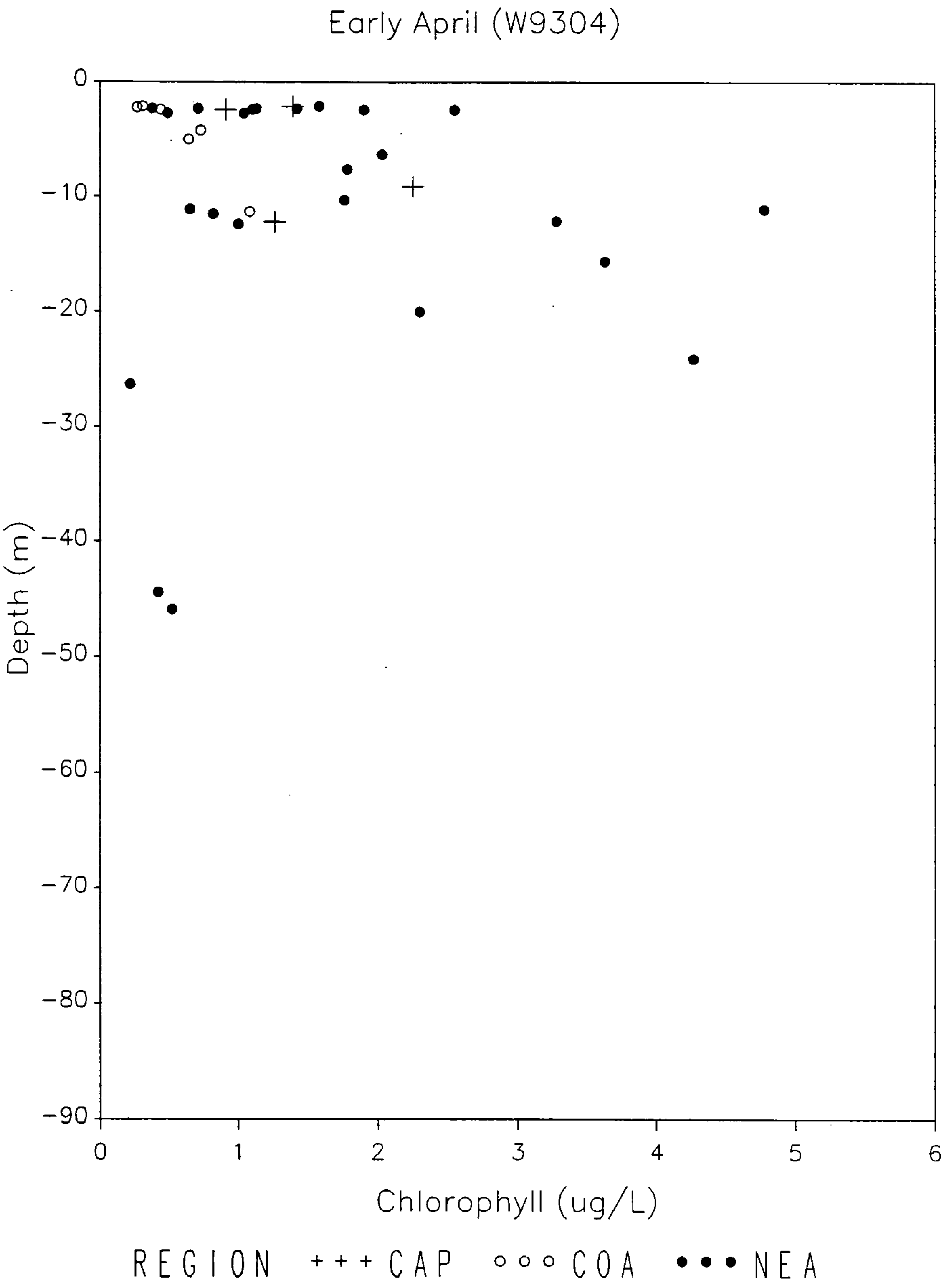


Figure 3-23. Chlorophyll (extracted samples) at BioProductivity stations and special station F25 as a function of depth in early April 1993. Data are from farfield (n=22) and nearfield (n=12) surveys. The regions correspond to three of the groups of stations shown in Figure 3-16.

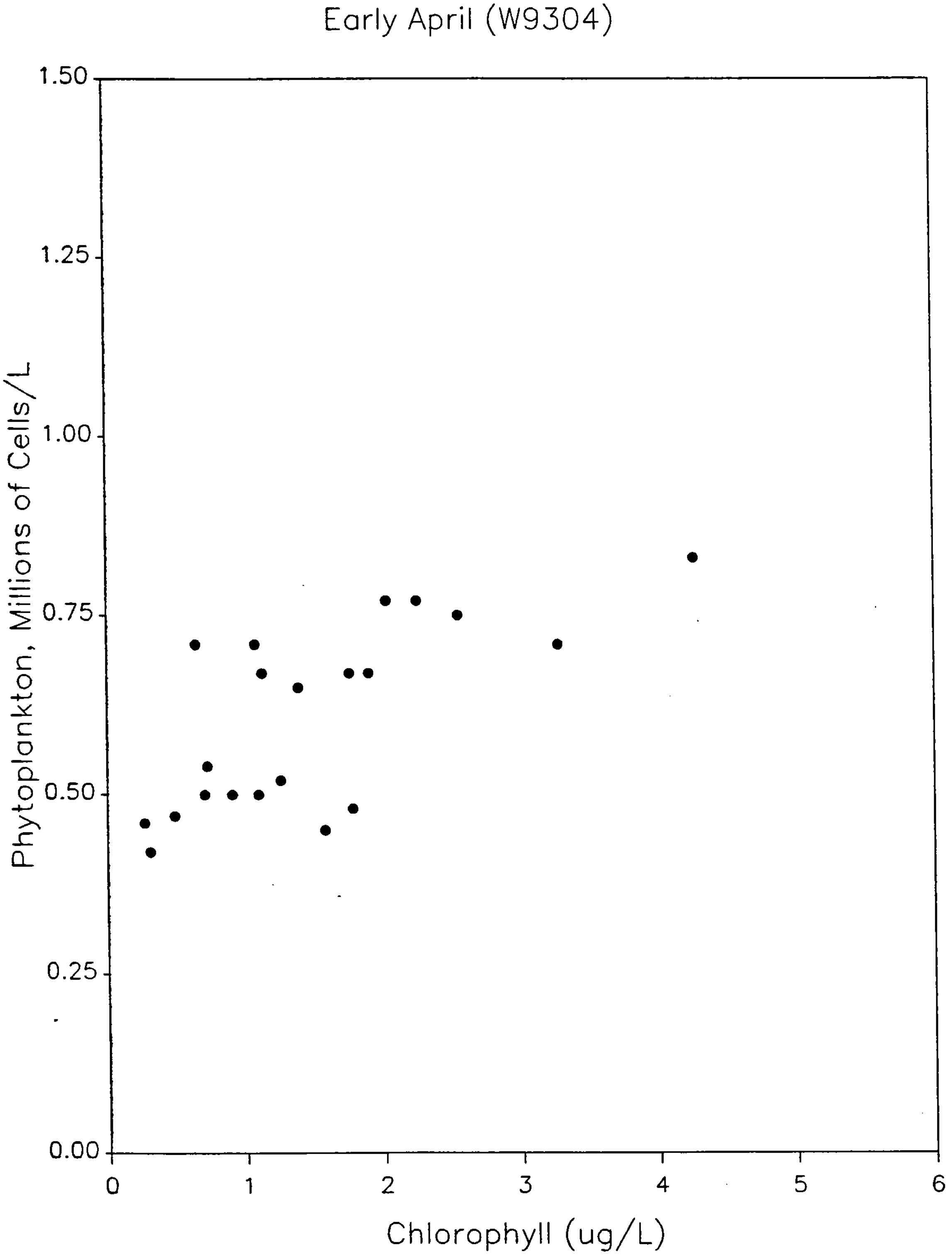


Figure 3-24. Total phytoplankton abundance vs. chlorophyll (extracted samples) at BioProductivity stations in early April 1993. Station N10P surface was analyzed for both farfield and nearfield surveys. Data are given in Appendices A and F.

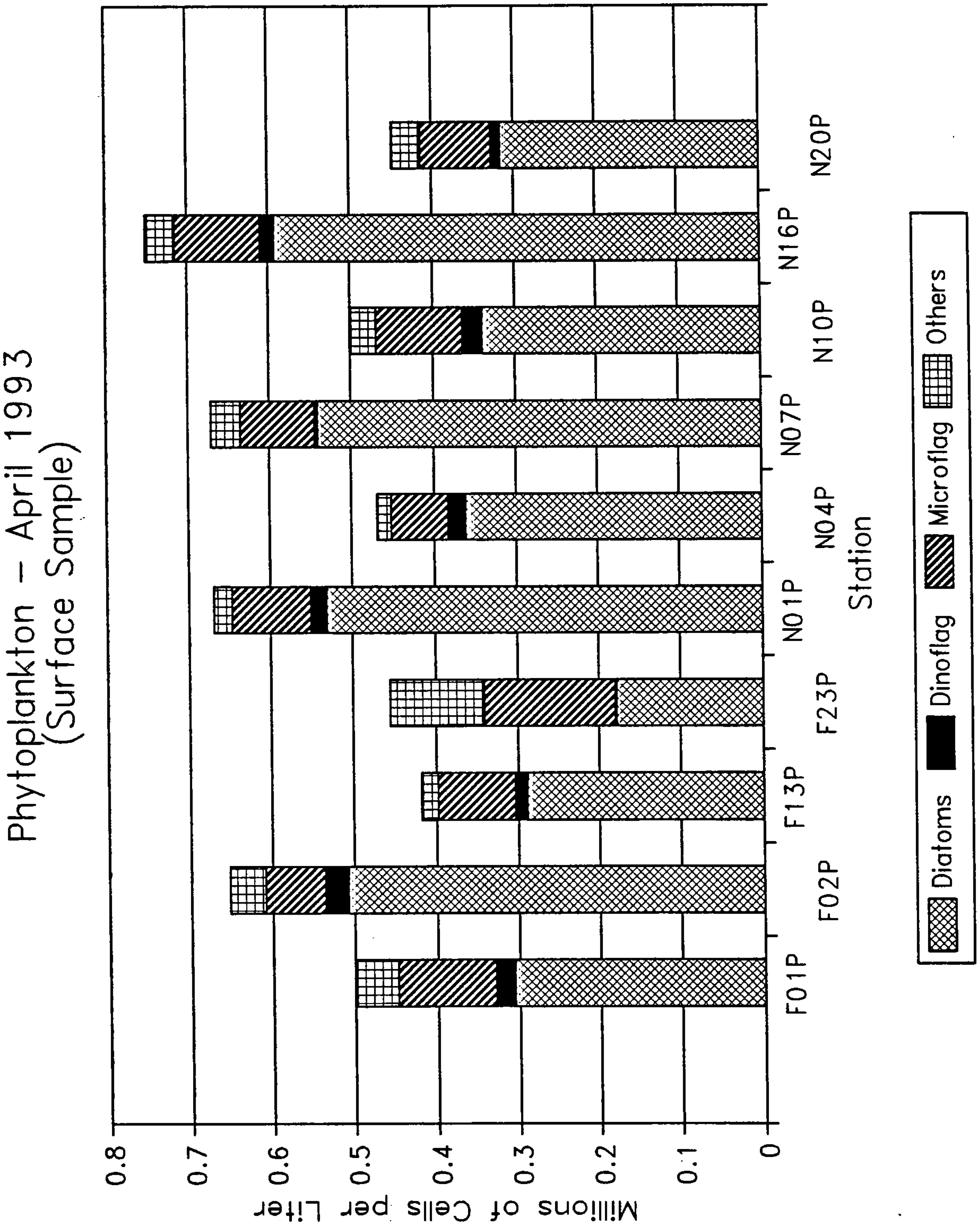


Figure 3-25. **Total phytoplankton abundance, by taxonomic groups, at BioProductivity stations in early April 1993. Data are given in Appendix F.**

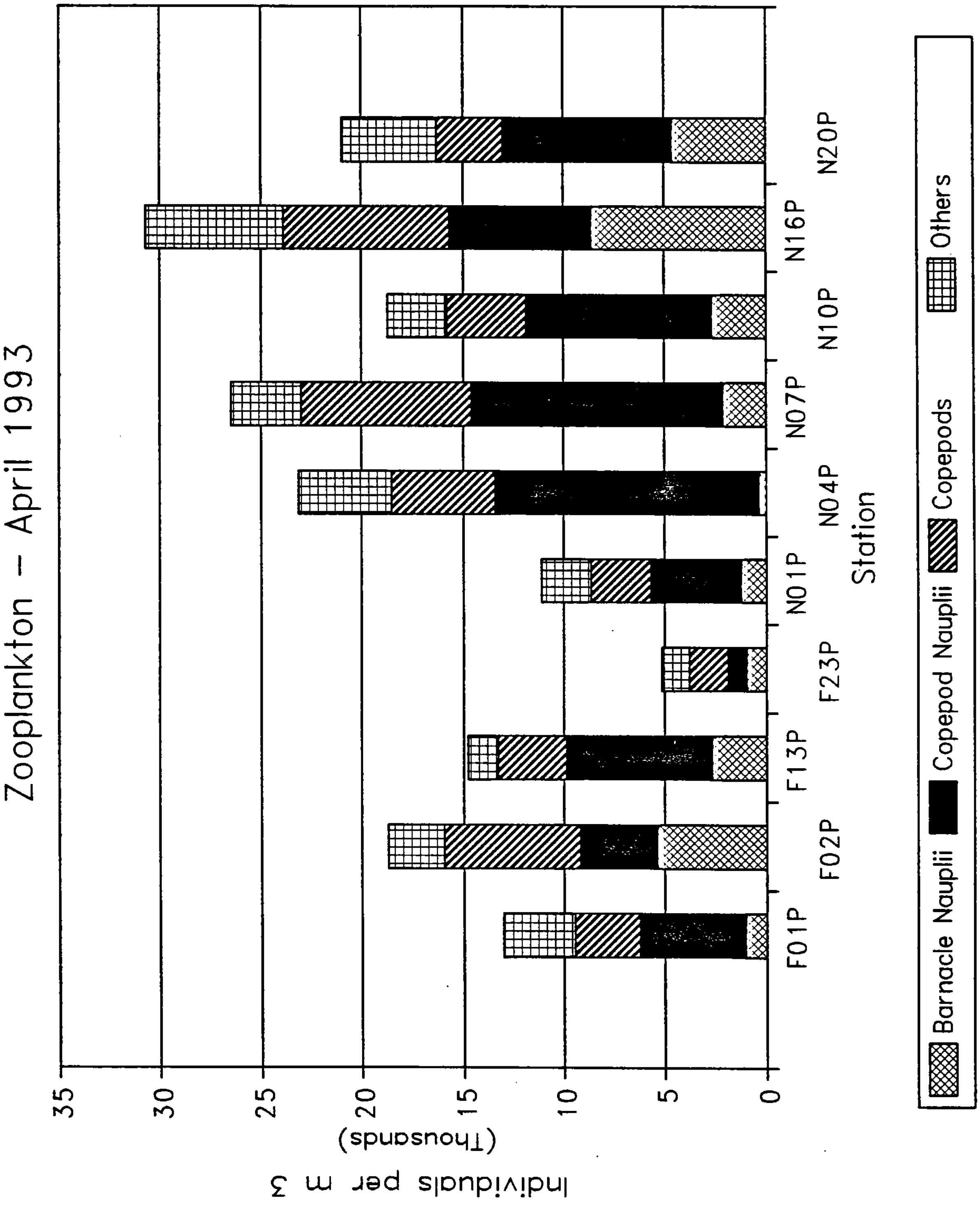
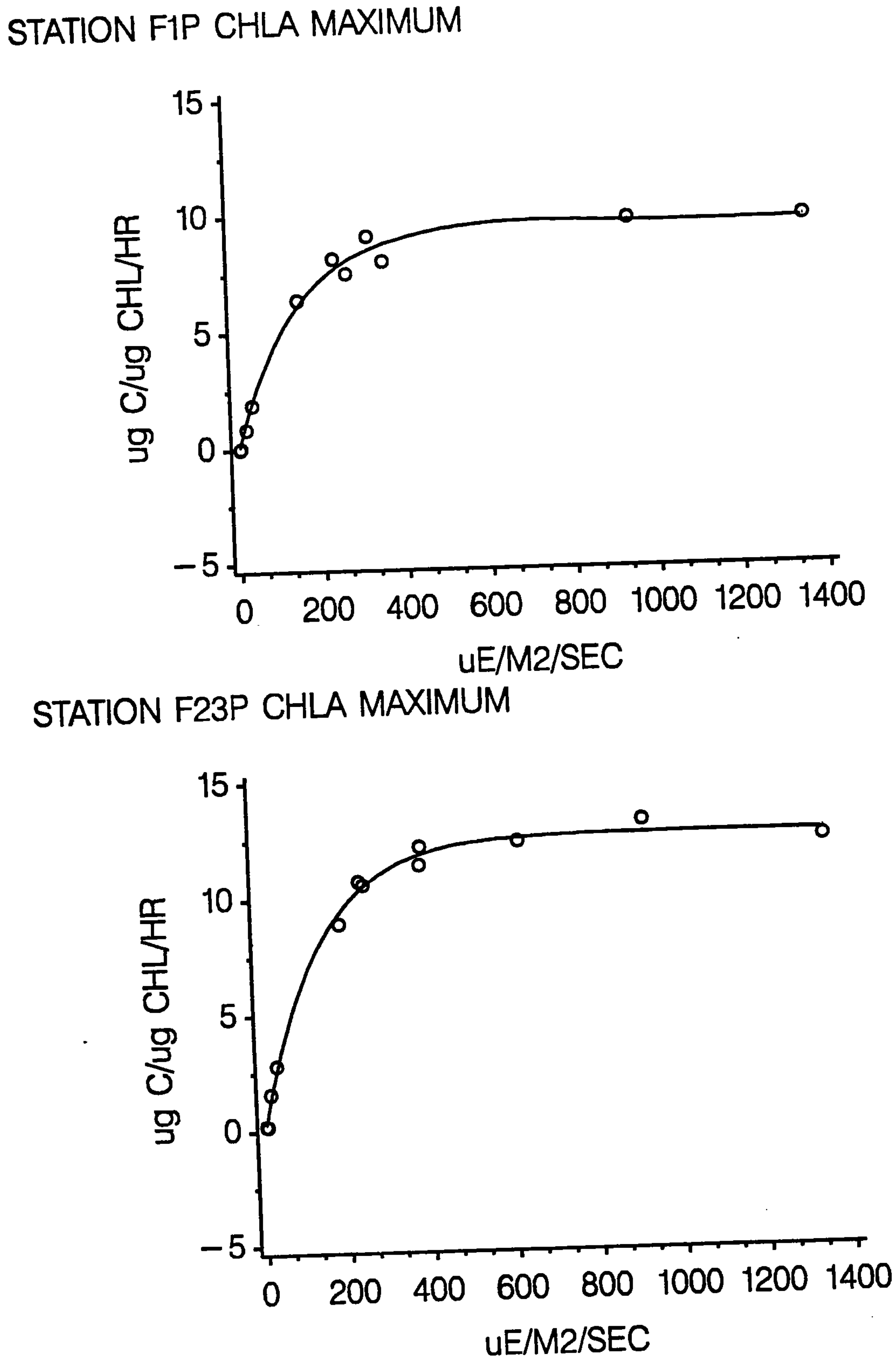


Figure 3-26. **Zooplankton abundance, by groups, at BioProductivity stations in early April 1993. Data are given in Appendix G.**



STATION F1P CHLA MAXIMUM

STATION F23P CHLA MAXIMUM

Figure 3-27. Selected net production (P) vs. irradiance (I) in early April 1993. Data are chlorophyll-normalized rates (see Appendix E).

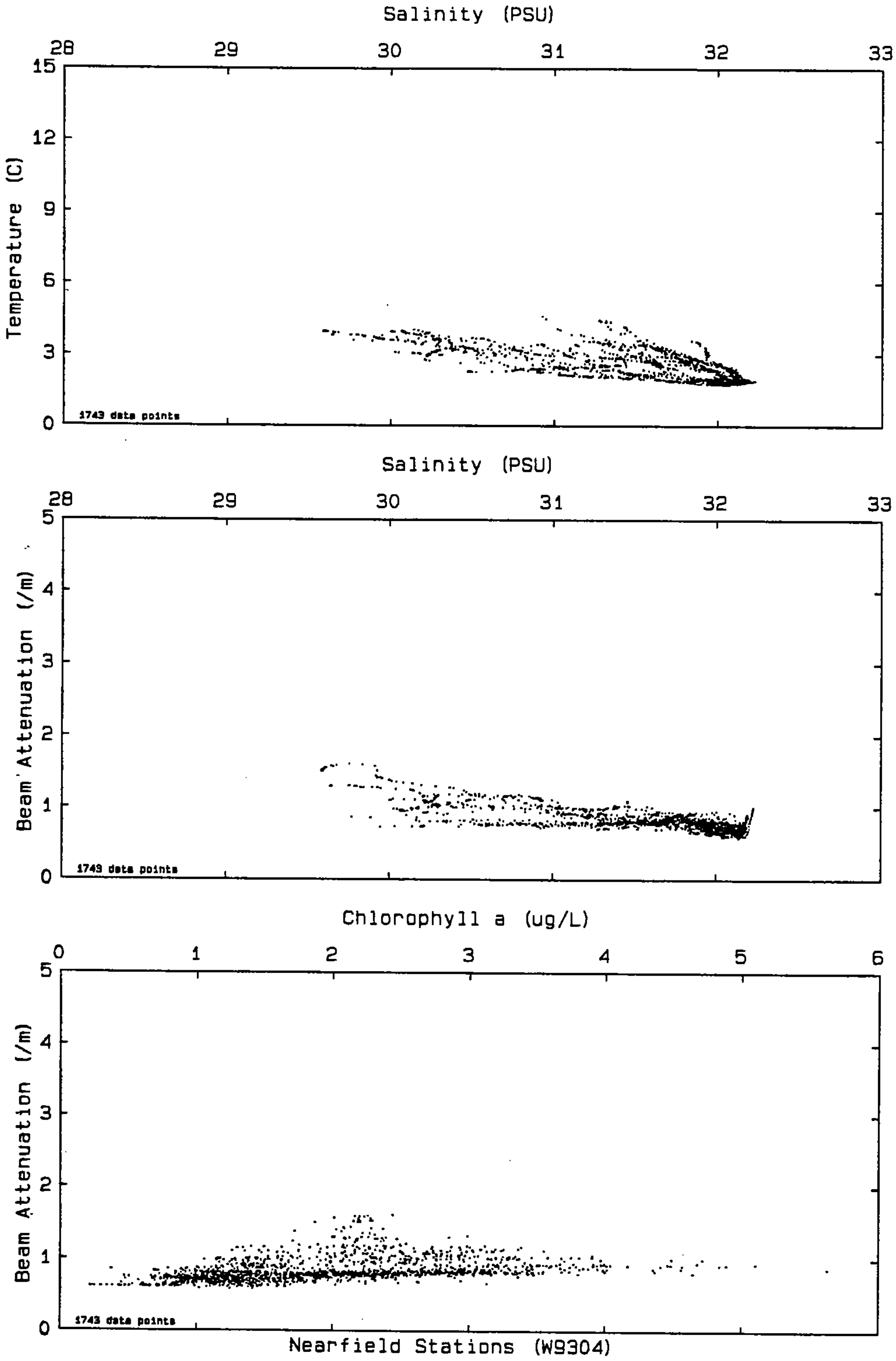


Figure 3-28a. Scatter plots for nearfield stations in early April. Compare to Figure 3-15a.

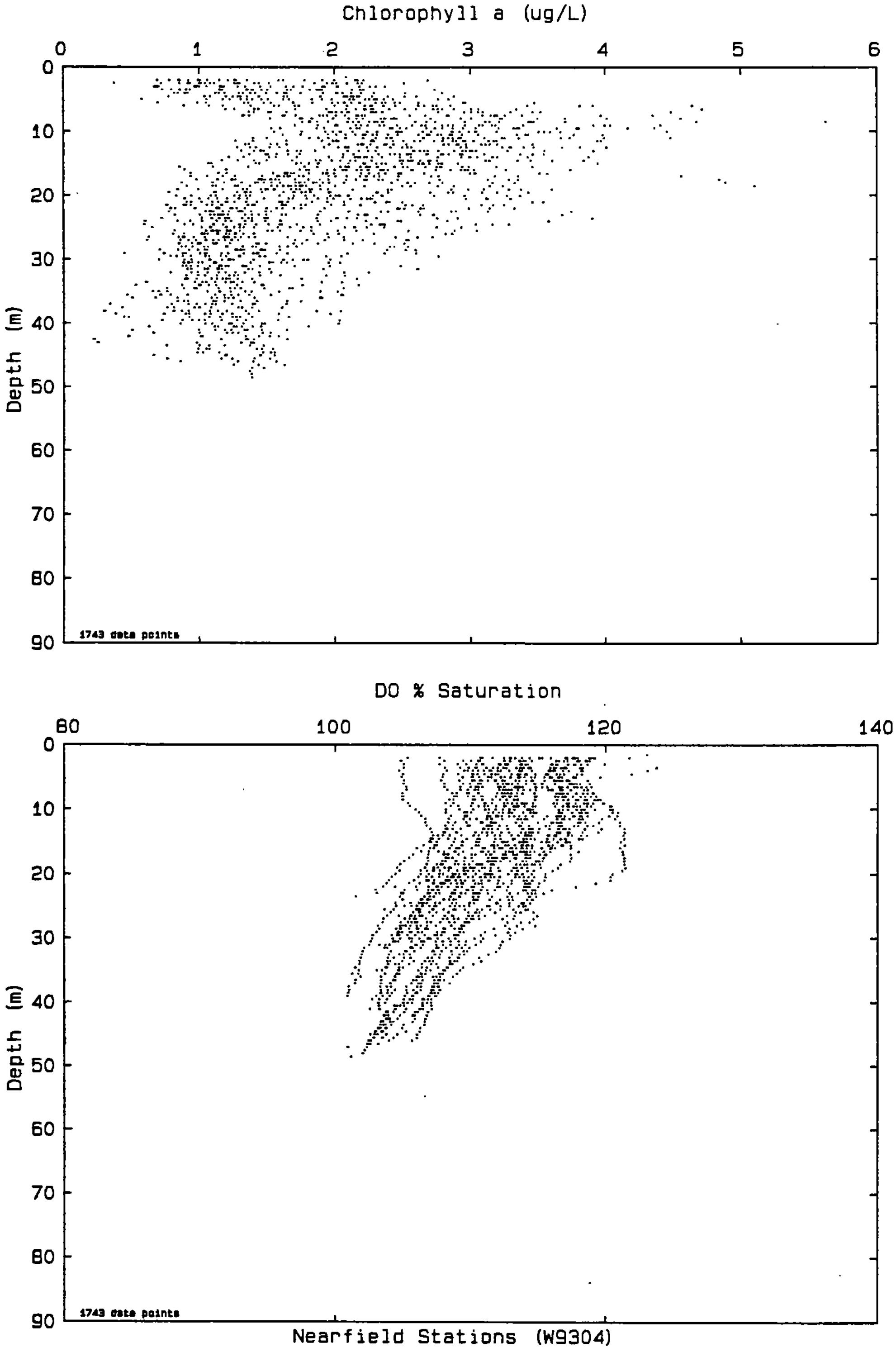


Figure 3-28b. Scatter plots for nearfield stations in early April. Compare to Figure 3-15b.

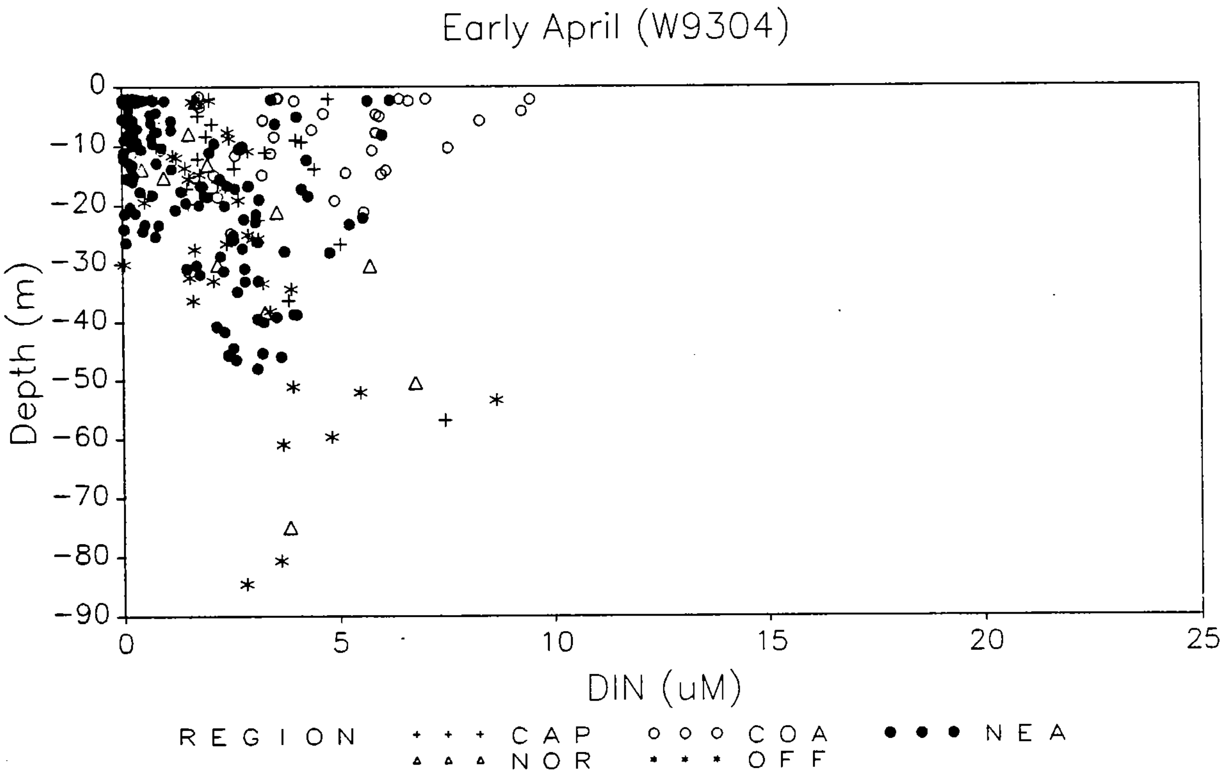


Figure 3-29a. DIN vs. depth in early April 1993. The regions correspond to the groups of stations shown in Figure 3-16.

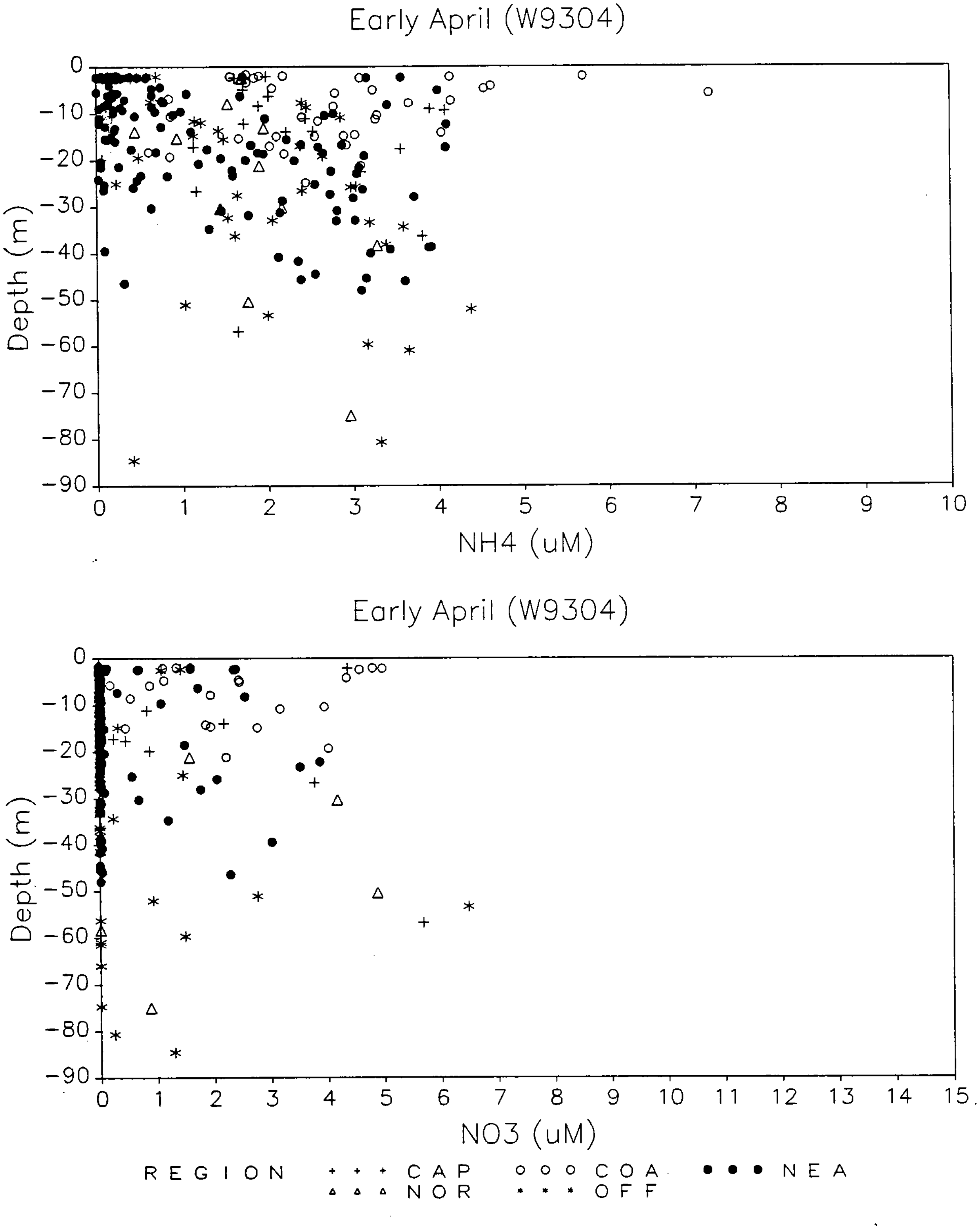


Figure 3-29b. NH$_4$ and NO$_3$ vs. depth in early April 1993. The regions correspond to the groups of stations shown in Figure 3-16.

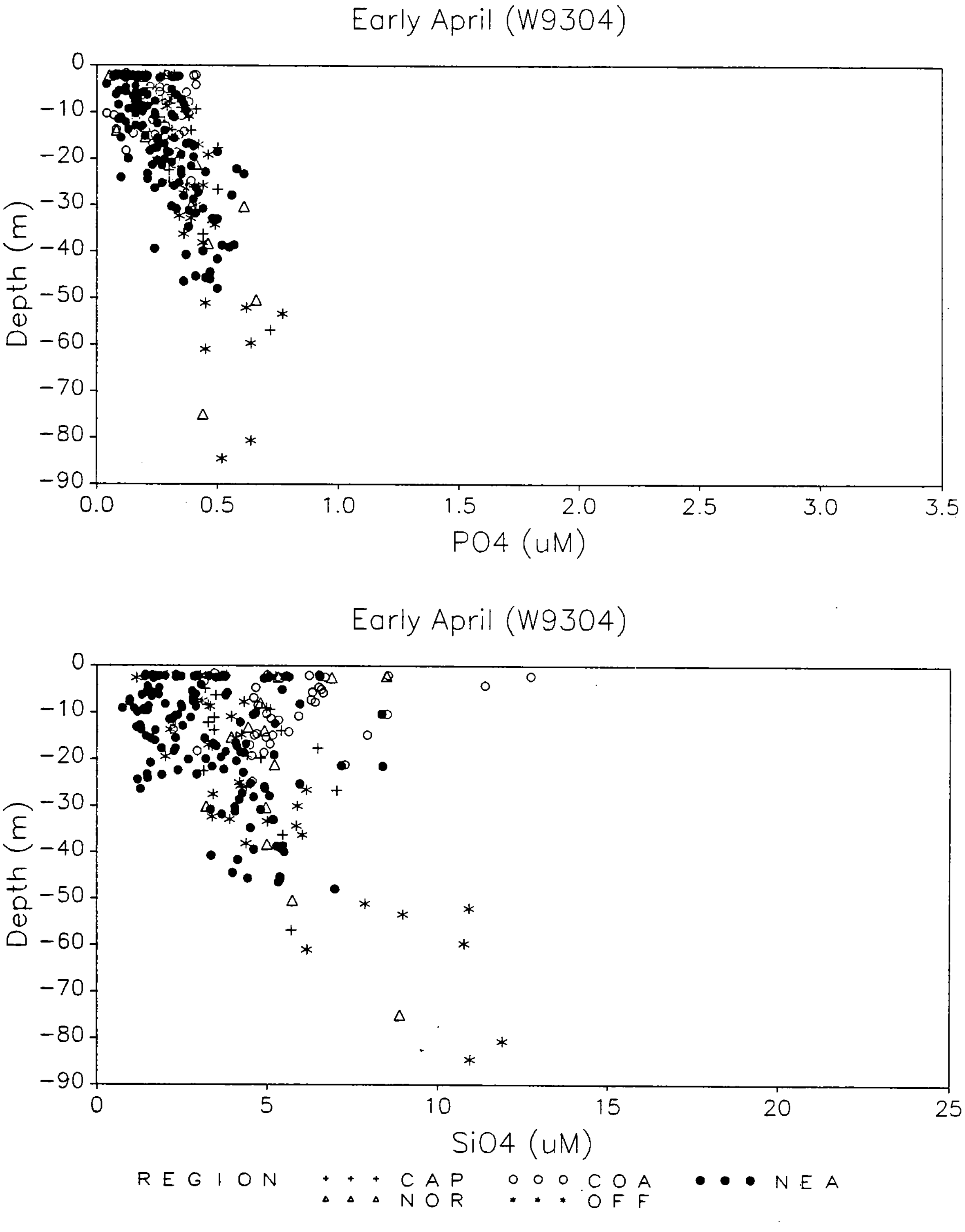


Figure 3-29c. PO_4 and SiO_4 vs. depth in early April 1993. The regions correspond to the groups of stations shown in Figure 3-16.

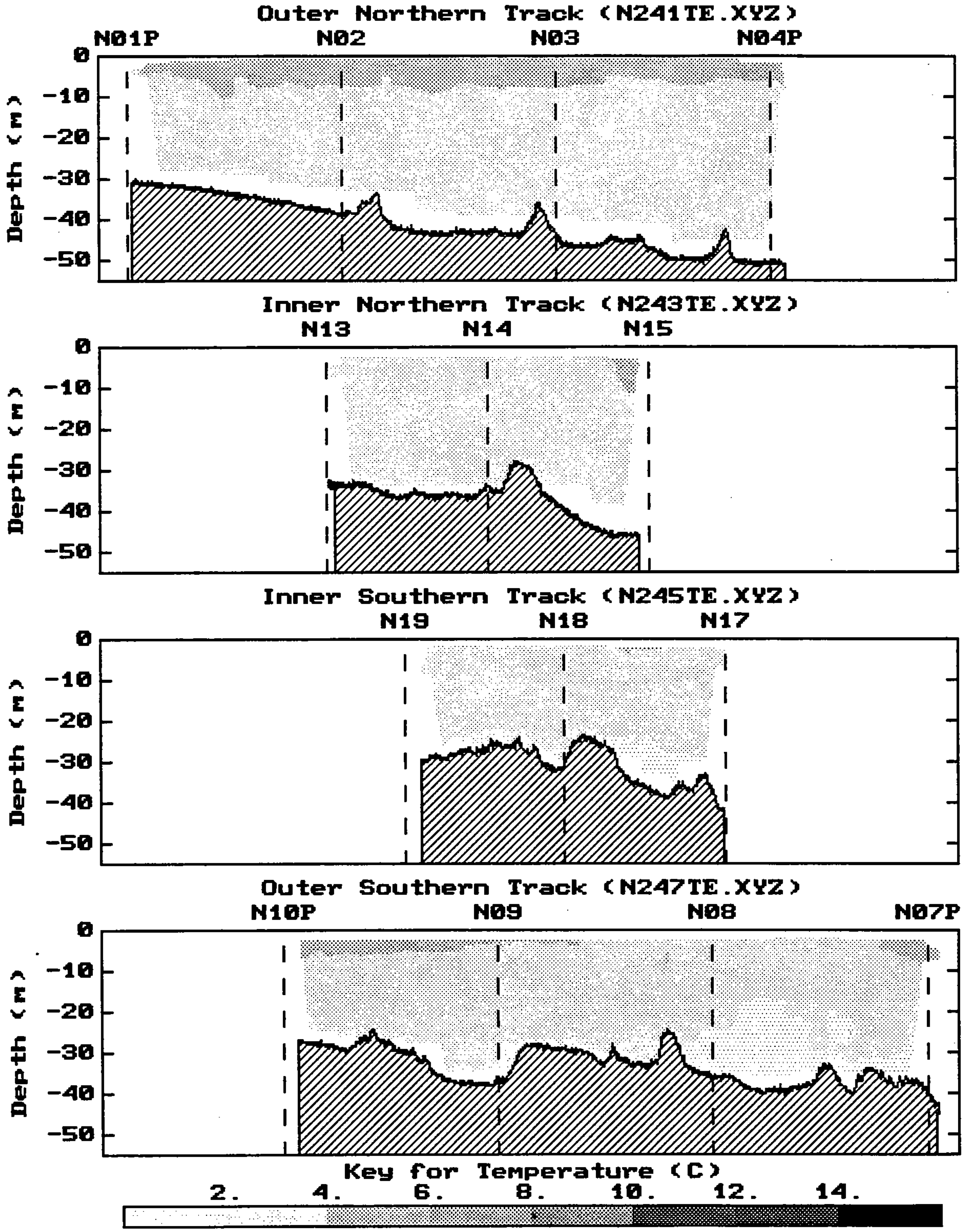


Figure 3-30a. Vertical section contours of temperature generated for tow-yo profiling conducted in early April 1993. The view is towards the north.

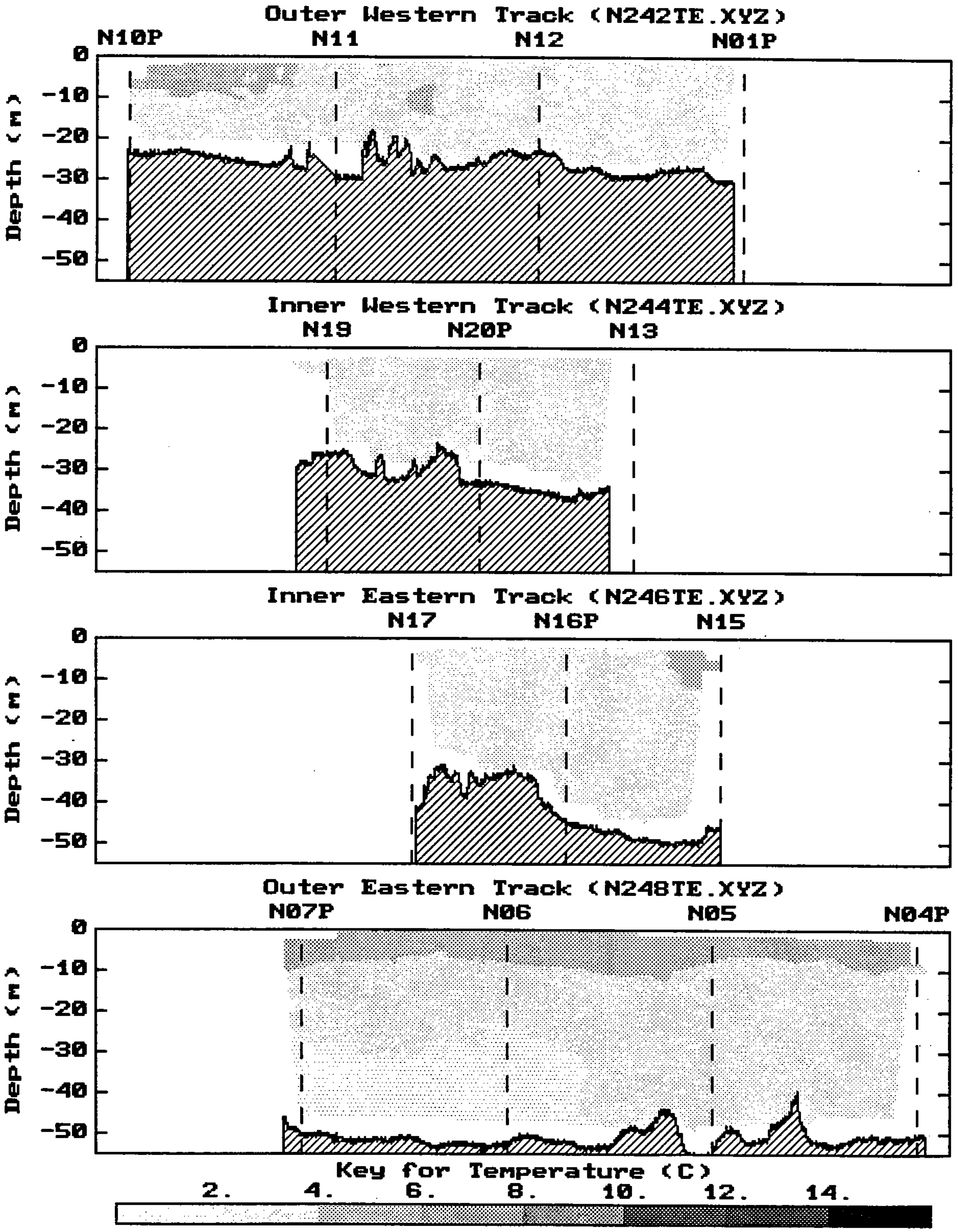


Figure 3-30b. Vertical section contours of temperature generated for tow-yo profiling conducted in early April 1993. The view is towards Boston Harbor.

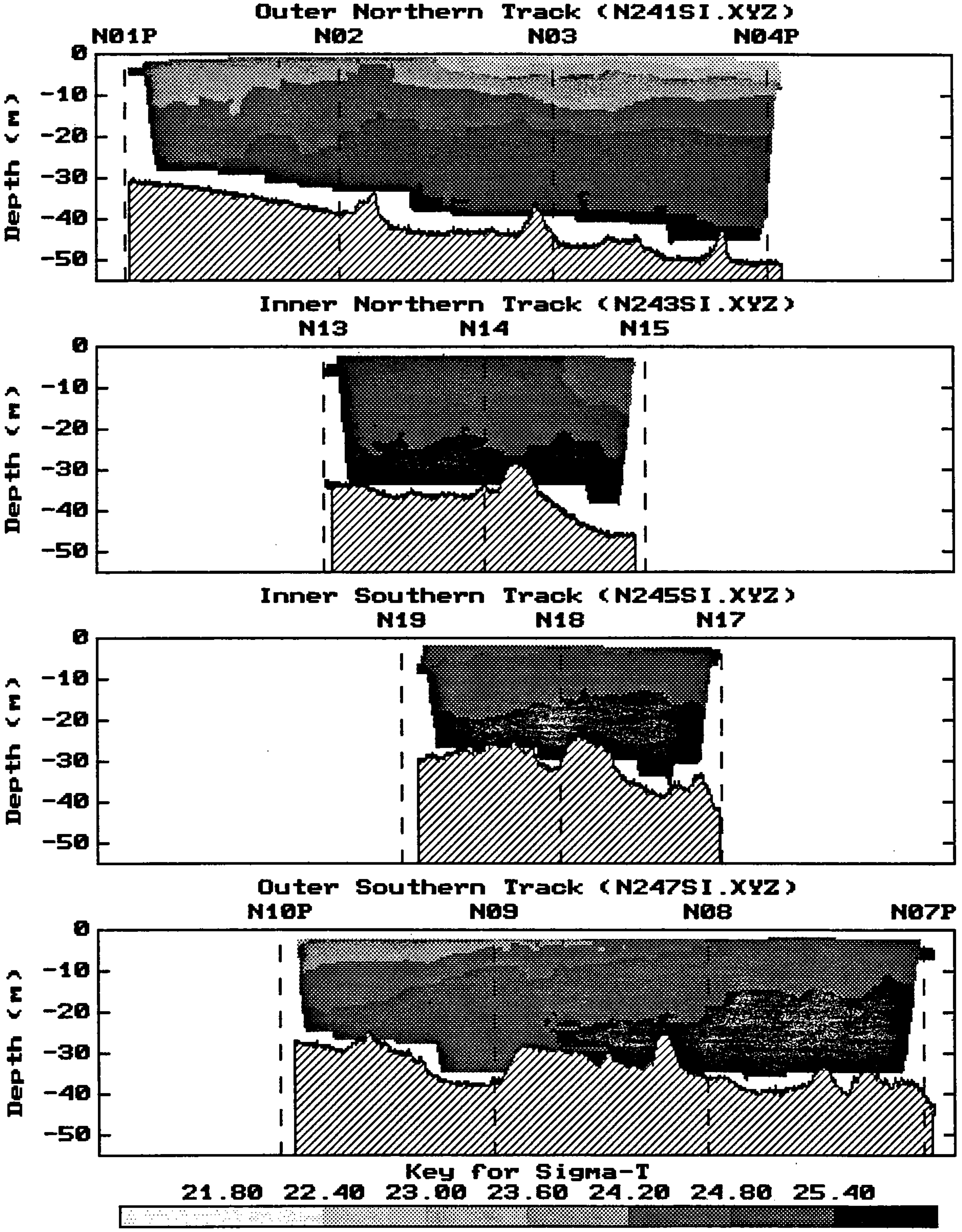


Figure 3-31a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in early April 1993. The view is towards the north.

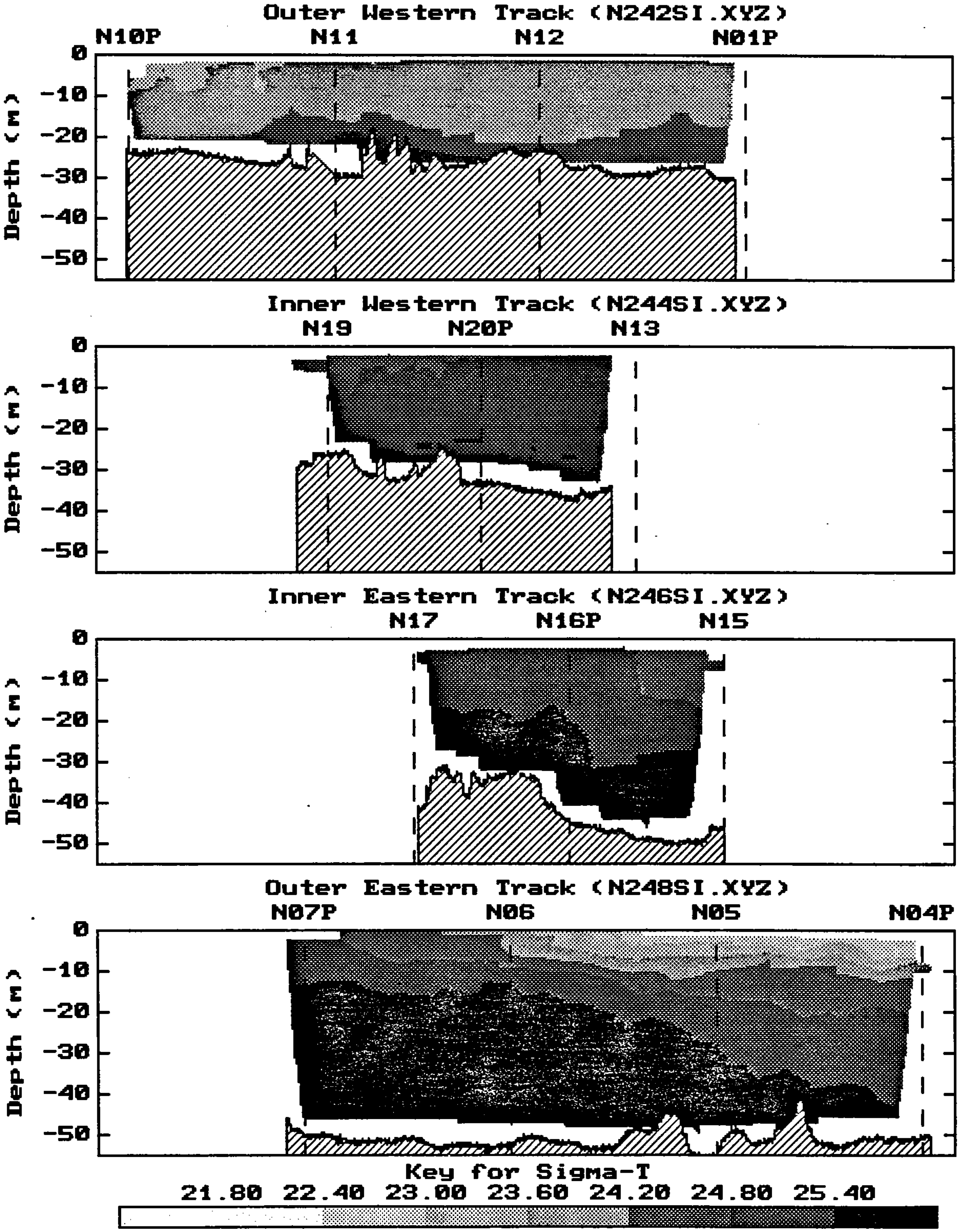


Figure 3-31b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in early April 1993. The view is towards Boston Harbor.

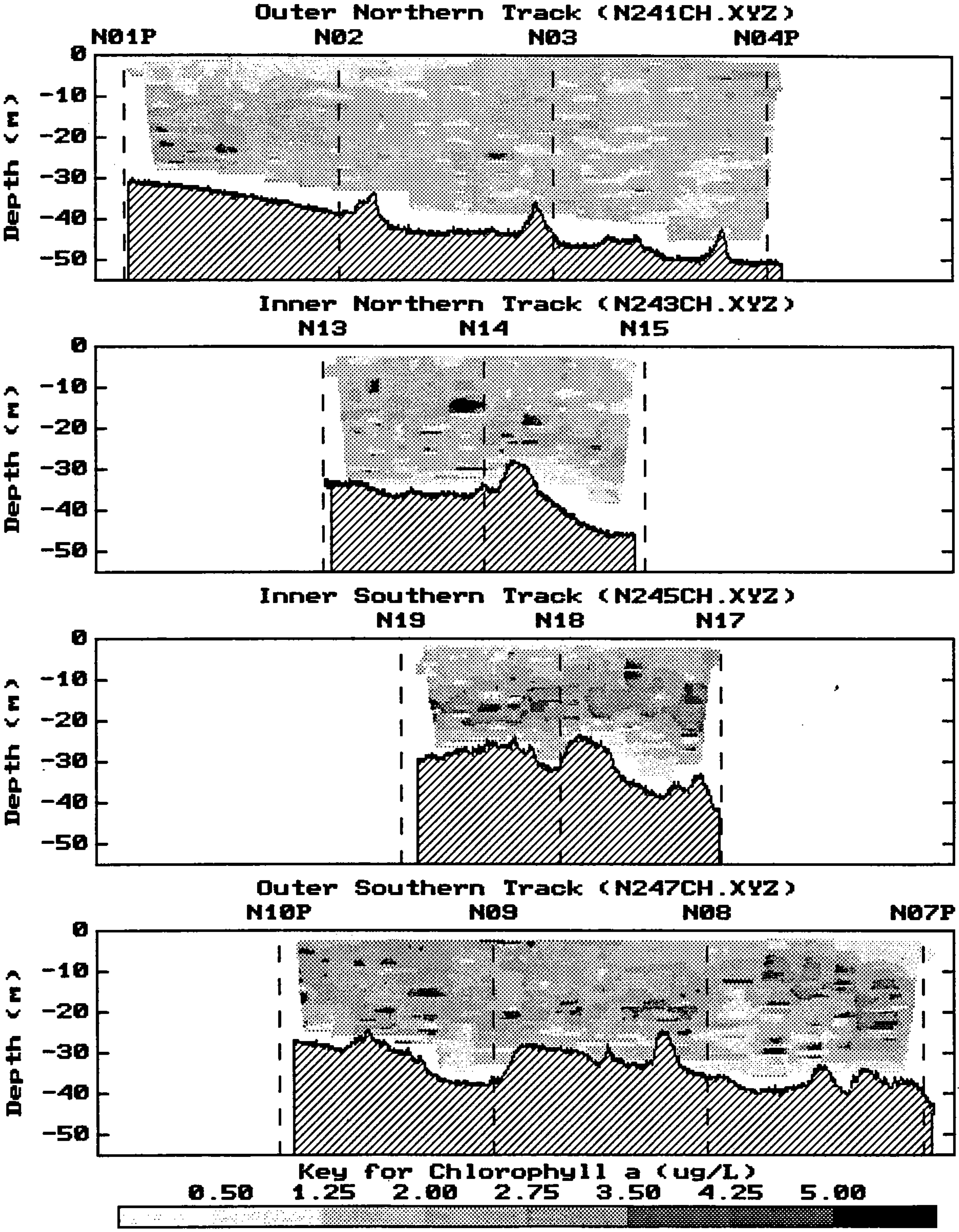


Figure 3-32a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in early April 1993. The view is towards the north.

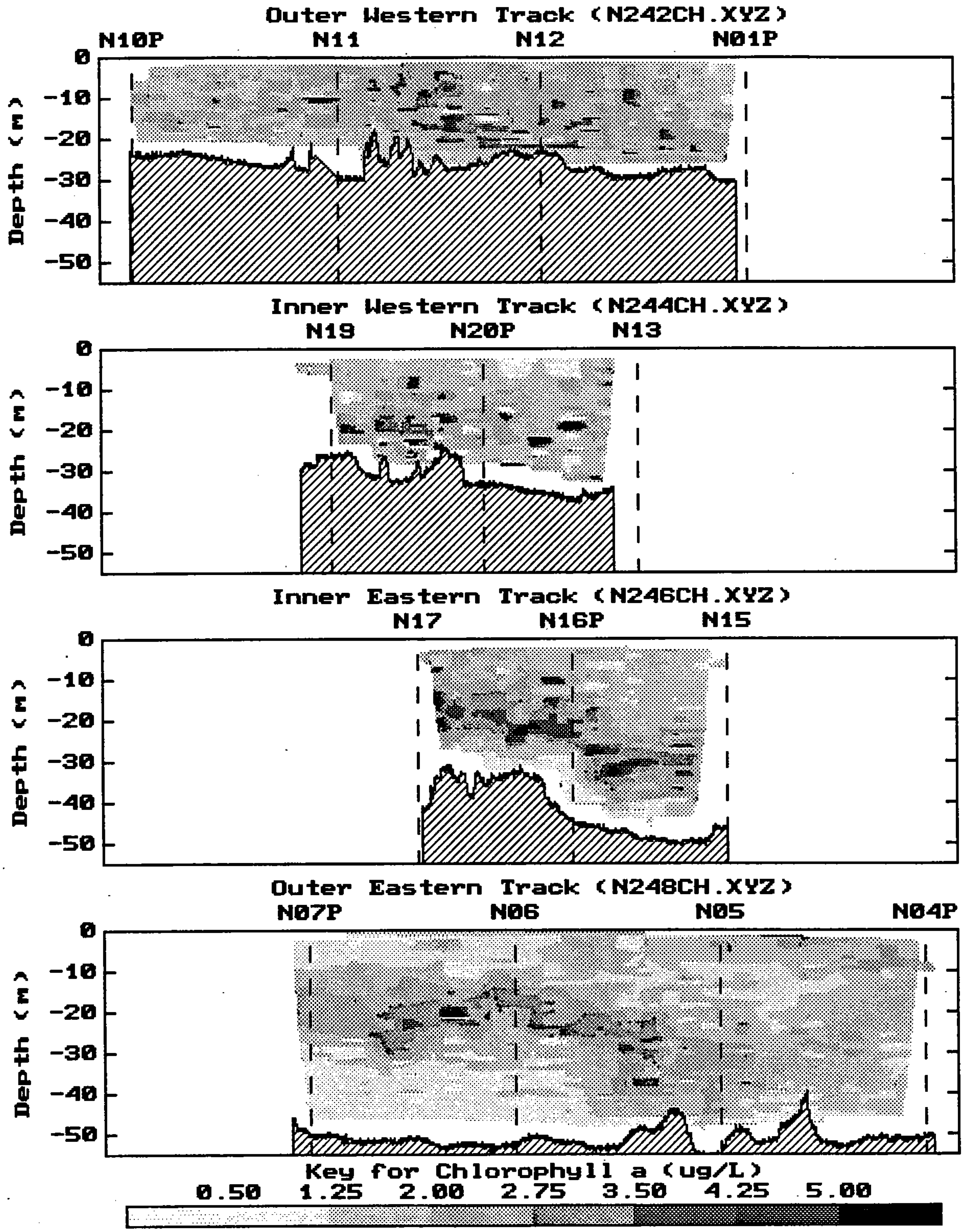


Figure 3-32b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in early April 1993. The view is towards Boston Harbor.

4.0 RESULTS OF LATE APRIL/EARLY MAY 1993 NEARFIELD SURVEY (W9305)

4.1 Distribution of Water Properties from Vertical Profiling

Vertical profiling and water sampling was conducted on May 1, 1993 at all 21 nearfield stations. Nutrient concentrations and profile plots are provided in Appendices A and B.

In general, temperature throughout all depths of sampling varied across the stations from about 3 to 6.5°C and salinity ranged between 29 and 32.1 PSU (Figure 4-1a). The deeper waters remained cold and more saline. The vertical profiles (Appendix B) indicated that the vertical structure of the water column varied across the nearfield. Vertical stratification at the shallow inshore stations was not well defined, whereas many middle-field stations had a near-surface pycnocline over the top 5-15 m. A double pycnocline, with three distinct layers of water, often characterized the more seaward deeper stations. In the latter case (e.g., stations N04P and N05), the middle layer of water was generally between 10-15 m and 30-35 m. A stronger vertical variation and layering was noted for salinity than for temperature. In general, surface temperature was near 6°C at all stations. However, the profiles indicate that the surface layer, more pronounced offshore, was lower in salinity than the surface water inshore. Such a feature may indicate a source of fresher surface water from the north—northeast into the nearfield area.

During the May 1 profiling, the range in beam attenuation was small (about 0.5 to 1.5 m^{-1}) and not well related to salinity or to chlorophyll (Figure 4-1a). In contrast to beam attenuation, chlorophyll ranged widely from about 0.5 to 4 $\mu g\ L^{-1}$ (Figure 4-1b), with a mean concentration of 1.6 $\mu g\ L^{-1}$. Peak concentrations, usually exceeding 2 $\mu g\ L^{-1}$ were characteristically found in mid-water depths. A sharp subsurface maximum, when present, was usually in or at the base of the surface layer at inshore, mid-field, and offshore stations. It must be noted that the chlorophyll-fluorescence calibration was imperfect (driven by a single high value; Appendix A) and may not faithfully estimate all chlorophyll values. For many samples, the resultant post-calibrated values may be overestimates of the actual chlorophyll *a* present at the time of the survey. Regardless of this possibility, a different calibration would not change the patterns observed. Surface DO concentrations, as noted in previous months, were supersaturated and the percent saturation declined somewhat with water depth (Figure 4-1b).

Nutrient concentrations vary with depth as shown in Figure 4-2. In general, there was an increase in DIN concentration with depth. DIN concentrations in surface water samples, however, were often >2 μM (Figure 4-2a), with significant contributions from both ammonia and nitrate (Figure 4-2b). The distribution of PO_4 with depth resembled that of NO_3 (Figure 4-2c). Neither PO_4 nor SiO_4 was ever near detection limits and only a few samples were virtually depleted in DIN.

The data in Appendix A indicate that surface water nutrient concentrations showed little geographic variation across the nearfield stations. Figures 4-3 and 4-4 also suggest that variability in nutrient concentrations was minor at 29-30.5 PSU, the approximate salinity range for most surface samples. Over the full salinity range, the plots suggest a slight increase in DIN, NH_4, and NO_3, but little pattern for silicate, as a function of increasing salinity. These results probably reflect the patterns of increasing salinity and nutrients with depth, and confirm the lack of strong horizontal nutrient gradients at the time of the early May survey.

4.2 Distribution of Water Properties from Towing

The tow-yo sampling was conducted on April 29, two days before vertical profiling. Only the tracks of the outer box and the track from station N19 to N13 of the "Inner Western Track" were completed (see Section 2). The towing revealed little vertical structure for temperature. Nearly all temperature data were confined to the 4-6°C interval used for contouring (Figure 4-5a, b). Small patches of water near the surface of stations N10P and N01P, the inshore corners of the nearfield, were slightly warmer than 6°C. Salinity differences contribute to vertical and horizontal density differences (Figure 4-6a,b), and considerable layering, as described above from vertical profiles, was apparent. A lens of lighter (less dense) water remained at the surface of the northeast corner of the field (stations N05-N04P-N03). A cell of heavy (more dense) bottom water was detected near the bottom of the water column at station N07P-N06, the deepest water sampled. Interestingly, station N10P, sampled on the "Outer Southern Track" (Figure 4-6a) had lighter water, which apparently shoaled towards station N09. The middle of the nearfield appeared to be a physically-complex region, sandwiched between an offshore surface water layer (fresher, lighter) and tidal outflux (fresher, perhaps warmer?) from the Harbor.

The chlorophyll distribution revealed by tow-yo sampling is patchy, but generally with low to intermediate concentrations and no large patches of high concentrations of chlorophyll (Figure 4-7a,b). The surface water layers were lower in chlorophyll and higher concentrations of were found in the mid-water regions. There were, however, no obvious differences in chlorophyll that corresponded with the physically-distinct surface layers in Figure 4-6 (e.g. N10P versus mid-field versus N04P).

4.3 Water Types and Analysis of Small-Scale Variability

An interesting aspect of the late April/early May nearfield survey was variation in the strength of stratification across the nearfield. The highest degree and most complex density stratification was generally in the northeastern offshore waters. Except for some occasional tidal-related stratification observed at station N10P, the shallower stations along the western side of the nearfield were only weakly stratified.

In spite of some physical complexity, and much vertical and horizontal heterogeneity in salinity and density, there were few corresponding patterns in chlorophyll and nutrient distributions. Vertical trends of (1) higher nutrient concentrations in bottom waters and (2) low to mid-level chlorophyll concentrations in mid-waters with a pycnocline were noted. However, aside from perhaps some of the usual (tidal) variability shown in vertical profiles at station N10P over the period of the survey, the surface waters were generally similar and independent of the physical characteristics over the short time and space scales that can be examined with the data. This observation suggests that during the late April/early May period, there may be few ecological differences across what would appear to be, from their physical attributes, surface waters of differing origins/histories.

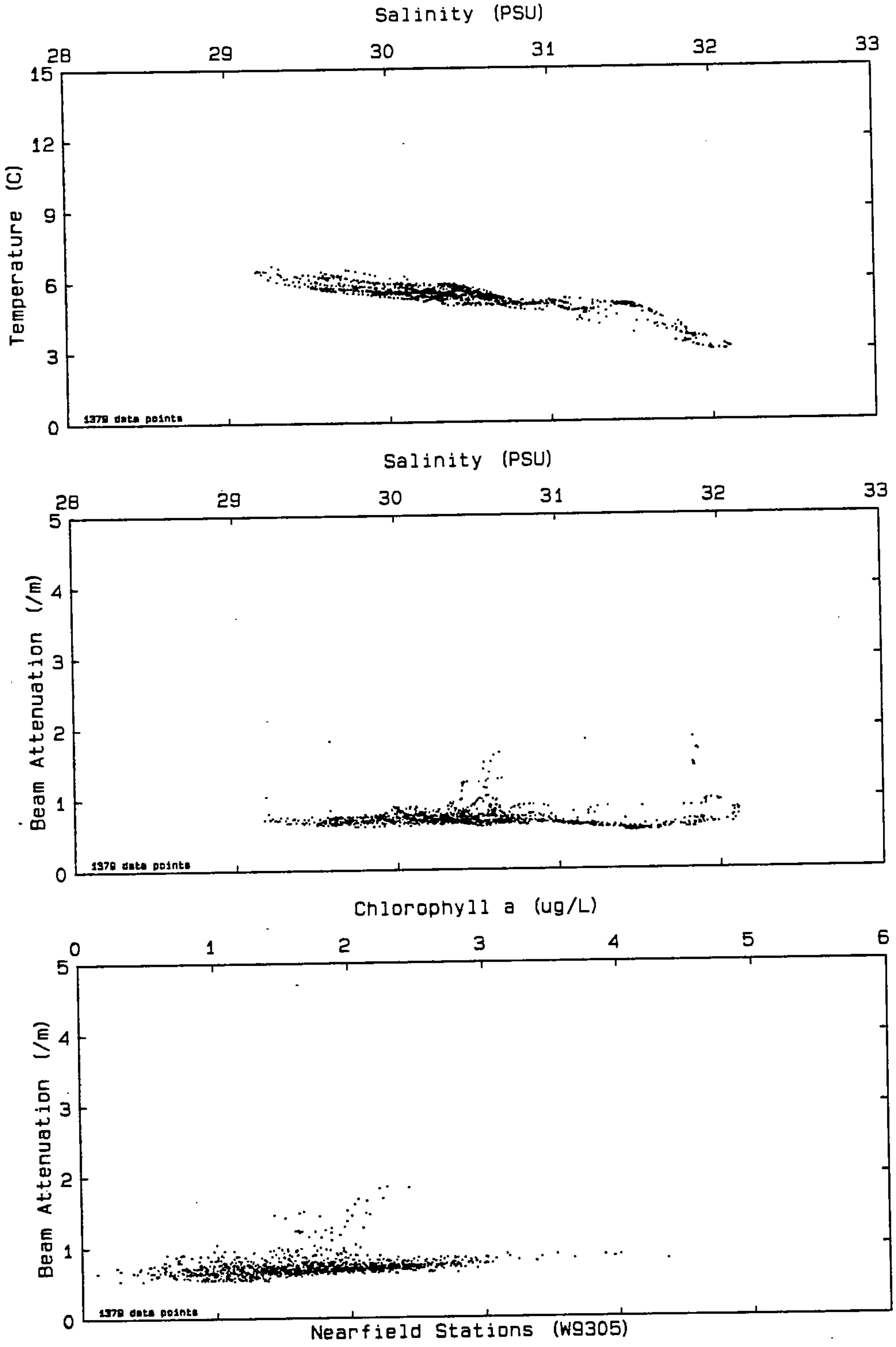


Figure 4-1a. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in early May 1993. Individual station casts that were used to produce this composite are included in Appendix B.

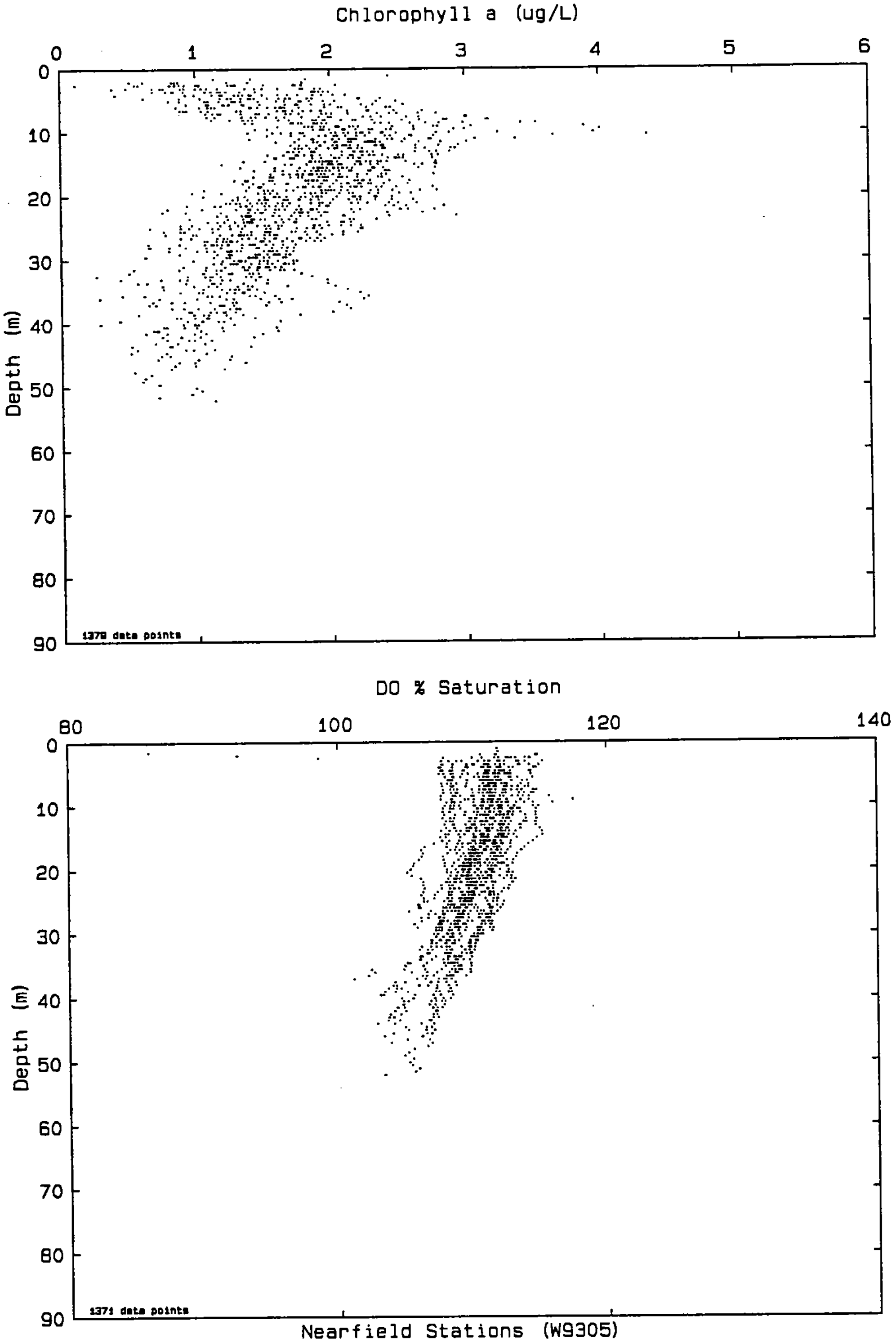


Figure 4-1b. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in early May 1993. Individual station casts that were used to produce this composite are included in Appendix B.

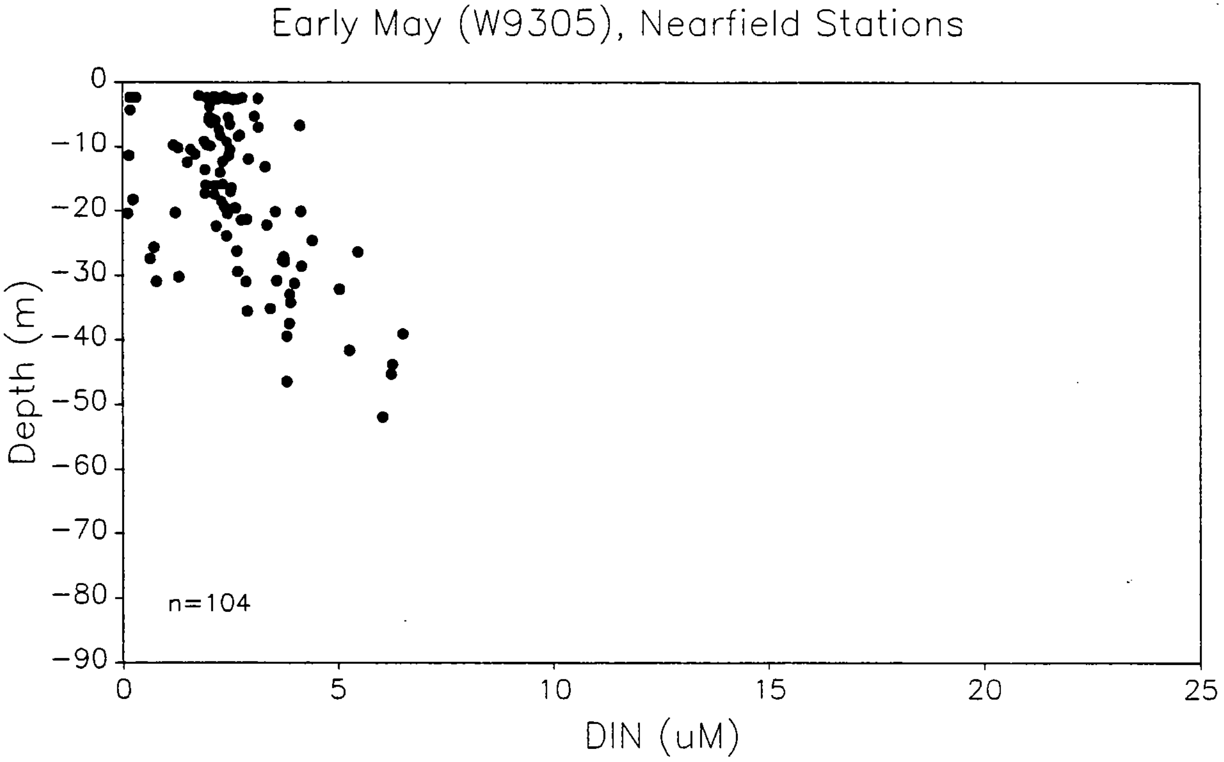


Figure 4-2a. DIN vs. depth in early May 1993.

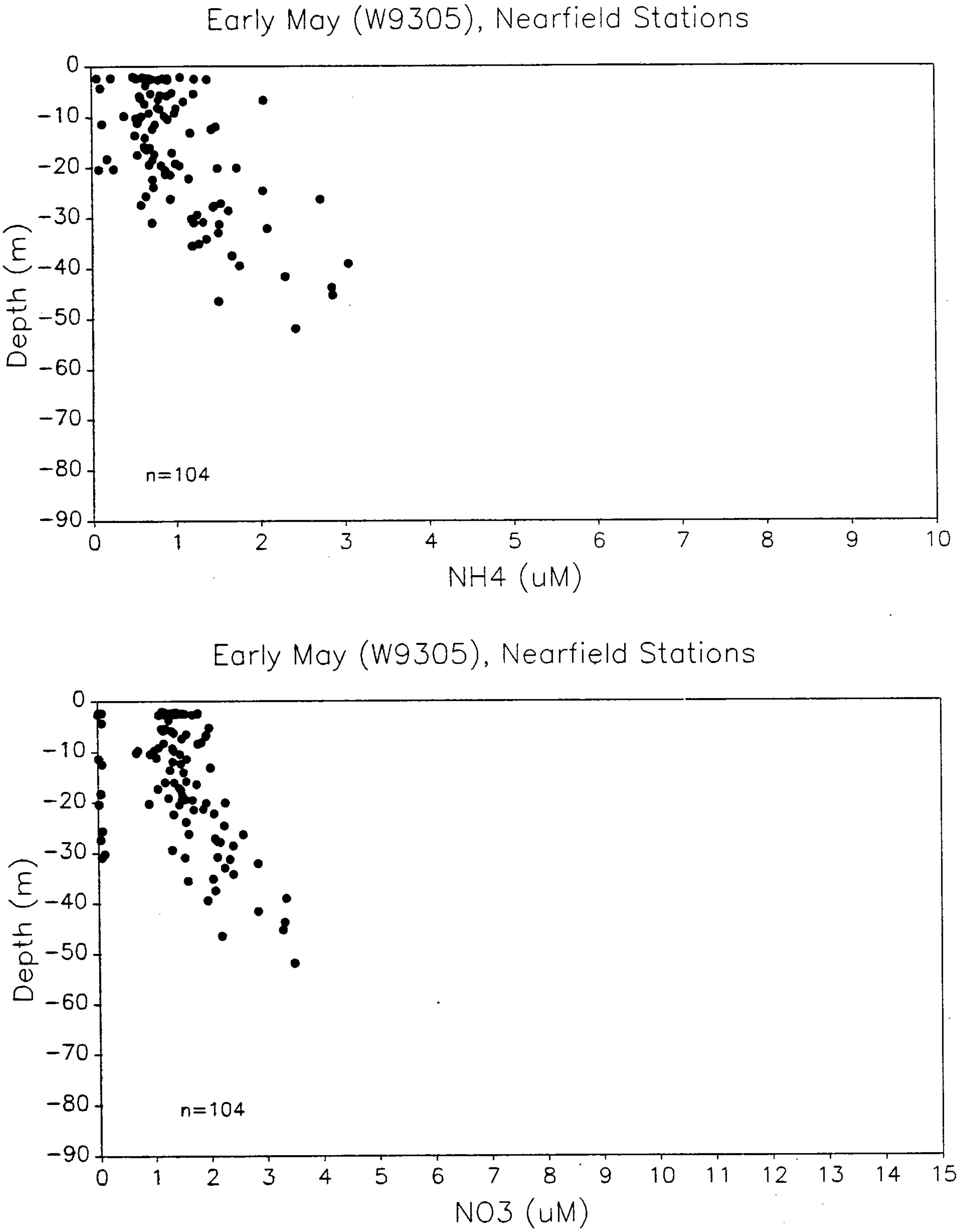


Figure 4-2b. NH_4 and NO_3 vs. depth in early May 1993.

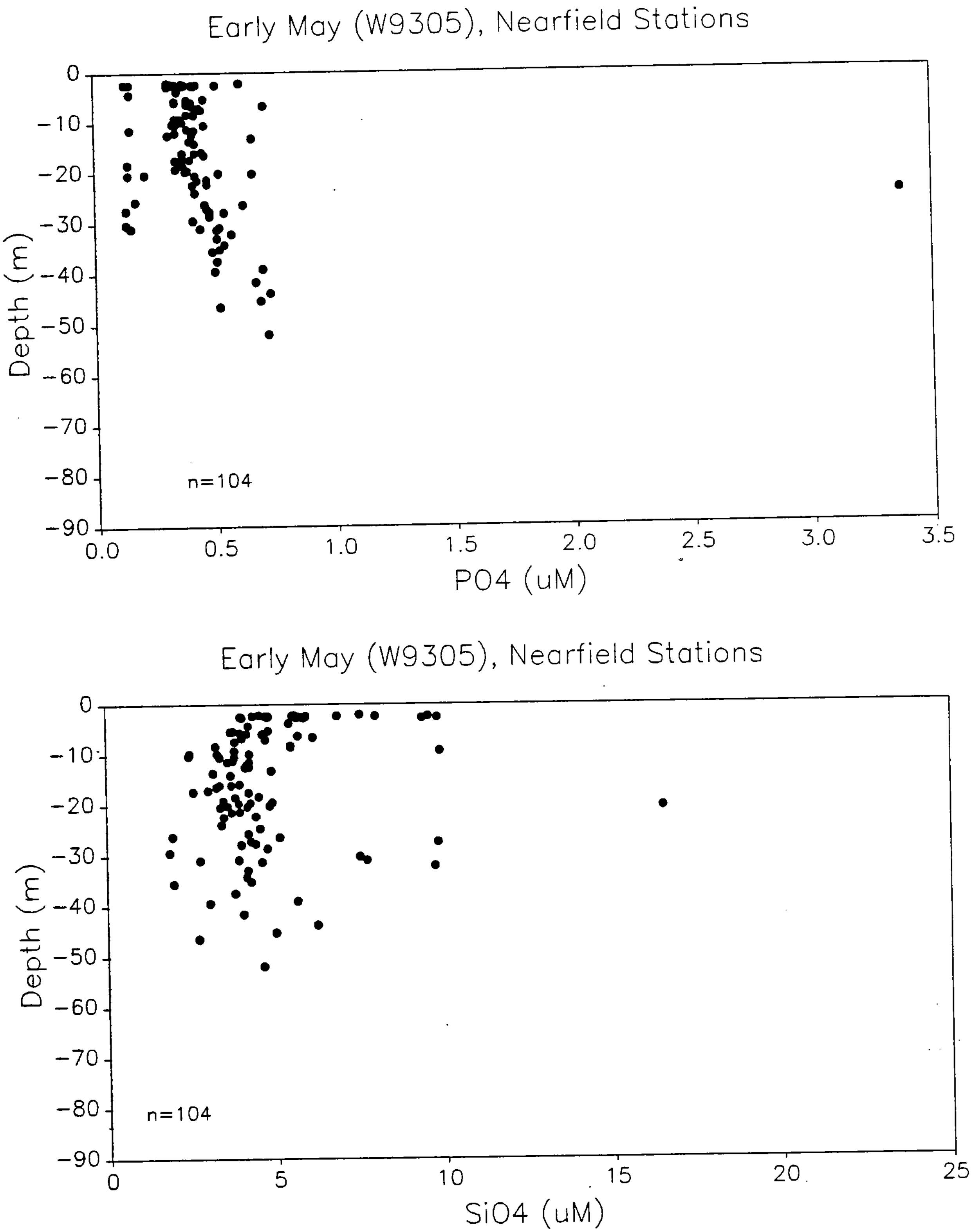


Figure 4-2c. PO_4 and SiO_4 vs. depth in early May 1993.

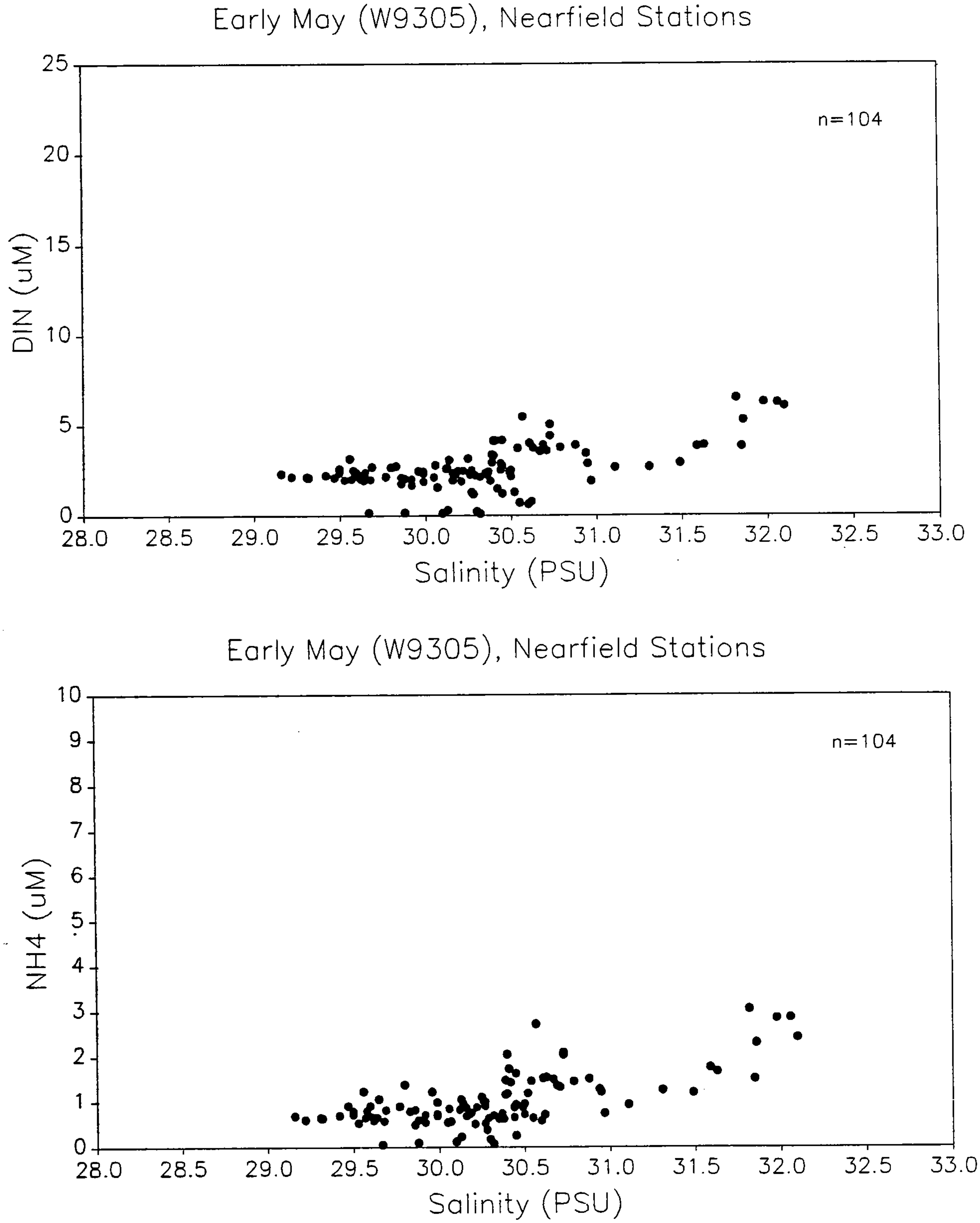
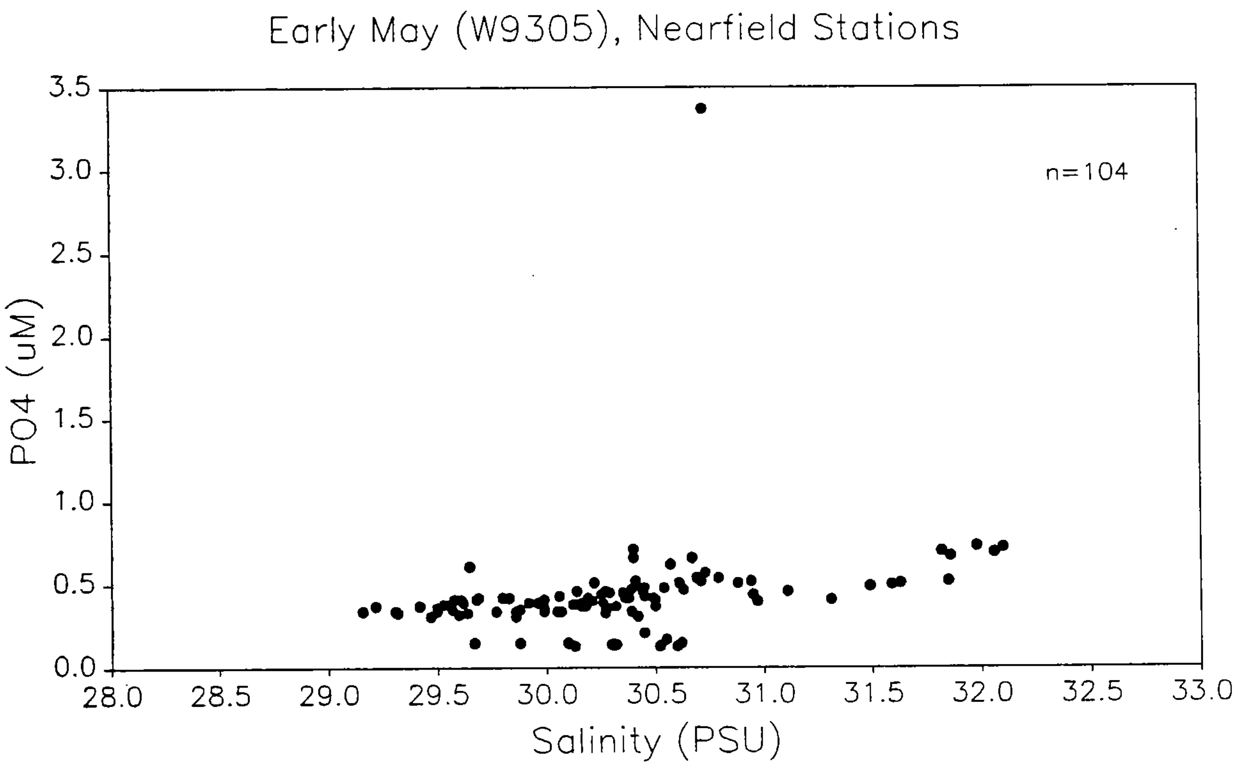


Figure 4-3. DIN and NH_4 vs. salinity in early May 1993.



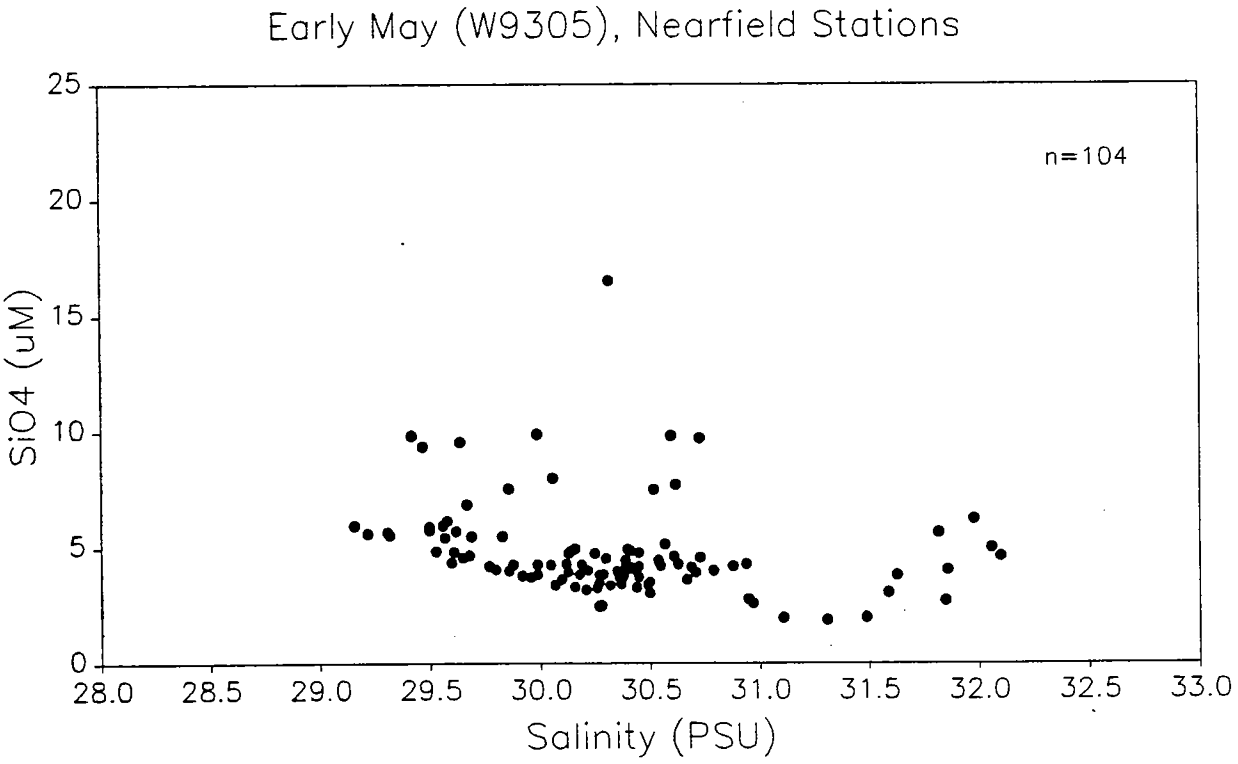


Figure 4-4. PO_4 and SiO_4 vs. salinity in early May 1993.

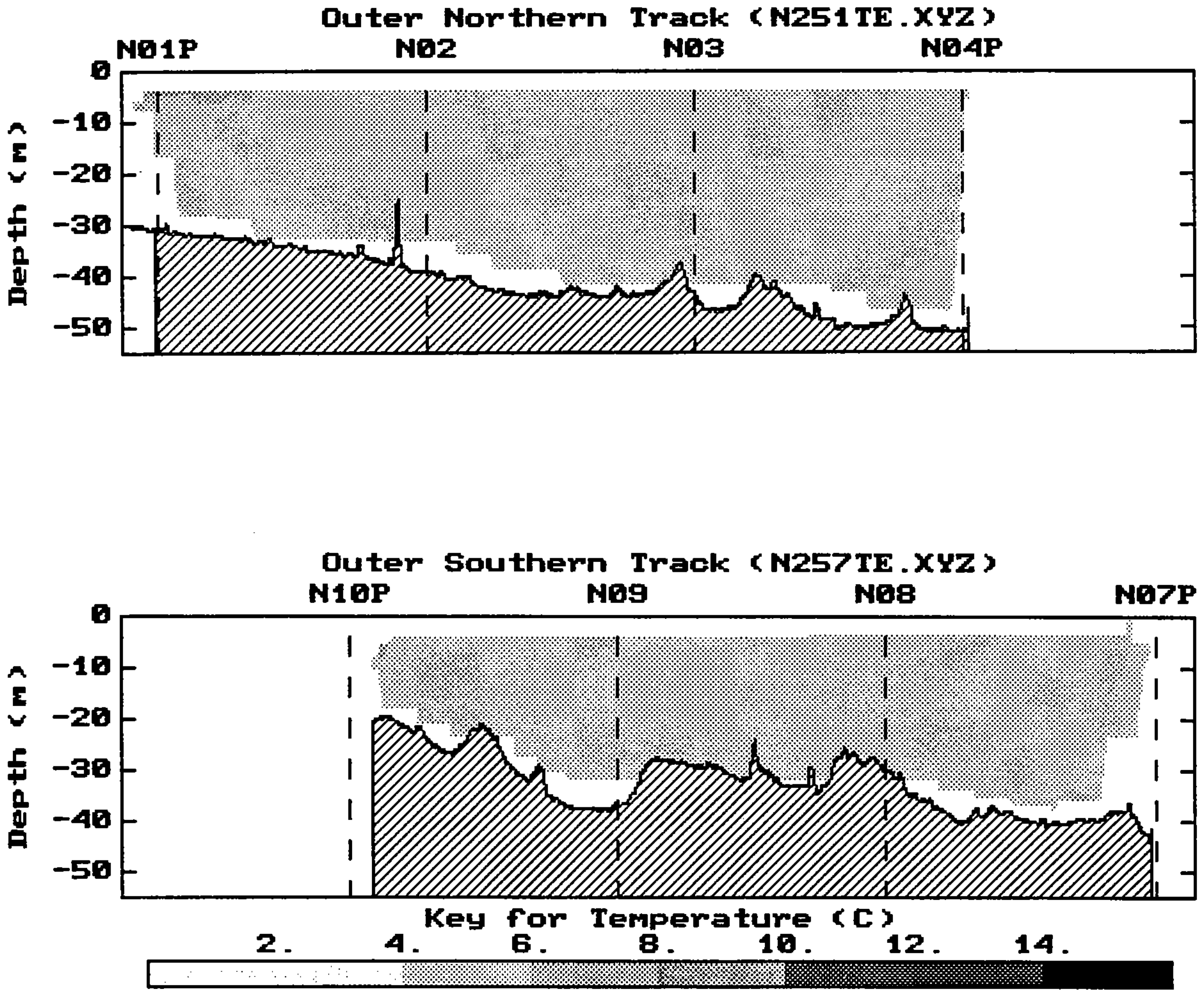


Figure 4-5a. Vertical section contours of temperature generated for tow-yo profiling conducted in late April 1993. The view is towards the north. Missing inner tracks are due to instrument problems (see Section 2).

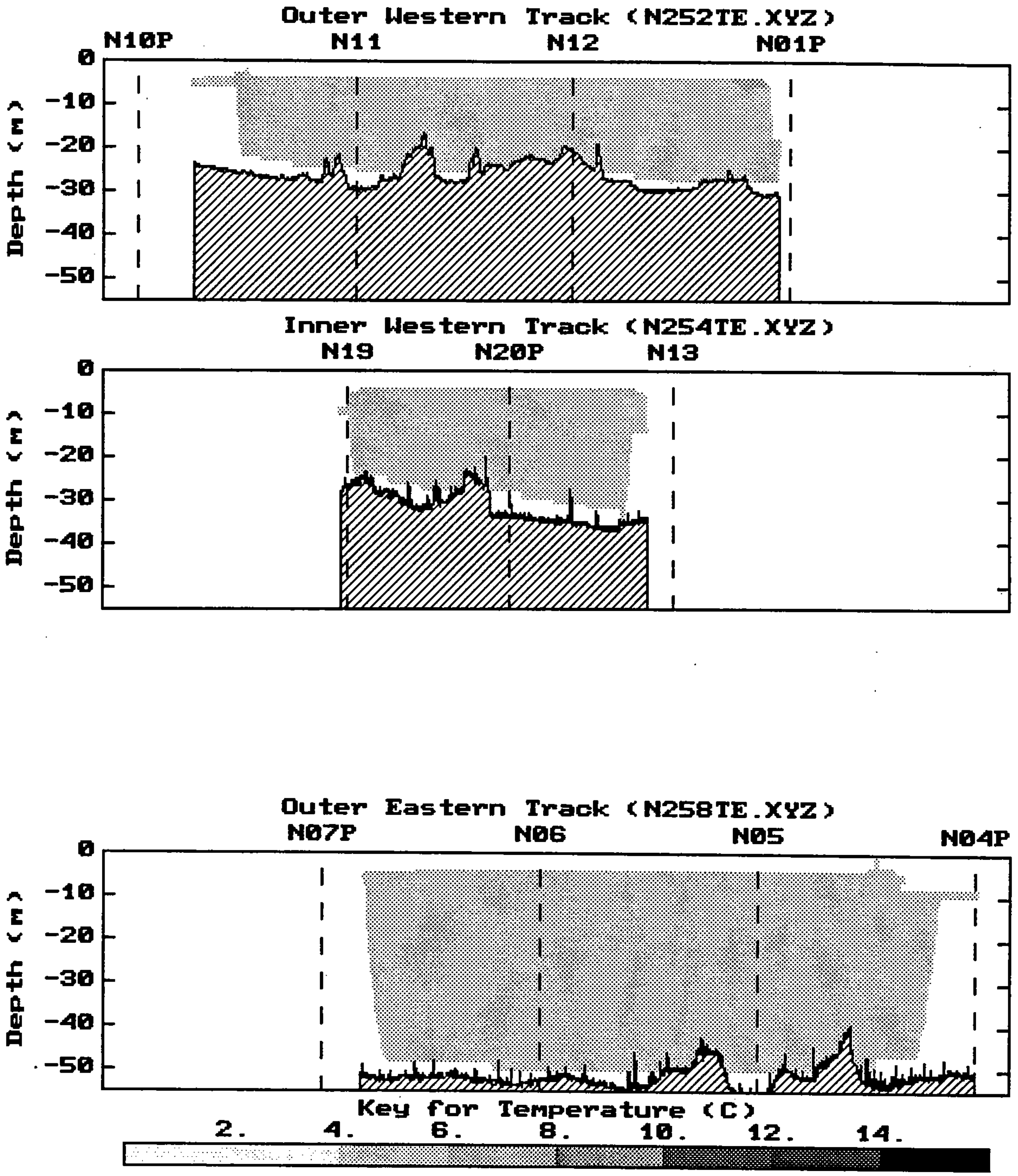


Figure 4-5b. Vertical section contours of temperature generated for tow-yo profiling conducted in late April 1993. The view is towards Boston Harbor. Missing tracks are due to instrument problems (see Section 2).

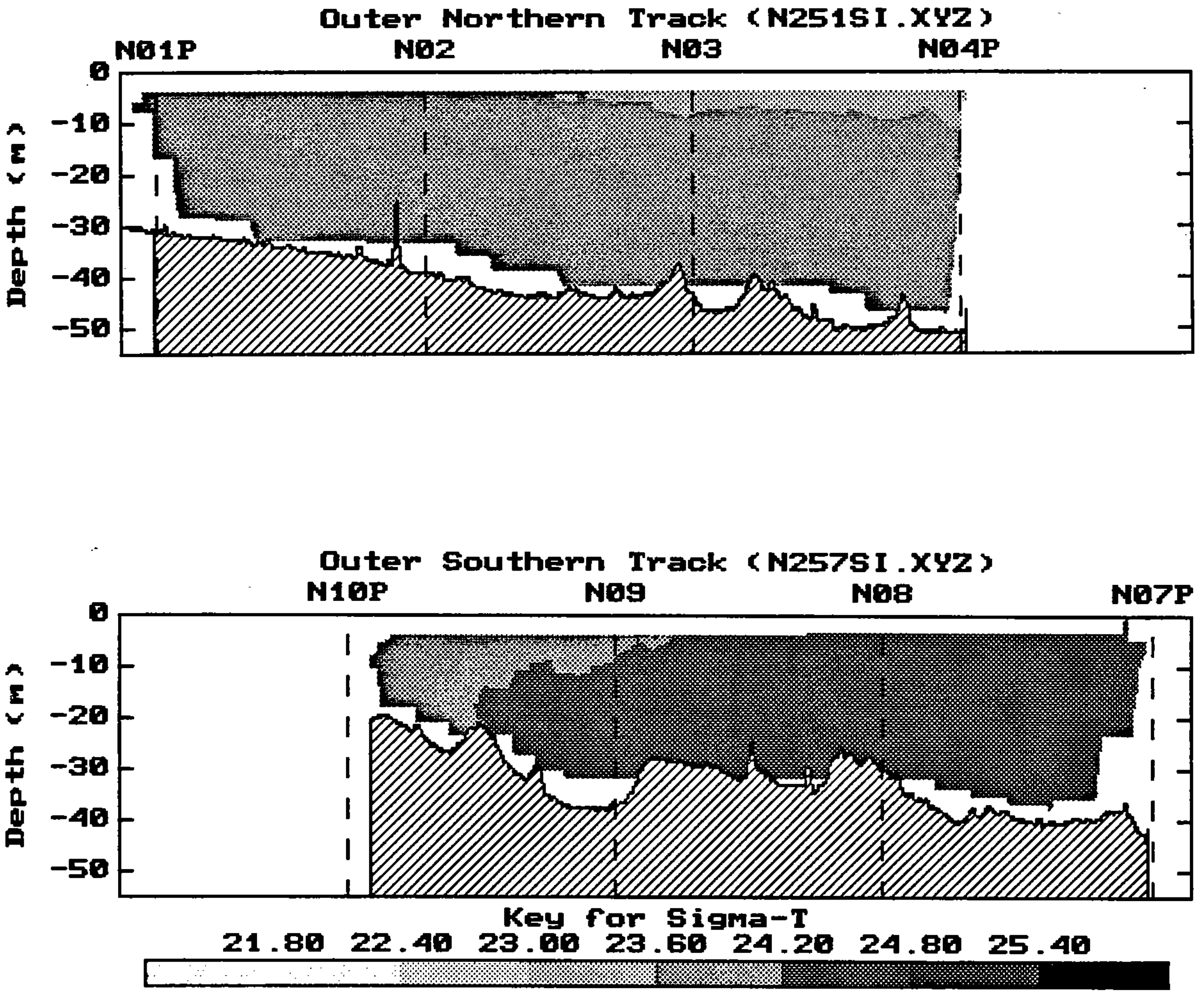


Figure 4-6a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in late April 1993. The view is towards the north. Missing tracks are due to instrument problems (see Section 2).

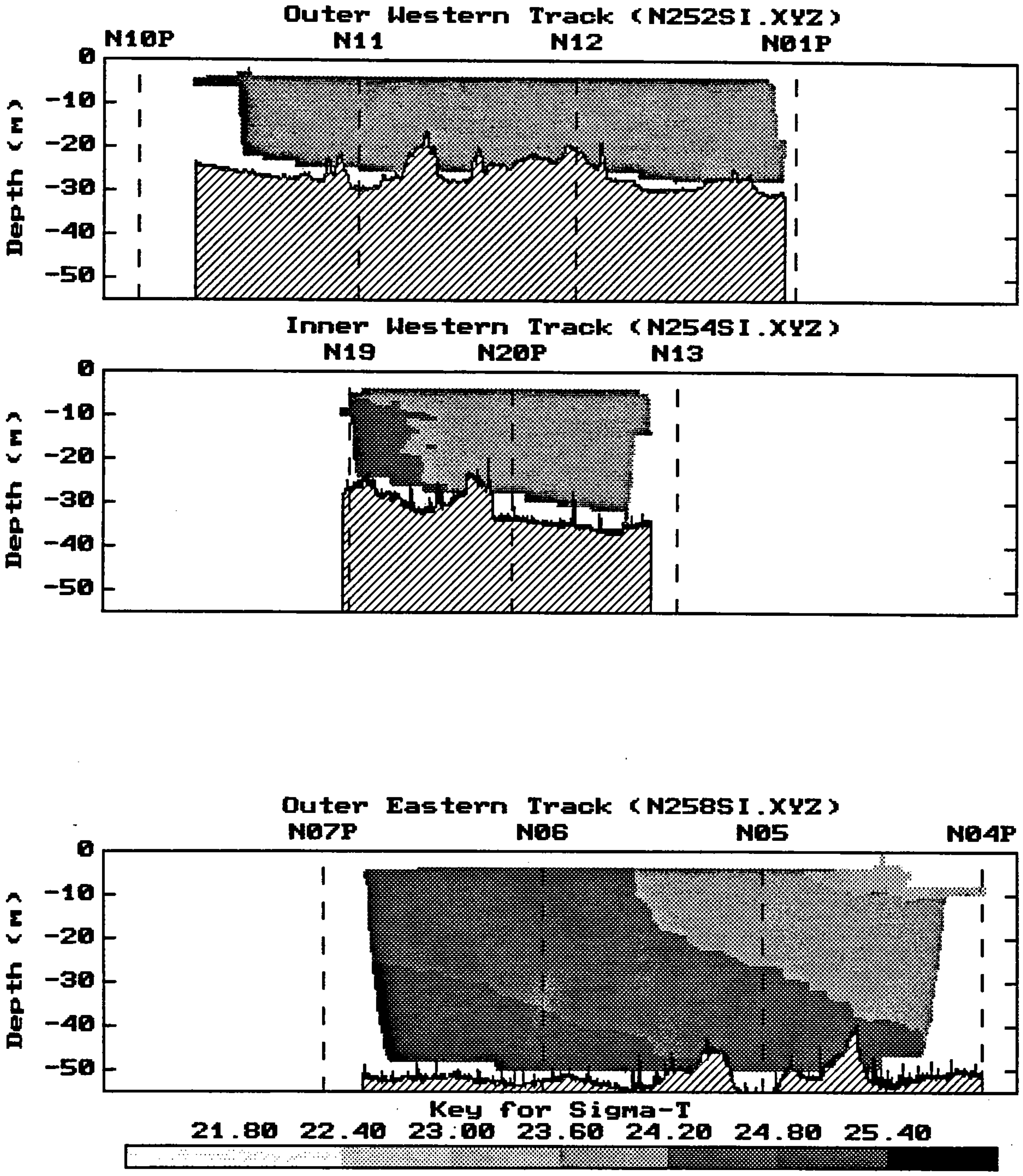


Figure 4-6b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in late April 1993. The view is towards Boston Harbor. Missing tracks are due to instrument problems (see Section 2).

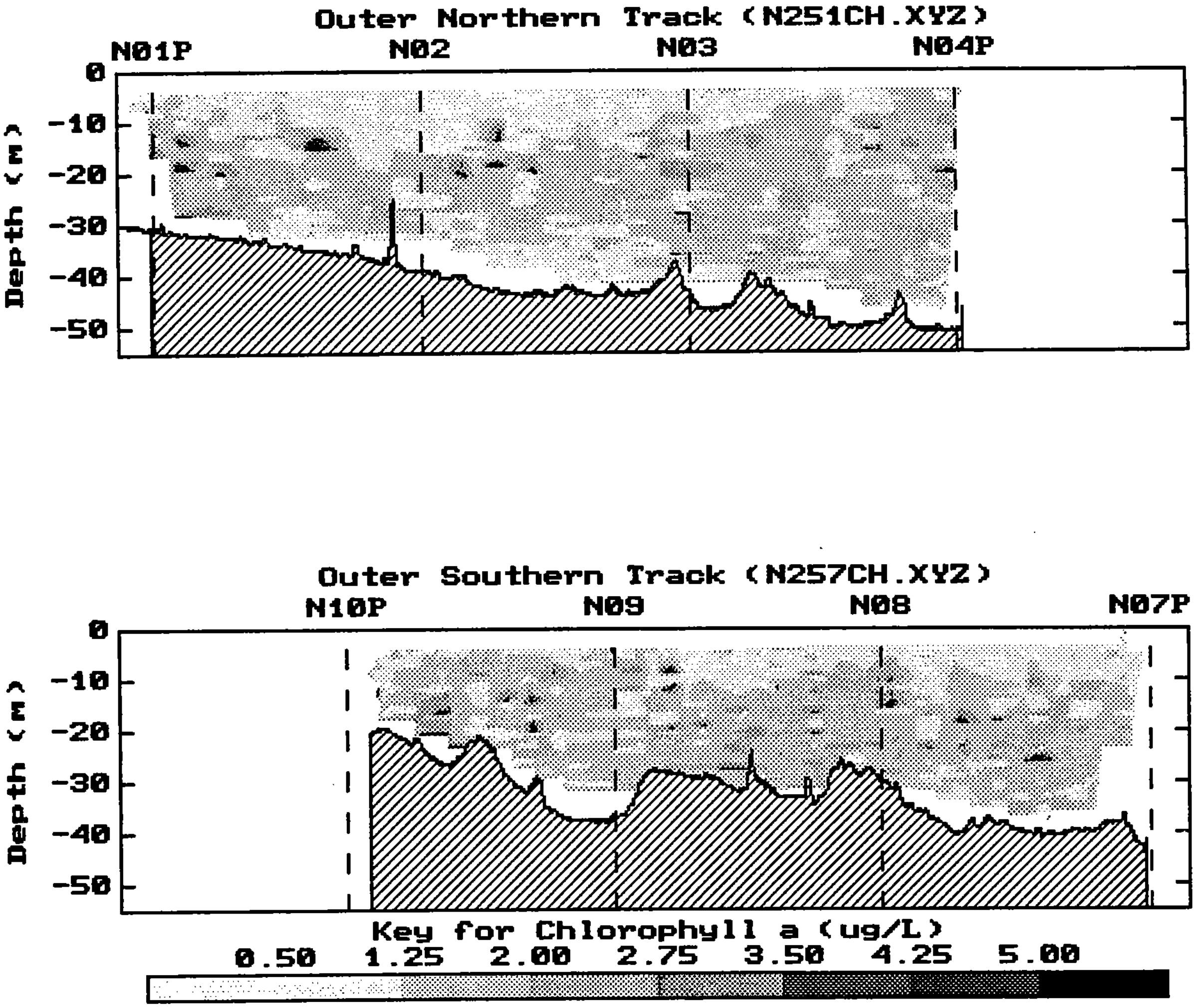


Figure 4-7a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in late April 1993. The view is towards the north. Missing tracks are due to instrument problems (see Section 2).

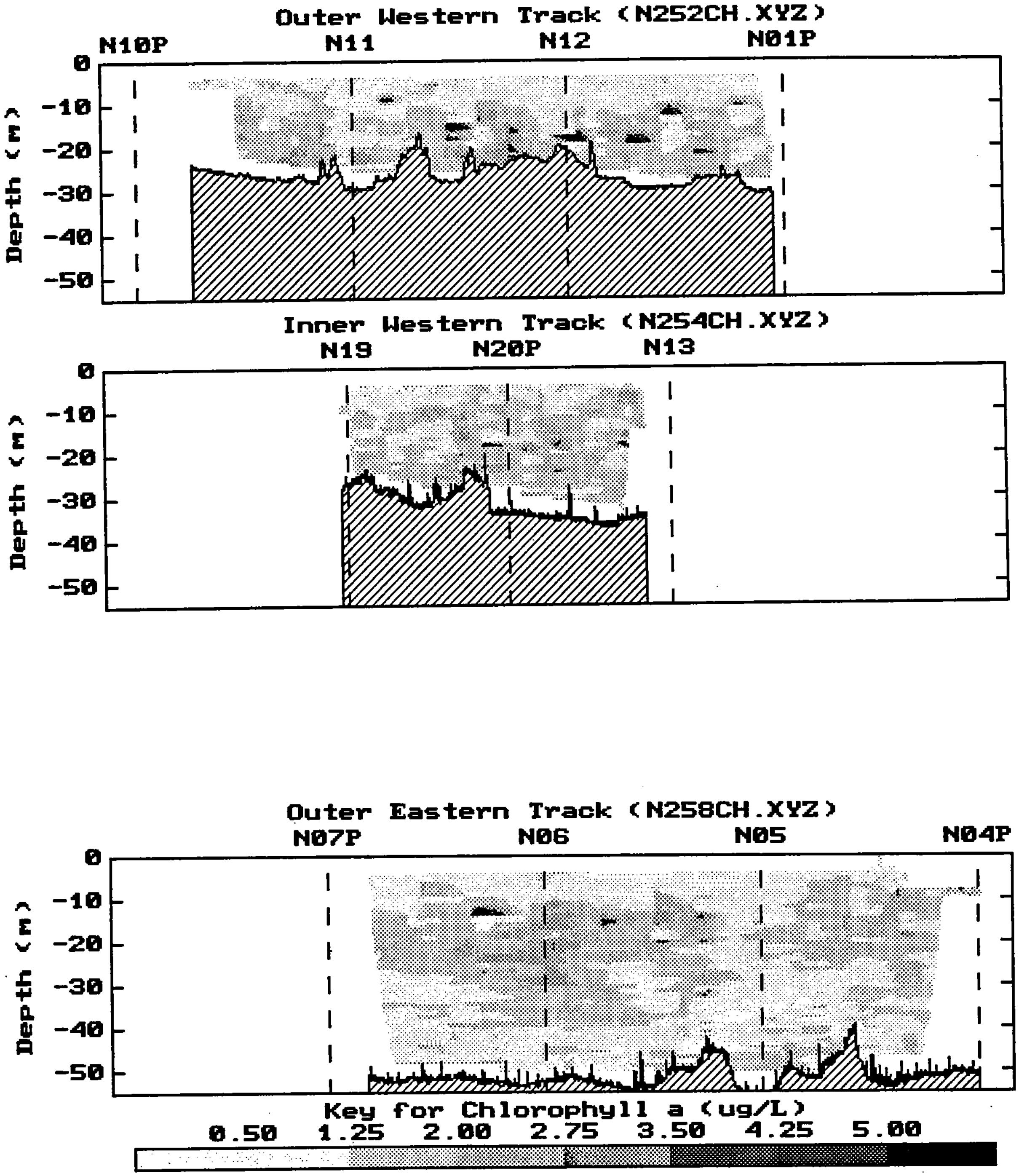


Figure 4-7b. Vertical section contours of fluorescence (as µg Chl L^{-1}) generated for tow-yo profiling conducted in late April 1993. The view is towards Boston Harbor. Missing tracks are due to instrument problems (see Section 2).

5.0 RESULTS OF LATE MAY 1993 NEARFIELD SURVEY (W9306)

5.1 Distribution of Water Properties from Vertical Profiling

Vertical profiling and water sampling were conducted on May 21; all the planned stations except station N18 were completed, (see Section 2). In the three weeks since the previous survey, the surface water column had warmed considerably and surface temperatures had reached about 11-13°C (Figure 5-1a, see also Appendix A,B). The salinity range was still about 29-32 PSU, with the more saline water being deeper and colder ($\approx$3.75-5°C).

The vertical hydrographic profiles in Appendix B indicated that strong vertical stratification had developed at all stations in the nearfield. Two layers were typically evident: (1) a surface layer of near-uniform temperature and salinity extending 7-15 m deep, depending on the station and (2) a pycnocline (halocline and thermocline) about 5-15 m thick and leading to a bottom water layer where temperature only gradually decreased and salinity gradually increased with increasing depth. Some near-surface warming during the day was suggested by some profiles at stations sampled in the afternoon (e.g., station N21).

As noted three weeks earlier, beam attenuation occurred in a narrow range and did not co-vary with salinity (Figure 5-1a). Generally, chlorophyll variations did not influence beam attenuation, but a few profiles showed a very slight, concomitant increase in beam attenuation when chlorophyll concentrations increased. Chlorophyll concentrations on average were low ($\sim$1-1.5 μg/L). Rather than a pattern of a mid-water chlorophyll maximum associated with the pycnocline, the chlorophyll peak occurred more often in the surface layer (0-10 m); concentrations decreased with depth from 1.5 to 3 μg L^{-1} near the surface to background concentrations $\leq$1 μg L^{-1} below 25 m (Figure 5-1b).

Generally, peak chlorophyll concentrations above 2 μg L^{-1} were noted at stations on the seaward side of the nearfield. A group of stations at the eastern side of the field in deeper water (e.g., stations N03, N04P, N05, N15, and N07P) revealed a chlorophyll peak between 5 and 10 m; this peak occurred in the surface layer above the top of the pycnocline. At other stations, particularly station N10P, chlorophyll increased to about 3 μg L^{-1} right to the top of the profile near the surface. Note in Appendix B that the 1% light level usually extended well into the pycnocline or bottom layer at most stations; the one exception was station N10P where beam attenuation exceeded 1 m^{-1}. Note also in Appendix A that chlorophyll concentration at station N10P may have been overestimated by the general chlorophyll-fluorescence model that fit the data, and the qualifications expressed for inshore chlorophyll in Section 3 may also apply to this station.

As found earlier in the year during spring bloom, surface waters remained supersaturated in DO (Figure 5-1b). Concentrations of DO, as percent saturation, decreased with depth. Most DO values were 92-98% of saturation near the bottom of profiles (at the closing of Niskin bottles, see Appendix A).

Nutrients showed a strong pattern with depth. The surface 10-15 m was very low in DIN and concentrations generally increased to about 6-7 μM at depth (Figure 5-2a). Generally, the depth distribution of DIN was determined equally by NH_4 and NO_3 (Figure 5-2b); nitrate however, was more uniformly depleted at the surface. Concentrations of surface water ammonium were somewhat higher in the western part of the field. Both phosphate and silicate showed patterns over depth as DIN (Figure 5-2c). Some surface-layer PO_4 concentrations were near detection limits; silicate, although very low near the surface (0.5 to 1 μM) was not as depleted as DIN or PO_4.

Station N10P at the southwest corner of the nearfield provided an anomalous data point running counter to the pattern and having high nutrients (6.13 μM NH_4, 1.05 μM PO_4, 3.97 μM SiO_4) at the surface. This location receives Harbor outflow, as demonstrated by past surveys.

Salinity—nutrient relationships shown in Figures 5-3 and 5-4 are similar to those that were characterized in the data of the early May survey. All nutrients increased slightly with salinity; for some nutrients, such as ammonia, this relationship revealed more scatter. For ammonia, its source from the Harbor may (geographically) complicate the otherwise strong nutrient-depth relationship that is responsible for the trend of increasing nutrients with increasing salinity.

5.2 Distribution of Water Properties from Towing

Towing was performed over all tracks of the nearfield inner and outer boxes (Figure 1-2) the day prior to conducting vertical hydrocast profiles. Results for temperature are presented in Figure 5-

5a,b. These figures clearly illustrate the two-layered water column and a sharp thermocline transition between layers at all stations, except N10P. The bottom layer is less extensive when the water depth is 20-30 m, in part because the thickness of the surface layer is fairly constant over space. This constant feature would indicate the overriding strength of atmospheric-climatic influence on temperature as compared, for example, to mixing of different water masses having different source characteristics.

The surface and bottom layer thermal and saline conditions were fairly uniform across the field (Appendix A,B), suggesting a uniformly structured field (Figure 5-6a,b). Figure 5-6 indicates that the pycnocline is deepest at the southeast corner (station N07P) and tilts slightly from the north to south and perhaps east to west. The only strong perturbation to the physical uniformity of the nearfield is near station N10P. Note that on the track from N10P to N01P ("outer western track", Figure 5-6b), the water column is well-mixed. Sampling on this track was shortly after low tide, whereas sampling on the "outer southern track" (Figure 5-6a) from N07P to N10P was conducted on an approaching high tide. The destratification in this corner of the nearfield is likely related to tidal influences.

No distinct spatial or depth-related patterns were noted for chlorophyll (Figure 5-7). Slightly higher ($>1.25\ \mu g\ L^{-1}$) chlorophyll concentrations were observed in a small patch near the surface at station N04P. Concentrations of chlorophyll at the surface along the inshore edge of the field ("outer western track", Figure 5-7b) and in some small, barely perceptible patches around the field were slightly higher than in deeper waters, confirming the vertical profile results. All chlorophyll concentrations, however, were low, less than 2 $\mu g\ L^{-1}$.

5.3 Water Types and Analysis of Small-Scale Variability

As pointed out above, some physical, geochemical, and biological variability was associated with short-term tidal dynamics as expressed in the anomalies and variability at station N10P. Generally, however, the field was uniform with respect to horizontal gradients and to the strongly stratified vertical profiles at each station. Temporally, the physical layering was strong and constant. But, comparing the vertical profiling data to the towing data, a sharp rise in surface chlorophyll concentrations over two days may be suggested for some locations .

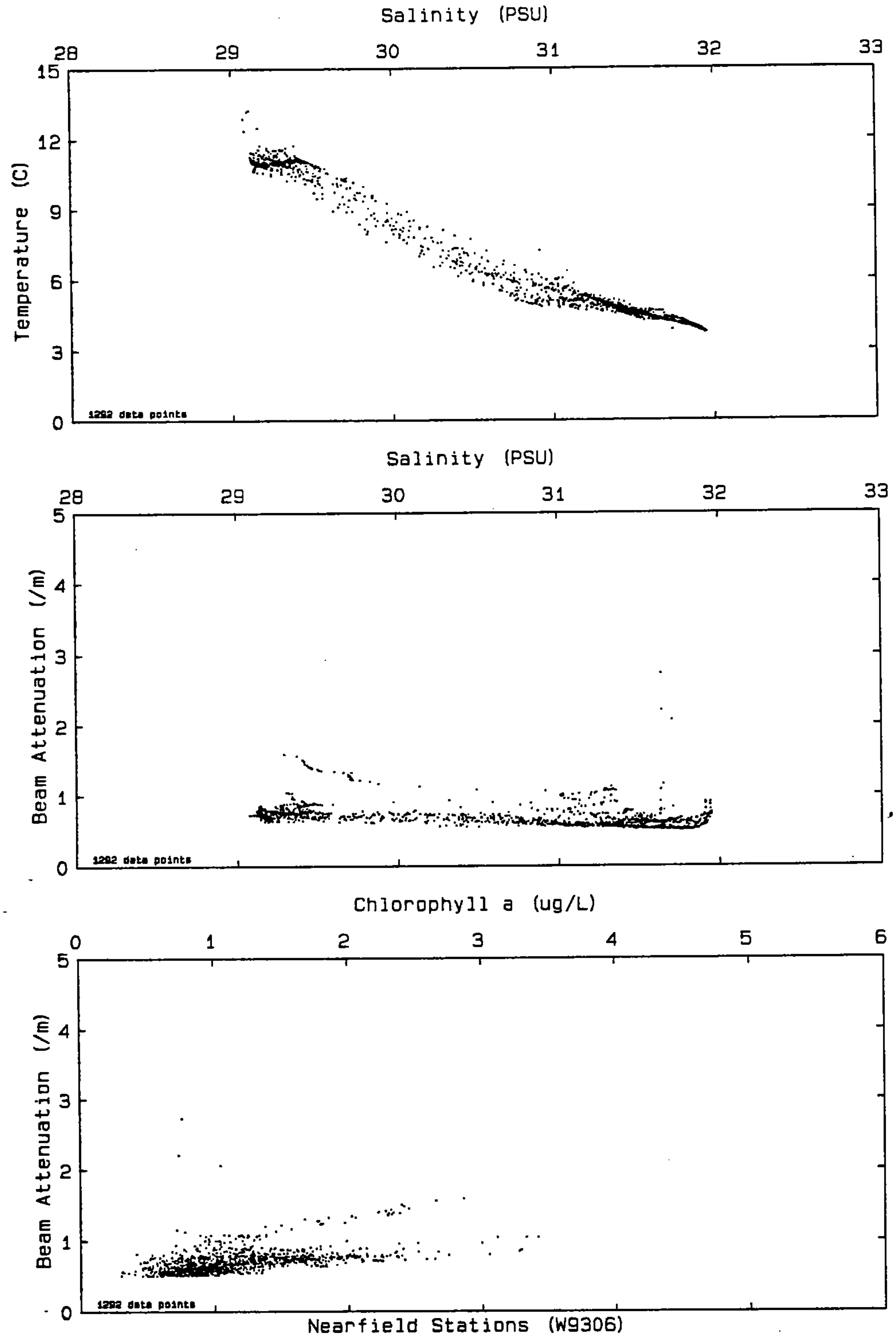


Figure 5-1a. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late May 1993. Individual station casts that were used to produce this composite are included in Appendix B.

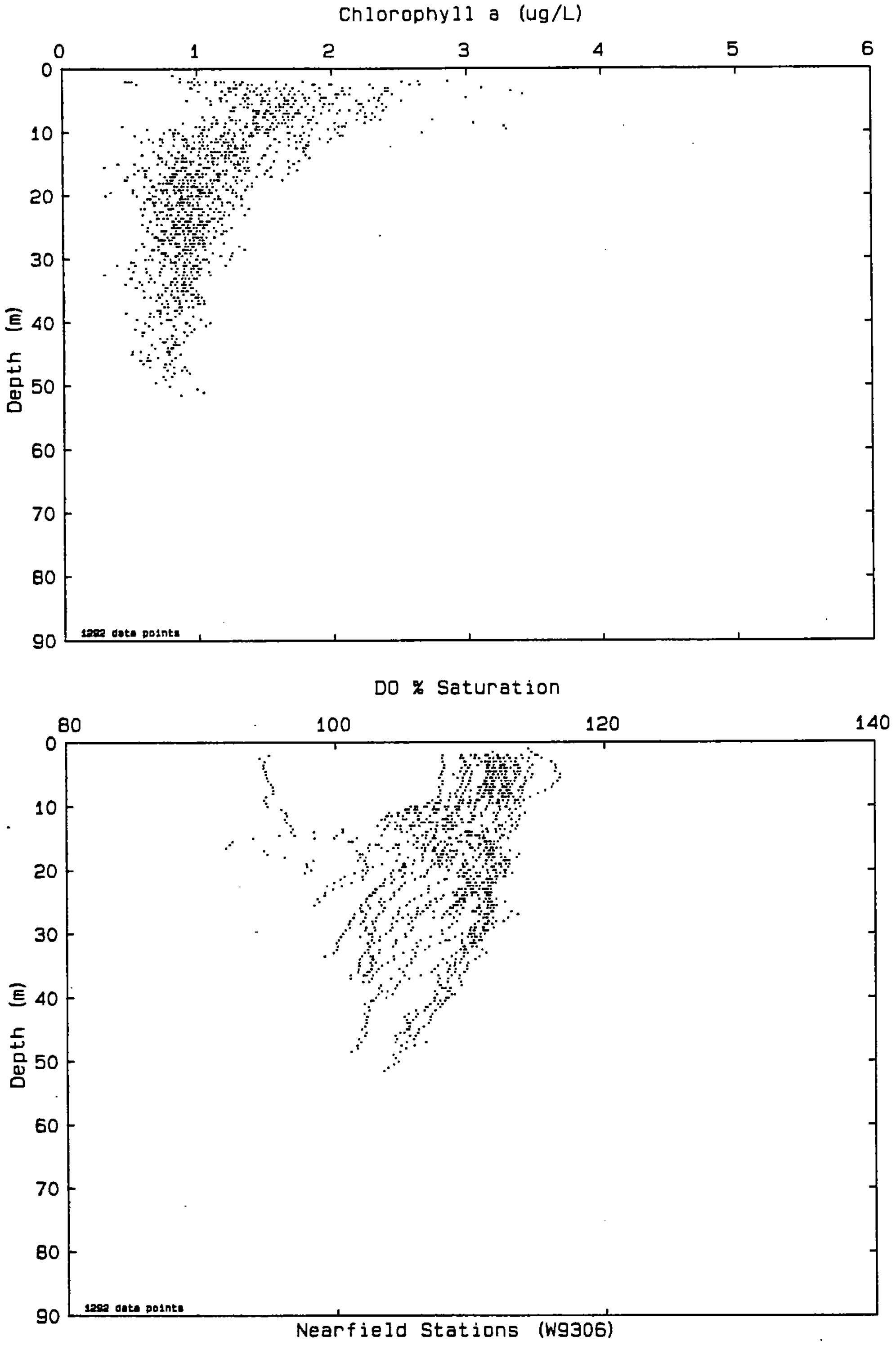


Figure 5-1b. Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late May 1993. Individual station casts that were used to produce this composite are included in Appendix B.

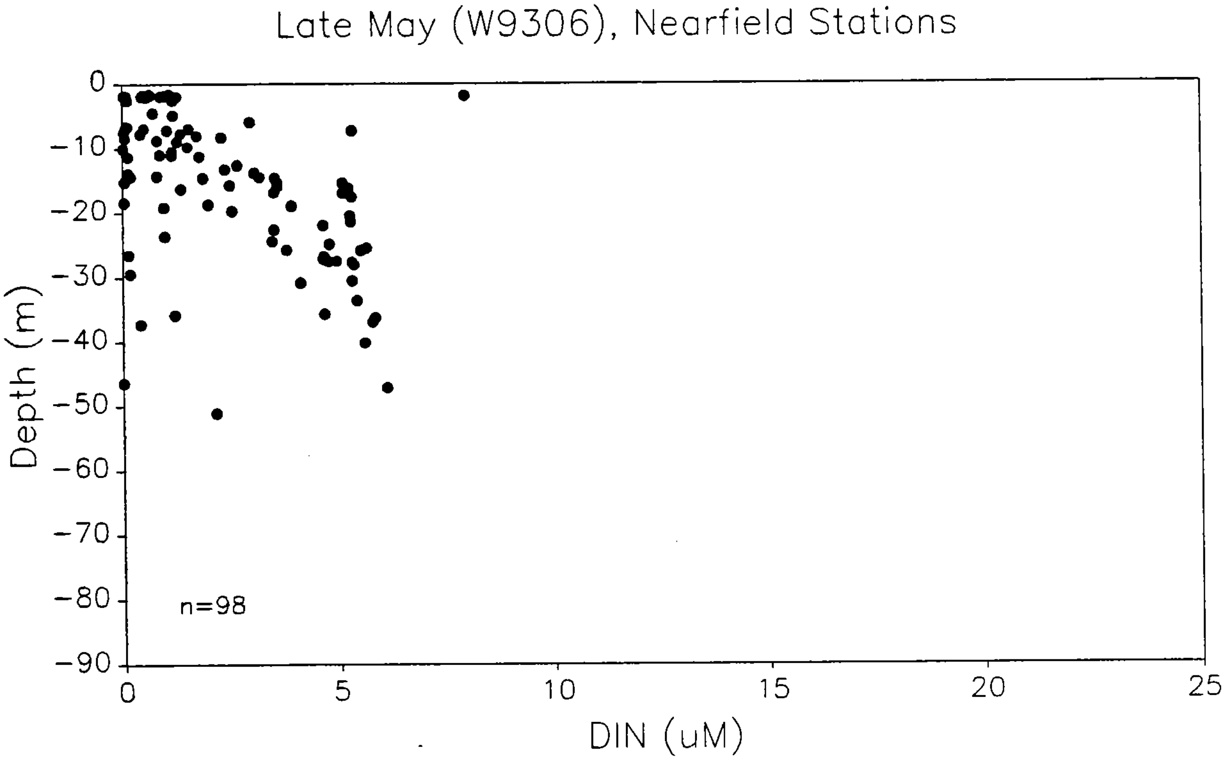
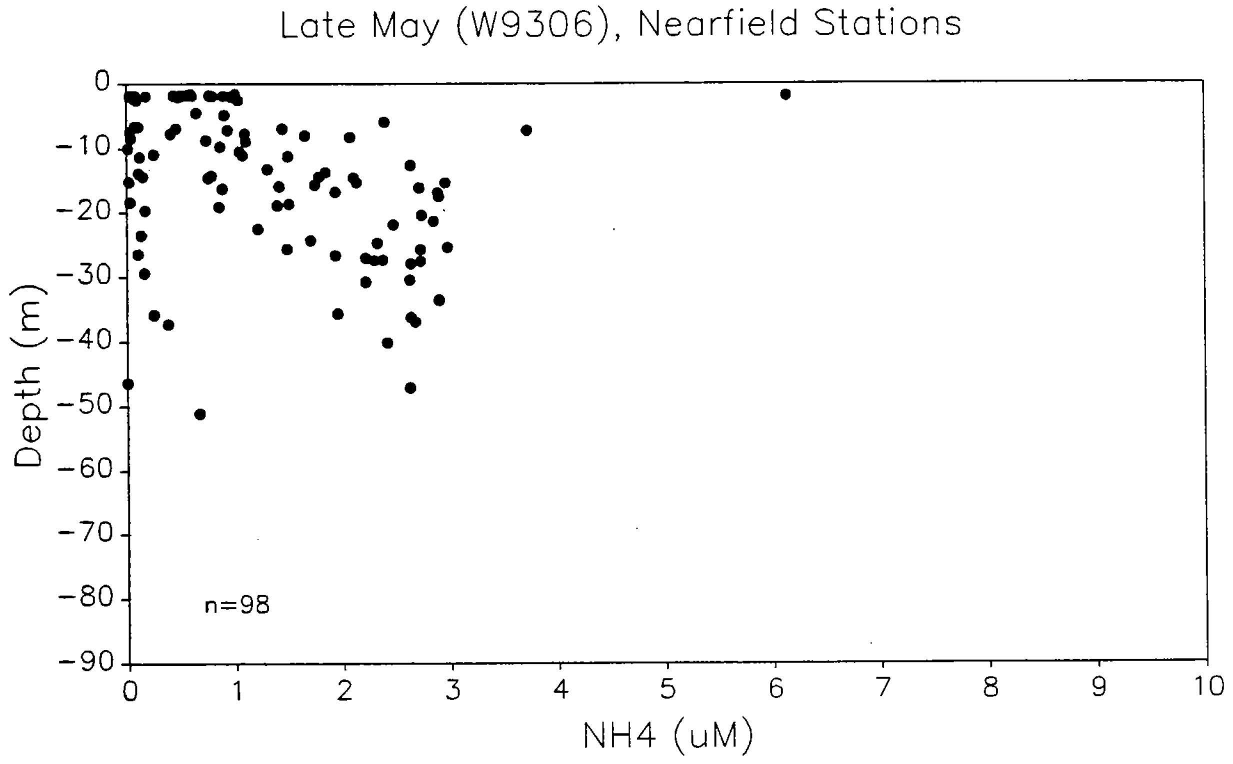


Figure 5-2a. DIN vs. depth in late May 1993.



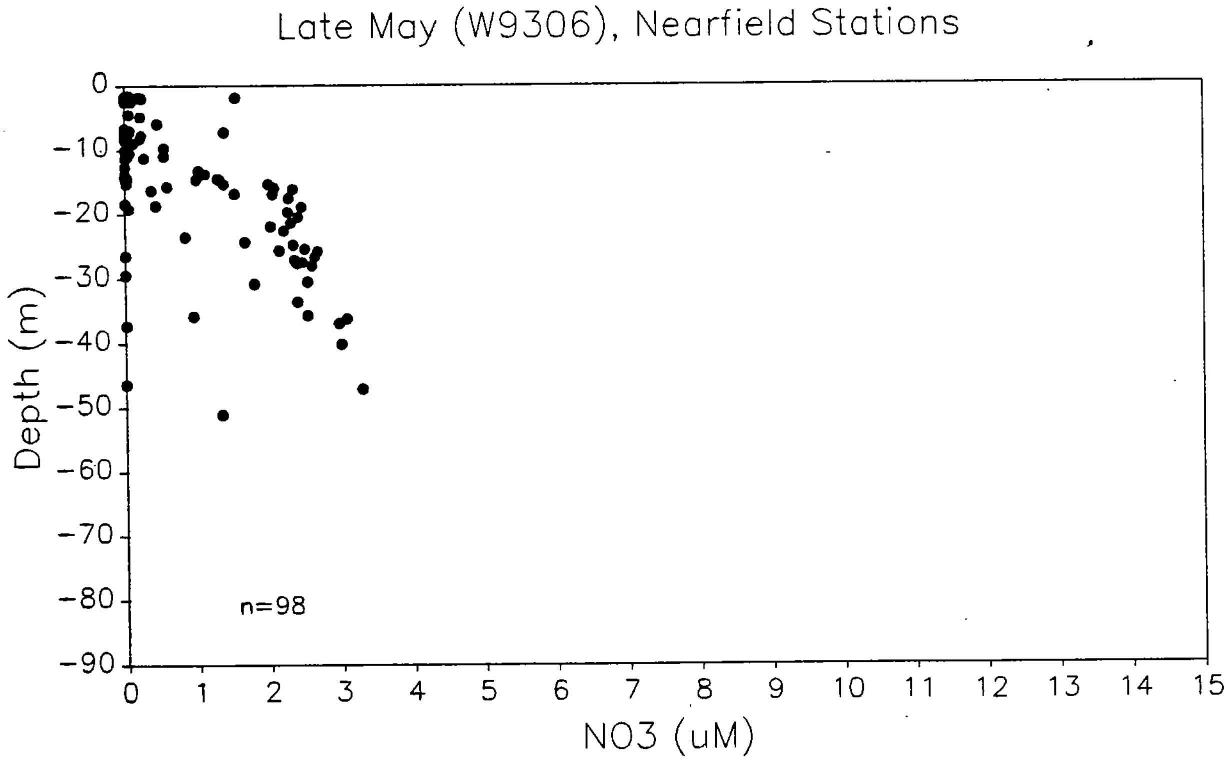


Figure 5-2b. NH_4 and NO_3 vs. depth in late May 1993.

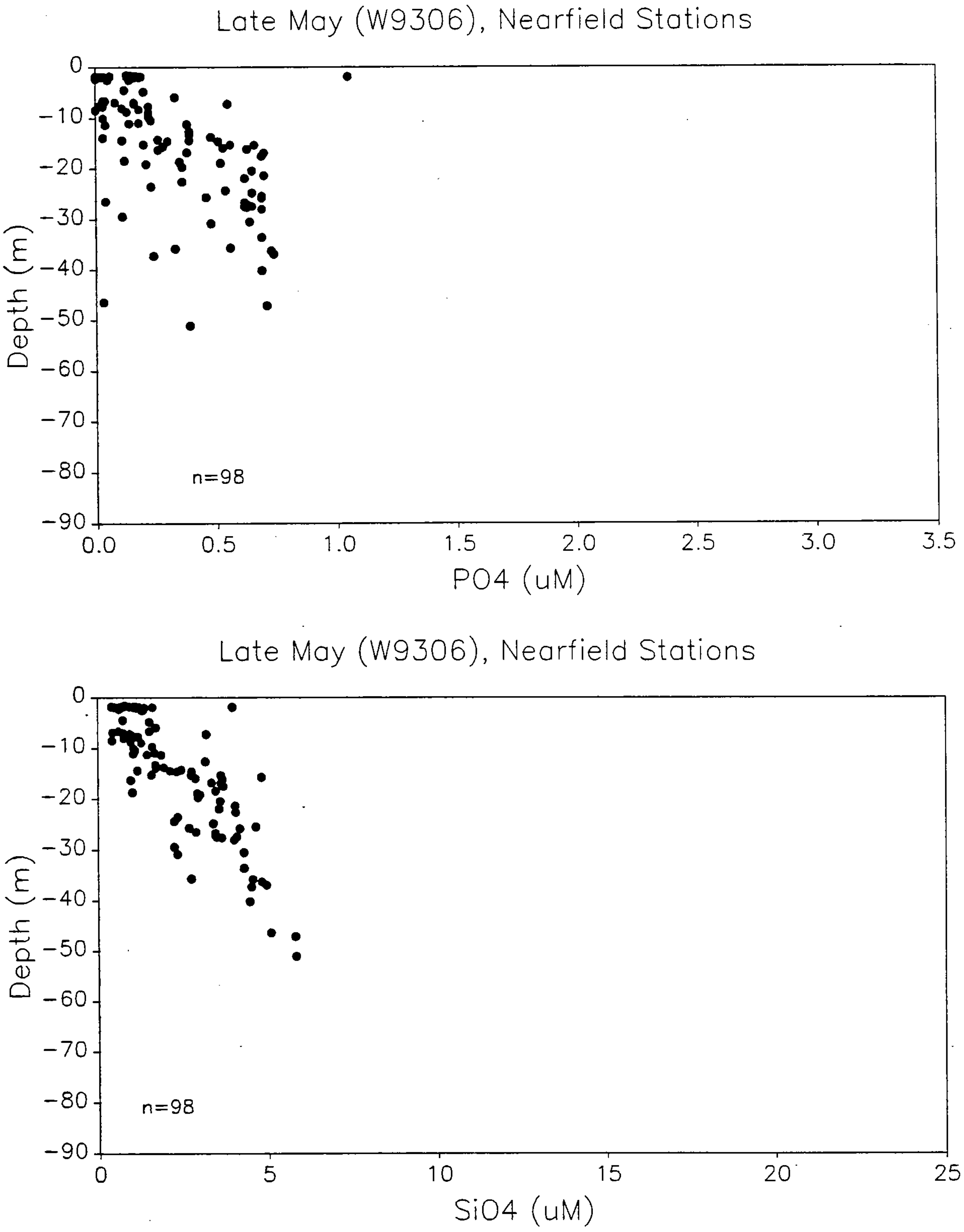


Figure 5-2c. PO_4 and SiO_4 vs. depth in late May 1993.

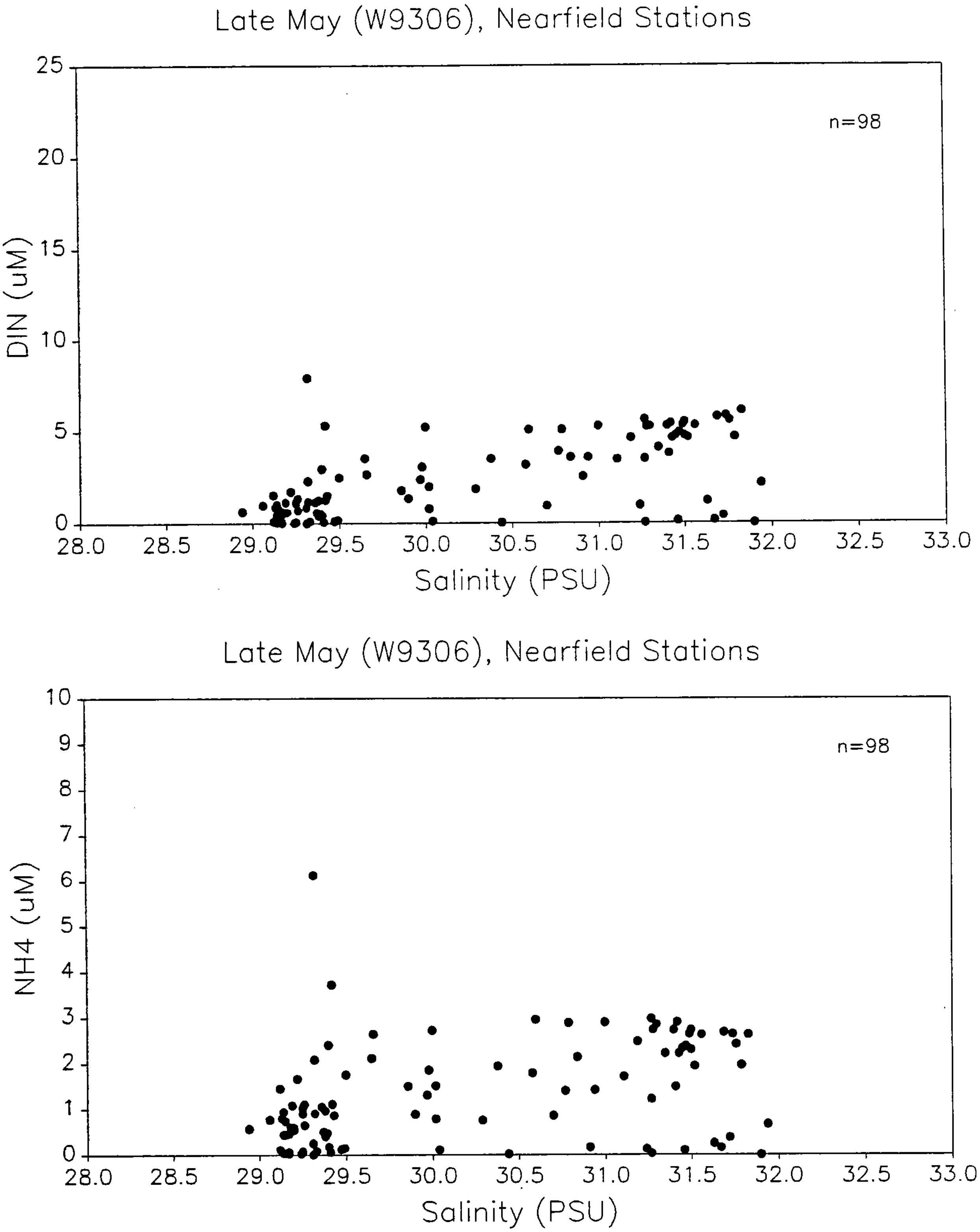
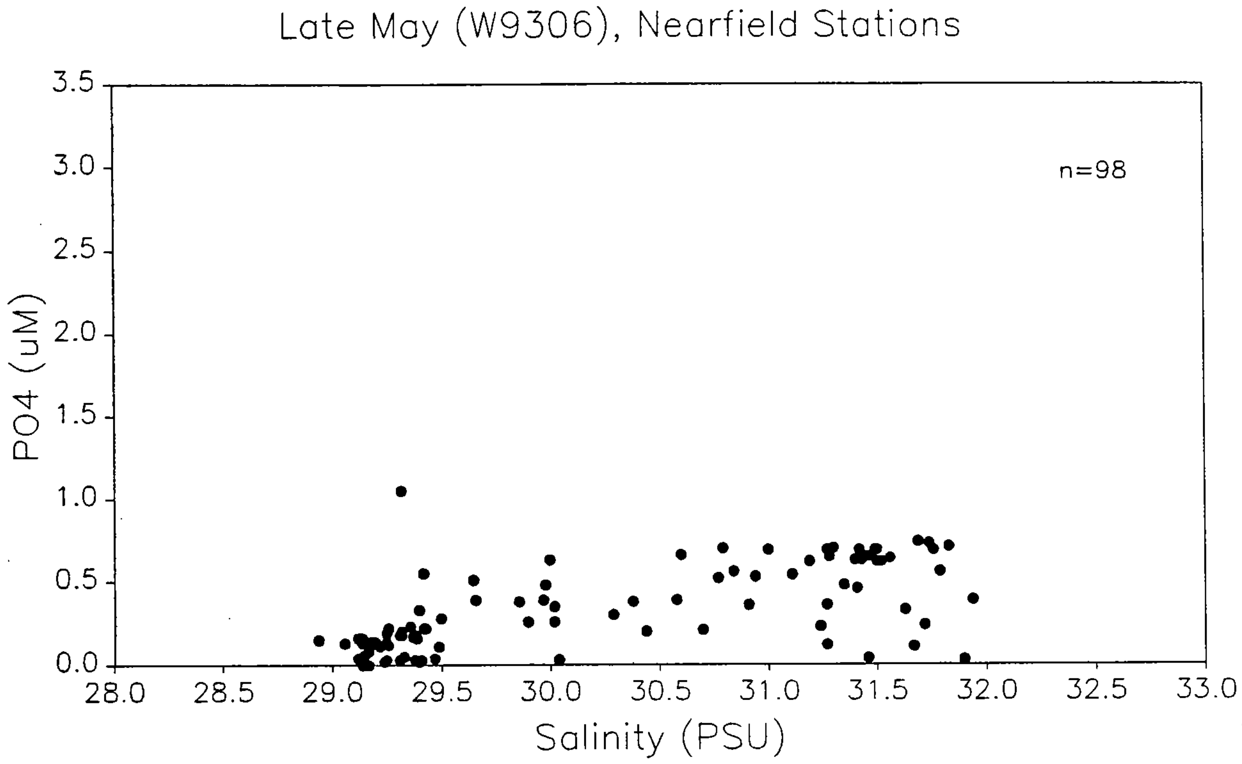


Figure 5-3. DIN and NH_4 vs. salinity in late May 1993.



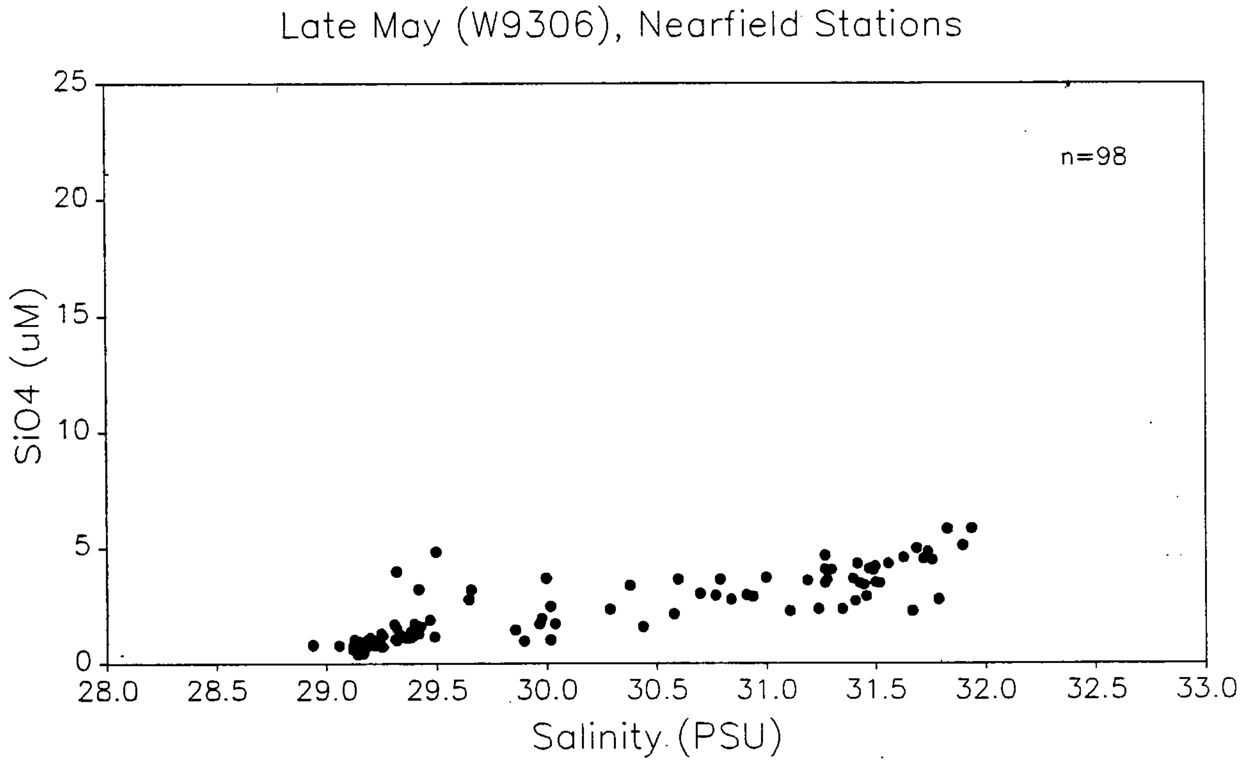


Figure 5-4. PO_4 and SiO_4 vs. salinity in late May 1993.

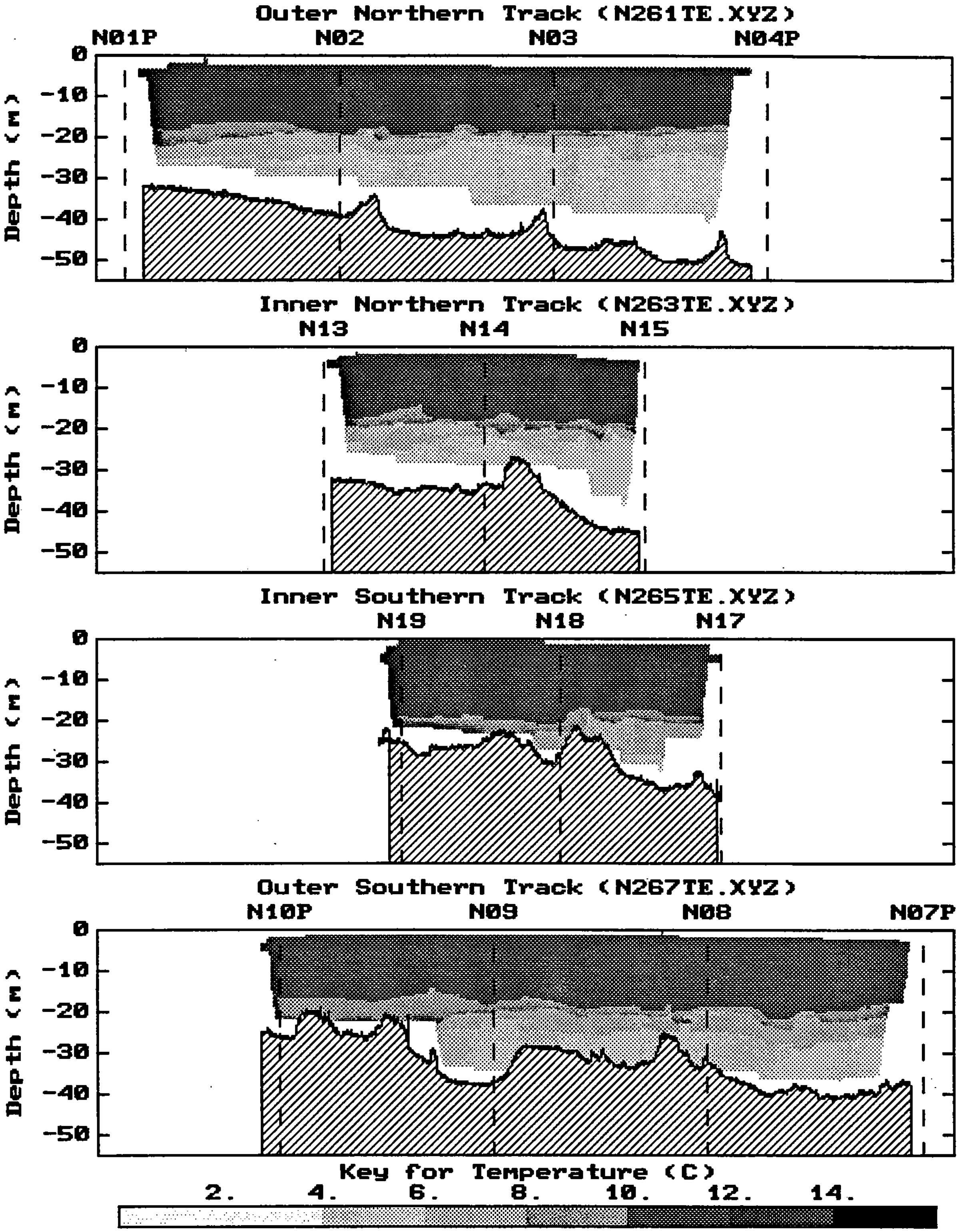


Figure 5-5a. Vertical section contours of temperature generated for tow-yo profiling conducted in late May 1993. The view is towards the north.

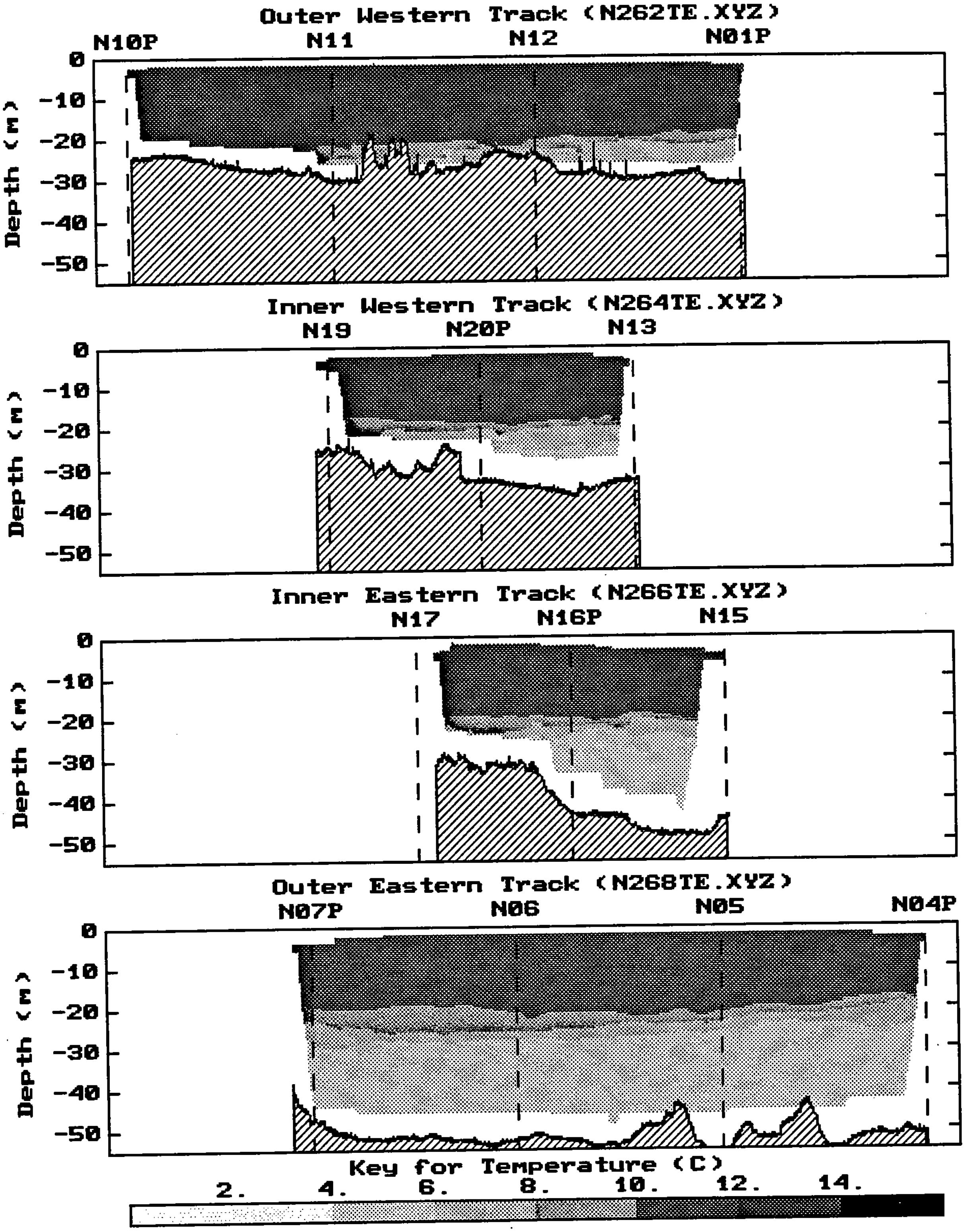


Figure 5-5b. Vertical section contours of temperature generated for tow-yo profiling conducted in late May 1993. The view is towards Boston Harbor.

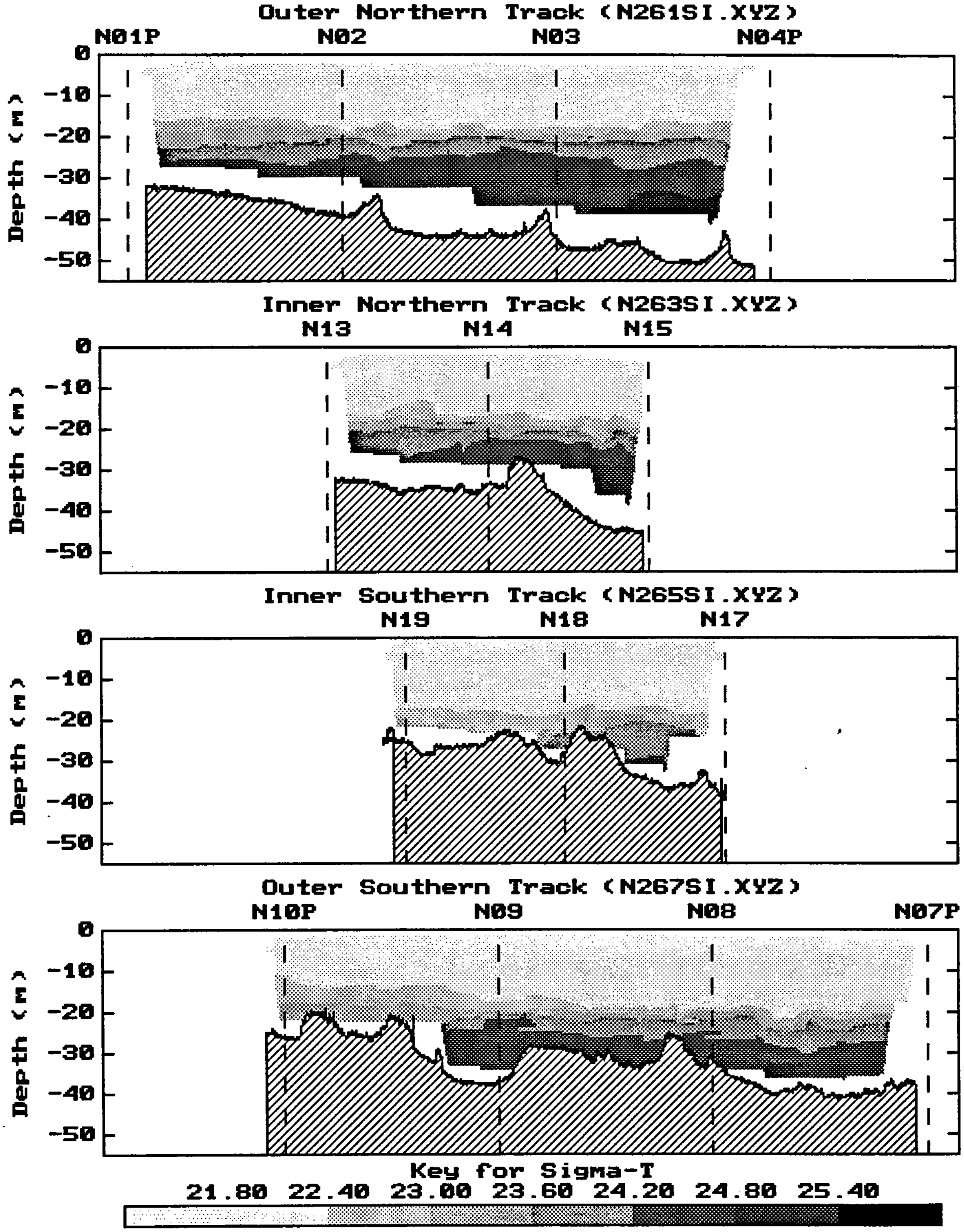


Figure 5-6a. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in late May 1993. The view is towards the north.

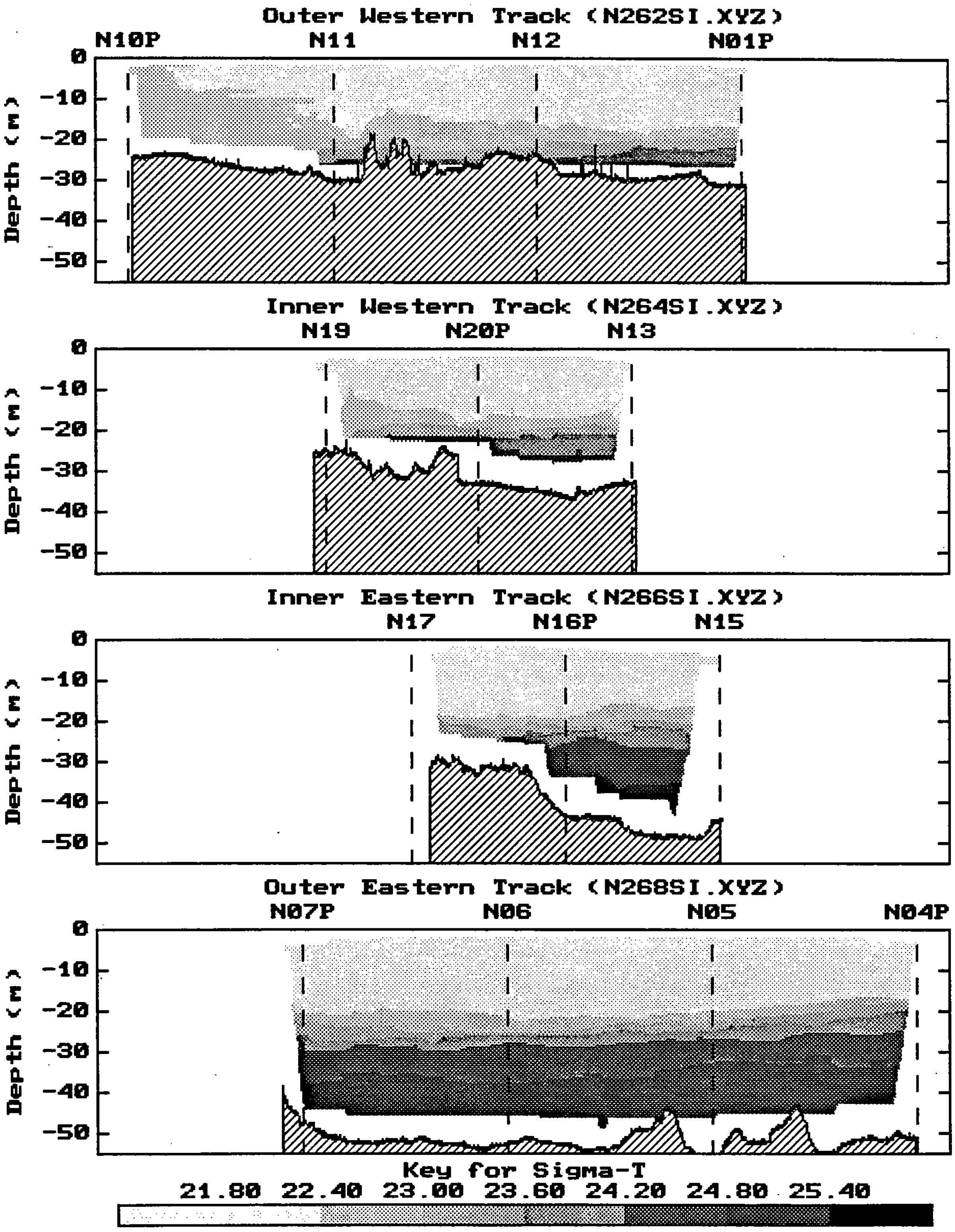


Figure 5-6b. Vertical section contours of density (σ_T) generated for tow-yo profiling conducted in late May 1993. The view is towards Boston Harbor.

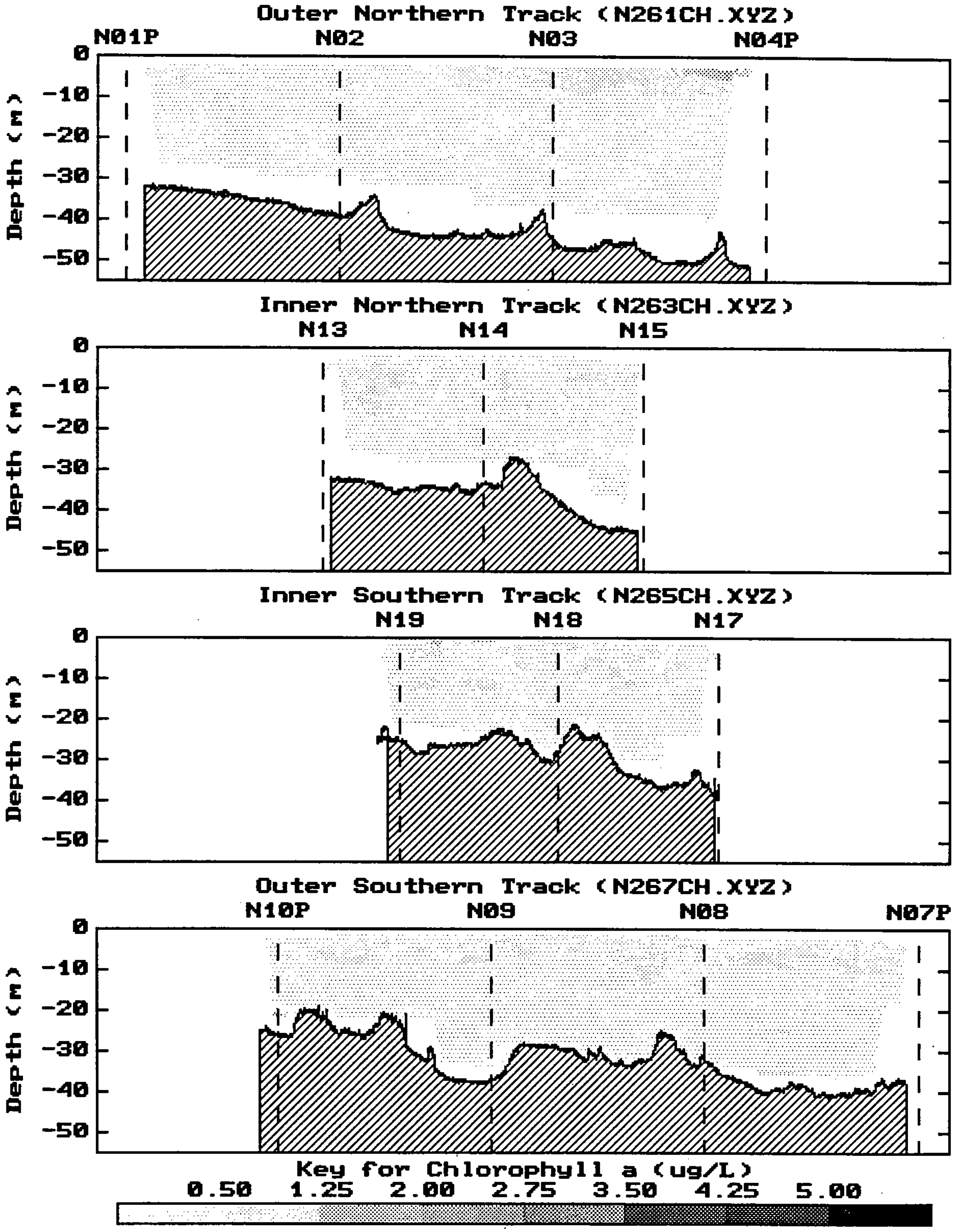


Figure 5-7a. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in late May 1993. The view is towards the north.

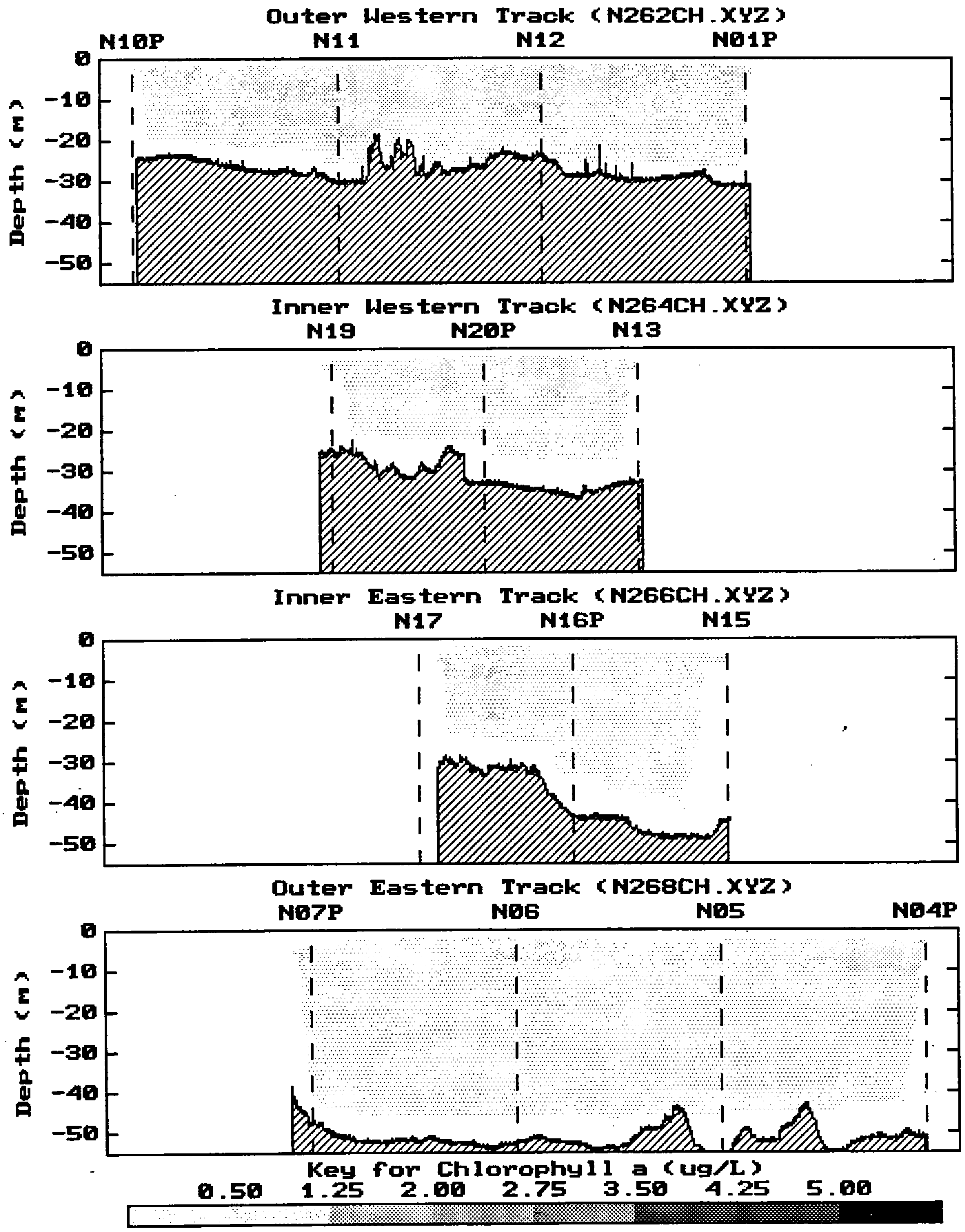


Figure 5-7b. Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yo profiling conducted in late May 1993. The view is towards Boston Harbor.

6.0 DISCUSSION OF THE LATE SPRING PERIOD OF SURVEYS

6.1 Water Properties

6.1.1 Variability at the Regional Scale

The only regional-scale sampling covered by this report was in early April. At that time, the physical parameters indicated a complex, and very likely, dynamic setting in surface waters of Massachusetts Bay. Surface water properties of Cape Cod Bay were similar to those found in some areas in Massachusetts Bay. Regionally, the main feature was a distinctly cooler and more saline water mass in the middle of Massachusetts Bay, crossing diagonally northwest to southeast the nearfield region.

This cooler, more saline, water mass segregated the offshore water — a warm, fresher surface water lens extending from the northeast to mid-Massachusetts Bay, but not the full length of Stellwagen Basin — from the inshore waters near Boston Harbor. A fresh, warmer surface water mass, apparently representing a coastal current plume, was found outside the Harbor, extending to Plymouth. Both the inshore and offshore waters had mild vertical density stratification and a distinct surface layer, whereas a weaker pycnocline near the surface was detected in the mid-nearfield surface water.

Each area of Massachusetts Bays — the inshore coastal plume, the mid-nearfield cell, and the northeasterly surface water mass — had some distinctive water-quality features. For example, the coastal plume was relatively turbid and nutrient-rich. The mid-nearfield cell at the surface was nitrogen-depleted but was characterized by some of the highest subsurface chlorophyll concentrations at the top of the pycnocline. The northeasterly surface water was characterized by intermediate DIN concentrations, chlorophyll concentrations comparable to the inshore plume, and relatively high silicate concentrations. In contrast, Cape Cod Bay was distinct in terms of physical characteristics, but had some geochemical and biological characteristics in common with the inshore region and/or the northeasterly area of Massachusetts Bay.

6.1.2 Variability in the Nearfield

Water quality characteristics in the nearfield area from early April to late May were highly variable both in space and in time. The space-time dynamic was a transition from a nearfield being the center of a mosaic of surface water conditions characterized by inshore-offshore gradients but weak vertical stratification in early April, to a uniformly and strongly stratified water column, with only subtle biological and chemical variability, in late May. The surface system changed from one dominated by horizontal advection with weak barriers to vertical exchange to one with very strong vertical stratification and probably more horizontal mixing than advection.

Interestingly, the seasonal progression towards thermal stratification was prolonged, then occurred rapidly. Stratification began as early as the end of March (Kelly *et al.,* 1993d), again in early April, and developed mildly in late April/early May. Apparently, though, well-defined stratification was delayed until a period of rapid surface warming in the last three weeks of May.

6.1.3 Coherence of Nearfield and Farfield Station Properties

As indicated in Section 3 and above (Section 6.1.1), in early April much of the nearfield surface water was distinctly different from all farfield regions in terms of physical and geochemical properties. Stations at the "edges" of the nearfield, however, shared some of the water quality characteristics of the neighboring surface water masses. Section 6.3 below compares the biological properties of the nearfield stations with the farfield stations in the light of the physical/nutritional differences.

6.1.4 Special Features: Comparison of 1993 with 1992

The nearfield surface temperatures showed distinct differences between the winter-spring periods of 1992 and 1993 (Figure 6-1). Early in the season, as described in the first periodic report (Kelly *et al.,* 1993d), the surface water at the 21 nearfield stations was about 1-2°C cooler in 1993 than in 1992, and cooling continued into late March. In early April 1993, the surface water had warmed about 2-3°C from late March 1993; but still was several degrees cooler than the same time in 1992. The rapid warming continued into late April/early May, being more rapid in 1993 than in 1992. At this time, nearfield surface temperatures in 1993 were comparable to those of 1992. By late May 1993, however, the nearfield was about 2-3°C warmer than in 1992. Thus, the 1992 and 1993 winter-spring seasons differed not only month-to-month, but also in the seasonal progression of thermal properties (i.e., the shapes of the temperature curves and rapidity of warming late in the season were strikingly different; Figure 6-1).

Figure 6-2 compares bottom water DO concentrations in 1992 and 1993, based on readings associated with the closing of Niskin bottles for nutrient sampling (Appendix A for 1993). The increase in average DO between February and April 1993 is concomitant with, and in part determined by, a decrease in temperature. From early April to late May in both years, as stratification ensued, DO concentrations decreased. The temporal progression was similar in both years, but in 1993, the late May DO concentrations did not drop to the low concentrations reported in May 1992.

6.2 Water Column Nutrient Dynamics

6.2.1 Vertical Structure and Initiation of Seasonal Stratification

Because thermal distribution, rather than salinity variations over depth, primarily regulates development of the seasonal thermocline, the temperature progression in surface waters can indicate the progression of stratification. Mild stratification and cooler temperatures occurred over a fairly long period in 1993, and was perhaps punctuated by brief intervals of full mixing of the water column (Kelly *et al.,* 1993d).

Strong nutrient depletion (especially DIN) in nearfield surface waters was not observed uniformly and consistently, perhaps due to the slow progression of stratification. It is possible that some vertical mixing of high nutrient water was still occurring, perhaps sporadically, during this period. By the time thermal stratification was well defined in late May, surface silicate concentrations were reduced to low concentrations, concomitant with lower DIN and PO_4 concentrations in surface waters.

In early April during the farfield survey, weak stratification (and stronger vertical mixing) was more characteristic of Cape Cod Bay stations than Massachusetts Bay stations. Concentrations of DIN in surface waters of Cape Cod Bay stations were less depleted than at mid-nearfield and non-coastal stations in Massachusetts Bay, although silicate concentrations were comparable. These observations support the notion that the progression of stratification may regulate nutrient concentrations and ratios in surface waters; spatial and temporal differences in the development of stratified conditions may account for some differences in seasonal ecological progressions in the pelagic community. This notion may be examined more extensively as a consistent data set is gathered for additional years having variability in winter-spring climatology.

6.2.2 Inshore-offshore Gradients

Strong inshore-offshore gradients for temperature, salinity, and stratification, as well as for nutrients were observed in early April. These gradients, which were most evident, near the Harbor (nutrient and freshwater source) were observed for silicate, phosphate, and nitrogen nutrients. Higher nutrients were evident at this time at lower salinity. At the salinities characteristic of the western half of the nearfield region, a nitrogen sink may be suggested in early April 1993.

The inshore-offshore nutrient gradient that characterized the nearfield surface water in April was not well defined in May. There was, however, some evidence for a sporadic (tidal) influx of nutrient-enriched water at the western edge and southeastern corner of the nearfield.

6.2.3 Influence of Northern Rivers

The possible influence of rivers to the north of Massachusetts Bay can be examined by comparing data from the nearfield stations with data from stations north of the nearfield. In early April, a water mass was present northeast of the nearfield area and perhaps progressed across at least the eastern edge of the nearfield. In terms of DIN, this surface layer of water was more enriched than the nearfield at this time, but DIN concentrations were less than at coastal inshore stations. Similar comments apply to silicate differences across these areas.

However, with respect to nitrogen, DIN provides an incomplete assessment because particulate organic nitrogen was a significant fraction of total N. Examining the data from the northeast corner (station N04P) or eastern edge of the nearfield, (stations N04P and N07P) it was apparent that neither the average DIN + PON nor total nitrogen concentration (see Section 3) in surface waters at these stations were outside the range measured at other stations in the nearfield (see also Appendix A). Water mass advection from the north was suggested from the physical measurements and *may* occur at this period, but this does not necessarily imply that the waters enrich surface waters of the nearfield to any significant degree — based on concentration differences alone, the data suggest no significant enrichment.

6.2.4 Special Features: Comparison of 1993 with 1992

The development of stratification, the peak nutrient concentrations, and the temporal and spatial variations in nutrients observed in the study area in 1993 were different than observations made in 1992. As shown in Figure 6-3, differences in seasonal progression in the nearfield surface layers are apparent. In 1992, beginning with the first survey, DIN concentrations decreased and were virtually undetectable through April and May. In 1993, more variability in DIN concentrations was noted between February and March, but there was no pattern of decreasing concentrations. By April, many samples were nearly depleted in DIN, but variability was still high. In early May, the average DIN concentrations increased slightly but decreased again in late May. Compared to 1992, greater variability in DIN concentrations throughout the upper 20 m, was noted in late May 1993. Because of differences in the location of the thermocline, some of these year-to-year variabilities might be less pronounced if comparisons were made in the upper 5-10 m rather than the upper 20 m. Nevertheless, the virtual removal of DIN from the nearfield surface waters observed between April and May 1992 (after stratification was established) was not observed during the same period in 1993. This suggests that brief intervals of full mixing of the water column in 1993 (Kelly *et al.,* 1993d) may have resulted in a delay in both the establishment of stratification and the depletion of nutrient concentrations until the end of May.

6.3 Biology in Relation to Water Properties and Nutrient Dynamics

6.3.1 Phytoplankton—Zooplankton Relationships

The relationship between phytoplankton cell counts and chlorophyll concentrations in early April was not as strong as earlier in the year (Kelly *et al.,* 1993d). Cell counts were low throughout the bays, never exceeding 1 million cells L^{-1} (Figure 6-4). However, Figure 6-5 suggests increasing zooplankton counts with increasing average chlorophyll concentrations. Zooplankton population normally lags development of the winter-spring phytoplankton bloom, in part because temperatures affect zooplankton growth more than phytoplankton growth. This early April survey may have coincided with the period when zooplankton population sizes begin to reflect the variation in resources that have been available over the preceding months, and thus yield a positive correlation with phytoplankton. Whether this relationship is more likely to occur following a prolonged, rather than a brief, winter-spring bloom period is unknown. The relationship in Figure 6-5 does suggest that, for a period after the early April survey, herbivory might soon have a significant role in determining chlorophyll distributions.

6.3.2 Plankton Species and Water Properties

Plankton species data for early April were collected at all BioProductivity stations and at the surface of station N10P during each nearfield survey. With respect to the farfield survey, it was noted earlier that there were distinct water quality differences across regions of the Bay encompassed by the Bioproductivity stations. Variations in chlorophyll were, by and large, independent of many of the physical/nutritional variations. In general, the plankton community composition was similar across the stations. Several diatoms and copepods were consistently the dominant species. One exception was station F23P at the edge of Boston Harbor which was distinctive in terms of nutrients, temperature, salinity, turbidity, and most water-quality characteristics. Higher fractions of small phytoplankton (microflagellates and cryptomonads), and fewer copepod nauplii and total zooplankton were observed at this station (see Section 3).

At station N10P, plankton samples were collected from the surface on April 6, April 9, May 1, and May 21 (Appendix F, Table F1). From April 6 to May 1, the species composition from the whole-water sampling was similar and the same group of diatoms was dominant, although the abundance of *Thalassiosira* (cf) *gravida/rotula* was reduced in the May 1 sample. The sample from May 21, however, was distinctly different and dominated by a dinoflagellate, *Heterocapsa triquetra*, as well as microflagellates and cryptomonads. As the seasonal stratification developed, the plankton community at station N10P, which characteristically receives some Harbor outflow water at the surface, changed to the mixed-flagellate, reduced-diatom community typical of summer stratified conditions.

Results of the screened ($>20\ \mu m$) surface-water plankton taxonomy are shown in Table 6-1. Although the abundance of these larger organisms was always very low (e.g., $<10^3$ cells L^{-1}) compared to dominants identified in whole-water samples (usually 10^4-10^5 cells L^{-1}), the progression in Table 6-1 suggests the increasing abundance of some larger dinoflagellates in May, particularly by late May. These results thus reinforce the impressions of change from diatoms to a mixed-flagellate community suggested by the whole-water analyses.

As shown in Table 6-1, *Alexandrium tamarense,* although still in low abundance, was detected at station N10P in late May. Recent hypotheses suggest that this organism, which is of concern because of paralytic shellfish poisoning (PSP), may be advected into the bay from the north (Franks and Anderson, 1992).

Overall, these phytoplankton compositional observations suggest that surface water temperature differences and strong stratification vs. well-mixed conditions inherent with seasonal changes foster distinctly cold- and warm-season biological communities. Seasonal plankton community differences are more distinct than those across horizontal differences in water quality (both physical and geochemical) in the bays during the winter-spring bloom.

6.3.3 Chlorophyll Biomass, Nutrients, and DO

In early April high chlorophyll biomass was found near the pycnocline interface in many locations; during the April-May sampling period, chlorophyll was generally highest in surface water rather than in deeper locations. Concomitantly, DO profiles suggested supersaturation in surface layers and decreasing saturation, to slightly undersaturated values (late May), in bottom waters. At the beginning of the sampling period, chlorophyll concentrations were patchy, but concentrations decreased and became more uniform as the season progressed.

Chlorophyll and DIN characteristically showed an inverse relationship. This pattern was somewhat evident in early April, if chlorophyll vs. total nitrogen is shown (Figure 6-6). The lack of the expected positive relationship between total nitrogen and chlorophyll is curious, but could arise in part, because light was limiting growth at some locations, even though nutrient concentrations were high. It is also possible that plankton growth was indeed a nitrogen sink mechanism during the April-May sampling time.

6.3.4 Metabolism and Environment

As discussed in Section 3, there was not a strong relationship between primary production rates and the average chlorophyll concentration at each station. For the sampling region, there was a weak relationship of increasing integrated production rates corresponding to increased integrated euphotic zone chlorophyll mass (Figure 6-7; $r^2=0.163$, $n=10$ stations). Estimates of production rates varied, sometimes almost a factor of 4, between calculations made using the P-I curve for a surface vs. subsurface population. Highest production rates were found around several nearfield locations and near station F13P, but the spatial pattern was somewhat random and the distribution of these stations did not suggest an association with a particular water mass identifiable from its water-quality characteristics. Perhaps further inspection would reveal some production-water quality associations, but they are not obvious from the data.

6.3.5 Special Features: Comparison of 1993 with 1992

A positive zooplankton-chlorophyll relationship and an inverse chlorophyll-DIN relationship was also observed in 1992 towards the end of the winter-spring diatom bloom. The seasonal progression of chlorophyll at all nearfield stations is shown in Figure 6-8 for both 1992 and 1993. The temporal patterns in 1992 and 1993 are different: in 1993, chlorophyll "bloom" conditions did not develop until April and low post-bloom chlorophyll concentrations were not detected until late May, even though stratification was well developed. In contrast, in 1992, chlorophyll concentrations following the bloom fell to uniformly low levels similar to pre-bloom concentrations.

6.4 Summary and Recommendations

Profound differences in the winter-spring dynamics and development of seasonal stratification were observed between 1992 and 1993. Clearly there is a climatological variability that can regulate the pace of and nature of ecological events over this period. During the winter-spring period, high variability across years and across stations should be expected, even in the restricted space of the nearfield area (about 100 km^2).

As suggested previously, conditions prior to the winter-spring bloom in Massachusetts Bay were probably captured by the present sampling events, but the conditions prior to development of high chlorophyll in Cape Cod Bay were not. An earlier sampling might be warranted if the background conditions in the two Bays are to be compared prior to outfall discharging. Data from an earlier sampling might be helpful in understanding the factors initiating and/or prolonging the period of winter-spring bloom conditions.

Table 6-1. Abundance of all identified phytoplankton taxa in screened (20μm) samples collected near the surface at station N10P in April and May 1993.

	N10P	N10P	N10P	N10P
	April 6	April 9	May 1	May 21
ALEXANDRIUM TAMARENSE				55
ALORICATE CILIATES	10	30	365	55
CERATIUM FUSUS	5		15	
CERATIUM LINEATUM	3		13	63
CERATIUM LONGIPES	30	10	215	275
CERATIUM TRIPOS			3	
DICTYOCHA SPECULUM	3	8	88	3
DINOPHYSIS ACUMINATA		3	28	263
DINOPHYSIS NORVEGICA	8		10	130
DINOPHYSIS OVUM	8		43	110
DINOPHYSIS SPP.			23	
EBRIA TRIPARTITIA				3
GYRODINIUM SPIRALE	13	20	3	
HETEROCAPSA TRIQUETRA	5	3		791
KATODINIUM SPP.	13	13	3	
MERISMOPEDIA SPP. COLONY	20			
MESODINIUM RUBRUM	18	10	218	
PROTOPERIDINIUM (CF) BREVIPES	3		5	
PROTOPERIDINIUM BREVE	3		8	68
PROTOPERIDINIUM DENTICULATUM	13	10		63
PROTOPERIDINIUM DEPRESSUM	3	3	18	5
PROTOPERIDINIUM PELLUCIDUM	15	5	13	15
PROTOPERIDINIUM SPP.	23	10	40	428
TINTINNIDS	35	45	13	180
UNID. ATHECATE DINOFLAGELLATE		5	3	
UNID. THECATE DINOFLAGELLATES	20	5		43

Units are cells L^{-1}

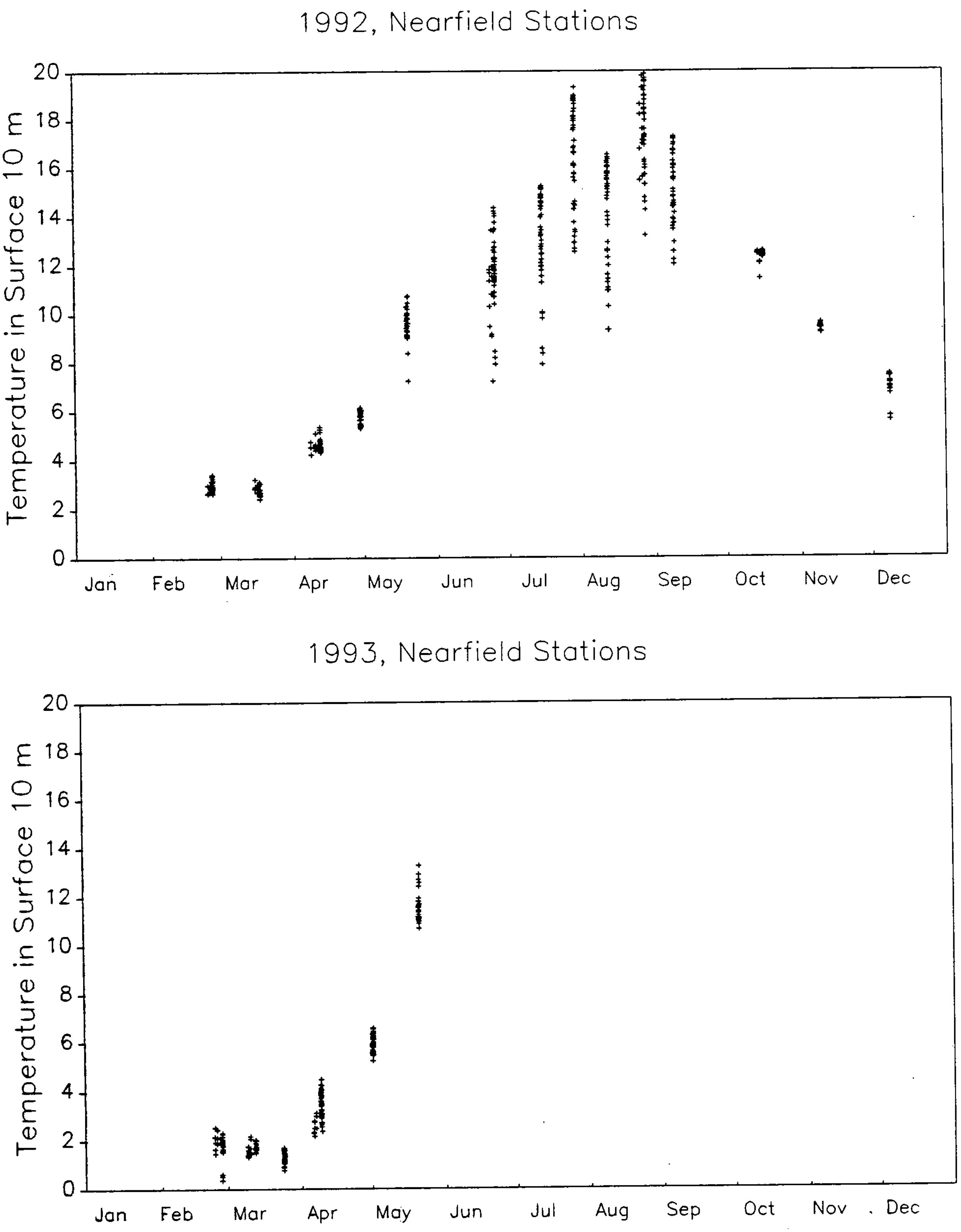


Figure 6-1. **Comparison of the nearfield region in 1993 to the annual cycle of 1992: temperature (°C).**

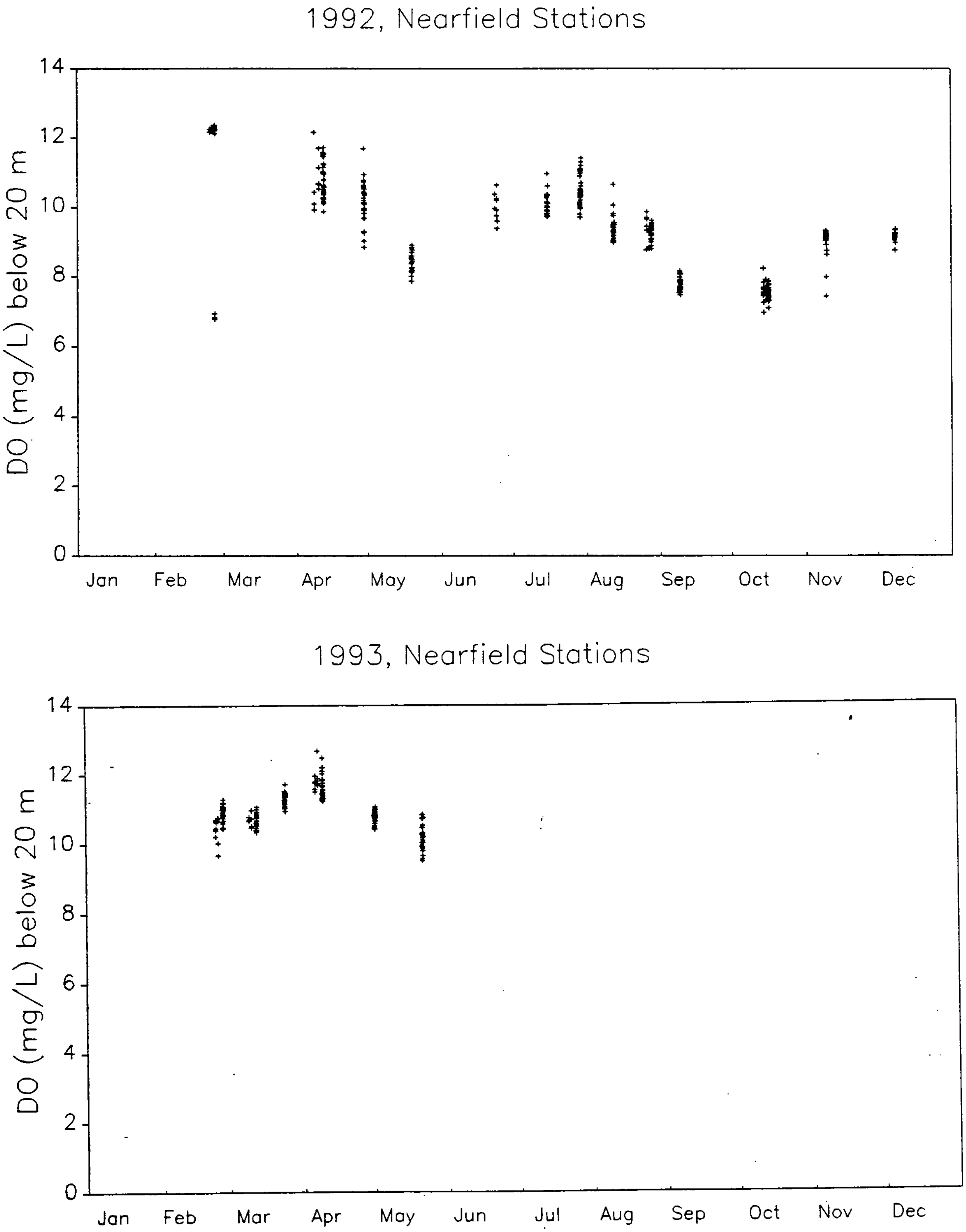
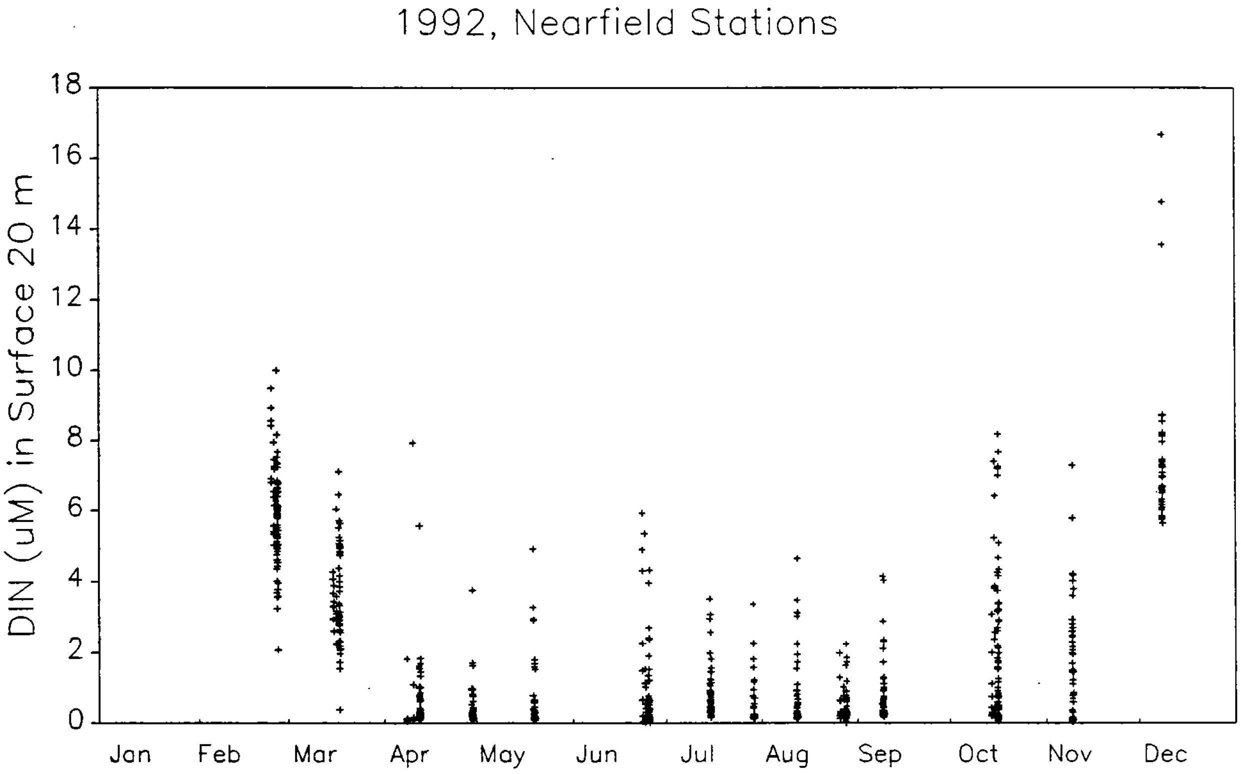
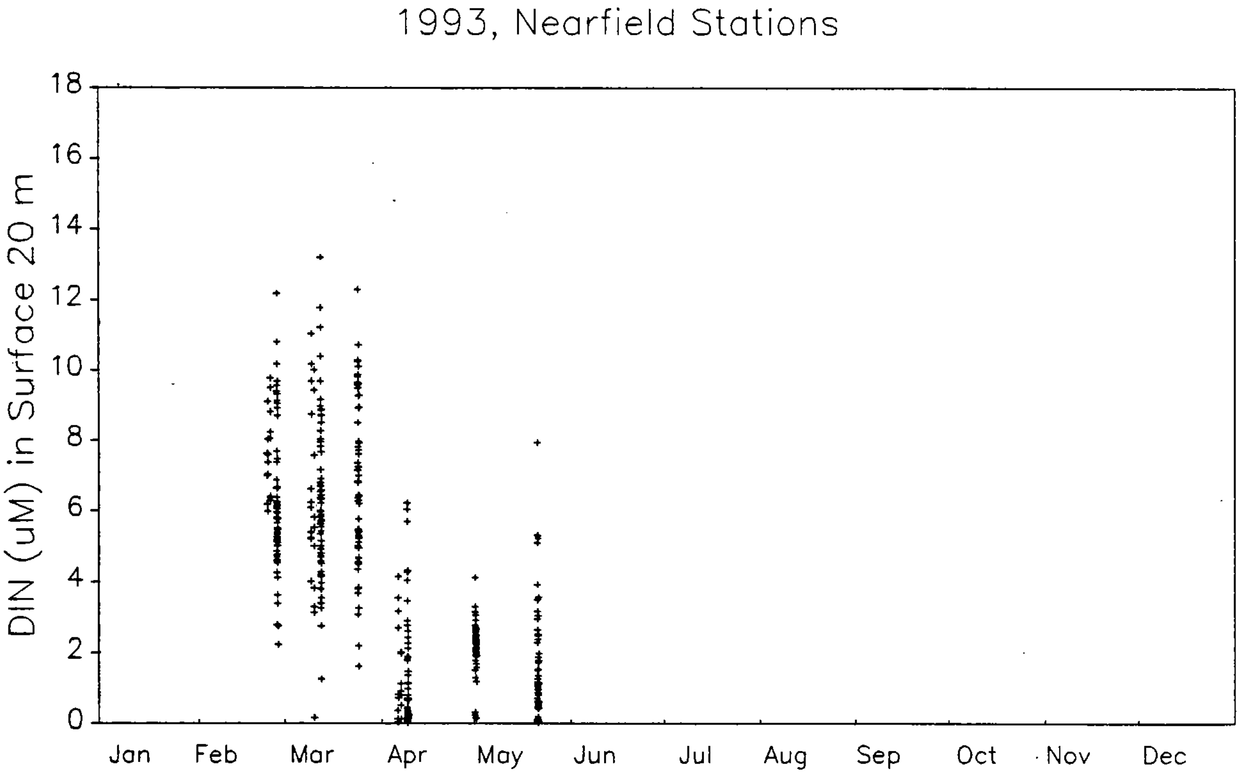


Figure 6-2. **Comparison of the nearfield region in 1993 to the annual cycle of 1992: dissolved oxygen (mg/L).**



1992, Nearfield Stations



1993, Nearfield Stations

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

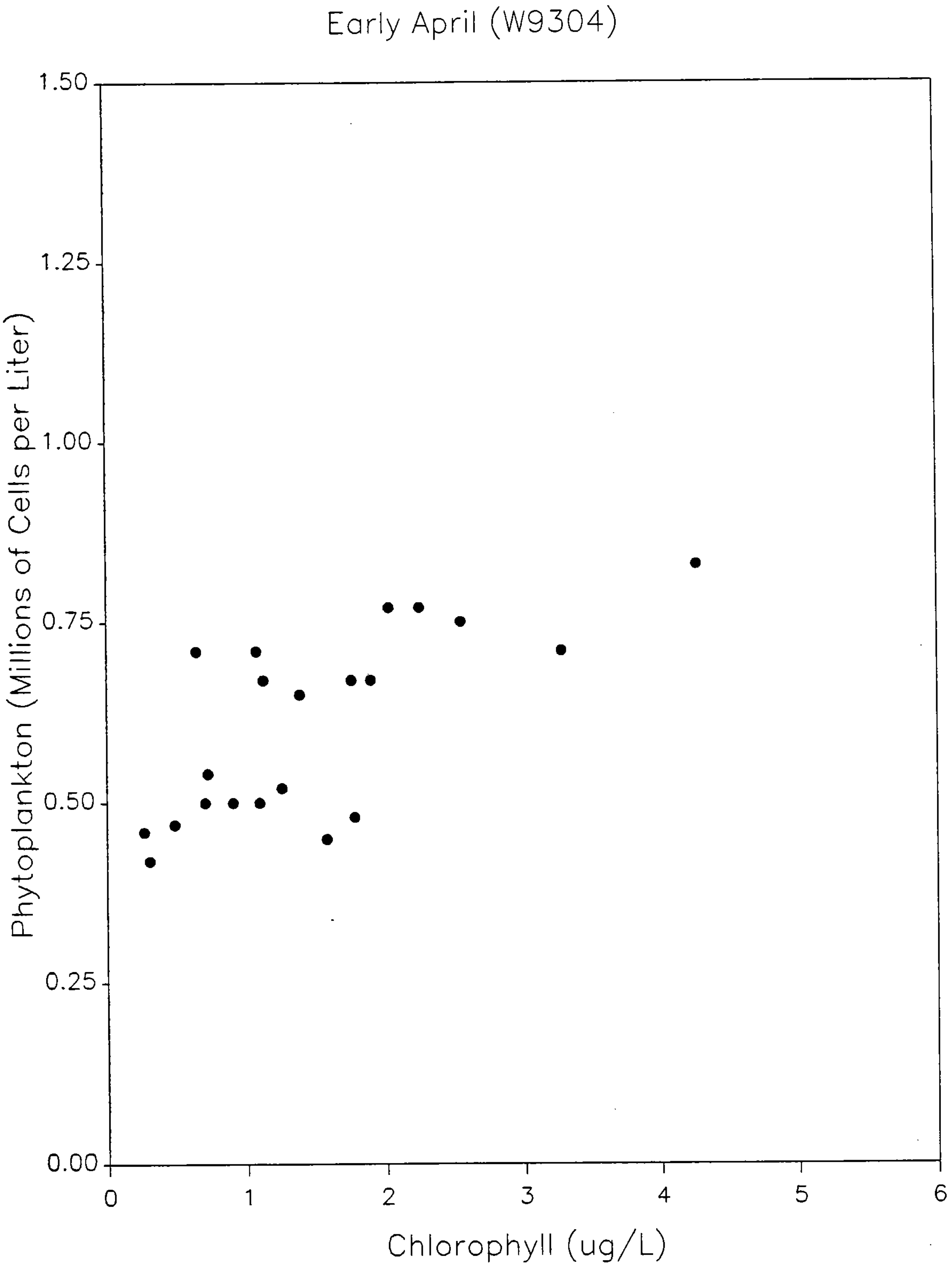


Figure 6-4. **Phytoplankton abundance compared to chlorophyll concentrations in samples from early April 1993.**

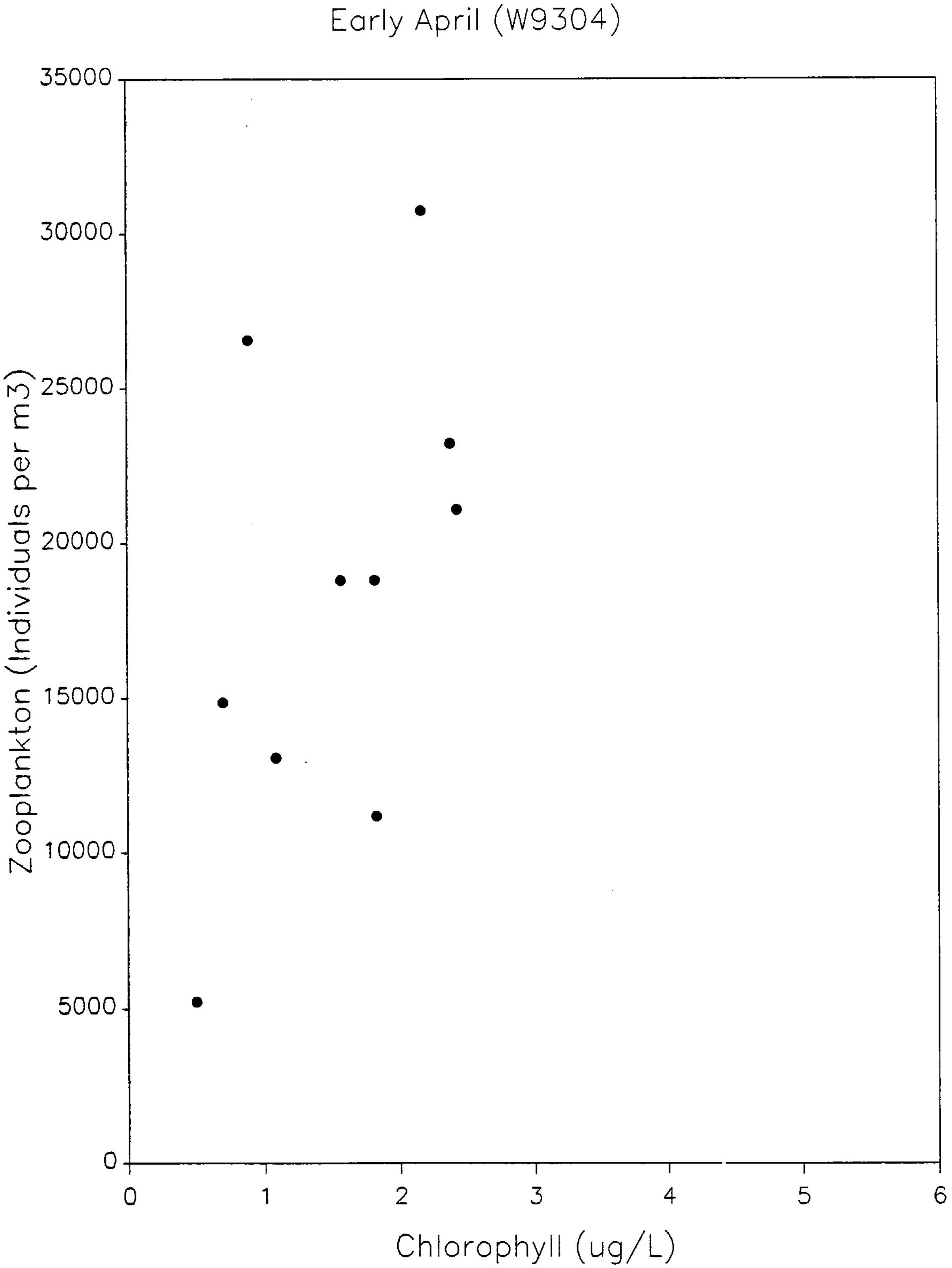


Figure 6-5. **Zooplankton abundance compared to the average chlorophyll (extracted) concentration (n=2 depths) in the water column in early April 1993.**

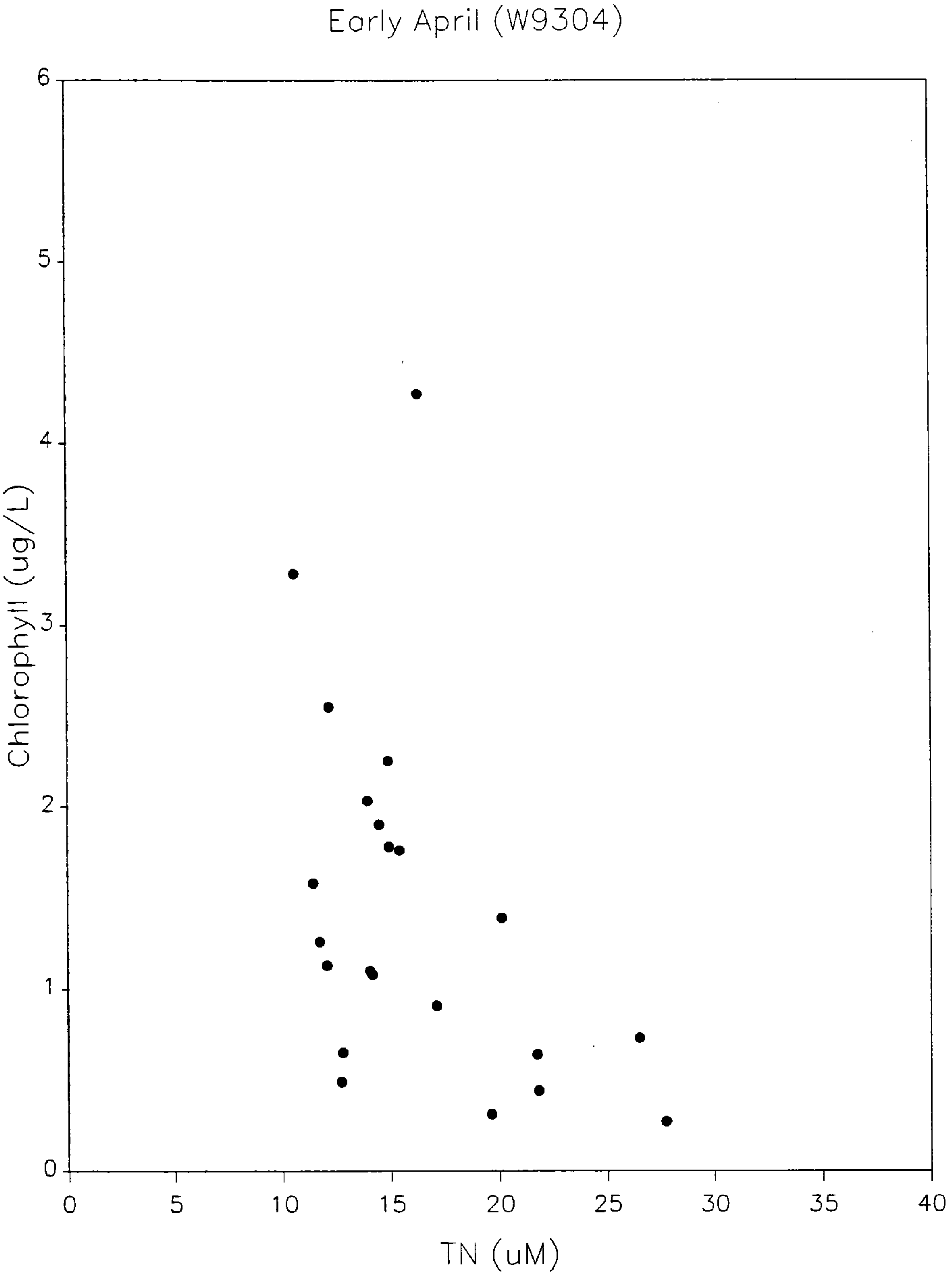


Figure 6-6. **Chlorophyll (extracted) and total nitrogen in samples from early April 1993.**

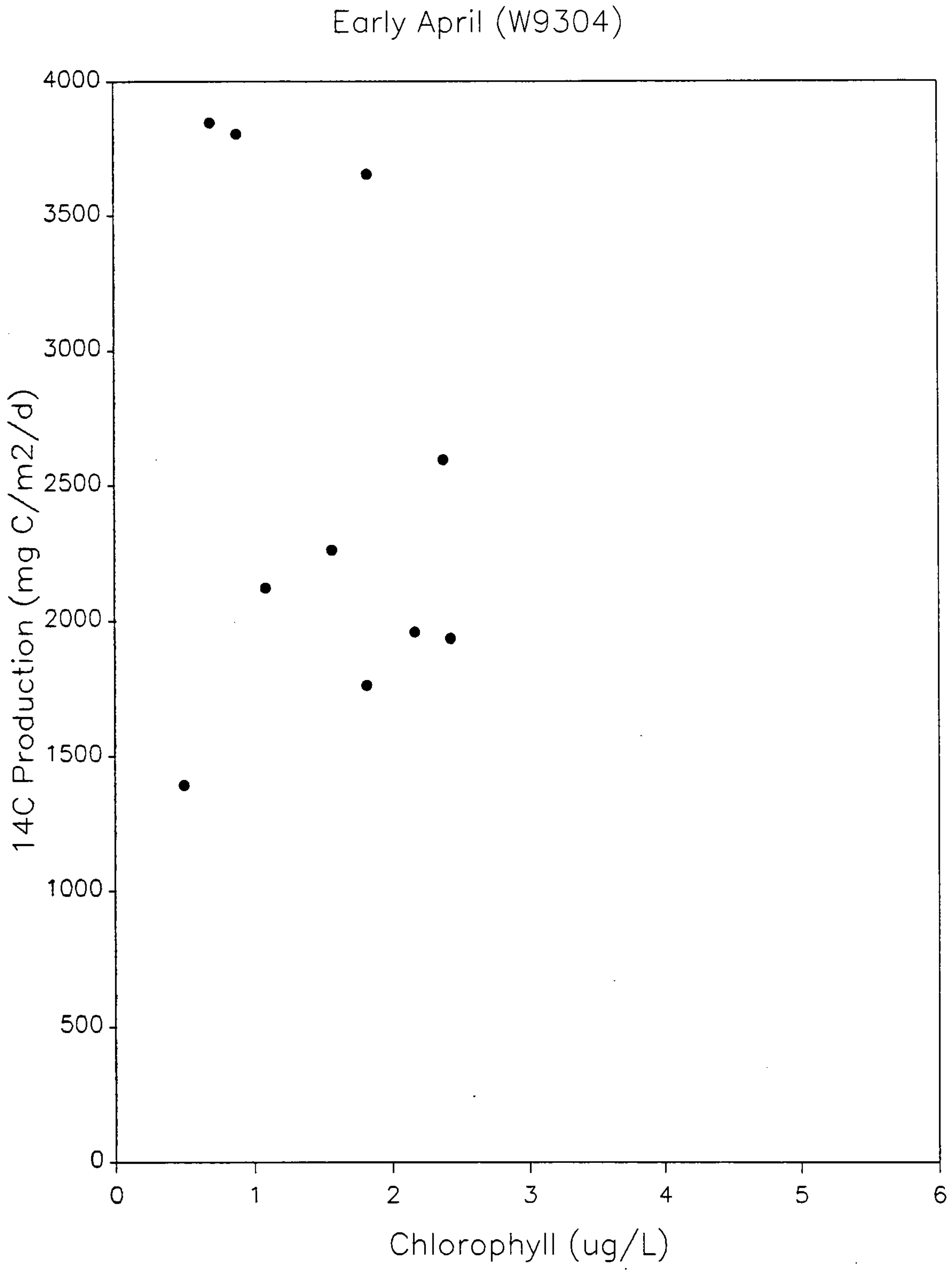
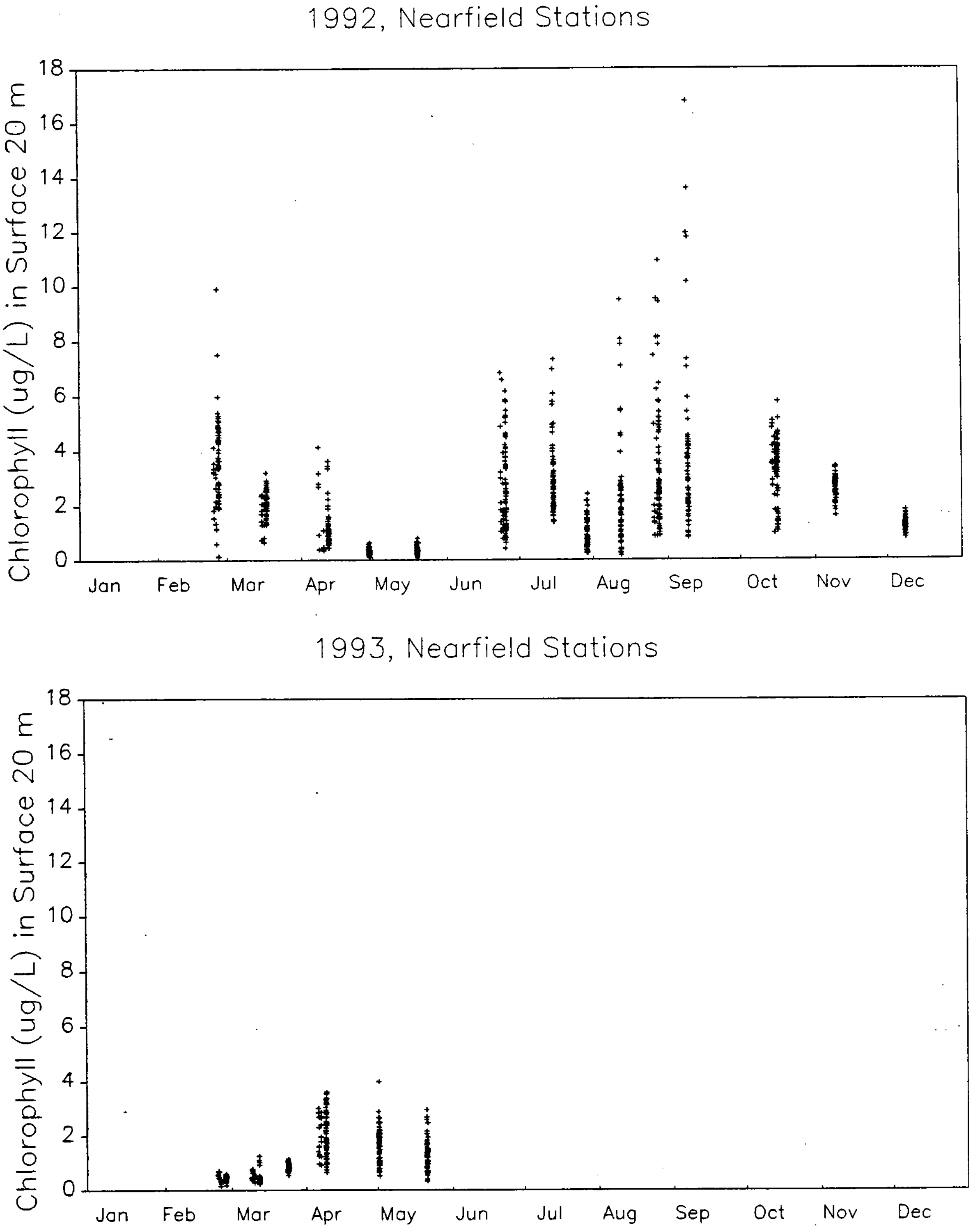


Figure 6-7. ^{14}C production compared to chlorophyll concentrations in samples from April 1993.



1992, Nearfield Stations

1993, Nearfield Stations

Figure 6-8. **Comparison of the nearfield region in 1993 to the annual cycle of 1992: chlorophyll (μg/L).**

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