# Water column monitoring in Massachusetts and Cape Cod Bays: annual report for 1993

Massachusetts Water Resources Authority

Environmental Quality Department
Technical Report Series No. 95-16

FINAL REPORT

# WATER COLUMN MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: ANNUAL REPORT FOR 1993

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October 30, 1995

Environmental Quality Department Technical Report Series 95-16

Citation:

Kelly, J.R and J. Turner. 1995. **Water column monitoring in Massachusetts and Cape Cod Bays: annual report for 1993**. MWRA Enviro. Quality Dept. Tech. Rpt. Series No. 95-16. Massachusetts Water Resources Authority, Boston, MA. 162 pp.

# EXECUTIVE SUMMARY

In 1992, the Massachusetts Water Resources Authority (MWRA) began an environmental monitoring program (MWRA, 1991) throughout Massachusetts and Cape Cod Bays that was intended to provide a consistent, comprehensive three-year set of baseline conditions prior to diversion of MWRA effluent about 15 km into western Massachusetts Bay. As part of this program water quality has been measured during 1992-1994 by scientists from Battelle Ocean Sciences, the University of Rhode Island, and the University of Massachusetts-Dartmouth. Results have been reported in a series of periodic reports for each year of study and an annual report summarized 1992 data (Kelly *et al.* 1993).

The purpose of this report is to present a compilation of results for 1993. Mean conditions, as well as spatial and temporal variability, are described for selected parameters that are viewed as key to monitoring objectives. A main objective is to provide a summary that depicts the annual cycle of ecological events in Massachusetts and Cape Cod Bays in 1993. Brief consideration is given to the scales of resolution possible with the monitoring design, and preliminary statistical testing is conducted to provide additional perspective of the power of the monitoring design to detect changes in water quality.

Water column parameters described in the report include: nutrients (nitrogen, phosphorus, silicate), chlorophyll, dissolved oxygen (DO), phytoplankton and zooplankton species and abundances, and net primary production. Results are summarized separately for farfield surveys conducted six times at 31 stations throughout the Bay and for nearfield surveys conducted 16 times at 21 stations. A brief description of major results, based on key parameters measured on farfield surveys, follows.

*Nutrients* — There were subtle differences in N, P, and Si concentrations across regions and depth, and in their respective annual cycles, but characteristically, data suggested that N was the most limiting nutrient. One-third of ~1100 measurements detected dissolved inorganic nitrogen (DIN = $NH_4 + NO_3 + NO_2$) at low concentrations (<0.75 $\mu$M). The overall mean value for farfield measurements was 3.91 $\mu$M. Higher DIN was characteristically found in coastal waters in and around Boston Harbor, which were also rich in $NH_4$. A decreasing concentration gradient of DIN and $NH_4$ was observed from the Harbor into western Massachusetts Bay.

In general, the 1993 annual cycle in surface water, like 1992, showed high DIN in early winter-spring, depletion of surface DIN by late spring that continued through late summer and a rise in concentration at fall overturn (October). Concomitantly, DIN in bottom waters was depleted by late spring and rose gradually during summer stratification. Most of the annual variability in Total Nitrogen (TN = DIN + organic dissolved and particulate forms) was due to seasonal variability in DIN.

*Chlorophyll* — The major ecological feature that distinguished the 1993 sampling year was the pronounced growth of phytoplankton and chlorophyll concentrations during an intense and spatially extensive fall bloom. Highest chlorophyll concentrations were observed at stations in western Massachusetts Bay, where concentrations in the fall bloom reached > 20 $\mu g\ L^{-1}$. On

average for the year, a decreasing concentration gradient from the Harbor-edge to the Bay was calculated for chlorophyll, and this roughly coincided with the average DIN gradient noted above.

As observed in 1992, the annual cycle of chlorophyll was different for Cape Cod Bay than for Massachusetts Bay. A marked difference was an earlier and more intense winter-spring bloom (February-March) in Cape Cod Bay. Cape Cod Bay stations exhibited a fall chlorophyll bloom, although it was not of the intensity detected in all Massachusetts Bay regions.

*DO* — Surface waters were characteristically supersaturated (108% on average) for the biologically-productive season (April-October, in Massachusetts Bay). Bottom waters on average were undersaturated (96%) and DO concentrations slowly and progressively decreased until destratification, which commenced in shallower locations by October.

At the annual oxygen minimum sampled in mid-October 1993, only a few bottom-water DO concentrations were <7 mg $L^{-1}$, in spite of the intense fall bloom. Differing degrees of physical mixing and the continued stratification of deeper waters can explain why DO concentrations in bottom waters nearer the coast were higher than in deeper waters offshore (>35 m) in mid-October. The observations support the notion that physical factors which locally affect water column stability during the fall period may influence bottom-water DO more strongly that local biological events.

*Plankton* — As often observed, the annual cycle showed dominance by diatoms in a winter-spring bloom. Interestingly, a Baywide bloom of *Phaeocystis pouchettii* noted in spring 1992 was not recorded in 1993. A mixed community with microflagellates, cryptomonads, and some diatoms was characteristic of the summer stratified period, and there were occasional small blooms of a dinoflagellate genera, *Ceratium*. The intense fall bloom in 1993 was caused by a succession of diatoms, culminating in full dominance by *Asterionellopsis glacialis* in October. As also observed previously, zooplankton were numerically dominated by two small forms, *Oithona similis* and *Paracalanus parvus*. There were occasional bursts of meroplanktonic larvae of benthic invertebrates, like barnacle nauplii, bivalve and gastropod veligers, and polychaete larvae. For zooplankton and for phytoplankton, there were few striking or consistent trends across regions of the Bays with respect to community composition.

*Net primary production* — $^{14}C$ incubations were performed to assess integrated water column primary production. Seasonal patterns in production varied among regions. For example, Cape Cod Bay had highest production in the spring bloom, whereas western Massachusetts Bay had its highest rates recorded during the fall bloom. The grand average for all measurements in 1993 (N=59) was 2.2 gC $m^{-2}$ $d^{-1}$. The range for daily rates during 1993 was 0-6.8 gC $m^{-2}$ $d^{-1}$, essentially matching the range as recorded in recent history of measurements. Daily rates were strongly related to the mean photic-layer chlorophyll concentration.

The report discusses perspectives gained from farfield and nearfield sampling scales, and furthermore compares results across regions, surveys, and the ~10-km gradient of conditions from inshore to offshore across the nearfield. Specific findings include:

- Statistical testing showed that, in 1993, surface-water DIN, dissolved organic nitrogen (DON), and TN concentrations were high in the coastal region compared to the other farfield sampling regions in Massachusetts and Cape Cod Bays regions. In contrast, surface-water chlorophyll was significantly different (lower) only for the offshore region of central Massachusetts Bay, including waters overlying Stellwagen Basin. Statistical tests also showed that there were significant seasonal differences in nutrients and chlorophyll. The fact that water quality differences were detected as a function of both region and season demonstrates that there are some fundamentally different seasonal cycles and concentration levels at different places in the Bays. Supporting these statistical results, graphic comparisons of water quality parameters throughout 1993 are presented for representative stations from the near-Harbor coastal region, the nearfield region, the offshore region over Stellwagen Basin, and central Cape Cod Bay.

- Statistical tests were likewise developed to compare west-to-east gradients in concentrations across the nearfield region. Results confirmed a virtual continuum of chlorophyll and DIN concentrations from inshore to offshore, with shallow-water western and deep-water eastern sides of the continuum being significantly different. The appearance of a continuum was muted, and the ability to show differences across the nearfield decreased, when statistical tests were performed using data from 6 nearfield stations on six farfield surveys as compared to data from 21 nearfield stations on 16 nearfield surveys. Supporting the statistical results, graphic comparisons of water quality parameters throughout 1993 are presented for representative stations from the western to eastern sides of the nearfield.

Finally, a concluding section displays and summarizes the spatial and temporal development of the fall diatom bloom — the defining ecological event of 1993. In spite of a relatively high spatial and temporal sampling frequency, it is was difficult to develop unequivocal evidence for the initiation of the bloom. Data suggest the bloom started inshore and moved outward, perhaps aided by tidal export and mixing, but data covering the whole region at a critical juncture are lacking. This provides an example to illustrate that while certain types of ecologically-important event-scale dynamics will be identified by the monitoring program, it may be difficult to provide mechanistic understanding as to causes of these events.

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# 1.0 INTRODUCTION

The Massachusetts Water Resources Authority began a baseline environmental monitoring program (MWRA, 1991) to describe conditions throughout Massachusetts and Cape Cod Bays prior to diversion of MWRA effluent from Boston Harbor directly into western Massachusetts Bay, about 15 km from the Deer Island Treatment Plant. As part of this program, water column monitoring was started in February 1992 with surveys every month from February to December in 1992, 1993, and 1994. An annual report summarizing water column results in 1992 was prepared by Kelly *et al.* (1993). Results of water column monitoring surveys have been presented in a series of periodic water column reports, each focusing on the surveys conducted within a season.

The purpose of this report is to present a compilation of results for 1993. A main objective is to provide a description of the annual cycle of ecological events for 1993 by focusing on a set of key monitoring parameters. In general, the key parameters and the summary of data in this report are similar to those presented in the 1992 annual report. By design, the report is organized to describe broad-scale features from "farfield" sampling throughout Massachusetts and Cape Cod Bays, followed by consideration of finer scales from more frequent and spatially intensive "nearfield" sampling in an approximately 100-km$^2$ area surrounding the future MWRA effluent outfall in western Massachusetts Bay. The content of this report is largely descriptive, but some regression analyses and statistical inference tests were conducted to examine patterns in the Bays, and to provide insight on the ability of the sampling design to assess geographic differences in parameters. The effort should be viewed as prelude to more comprehensive statistical analyses that include testing of interannual trends.

The key water column monitoring categories described in this report include the following:

- Nutrients (nitrogen, phosphorus, and silicate)
- Chlorophyll
- Dissolved oxygen

- Phytoplankton and zooplankton
- $^{14}C$ primary production

The rationale behind the focus on these key parameters is given in MWRA (1991). Briefly, the distribution and concentration of nutrients are of interest because diversion of the effluent will bring nutrients directly to bottom waters of western Massachusetts Bay, rather than deliver them indirectly via export from Boston Harbor in surface water exchange (Kelly, 1993a). Further, the loading and concentration of nutrients are linked in aquatic ecosystems to the other listed biological and chemical parameters because these other parameters respond to nutrient enrichment (e.g., Nixon *et al.*, 1986). The nature of the interaction among the five key parameter categories can not be predicted in any given coastal ecosystem and the interaction is, in part, regulated by physical conditions. In general, nutrients influence phytoplankton biomass (chlorophyll) and can influence the taxonomic composition of the pelagic community (phytoplankton and zooplankton), a main concern being unwanted stimulation of toxic or noxious phytoplankton species. Chlorophyll concentrations and net primary production can influence dissolved oxygen concentrations, potentially resulting in low oxygen concentrations in bottom water layers.

This report is organized as follows:

- Description of data sources and analyses used in this report are included in Section 2.
- Results, including data summary and description of annual cycles based on farfield surveys for key monitoring categories, are discussed in Section 3.
- Results, including data summary and description of annual cycles based on nearfield surveys for key monitoring categories, are discussed in Section 4.
- Discussion, which emphasizes geographic and temporal patterns evident for 1993 at farfield and nearfield sampling scales, and including comments on the defining features for ecological events in 1993, is presented in Section 5.

# 2.0 DATA SOURCES, STATIONS, AND SURVEYS

The data used in this report are from the MWRA Harbor Studies Database, and have been presented in previous water quality monitoring reports and their appendices. The periodic reports covering the 1993 calendar year monitoring are Kelly *et al.* (1994a,b,c,d) and Libby *et al.* (1994). The reader is referred to these reports and Albro *et al.* (1993) for details of sampling, and full descriptions of physical, chemical, and biological conditions at sampling stations on a survey-by-survey basis.

The MWRA water column sampling stations are located throughout Massachusetts and Cape Cod Bays (Figure 2.1-1). Twenty-one nearfield stations (labeled "N") are from an area approximately 100 km$^2$, the center of which is near the midpoint of the planned 2-km-long MWRA effluent diffuser. Twenty-five farfield stations (labeled "F") extend from the edge of Boston Harbor to Stellwagen Basin to the east and, in the north-south direction from Cape Cod Bay to the east of Salem in deep offshore water. At 10 stations of the 46 stations (labeled "P"), more extensive measurements were made, including those for organic nutrients, biology, and productivity.

Figure 2.1-1 also indicates how stations were classified into five regions, by depth and geography. The regions in Massachusetts Bay are (1) coastal (near the shoreline in western Massachusetts Bay), (2) nearfield, as defined above, (3) offshore (deeper water stations, the eastern half of which are within Stellwagen Basin), and (4) northern transect (from nearshore to the northern head of Stellwagen Basin). There are four water quality monitoring stations in the Cape Cod Bay region. The regional nomenclature is used throughout this report and regional comparisons are made by partitioning the total data set. Another data partitioning focused on deep water (>50 m) in Massachusetts Bay; water >50 m was regularly sampled at stations F22, F19, F17, F12, and F08 in Stellwagen Basin, and occasionally at other stations >40-m depth contour (Figure 2.1-1).

The nearfield stations were sampled on 16 surveys in 1993 (Table 2-1). The nearfield "P" stations were visited several times during the course of six "combined farfield/nearfield" surveys (Table 2-1). All farfield stations were sampled during these combined surveys. Comparisons of plots depicting events in farfield regions (Section 3) and for all nearfield surveys (Section 4) illustrate different frequencies of sampling for different stations, a topic discussed in Section 5. Additionally, data from farfield and nearfield surveys were used to derive some mean values for various parameters and, thus, summarize data from either 6 or 16 surveys during the year.

Data summaries, partitioning and analyses of the data set, and data manipulations are described in the appropriate sections of this report. Plots and statistical analyses were generated using Battelle Ocean Sciences (BOS) propriety software, SAS (1988a,b), Surfer (1994), and Quattro Pro (Borland, 1993).

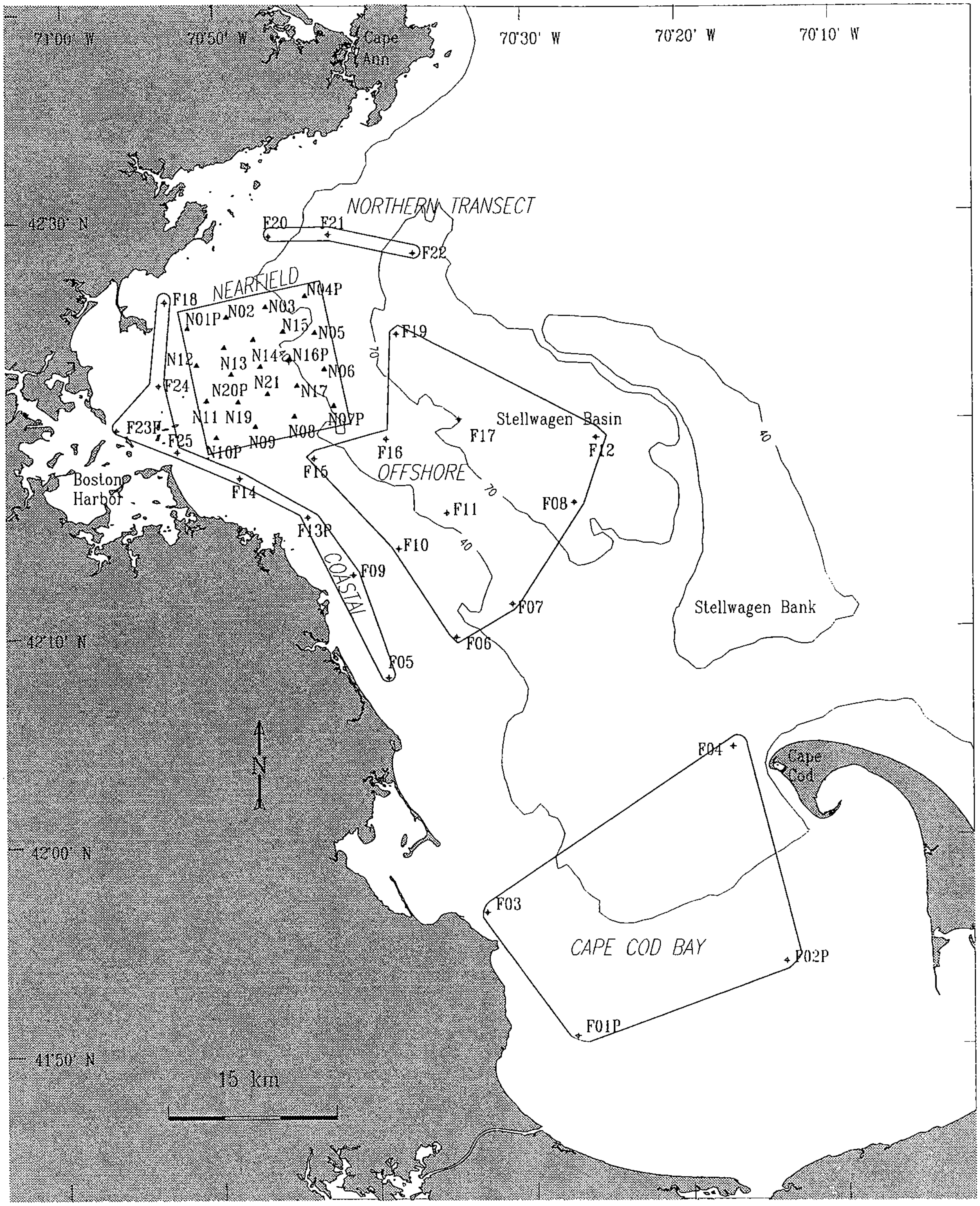


Figure 2.1-1. Water quality sampling stations in Massachusetts and Cape Cod Bays. Station codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Five groups of stations that are referred to in the text and in other figures are identified — Northern Transect, Nearfield, Coastal, Offshore, and Cape Cod Bay.

**Table 2-1. Schedule of water quality surveys for calendar year 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 |

# 3.0 FARFIELD SURVEY RESULTS

As described in Section 2, farfield sampling was conducted six times during 1993. Included in the following data summaries are the six nearfield stations that were sampled during the farfield and nearfield sequence of a combined farfield/nearfield survey. Farfield sampling thus included 31 stations, 25 outside the nearfield region. The data set examined here includes a total of 1104 Niskin bottle sampling events, for which there were no missing data for all *in-situ* sensor parameters, except DO. A total of 1098 DO values were available for analysis (6 missing data points).

## 3.1 NUTRIENTS

For all farfield survey stations and depths, the nutrient data represent analyses of samples collected by Niskin bottles on the upcast of a hydrocast at each station. In 1993, there were nearly 1100 data values for each of the inorganic nutrients — ammonium ($NH_4$), nitrate ($NO_3$), nitrite ($NO_2$), phosphate ($PO_4$), and silicate ($SiO_4$). The range in the number of data points varied from N=1089 to 1104, depending on the nutrient species. Summary statistics for each parameter are included in the Appendix. To introduce the 1993 data, frequency distribution plots are presented; this is followed by descriptions of annual nutrient cycles.

### 3.1.1 Frequency Distribution of Nutrients

***Dissolved Inorganic Nitrogen.*** For dissolved inorganic nitrogen (DIN = $NH_4 + NO_3 + NO_2$), the distribution shows that one third of the measured concentrations was below 0.75 $\mu$M (Figure 3.1-1). The frequency distribution of samples was skewed to the lowest concentration class and the frequency of observations fell sharply with increasing concentration to a maximum observed concentration of 21.08 $\mu$M. The overall mean value was 3.91 $\mu$M.

DIN concentrations >11.5 μM were measured in coastal waters at the edge of Boston Harbor and, in a few cases, within the nearfield region that receives exported water from this coastal zone. Thus, relative to other regions, more samples from coastal waters were higher in DIN concentrations; moreover, the average DIN concentration in the coastal region was high. Regional DIN means (all stations and depths) were 3.69 μM (northern transect), 3.54 μM (nearfield), 4.90 μM (coastal), 4.15 μM (offshore), and 2.52 μM (Cape Cod Bay). The frequency distribution of $NH_4$ also showed that higher concentrations (>4.5 μM) were almost exclusively found at coastal stations (Figure 3.1-2).

Spatial Pattern of DIN in Western Massachusetts Bay. The trend of higher concentrations at the coastal monitoring stations has been a common finding (cf. Kelly *et al.*, 1993). A gradient of decreasing surface water DIN and $NH_4$ concentrations with distance from Boston Harbor has repeatedly been demonstrated in recent monitoring (see Kelly, 1993a) and many surveys in 1993 displayed the gradient pattern (e.g., Kelly *et al.*, 1993 ; Libby *et al.*, 1994 ). The mean values (n=6 surveys) for surface observations at each station in western Massachusetts Bay in 1993 clearly show the average DIN gradient (Figure 3.1-3a). The mean DIN concentration at station F23P at the edge of Boston Harbor was >8 μM and concentrations graded to about 2 μM at the eastern edge of the nearfield region. There was also a decrease in $NH_4$ away from the Harbor (Figure 3.1-3b), with mean concentrations >2 μM at the three stations closest to the Harbor and highest at station F23P (3.8 μM). For both DIN and $NH_4$, stations along the coast to the south of the Harbor generally had mean concentrations that were higher than stations equidistant from the Harbor, but located in the eastern nearfield. Previously, a linear relationship between $NH_4$ and salinity has been noted in the area of interaction between the Harbor and the nearfield in western Massachusetts Bay (Kelly, 1993a). The 1993 data confirm $NH_4$ as a valuable medium-scale (1s to 10s of kilometers) indicator of discharged effluent and, to an extent, show some of the present dispersion of Harbor water into Massachusetts Bay.

***Phosphate.*** $PO_4$ concentrations for more than 50% of the samples were <0.5 μM (Figure 3.1-4). Unlike DIN, the lowest concentration class for $PO_4$ was not the modal class. Repeatedly, monitoring has shown that phosphate is present at measurable concentrations when DIN concentrations are virtually undetectable. Such differences in DIN and $PO_4$ concentrations, especially in surface waters of the Bays, suggest relative nitrogen limitation in the productive season of the year. General patterns in N/P ratios, presented below in context of the annual cycle, reinforce this concept.

Like DIN, samples with higher $PO_4$ concentrations (>1 $\mu$M) characteristically were from the coastal or nearfield regions; additionally, a few samples with higher concentrations were collected in the deep waters of Stellwagen Basin (offshore region). The overall mean $PO_4$ concentration for 1993 was 0.47 $\mu$M. Mean concentrations of $PO_4$ by region, encompassing data from all depths as included in Figure 3.1-4, were 0.46, 0.45, 0.48, 0.51, and 0.42 $\mu$M for the northern transect, nearfield, coastal, offshore, and Cape Cod Bay regions, respectively.

***Silicate.*** In contrast to the other nutrients, the frequency distribution of $SiO_4$ concentrations was bimodal (Figure 3.1-5), a feature also noted in 1992 (Kelly *et al.*, 1993). One mode was in the lowest concentration class (about 1.5 $\mu$M and below) and a second mode was at 9-10 $\mu$M. Samples showing the highest concentrations were generally from the offshore or nearfield regions rather than from the coastal area. The overall mean $SiO_4$ concentration for 1993 was 5.45 $\mu$M. By region, mean concentrations of $SiO_4$ were 5.78 $\mu$M (northern transect), 5.21 $\mu$M (nearfield), 5.40 $\mu$M (coastal), 6.09 $\mu$M (offshore), and 4.46 $\mu$M (Cape Cod Bay).

In 1993, the slight differences in the frequency distributions for $SiO_4$, DIN, and $PO_4$ concentrations were similar to differences observed in 1992 (Kelly *et al.*, 1993). This is expected because fundamental concentrations of dissolved inorganic nutrients and the relationships between major plant nutrients were consistent across both years, even though there were occasional geographic anomalies and unusual short-term events related to variations in plankton communities and specific population abundances (e.g., Kelly, 1993a).

### 3.1.2 Annual Cycle of Nutrients

***Nitrogen Forms.*** The pattern for surface water DIN concentrations (Figure 3.1-6) shows a nutrient cycle in 1993 similar to what has been observed previously (cf. Kelly *et al.*, 1993). In spite of some inter- and intra-regional variability early in the year, DIN concentrations were generally high during well-mixed (winter) conditions and low (often near detection) during the productive stratified (summer) season. Figure 3.1-7 shows the DIN concentrations in surface and bottom waters of four major sampling regions. In the coastal region, where waters are shallow and more often well mixed, bottom waters were generally less enriched in DIN relative to surface water during the summer stratified period (Figure 3.1-7). In the other three regions, pronounced seasonal disjunction was evident between the surface and bottom water DIN concentrations, starting either as stratification began (April survey, ≈day 95) or when it was fully developed (June survey, ≈day 175). In each region other than the coastal region, a progressive increase in bottom water concentrations was suggested during the course of the stratified period (through October, ≈ day 285).

In terms of overall mean DIN concentrations, the relative ranking by region is: coastal > offshore > nearfield > Cape Cod Bay (Figure 3.1-7). In part, the offshore is ranked second because it generally has deeper water, and higher concentrations are a function of sampling depth. Note that DIN concentrations in the deepest waters of the Bay (the eastern side of the nearfield, the entire offshore region, and Cape Cod Bay station F04) reached peak annual concentrations in October, when surface concentrations were generally still near detection limits. In addition to the gradation in average concentrations, some subtle differences across regions and locations were apparent in the temporal cycle. For example, the annual pattern of a sharp decrease in DIN in surface waters during the first 100 days of the year was similar in all regions, but early season DIN concentrations were already low in Cape Cod Bay because a winter-spring bloom had already begun (Kelly *et al.*, 1994d; see also Section 3.2).

Sampling for organic forms of nitrogen was limited to a subset of stations, including three from the coastal region, six from the nearfield region, and two from Cape Cod Bay. Samples were collected at the surface and near a mid-depth chlorophyll maximum if it existed. The depth of this latter sample generally ranged from about 5 to 20 m, usually within the surface layer or upper level of the pycnocline, and it varied across stations and surveys. Figures 3.1-8, 3.1-9, and 3.1-10 include data from both sampling depths without distinction and thus characterize the range in the surface "layer." Neither DON nor PON concentrations in surface layers showed the strong seasonal cycle of DIN (Figure 3.1-8 and 3.1-9). Highest individual DON values were measured in March, but overall there was a concentration range of 4-6 $\mu$M during any given survey and mean values for each survey were approximately 8-12 $\mu$M. A winter-summer difference, as noted for DIN, was not evident. PON concentrations ranged considerably for individual surveys but, like DON, mean concentrations were generally within the narrow range of $\approx$3-4 $\mu$M. A stratified/unstratified season distinction was not evident.

In the surface layer, the seasonal cycle for Total N (TN = DIN + DON + PON) was driven primarily by seasonal variation in DIN (Figure 3.1-10). The sum of the organic forms (DON + PON) was relatively stable at about 10-15 $\mu$M. For 1993, the ranking of regions by annual mean TN was: the coastal region (mean = 20.9 $\mu$M, max = 36.4 $\mu$M, N=36) > nearfield (mean 14.2 $\mu$M, max=27.8 $\mu$M, N=70) > Cape Cod Bay (mean 12.5 $\mu$M, max= 20.14 $\mu$M, N=23). This order is the same as the ranking for DIN concentrations.

***Phosphorus Forms.*** The overall annual cycle for $PO_4$ was similar to DIN in that summer $PO_4$ concentrations in surface waters were low compared to winter concentrations (Figure 3.1-11). However, as noted in the frequency distributions, there was generally a significant concentration of $PO_4$ in Bay surface water throughout the summer. Particulate P was not measured for the monitoring program, but the pattern for total dissolved phosphorus (TDP = $PO_4$ + DOP) over the year (Figure 3.1-12) mimicked $PO_4$ seasonal variability. Thus, like nitrogen, annual patterns were probably driven by variability in dissolved inorganic forms, rather than by organic forms.

Although dissolved inorganic N and P had broad winter-summer patterns, the relative changes in DIN and $PO_4$ were different in the summer. This can been seen in Figure 3.1-13 where N/P ratios for samples are shown as a function of time during 1993. Early in the year, the ratios for both bottom and surface waters were, on average, slightly below a Redfield ratio (16 N:1P). The ratio dipped sharply in the summer, more noticeably in surface water than in bottom water. Surface water N/P ratios were generally <2:1 in summer. Other data on cycling of N and P are needed to fully understand relative nutrient limitations; nonetheless, these concentration data suggest that, through the entire year, there occurs relative N limitation and it is most severe in the summer season.

***Silicate.*** The annual silicate cycle was similar to DIN and $PO_4$ in that surface water $SiO_4$ concentrations dropped sharply between winter and summer (Figure 3.1-14). In all Bay surface water samples, silicate remained low from late spring through October. The low silicate concentration detected in October was due, in part, to an intense fall 1993 diatom bloom (see Section 3.4).

As observed for DIN, plots of $SiO_4$ concentrations by four major sampling regions (Figure 3.1-15) indicate several regional patterns. As noted in previous reports (Kelly *et al.*, 1994a,b,c,d and Libby *et al.*, 1994), $SiO_4$ was low early in the year (February and March) at several Cape Cod Bay stations where the winter-spring diatom bloom was well underway (Figure 3.1-14 and 3.1-15). However, unlike DIN, in the spring coastal region waters were not enriched relative to the nearfield and offshore regions. Similar to DIN, the coastal region showed the least difference between surface and bottom waters. Lastly, bottom waters in non-coastal regions were high in $SiO_4$ throughout the stratified period, starting in June (≈day 175) and remaining stable or slightly increasing through October.

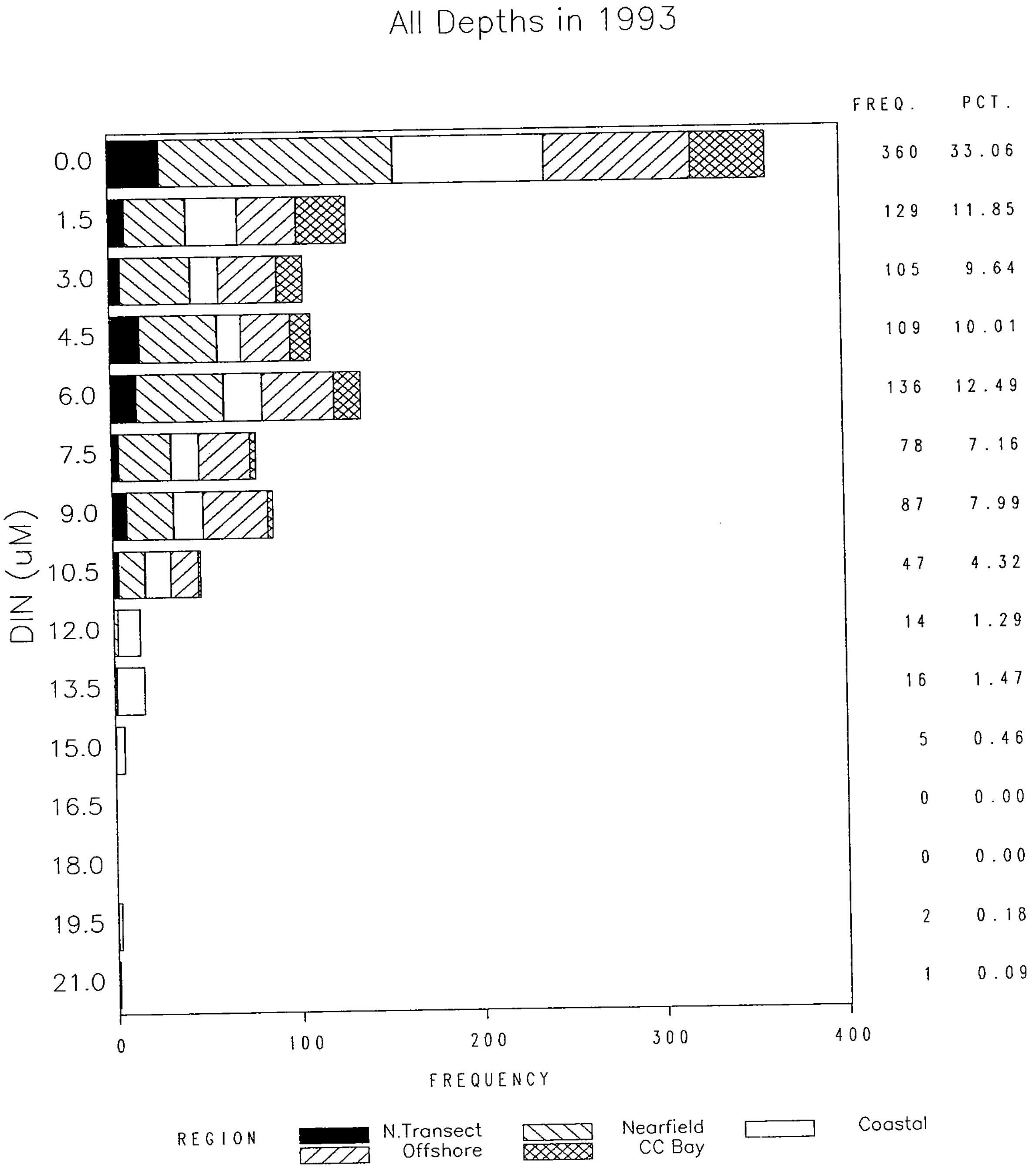


Figure 3.1-1 Frequency distribution of DIN concentrations for all stations sampled in 1993.

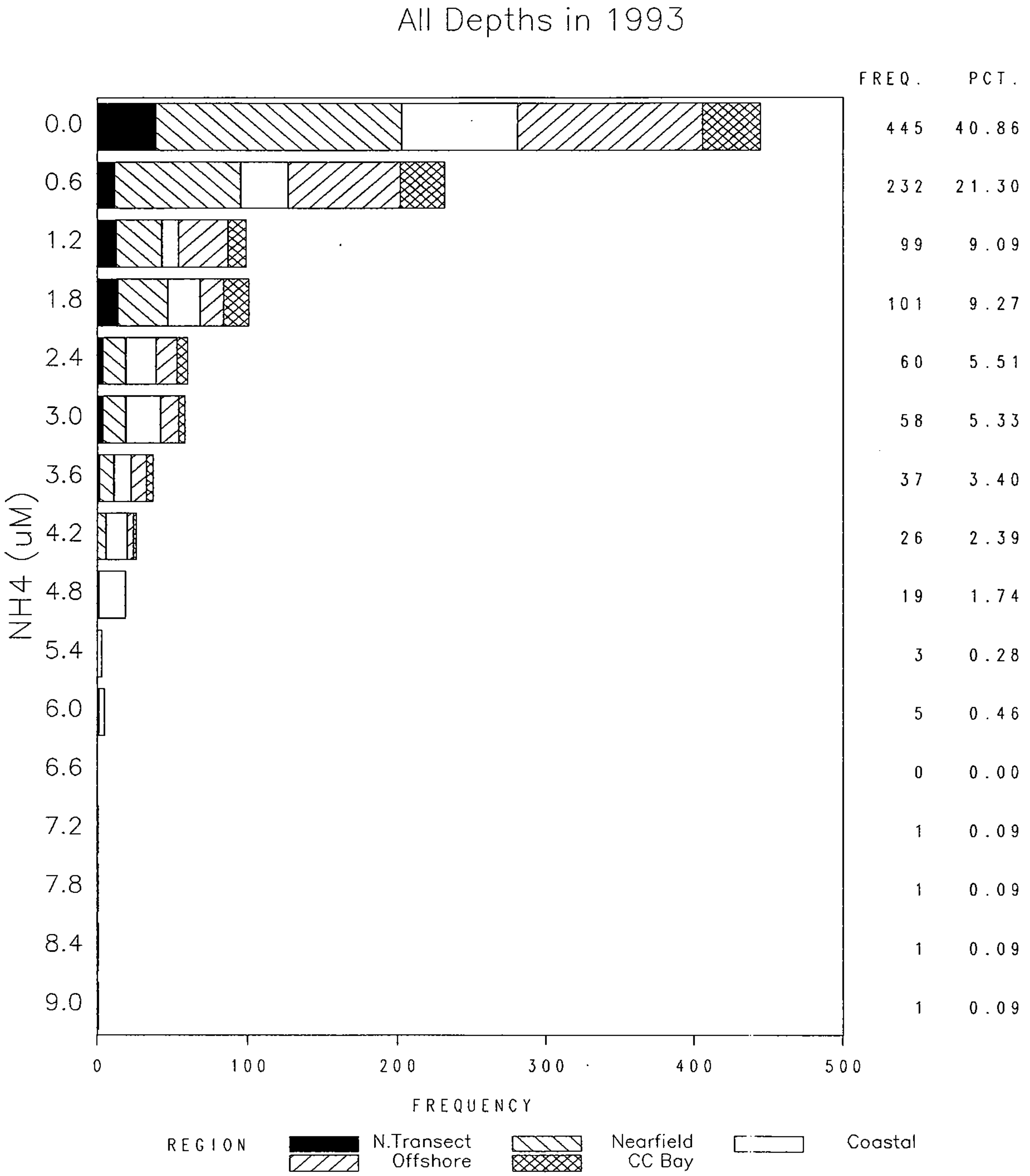


Figure 3.1-2 Frequency distribution of $NH_4$ concentrations for all stations sampled in 1993.

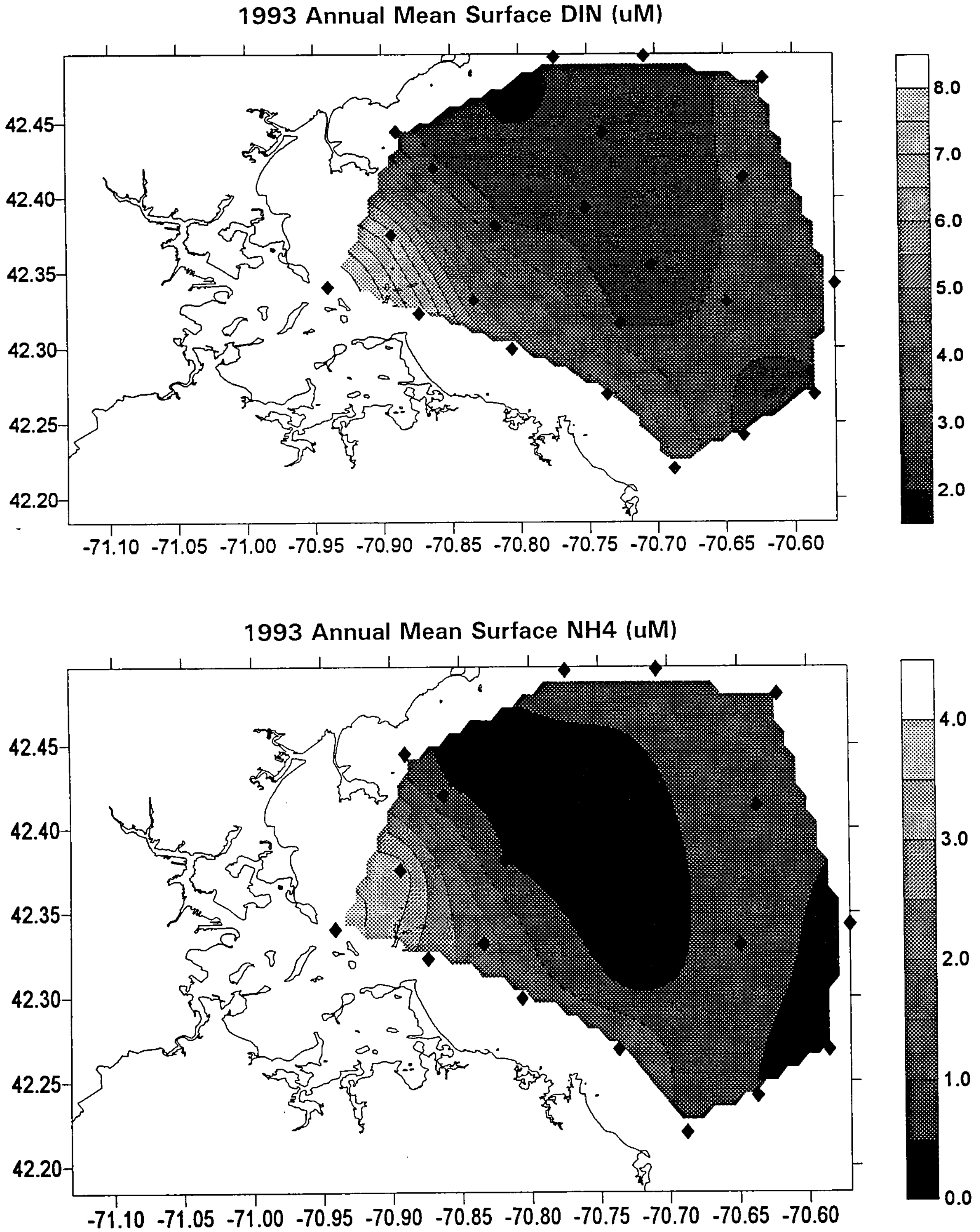


Figure 3.1-3 Spatial pattern of nutrient concentrations in western Massachusetts Bay. Data are surface water means from six farfield surveys in 1993.

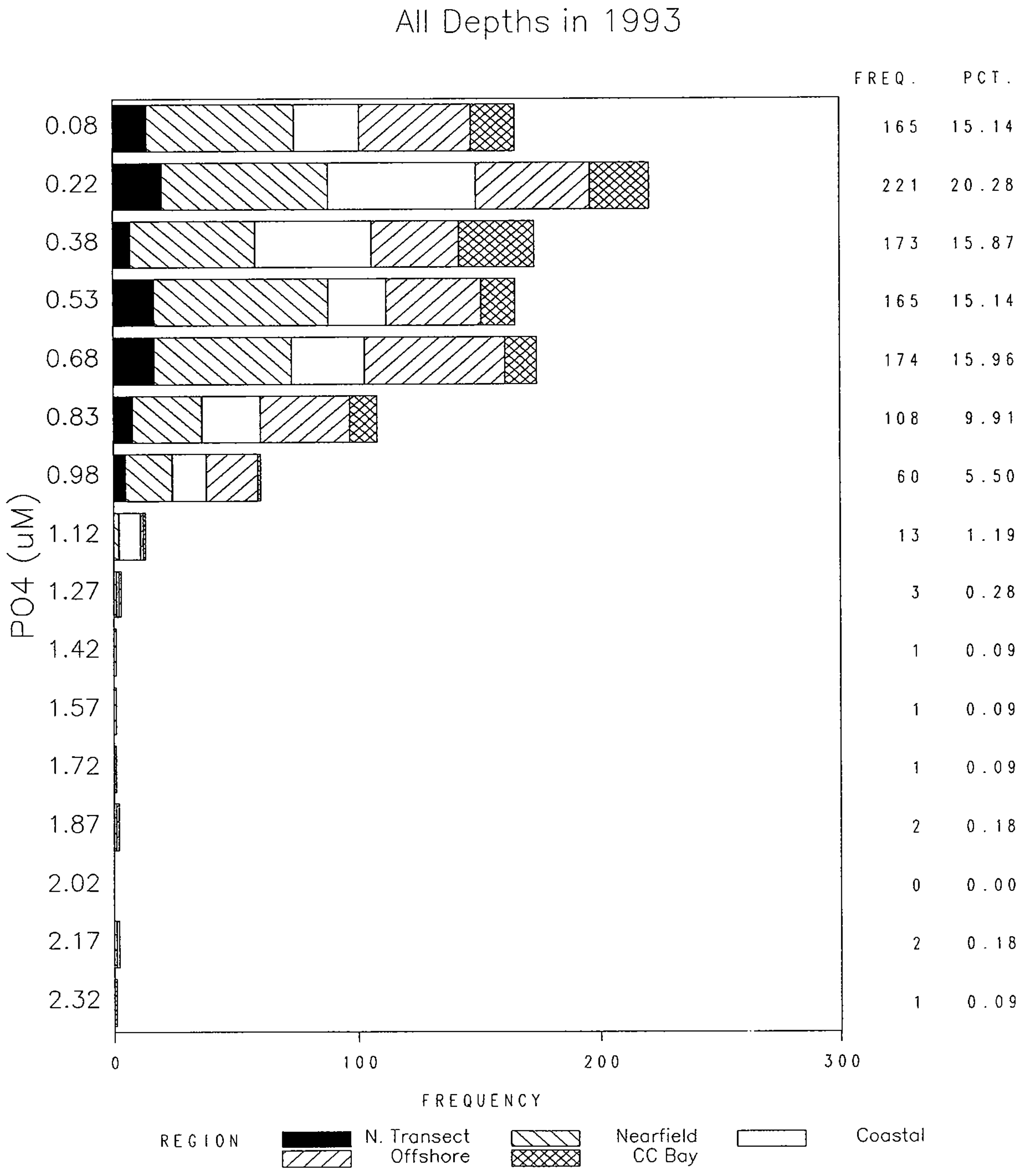


Figure 3.1-4 Frequency distribution of $PO_4$ concentrations for all stations sampled in 1993.

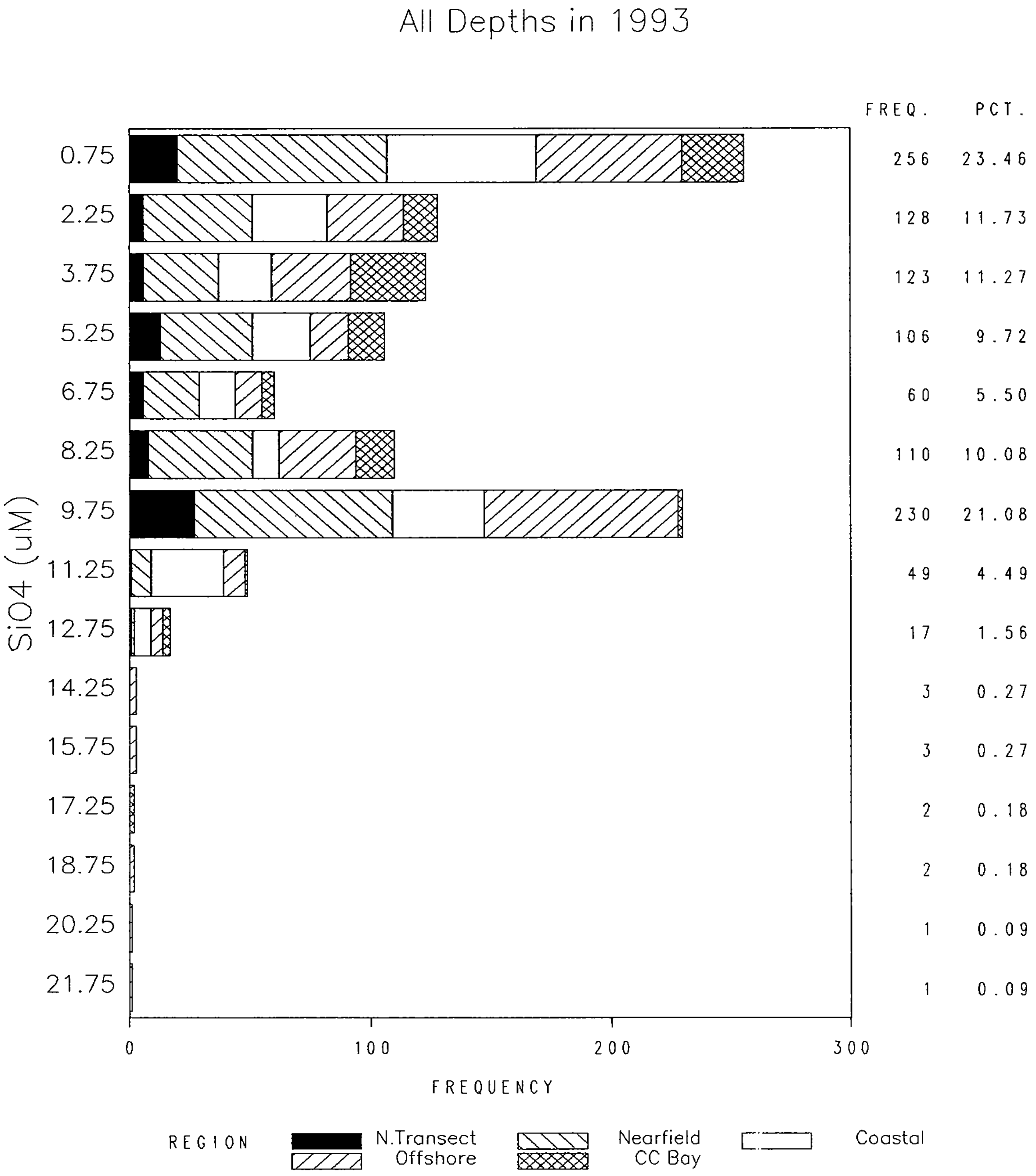


Figure 3.1-5 Frequency distribution of $SiO_4$ concentrations for all stations sampled in 1993.

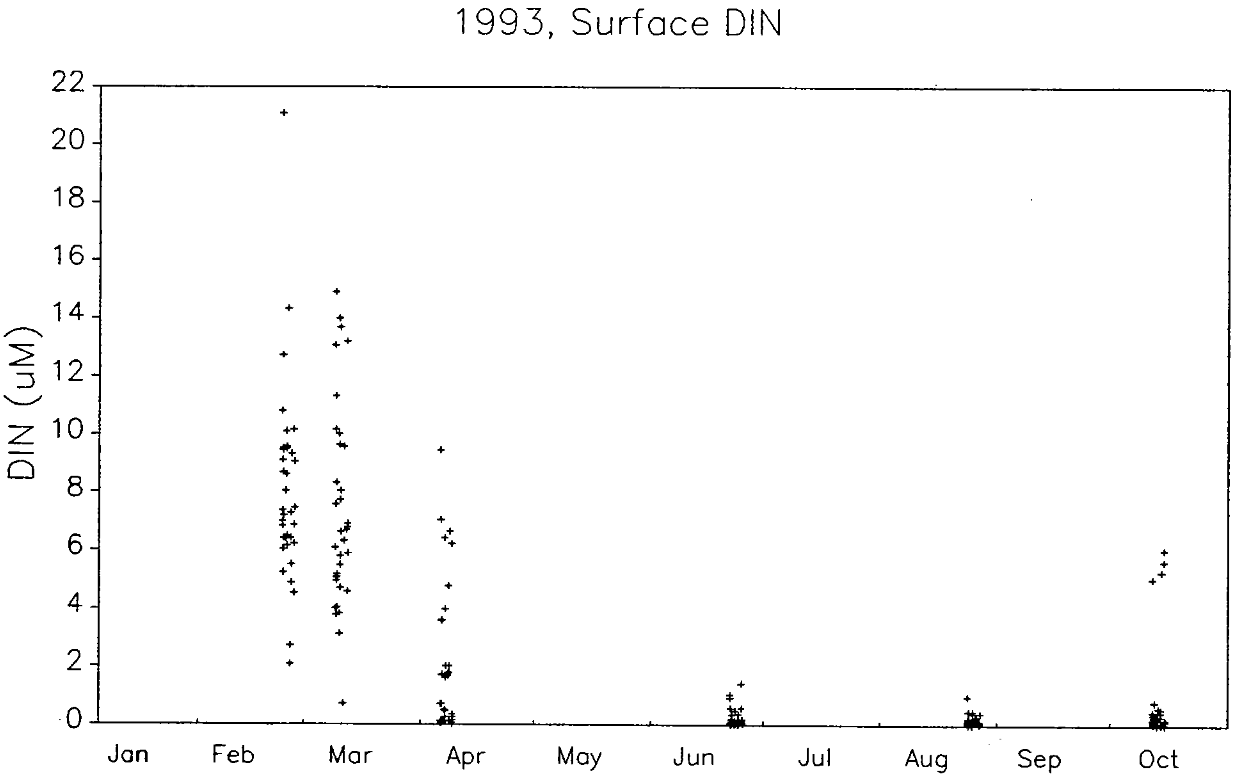


Figure 3.1-6 Annual cycle of DIN concentrations in surface waters of Massachusetts and Cape Cod Bays.

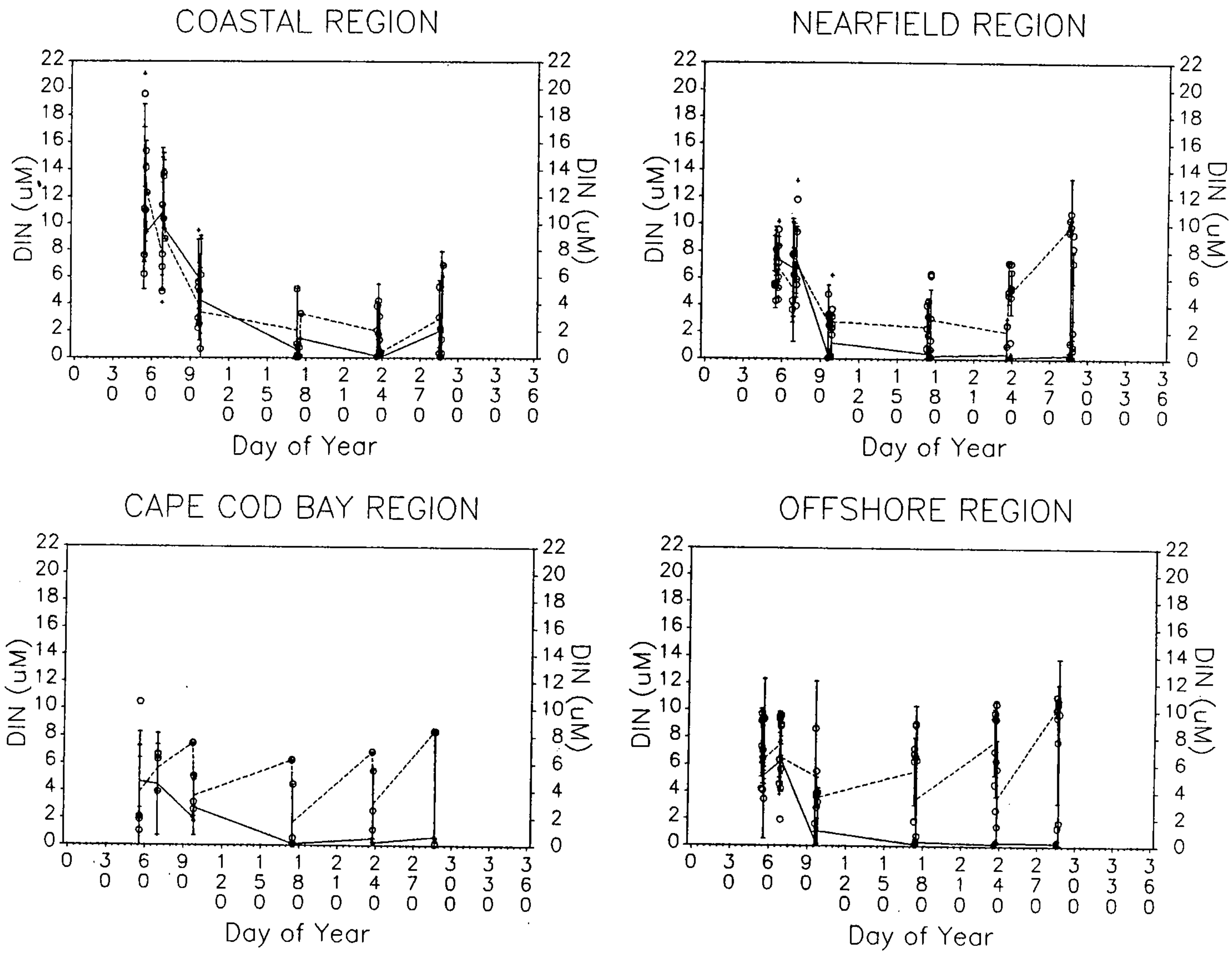


Figure 3.1-7 Comparison of annual DIN cycle in surface and bottom waters in four major sampling regions of Massachusetts and Cape Cod Bays. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling, so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

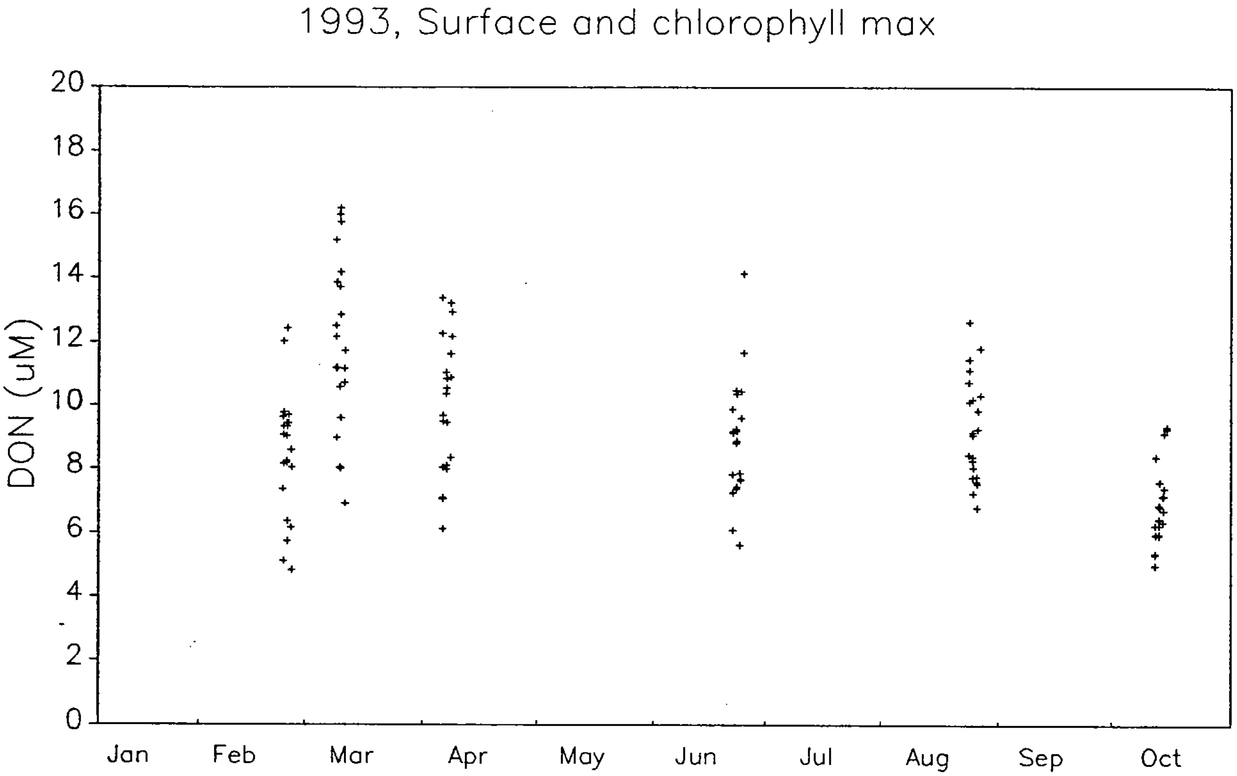


Figure 3.1-8 DON concentrations through the annual cycle in the surface layer of Massachusetts and Cape Cod Bays.

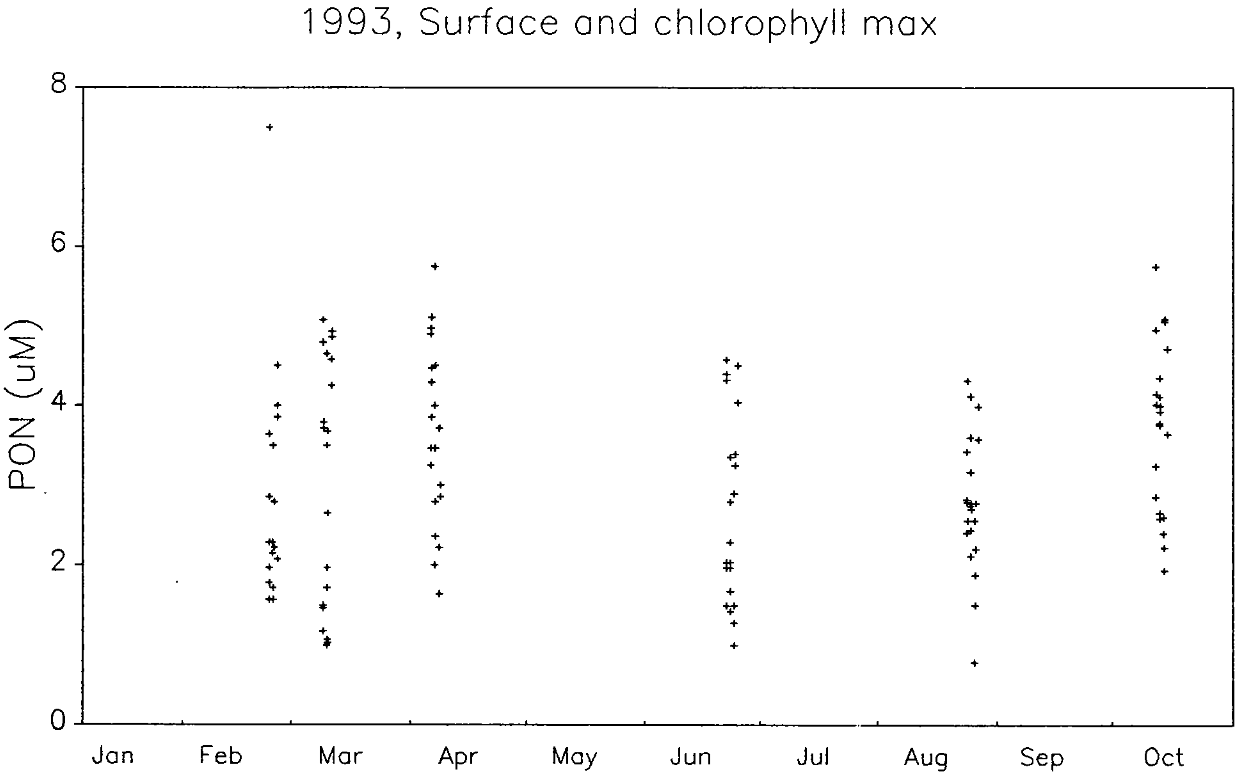


Figure 3.1-9 PON concentrations through the annual cycle in the surface layer of Massachusetts and Cape Cod Bays.

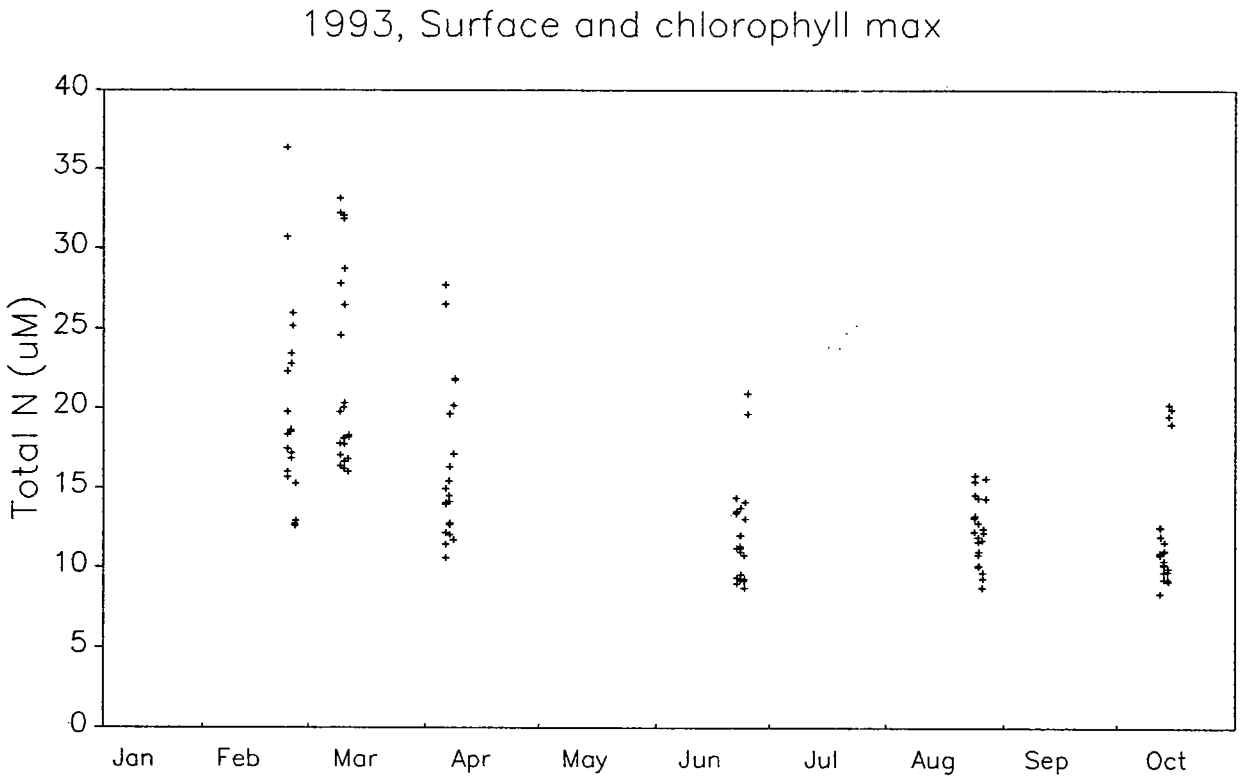


Figure 3.1-10 Total nitrogen (TN) concentrations through the annual cycle in the surface layer of Massachusetts and Cape Cod Bays.

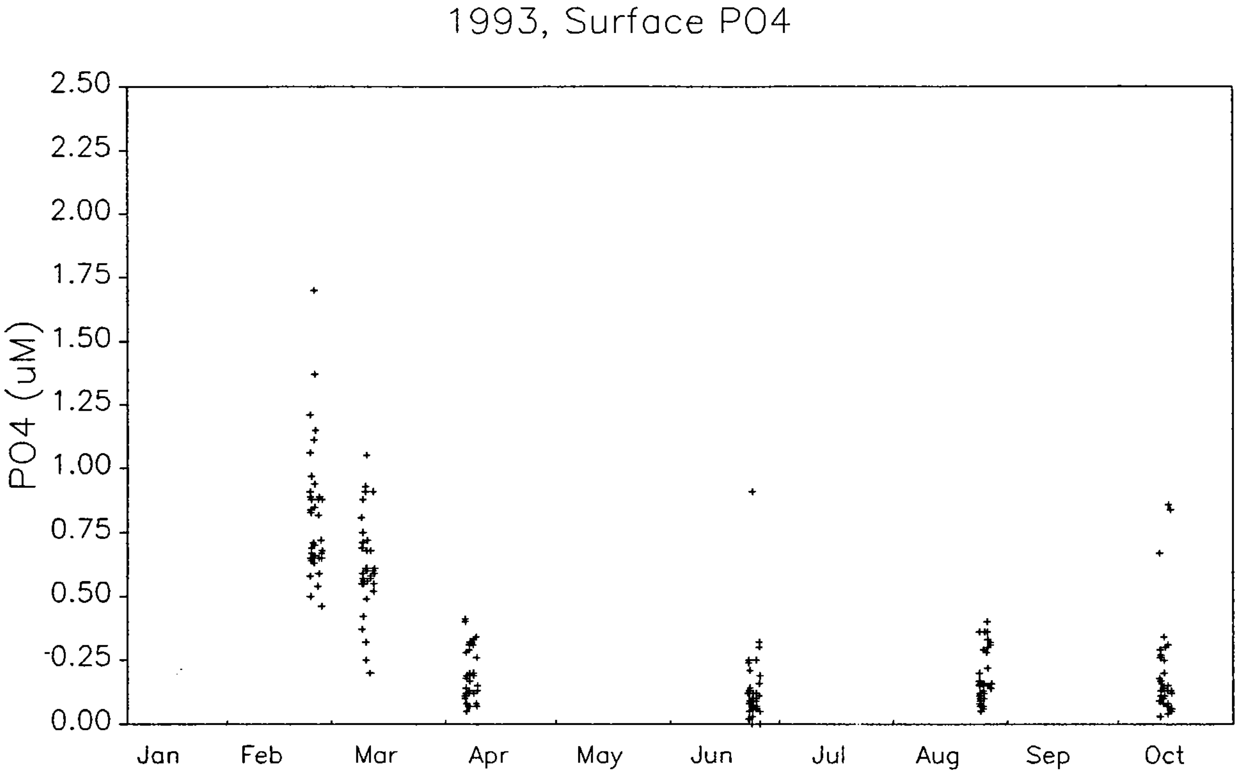


Figure 3.1-11 $PO_4$ concentrations through the annual cycle in surface waters of Massachusetts and Cape Cod Bays.

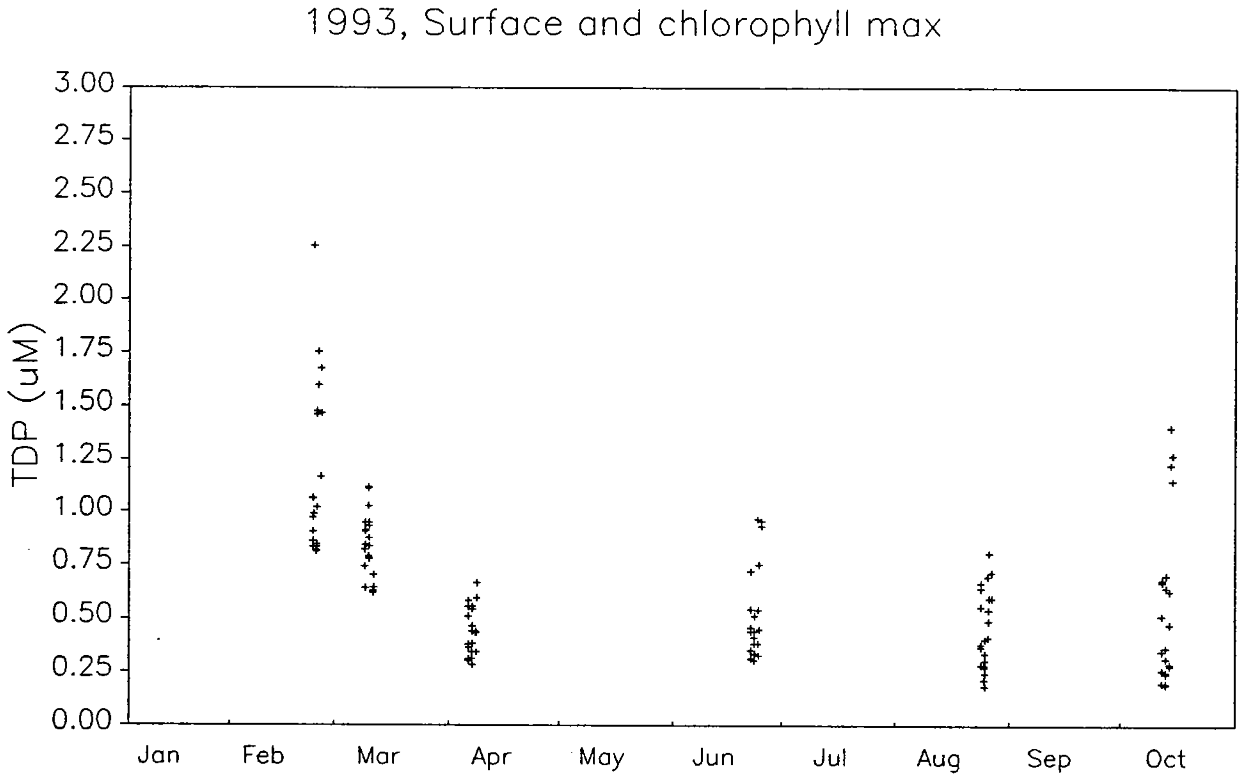
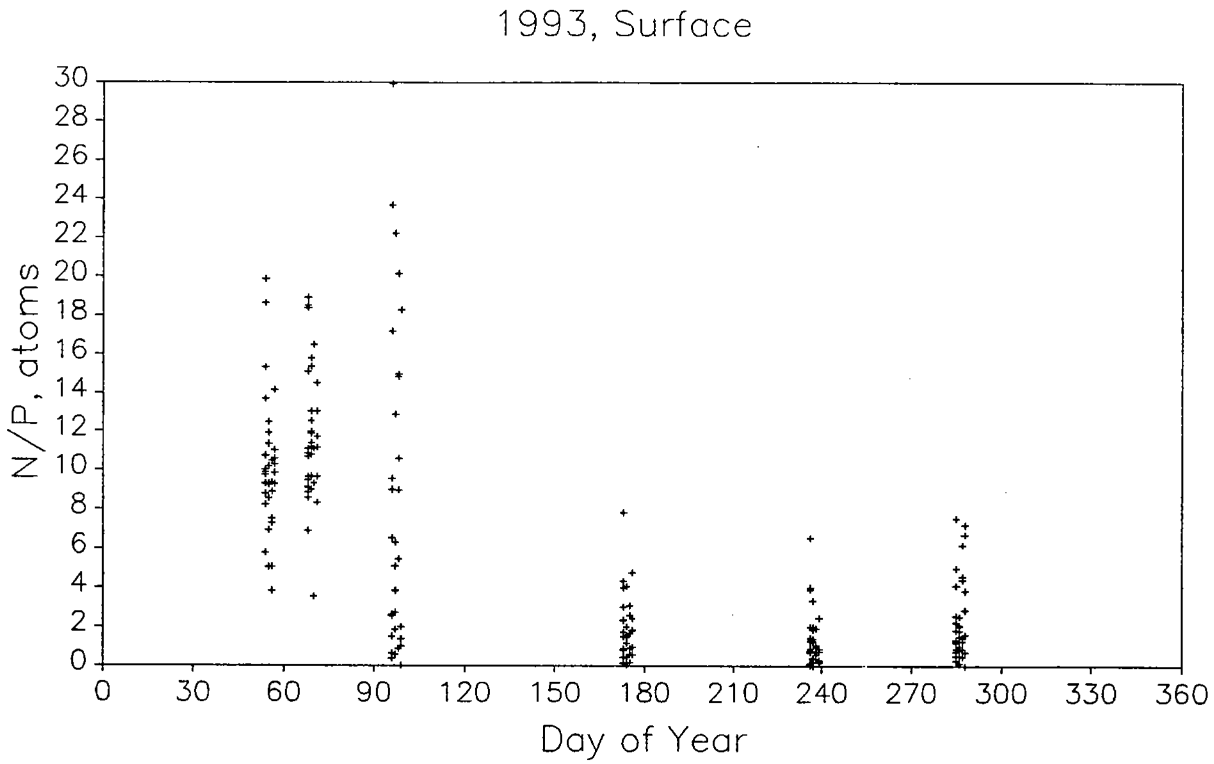


Figure 3.1-12 Total dissolved phosphorus (TDP) concentrations through the annual cycle in surface waters of Massachusetts and Cape Cod Bays.



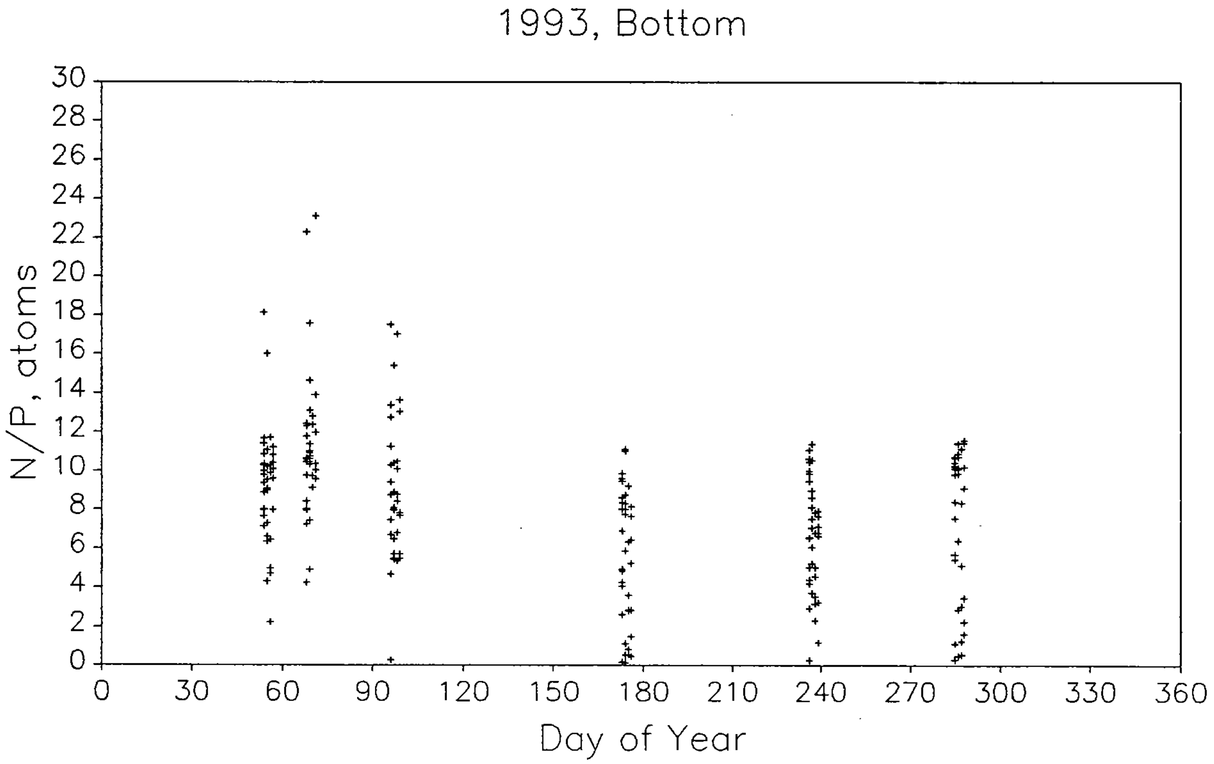


Figure 3.1-13 DIN/$PO_4$ (N/P) ratio in surface and bottom waters through the annual cycle in Massachusetts and Cape Cod Bays.

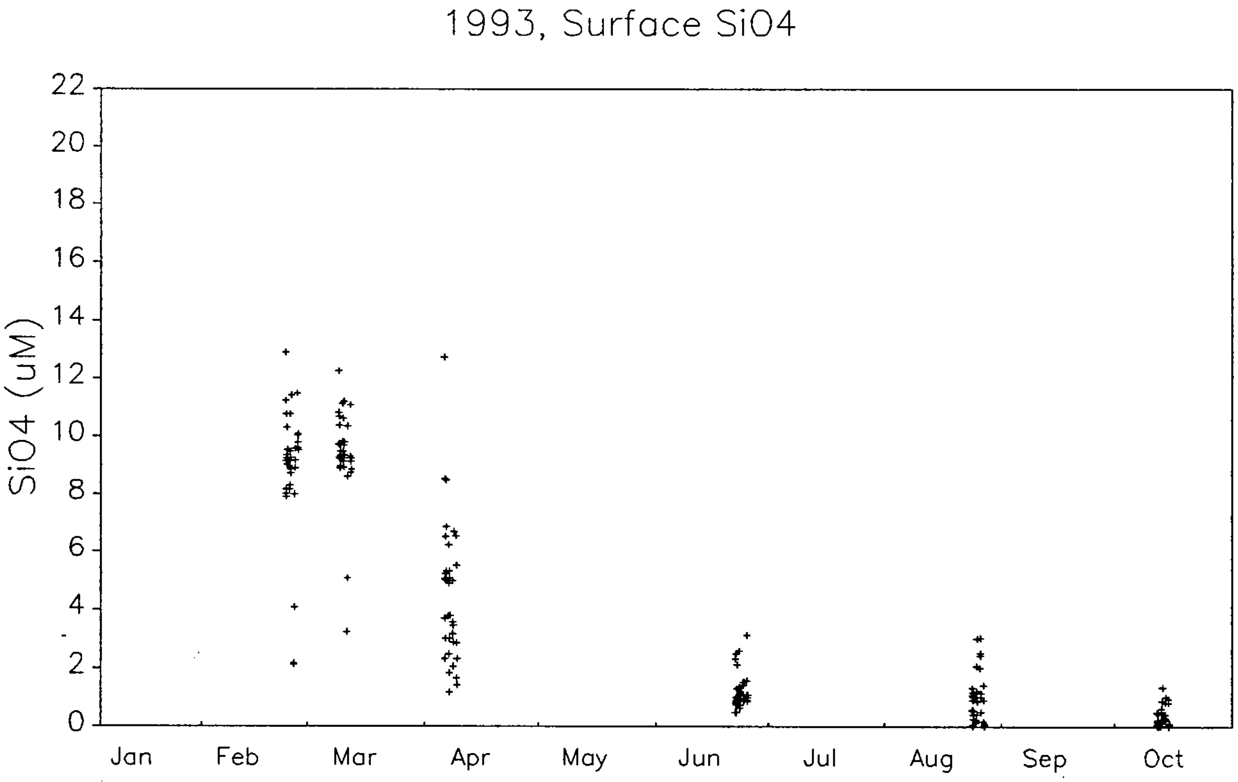


Figure 3.1-14 $SiO_4$ concentrations through the annual cycle in surface waters of Massachusetts and Cape Cod Bays.

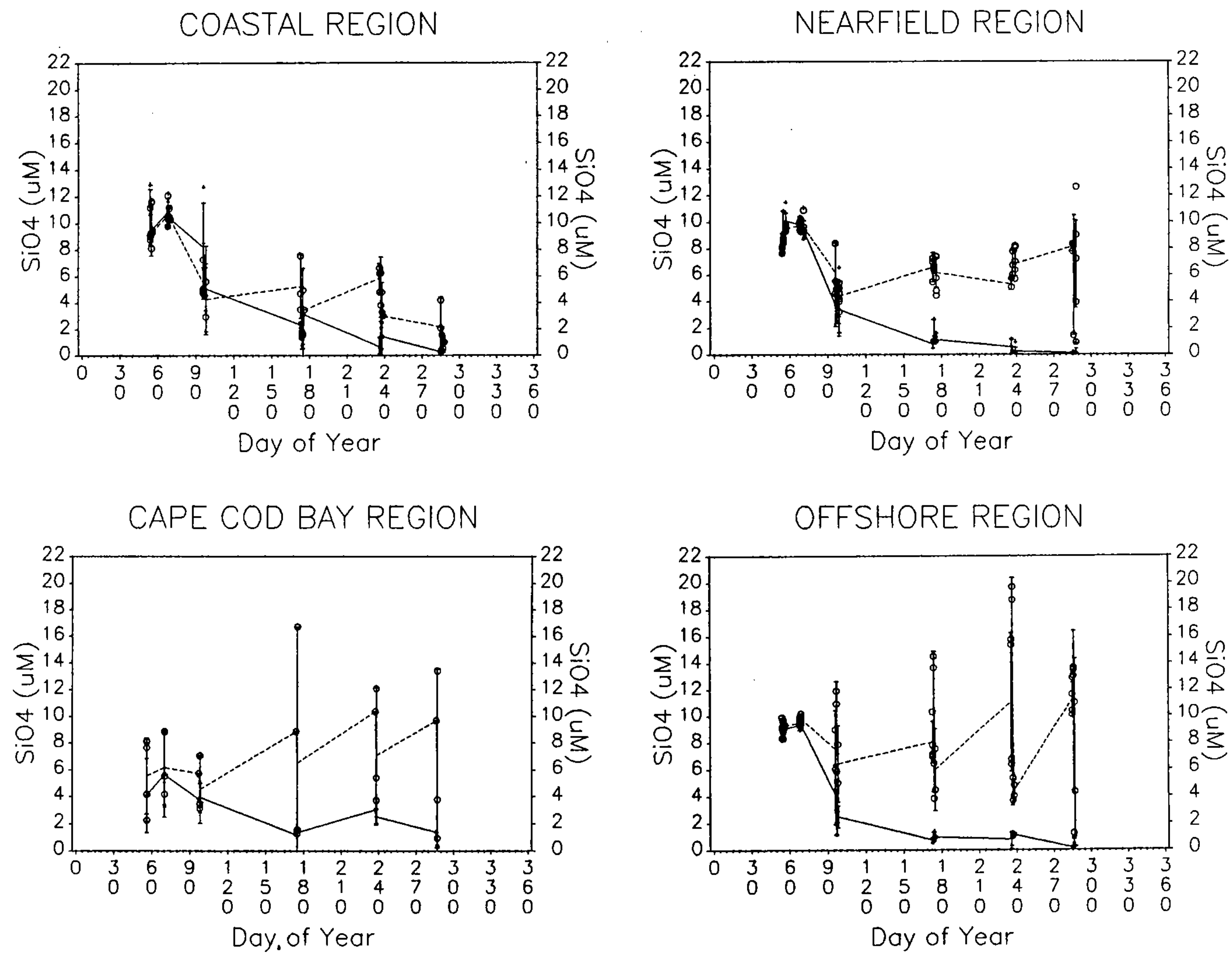


Figure 3.1-15 Comparison of annual $SiO_4$ cycle in surface and bottom waters in four major sampling regions of Massachusetts and Cape Cod Bays. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling, so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

## 3.2 CHLOROPHYLL

Chlorophyll data were available for all stations from measurements of *in-situ* fluorescence. For each survey, fluorescence measurements were calibrated with chlorophyll *a* measurements made at a subset of stations on each farfield and nearfield survey (cf. Albro *et al.*, 1993). Unless specified by analytical technique and referred to as chlorophyll *a*, the terms fluorescence and chlorophyll are used interchangeably in this report and refer to these post-survey calibrated values. The data used in this report represent readings made at the closing of Niskin bottles on a hydrocast upcast. Thus, they can be directly related to chlorophyll *a* used for calibration, and also to nutrient, DO, and phytoplankton data presented in this report. Detailed vertical profiles (0.5-m bin-averaging) for *in-situ* measurements on hydrocast downcasts have been presented in the series of 1993 water column monitoring reports that are referenced in Section 2.

### 3.2.1 Frequency Distribution of Chlorophyll

A total of 1103 values for fluorescence were used to develop the frequency distribution plot which covers all farfield survey sampling depths (Figure 3.2-1). The maximum concentration was 21.1 $\mu$g $L^{-1}$; 7 individual concentrations exceeded 20 $\mu$g $L^{-1}$. For comparison, the maximum chlorophyll *a* concentration from standard extraction techniques was 26.7 $\mu$g $L^{-1}$ (N=204 analyses). More than 75% of the samples had concentrations in the three lowest concentration classes (Figure 3.2-1) and thus were below 3.75 $\mu$g $L^{-1}$. In each region, some samples exceeded 10 $\mu$g $L^{-1}$. The overall mean concentration was 2.84 $\mu$g $L^{-1}$ based on fluorescence (N=1103, standard deviation=3.85) and 2.92 $\mu$g $L^{-1}$ based on chlorophyll *a* (N=204, standard deviation=3.92). By region, the mean fluorescence concentrations were 2.56 $\mu$g $L^{-1}$ (northern transect), 2.95 $\mu$g $L^{-1}$ (nearfield region), 3.67 $\mu$g $L^{-1}$ (coastal region), 1.97 $\mu$g $L^{-1}$ (offshore region), and 3.29 $\mu$g $L^{-1}$ (Cape Cod Bay).

### 3.2.2 Distribution of Chlorophyll Over Depth

Figure 3.2-2 provides a regional comparison of 1993 fluorescence measurements. As shown by this figure, the highest chlorophyll maxima were detected in the coastal and nearfield regions; concentrations >20 $\mu$g $L^{-1}$ were found in both regions. Aside from a cluster of data at 8-14 $\mu$g $L^{-1}$ in the surface 20 m of the offshore region (see time trends below), the data define a mid-depth chlorophyll maxima (15-30 m) underlying low surface values — a feature commonly described for individual surveys and stations in reports covering the stratified period of the year (cf. Kelly *et al.*, 1994d). Figure 3.2-2 also illustrates slightly different frequency distributions for the regions; these differences are due to different water depths. As suggested in the discussion of frequency distributions presented in the previous section, most of the concentrations were <4 $\mu$g $L^{-1}$ in *each* region, yet concentrations as high as ≈14 $\mu$g $L^{-1}$ were also observed in the surface layer within each region. Baywide, high concentrations (>10 $\mu$g $L^{-1}$) were unusual at depths <30 m and concentrations were nearly always <2 $\mu$g $L^{-1}$ in water depths >40 m. Because of depth variations and to compare the data by regions, the focus of this section is limited to surface waters.

### 3.2.3 Annual Cycle for Chlorophyll in Surface Waters

Figure 3.2-3 presents an annual cycle based on surface measurements at stations within the four major regions that were sampled. Two aspects of the temporal patterns are noteworthy. First, all regions from Massachusetts Bay show approximately the same annual trend: low values in the first part of the year, a minor increase in April and, thereafter, increasing surface chlorophyll concentrations to the annual maximum in October. The pattern for the northern transect region (not shown in Figure 3.2-3) was the same as the pattern for other Massachusetts Bay regions. Concentrations >6 $\mu$g $L^{-1}$ were only detected in October. Of the Massachusetts Bay groups, the coastal and nearfield regions showed the earliest (June) summer rise in chlorophyll and reached the highest Baywide concentrations (October). The offshore region had the small April chlorophyll peak that was characteristic of Massachusetts Bay, but this region did not show elevated concentrations through the summer, even though the October concentrations were in the range that characterized the coastal stations.

The second noteworthy aspect of the temporal patterns shown in Figure 3.2-3 is the contrast between Cape Cod Bay and Massachusetts Bay. This contrast has been consistently noted in recent studies (Geyer *et al.*, 1992; Becker, 1992; Kelly *et al.*, 1993). The marked difference between the Bays was the occurrence of a seasonal chlorophyll peak (3-4 $\mu$g $L^{-1}$) in early winter-spring (February and March) in Cape Cod Bay that was not observed in surface waters of Massachusetts Bay. Other differences between Bays that were evident in 1993 include (1) a later initiation of winter-spring peak chlorophyll concentrations in Massachusetts Bay (e.g., April versus February-March in Cape Cod Bay) and (2) lower maximum concentrations in Massachusetts Bay surface water during the winter-spring season (contrast Cape Cod Bay in March with any Massachusetts Bay region in April). These differences were not as pronounced in 1993 as they were in 1992 (cf. Kelly *et al.*, 1993). It is also noteworthy that Cape Cod Bay exhibited a fall chlorophyll bloom (Figure 3.2-3), although not as intense as in the Massachusetts Bay regions.

### 3.2.4 Spatial Distribution of Chlorophyll in Surface Water in Western Massachusetts Bay

For each station sampled in 1993, the mean chlorophyll concentrations in surface water were calculated and are displayed for the western region of Massachusetts Bay in Figure 3.2-4. The area shown in Figure 3.2-4 extends north to the three stations of the northern transect, east of the nearfield to include stations F19 and F17 in Stellwagen Basin, and south to the Scituate transect (stations F09-F10-F11). A general inshore-offshore gradient of decreasing mean chlorophyll concentrations is evident in the figure. This type of gradient has been observed using annual averages from other recent years (Kelly, 1993a). The highest average concentration (>4.5 $\mu$g $L^{-1}$) was found at station F24 near the seaward edge of the tidal excursion (cf. Signell and Butman, 1992). This location is apparently an area where chlorophyll is stimulated, perhaps due to a rapid drop in turbidity or as a consequence of mixing and/or upwelling (cf. Kelly and Albro, 1994). Average concentrations >3 $\mu$g $L^{-1}$ were regularly found at coastal locations near Boston Harbor and to the middle of the nearfield area (station N20P), as well as at stations F20 and F21 on the northern transect extending about 10-15 km from Salem Harbor. Seaward and south of the mid-nearfield, the average concentrations ranged from <1.5 to ≈3 $\mu$g $L^{-1}$. The overall range of average concentrations, as well as the spatial pattern for the 1993 annual mean surface chlorophyll, are similar to observations made in 1992 and 1989/1990 and summarized by Kelly (1991, 1993a). Each of these annual data sets was derived from six annual surveys conducted approximately at the same times that the 1993 surveys were conducted.

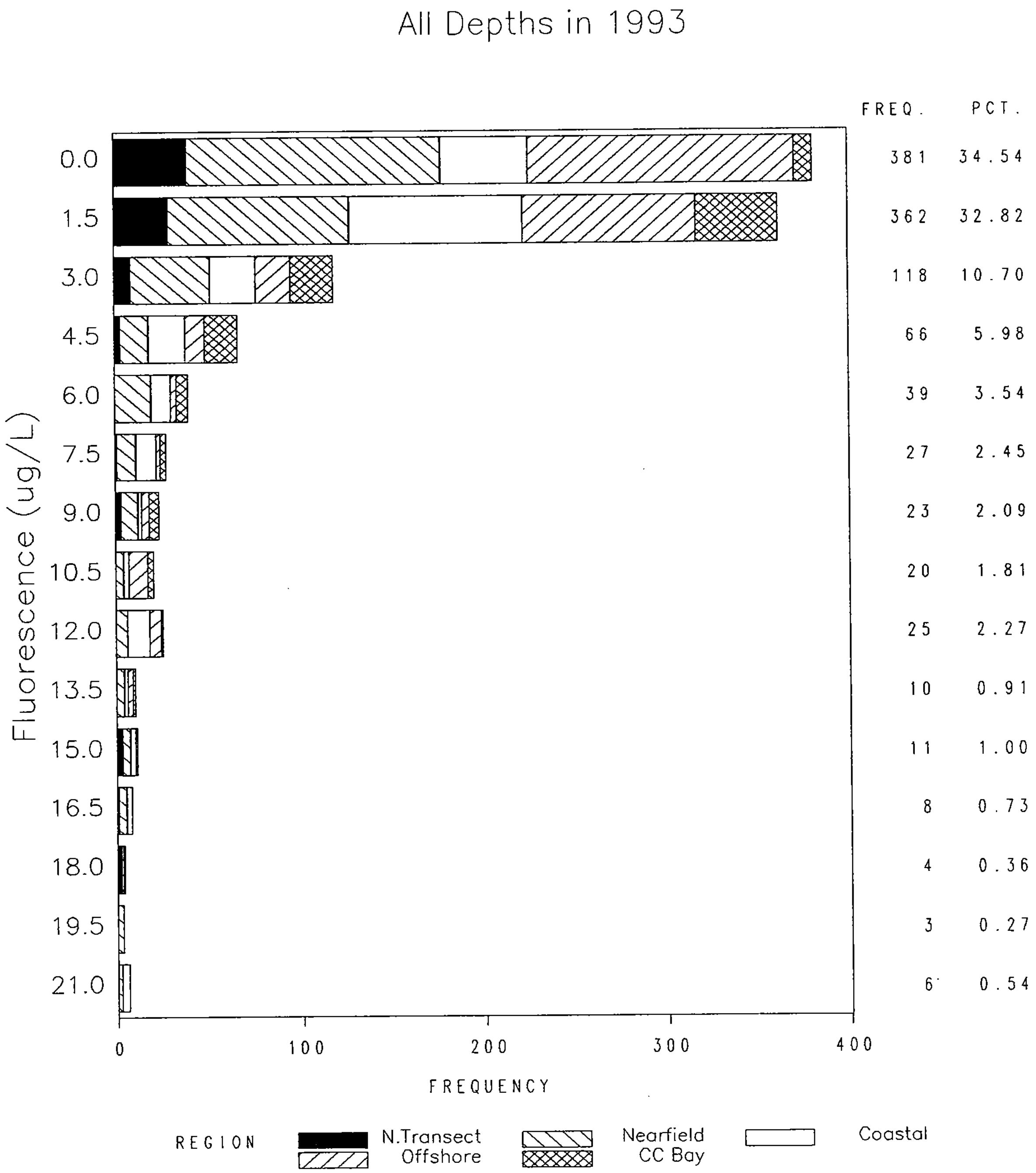


Figure 3.2-1 Frequency distribution of fluorescence for all stations sampled in 1993.

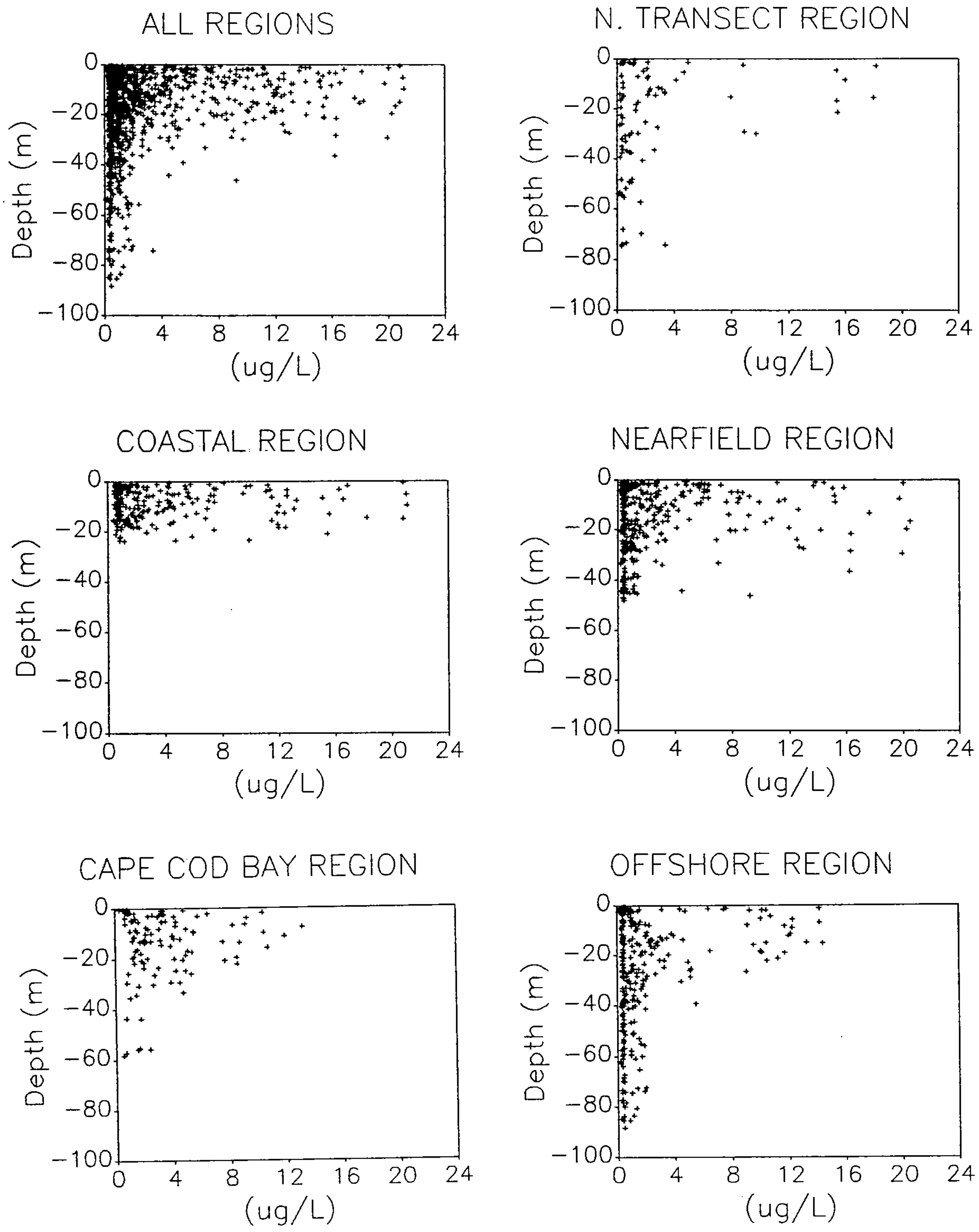


Figure 3.2-2 Fluorescence over depth, by sampling regions, for all surveys in 1993.

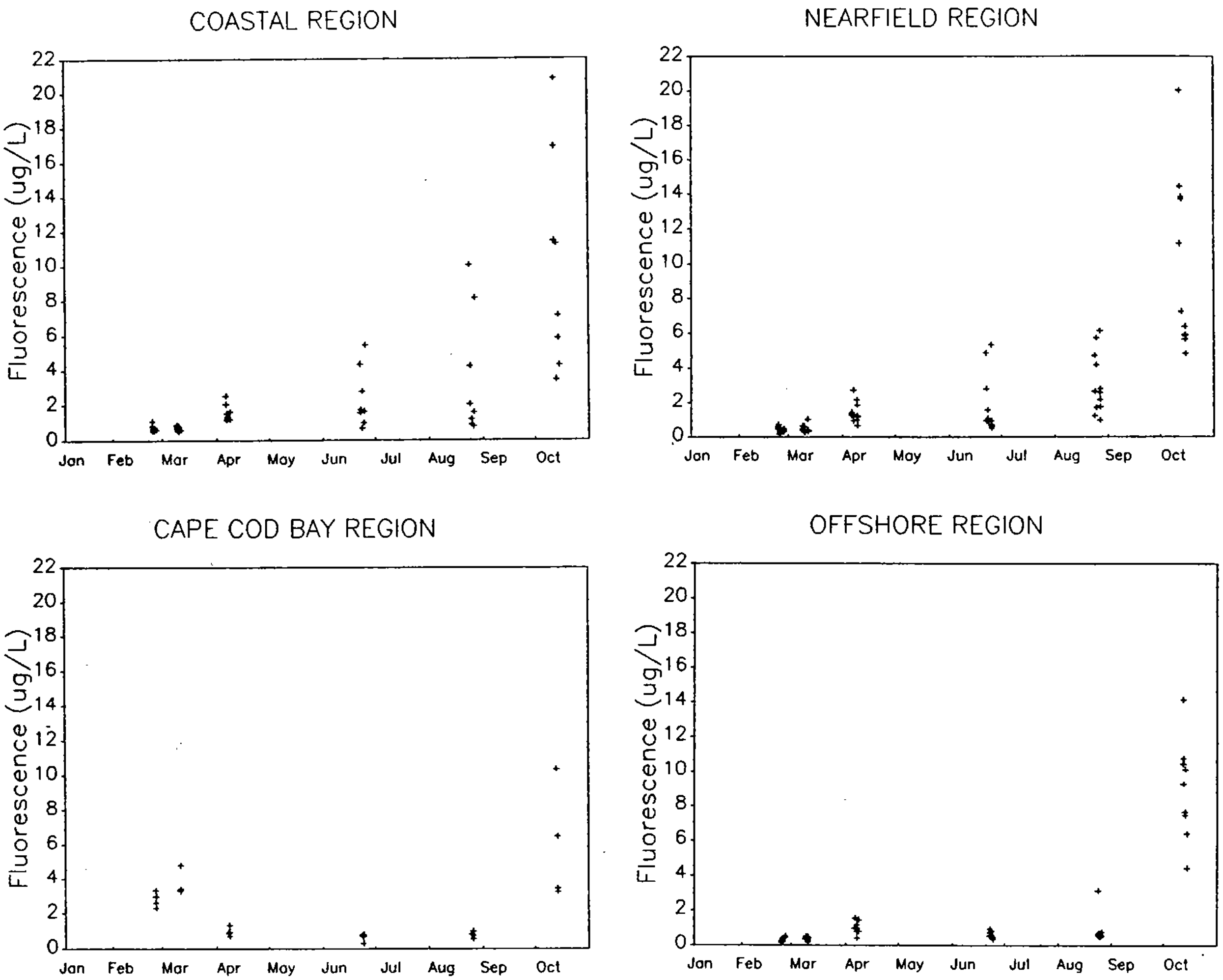


Figure 3.2-3 Fluorescence through the annual cycle in surface waters for four major sampling regions of Massachusetts and Cape Cod Bays.

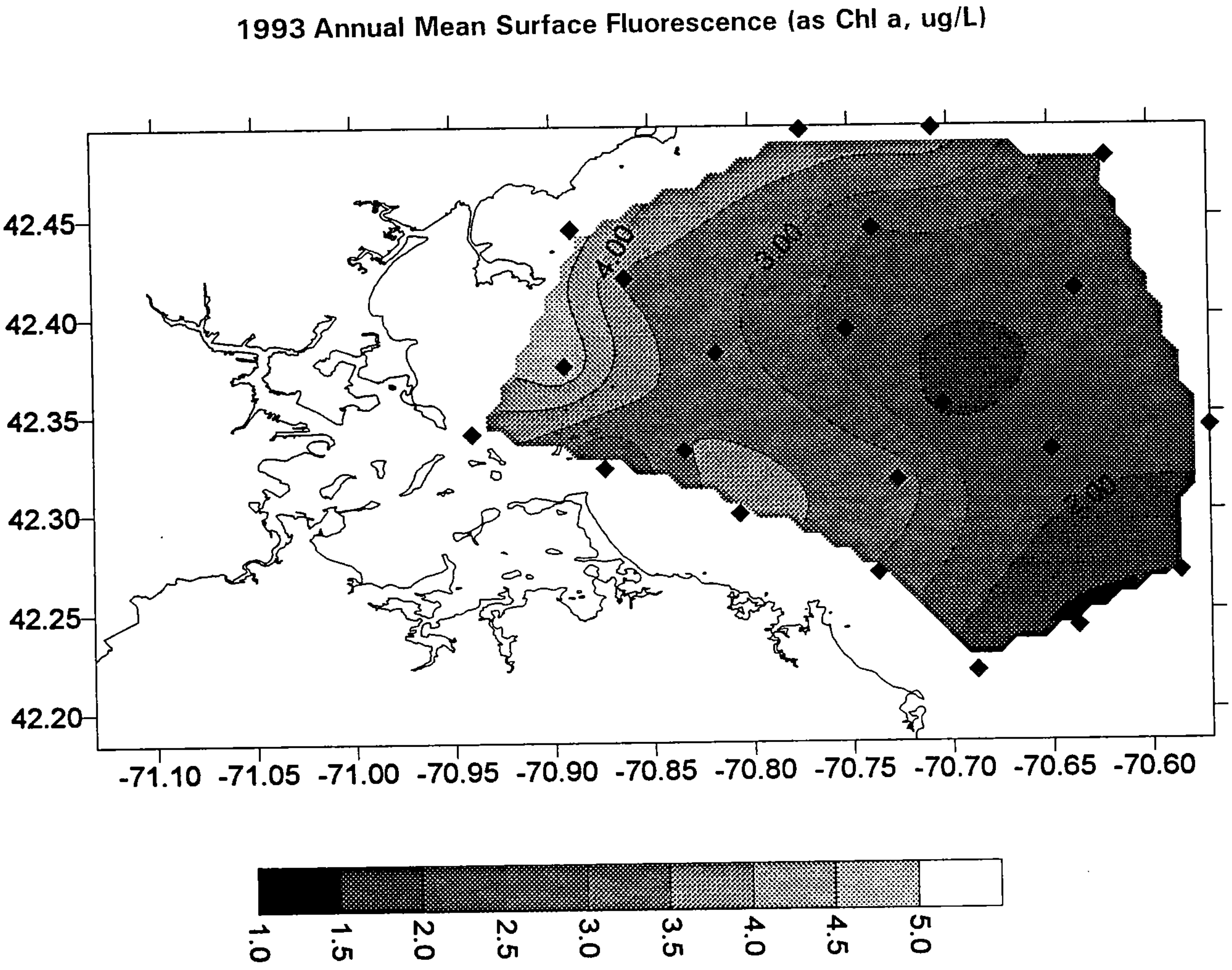


Figure 3.2-4 Spatial pattern of fluorescence in western Massachusetts Bay. Data are surface water means from six farfield surveys in 1993.

## 3.3 DISSOLVED OXYGEN

Dissolved oxygen (DO) concentrations were measured continuously by an *in-situ* sensor during hydrocasts at all stations. For each survey, *in-situ* sensor data were calibrated against DO concentrations determined by a standard Winkler titration using an autotitration method (see Albro *et al.*, 1993). Duplicate 300-mL BOD bottles were filled from a Niskin bottle that was triggered on the upcast at a set of stations throughout the Bays. In general, the sensor and titration data for each survey agreed within 5-10%, and the calibration curves were similar across surveys (see Appendix A for 1993 periodic reports cited in Section 2). The calibrated DO sensor data that are used in this report are based on time-averaged readings concurrent with separate Niskin bottle closings at each of the five depths during the upcast at each station. The DO data can be directly related to all nutrient, fluorescence, and hydrographic measurements associated with the Niskin bottle, including the DO data with which they were calibrated. The DO sensors used for this monitoring program have a lagged response to temperature. However, the sensors had a relatively long temperature adjustment period (compared to the more rapid, continuous downcast) prior to bottle closure. Thus, these "bottle-closing" data provide the most comprehensive and reliable set of MWRA water column DO.

### 3.3.1 Frequency Distribution of Dissolved Oxygen

For the six farfield surveys, 1098 data points were available to develop DO frequency distributions (Figures 3.3-1 and 3.3-2). The stacked bar graph displays each region's frequency distribution as well as the total. The minimum DO concentration detected was 6.68 mg $L^{-1}$ in bottom water during October. For reference, all Winkler-titration samples (N=8), collected from depths >40 m in October, were generally in the range of 7.22 mg $L^{-1}$ to 7.85 mg $L^{-1}$ (Libby *et al.*, 1994). The maximum DO value was 13.19 mg $L^{-1}$ and the mean was 10.31 mg $L^{-1}$. Less than 4% of the readings were <8 mg $L^{-1}$ and less than 0.3% of the readings were <7.5 mg $L^{-1}$. The frequency distribution for the percent saturation (Figure 3.3-2) was centered near 100% saturation and more than 50% of the values exceeded 100% saturation (median = 101.7%). For the entire data set, the mean percent saturation was 102.6, with a minimum of 71.9 and a maximum of 132. Few regional distinctions are apparent from these plots. Mean values for each region were nearly identical (regional means ranged from 102 to 104% saturation).

### 3.3.2 Annual Cycle of Dissolved Oxygen

As expected, DO concentrations were higher in winter-spring than in summer-fall (Figure 3.3-3). Highest concentrations were observed in surface waters in April when the winter-spring chlorophyll concentrations in western Massachusetts Bay were at their peak. Interestingly, surface and bottom water DO concentrations were similar during most surveys; surface and bottom water DO concentrations diverge only slightly in October. The overall similarity in surface and bottom water DO concentrations is in part created by temperature differences in surface and bottom waters, because DO concentrations at saturation are higher at colder temperature. Therefore, the differences between surface and bottom water DO are more appropriately expressed as percent saturation than as concentration.

Figure 3.3-4 displays a comparison of oxygen saturation in surface and bottom waters measured during the six nearfield/farfield surveys, surface-water values were above 100% saturation at the beginning of April and continuing through the summer-fall sampling months. For the year, the mean percent saturation in surface waters was 108. Values >100% signal net primary productivity in surface waters, i.e. that the surface layer was autotrophic (a net excess of production over consumption) during these months. Surface waters in the months prior to the spring bloom (February and March) had generally balanced production and consumption, and thus were near 100% saturation, if not slightly below. Undersaturation can indicate a heterotrophic condition (where consumption exceeds production). In contrast to the surface waters, bottom waters were only 96% saturated on average for the year, and from June (after strong thermal stratification of the water column ensued) to October became progressively more undersaturated. The difference between surface and bottom layers during the stratified season indicates that the system, in general, can be represented by an autotrophic surface layer and a heterotrophic bottom layer.

The lowest annual bottom water DO concentrations were measured at many locations during the October survey. This pattern is consistent with results of recent studies (Kelly, 1993). Note, however, that the range of DO concentrations was large in October (Figures 3.3-3 and 3.3-4). Figure 3.3-5 displays a frequency distribution for bottom water DO measured during the October survey. Two interesting features are revealed in this figure. First, measurements made in the coastal region, including Boston Harbor where nutrient enrichment is highest, were biased to the higher end of the range. Second, the deep waters of Stellwagen Basin in the offshore region generally were low in DO. Examining DO concentrations in relation to sampling depth (Figure 3.3-6) shows a relatively narrow range of values for all samples below ≈35 m. At depths <35 m, stratification was weak or not defined in the Bays; the breakdown of seasonal stratification generally begins in nearshore shallow waters and proceeds seaward (cf. Libby *et al.*, 1994). The one low DO value in Cape Cod Bay (station F02P at ≈30 m depth, Figure 3.3-6) was noted within a deep near-bottom thermocline/pycnocline (Libby *et al.*, 1994, see also Section 5). Different degrees of mixing and the continued stratification of deeper waters at this time can explain the variability shown in Figure 3.3-3 and the pattern in Figure 3.3-6. Considering this, it is possible that physical factors which affect water column stability during October can influence bottom water DO more strongly than most local biological events.

### 3.3.3 Rates of DO Decline in Bottom Waters During Stratification

In the Bays, DO data from the deepest waters (>50 m and all within Stellwagen Basin) can provide approximate rates of DO decline during stratification (e.g., Kelly, 1993a). Figure 3.3-7 shows the time trend for DO at stations where water sampling depths were consistently >50 m (stations F08, F12, F17, F19, and F22). Note that both concentration and percent saturation show a progressive decline from about April to October. These deep waters were near 100% saturation in April but had become, on average, undersaturated by June. This saturation deficit, markedly increased by October, confirms that the observed decline in DO concentration over the stratified period was due to heterotrophic processes, not just a response to decreased oxygen-holding capacity because of temperature warming. Linear regression analyses of concentration vs. time from April through October indicated a significant decline (Prob>F=0.0001, $R^2$= 0.94, N=23) in DO at an estimated rate (slope±standard error) of 0.0181 (±0.0008) mg $L^{-1}$ $d^{-1}$. Regression analyses for the data from June through October also indicated a significant decline (Prob>F=0.0001, $R^2$=0.90, N=33) in DO, but at a faster estimated rate (slope±standard error) of 0.0216 (±0.0016) mg $L^{-1}$ $d^{-1}$. DO decreases implied from data gathered at these same stations during water column monitoring over the same period (April-October) in 1992 were similar and ranged from 0.015 to 0.023 mg $L^{-1}$ $d^{-1}$. The faster rate was again associated with the June-October period and the slower rate was between April and October (Kelly, 1993a).

The difference between rates for the two periods suggests an increasing rate of bottom water DO decline over the period of stratification. The temperature in deep water increased substantially during the summer (see Section 5) and a nonlinear rate of DO utilization could thus be expected. This observation suggests that projection of ultimate DO concentrations achieved before destratification, at a minimum, may have to take bottom water temperature changes and a nonlinear rate of oxygen uptake into account to achieve the best predictions. Because farfield sampling in 1993 was not conducted after October and because Stellwagen Basin remained strongly stratified at that time, it is likely that the lowest bottom water Basin DO concentrations were not measured during 1993.

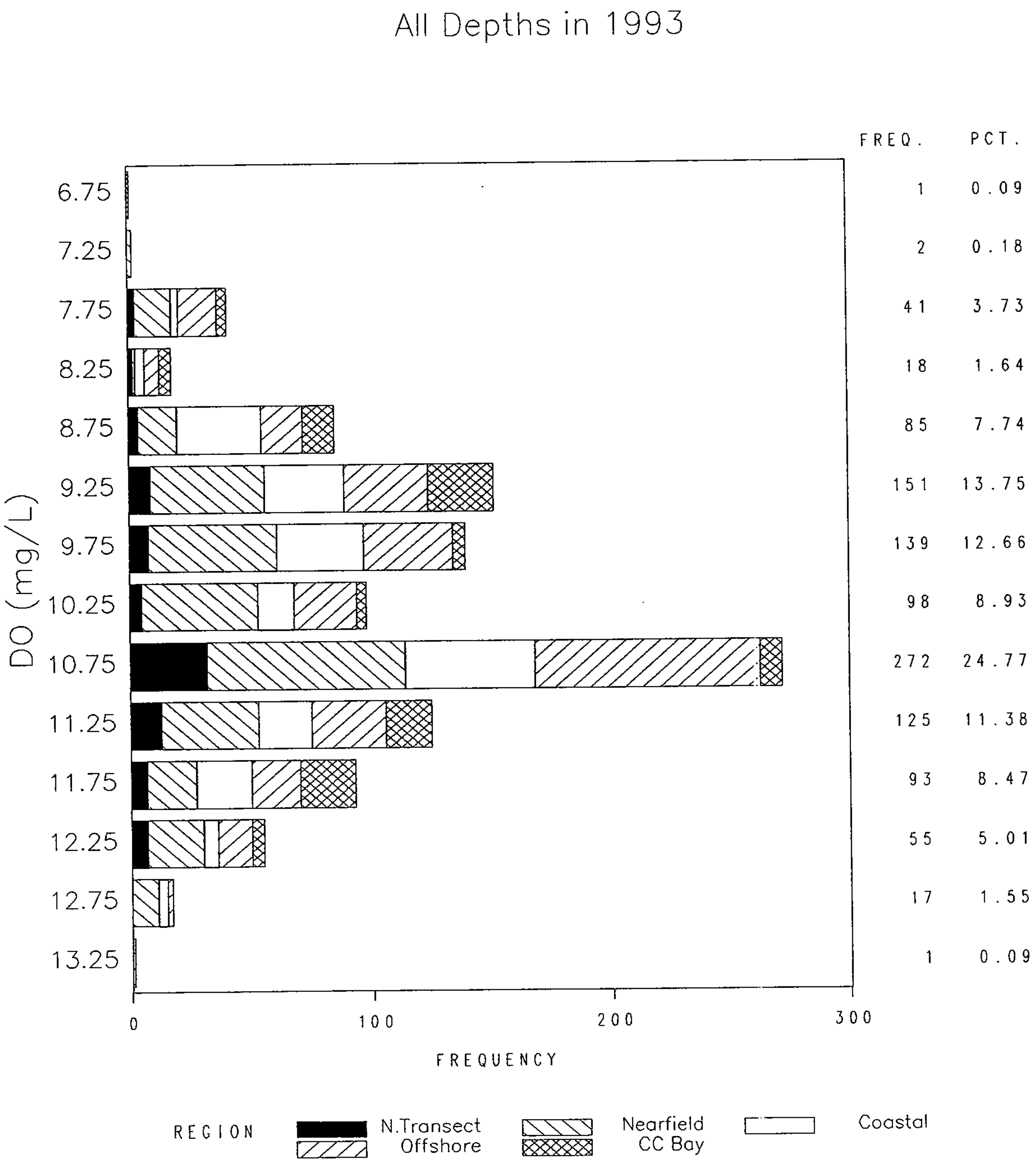


Figure 3.3-1 Frequency distribution of DO concentration for all stations sampled in 1993.

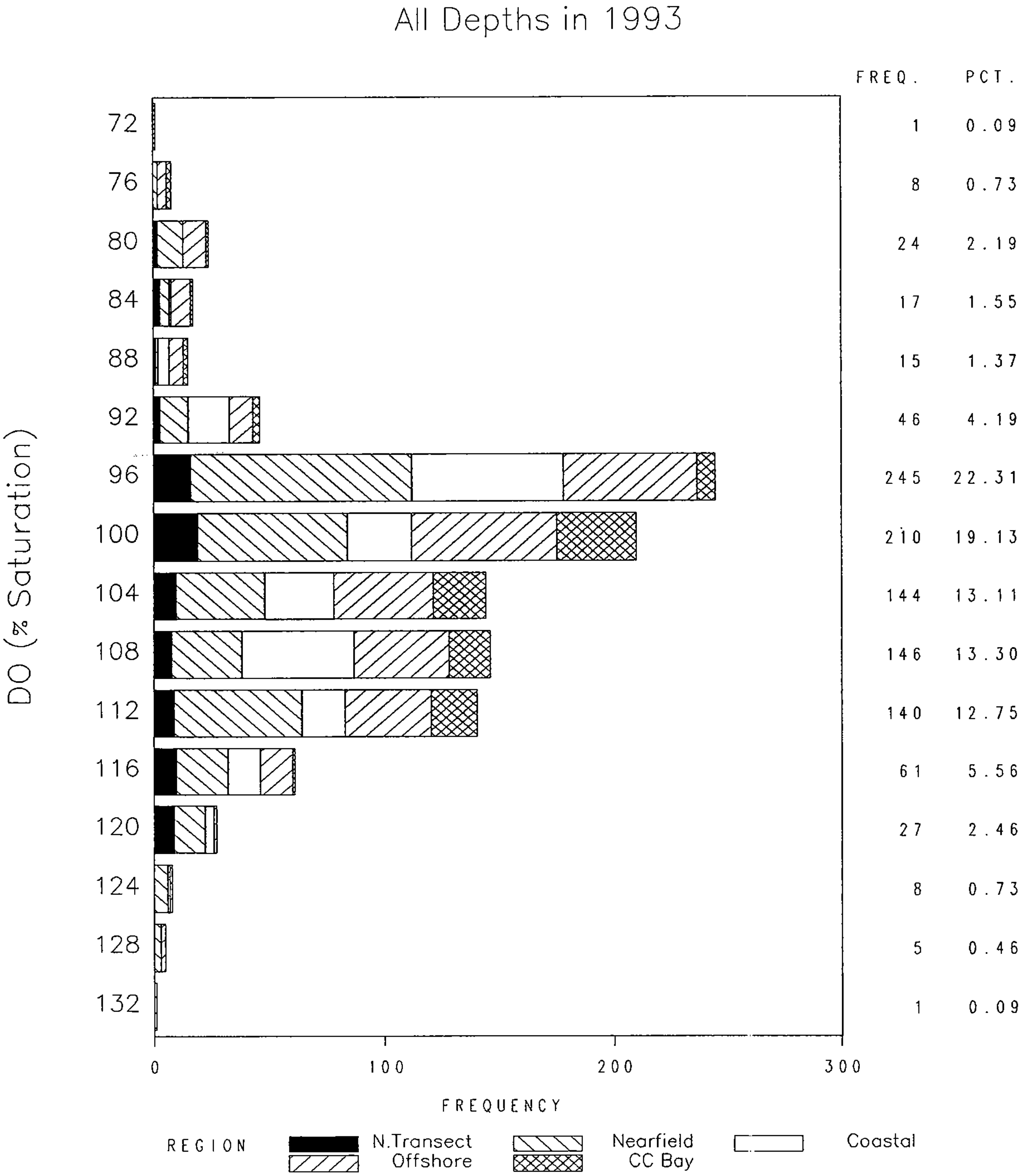


Figure 3.3-2 Frequency distribution of DO saturation for all stations sampled in 1993.

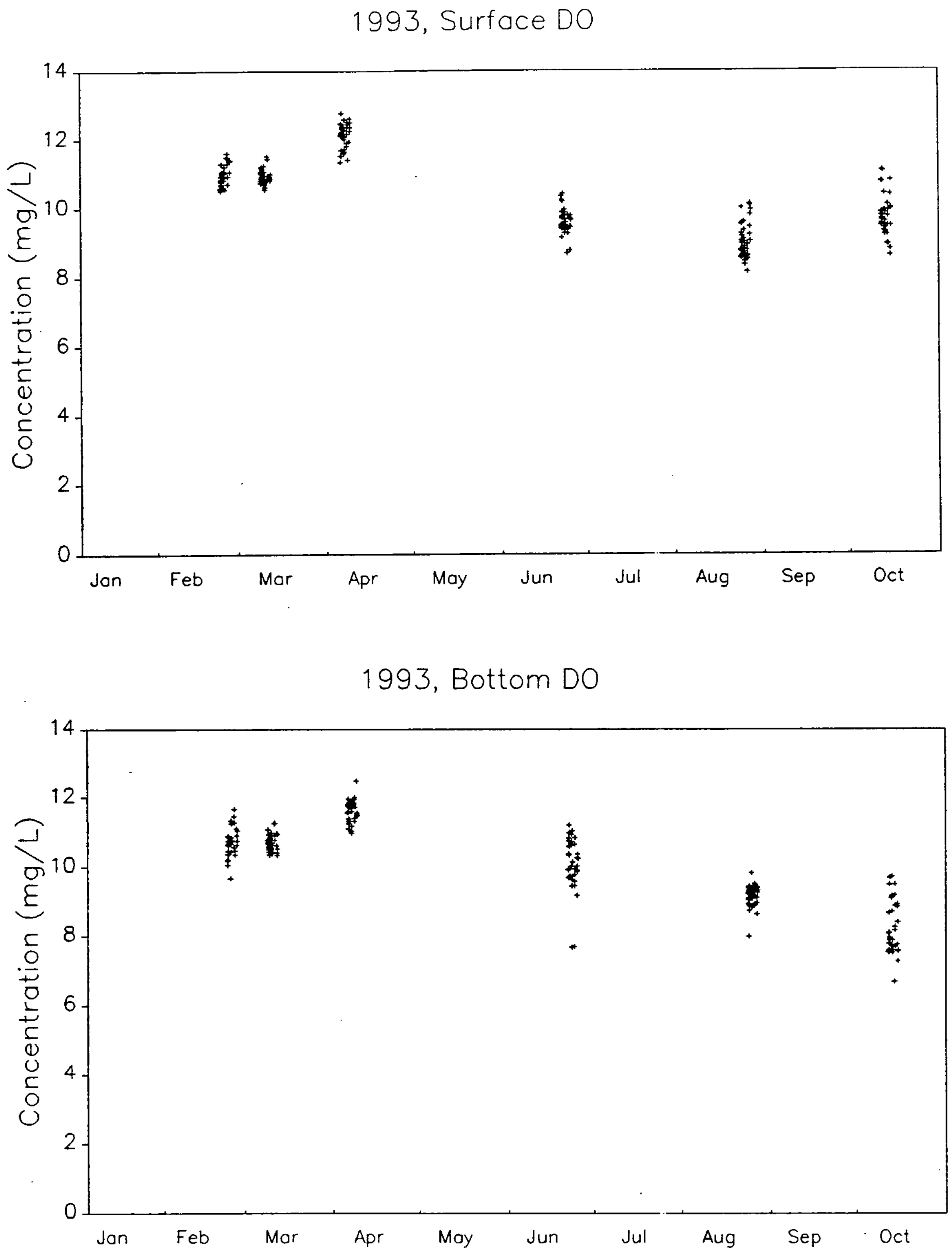


Figure 3.3-3 DO concentration in surface and bottom waters through the annual cycle in Massachusetts and Cape Cod Bays.

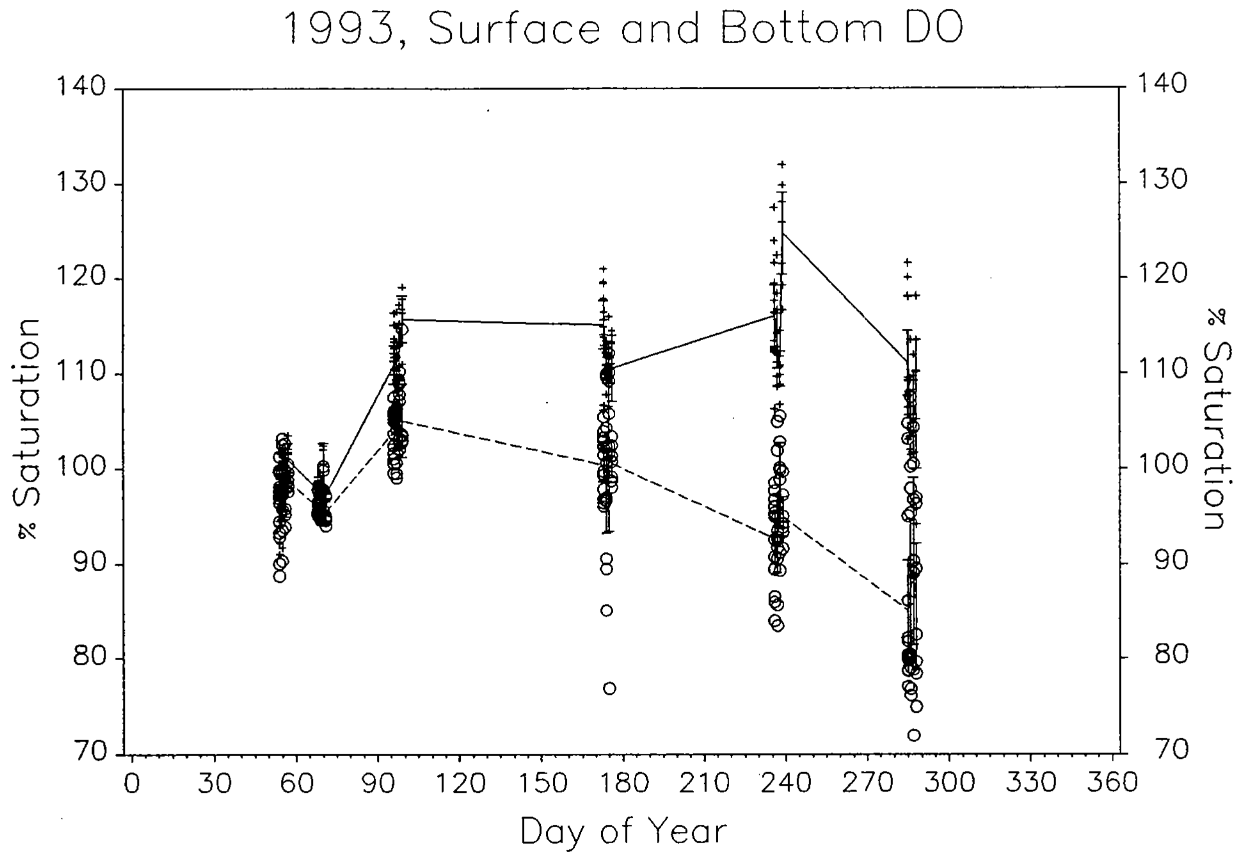


Figure 3.3-4 DO saturation in surface and bottom waters through the annual cycle in Massachusetts and Cape Cod Bays. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling, so sharp variations within a survey (≈3 days) are often indicated. Vertical lines with bars indicate ± standard error of the mean.

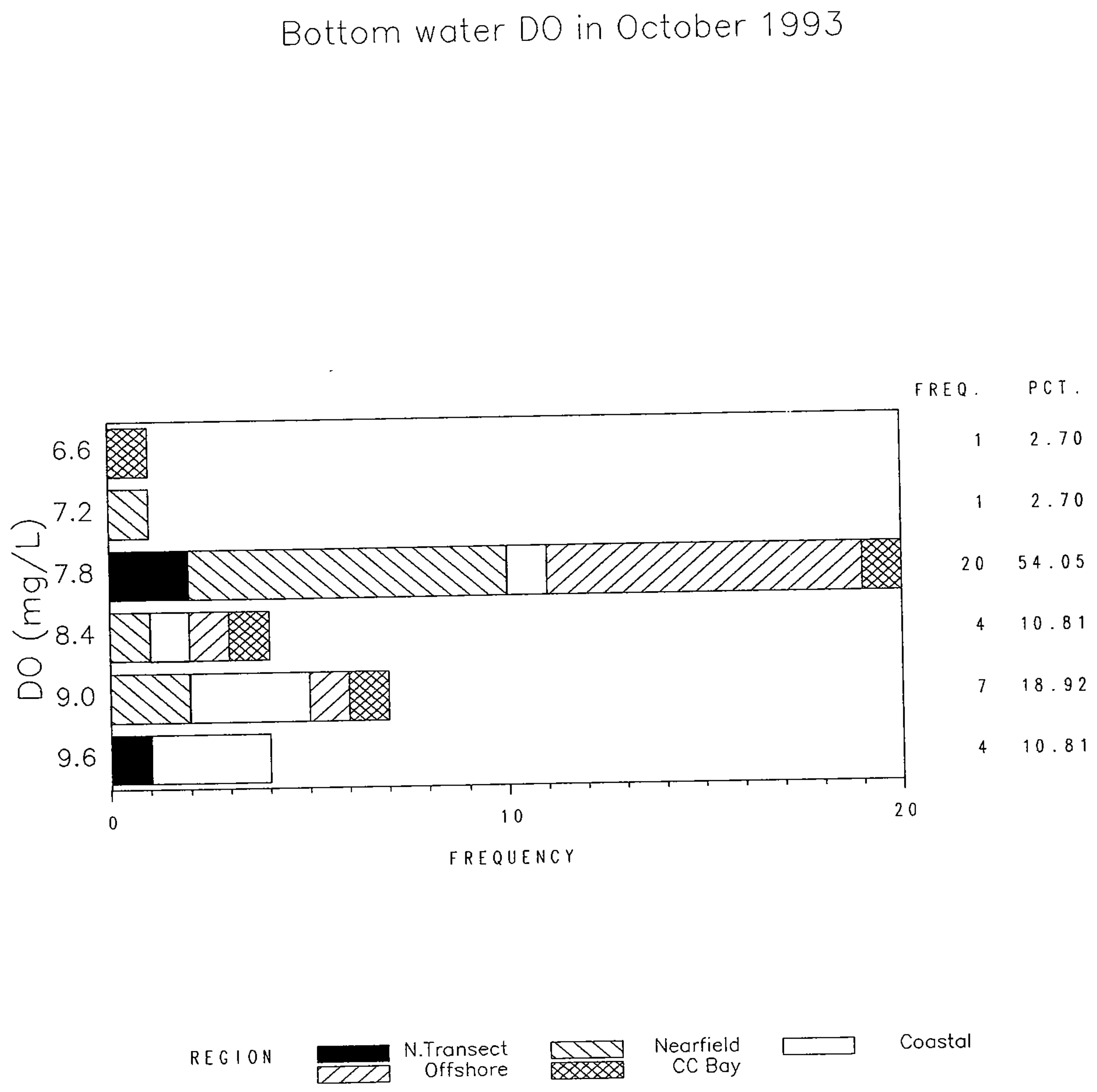


Figure 3.3-5 Frequency distribution of DO concentration for bottom water at stations sampled in October 1993.

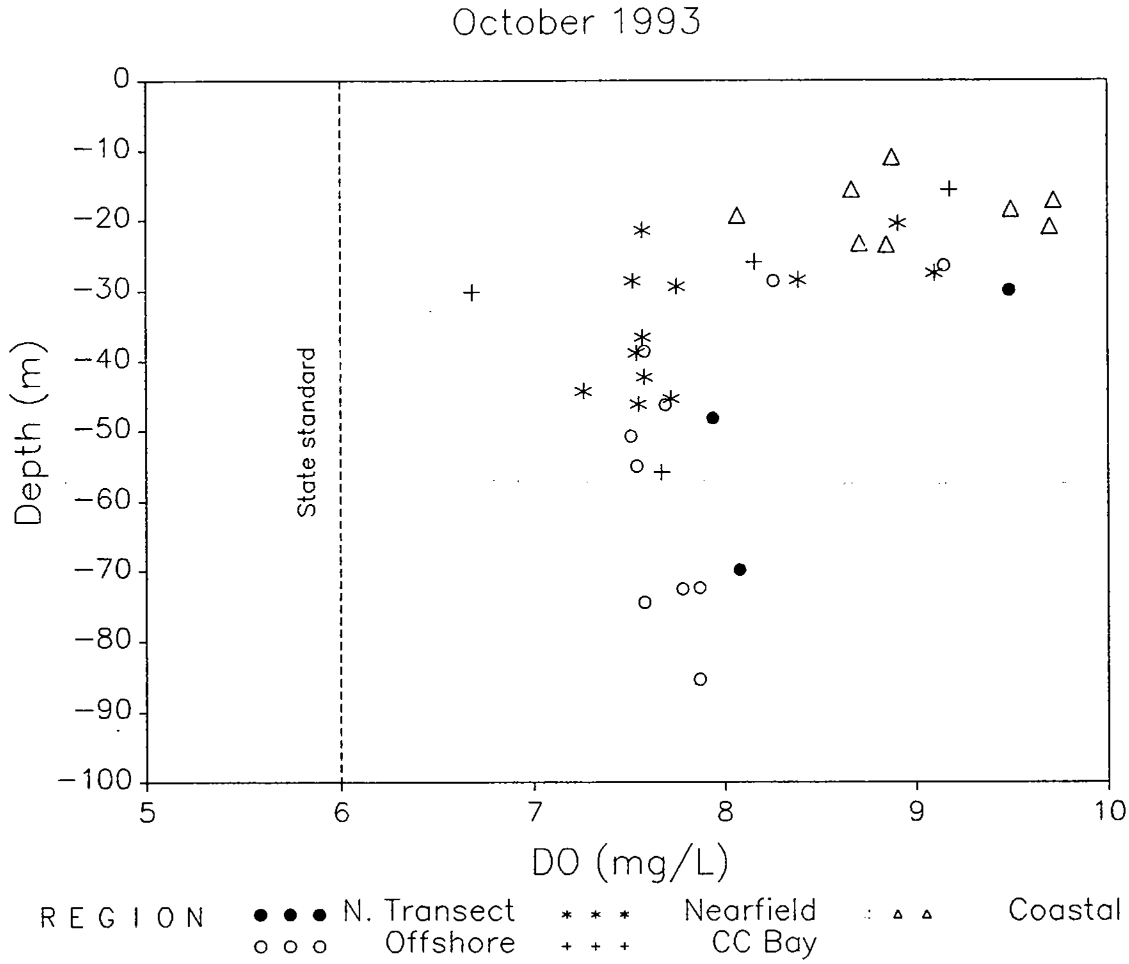
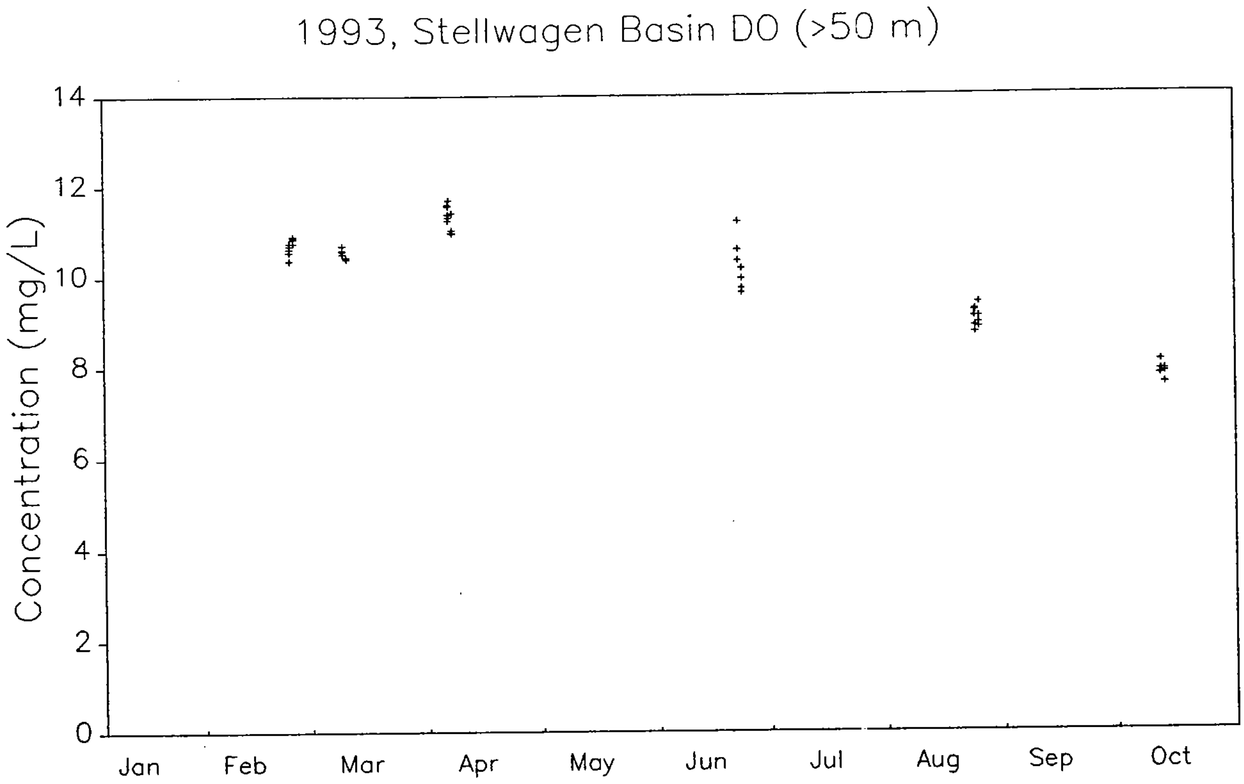


Figure 3.3-6 DO concentration as related to depth of sampling for all bottom waters sampled in October 1993.



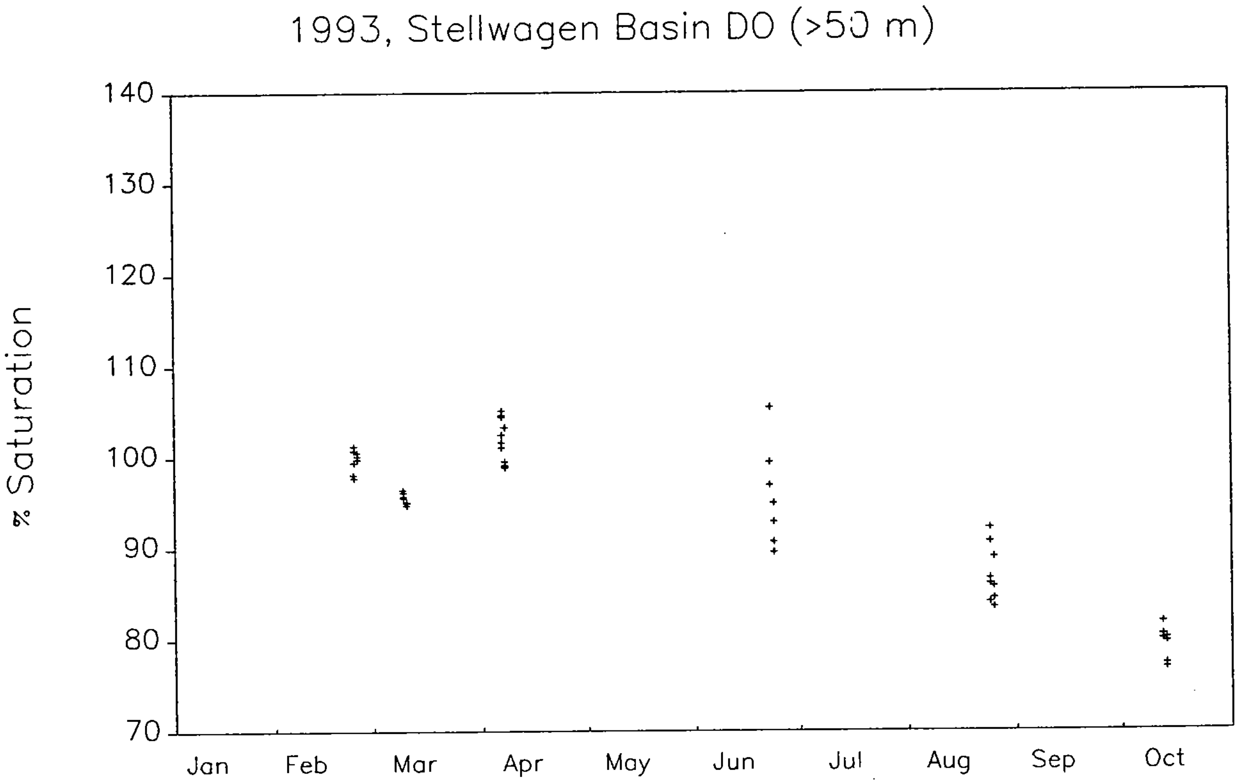


Figure 3.3-7 DO concentration and saturation through the annual cycle in deep water from Stellwagen Basin stations sampled in 1993.

## 3.4 PLANKTON

Whole-water samples for phytoplankton counts were collected from the 10 "P" stations in Massachusetts and Cape Cod Bays. Water samples were obtained from the Niskin bottles that were used for nutrient sampling (cf. Albro *et al.*, 1993). At each of these stations, vertical-oblique zooplankton tows were also conducted. For samples collected on the farfield surveys, both phytoplankton and zooplankton taxa were identified and counted. Phytoplankton were also identified and counted for station N10P surface water collected on all nearfield surveys. Additional (screened) phytoplankton sampling and analysis was performed and all data have been previously reported in the 1993 periodic reports (and appendices). The interested reader should consult those reports for more detail on the taxonomy of the plankton community found in the water column during each survey. The emphasis in this section of the report is on a description of the overall seasonal progression in abundance, dominant groups, and selected dominant taxa in 1993, using the farfield surveys and contrasting events by regions where appropriate. Comparisons to 1992 patterns (Kelly *et al.*, 1993; Turner, 1994) are also presented.

### 3.4.1 Phytoplankton in 1993

In February, diatoms dominated the phytoplankton throughout the system. Most abundant diatom taxa included *Skeletonema costatum, Cylindrotheca closterium, Nitzschia seriata, N. delicatissima, Thalassionema nitzschoides,* and several species of the genus *Chaetoceros (debilis, compressus, socialis, decipiens).* In Cape Cod Bay, the diatoms *Thalassiosira nordenskioldii* and *Leptocylindrus danicus* were also abundant at the surface at station F01P and at the chlorophyll maximum at station F02P, respectively. Microflagellates and cryptomonads were also present at most stations, but were not as abundant as the diatoms as a group.

Total phytoplankton abundances in February were generally low (0.2->0.3 million cells $L^{-1}$) at all stations except F01P and F2) in Cape Cod Bay. There the winter-spring diatom bloom, comprised mainly of *Chaetoceros* spp., was well underway with total abundances of >0.8->1.0

million cells $L^{-1}$. Dinoflagellate abundance was negligible (3-145 cells $L^{-1}$), with most values <10 cells $L^{-1}$.

In March, the phytoplankton population was again dominated by a combination of several diatom species, including *Cylindrotheca closterium, Thalassiosira gravida, T. rotula, T. nordenskioldii, Nitzschia delicatissima, Skeletonema costatum,* and several *Chaetoceros* species *(debilis, socialis, compressus).* Cryptomonads and microflagellates were again subdominants and dinoflagellate abundance was negligible (one to tens of cells $L^{-1}$ for individual species).

Total phytoplankton abundance in March was approximately 0.2 million cells $L^{-1}$ or less everywhere except in Cape Cod Bay. There, total abundance was >1.0-1.3 million cells $L^{-1}$, where a major bloom of *Chaetoceros debilis,* other *Chaetoceros* species, *Thalassiosira nordenskioldii,* and *Leptocylindrus danicus* was continuing.

In April, diatom dominance continued. Species included *Thalassiosira gravida/rotula* and the same combination of *Chaetoceros* species *(debilis, compressus,* and *socialis)* reported in February and March. Microflagellates and cryptomonads continued as subdominants, with "*Nostoc*-like" *Cyanophyceae* (≈4 µm diameter) at the chlorophyll maximum at station N07P. Dinoflagellate abundance was still low, but in contrast to the previous months, larger dinoflagellates, such as *Ceratium longipes, Gyrodinium spirale, Katodinium* spp. and several species of the genera *Dinophysis* and *Protoperidinium,* were generally present in the 20 µm-screened samples at abundances of tens of cells $L^{-1}$, rather than primarily several cells $L^{-1}$.

Total phytoplankton abundance in April generally remained low but, unlike February and March, the discrepancy between Cape Cod Bay and the rest of the system was not as great. Total abundance in April was 0.4-0.8 million cells $L^{-1}$, unlike previously when levels were <0.2 million cells $L^{-1}$ everywhere but Cape Cod Bay where they exceeded 1 million cells $L^{-1}$. Apparently the winter-spring bloom throughout the system caught up to that which began earlier in Cape Cod Bay. A similar pattern was recorded in 1992.

The major difference in phytoplankton in April 1993, compared to April 1992, was the absence of a major bloom of *Phaeocystis pouchetii* in April 1993. In April 1992, this species was a system-wide dominant; it was not recorded in April 1993.

In June, microflagellates and cryptomonads dominated abundance at many stations, and the dominant diatoms (*Leptocylindrus danicus* and other *Chaetoceros* species) slipped from first or second in abundance to fourth or fifth at many stations. Dinoflagellate abundance increased dramatically with hundreds of *Ceratium fusus* cells $L^{-1}$ and hundreds to thousands of cells of *Ceratium longipes* $L^{-1}$ in the 20 µm-screened samples. Several species of the genera *Dinophysis* and *Protoperidinium* were present at tens to hundreds of cells $L^{-1}$ in 20 µm-screened samples. Also, an unidentified athecate dinoflagellate *(Gymnodinium?)* was present at concentrations of thousands to tens-of-thousands of cells $L^{-1}$ in whole-water phytoplankton samples from stations N01P, N04P, or N07P.

Total phytoplankton abundance in June was uneven between stations. In surface samples there were <0.5 million cells $L^{-1}$ at stations F01P and F02P in Cape Cod Bay, >2.0-2.5 million cells $L^{-1}$ at the coastal stations F13P and F23P and at the nearfield stations N10P and N20P, and 0.5-1.0 million cells $L^{-1}$ at the other nearfield stations (N01P, N04P, N07P, and N16P). The same general trends of high abundance (1.5 million cells $L^{-1}$ or greater at stations F13P, F23P, N10P, and N20P) and low abundances elsewhere were also found in the chlorophyll-maximum samples.

By August, microflagellates and cryptomonads had become dominant phytoplankters at virtually all stations. However, the chain-forming diatoms *Leptocylindrus danicus, Ceratulina pelagica,* and *Rhizosolenia delicatula* were subdominants at all stations. Also, the diatoms *Stephanopyxis palmeriana* and *Thalassionema nitzschoides* were moderately abundant (9,000 to 15,000 cells $L^{-1}$) at stations F01P and F02P in Cape Cod Bay. The dinoflagellate *Ceratium fusus* was present in hundreds of cells $L^{-1}$ in the 20 µm-screened samples from all stations and was the third most-abundant species in unscreened samples from station F02P in Cape Cod Bay (22,000 cells $L^{-1}$). Also, an unidentified small species of *Gymnodinium* was the third most-abundant species in unscreened samples from station N20P (37,000 cells $L^{-1}$), but because it was athecate and <20 μm in diameter, it likely passed through or was disrupted by 20 μm-mesh screens and thus was not recorded for 20 μm-screened samples. Other larger thecate dinoflagellate taxa recorded for 20 μm-screened samples in generally tens to hundreds of cells $L^{-1}$ included *Ceratium longipes, Ceratium tripos,* with lesser and more sporadic abundances of various species of the genera *Dinophysis* and *Protoperidinium* and, at the surface at station F23P, *Prorocentrum micans.*

Total phytoplankton abundance was uneven between stations with surface concentrations of 2.0 million cells $L^{-1}$ or greater at half of the stations (F23P, N01P, N04P, N10P, and N16P), and concentrations of 1 million cells $L^{-1}$ or less at the other stations. Abundance levels from chlorophyll-maximum samples were less disparate, with concentrations >1.5 million cells $L^{-1}$ only at four stations (F23P, N01P, N04P, and N10P); values from other stations were between 0.5 and 1.5 million cells $L^{-1}$.

The major phytoplankton event of 1993 was the system-wide bloom of the diatom *Asterionellopsis glacialis* in October. At all locations, except in Cape Cod Bay, this was the dominant species and total counts of phytophytoplankton were dominated by it; abundances ranged between 1.2 and 6.5 million cells $L^{-1}$ (average = 4.0 million cells $L^{-1}$). *Asterionellopsis glacialis* was not a dominant at station F01P and was only the second most-abundant species at station F02P (0.85 million cells $L^{-1}$). The abundance dominant in Cape Cod Bay was the diatom *Leptocylindrus minimus* (1.14-2.54 million cells $L^{-1}$), a species that was a subdominant (0.19-1.03 million cells $L^{-1}$) at three other stations (F13P, N04P, and N07P).

Relative to other locations, the reduced abundance of *Asterionellopsis glacialis* in Cape Cod Bay may be a temporal as well as spatial phenomenon. The bloom was dominant at both surface and chlorophyll-maximum depths everywhere except in Cape Cod Bay when stations were sampled on 12-13 October. From repeated sampling in the nearfield, it was noted (Libby *et al.*, 1994) that, at a number of stations, chlorophyll sank from surface waters during the short period between farfield sampling (October 12-14) and nearfield sampling (October 15). Abundance subdominants in October included microflagellates and cryptomonads, and the diatoms *Skeletonema Costatum, Leptocylindrus danicus,* and *Rhizosolenia delicatula.*

Dinoflagellate abundance was proportionately minuscule in October compared to the abundance of *Asterionellopsis glacialis* but, was, nonetheless, substantial compared to dinoflagellate abundance during other periods. With the exception of station F23P in Boston Harbor, abundance of *Ceratium fusus* in 20 μm-screened samples was hundreds to thousands of cells $L^{-1}$. There was also a diverse assemblage of other dinoflagellates sporadically present at lower abundances.

Between 1992 and 1993, the phytoplankton patterns showed major interannual differences. A major bloom of *Phaeocystis pouchetii* in April 1992 was not repeated in April 1993. The major bloom event of the two years was the *Asterionellopsis glacialis* bloom in October 1993. The high abundance of this species completely skewed patterns of total phytoplankton abundance for the two years (Figure 3.4-1).

Similarities between the two years included winter-spring (February and March) blooms of the same suites of chain-forming diatoms, and blooms of large dinoflagellates such as *Ceratium longipes* and *Ceratium tripos* in the summer. Also, microflagellates were generally more abundant than diatoms in the summer of both years with the reverse in winter-spring and fall.

### 3.4.2 Zooplankton in 1993

In 1993, as well as in 1992, the most abundant zooplankters generally at all stations and at all times were copepod nauplii, copepodites, and adults. Although a total of 18 copepod species was recorded over the annual cycle, in most cases, only a handful of species overwhelmingly dominated abundance at a given time. Although copepod nauplii were not categorized to species or stage, they generally represented the species that dominated abundance of copepodites and adults at the same time. Most other abundant taxa were due to pulses of meroplanktonic larvae of benthic invertebrates.

In February, copepod nauplii and copepod adults + copepodites comprised 14.3-53.8% (mean = 33.8%) and 13.7-41.7% (mean = 28.1%), respectively, of total zooplankton abundance. Most abundant copepod species at most stations were *Oithona similis* and *Paracalanus parvus.* Subdominant copepod species present at some stations included *Acartia hudsonica* (stations F01P, F02P, and F23P), *Pseudocalanus newmanii,* and *Microsetella norvegica.* Taxa other than copepod nauplii, copepodites and adults (hereafter referred to as "non-copepods") comprised 5.5-69.3% (mean = 37.8%) of total zooplankton abundance. Most abundant were unidentified polychaete larvae and barnacle nauplii.

Total zooplankton abundance in February ranged from 6.3 to 28.9 thousand animals m$^{-3}$ (mean = 16.3). There was no apparent pattern in terms of groups of stations exhibiting high versus low abundance (Figure 3.4-2).

In March, the zooplankton assemblage was similar to the previous month. Copepod nauplii and copepodites + adults comprised 21.5-55.0% (mean = 37.2%) and 28.2-53.4% (mean = 36.4%), respectively, of total zooplankton abundance. The copepod assemblage was again numerically dominated by *Oithona similis,* with trace contributions by the same other species recorded during the previous month. Non-copepods comprised 15.8-38.2% (mean = 26.5%) of total zooplankton abundance, again dominated by barnacle nauplii and polychaete larvae. However, at all stations except F23P and N10P, the appendicularian *Oikopleura dioica* was present, comprising 0.5-8.5% of total zooplankton abundance.

Total zooplankton abundance in March varied from 3.7 to 13.4 thousand animals m$^{-3}$ (mean = 7.4), with highest values at stations F01P, F02P, and N20P. The only station with values <4,000 m$^{-3}$ was F23P in Boston Harbor.

In April, the contributions of copepod nauplii and copepodites + adults were 19.4-56.6% (mean = 38.6%) and 15.7-36.5% (mean = 26.6%), respectively. Again, *Oithona similis* numerically dominated the copepod assemblage but, unlike previous findings, *Calanus finmarchicus* (primarily copepodites) was present at all stations, comprising 0.5-8.7% (mean = 3.4%) of total zooplankton abundance. Non-copepods comprised 20.9-50.1% of total zooplankton abundance, again primarily barnacle nauplii, polychaete larvae, and *Oikopleura dioica.*

Total zooplankton abundance in April ranged from 5.2 to 30.8 thousand animals $m^{-3}$ (mean = 18.4). Again, there was considerable variability between stations, with minimum values at station F23P in Boston Harbor and values 4-6 times higher at nearfield stations N04P, N07P, N16P, and N20P.

Zooplankton abundance in April 1993 was consistently higher than in April 1992 (Figure 3.4-3). This is most likely due to inimical effects of the April 1992 bloom of the toxic gelatinous algae *Phaeocystis pouchetii.* Blooms of this species have been associated with zooplankton declines in European waters (Turner, 1994).

In June, the contributions of copepod nauplii and adults + copepodites were 17.2-36.1% (mean = 25.2%) and 35.7-72.2% (mean = 56.4%), respectively. Again, the dominant copepod species was *Oithona similis* but other species, such as *Temora longicornis* and *Paracalanus parvus,* were subdominants (generally comprising <10% of total abundance). At station F23P in Boston Harbor, *Acartia tonsa* copepodites + adults comprised 16.2% of total zooplankton abundance. Non-copepods comprised 2.2-47.1% (mean = 18.5%) of total zooplankton abundance. These were mostly bivalve and gastropod veliger larvae, but polychaete larvae and other meroplankters, and the marine cladocerans *Podon polyphemoides* and *Evadne nordmani* were also included. Although barnacle nauplii were still present at some stations, their numbers were greatly diminished compared to earlier in the year.

Total zooplankton abundance in June was 19.1-55.4 thousand animals $m^{-3}$ (mean = 34.0). As noted previously, there was considerable interstation variability in abundance. Highest values were found at stations F23P, N10P, N16P, and N20P. Other stations had abundances that were half or less of that group of stations.

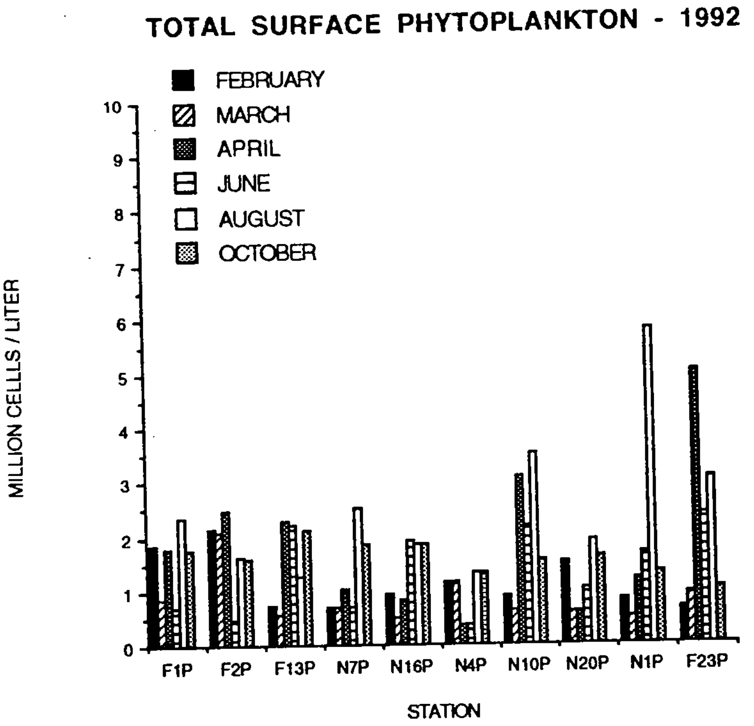
In August, the contribution of copepod nauplii (9.8-20.7% of total abundance, mean = 15.8%) was reduced compared to previous months, and the contribution of copepod adults + copepodites (35.0-82.8% of total abundance, mean = 69.1%) was greatly increased. As before, the copepod assemblage was dominated by *Oithona similis*, with lesser contributions from *Paracalanus parvus, Temora longicornis,* and numerous other species. At station F23P in Boston Harbor, *Acartia tonsa* (13.8% of total abundance) was a dominant. Non-copepods comprised only 2.7-45.3% of total abundance (mean = 15.1%). These were mostly bivalve and gastropod veligers, other meroplankters, and marine cladocerans; at some stations, *Oikopleura dioica* was recorded.

Total zooplankton abundance in August (43.5-80.4 thousand animals $m^{-3}$, mean = 63.3) was, at most stations, the highest of the year (Figure 3.4-2) and, with one exception, levels of abundance were more uniformly high than previously recorded (>50,000 animals $m^{-3}$).

In October, the proportions of total zooplankton abundance due to copepod nauplii and copepodites + adults were 7.8-47.3% (mean = 25.7%) and 17.6-58.5% (mean = 34.6%), respectively. Again, the copepod assemblage was dominated by *Oithona similis* and *Paracalanus parvus,* with lesser contributions by other species recorded in the summer. Again, *Acartia tonsa* dominated at station F23P (18% of total zooplankton abundance), and the copepodites and adults of *Centropages typicus* and *Centropages hamatus* were subdominants at many stations. Non-copepods comprised 21.3-69.6% (mean = 39.7%) of total abundance. Mostly these were bivalve veligers with lesser contributions by polychaete larvae, other meroplankters, marine cladocerans and, at some stations, *Oikopleura dioica.*

Total zooplankton abundance in October was highly variable between stations, with a range of 16.6 to 142.9 thousand animals $m^{-3}$ (mean = 49.9). At three stations (F01P, F02P, and N16P), October abundances were the highest of the year. At all stations except one, abundances were <70,000 animals $m^{-3}$, but at station N16P, the abundance was more than twice that. This abundance peak was mostly due to much higher numbers of bivalve veligers (>93,000 $m^{-3}$) at station N16P than at other stations (1,380-40,006 $m^{-3}$, mean = 13,383).

In 1993, as in the previous year, there was a predictable seasonal cycle characterized by low zooplankton abundance in winter and spring, increases through June to maximum August values or, in some cases in 1993, October values. The zooplankton assemblage was generally numerically dominated by copepod nauplii, copepodites and copepod adults; of these, most were the small species *Oithona similis* and *Paracalanus parvus.* However, various meroplankters were sporadically abundant, occasionally outnumbering the copepods. Included were barnacle nauplii in winter, bivalve and gastropod veligers in summer and fall, and polychaete larvae throughout most of the year. Finally, there was considerable interannual variability in abundance of taxa as well as total zooplankton (Figure 3.4-2). In some cases, this variability appeared to be related to phytoplankton events, such as the April 1992 *Phaeocystis pouchetii* bloom. In other cases, the zooplankton variability was related to non-planktonic parameters, such as spawning of benthic invertebrates which produced pulses of meroplanktonic larvae.



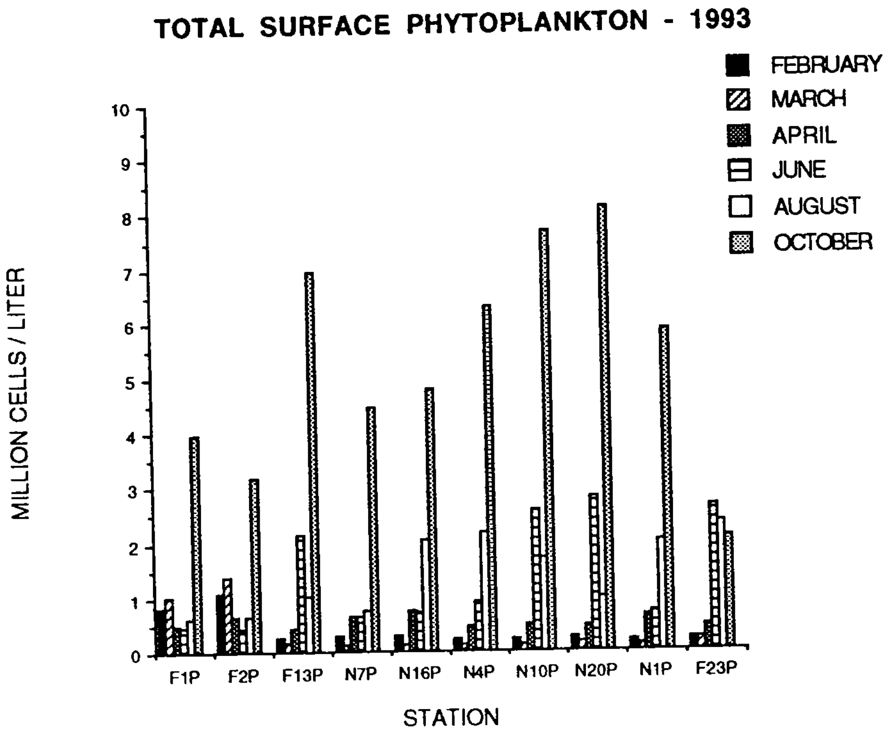
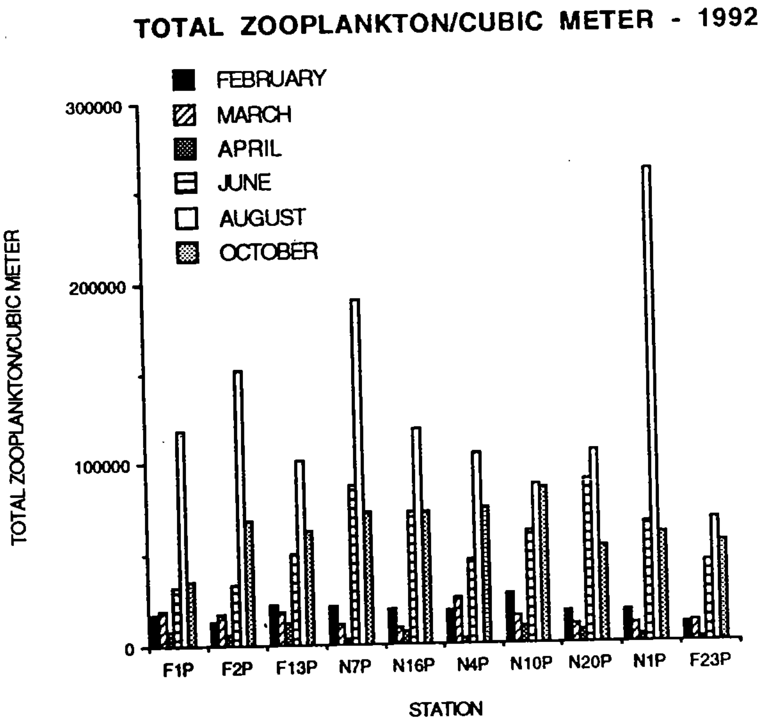


Figure 3.4-1 Total phytoplankton counts at Massachusetts and Cape Cod Bay sampling stations by surveys: comparison of 1993 with 1992.



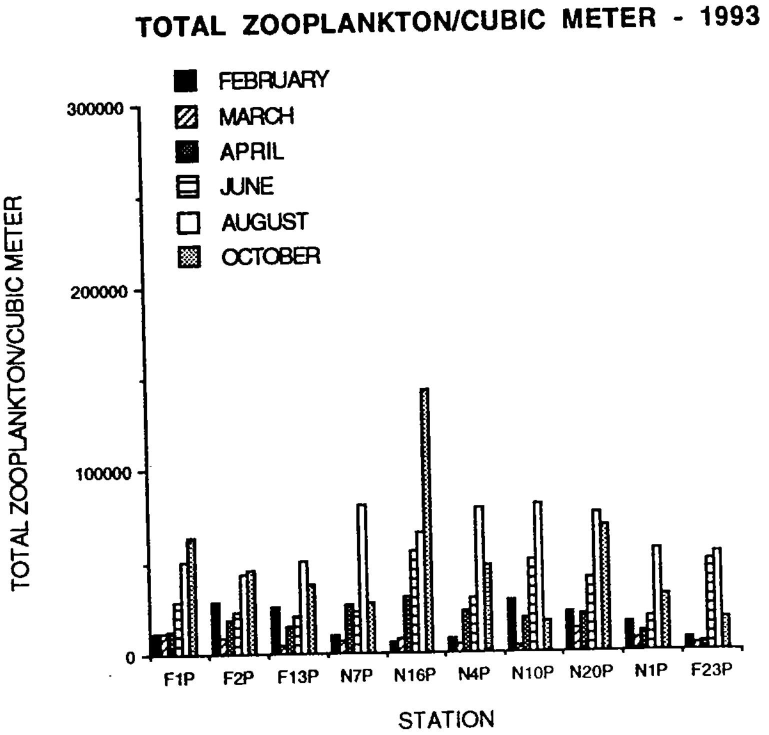


Figure 3.4-2 Total zooplankton counts at Massachusetts and Cape Cod Bay sampling stations by surveys: comparison of 1993 with 1992.

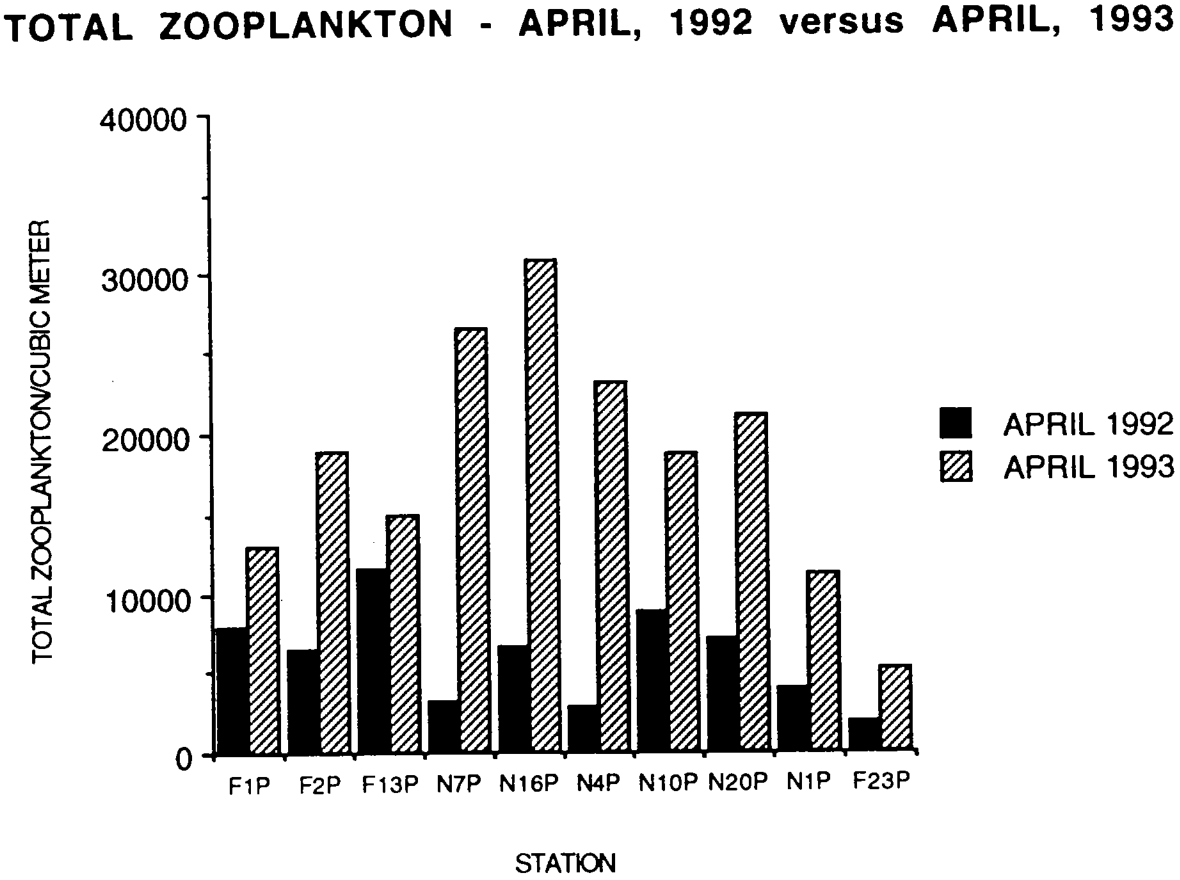


Figure 3.4-3 Total zooplankton counts at Massachusetts and Cape Cod Bay sampling stations in April: comparison of 1993 with 1992. A bloom of *Phaeocystis pouchetii* was widespread in the Bays during sampling in 1992.

## 3.5 $^{14}$C PRIMARY PRODUCTION

In 1993, primary production was determined using $^{14}$C standard oceanographic methods (e.g., Parsons *et al.*, 1984): shipboard incubations and a range of irradiance levels to develop P-I curves for samples of water from Massachusetts and Cape Cod Bays (Albro *et al.*, 1993). Details of analytical treatment of the data and calculation of integrated water column primary production (g C $m^{-2}$ $d^{-1}$) are provided in references cited in Section 2. Except for switching from an oxygen-based to $^{14}$C-based measurement, the incubations made in 1993 followed the same procedures (e.g., bottle sizes, incubation times, irradiance levels) used in 1992.

Although in 1993 the analytical treatment of the data (using the $^{14}$C technique) was similar to that in 1992 (Kelly *et al.*, 1993a), it differed in three details: (1) a respiration term was not directly included in the P-I modeling as it had been for oxygen; rather, data for light bottles were first corrected for uptake of $^{14}$C in dark bottles prior to P-I modeling; (2) the series of P-I models, routinely used to fit 1992 data, was modified for surveys beginning in April 1993; this modification was adopted to provide equivalence between photoinhibition and non-photoinhibition models when the photoinhibition term was zero (Kelly *et al.*, 1994b); and (3) for oxygen-based results in 1992, the depth integration for production was performed to the shallower of the following: (a) the depth at which net respiration (oxygen uptake rather than production, due to low light) was indicated by the modeling or (b) the bottom of the hydrocast profile if net respiration to the greatest depth sampled was not indicated. In contrast, the 1993 incubations with $^{14}$C did not provide an indication of the depth below which net respiration occurred. Therefore, we chose the depth of the 0.5% light level, as indicated by the irradiance profile during the hydrocast (cf. Kelly *et al.*, 1994b), as the standard depth to which all integrations were performed. The contribution to integrated production from the deepest part of the profile (e.g., low light levels, 1% or less) generally was not substantial (<10%).

While not assessed, the analytical differences listed above may have a smaller influence on primary production results than the fundamental switch in methodology to $^{14}$C from oxygen incubations. With either methodology, the uncertainty inherent in rate calculations is high.

Moreover, there are frequently substantial differences in rates calculated from a sample collected from the surface vs. a sample collected from the depth of a subsurface chlorophyll maximum at a given station (Kelly, 1993b). For this and other reasons, the analytical uncertainties in the calculations deserve further examination, including the recommendations of Kelly *et al.* (1993). Because of the fundamental methodological switch, 1993 production results are not exactly comparable to 1992 results (Kelly *et al.*, 1993a; cf. Doering *et al.*, 1993).

In 1993, 10 stations were normally occupied for production measurements during each of the six farfield surveys. These stations included F23P and F13P in the coastal region, all six "P" stations in the nearfield region, and stations F01P and F02P in Cape Cod Bay. In February 1993, production calculations were not made for station N10P due to a lack of irradiance profile data. Integrated $^{14}C$ primary production was thus calculated for 118 incubations — 59 for surface water and 59 for water collected at the subsurface chlorophyll maximum. The summary of rates compiled here is drawn directly from tables of each survey presented in Kelly *et al.*,1994a,b,c,d and Libby *et al.*, 1994.

In the winter (February and March), most P-I incubations (31 of 38) were fit by a model with a photoinhibition term (Platt *et al.*, 1980). The photoinhibition term for nearly all of these incubations was not large and, therefore, not highly influential in the resultant rate, especially because incident irradiance during winter is relatively low. For surveys conducted in April, June, August, and October, only 9 of 80 P-I data sets were fit using the Platt *et al.* (1980) model; most of the data were fit by a negative exponential model (without photoinhibition, Webb *et al.*, 1974). From these data, photoinhibition generally did not strongly influence integrated production rates. It must be mentioned that incubation procedures did not provide irradiance in the UV range; under natural conditions, additional photoinhibition from UV would be expected at higher irradiance levels.

As suggested above, rates calculated for the near-surface or subsurface chlorophyll maximum ("chl-max") samples collected from a given station varied. However, when the complete 1993 data set is examined (Figure 3.5-1), a general pattern was, nonetheless, evident. A linear regression of paired surface versus subsurface production rates was significant ($R^2 = 0.695$, N=59) and is described by the relationship $Y = 0.82\ (\pm 0.14)\ X + 0.54\ (\pm 0.39)$, where rates are expressed as g C $m^{-2}$ $d^{-1}$. The parenthetical indicate the 95% confidence interval for the slope and intercept. The slope of the least-squares linear regression suggests that the subsurface water incubation yielded a rate that was generally about 18% lower than the surface water incubation, although the 95% confidence interval on the slope indicates that subsurface rates may be lower by a range of 4 to 33%. A functional regression, which more appropriately allows for the error in both $X$ and $Y$ (Ricker, 1973), yielded the relationship $Y = 0.98\ X - 0.11$. The functional regression slope of $\approx 1$ indicates that, on average, the two estimates yield approximately equivalent rates. There are cases where the two estimates differ greatly (Figure 3.5-1), but the general scatter around the main trend suggests that it is reasonable to use the two incubations as replicate estimates for a station. Accordingly, the station average is used to present time and space trends for production in 1993.

Average production rates for all stations (N=59) are shown in Figure 3.5-2. For each survey, the range within a region is indicated by connecting vertical lines. The pattern for regions is different. Cape Cod Bay production rates were high early in the year, fell slightly to lower levels between April through August, and increased slightly in October. The rates at coastal and nearfield stations in Massachusetts Bay were very low until April, and tended to be high in April and thereafter. In the nearfield region, October rates, which were uniformly very high and were associated with high average photic layer chlorophyll (Figure 3.5-3), exceeded rates at the coastal stations. In general, there was a significant correlation ($R^2 = 0.55$, N=59) between production and chlorophyll, within and across regions (Figure 3.5-3). Thus, the seasonal differences between Cape Cod Bay, with high production in early winter-spring, and Massachusetts Bay, with a late winter-spring rise in production and a very high fall peak in production, are consistent and coincident with observed differences in the seasonal patterns of chlorophyll concentration at sampling stations in the two Bays.

Based on measurements made throughout 1993, the average integrated $^{14}C$ production was 1.95, 2.38, and 1.89 gC $m^{-2}$ $d^{-1}$, respectively for the Cape Cod Bay (N=12), nearfield (N=35), and coastal (N=12) regions. The grand average for measurements in 1993 was 2.2 gC $m^{-2}$ $d^{-1}$.

Although not strictly comparable (see above) to 1993, the calculated 1992 average production rate (converted from oxygen) was lower — 1.25 gC $m^{-2}$ $d^{-1}$ (Kelly *et al.*, 1993). The regional patterns suggested by the 1993 data appear to differ, with respect to both time and space, from those suggested by the 1992 data (see Kelly *et al.*, 1993). In contrast to 1993, for example, the highest regional average rates (1.91 gC $m^{-2}$ $d^{-1}$) in 1992 were measured in Cape Cod Bay. The lowest average rates were measured at the coastal stations during both years, but the 1992 average rate (0.96 gC $m^{-2}$ $d^{-1}$) was about one-half of the average 1993 rate. Moreover, the 1992 peak daily rates (5-10 gC $m^{-2}$ $d^{-1}$) were measured in Cape Cod Bay in April during an extensive Baywide *Phaeocystis* bloom and 1992 generally lacked the fall seasonal peak observed in 1993.

The range in integrated daily $^{14}C$ rates for the nearfield area during 1993 (e.g., Figure 3.5-2) was 0-6.8 gC $m^{-2}$ $d^{-1}$ (cf. Kelly, 1993a, Figure 5-1a), essentially the same as recorded in the recent history of measurements (1973-1992). Additionally, the 1993 rates were, on average, similar to those recorded by Smayda in 1987/88 using the $^{14}C$ technique; based on 25 measurements (MWRA, 1988, 1990), Smayda obtained an average rate of 1.98 gC $m^{-2}$ $d^{-1}$ . Compared to historical seasonal patterns, however, there is no record of a high fall (September-October) peak production that is comparable to measurements obtained in the nearfield in 1993 (cf. Kelly, 1993a).

*A final caveat.* Although interesting, it is important to note that rate comparisons, such as those discussed above, suffer from differences in the details of incubations, modeling, and calculations, even if the same fundamental technique was used (cf. Kelly *et al.*, 1993). When making such comparisons, it is particularly important to recognize that large differences can be a function of the exact date that a measurement was made, with respect to incident irradiance as determined by weather and sky conditions. The weather on the days that production measurements are made can influence the apparent seasonal pattern. Within the 1993 and 1992

MWRA data sets, incident irradiance has been standardized across stations by use of a survey average value. As a result, focusing on a patterns between stations and regions may be more valid than attempting to describe broad seasonal patterns based on data from only a few days. As suggested by several researchers and as explored by Kelly (1993b), a simple model for extrapolation of production — based on more frequent measurements of irradiance, extinction rates, and chlorophyll in the photic zone — may be the best tool for projecting seasonal and annual patterns and rates of primary production.

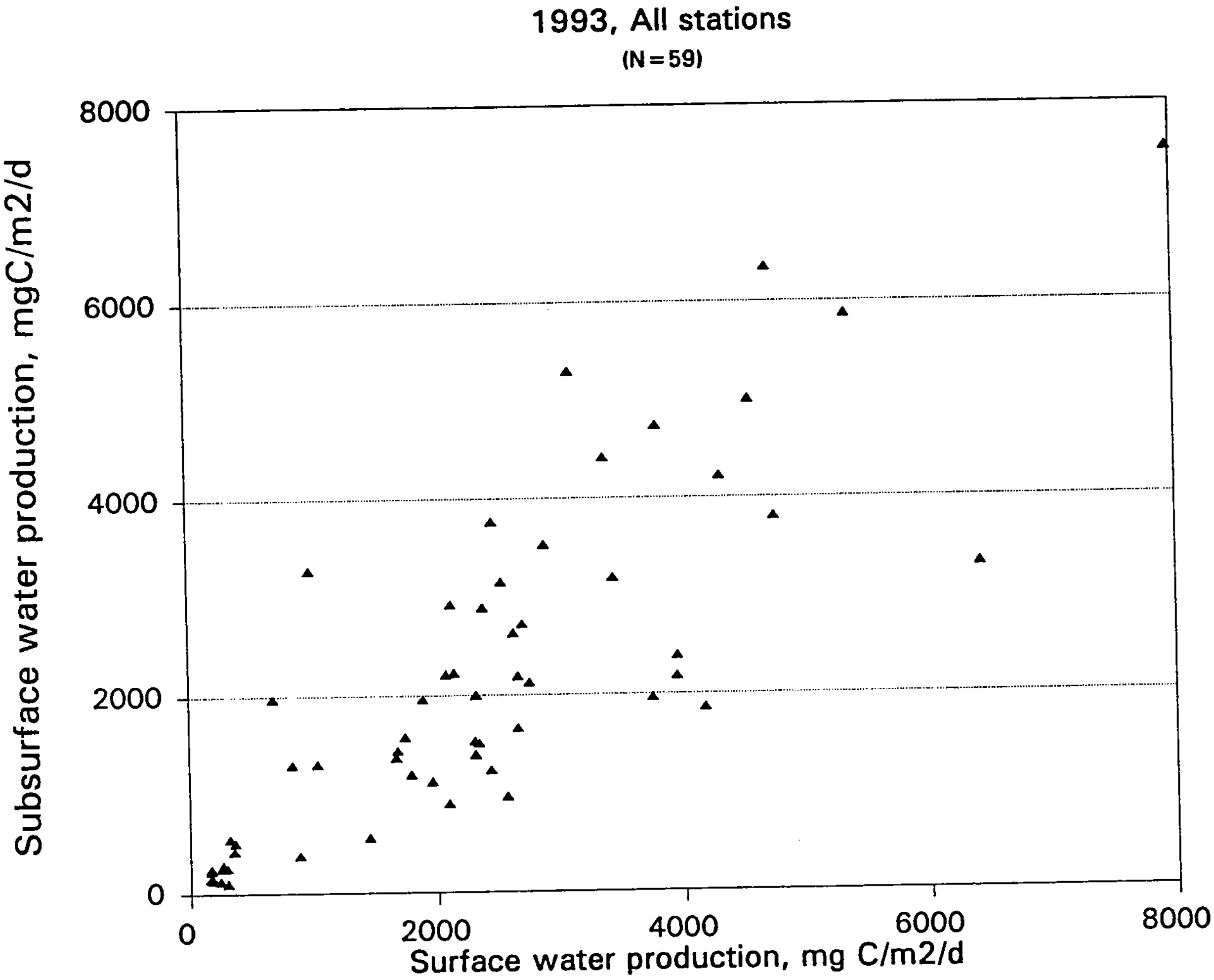


Figure 3.5-1 $^{14}C$ production rates: comparison of surface water incubation rates and subsurface chlorophyll maximum water incubation rates at each station occupied during 1993.

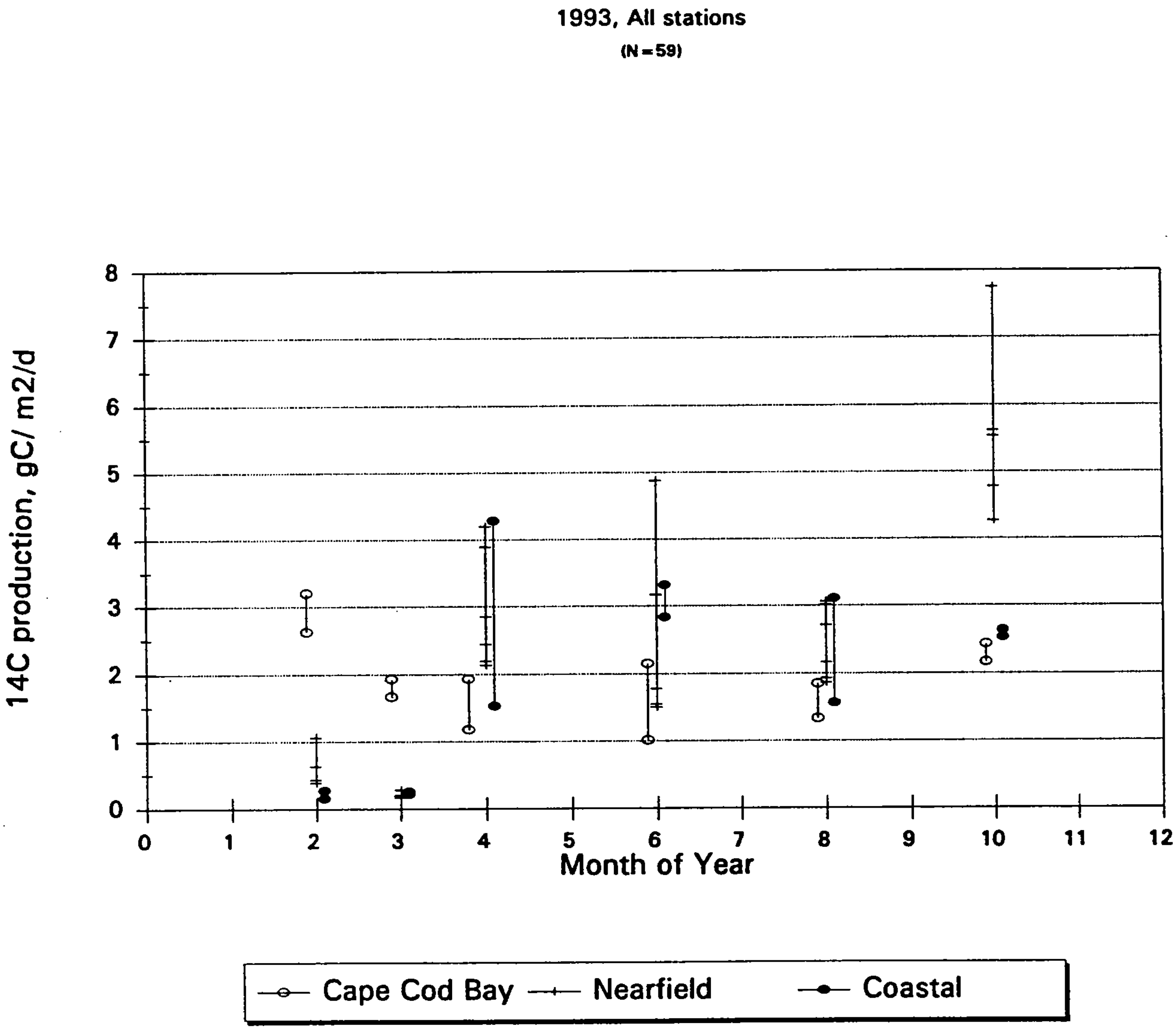


Figure 3.5-2 $^{14}$C production rates through the annual cycle for sampling regions in Massachusetts and Cape Cod Bays.

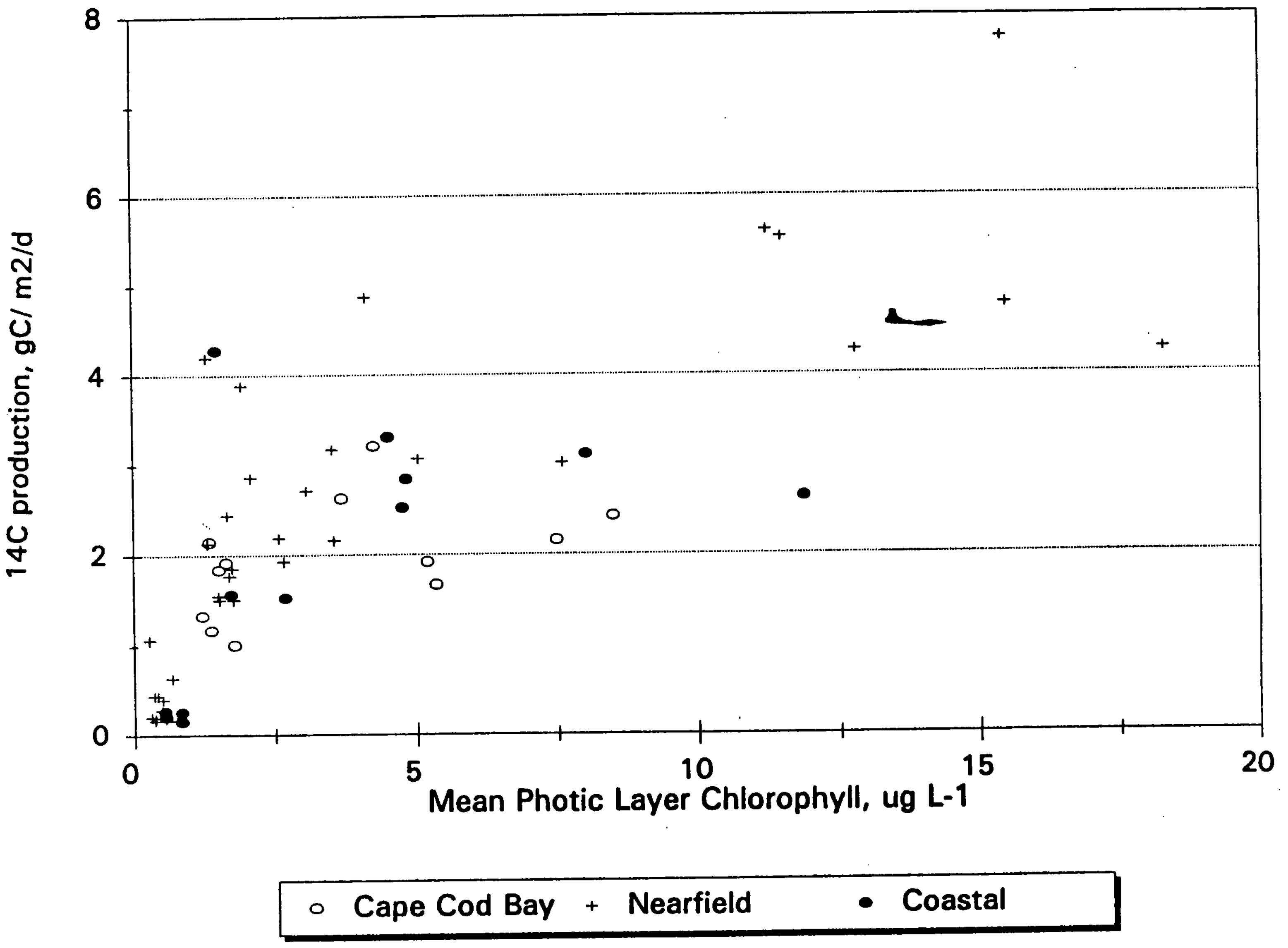


Figure 3.5-3 $^{14}$C production rates as related to photic layer chlorophyll concentrations for all stations occupied during 1993.

# 4.0 NEARFIELD SURVEY RESULTS

The nearfield region was sampled on 16 surveys during 1993; the temporal distribution is presented in Section 2. In the following descriptions and analyses, unless otherwise stated, data are presented for all nearfield stations that were sampled. Included are data from the six "P" stations (distributed at the corners and near the center of the nearfield as shown in Figure 2.1-1) that were sampled on the farfield portion of the six farfield surveys (discussed in Section 3) and that were resampled on the nearfield survey day. The nearfield survey sampling, in addition to being more frequent, was more spatially intense and included a total of 21 stations. The data set examined here included a total of 1850 Niskin bottle sampling events, for which there were no missing *in-situ* sensor data and only 4 ($PO_4$, $SiO_4$, $NO_3$) or 5 ($NH_4$, and thus DIN) missing results for nutrients.

By design, the nearfield and farfield sampling schemes explicitly emphasize different space and time scales of observation. The focus in this section is similar to that in Section 3; parameter frequency distributions and annual trends, as well as select spatial patterns, for the entire nearfield data set are included. The entire nearfield data set, in contrast to the limited set included in the farfield results, implicitly provides perspective on the annual cycle of 1993 from a different scale of observation.

## 4.1 NUTRIENTS

### 4.1.1 Nutrient Frequency Distributions

***Dissolved Inorganic Nitrogen.*** Figures 4.1-1 and 4.1-2 give the frequency distribution plots for DIN and $NH_4$, respectively. In more than 50% of the measurements, DIN concentrations were $<3.6$ $\mu$M and $NH_4$ concentrations were $<0.6$ $\mu$M. In general, the frequencies tailed off exponentially to higher concentration classes and few (about 5% or less) of the concentrations were $>10$ $\mu$M for DIN or $>3$ $\mu$M for $NH_4$. The average DIN concentration was 3.44 $\mu$M (standard deviation = 3.29) and the maximum measured concentration was 22.4 $\mu$M. These results compare closely to those based on six farfield surveys (Section 3), which in comparison had a mean of 3.54 $\mu$M and a maximum of 13.2 $\mu$M. The average $NH_4$ concentration was 0.97 $\mu$M (standard deviation = 1.21) and the maximum measured concentration was 12.4 $\mu$M.

DIN Spatial Pattern. Figure 4.1-3 displays the spatial distribution of DIN using annual means calculated from surface water concentrations measured on all 16 surveys in 1993. The data demonstrate a decreasing DIN concentration gradient seaward, with concentrations at the southwest corner more than double those on the eastern side of the nearfield. Unlike Figure 3.1-3, which used data from the 6 farfield surveys, all 21 nearfield stations were included in Figure 4.1-3. The spatial pattern is, however, remarkably similar in the two figures.

***Phosphate.*** Figure 4.1-4 demonstrates that most $PO_4$ concentrations were generally low. The frequency distribution is similar to that shown for farfield samples. The mean $PO_4$ concentration was 0.50 $\mu$M (standard deviation = 0.30) and the maximum concentration that was measured was 3.37 $\mu$M. These results are similar to those from the farfield sampling, with a mean of 0.45 $\mu$M and a maximum concentration of 2.23 $\mu$M.

***Silicate.*** Figure 4.1-5 illustrates the bimodal frequency distribution for $SiO_4$ concentrations that has been typically observed for most regions of the Bay for annual summaries of 1992 and 1993. The first mode is at low concentration and a second mode is at 8-10 $\mu$M. The mean $SiO_4$ concentration was 4.86 $\mu$M (standard deviation = 3.52) and the maximum concentration was 17.74 $\mu$M. These results are similar to those from the farfield sampling, with a mean of 5.21 $\mu$M and a maximum concentration of 12.61 $\mu$M.

In summary, the nearfield (Section 4) and farfield (Section 3) survey summaries provide generally similar overall mean estimates. However, the maxima, in the case of all nutrients (DIN, $PO_4$, $SiO_4$), were higher for the 16-survey data set available for the nearfield.

### 4.1.2 Annual Cycle of Nutrients

***Nitrogen Forms.*** Figure 4.1-6 provides a detailed description of DIN in surface and bottom waters throughout the year. The broad seasonal pattern is strikingly similar to that shown in Figure 3.1-7. The surface and bottom water DIN concentrations were similar through March. They diverged as the water column stratified in April (≈day 95), not to become similar again until the November survey, when the DIN concentrations in surface waters were again uniformly >2 $\mu$M. The November and December surveys confirmed a return, throughout the water column, to higher average DIN concentrations that were similar to, but slightly higher, than the pre-bloom conditions detected early in 1993. The frequent sampling also confirmed that, between April and June, bottom water DIN concentrations remained higher than in the surface waters. Moreover, from June to August, the nearfield surveys confirmed a progressive increase in the average bottom water DIN concentrations in the nearfield. For each survey during the stratified period, the variance in surface water DIN concentrations was very low; uniformly low concentrations were observed across the field and a summer shore-to-sea DIN gradient was absent. In contrast, the variation in bottom water DIN concentrations across stations during each survey was considerable. This variance, in part, reflects differences in depth across the nearfield, with higher DIN concentrations usually found at greater depths.

1992 vs. 1993 Annual Cycles of DIN. Figure 4.1-7 shows the 1992 annual cycle for DIN concentrations in surface and bottom water, for comparison to results for 1993 (Figure 4.1-6). Except for one extra survey conducted in 1993 (late September (≈day 270), the timing of surveys in 1992 and 1993 was nearly identical. In both years, the overall DIN concentrations, the differences between surface and bottom water, and the temporal patterns were very similar, especially from July onward.

Also for both years, the highest bottom water concentrations of DIN were found in October. Peak water column DIN concentrations were found during well-mixed conditions in winter (December to February). Winter peak values were several $\mu$M higher in 1993 than in 1992. For both 1992 and 1993, average DIN concentrations for a given survey were slightly higher in

December than in the preceding February, and the average in December 1992 was about 1 $\mu$M higher than February 1993. The range of concentrations between December and February surveys was generally overlapping, and the data suggest that some, although minor, removal of DIN from the water column may have occurred between December and February, consistent with the observation of low and fairly stable chlorophyll concentrations in early winter-spring.

Between 1992 and 1993, the period from March to June differed slightly. For example, in 1992, the decrease in DIN concentration began by March and uniformly depleted surface and bottom waters. In 1992, differences in DIN concentrations between surface and bottom waters were not apparent until June, compared to April in 1993. Interannual variability during the winter-spring period in 1993 has been extensively discussed in Kelly *et al.* (1994a,b).

TN concentrations at six nearfield stations (Figure 4.1-8) were more constant and a less pronounced seasonal cycle was observed than for DIN. However, there was a slight decrease in TN concentrations over the year and pre-bloom (February and March) concentrations were, on average, higher ($\approx$18-20 $\mu$M) than in the summer-fall ($\approx$11-13 $\mu$M in August and October). This difference primarily reflects the seasonal drop of DIN in surface waters (see Section 3). There was no consistent difference in TN concentration between the two sampling depths (generally 2-25 m) at any time.

***Phosphate and Silicate.*** The seasonal cycle of $PO_4$ and $SiO_4$ in nearfield surface and bottom waters generally showed the same annual pattern that was observed for DIN (Figure 4.1-9); some minor variations were noted. Unlike $PO_4$ and DIN, $SiO_4$ concentrations in surface and bottom waters did not appear to diverge until May ($\approx$day 140). In contrast to DIN, both $PO_4$ and $SiO_4$ concentrations in surface water during the spring never reached concentrations near detection limits and, thus, were never fully depleted. Moreover, silicate concentrations in bottom waters were more constant during the stratified period and did not exhibit the strong progressive increase that was observed for the other nutrients. Like DIN, water column concentrations of both $PO_4$ and $SiO_4$ were higher, on average, in December than in February.

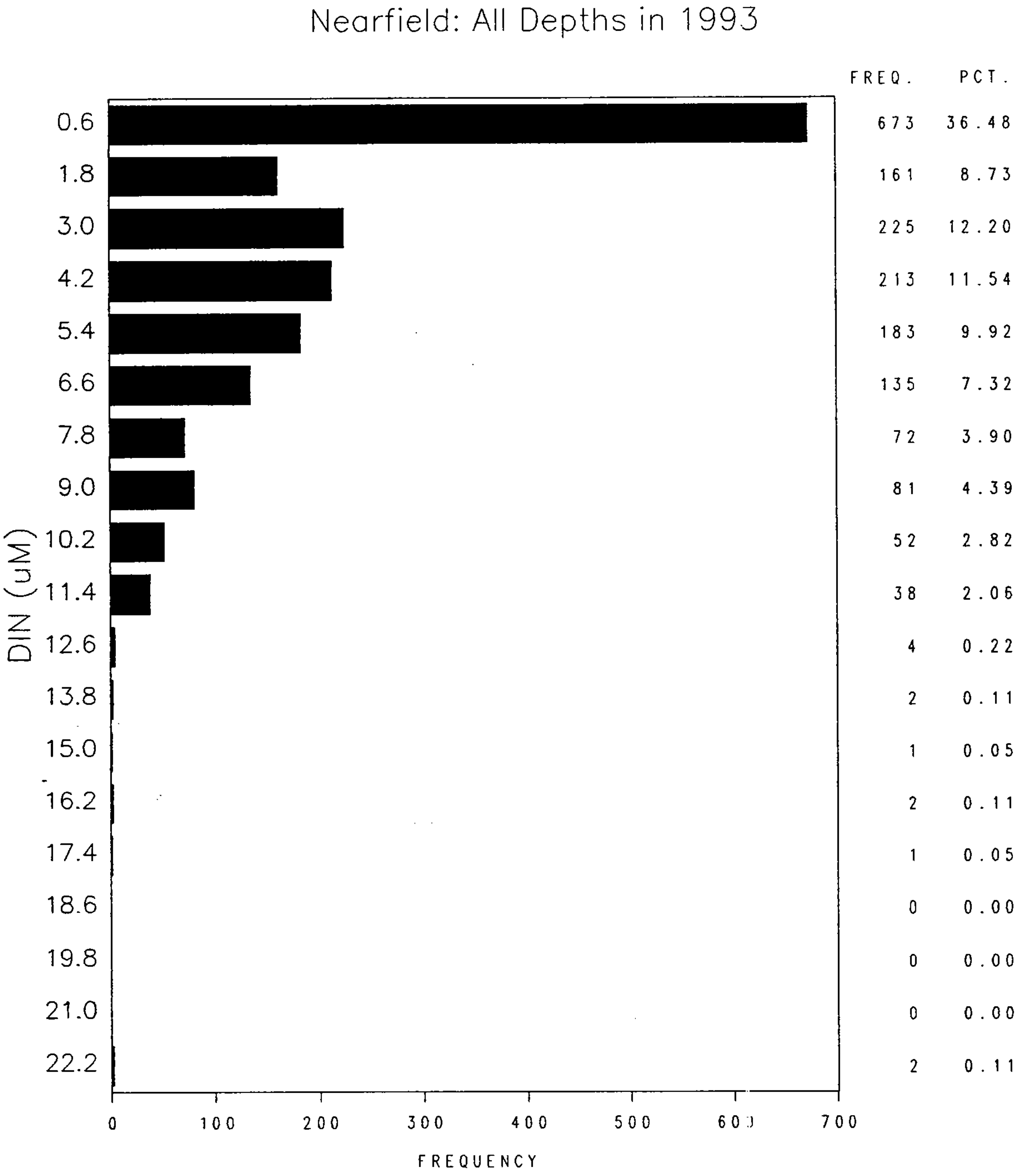


Figure 4.1-1 Frequency distribution of DIN concentrations for all nearfield samples in 1993.

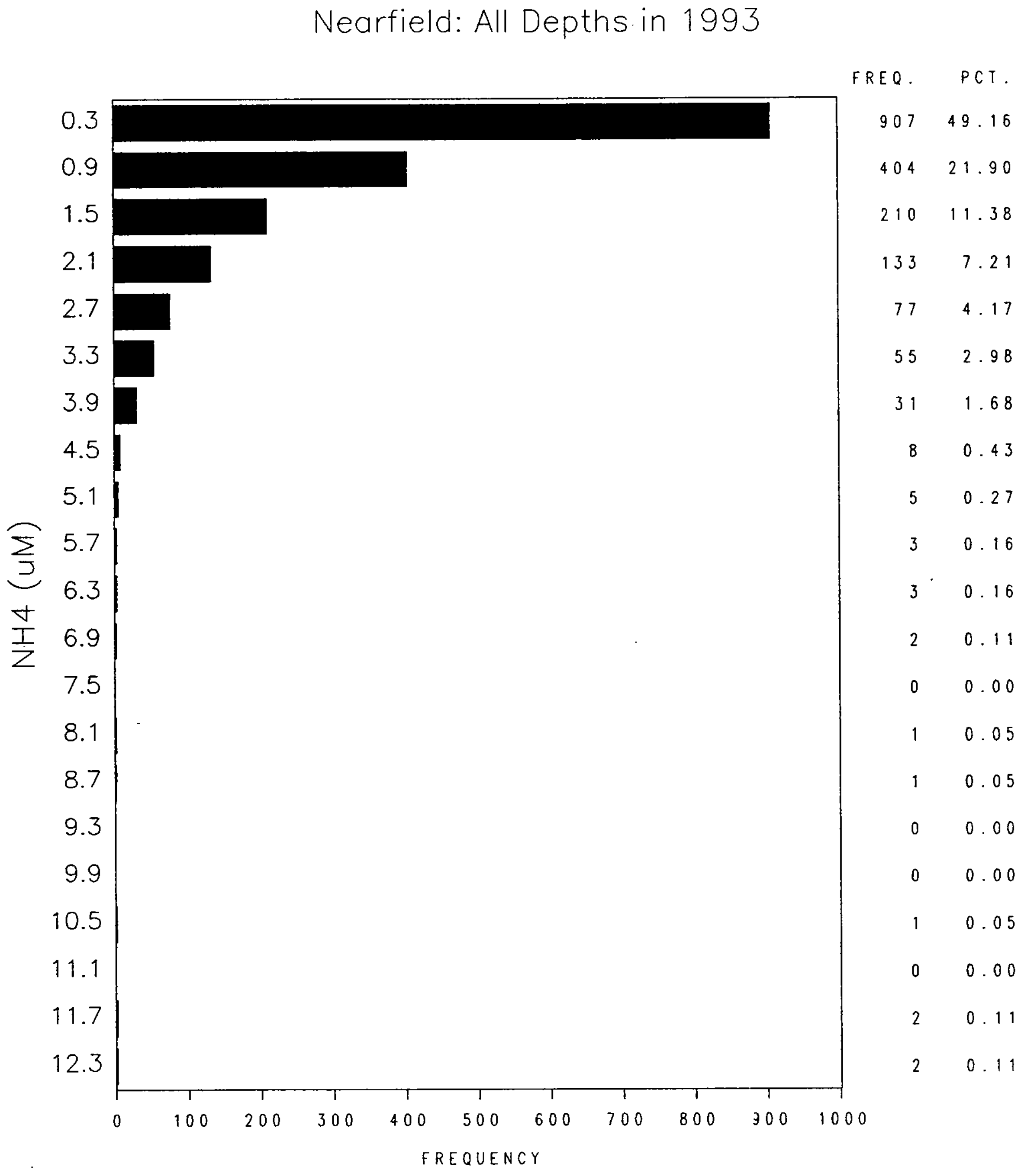


Figure 4.1-2 Frequency distribution of $NH_4$ concentrations for all nearfield samples in 1993.

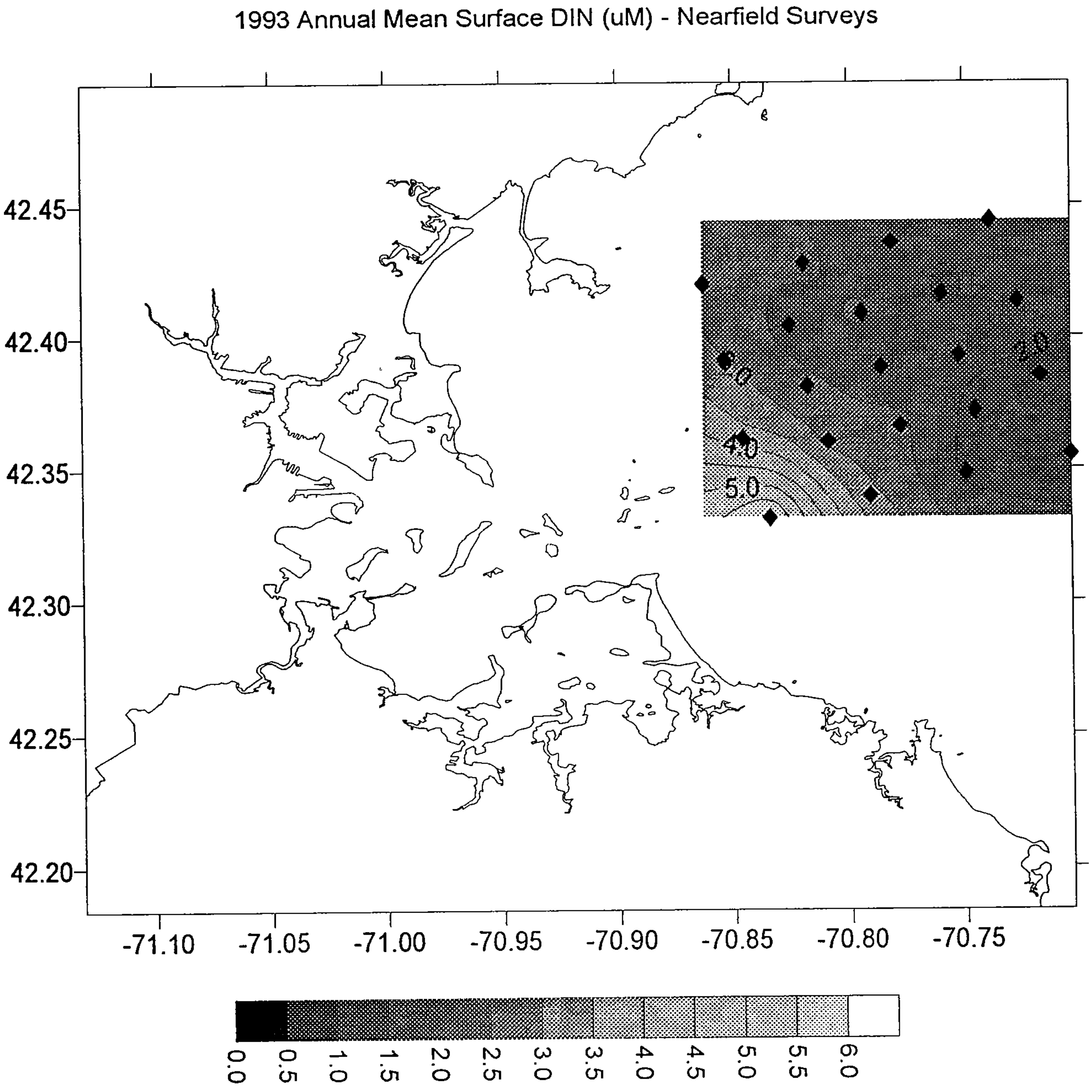


Figure 4.1-3 Spatial pattern of nutrient concentrations in the nearfield. Data are surface-water means from 16 nearfield surveys.

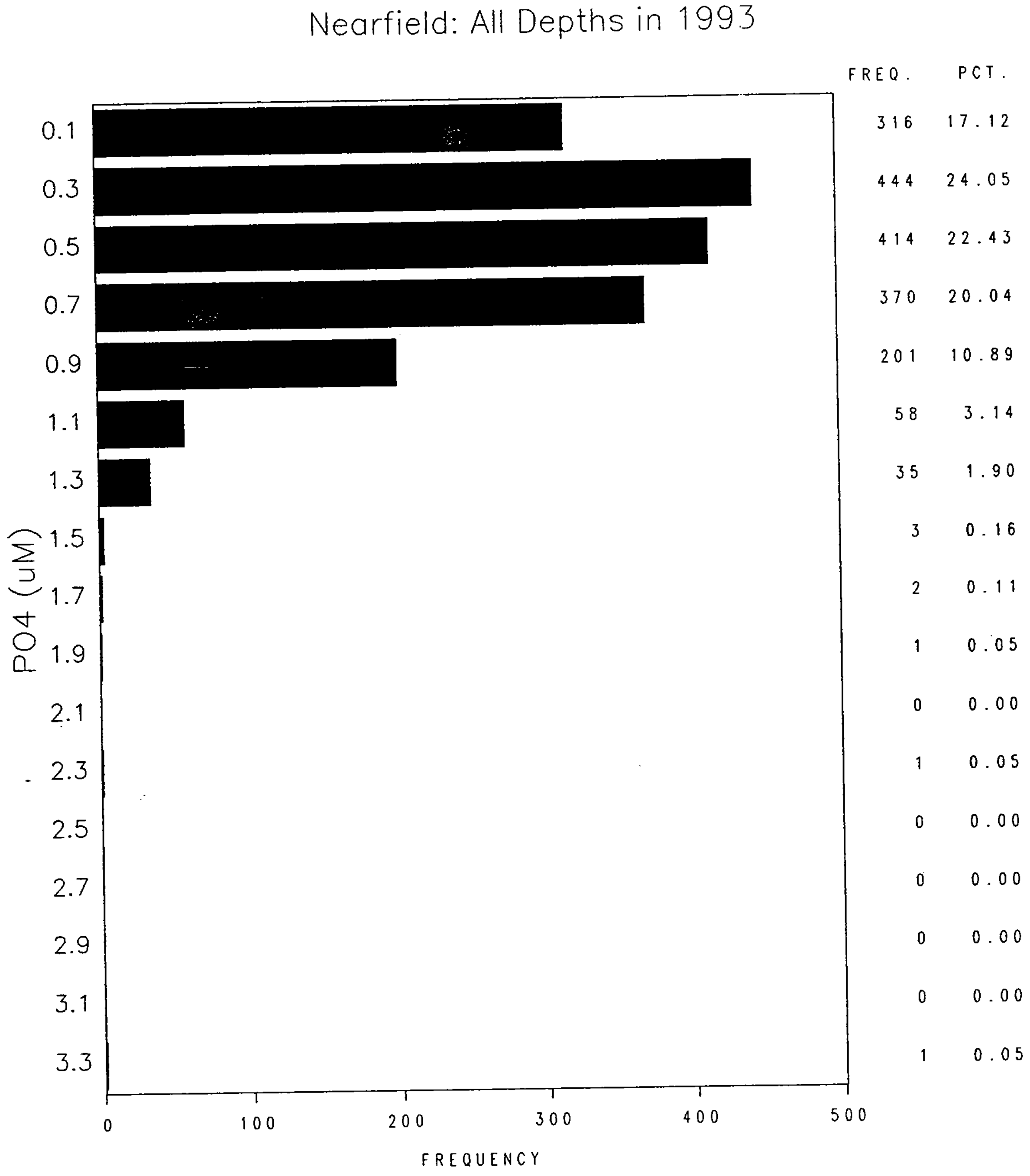
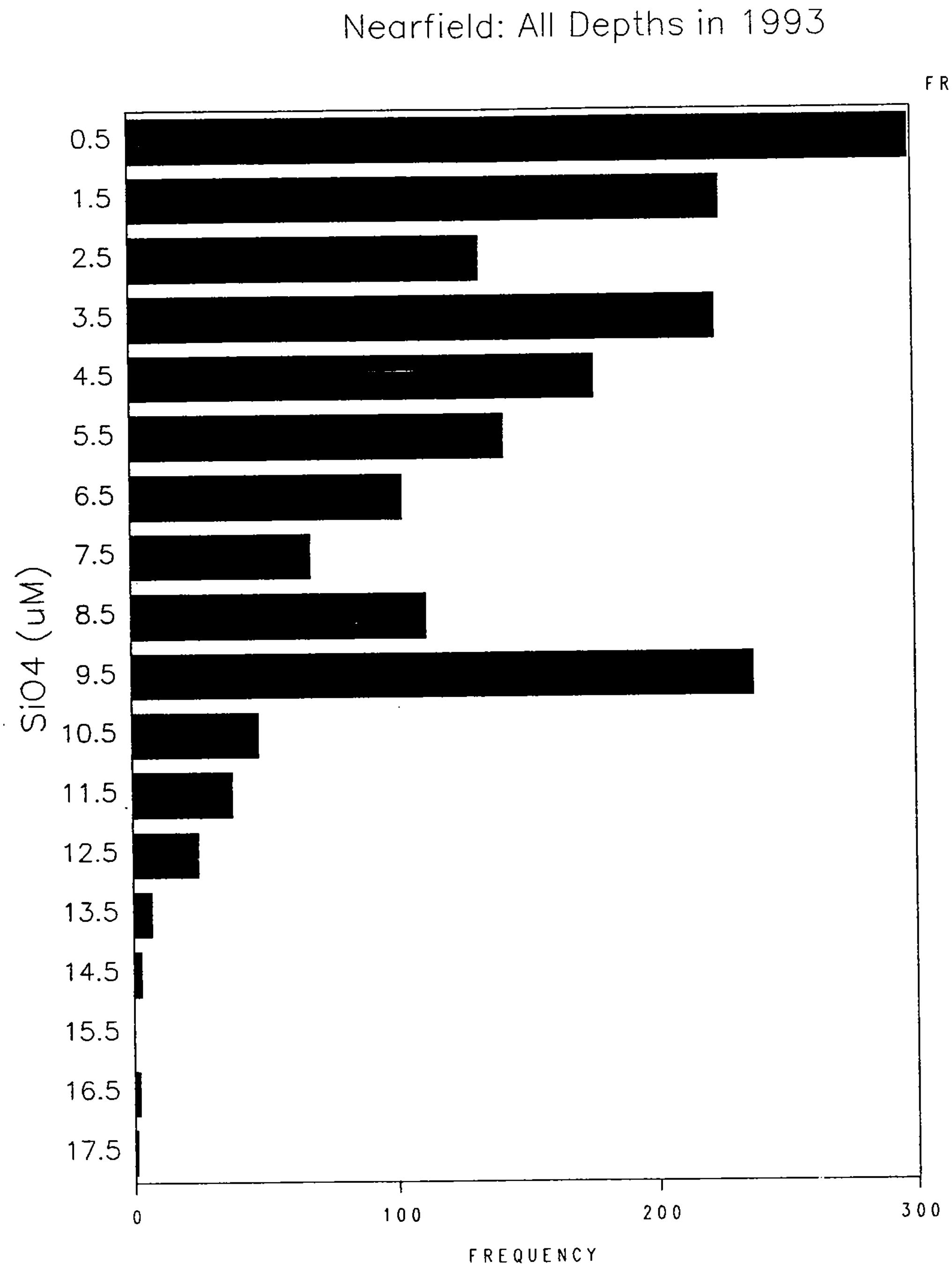


Figure 4.1-4 Frequency distribution of $PO_4$ concentrations for all nearfield samples in 1993.



| SiO4 (uM) | FREQ. | PCT. |
|---|---|---|
| 0.5 | 299 | 16.20 |
| 1.5 | 226 | 12.24 |
| 2.5 | 133 | 7.20 |
| 3.5 | 224 | 12.13 |
| 4.5 | 177 | 9.59 |
| 5.5 | 142 | 7.69 |
| 6.5 | 103 | 5.58 |
| 7.5 | 68 | 3.68 |
| 8.5 | 112 | 6.07 |
| 9.5 | 238 | 12.89 |
| 10.5 | 48 | 2.60 |
| 11.5 | 38 | 2.06 |
| 12.5 | 25 | 1.35 |
| 13.5 | 7 | 0.38 |
| 14.5 | 3 | 0.16 |
| 15.5 | 0 | 0.00 |
| 16.5 | 2 | 0.11 |
| 17.5 | 1 | 0.05 |

Figure 4.1-5 Frequency distribution of $SiO_4$ concentrations for all nearfield samples in 1993.

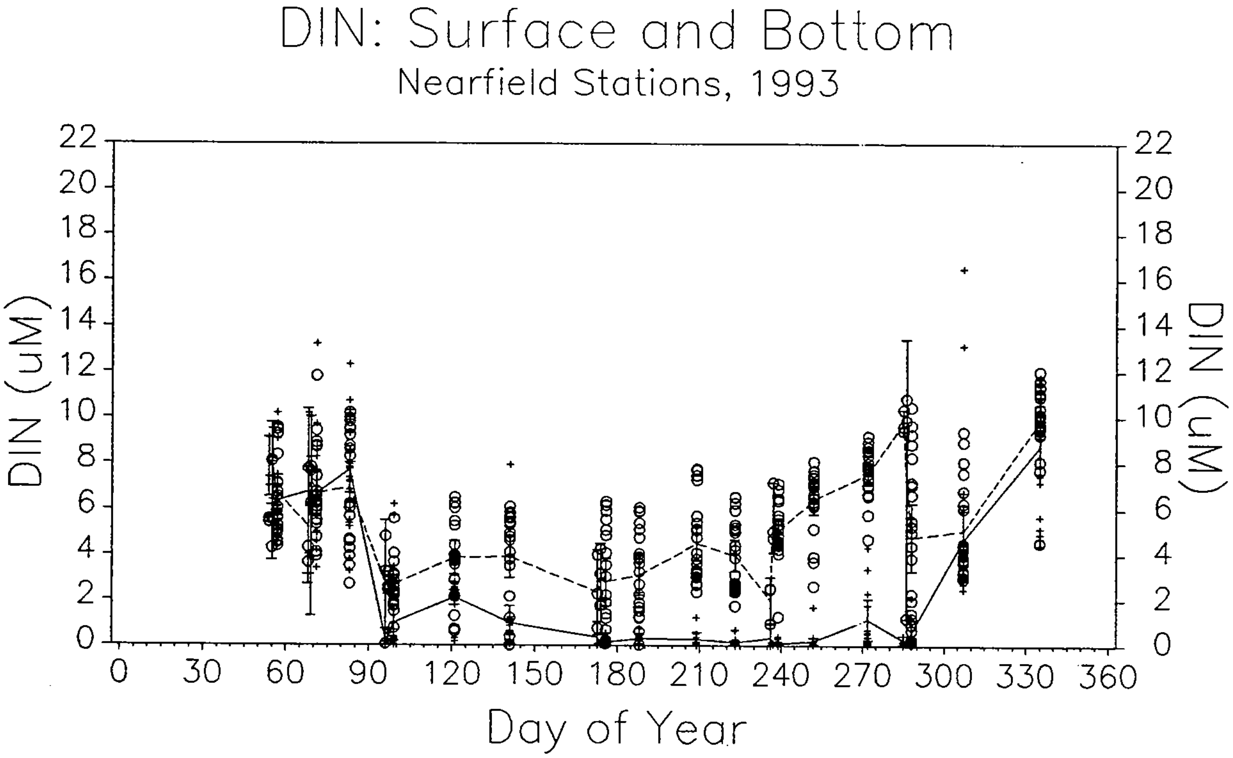


Figure 4.1-6 DIN concentrations in nearfield surface and bottom waters through the annual cycle in 1993. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

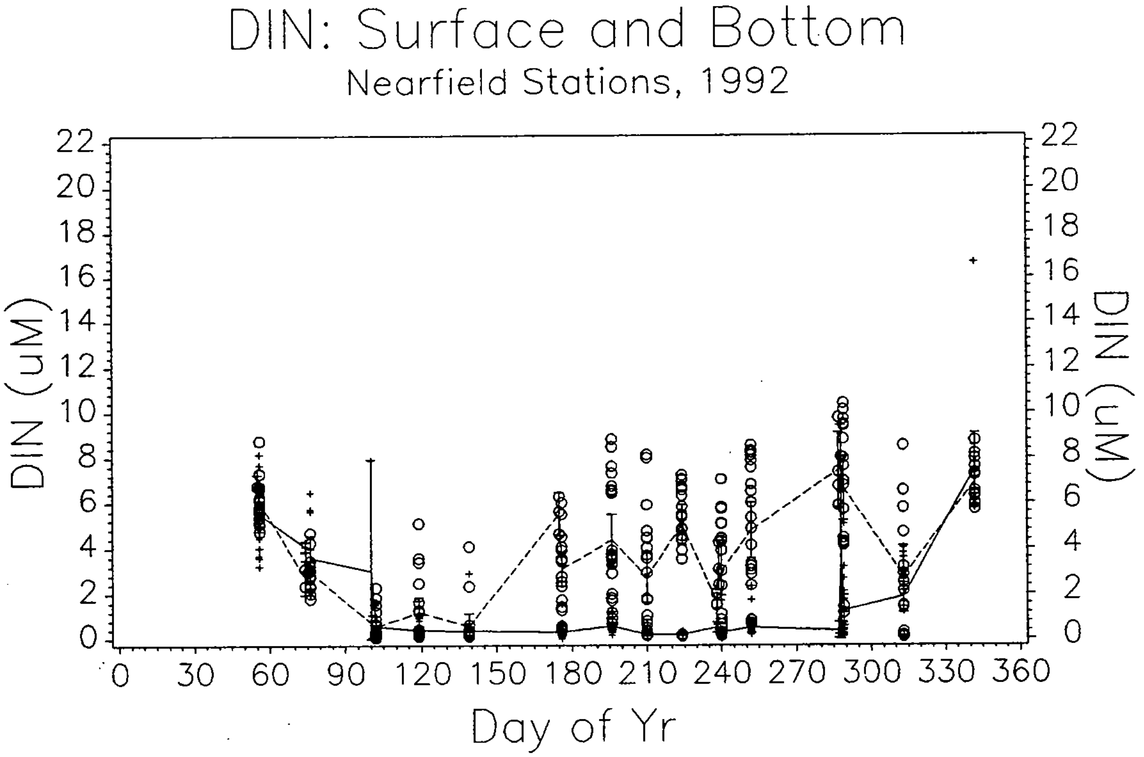


Figure 4.1-7 DIN concentrations in nearfield surface and bottom waters through the annual cycle in 1992 [modified from Kelly *et al.*, 1993]. Surface data are represented by the plus symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

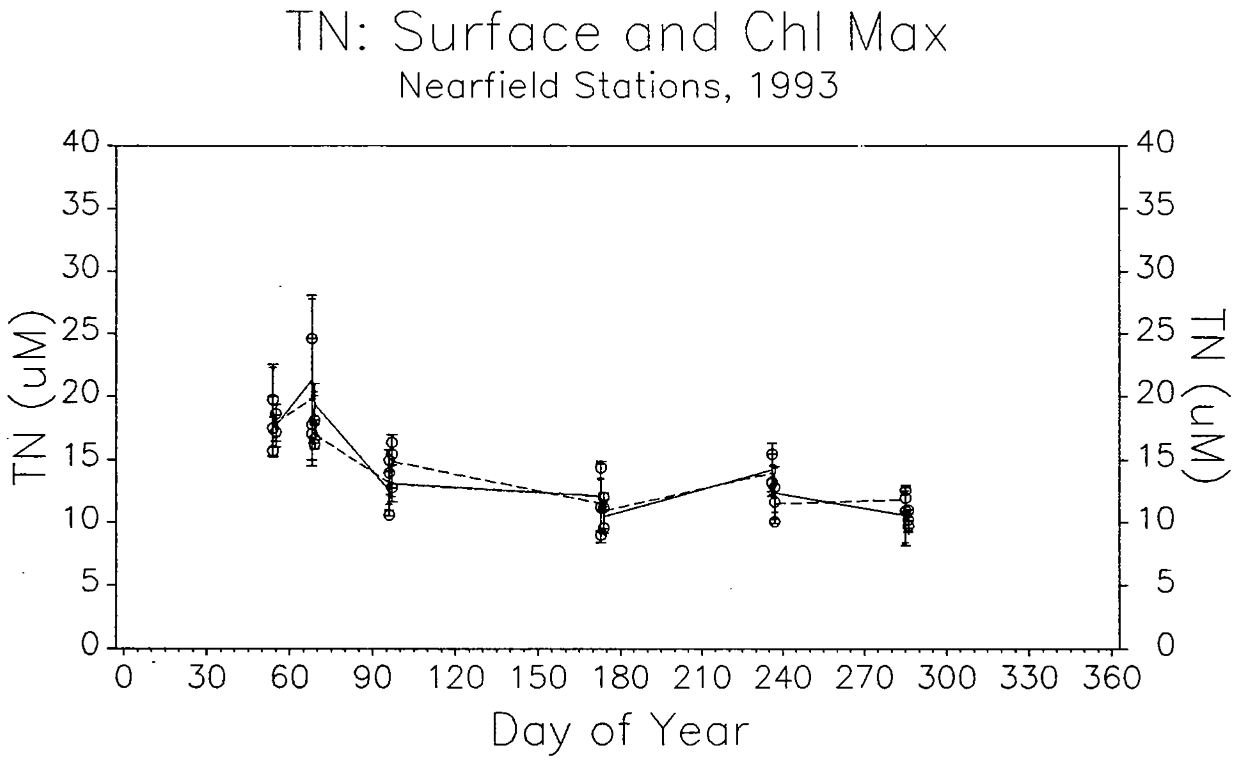
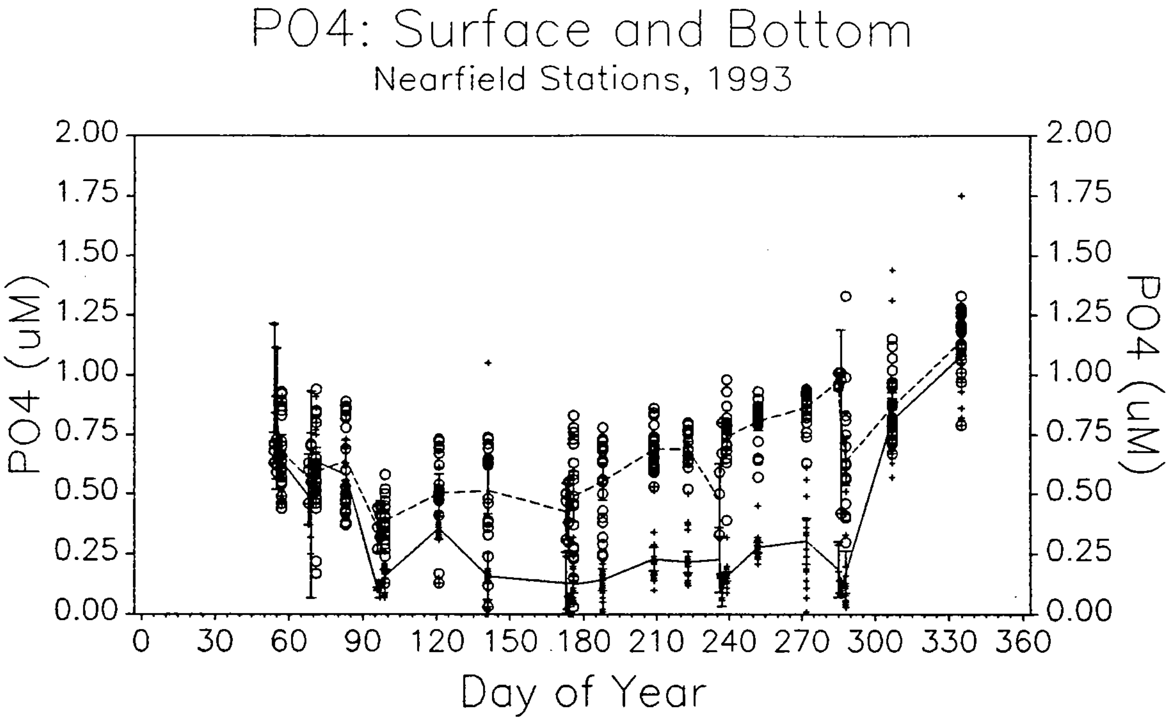


Figure 4.1-8 Total N (TN) concentrations at the nearfield surface and chlorophyll maximum sampling depths through the annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Mid-depth chlorophyll maximum data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.



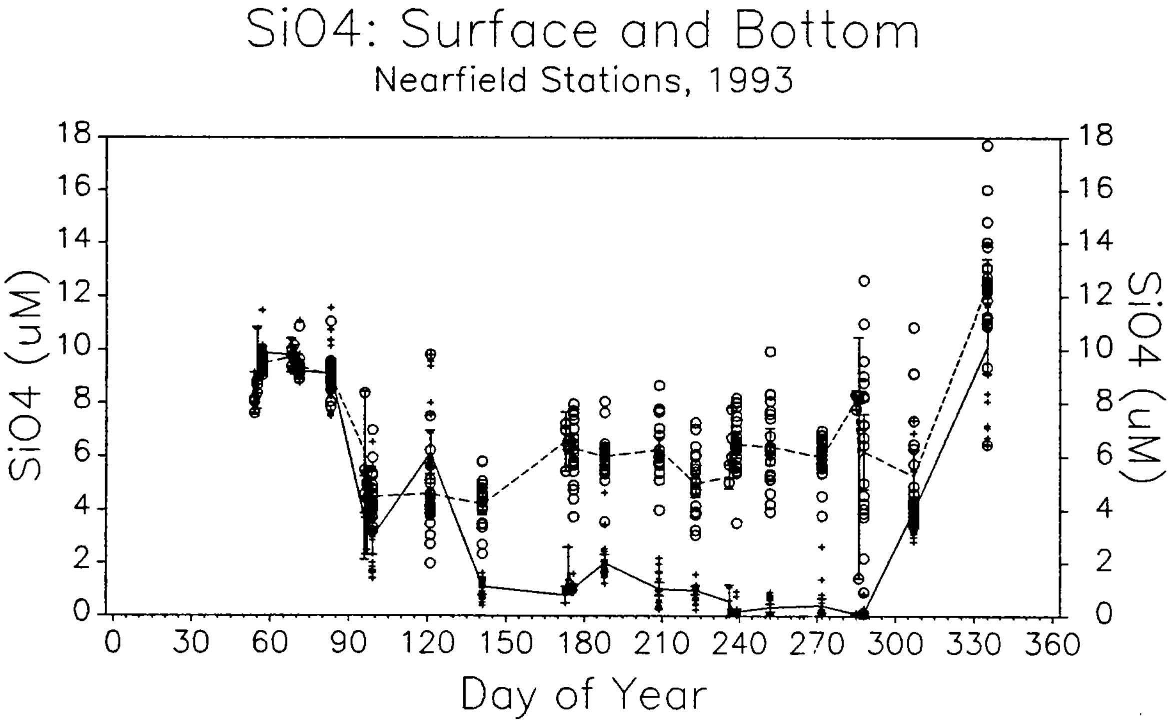


Figure 4.1-9 $PO_4$ and $SiO_4$ concentrations in nearfield surface and bottom waters through the annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean. One high value of $PO_4$ has been excluded (≈3.4 $\mu$M at day 120).

## 4.2 CHLOROPHYLL

### 4.2.1 Frequency Distribution of Chlorophyll

Figure 4.2-1 shows the frequency distribution plots for fluorescence measured on the 1993 nearfield surveys. The modal class, with almost 50% of the observations, was a low concentration (1.2 $\mu$g $L^{-1}$, interval 0.6-1.8 $\mu$g $L^{-1}$). Frequencies tailed off exponentially to higher concentration classes and few ($\approx$5% or less) of the concentrations were >10 $\mu$g $L^{-1}$. The average concentration was 2.36 $\mu$g $L^{-1}$ (N=1850, standard deviation = 3.11) and the maximum concentration was 20.52 $\mu$g $L^{-1}$. These nearfield survey results are comparable to those obtained from the six "P" stations occupied during the farfield surveys; based on the six stations, the nearfield-survey mean for fluorescence was 2.95 $\mu$g $L^{-1}$. On samples collected from six "P" stations during each survey and selected other farfield stations, chlorophyll *a* was measured by chemical extraction (and used for fluorescence sensor calibration purposes). The mean chlorophyll *a* concentration, based on these 260 samples, was 2.40 $\mu$g $L^{-1}$; the maximum concentration was 26.8 $\mu$g $L^{-1}$.

### 4.2.2 Annual Cycle of Chlorophyll

Figure 4.2-2 shows that fluorescence was consistently low in bottom water. However, concentrations increased during the fall overturn event as the bloom settled — a feature described in detail by Libby *et al.* (1994) and mentioned in Section 3.4 above. Surface chlorophyll concentrations increased gradually during the summer and then increased sharply in September and October 1993 as the intense fall diatom bloom of 1993 occurred (see Section 3.4). The annual cycle of total phytoplankton counts in surface water, available for one nearfield station (N10P), confirms the fundamental temporal pattern of chlorophyll (Figure 4.2-3).

Unfortunately, sampling was not conducted in late September 1992 as it was in 1993 (Figure 4.2-4). Because fall overturn had occurred by mid-October 1992, it was not possible to determine if an intense fall bloom also occurred in late September 1992. The progression in chlorophyll during August and September 1992 suggests that this was possible. In contrast, surface chlorophyll concentrations in the nearfield during winter-spring of 1992 and 1993 were different in timing and magnitude of peak concentrations (see Kelly *et al.*, 1994a).

### 4.2.3 Spatial Distribution of Chlorophyll

Mean annual surface water chlorophyll concentrations at each station show a fairly smooth gradient from west to east-southeast in the nearfield (Figure 4.2-5). However, spatial variability and a considerable range in the concentration of surface water chlorophyll were observed during many surveys (Figure 4.2-4). This was not the case during periods of low biological activity (pre-bloom winter, post-bloom spring after DIN was depleted, and post-bloom fall). The chlorophyll concentration range is typically broad and, because the gradient regularly exists, it is noticeable using either the nearfield or farfield sampling designs (cf. Figure 4.2-5 and Figure 3.2-4). The pattern also has substantial fine-scale variability, and has been observed to change in days and hours (e.g., Kelly and Albro, 1993). Temporal-spatial variability in chlorophyll is further presented in Section 5.3, which focuses on development of the fall bloom as the defining ecological feature in western Massachusetts Bay in 1993.

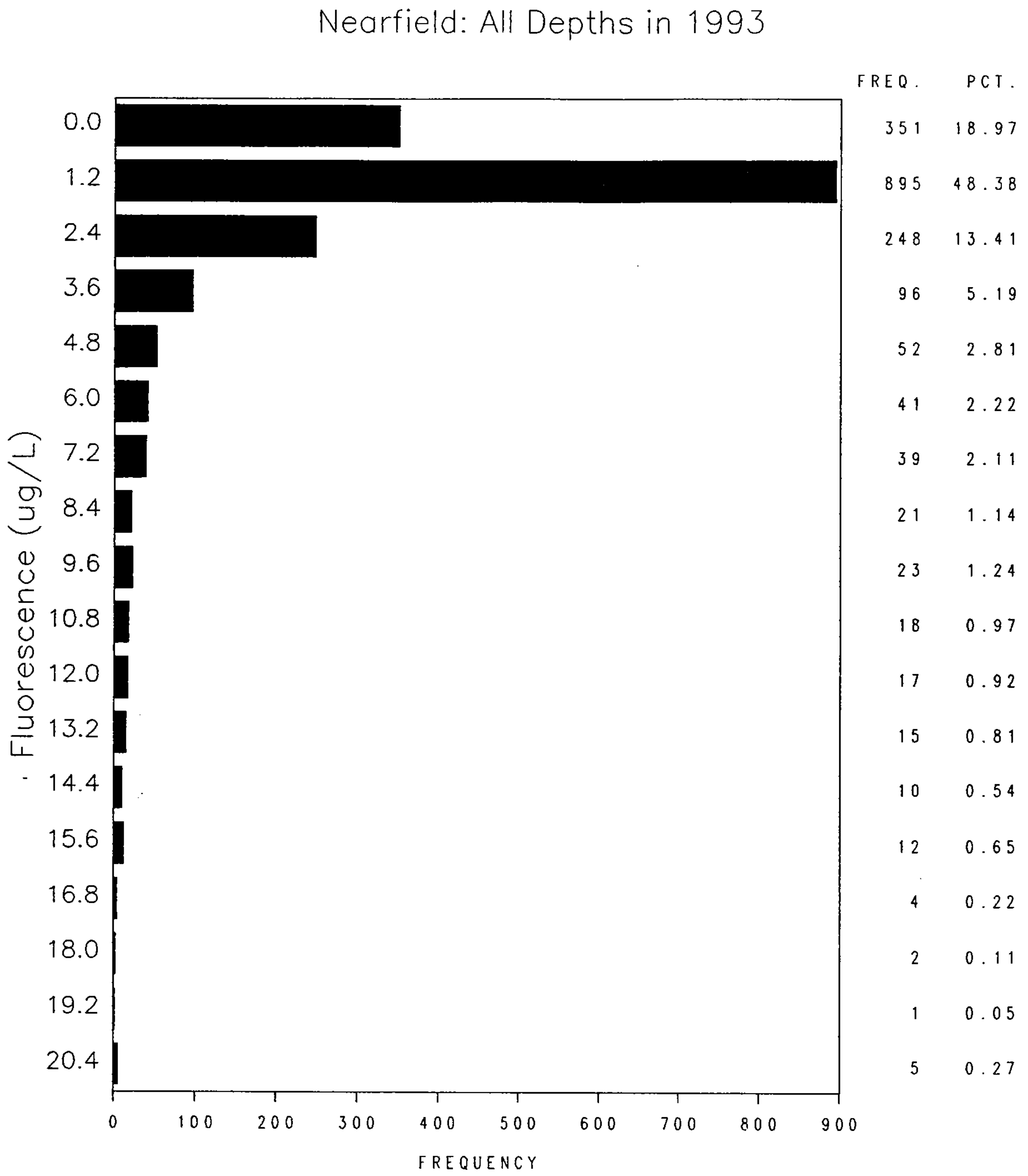


Figure 4.2-1 Frequency distribution of fluorescence concentrations for all nearfield samples in 1993.

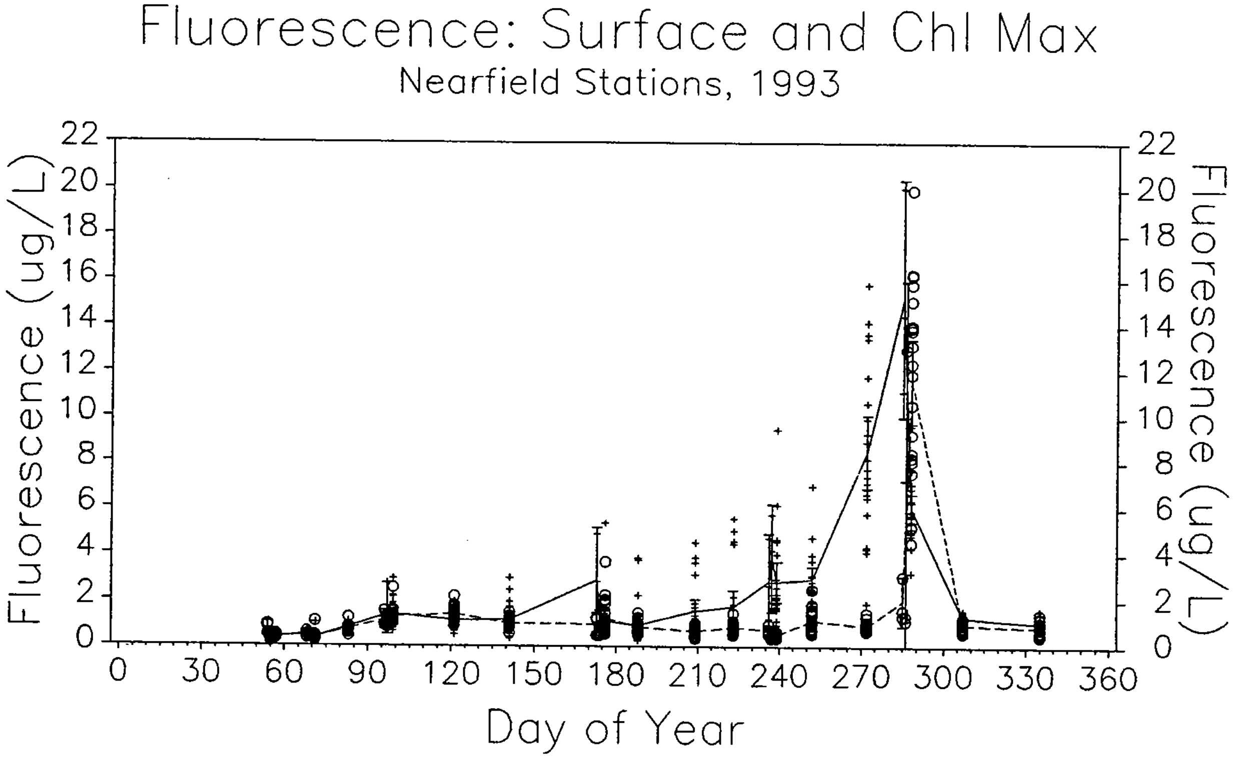


Figure 4.2-2 Fluorescence concentrations at nearfield surface and bottom waters through the annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Mid-depth chlorophyll maximum data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

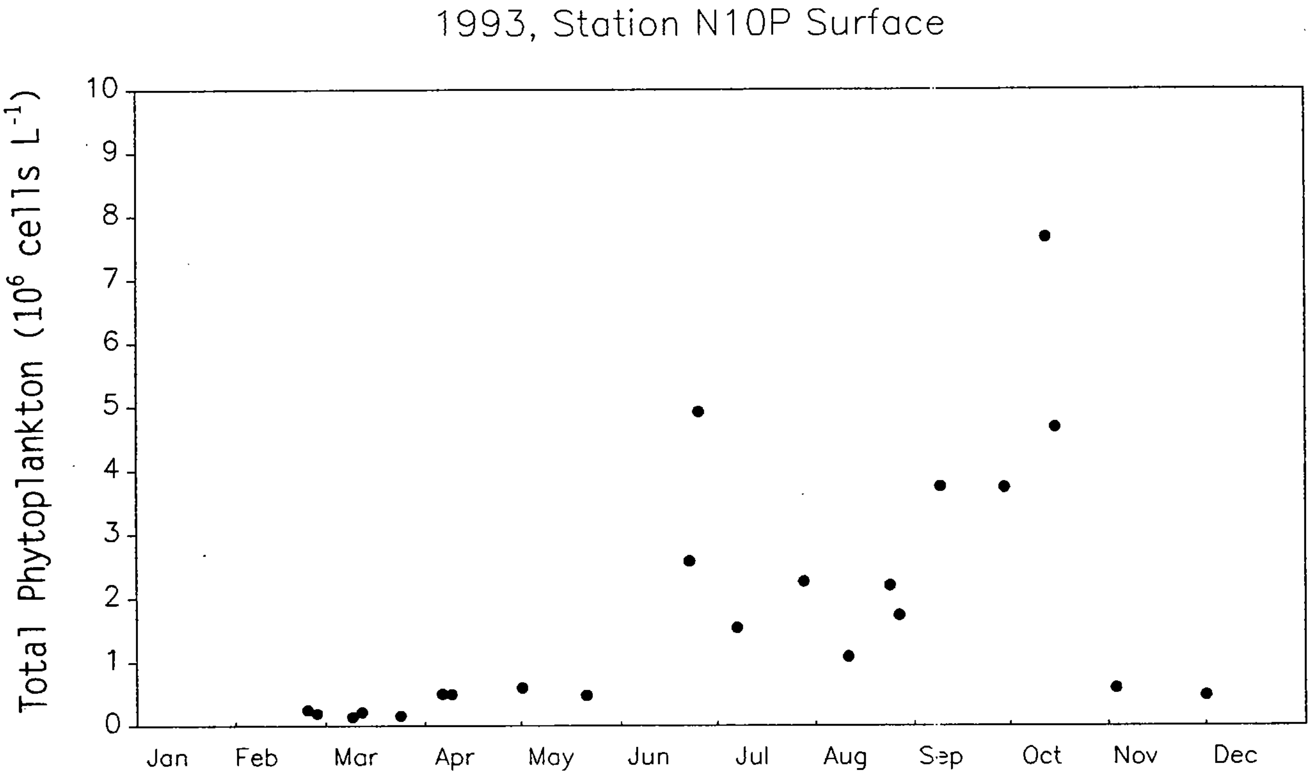


Figure 4.2-3 Total phytoplankton counts in surface water at station N10P in 1993.

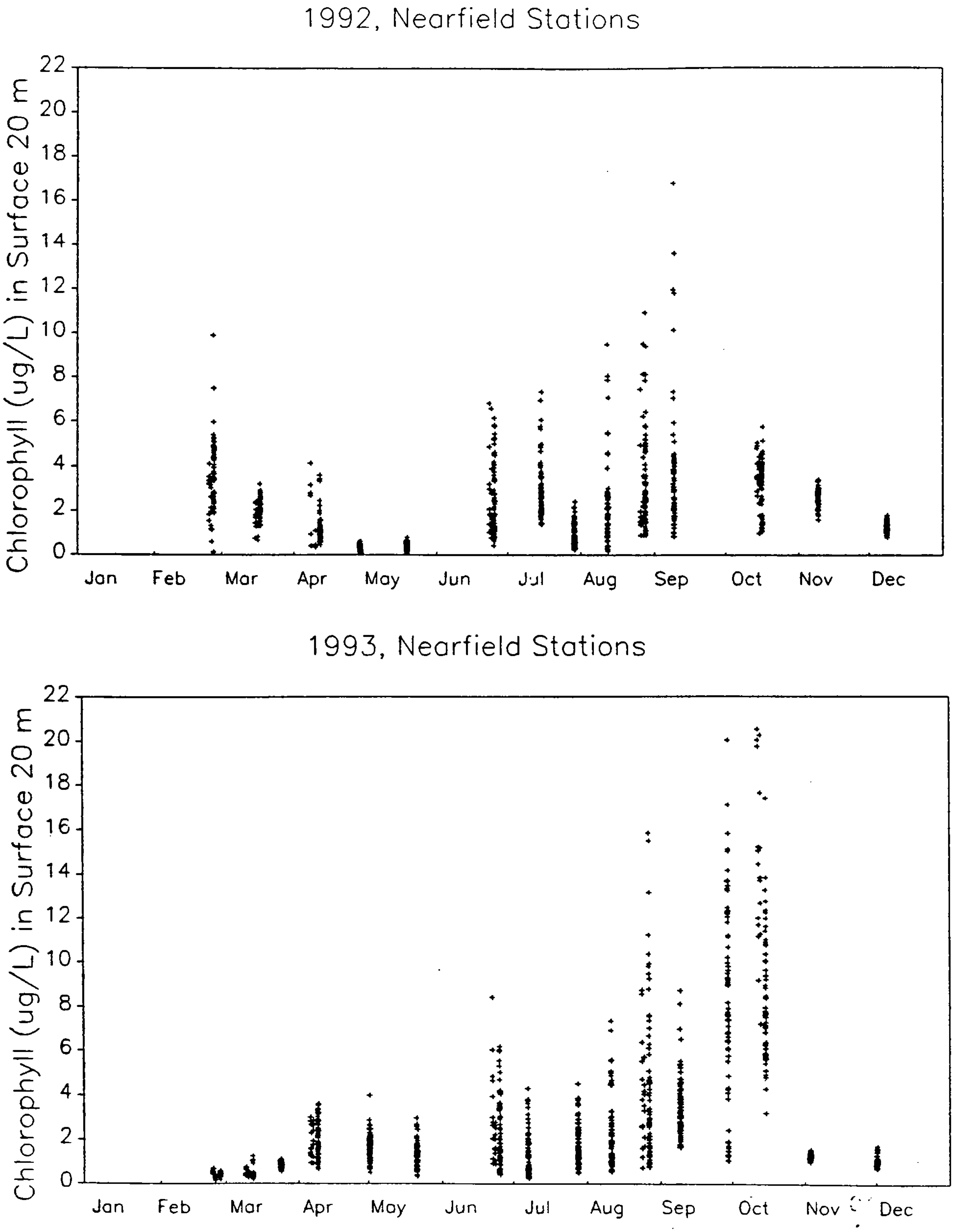


Figure 4.2-4 Fluorescence in nearfield surface waters through the annual cycle in 1993 and 1992 [from Libby *et al.*, 1994].

1993 Annual Mean Surface Fluorescence (as Chl a, ug/L) - Nearfield Surveys

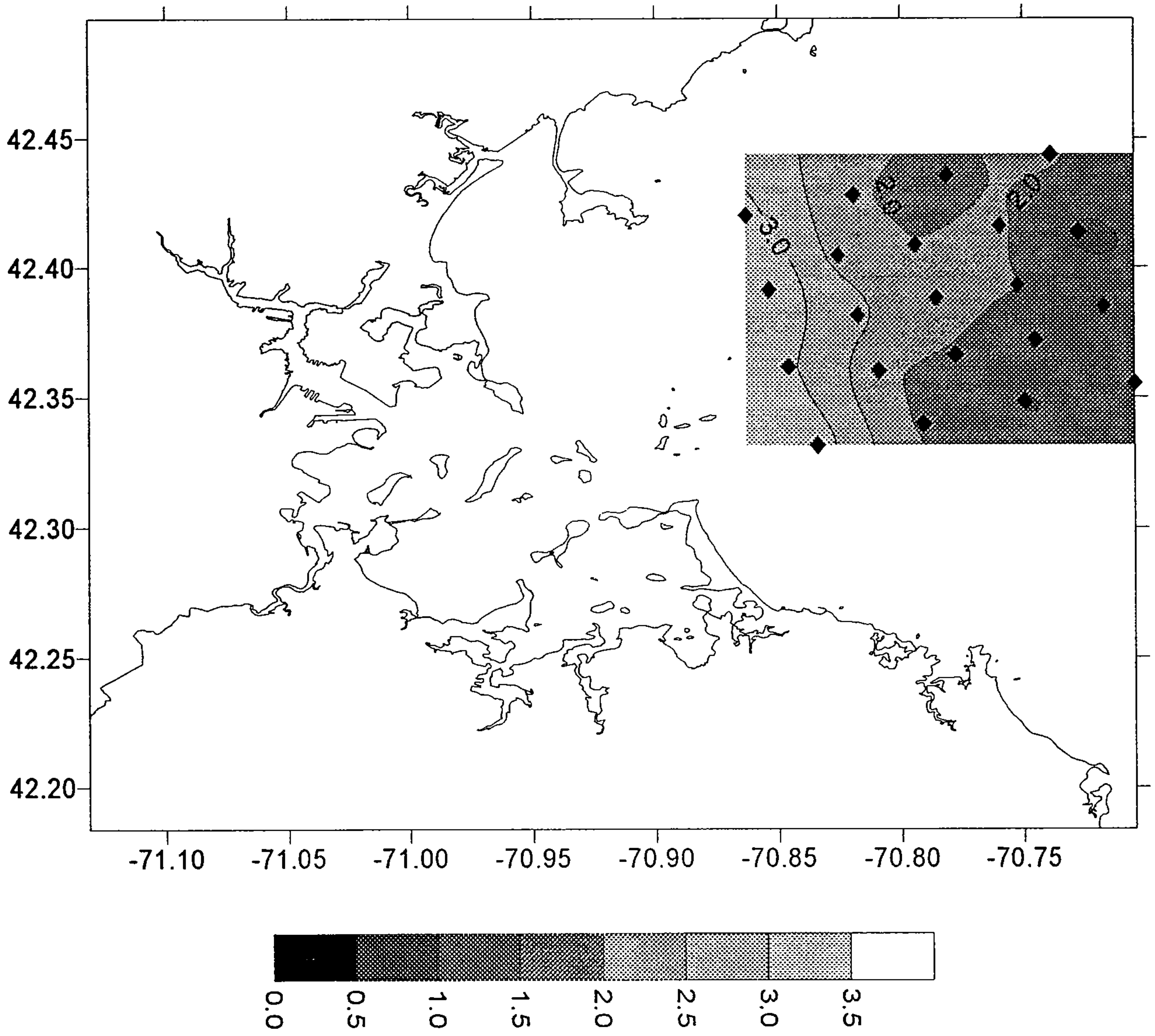


Figure 4.2-5 Spatial pattern of fluorescence in the nearfield. Data are surface water means from 16 nearfield surveys.

## 4.3 DISSOLVED OXYGEN

### 4.3.1 Frequency Distribution in Bottom Waters

The frequency distribution of all nearfield DO concentrations (N=1850) is shown in Figure 4.3-1. DO concentrations ranged from 6.70 to 13.19 mg $L^{-1}$, with a mean of 10.02 mg $L^{-1}$. In comparison, the minimum and maximum concentrations for this region, based on the six farfield surveys, were 7.26 and 13.19 mg $L^{-1}$, respectively, with a mean of 10.38 mg $L^{-1}$. There were only several nearfield samples with concentrations less than DO concentrations detected in the farfield series. This small subset represented <1% of the total observations (Figure 4.3-1).

### 4.3.2 Annual Cycle of Dissolved Oxygen

The temporal DO pattern for nearfield surface and deep waters was similar to the pattern described by the farfield sampling, but the higher frequency of nearfield sampling provided more temporal detail (Figure 4.3-2). The higher sampling frequency confirmed that the persistent difference in the mean degree of saturation of surface and bottom waters was present from about April (≈day 95) to December (day 330). The period between April and mid-October 1993 (≈day 290) defined the period of stratification for most of the nearfield. Moreover, consistently supersaturated DO in the surface water from April to mid-October 1993 crisply defined most of the biologically productive season in the nearfield area in 1993. Notably, slightly heterotrophic surface water (mild undersaturation of DO) was suggested during the early winter prior to the spring bloom (February and March) and during late fall (early November to December).

For the bottom waters, high saturation values appeared in April when seasonal chlorophyll and $^{14}C$ production peaks were documented (Sections 4.2 and 3.5), and when stratification was not strongly developed (Kelly *et al.*, 1994b). Following development of strong stratification, a minor, transient dip in the average bottom water DO (percent saturation) was measured in May. From June through mid-October, the mean DO concentration in the nearfield declined. Although some samples had low DO concentrations after October, the average bottom water DO increased in November and December. The mean percent saturation for surveys increased from a low near 80% in mid-October (just prior to mixing) to about 85% thereafter (Figure 4.3-2).

A Late Season Gradient in Bottom Water Dissolved Oxygen Across the Nearfield. Low DO values (<7.6 mg $L^{-1}$) were observed in bottom waters at some stations during the last three surveys of 1993 (Figure 4.3-3). The lowest value was recorded in early November. In comparison, the 1992 annual DO minima were detected in October 1992 (Figure 4.3-3). The low late-season near-bottom DO concentrations are from stations where sampling depths were >40 m (Figure 4.3-4). These stations are located on the eastern side of the nearfield on the western slope of Stellwagen Basin. A plot of temperature revealed that a two-layered vertical structure still persisted in early November (Figure 4.3-4). At that time, the temperatures were fairly uniform (indicating full mixing) to about 40 m, with a layer of deep colder water underlying the surface layer.

The spatial gradient of bottom water DO across the nearfield is illustrated by Figure 4.3-5. In mid-October, the progression of lower percent saturation that is apparent from west to east is related to deepening of the water column. A local event at station N19, where the water column was completely mixed to the deepest sampling depth (≈22 m), caused the high-chlorophyll, supersaturated surface layer to mix with underlying water and apparently vented the bottom water (cf. Libby *et al.*, 1994). In general, the southwestern corner of the nearfield is strongly influenced by tidal exchange and mixing processes (cf. Kelly and Albro, 1993). The local feature suggests that fine-scale turbulence and perhaps local bathymetric features influence destratification even though, on the broad scale, fall overturn progressed from the shallow shoreward side of the nearfield to the deeper eastern side. By November, most of the nearfield had vented, was vertically well mixed to the bottom (Figure 4.3-4), and had a uniform DO concentration and 90-95% saturation (Figure 4.3-5). At this time, the gradient in bottom water DO was restricted to the eastern third of the nearfield and, at many of these stations, the percent saturation was higher than observed in mid-October, although the deepest water (≈48 m) at the four stations along the eastern track continued to declined in DO (Figures 4.3-4 and 4.3-5). This analysis of the nearfield data set reveals the progression of destratification in western Massachusetts Bay and, as discussed previously, suggests that DO minima in deep waters of the Bay will be affected by the seasonal timing of destratification.

### 4.3.3 Rates of Dissolved Oxygen Change in Nearfield Bottom Waters During the Stratified Period

Nearfield bottom water DO concentrations were regressed against time to estimate rates of DO decline during stratification. Using April to mid-October data for all nearfield stations, a significant decline was indicated (Prob>F=0.0001, $R^2$=0.84, N=254). The slope (and standard error) of the decline was 0.0180 (± 0.0005) mg $L^{-1}$ $d^{-1}$. This estimate is equal to that derived from all regions using the farfield data over the same period (Section 3.3). As found for the farfield data set, the estimated rate for the nearfield region (if the time period was restricted to June through mid-October) was higher, 0.023 (± 0.0008) mg $L^{-1}$ $d^{-1}$ (Prob >F=0.0001, $R^2$ =0.81, N=186). The estimate was even higher if restricted to depths >40 m that were sampled between late August and mid-October (day 231 to day 299); for this subset (Prob>F=0.0001, $R^2$=0.94, N= 25), the estimated rate was 0.0339 (± 0.0018) mg $L^{-1}$ $d^{-1}$.

This analysis suggests that there is a non-linear rate of DO decline in western Massachusetts Bay bottom waters during the stratified-period, with the rate of decline increasing towards the end of the period. This increasing rate of decline is coincident with an increasing bottom water temperature, which is likely a controlling factor. However, as pointed out by Giblin *et al.* (1994), the fall 1993 period was one of increasing surface biomass and productivity (and perhaps organic deposition to bottom water and sediments), as well as increasing bottom temperature, so that two principal factors (temperature and organic matter) that can affect bottom-layer respiration (and therefore DO decline) both were increasing sharply at the time when DO decline appeared to be highest.

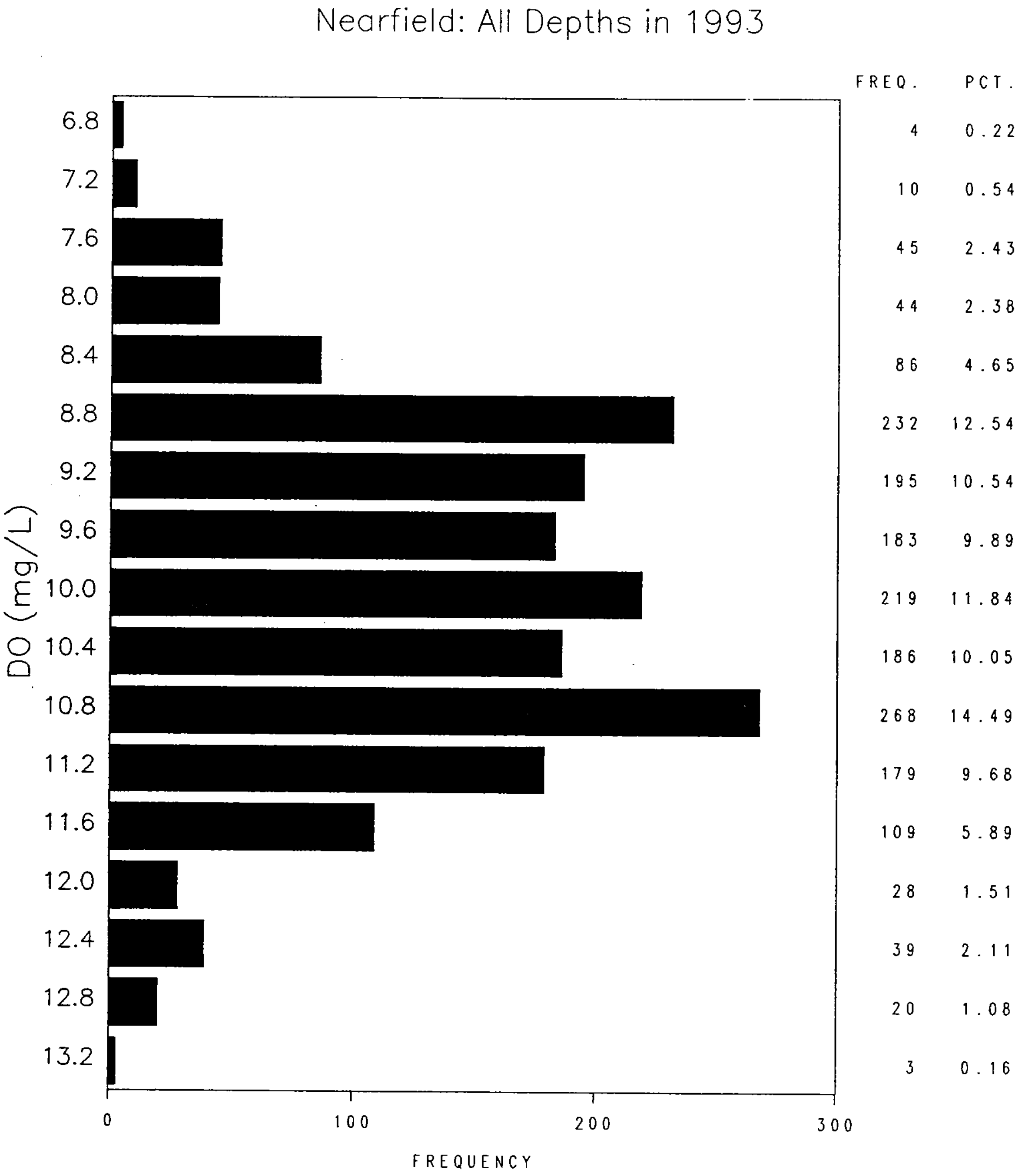


Figure 4.3-1 Frequency distribution of DO concentrations for all nearfield samples in 1993.

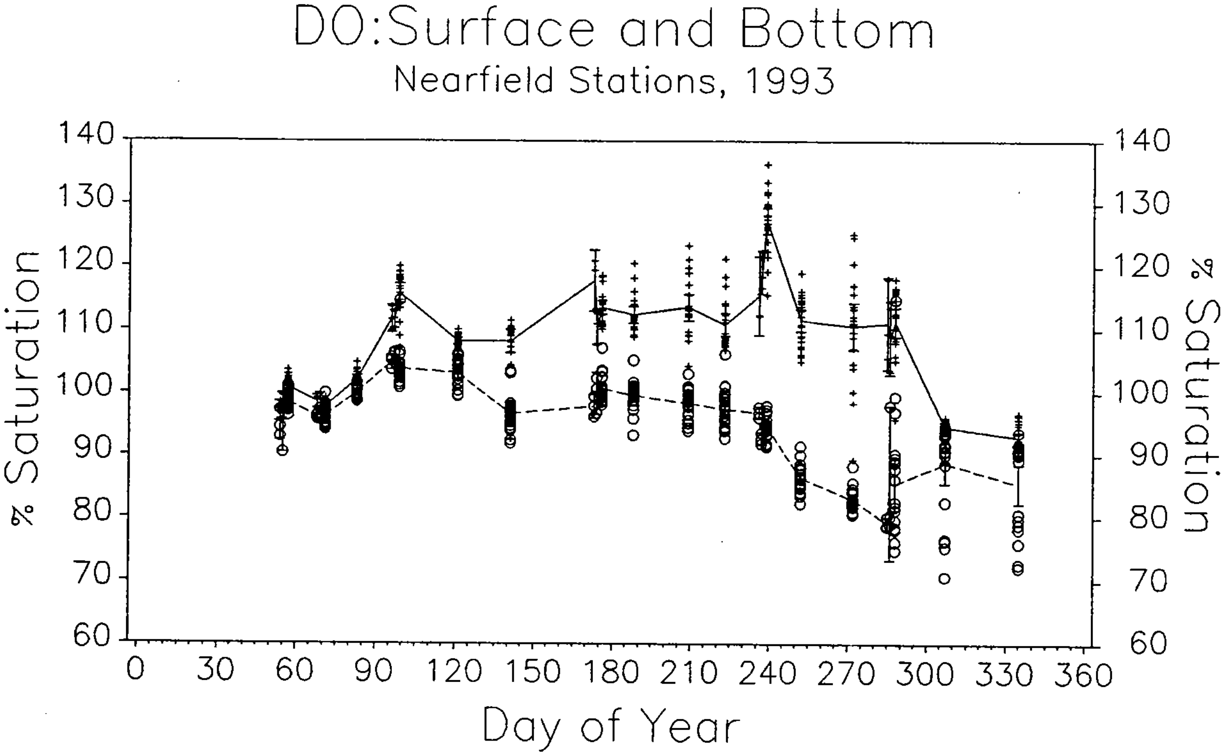


Figure 4.3-2 DO (% saturation) in nearfield surface and bottom water through the annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

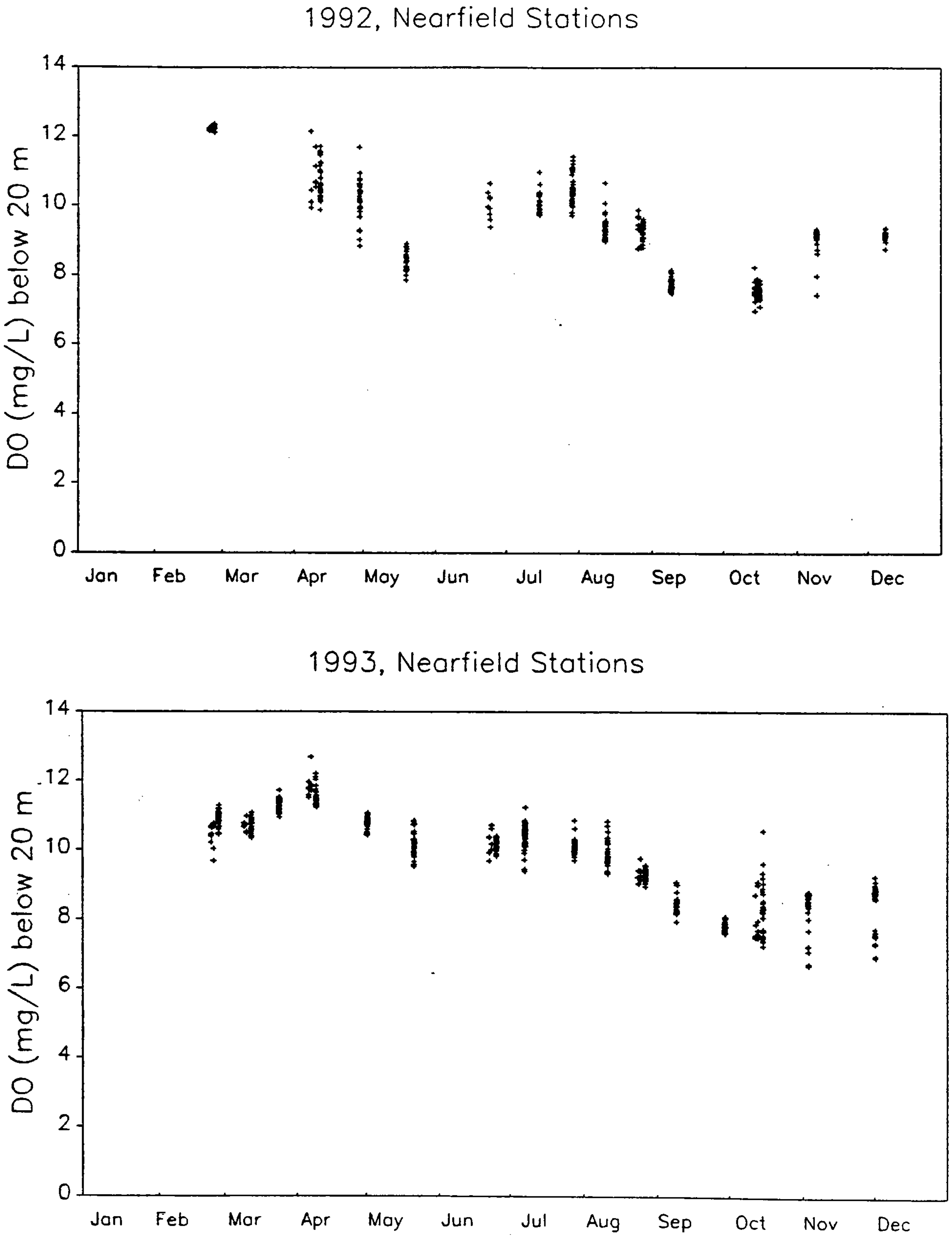
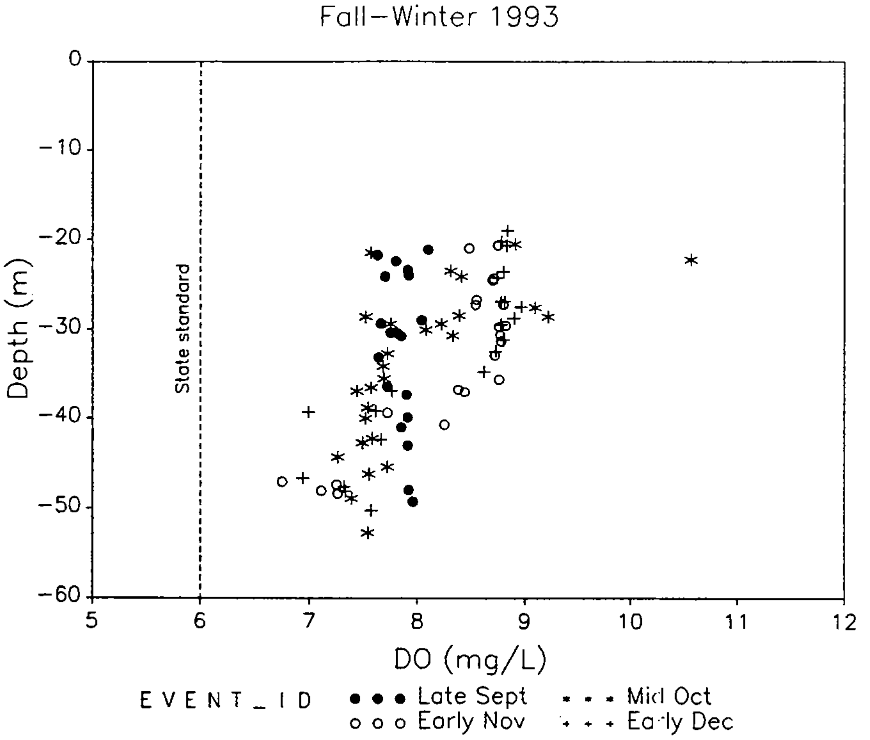


Figure 4.3-3 Comparison of bottom water DO concentrations in the nearfield region in 1993 to the annual cycle of 1992 [From Libby *et al.*, 1994].



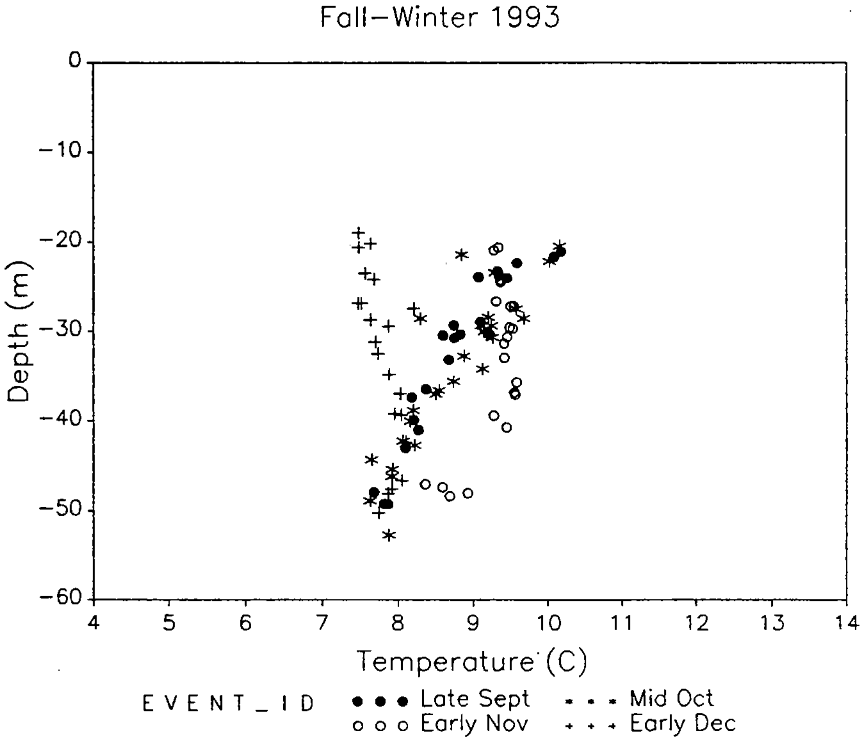


Figure 4.3-4 DO concentrations (top panel) and temperature (bottom panel) in bottom waters as a function of sampling depth. Data are from the nearfield stations for the period of late September to early December 1993.

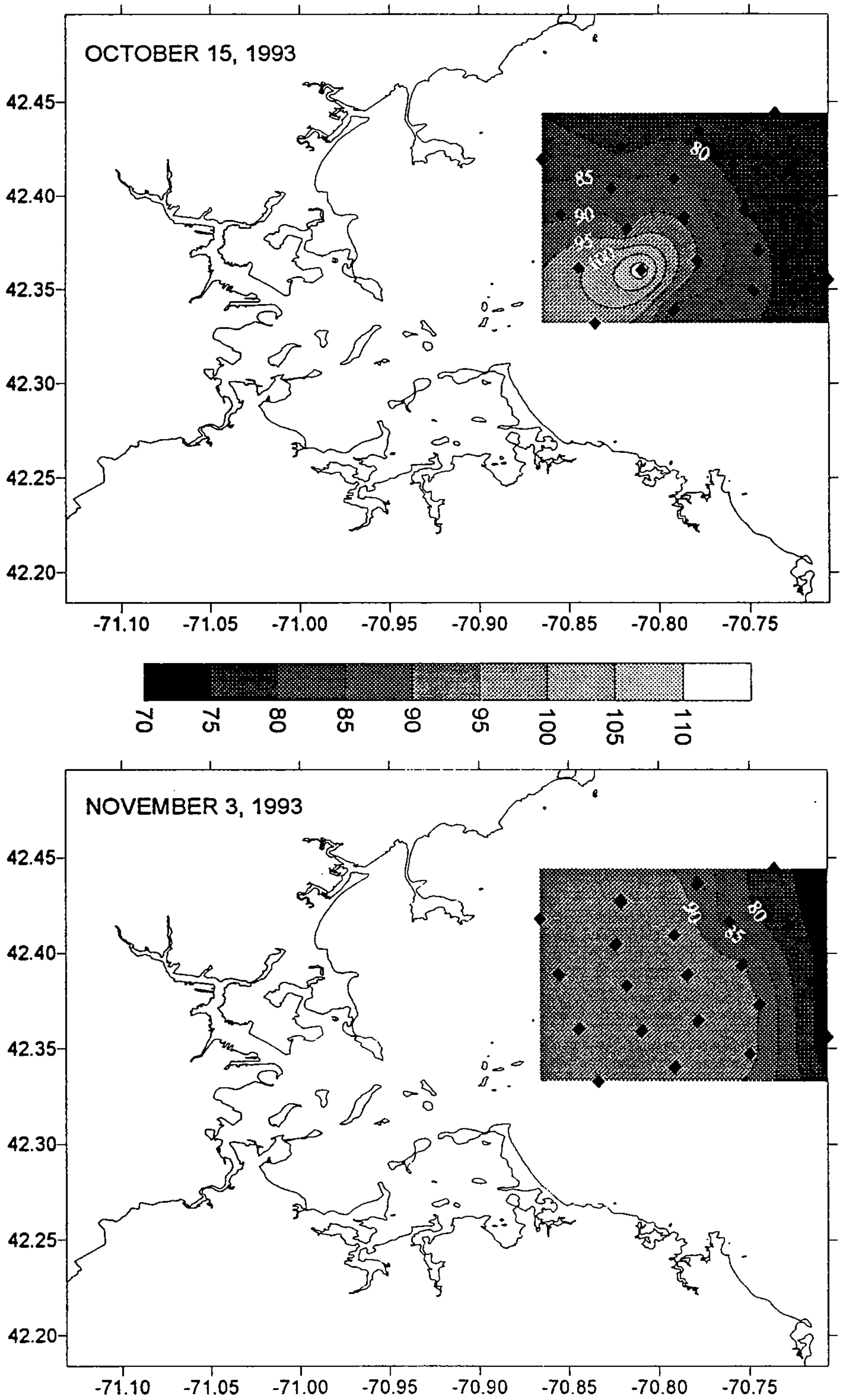


Figure 4.3-5 Spatial pattern of DO (% saturation) in bottom water in the nearfield in October and November 1993.

# 5.0 DISCUSSION

Three principal topics relating to the 1993 water column monitoring results are discussed in this section. The first two topics are associated with temporal and spatial issues, and how patterns of key monitoring parameters differ at regional and nearfield scales of observation. The last topic is a thorough discussion of the major ecological event — the fall bloom — that defines and that may distinguish 1993 from other years.

## 5.1 FARFIELD/REGIONAL SCALES

Major aspects of the time and space variability of nutrients, chlorophyll/plankton, and DO in the farfield were summarized in Section 3. The discussion of these data focuses on trends in space and time at specific stations located in different regions of Massachusetts and Cape Cod Bays. The specificity enables examination of physical, chemical, and biological trends at one time, thereby providing a strong sense of the interaction of key monitoring variables that complement the previous univariate presentation of results. This presentation provides broad perspective on time-space patterns across stations and regions. Moreover, it efficiently summarizes principal trends and serves as a prelude to statistical inference testing that confirms regional differences and time trends in the data.

### 5.1.1 Annual Cycle in 1993 at Selected Stations

A single station from each of four regions in the system was chosen to illustrate representative trends in water quality over the year. Plots of temperature, fluorescence, DIN, and DO over depth and time were developed for station F24 (coastal region, outside Boston Harbor at ≈20 m depth), station N16P (nearfield region, east end of proposed diffuser at ≈44 m depth), station F02P (Cape Cod Bay region, east-central basin at ≈34 m depth), and station F19 (offshore region, Stellwagen Basin at ≈82 m depth). The 1993 water column monitoring data for the farfield included five sample depths (Niskin bottle sampling) at each station during each of six surveys. The sampling points used as the basis for contouring (Surfer, 1994) over the year and over depth are indicated in each of the following figures. As a reference for the plots, the farfield surveys occurred in February (≈day 54), March (≈day 70), April (≈day 98), June (≈day 170), August (≈day 235), and October (≈day 285). Note that the depth scales for Figures 5.1-1 to 5.1-4 vary according to the water depth of the station.

***Station F24P (Coastal).*** The period of strong thermal stratification encompassed June through August. The water column was nearly isothermal in October when only a thin near-bottom water layer was thermally distinct (Figure 5.1-1). There was no distinct winter-spring phytoplankton bloom. Instead, chlorophyll concentrations increased progressively (<2 to 8-12 $\mu$g $L^{-1}$) from February to October. In June and August, chlorophyll concentrations were highest in the surface layer. In October, the highest chlorophyll (14-16 $\mu$g $L^{-1}$) for the year at this station was detected in the weak thermocline between 15 and 20 m. DIN concentrations were highest (10-12 $\mu$M) near the surface in February and March. Through the summer, DIN concentrations were very low throughout the water column. They began to increase again in October, both at the surface and in the thin near-bottom layer. High DO readings were made at mid-depth near the base of a surface chlorophyll layer in April and also in mid-water at the subsurface chlorophyll maximum in October. There was no evidence for a difference in surface and bottom-water DO concentrations during the stratified period, but the DO minimum for the year occurred in the near-bottom water in October.

***Station N16P (Nearfield).*** The period of strong thermal stratification in the east-central nearfield region occurred from June through August. However, the entire lower half of the water column was thermally layered in October (Figure 5.1-2). There was no distinct winter-spring phytoplankton bloom and chlorophyll concentrations increased from <2 $\mu$g $L^{-1}$ between February and April to a peak of 10-12 $\mu$g $L^{-1}$ throughout the surface mixed layer (upper 20 m) in October. The base of the surface chlorophyll layer (>2 $\mu$g $L^{-1}$) throughout the summer was found at 15-25 m, approximately coincident with a 8-10°C isotherm. In April, June, and August, chlorophyll concentrations had mid-depth maxima. DIN concentrations were essentially the opposite of chlorophyll and, thus, were highest in February and March and within bottom waters throughout the year. Lowest concentrations were measured in the surface layer from April to October. DIN concentrations in near-bottom water increased over the stratified period, especially the latter months. DO concentrations in surface waters peaked in April and were similar for much of the remainder of the year. In contrast, bottom water DO decreased from April to October, mimicking the DIN increase. The lowest DO concentration was thus observed in bottom water in October.

***Station F02P (Cape Cod Bay).*** The period of strong thermal stratification included June and August, but there was still slight thermal stratification in October (Figure 5.1-3). In contrast to the Massachusetts Bay stations, there was a strong winter-spring phytoplankton bloom, lasting through February and March but diminished in April. The summer period was generally characterized by low chlorophyll, although minor mid-depth concentration peaks were observed in both June and August. There was also a fall chlorophyll concentration peak (8-10 $\mu g\ L^{-1}$) in the surface mixed layer which was most intense at mid-depth. The peak concentrations in the fall (and integrated photic zone chlorophyll) were higher in October than in February and March. DIN concentrations reached annual maxima ($\approx 8\ \mu M$) in bottom water below the thermocline in October. In Cape Cod Bay, the surface water DIN seasonal patterns differed from those in Massachusetts Bay. During the early winter-spring-bloom, as well as during the fall bloom and throughout summer, DIN concentrations were low ($<2\ \mu M$) in the surface layer. April was an unusual month in that DIN concentrations increased throughout the water column. In contrast to all other samplings at station F02P, in April the DIN concentrations in the surface water were similar to the concentrations in the bottom water. Bottom-water DIN increased slightly from February to October. High DO readings were associated with the timing and vertical location of chlorophyll peaks (i.e., DO was relatively high through most of the water column in winter-spring, at mid-depth in June, and again within the surface layer in October). The lowest DO reading ($<7$ mg $L^{-1}$) for the year occurred near the bottom in October.

***Station F19 (Offshore).*** In deeper offshore water, the temperature was lowest in March and April rather than in February (Figure 5.1-4). Surface warming was indicated in April and strong thermal stratification persisted from June through October. There was no early winter-spring phytoplankton bloom. Mid-water peaks in chlorophyll concentrations became evident in April, more intense in June, and were still noted in August. This pattern is similar to the one observed at station N16P (Figure 5.1-2). The base of the mid-water chlorophyll layer was characteristically deep (≈30-40 m). A fall chlorophyll peak in the surface 10-15 m presented the annual maximum chlorophyll (8-10 $\mu$g $L^{-1}$) for this station. DIN concentrations were high (6-10$\mu$M) throughout the water column in February and March. During the stratified season, there was a distinct chemocline with high bottom water DIN and often undetectable concentrations in surface water. Bottom-water DIN concentrations below the thermocline generally increased during the stratified period and the highest DIN concentration detected at this station was in near-bottom water in October. This October near-bottom sample that was high in DIN also had the lowest DO concentration (<7.5 mg $L^{-1}$) for the year. DO concentrations gradually decreased over time during the stratified period. DO was clearly a function of depth during the stratified period, a pattern similar to the DIN time and depth increases in the subthermocline deep water of this Stellwagen Basin station. During surveys between April and August, the mid-water DO maxima coincided with mid-water chlorophyll maxima.

The overall impressions gained from these four patterns is that they have a similar annual cycle, but that there are some minor time-depth variations and slightly different concentrations. Some variations in concentrations (e.g., DO) relate to the depth of the station and water column depth influences on stratification. Other variations involve differences in timing of events (e.g., Cape Cod Bay early winter-spring bloom vs. Massachusetts Bay) for reasons that are not fully understood. Chlorophyll maxima tend to be closer to the surface in shallower water and grade to greater depth in deep water. The period and intensity of high chlorophyll conditions appears to be greater in the coastal region, where DIN is easily detectable in surface water for much of the year.

### 5.1.2 Differences in Surface Water Concentrations Across Farfield Regions and Surveys.

***Statistical Testing.*** As a preliminary exercise to complement the data summary, an effort was made to determine how regions differed statistically during 1993. Using only surface water concentrations, fluorescence, various nitrogen forms, and total phytoplankton counts were evaluated using two-way (space and time) analysis of variance (ANOVA) tests of means, followed by multiple comparison tests (SAS, 1988a,b).

These procedures require that data originate from a normal distribution with homogeneity of variance across groups. Univariate examination (cf. Section 3) regularly revealed non-normality (confirmed by the Shapiro-Wilk test) for parameters, so all tests were performed on transformed data ($\log_{10}$). Thus, the differences assessed were among geometric means of the concentration data. Non-parametric tests were also run for each parameter. The results obtained were the same as from the parametric tests.

For this effort, all stations within each defined region of Massachusetts Bay were considered sampling replicates. Therefore, there is an implicit assumption that station results within a region arose from the same underlying distribution. In this way, testing (F-test) could be performed for a "group" of surveys to examine the effects of region, survey, *and* the interaction of region and survey, where the interaction addresses whether there are regional differences over time. Significance was determined using a "Type-III" test which assumes that there are other effects in the model in addition to the one being examined. Statistical significance is assumed if the Pr>F was $\leq 0.05$.

When an F-test indicated significance, the Tukey studentized range test determined the regions (or surveys) that had significantly different geometric mean concentrations. Tukey's test controls for what is termed the overall "Type-I" error. This means that significance (again at the 0.05 level) is determined for pairwise comparisons only, ignoring the possibility of other effects. An F-test controlling Type-III error may conclude significance, but it will not always follow that Tukey's test will find significant pairwise differences among groups or their interaction. It is recognized that additional statistical tests might be conducted in a multivariate rather than univariate mode, that depth strata might also be included in designing tests, and that ANOVA using repeated measures may be an appropriate consideration in some cases (more likely the nearfield survey sequence than the farfield). Nonetheless, the results provide a highly useful guide for detecting statistical differences.

***Regions, Surveys, and Interaction.*** Table 5-1 shows that generally there were significant differences for the chosen parameters across regions, surveys, and the interaction thereof. Note that PON, DON, TN, and total phytoplankton are based on fewer total stations (11) and only the coastal, nearfield, and Cape Cod Bay regions are included in the analyses. Neither PON nor total phytoplankton were different across regions. Note that for DON the interaction term was not significant. Otherwise, it is suggested that regions differ, surveys differ, and the pattern of results over time differs across regions. Comparison tests (Tables 5-2 and 5-3) add definition where significant differences were detected for a given parameter (See Table 5-1). In the tables, note that for each parameter, the regions or surveys are sequenced, left to right, in order of *decreasing* geometric means.

For most nutrient forms (DIN, DON, and TN), the concentrations in the coastal region were different from the other regions which, as a group, were not different from each other. For $NH_4$, the coastal region was similar to the northern transect and Cape Cod Bay, but was different from the nearfield and offshore regions. In terms of fluorescence, the offshore region was significantly lower in surface water concentration than the other four regions. The other four regions formed two overlapping subsets of stations with the coastal, Cape Cod Bay, and nearfield regions not having significantly different geometric means.

For the surface waters that were tested, the untransformed mean surface fluorescence for the offshore region was about 1.9 $\mu g\ L^{-1}$. This region was statistically different from the others that had untransformed mean values ranging from 2.4 to 3.3 $\mu g\ L^{-1}$. Untransformed coastal DIN concentrations averaged 5.2 $\mu M$, compared to other regions where concentrations ranged between 1.98 and 2.7 $\mu M$. The geometric mean testing thus detected differences when the untransformed means differed by ≈1-2 $\mu$g $L^{-1}$ for fluorescence or by ≈2-3 $\mu$M for nitrogen, based on six surveys. Note also, that for DIN and other N forms, a difference was detected between coastal waters and the present conditions surrounding the future MWRA effluent outfall site. Stations in this coastal region are at the high end of the nutrient concentration gradient that extends into the Bay and presently receive enriched inshore water containing MWRA effluent (dispersed to various levels because of the varying distances from sources; see Figure 2-1.1). An inference that can be drawn from this analysis is that if, in the future, similar enrichment occurred in the nearfield, it would most likely be detectable under this monitoring design.

The results of tests for significant differences among the 1993 farfield surveys (Table 5-3) generally suggest a trend for phytoplankton (fluorescence and counts). These parameters are significantly higher in October, significantly lower in winter-spring (February-March), and at an intermediate level for stratified conditions (April, June, August). For DIN, $NH_4$, and TN, there were significantly high winter-spring concentrations and significantly low summer (and sometimes early fall) concentrations. Both of these results statistically support the contention that there are strong seasonal cycles for surface chlorophyll and nutrients, as evident in the plots previously presented for these parameters through the 1993 annual cycle. In contrast, only March and October were different for PON concentrations, and only a weak seasonal trend is supported by the data. Finally, note that the significant interaction of time and space is complicated to interpret or display, but the interpretation, in part, involves the observed variations in timing and intensity of spring and fall bloom events in the different regions.

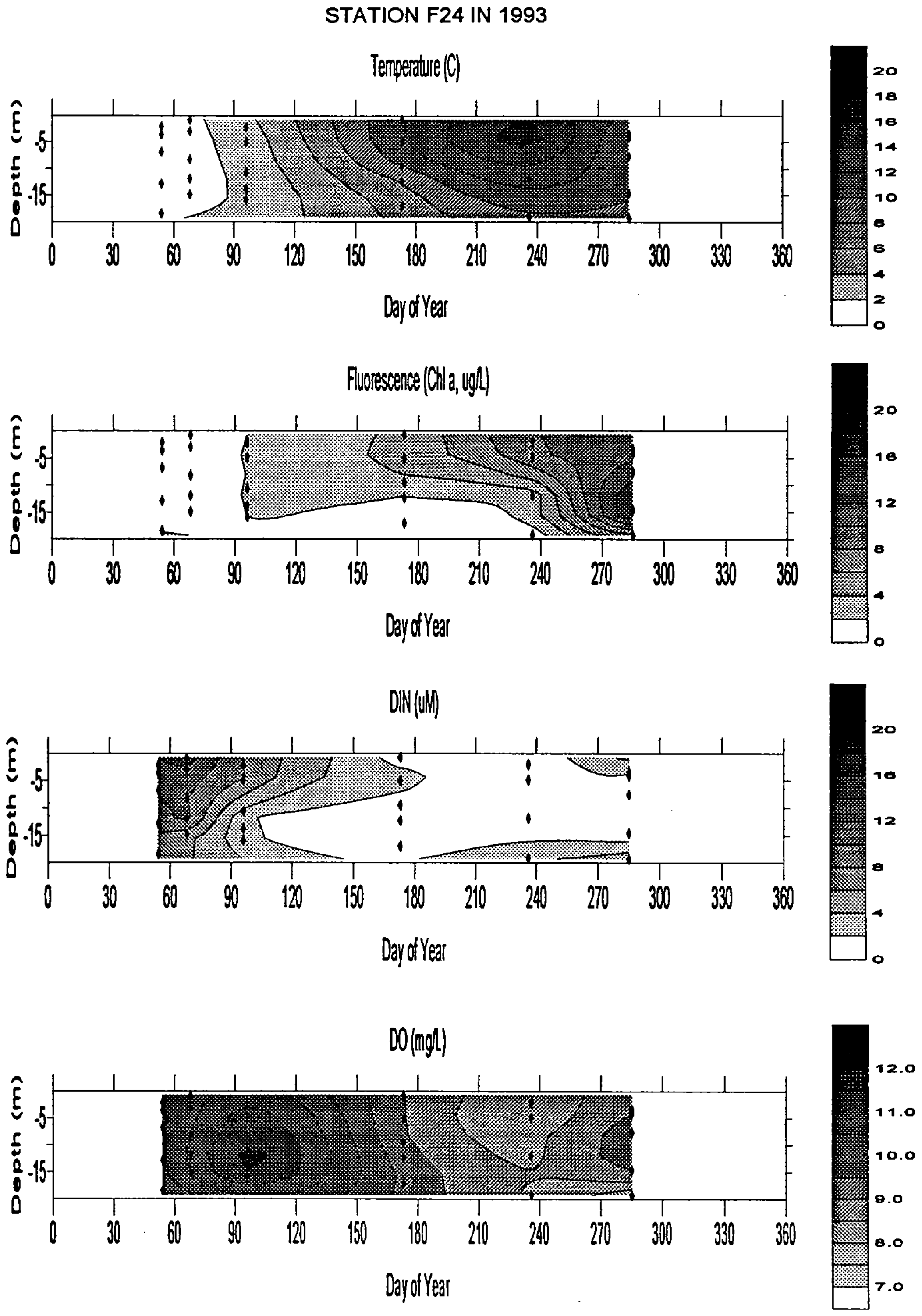


Figure 5.1-1 Annual cycle of temperature, fluorescence, DIN, and DO at station F24P, a representative of the coastal region.

STATION N16P IN 1993

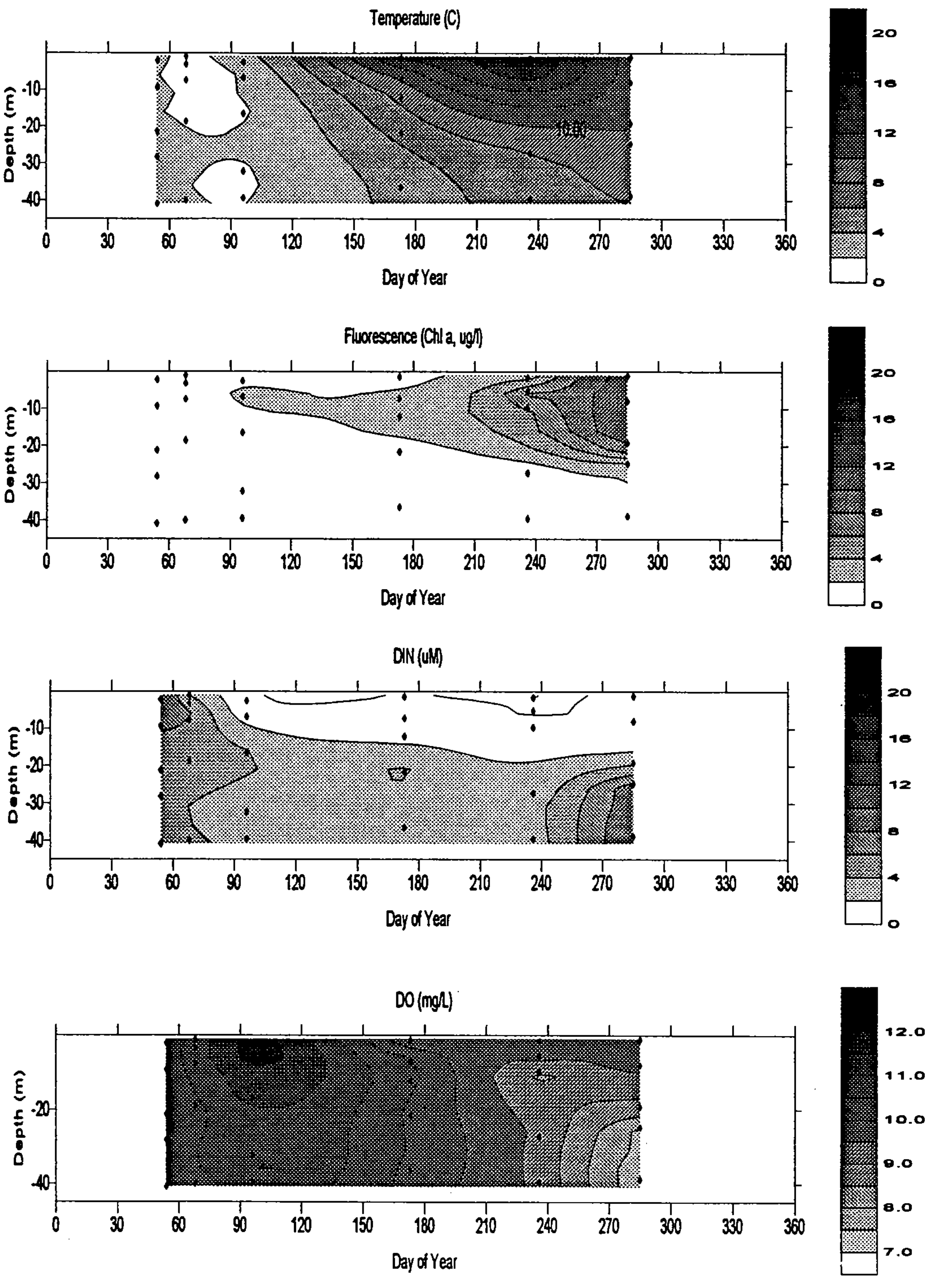


Figure 5.1-2 Annual cycle of temperature, fluorescence, DIN, and DO at station N16P, a representative of the nearfield region.

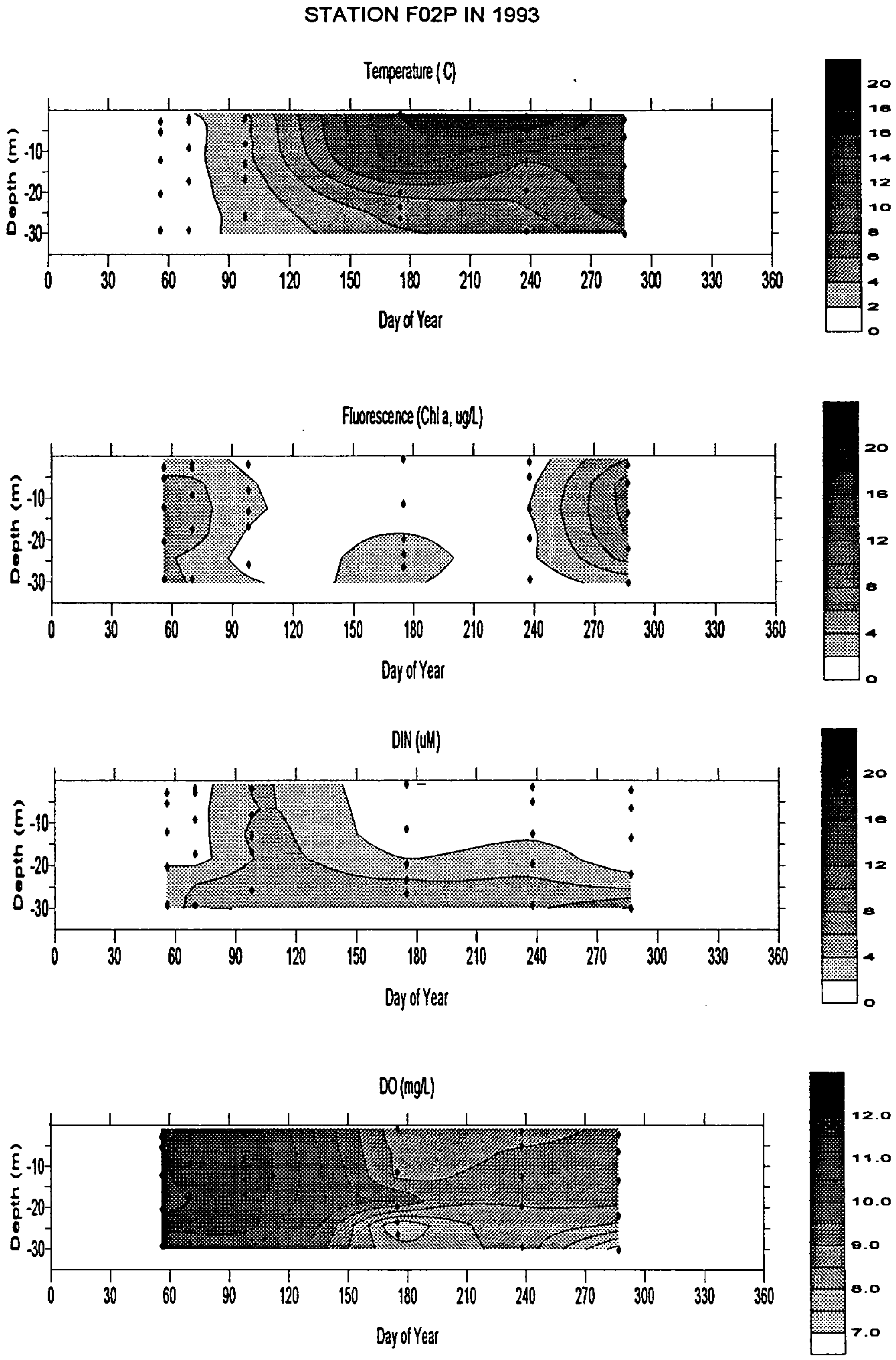


Figure 5.1-3 Annual cycle of temperature, fluorescence, DIN, and DO at station F02P, a representative of the Cape Cod Bay region.

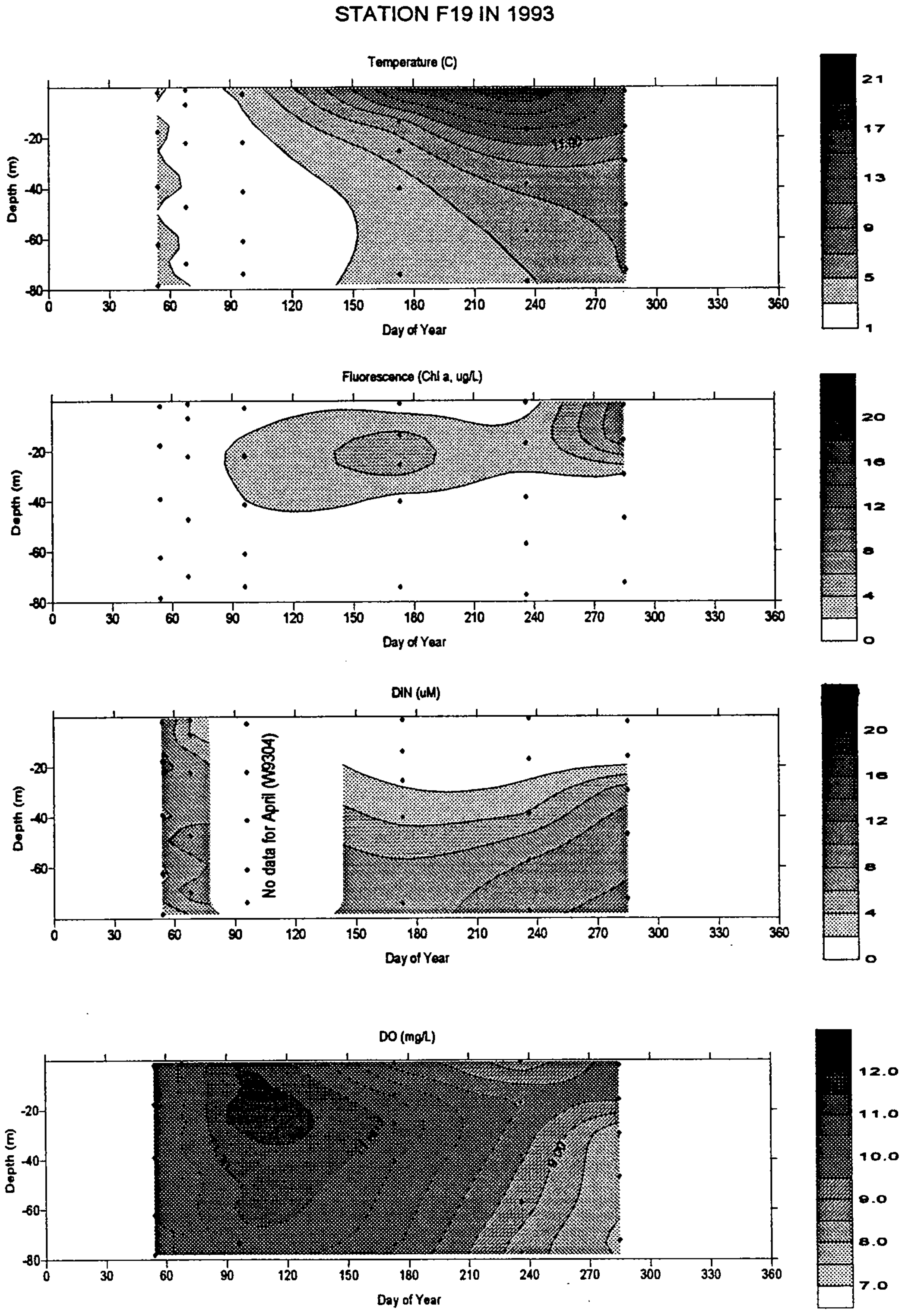


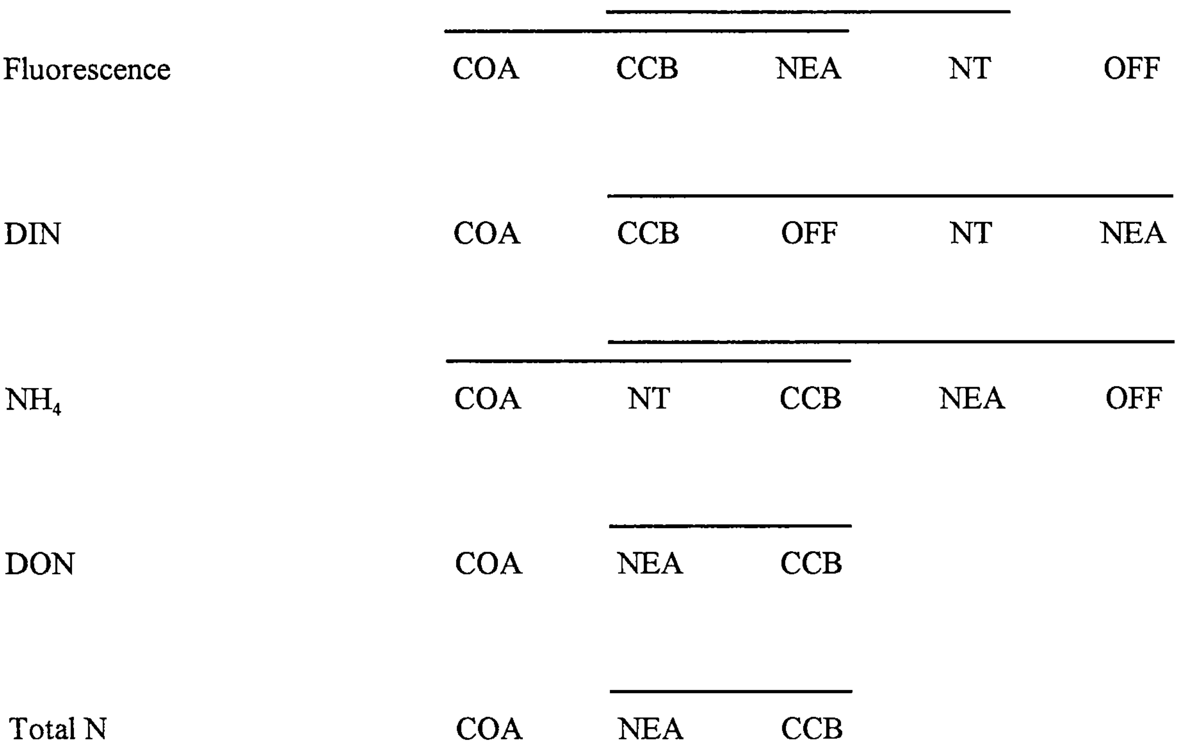
Figure 5.1-4 Annual cycle of temperature, fluorescence, DIN, and DO at station F19P, a representative of the offshore region.

## Table 5-1. Type III ANOVA Significance Levels (Pr>F) for 1993 Farfield Survey Surface Water Data

| Parameter | Region[a] | Survey | Region*Survey Interaction |
|---|---|---|---|
| Fluorescence | 0.0001 | 0.0001 | 0.0001 |
| DIN | 0.0001 | 0.0001 | 0.001 |
| $NH_4$ | 0.0001 | 0.0001 | 0.025 |
| PON | 0.063 | 0.035 | 0.0001 |
| DON | 0.0007 | 0.0001 | 0.054 |
| Total N | 0.0001 | 0.0001 | 0.0019 |
| Total Phytoplankton | 0.487 | 0.0001 | 0.0001 |

[a] Regions = northern transect, nearfield, coastal, offshore, and Cape Cod Bay for fluorescence, DIN and $NH_4$, but only coastal, nearfield, and Cape Cod Bay for PON, DON, total N, and total phytoplankton

## Table 5-2. Results of Tukey's Multiple Comparisons Test to Note Significant Differences Among Surface Waters in Regions of the Bays in 1993



| Parameter | | | | | |
|---|---|---|---|---|---|
| Fluorescence | COA | CCB | NEA | NT | OFF |
| DIN | COA | CCB | OFF | NT | NEA |
| $NH_4$ | COA | NT | CCB | NEA | OFF |
| DON | COA | NEA | CCB | | |
| Total N | COA | NEA | CCB | | |

NT = northern transect
COA = coastal
NEA = nearfield
OFF = offshore
CCB = Cape Cod Bay

Note: Lines connect groups not significantly different from each other.

## Table 5-3. Results of Tukey's Multiple Comparisons Test to Note Significant Differences Among Farfield Surveys in 1993

| **Parameter** | | | | | | |
|---|---|---|---|---|---|---|
| Fluorescence | Oct | Aug | Apr | Jun | Mar | Feb |
| DIN | Feb | Mar | Apr | Oct | Aug | Jun |
| $NH_4$ | Mar | Feb | Apr | Oct | Aug | Jun |
| PON | Oct | Apr | Aug | Jun | Feb | Mar |
| DON | Mar | Apr | Aug | Jun | Feb | Oct |
| Total N | Mar | Feb | Apr | Aug | Jun | Oct |
| Total Phytoplankton | Oct | Aug | Jun | Apr | Feb | Mar |

Note: Lines connect groups not significantly different from each other.

## 5.2 NEARFIELD SCALES

Major aspects of the time and space variability within the nearfield data set were defined in Section 4. Discussion here focuses on fine-scale variability at stations along a distance and concentration gradient that extends from shore (i.e., ≈10 km from west to east across the nearfield). Fluorescence was selected as the parameter to illustrate patterns of trends away from shore, with depth, and over time. A secondary theme of the discussion is a comparison of understanding and characterization of ecological events in the nearfield as the frequency of sampling is varied empirically from 6 to 16 events. This section also provides a perspective on the gradient across the nearfield that has been described earlier in this report and in recent major synthesis reports (Kelly, 1991, 1993a). Similar to the farfield discussion, a graphical presentation serves as prelude to statistical inference testing that confirms the detectability of environmental differences that presently exist within this region.

### 5.2.1 Annual Cycle in 1993 at Selected Stations

***Station N16P.*** Using all 1993 survey data, the pattern for fluorescence at station N16P (Figure 5.2-1) may be compared to the data from the six farfield surveys that were previously discussed (Figure 5.1-2). In Figure 5.2-1, the fundamental event of an intense fall bloom remains the dominant feature. However, because the nearfield surveys from April to August showed uniformly low chlorophyll ($<2\ \mu g\ L^{-1}$) over depth, the image conveyed (Figure 5.1-2) by only six surveys (e.g., a persistent mid-water chlorophyll maximum at 10-20 m and a gradual progression through the summer to a fall peak) is not born out by the data from 16 surveys. Rather, the minor mid-depth peaks ($>2\ \mu g\ L^{-1}$) in April and June were confined to these time periods and were somewhat isolated events. Figure 5.2-1 suggests that the fall bloom was initiated at the surface in early August (≈day 220) and had developed over the entire water column by September (≈days 250 and 270). Peak concentrations ($>12\ \mu g\ L^{-1}$) were observed near the surface in late September, but the maximum peak ($>10\ \mu g\ L^{-1}$) had shifted to 30-40 m by mid-October. Concentrations were tailing off by November and returned to winter levels in

December. Libby *et al.* (1994) noted a downward shift in chlorophyll within the nearfield *during* the survey in mid-October. The shift suggested in Figure 5.2-1 may or may not have been due, in part, to a rapid change in physical structure (cf. Libby *et al.* 1994), but does appears to signal rapid sedimentation of the major bloom event of the year.

***Station N20P.*** The pattern for chlorophyll at station N20P, located several kilometers west of station N16P in water almost 10 m shallower, was strikingly similar to the pattern observed at station N16P (Figure 5.2-1). Relative to station N10P, chlorophyll maxima were located closer to or at the surface. The surface layer chlorophyll concentrations were chronically above 2 $\mu$g $L^{-1}$ for the entire June-October period. Peak surface and subsurface maxima in October were >14 $\mu$g $L^{-1}$

***Station N12.*** This station is located further west of station N20P and, being near the Harbor, represents one end of the nutrient enrichment gradient that chronically exists across the nearfield. This station receives some water that is released from the Harbor-Bay tidal cycles (Kelly and Albro, 1994). From April to October, chlorophyll concentrations at station N12 were >2 $\mu$g $L^{-1}$ more regularly than at station N20P (Figure 5.2-2). The station N12 chlorophyll pattern was more similar to that observed at station N20P than at station N16P. Of these three stations, the highest average surface chlorophyll was detected at station N12.

***Station N06.*** Compared with station N12, station N06 is located at the eastern edge of the nearfield in deeper water (>50 m) and is at the opposite end of the enrichment gradient. During 1993, the chlorophyll pattern at these two stations (Figure 5.2-2) suggests higher average chlorophyll and a chlorophyll enrichment that is more often present at the nutrient-rich western boundary station. Clearly, most of the same temporal features that were observed at stations N12, N20P, and N16P, were also observed at station N06. For example, minor mid-depth maxima occurred in April and in June, and a fall bloom occurred in September-October. Interestingly, the shift from a near-surface chlorophyll peak in late September with the appearance of a local maximum in near-bottom water in October suggests that a similar decline in the fall bloom occurred across the range of depths of the nearfield.

In summary, the chlorophyll patterns across these four nearfield stations illustrate a continuum in spatio-temporal features. Across the nearfield, variation in water depth, as well as in the physical environment, complicates the simple interpretation of chlorophyll variability as a singular response to nutrient enrichment. On the other hand, patterns mimic the results of many enrichment experiments and comparisons from other coastal areas (e.g., Nixon *et al.*, 1986; Kelly, 1991, 1993). The ends of the spatial continuum (stations N12 and N06, Figure 5.2-2) best illustrate a difference moving away from the Harbor seaward across the nearfield — patches of chlorophyll tend to be less concentrated, more isolated in time, more restricted in space, and perhaps more regularly in the subsurface than in the surface.

### 5.2.2 Nearfield Spatial Gradient and Temporal Trends

***Statistical Testing.*** Statistical tests followed the same procedures as outlined for the farfield (Section 5.1.2). Only surface water concentrations of fluorescence, DIN, $NH_4$, and total phytoplankton were examined. Rather than focusing on regions, testing was conducted on groups of stations that generally form north to south-southeast oriented lines graded from shore. The five station groups included "lines" in the west, west-central, central, east-central, and east sectors of the nearfield (lines are about 2-3 km apart; see Table 5-4 for stations included and Figure 2-1.1 for positions). "Lines," surveys, and their interaction were statistically examined. Because of the many comparisons across surveys and the complicated nature of comparison tables, multiple comparison results for surveys are not presented here; in general, they reinforce the interpretation of seasonality gained from farfield testing (e.g., Table 5-3).

***Lines, Surveys, and Interactions.*** Table 5-4 shows that significant differences were obtained for parameters investigated at the 16-survey-per-year frequency, with respect to space, time, and their interaction. Significance of the interaction term suggests that different timing of events and their subsequent effects on concentrations do occur from one side of the nearfield to the other side.

The results of tests that used data at the farfield frequency of six per year (the actual farfield surveys were used) are also presented in Table 5-4. Again, results primarily indicated that there was significance, except for the interaction term for fluorescence, and the line and interaction effects for phytoplankton counts. Thus, in spite of significant fluorescence effects, from west to east across the nearfield, there was no evidence for a significant difference in phytoplankton counts. Counts are measured at only 6 of 21 stations and at a maximum of two stations in any line, so the limited amount of data (compared to fluorescence) limits the detection of spatial differences.

Comparisons among lines (Table 5-5) suggest that differences along this commonly observed shore-to-sea concentration gradient are statistically significant. In general, west and east lines were different, and these were each usually different from one to three of the central lines. Thus, differences on the scale of kilometers across the field that have been previously identified (Kelly, 1993a) are confirmed statistically. It was noted that fewer differences among paired line comparisons were evident when the data from six farfield surveys were used, compared to the nearfield set of sixteen. This is expected based on the increase in the number of samples and thus the statistical power, but it also begins to provide an indication of the scales of detectable change that may be observed with increased or reduced sampling effort.

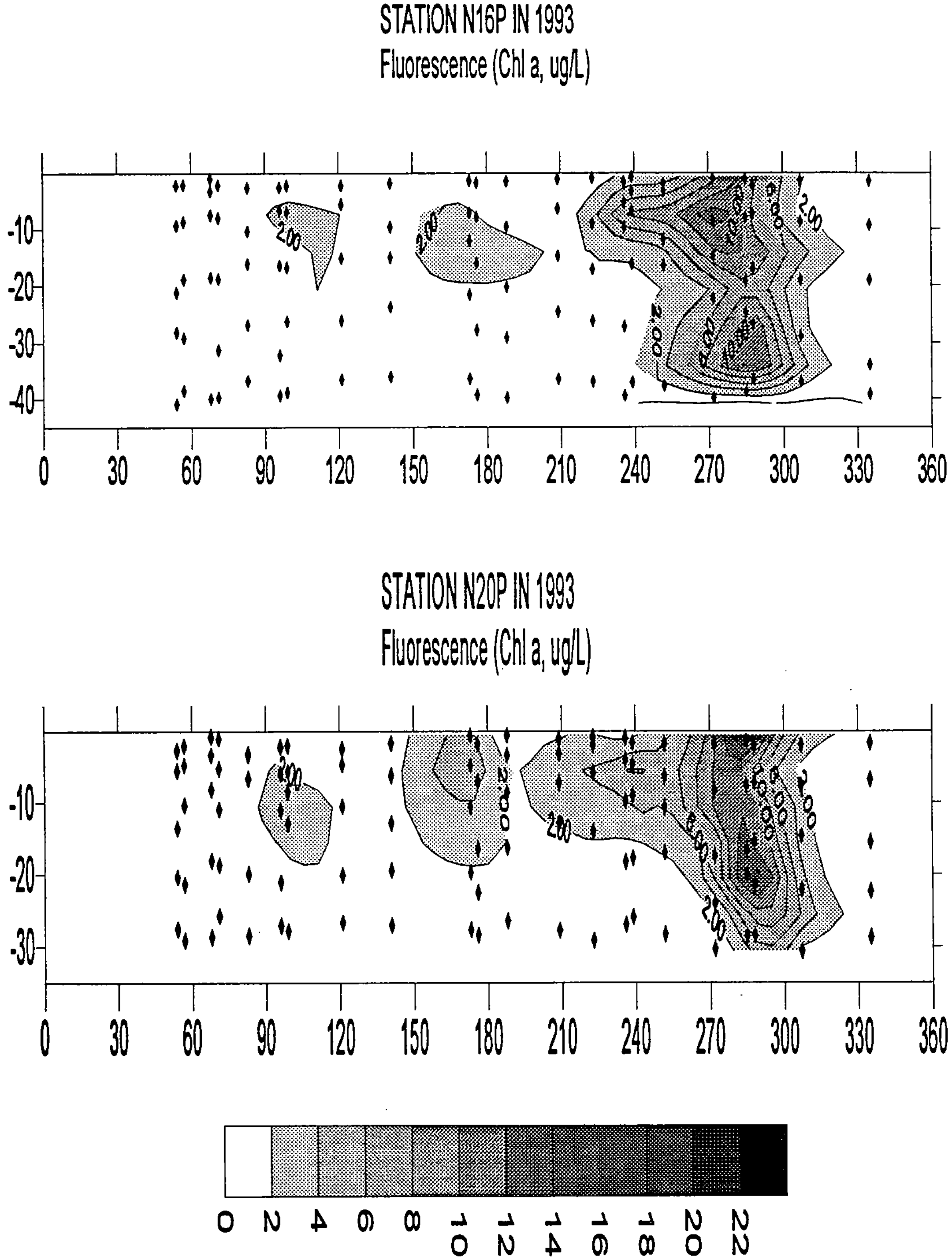


Figure 5.2-1 Annual cycle of fluorescence at stations N16P and N20P, representatives of the east-central and west-central nearfield lines, respectively.

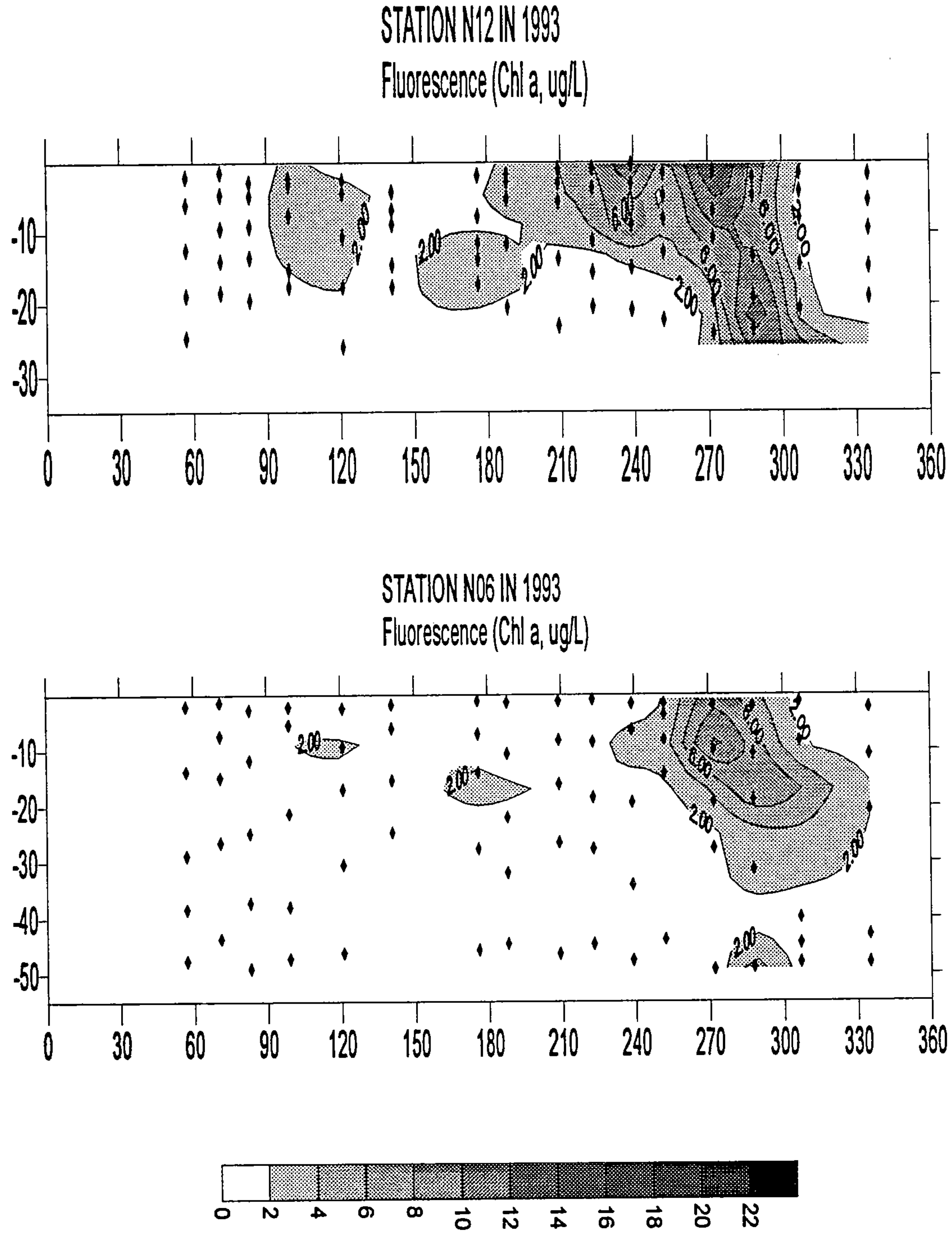


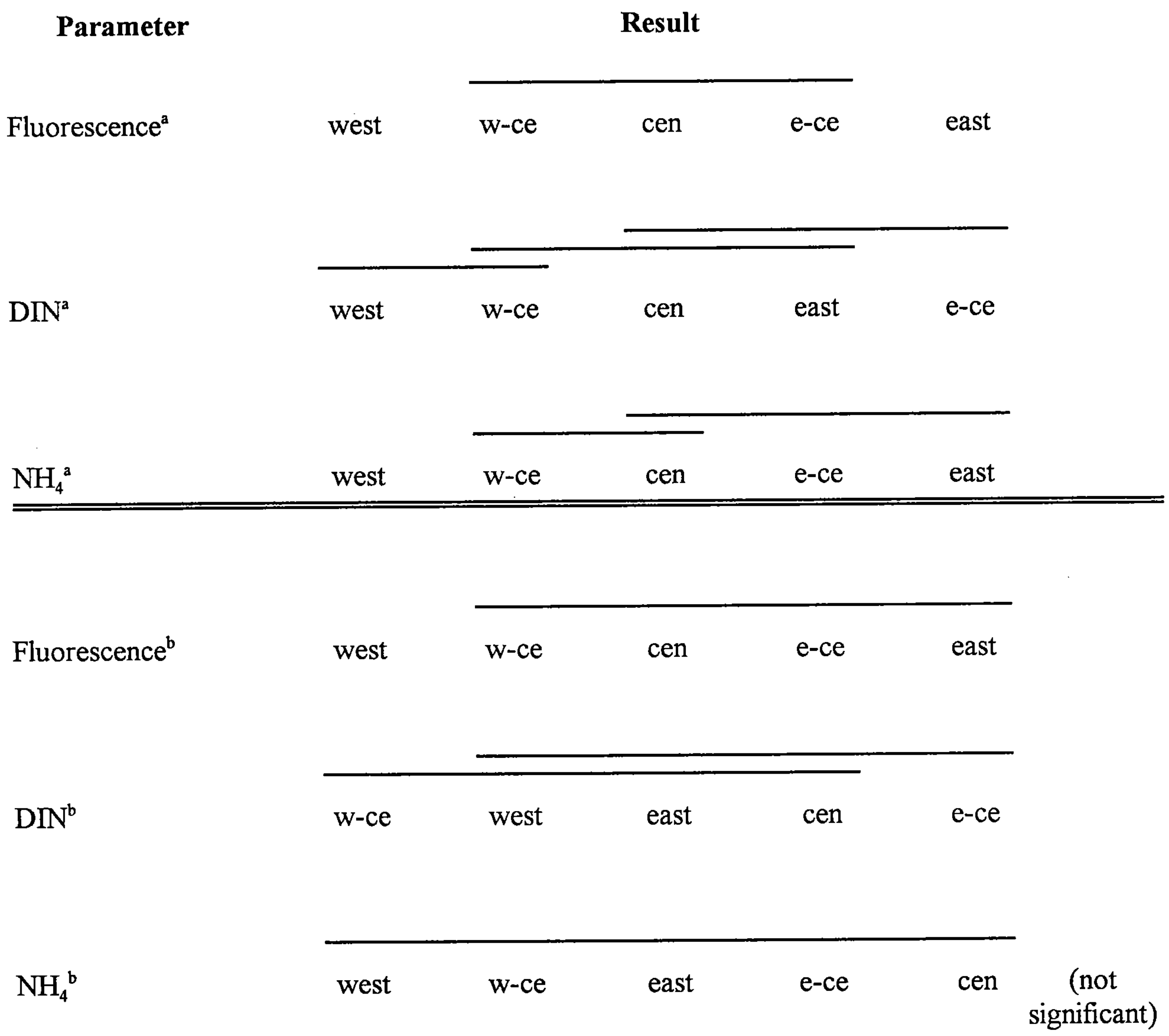
Figure 5.2-2 Annual cycle of fluorescence at stations N12 and N06, representatives of the western and eastern nearfield lines, respectively.

**Table 5-4. Type III ANOVA Significance Levels (Pr>F) for 1993 Nearfield Survey Surface Water Data**

| Parameter | Line[c] | Survey | Line *Survey Interaction |
|---|---|---|---|
| Fluorescence[a] | 0.0001 | 0.0001 | 0.0001 |
| DIN[a] | 0.0001 | 0.0001 | 0.0001 |
| $NH_4$[a] | 0.0001 | 0.0001 | 0.0001 |
| Fluorescence[b] | 0.0001 | 0.0001 | 0.215 |
| DIN[b] | 0.03 | 0.0001 | 0.0011 |
| $NH_4$[b] | 0.018 | 0.0001 | 0.0021 |
| Total Phytoplankton[b] | 0.425 | 0.0001 | 0.457 |

[a] = 16 surveys
[b] = 6 surveys
[c] west = (stations N10P, N11, N12, N01P)
w-ce = west-central (stations N02, N13, N20P, N19, N09)
cen = central (stations N14, N21, N18)
e-ce = east-central (stations N03, N15, N16P, N17, N08)
east = (stations N04P, N05, N06, N07P)

## Table 5-5. Results of Tukey's Multiple Comparisons Test to Note Significant Differences Among Surface Waters in North-South Lines Across the Nearfield in 1993



| Parameter | Result | | | | | |
|---|---|---|---|---|---|---|
| Fluorescence[a] | west | w-ce | cen | e-ce | east | |
| DIN[a] | west | w-ce | cen | east | e-ce | |
| $NH_4$[a] | west | w-ce | cen | e-ce | east | |
| Fluorescence[b] | west | w-ce | cen | e-ce | east | |
| DIN[b] | w-ce | west | east | cen | e-ce | |
| $NH_4$[b] | west | w-ce | east | e-ce | cen | (not significant) |

[a] For 16 survey set, see Table 5-4.
For description of line, see Table 5-4.
[b] For 6 survey set, see Table 5-4.

Note: Lines connect groups not significantly different from each other.

## 5.3 WESTERN MASSACHUSETTS BAY AND THE FALL BLOOM: A DEFINING FEATURE OF 1993.

Having characterized the fall bloom as a defining event of 1993, it seems appropriate to end this annual report by showing the pattern of spatial development of the bloom (Figure 5.3-1). In viewing the sequence of panels in Figure 5.3-1, remember that some spatial variation must reflect the fact that results of sampling are strongly influenced by the tide, at least at the western edge of the field (Kelly and Albro, 1994). However, for this discussion, sampling results from the 21 stations have not been tidally rectified in any way.

The sequence examines surface water concentrations, and flips between nearfield and farfield surveys, using only the 6 "P" stations of the nearfield when the farfield scale is presented. For the combined farfield/nearfield surveys (e.g., Figure 5.3-1b), both portions (and thus spatial scales) are presented.

The sequence starts with the early August nearfield survey (Figure 5.3-1a) when the western line of stations had slightly higher fluorescence concentrations (>3 $\mu$g $L^{-1}$) than the rest of the field, similar to the pattern indicated by statistical testing. The nearfield was not much different in late August, although inshore concentrations were higher than at the western line of the nearfield. Several days later on the nearfield portion of the survey, concentrations had increased above 6 $\mu$g $L^{-1}$ at the northern portion of the western line, a development that seemed to be a seaward progression from the previous days (cf. Figure 5.3-1b, top and bottom).

On September 9 (Figure 5.3-1c), less than two weeks later, there was a retrogression in concentrations and a different spatial pattern, one not reflecting a strong line-by-line decrease offshore. This early September retrogression may mark a pause or transition between major dominants of the diatom succession in the fall 1993 bloom. *Rhizosolenia delicatula* and, secondarily, *Leptocylidrus danicus* had been dominant at nearfield and coastal stations throughout August (see Section 3 and Kelly *et al.*, 1994d). In early September, based on analysis of surface water samples at station N10P (Kelly *et al.*, 1994d), *L. danicus* had become dominant and *R. delicatula* was no longer among the dominants. However, by late September at station N10P, and then throughout the entire region in mid-October, *Asterionellopsis glacialis* had become dominant, with concentrations routinely $>10^6$ cells $L^{-1}$ (see Section 3.4). Thus, in late September, only 20 days later (Figure 5.3-1c), almost all of the nearfield had fully "bloomed." There were maximum concentrations in the central-northern portion of the field and, interestingly, there was now a rotation of spatial pattern to an apparent concentration gradient now mostly oriented to the southeast.

By the time of the farfield survey in mid-October (Figure 5.3-1d), the middle of the field (station N20P) reached the peak annual concentration ($>18\ \mu g\ L^{-1}$). Virtually the entire nearfield had surface values $>9\ \mu g\ L^{-1}$ and, in most locations, fluorescence exceeded 12 $\mu g\ L^{-1}$. The region to the north was also very high (about 15 $\mu g\ L^{-1}$) in fluorescence but, in the east, west, and south, concentrations were lower.

Only days later, on the nearfield survey (Figure 5.3-1d bottom), the scene had changed markedly and chlorophyll concentrations were generally $<6\ \mu g\ L^{-1}$. This rapid loss of chlorophyll from surface waters has been described in some detail by Libby *et al.* (1994) and this event abruptly ended the fall bloom. At the next nearfield sampling on November 9, chlorophyll was $<3\ \mu g\ L^{-1}$ over the field.

While the stages of bloom development need additional scrutiny and analysis, several features are noteworthy. The initial *Rhizosolenia/Leptocylindrus* phase in August appeared to progress into the nearfield from the inshore. Thus, perhaps the nearfield was seeded, in part, by Harbor water and tidal exchange. Unfortunately, at the beginning of the *Asterionellopsis* phase later in September, measurements surrounding the nearfield were not made. Without them, suggesting the source and distribution of this phase of the bloom is problematic. Near bloom termination, it was noted in October that high concentrations were also observed north of the nearfield and lower concentrations were observed inshore. Rather than relate to bloom sources and initiation, this pattern may relate to the shore-to-sea progression of vertical mixing and its effect upon destratification of the water column that was described in Section 4.3.

It is possible to supplement the data and patterns shown in Figure 5.3-1 with data of additional sampling days in the nearfield when high-resolution towing was performed (see Kelly *et al.*, 1994d and Libby *et al.*, 1994). Incorporation of such additional data may be an important aid in understanding the dynamics of this fall event.

In summary, the relatively high frequency of sampling that was maintained during August-October demonstrates a highly resolved image of a major bloom event (Figure 5.3-1) and the fortuitous timing of sampling captured some remarkable, rapid changes (e.g., October). However, sampling may not always be fortuitously timed. Moreover, the mechanisms promoting an intense bloom (weeks in duration), as well as the sources that encourage and maintain its development, may not be deduced easily without a significant analytical effort and probably cannot be adequately confirmed without a specific, directed study to resolve the chronology of environmental events in all waters that interact with the field of interest in the time frame of interest. This observation does not indicate a fundamental flaw in the present monitoring design, but rather is intended as an introspective look at some of the limitations of a rigid design and thus provides useful perspective relative to the design of continued MWRA monitoring efforts.

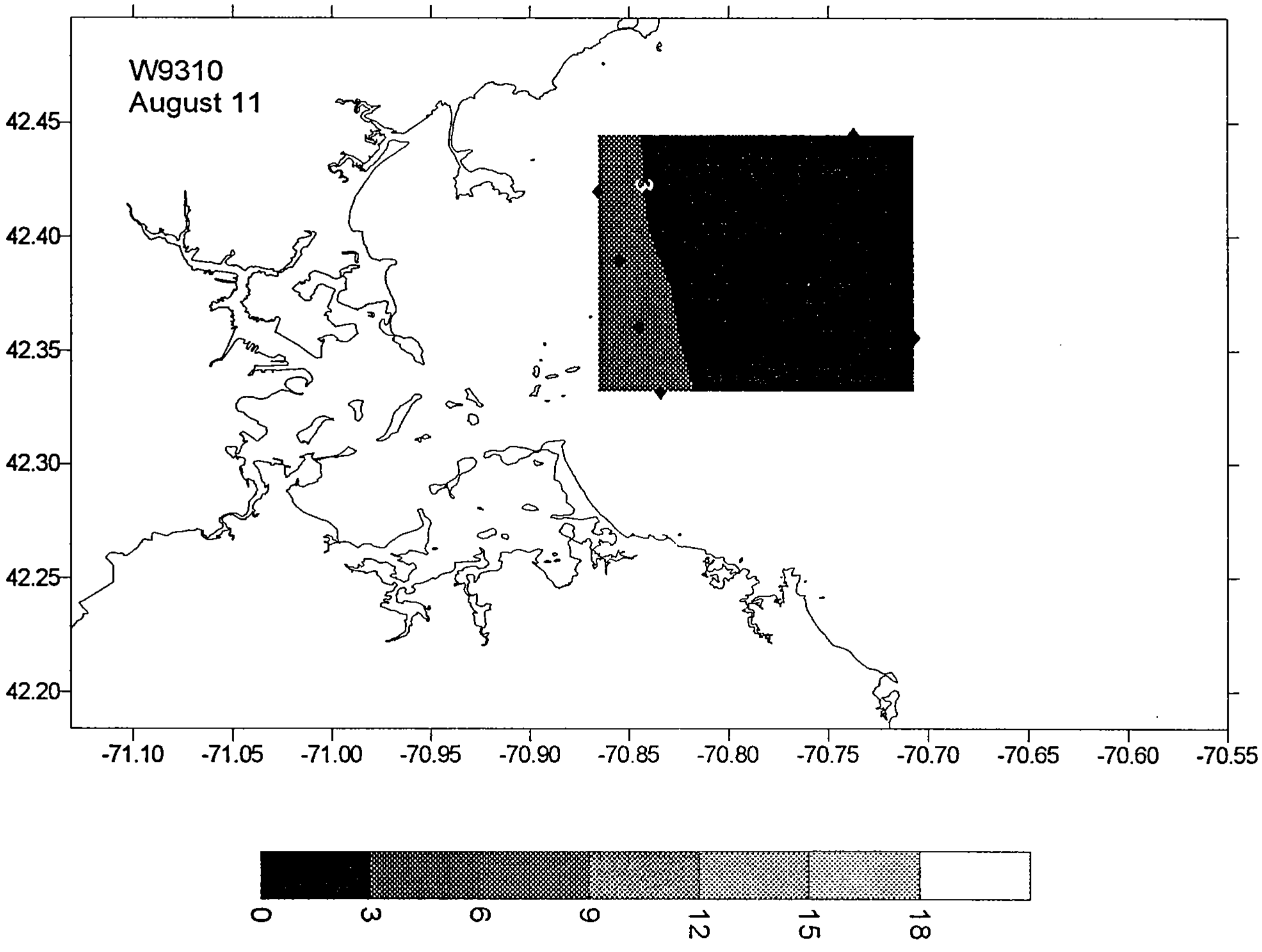


Figure 5.3.1a Development of the fall bloom in western Massachusetts Bay. Data are surface water readings of fluorescence ($\mu$g $L^{-1}$ as chlorophyll *a*).

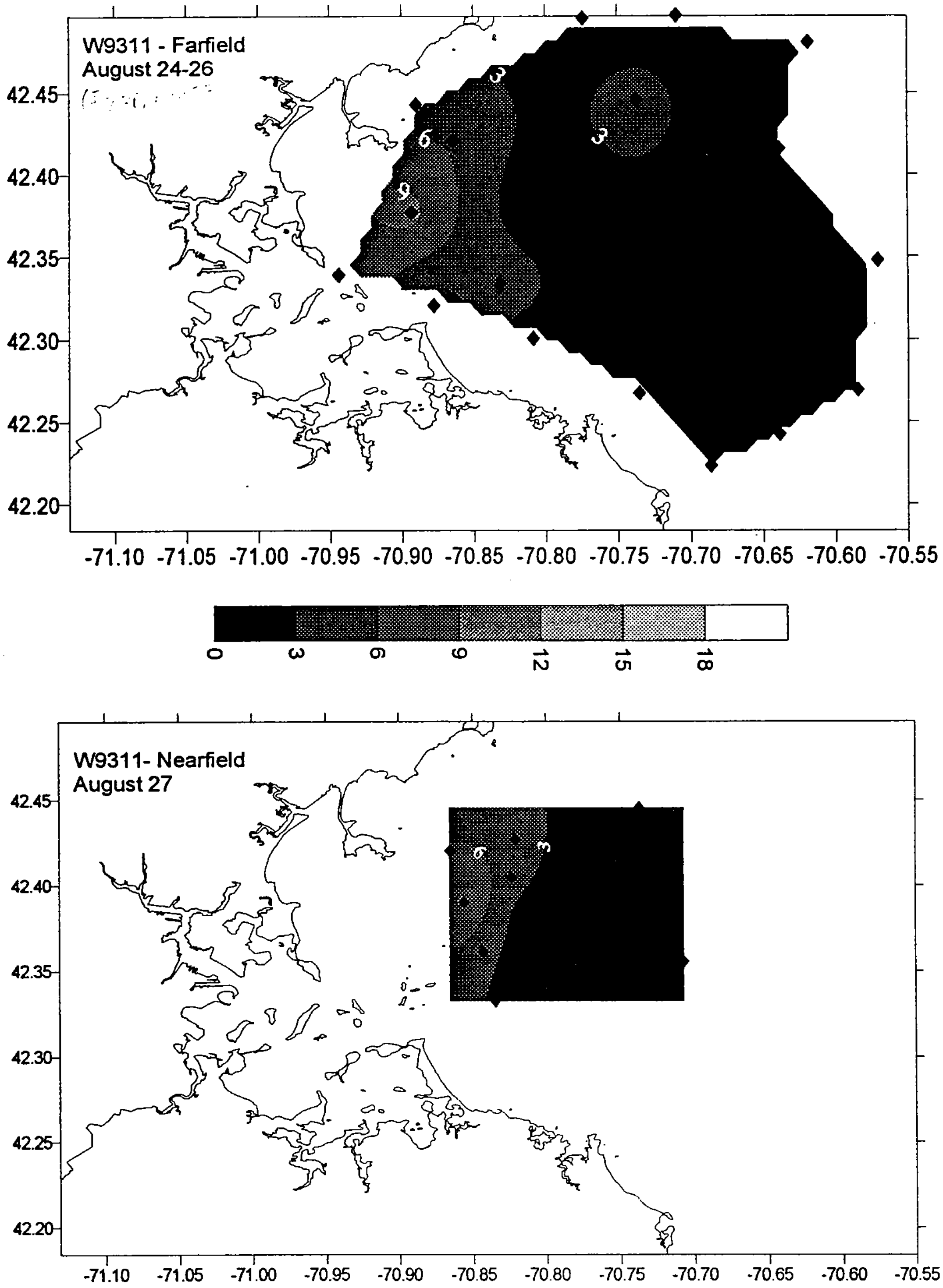


Figure 5.3.1b Development of the fall bloom in western Massachusetts Bay (continued). Data are surface water readings of fluorescence ($\mu$g $L^{-1}$ as chlorophyll *a)*.

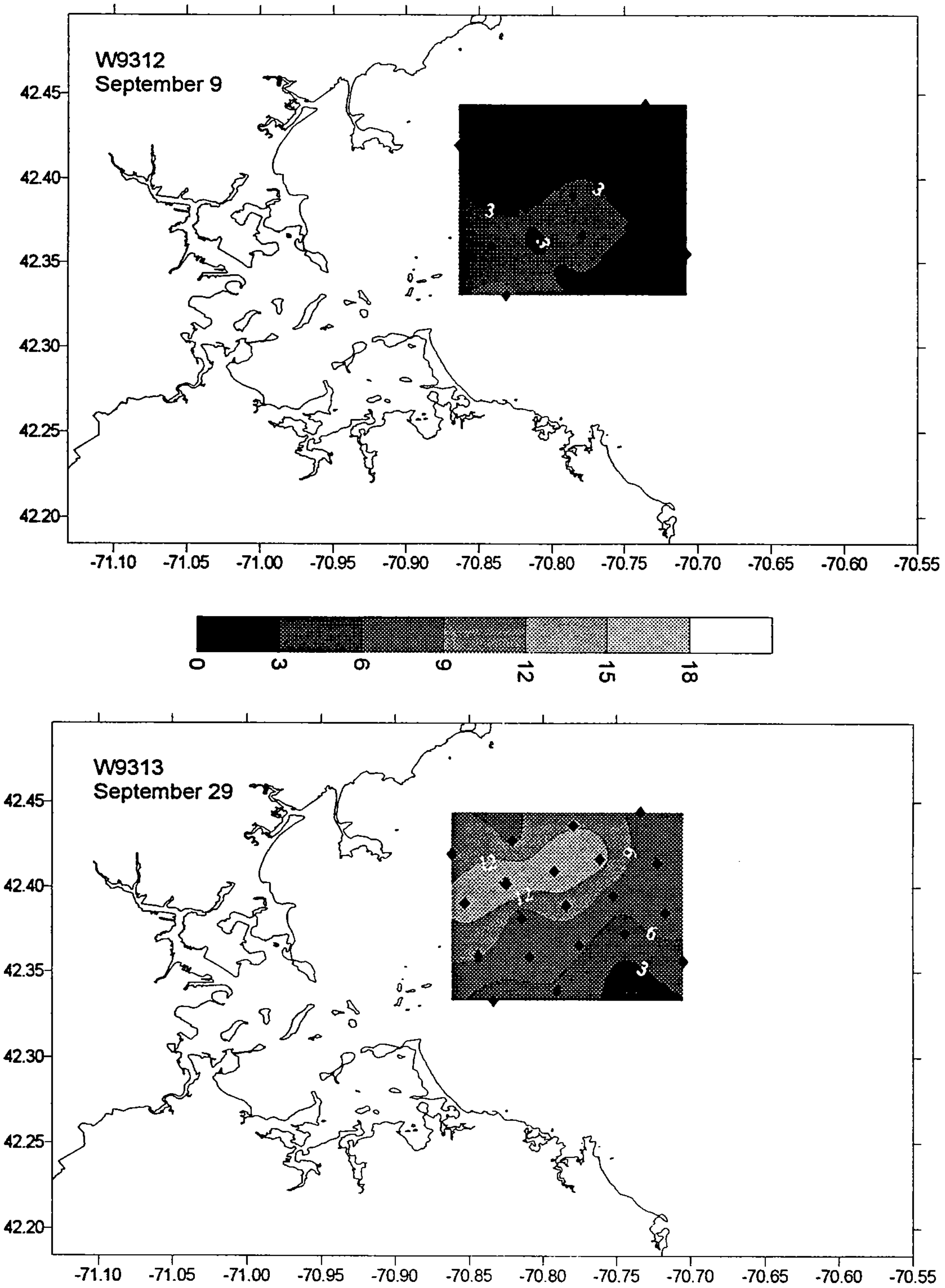


Figure 5.3.1c Development of the fall bloom in western Massachusetts Bay (continued). Data are surface water readings of fluorescence ($\mu$g $L^{-1}$ as chlorophyll *a*).

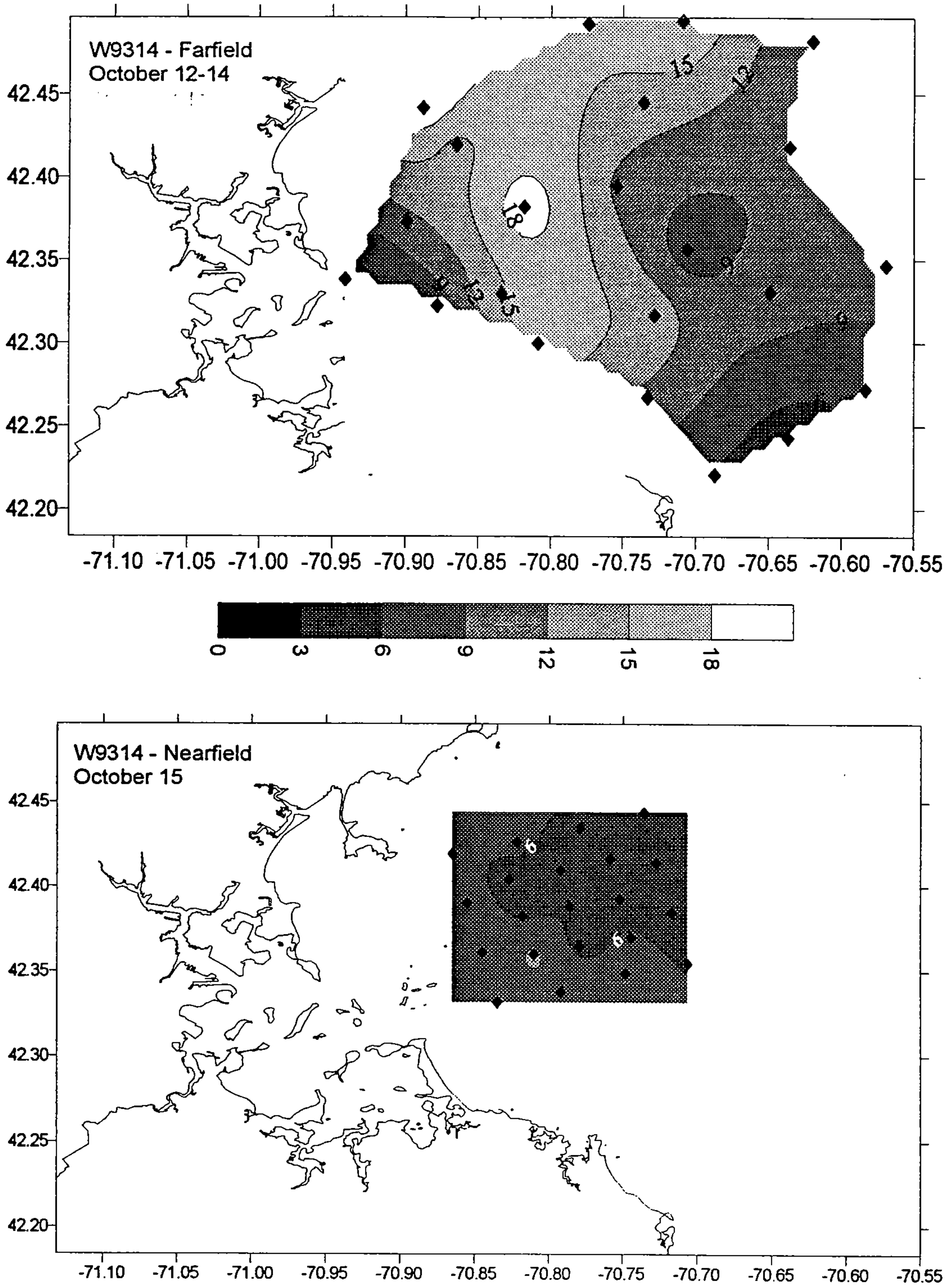


Figure 5.3.1d Development of the fall bloom in western Massachusetts Bay (continued). Data are surface water readings of fluorescence ($\mu g\ L^{-1}$ as chlorophyll *a)*.

# 6.0 REFERENCES

Albro, C.S., J.R. Kelly, and J. Hennessy. 1993. Combined work/quality assurance project plan for baseline water quality monitoring. Prepared for the Massachusetts Water Resources Authority, Boston, MA. 73 pp.

Becker, S.M. 1992. The seasonal distribution of nutrients in Massachusetts and Cape Cod Bays. M.S. Thesis. University of New Hampshire, Durham. 127 pp.

Borland. 1993. User's Guide, Version 5.0, Quattro Pro for Windows. Borland International, Inc., Scotts Valley, CA 95067-0001. 638 pp.

Doering, P.D., V. Berounsky, and C. Heil. 1993. Comparison of $^{14}C$ and $O_2$ techniques for measuring primary production. Appendix H. In: Kelly, J.R., C.S. Albro, and J.T. Hennessy, Appendices to water quality monitoring in Massachusetts and Cape Cod Bays: August-November 1992. Prepared for Massachusetts Water Resources Authority, Boston, MA 02129.

Geyer, W.R., G.B. Gardner, W.S. Brown, J. Irish, B. Butman, T. Loder, and R. Signell. 1992. Physical oceanographic investigation of Massachusetts and Cape Cod Bays. Final Report to Massachusetts Bays Program (MBP-92-03). Boston, Massachusetts. 497 pp.

Giblin, A.E., C. Hopkinson, J. Tucker, B. Nowicki, and J.R. Kelly. 1994. Metabolism, nutrient cycling and denitrification in Boston Harbor and Massachusetts Bay sediments in 1993. MWRA Enviro. Quality Dept. Tech. Rpt. Series No. 94-5. Massachusetts Water Resources Authority, Boston, MA. 54 pp.

Kelly, J.R. 1991. Nutrients and Massachusetts Bay: A synthesis of eutrophication issues. MWRA Enviro. Quality Tech. Rpt. Series No. 91-10. Massachusetts Water Resources Authority, Boston, MA. 66 pp.

Kelly, J.R. 1993a. Nutrients and Massachusetts Bay: An update of eutrophication issues. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 93-17 Massachusetts Water Resources Authority, Boston, MA. 119 pp.

Kelly, J.R. 1993b. Letter-report on primary productivity modeling comparison. Prepared for Massachusetts Water Resources Authority, Boston, MA. December 6, 1993. 14 pp.

Kelly, J.R. and C.S. Albro. 1994. June 1993 Harbor-Bay mapping. Final letter report to Massachusetts Water Resources Authority, Boston, MA. 60 pp.

Kelly, J.R., C.S. Albro, P. Doering, K. Foster, J. Hennessy, L. Reed, and E. Requintina. 1993. Water column monitoring in Massachusetts and Cape Cod Bays: Annual Report for 1992. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 93-16. Massachusetts Water Resources Authority, Boston, MA. 129 pp.

Kelly, J.R., C.S. Albro, J.T. Hennessy, J. Turner, D. Borkman, and P. Doering. 1994a. Water quality monitoring in Massachusetts and Cape Cod Bays: December 1992, February and March 1993. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 94-2. Massachusetts Water Resources Authority, Boston, MA. 197 pp.

Kelly, J.R., C.S. Albro, J.T. Hennessy, J. Turner, D. Borkman, and P. Doering. 1994b. Water quality monitoring in Massachusetts and Cape Cod Bays: April and May 1993. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 94-3. Massachusetts Water Resources Authority, Boston, MA. 143 pp.

Kelly, J.R., C.S. Albro, J.T. Hennessy, J. Turner, D. Borkman, and P. Doering. 1994c. Water quality monitoring in Massachusetts and Cape Cod Bays: June and July 1993. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 94-11. Massachusetts Water Resources Authority, Boston, MA. 152 pp.

Kelly, J.R., C.S. Albro, J.T. Hennessy, P.S. Libby, J. Turner, D. Borkman, and P. Doering. 1994d. Water quality monitoring in Massachusetts and Cape Cod Bays: August and September 1993. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 94-12. Massachusetts Water Resources Authority, Boston, MA. 172 pp.

Libby, P.S., J.R. Kelly, C.S. Albro, J.T. Hennessy, J. Turner, D. Borkman, and P. Doering. 1994. Water quality monitoring in Massachusetts and Cape Cod Bays: October - December 1993. MWRA Environ. Qual. Dept. Tech. Rpt. Ser. No. 94-13. Massachusetts Water Resources Authority, Boston, MA. 143 pp.

MWRA. 1991. Massachusetts Water Resources Authority effluent outfall monitoring plan phase I: baseline studies. MWRA Environ. Qual. Dept., November 1991. Massachusetts Water Resources Authority, Boston, MA. 95 pp.

MWRA. 1990. Marine resources extended monitoring program. Vol. 2. Massachusetts Water Resources Authority, Boston, MA.

MWRA. 1988. Secondary treatment facilities plan. Vol. 5, Appendix Y: Nutrient analysis. Massachusetts Water Resources Authority, Boston, MA.

Nixon, S.W., C.A. Oviatt, J.Frithsen, and B. Sullivan. 1986. Nutrients and the productivity of estuarine and coastal marine ecosystems. *J. Limnol. Soc. South. Afr.* 12(1/2):43-71.

Parsons, T.R.Y. Maita, and C.M. Lalli. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, Oxford. 173 pp.

Platt, T., C.L. Gallegos, and W.G. Harrison. 1980. Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton. *J. Mar. Res.* 38:687-701.

Ricker, W.E. 1973. Linear regressions in Fishery Research. *J. Fish. Res. Board. Can.* 30:409-434.

SAS. 1988a. SAS Institute Inc. SAS Procedures Guide, Release 6.03 Edition. Cary, NC. 441 pp.

SAS. 1988b. SAS Institute Inc. SAS/GRAPH User's Guide, Release 6.03 Edition. Cary, NC. 549 pp.

Signell, R.P. and B. Butman. 1992. Modeling tidal exchange and dispersion in Boston Harbor. *J. Geophys. Res.* 97:15,591-15,606.

Surfer. 1994. User's Guide, Surfer for Windows. Golden Software, Golden, CO 80401-1866.

Turner, J.T. 1994. Planktonic copepods of Boston Harbor, Massachusetts Bay and Cape Cod Bay, 1992. *Hydrobiologia* (in press).

Webb, W.L., M. Newton, and D. Starr. 1974. Carbon dioxide exchange of *Alnus ubra:* A mathematical model. *Oecologia* 17:281-291.

# *APPENDIX*

## *Data Summaries for 1993*
## *Water Column Monitoring in Massachusetts*
## *and Cape Cod Bays*

# *TABLE A-1*

```
     Table A-1:  Statistics by Parameter for Farfield Surveys in 1993
                                All Depths in 1993

N Obs  Variable     N        Minimum        Maximum           Mean        Std Dev
-----------------------------------------------------------------------------------

 1104  LATITUDE   1104     41.8487500     42.4968300     42.3041724      0.1517361
       LONGITUD   1104    -70.9465000    -70.2255000    -70.6850539      0.1643256
       DEPTH      1104      0.4300000     88.2700000     17.5879801     17.2230944
       JUL_DAY    1104     54.0000000    288.0000000    153.6177536     86.6955819
       DAYTIME    1104      0.2183333      0.8437500      0.4744456      0.1414517
       TEMP       1104      0.3600000     20.1120000      6.5911594      5.1619465
       SAL        1104     27.9910000     32.7600000     31.6313207      0.6724442
       SIGMA_T    1104     21.6860000     26.0300000     24.6744828      1.1058231
       TRANS      1104      0.5341100      6.0400000      1.3748807      0.6891270
       FLU        1103      0.0900000     21.1060000      2.8436833      3.8542172
       DO         1098      6.6800000     13.1900000     10.3103461      1.1528076
       OXSAT      1104      7.5423063     11.6614636     10.0930244      1.1295446
       SATUR      1098     71.8929177    131.9778648    102.6132385      8.9801579
       COND       1104     26.1400000     43.0930000     31.9303469      4.1277551
       PRES       1104      0.4300000     88.2700000     17.5903080     17.2212417
       SURFACE_    845      0.2300000        3046.22        1770.71    953.1422360
       LIGHT       843      0.0300000        1753.43    198.5483511    367.6351637
       DEP_CODE    442      1.0000000      3.0000000      2.0000000      1.0011331
       REGION     1104      1.0000000      5.0000000      2.9918478      1.1579387
       NH4        1089              0      9.0200000      1.1046465      1.3554426
       NO3        1104              0     11.7000000      2.6579801      3.1915326
       NO2        1091              0      2.3500000      0.1108158      0.1814867
       PO4        1090              0      2.3400000      0.4728165      0.3011433
       SIO4       1091              0     22.4100000      5.4540697      3.9109085
       CHLA        204      0.0550000     26.7900000      2.9212525      3.9185558
       PHA         204     -2.6500000      4.2800000      0.9773284      0.7731406
       DOC         132     66.3104200    557.1508300    118.3661680     49.1422377
       POC         131      4.2500000     41.1666650     17.5722202      7.4669251
       PON         129      0.7896800      7.5000000      3.0732838      1.2677186
       TDN         132      5.5400000     28.8550000     12.7353788      5.7216158
       TDP         132      0.1850000      4.3050000      0.7275000      0.5905653
       TSS         203      0.0750000     13.4050000      2.0446980      1.6614824
       TOT_PHY     126      0.1180000      8.1240000      1.5975159      1.9768147
       NDEPTH     1104    -88.2700000     -0.4300000    -17.5879801     17.2230944
       TOTALN      129      8.3969650     36.3550000     15.7524698      6.0477687
       DIN        1089              0     21.0800000      3.9101928      3.7836836

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From file 93fargch.sas/*.log/*.lst
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Most parameter abbreviations are self-explanatory, but

Trans = beam attenuation
Flu = fluorescence
Oxsat = oxygen saturation at sample conditions
Satur = % of oxsat
Surface_ = incident irradiance
Light = underwater light readings

## *TABLE A-2*

Table A-2: Means by station for surface water samples based on farfield surveys in 1993.

| OBS | STATION | _TYPE_ | _FREQ_ | FLU | TRANS | PO4 | SIO4 | DIN | NH4 | PON | TDN | DP | TOTALN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ALL | 0 | 311 | 2.44712 | 1.42614 | 0.34570 | 4.09699 | 2.87354 | 0.75656 | 2.98770 | 12.6176 | 6.3659 | 15.5548 |
| 2 | F01P | 1 | 6 | 2.14488 | 1.08316 | 0.43500 | 2.91500 | 2.56833 | 0.64833 | 2.72835 | 10.4575 | 5.2967 | 13.1858 |
| 3 | F02P | 1 | 6 | 2.52630 | 1.04089 | 0.24500 | 2.37000 | 1.35000 | 0.15500 | 2.91003 | 9.7658 | 4.2600 | 12.6759 |
| 4 | F03 | 1 | 6 | 1.93668 | 1.49361 | 0.39833 | 4.05833 | 2.67500 | 0.69333 | . | . | . | . |
| 5 | F04 | 1 | 5 | 3.22940 | 0.97593 | 0.31800 | 2.30200 | 1.18800 | 0.53400 | . | . | . | . |
| 6 | F05 | 1 | 6 | 1.23637 | 1.89902 | 0.47500 | 4.97333 | 4.67000 | 1.25833 | . | . | . | . |
| 7 | F06 | 1 | 6 | 1.73465 | 1.10426 | 0.41500 | 4.23500 | 2.66667 | 0.86333 | . | . | . | . |
| 8 | F07 | 1 | 6 | 1.75287 | 1.01066 | 0.32500 | 3.96667 | 2.47333 | 0.18000 | . | . | . | . |
| 9 | F08 | 1 | 6 | 2.09595 | 0.97196 | 0.28667 | 3.52833 | 1.94833 | 0.63833 | . | . | . | . |
| 10 | F09 | 1 | 6 | 1.66398 | 1.46331 | 0.34500 | 4.48667 | 3.51667 | 0.79000 | . | . | . | . |
| 11 | F10 | 1 | 6 | 1.33570 | 1.15230 | 0.29667 | 3.97667 | 2.36000 | 0.49333 | . | . | . | . |
| 12 | F11 | 1 | 6 | 1.48665 | 1.02727 | 0.31333 | 3.81667 | 2.37333 | 0.26000 | . | . | . | . |
| 13 | F12 | 1 | 6 | 0.41802 | 1.00446 | 0.37000 | 3.82000 | 2.94500 | 0.34167 | . | . | . | . |
| 14 | F13P | 1 | 6 | 2.93285 | 1.83517 | 0.66333 | 4.62833 | 4.19500 | 1.64500 | 2.79524 | 14.5100 | 6.9902 | 17.3052 |
| 15 | F14 | 1 | 6 | 3.82728 | 2.01455 | 0.38167 | 5.12167 | 4.73167 | 1.30000 | . | . | . | . |
| 16 | F15 | 1 | 6 | 3.31897 | 1.44490 | 0.25000 | 4.02167 | 2.44333 | 0.10667 | . | . | . | . |
| 17 | F16 | 1 | 6 | 2.21100 | 1.03902 | 0.33667 | 3.88000 | 2.62667 | 0.81667 | . | . | . | . |
| 18 | F17 | 1 | 6 | 2.25547 | 1.03984 | 0.39000 | 4.07000 | 3.02400 | 0.23400 | . | . | . | . |
| 19 | F18 | 1 | 6 | 4.89693 | 1.88480 | 0.28333 | 4.42333 | 2.69500 | 0.68000 | . | . | . | . |
| 20 | F19 | 1 | 6 | 2.06857 | 1.26735 | 0.35800 | 4.06200 | 2.61200 | 0.84600 | . | . | . | . |
| 21 | F20 | 1 | 6 | 3.91758 | 1.40639 | 0.28833 | 4.86167 | 2.02000 | 0.82000 | . | . | . | . |
| 22 | F21 | 1 | 6 | 3.90838 | 1.47225 | 0.28000 | 4.34167 | 2.06833 | 0.92833 | . | . | . | . |
| 23 | F22 | 1 | 6 | 1.96457 | 1.08110 | 0.34333 | 4.57833 | 2.80667 | 0.68500 | . | . | . | . |
| 24 | F23P | 1 | 6 | 3.67475 | 2.57481 | 0.62000 | 7.23000 | 8.83000 | 3.82333 | 3.93930 | 20.0067 | 12.7693 | 23.9460 |
| 25 | F24 | 1 | 6 | 4.95488 | 2.47365 | 0.44500 | 5.78667 | 6.17833 | 3.32833 | . | . | . | . |
| 26 | F25 | 1 | 6 | 2.24552 | 2.02572 | 0.60667 | 5.38667 | 6.75500 | 2.17667 | 3.17279 | 15.3510 | 8.4788 | 18.5238 |
| 27 | N01P | 1 | 12 | 3.37382 | 1.46320 | 0.33667 | 4.03417 | 2.62417 | 0.59917 | 3.07469 | 11.7417 | 6.1330 | 14.8164 |
| 28 | N02 | 1 | 6 | 2.33500 | 1.28570 | 0.34500 | 3.83500 | 2.70500 | 0.41500 | . | . | . | . |
| 29 | N03 | 1 | 6 | 1.63145 | 1.11403 | 0.29000 | 3.95500 | 1.99500 | 0.94667 | . | . | . | . |
| 30 | N04P | 1 | 12 | 2.47695 | 1.21846 | 0.22500 | 4.18917 | 2.17545 | 0.33364 | 2.24081 | 11.5408 | 3.1760 | 12.9198 |
| 31 | N05 | 1 | 6 | 1.46073 | 1.01490 | 0.30333 | 4.28167 | 2.59000 | 0.19333 | . | . | . | . |
| 32 | N06 | 1 | 6 | 1.45282 | 1.07641 | 0.27833 | 3.70000 | 1.67167 | 0.35667 | . | . | . | . |
| 33 | N07P | 1 | 12 | 1.82035 | 1.17681 | 0.28667 | 3.79417 | 2.01667 | 0.34417 | 2.19832 | 10.7508 | 4.5667 | 12.9492 |
| 34 | N08 | 1 | 6 | 2.05870 | 1.27556 | 0.29000 | 3.72500 | 2.02500 | 0.28667 | . | . | . | . |
| 35 | N09 | 1 | 6 | 2.35997 | 1.42604 | 0.38833 | 3.95667 | 2.83667 | 0.49333 | . | . | . | . |
| 36 | N10P | 1 | 12 | 3.49873 | 2.08176 | 0.46250 | 4.87333 | 4.52500 | 1.79083 | 3.87012 | 13.8050 | 6.9435 | 17.6751 |
| 37 | N11 | 1 | 6 | 2.67115 | 1.46707 | 0.33833 | 4.32833 | 3.13833 | 1.39500 | . | . | . | . |
| 38 | N12 | 1 | 6 | 3.57588 | 3.83020 | 0.29000 | 4.05000 | 2.54000 | 0.72167 | . | . | . | . |
| 39 | N13 | 1 | 6 | 1.88568 | 1.25662 | 0.30167 | 3.72667 | 2.00833 | 0.67000 | . | . | . | . |
| 40 | N14 | 1 | 6 | 1.50972 | 1.18462 | 0.31500 | 3.63000 | 2.82167 | 0.26167 | . | . | . | . |
| 41 | N15 | 1 | 6 | 1.52447 | 1.20771 | 0.28833 | 3.66833 | 1.90833 | 0.25667 | . | . | . | . |
| 42 | N16P | 1 | 12 | 2.26281 | 1.27755 | 0.27583 | 3.51667 | 2.38167 | 0.19750 | 2.73125 | 10.0908 | 4.9729 | 12.8221 |
| 43 | N17 | 1 | 6 | 1.76643 | 1.20739 | 0.24667 | 3.56500 | 1.52667 | 0.69000 | . | . | . | . |
| 44 | N18 | 1 | 6 | 1.75370 | 1.25067 | 0.32167 | 3.59833 | 2.32667 | 0.19333 | . | . | . | . |
| 45 | N19 | 1 | 6 | 2.27365 | 1.23755 | 0.34667 | 3.96000 | 2.53333 | 0.15500 | . | . | . | . |
| 46 | N20P | 1 | 12 | 3.15667 | 1.41258 | 0.36333 | 3.71833 | 2.59333 | 0.47417 | 3.11020 | 11.2292 | 5.7269 | 14.3394 |
| 47 | N21 | 1 | 6 | 1.86608 | 1.20267 | 0.26833 | 3.66167 | 2.02833 | 0.40167 | . | . | . | . |

Note that all nearfield stations are summarized, using the combined sampling of each of the six farfield/nearfield surveys.

From 93tstnh4.sas/*.log/*.lst

## *TABLE A-3*

Table A-3: Selected parameter statistics by all stations,
for surface water samples based on combined farfield/nearfield surveys in 1993.

| STATION | N Obs | Variable | N | Minimum | Maximum | Mean | Std Dev |
|---|---|---|---|---|---|---|---|
| F01P | 6 | FLU | 6 | 0.5635000 | 4.7900000 | 2.1448833 | 1.6999331 |
| | | TRANS | 6 | 0.7283500 | 1.4800000 | 1.0831650 | 0.3416177 |
| | | PO4 | 6 | 0.1300000 | 0.8800000 | 0.4350000 | 0.2851491 |
| | | SIO4 | 6 | 0.8100000 | 5.0800000 | 2.9150000 | 1.6295858 |
| | | DIN | 6 | 0.1400000 | 6.4300000 | 2.5683333 | 3.0071343 |
| | | NH4 | 6 | 0.1100000 | 1.6200000 | 0.6483333 | 0.5513408 |
| | | PON | 6 | 1.5000000 | 4.9285700 | 2.7283450 | 1.4126616 |
| | | TDN | 6 | 7.7450000 | 14.9150000 | 10.4575000 | 3.1639007 |
| | | DP | 6 | 1.6400000 | 11.2685700 | 5.2966783 | 4.3859352 |
| | | TOTALN | 6 | 9.2700000 | 18.1835700 | 13.1858450 | 4.1400068 |
| F02P | 6 | FLU | 6 | 0.6710000 | 6.4788000 | 2.5263000 | 2.1990017 |
| | | TRANS | 6 | 0.6688100 | 1.3264800 | 1.0408900 | 0.2651944 |
| | | PO4 | 6 | 0.0600000 | 0.5400000 | 0.2450000 | 0.1793042 |
| | | SIO4 | 6 | 0.3200000 | 4.9900000 | 2.3700000 | 1.5947790 |
| | | DIN | 6 | 0.0100000 | 4.7900000 | 1.3500000 | 1.8421726 |
| | | NH4 | 6 | 0 | 0.2600000 | 0.1550000 | 0.0857321 |
| | | PON | 6 | 0.7896800 | 4.5714300 | 2.9100308 | 1.6227180 |
| | | TDN | 6 | 6.6750000 | 16.4250000 | 9.7658333 | 3.6285843 |
| | | DP | 6 | 0.9896800 | 8.5042900 | 4.2600308 | 3.0232254 |
| | | TOTALN | 6 | 8.7446800 | 20.1392900 | 12.6758642 | 4.6068575 |
| F03 | 6 | FLU | 6 | 0.2897000 | 3.4000000 | 1.9366833 | 1.4165608 |
| | | TRANS | 6 | 0.6911300 | 2.2000000 | 1.4936133 | 0.7184325 |
| | | PO4 | 6 | 0.0900000 | 0.8200000 | 0.3983333 | 0.2643798 |
| | | SIO4 | 6 | 0.4200000 | 8.6300000 | 4.0583333 | 3.4730817 |
| | | DIN | 6 | 0.0800000 | 7.3000000 | 2.6750000 | 3.2739380 |
| | | NH4 | 6 | 0.0300000 | 1.7400000 | 0.6933333 | 0.6458070 |
| | | PON | 0 | . | . | . | . |
| | | TDN | 0 | . | . | . | . |
| | | DP | 0 | . | . | . | . |
| | | TOTALN | 0 | . | . | . | . |
| F04 | 5 | FLU | 5 | 0.7451000 | 10.3526000 | 3.2294000 | 4.1262910 |
| | | TRANS | 5 | 0.7017200 | 1.3501500 | 0.9759280 | 0.2825421 |
| | | PO4 | 5 | 0.0700000 | 0.5400000 | 0.3180000 | 0.1679881 |
| | | SIO4 | 5 | 1.1800000 | 3.8000000 | 2.3020000 | 1.1099414 |
| | | DIN | 5 | 0.1100000 | 2.7300000 | 1.1880000 | 1.1271291 |
| | | NH4 | 5 | 0.0400000 | 1.9900000 | 0.5340000 | 0.8202012 |
| | | PON | 0 | . | . | . | . |
| | | TDN | 0 | . | . | . | . |
| | | DP | 0 | . | . | . | . |
| | | TOTALN | 0 | . | . | . | . |
| F05 | 6 | FLU | 6 | 0.5400000 | 3.4400000 | 1.2363667 | 1.1079120 |
| | | TRANS | 6 | 0.7276400 | 3.2700000 | 1.8990233 | 1.0579016 |
| | | PO4 | 6 | 0.1000000 | 1.0500000 | 0.4750000 | 0.3805128 |
| | | SIO4 | 6 | 0.5100000 | 11.1900000 | 4.9733333 | 4.5038191 |
| | | DIN | 6 | 0 | 13.6700000 | 4.6700000 | 5.9022064 |
| | | NH4 | 6 | 0 | 3.9700000 | 1.2583333 | 1.7847063 |
| | | PON | 0 | . | . | . | . |

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                    1993 Surface- Farfield surveys

STATION     N Obs  Variable   N      Minimum      Maximum         Mean      Std Dev
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F05             6  TDN        0            .            .            .            .
                   DP         0            .            .            .            .
                   TOTALN     0            .            .            .            .

F06             6  FLU        6    0.2000000    7.6454000    1.7346500    2.9057190
                   TRANS      6    0.7674400    1.5848300    1.1042633    0.3317566
                   PO4        6    0.0700000    1.3700000    0.4150000    0.5063892
                   SIO4       6    0.4900000    9.6800000    4.2350000    4.0737882
                   DIN        6            0    9.5300000    2.6666667    4.0543294
                   NH4        6            0    3.8300000    0.8633333    1.4823720
                   PON        0            .            .            .            .
                   TDN        0            .            .            .            .
                   DP         0            .            .            .            .
                   TOTALN     0            .            .            .            .

F07             6  FLU        6    0.3400000    7.4721000    1.7528667    2.8175437
                   TRANS      6    0.6928900    1.5110800    1.0106617    0.3156223
                   PO4        6    0.0900000    0.6800000    0.3250000    0.2734045
                   SIO4       6    0.8800000    9.2500000    3.9666667    3.9777867
                   DIN        6            0    7.7300000    2.4733333    3.5045665
                   NH4        6            0    0.4200000    0.1800000    0.1663731
                   PON        0            .            .            .            .
                   TDN        0            .            .            .            .
                   DP         0            .            .            .            .
                   TOTALN     0            .            .            .            .

F08             6  FLU        6    0.1700000   10.1297000    2.0959500    3.9440099
                   TRANS      6    0.6822200    1.5886500    0.9719617    0.3301785
                   PO4        6    0.0600000    0.7000000    0.2866667    0.2523225
                   SIO4       6    0.2000000    8.9300000    3.5283333    4.1752768
                   DIN        6    0.0700000    6.4900000    1.9483333    2.8875416
                   NH4        6            0    2.9200000    0.6383333    1.1346262
                   PON        0            .            .            .            .
                   TDN        0            .            .            .            .
                   DP         0            .            .            .            .
                   TOTALN     0            .            .            .            .

F09             6  FLU        6    0.5900000    5.8117000    1.6639833    2.0452126
                   TRANS      6    0.8463200    2.3200000    1.4633133    0.6127311
                   PO4        6    0.0800000    0.8900000    0.3450000    0.3271544
                   SIO4       6    0.2300000   10.3500000    4.4866667    4.3989211
                   DIN        6    0.0400000    9.5800000    3.5166667    4.6450002
                   NH4        6    0.0200000    1.7600000    0.7900000    0.8360861
                   PON        0            .            .            .            .
                   TDN        0            .            .            .            .
                   DP         0            .            .            .            .
                   TOTALN     0            .            .            .            .

F10             6  FLU        6    0.4536000    4.4291000    1.3357000    1.5633118
                   TRANS      6    0.7336800    1.8400000    1.1523033    0.4398673
                   PO4        6    0.0400000    0.6500000    0.2966667    0.2484083
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                         1993 Surface- Farfield surveys

STATION     N Obs  Variable    N      Minimum       Maximum          Mean        Std Dev
----------------------------------------------------------------------------------------
F10             6  SIO4        6    0.2500000     9.8100000     3.9766667      4.2735543
                   DIN         6    0.0300000     6.6400000     2.3600000      2.7894085
                   NH4         6    0.0300000     1.4300000     0.4933333      0.4930585
                   PON         0            .             .             .              .
                   TDN         0            .             .             .              .
                   DP          0            .             .             .              .
                   TOTALN      0            .             .             .              .

F11             6  FLU         6    0.3400000     6.3971000     1.4866500      2.4111485
                   TRANS       6    0.6154000     1.5172600     1.0272650      0.3253830
                   PO4         6    0.0700000     0.7200000     0.3133333      0.2710474
                   SIO4        6    0.2800000     9.3500000     3.8166667      4.2554984
                   DIN         6    0.0700000     8.0500000     2.3733333      3.5133156
                   NH4         6    0.0400000     0.8800000     0.2600000      0.3129856
                   PON         0            .             .             .              .
                   TDN         0            .             .             .              .
                   DP          0            .             .             .              .
                   TOTALN      0            .             .             .              .

F12             6  FLU         5    0.2500000     0.5500000     0.4180200      0.1142289
                   TRANS       6    0.7028900     1.7550900     1.0044617      0.3943651
                   PO4         6    0.1100000     0.9400000     0.3700000      0.3398823
                   SIO4        6    0.2600000     9.3500000     3.8200000      4.2841569
                   DIN         6    0.0800000     9.5800000     2.9450000      3.8194699
                   NH4         6    0.0700000     0.6500000     0.3416667      0.2224785
                   PON         0            .             .             .              .
                   TDN         0            .             .             .              .
                   DP          0            .             .             .              .
                   TOTALN      0            .             .             .              .

F13P            6  FLU         6    0.5100000    11.2590000     2.9328500      4.1613881
                   TRANS       6    1.1803700     2.4128700     1.8351733      0.5512009
                   PO4         6    0.1300000     1.7000000     0.6633333      0.5773618
                   SIO4        6    0.4200000    10.6100000     4.6283333      4.6407948
                   DIN         6    0.0400000     9.6400000     4.1950000      4.5435570
                   NH4         6    0.0300000     4.6100000     1.6450000      1.9599566
                   PON         6    1.7142900     3.9996800     2.7952400      0.7948605
                   TDN         6    7.0950000    23.8300000    14.5100000      7.2092663
                   DP          6    2.8603250    12.2828600     6.9902400      3.9956830
                   TOTALN      6   10.1003250    26.4728600    17.3052400      6.6703613

F14             6  FLU         6    0.6500000    16.8856000     3.8272833      6.4184399
                   TRANS       6    1.1920000     2.9700000     2.0145500      0.6170959
                   PO4         6    0.0800000     0.8300000     0.3816667      0.3250487
                   SIO4        6    0.0700000    10.7700000     5.1216667      4.9288515
                   DIN         6    0.0700000    12.7300000     4.7316667      5.8194035
                   NH4         6    0.0200000     2.8500000     1.3000000      1.2498960
                   PON         0            .             .             .              .
                   TDN         0            .             .             .              .
                   DP          0            .             .             .              .
                   TOTALN      0            .             .             .              .
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                      1993 Surface- Farfield surveys

STATION     N Obs  Variable    N     Minimum       Maximum        Mean       Std Dev
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F15            6   FLU         6   0.1400000    14.1371000    3.3189667    5.4129899
                   TRANS       6   0.7062300     2.6063100    1.4449017    0.7120966
                   PO4         6   0.0200000     0.7100000    0.2500000    0.2863564
                   SIO4        6   0.0500000     9.7100000    4.0216667    4.3000112
                   DIN         6   0.0400000     7.5900000    2.4433333    3.7073908
                   NH4         6   0.0200000     0.4100000    0.1066667    0.1493542
                   PON         0           .             .            .            .
                   TDN         0           .             .            .            .
                   DP          0           .             .            .            .
                   TOTALN      0           .             .            .            .

F16            6   FLU         6   0.2600000    10.4370000    2.2110000    4.0374962
                   TRANS       6   0.7380000     1.4078400    1.0390200    0.2466633
                   PO4         6   0.0800000     0.8900000    0.3366667    0.3350025
                   SIO4        6   0.2200000     9.2300000    3.8800000    4.2264264
                   DIN         6   0.0100000     9.5300000    2.6266667    3.8955291
                   NH4         6           0     3.1200000    0.8166667    1.1659960
                   PON         0           .             .            .            .
                   TDN         0           .             .            .            .
                   DP          0           .             .            .            .
                   TOTALN      0           .             .            .            .

F17            6   FLU         6   0.1500000    10.7517000    2.2554667    4.1722380
                   TRANS       6   0.7650700     1.4000700    1.0398433    0.2368169
                   PO4         5   0.0900000     0.8800000    0.3900000    0.3531997
                   SIO4        5   0.1900000     9.2400000    4.0700000    4.5839884
                   DIN         5   0.2100000     8.3400000    3.0240000    3.8928242
                   NH4         5   0.1200000     0.3600000    0.2340000    0.0950263
                   PON         0           .             .            .            .
                   TDN         0           .             .            .            .
                   DP          0           .             .            .            .
                   TOTALN      0           .             .            .            .

F18            6   FLU         6   0.5300000    20.8254000    4.8969333    7.9185831
                   TRANS       6   0.8303100     3.1724700    1.8847967    0.9090016
                   PO4         6   0.0800000     0.6700000    0.2833333    0.2215100
                   SIO4        6   0.0500000     9.7600000    4.4233333    4.2347216
                   DIN         6   0.1300000     7.2000000    2.6950000    2.7797968
                   NH4         6   0.1200000     2.1900000    0.6800000    0.7782545
                   PON         0           .             .            .            .
                   TDN         0           .             .            .            .
                   DP          0           .             .            .            .
                   TOTALN      0           .             .            .            .

F19            6   FLU         6   0.1700000     9.2876000    2.0685667    3.5485635
                   TRANS       6   0.8546300     2.0319800    1.2673533    0.4978992
                   PO4         5   0.1100000     0.8800000    0.3580000    0.3462225
                   SIO4        5   0.0900000     9.3600000    4.0620000    4.8387777
                   DIN         5   0.1600000     8.7000000    2.6120000    3.7457870
                   NH4         5   0.1000000     3.6500000    0.8460000    1.5679062
                   PON         0           .             .            .            .
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## 1993 Surface- Farfield surveys

| STATION | N Obs | Variable | N | Minimum | Maximum | Mean | Std Dev |
|---|---|---|---|---|---|---|---|
| F19 | 6 | TDN | 0 | . | . | . | . |
| | | DP | 0 | . | . | . | . |
| | | TOTALN | 0 | . | . | . | . |
| F20 | 6 | FLU | 6 | 0.4000000 | 15.3772000 | 3.9175833 | 5.8701405 |
| | | TRANS | 6 | 0.9800000 | 1.7679500 | 1.4063850 | 0.3247058 |
| | | PO4 | 6 | 0.0500000 | 0.6900000 | 0.2883333 | 0.2788847 |
| | | SIO4 | 6 | 0.0900000 | 9.5400000 | 4.8616667 | 4.7526642 |
| | | DIN | 6 | 0.0700000 | 6.4300000 | 2.0200000 | 2.9621816 |
| | | NH4 | 6 | 0 | 3.7900000 | 0.8200000 | 1.4788644 |
| | | PON | 0 | . | . | . | . |
| | | TDN | 0 | . | . | . | . |
| | | DP | 0 | . | . | . | . |
| | | TOTALN | 0 | . | . | . | . |
| F21 | 6 | FLU | 6 | 0.3700000 | 18.1575000 | 3.9083833 | 7.0111253 |
| | | TRANS | 6 | 1.0300000 | 1.9959400 | 1.4722483 | 0.4148631 |
| | | PO4 | 6 | 0.0500000 | 0.6400000 | 0.2800000 | 0.2527449 |
| | | SIO4 | 6 | 0.0100000 | 10.3100000 | 4.3416667 | 4.5425958 |
| | | DIN | 6 | 0.0600000 | 5.2600000 | 2.0683333 | 2.4946857 |
| | | NH4 | 6 | 0 | 2.9800000 | 0.9283333 | 1.1884177 |
| | | PON | 0 | . | . | . | . |
| | | TDN | 0 | . | . | . | . |
| | | DP | 0 | . | . | . | . |
| | | TOTALN | 0 | . | . | . | . |
| F22 | 6 | FLU | 6 | 0.2000000 | 8.8433000 | 1.9645667 | 3.3796821 |
| | | TRANS | 6 | 0.7900000 | 1.7100000 | 1.0811000 | 0.3497838 |
| | | PO4 | 6 | 0.0500000 | 0.9700000 | 0.3433333 | 0.3547205 |
| | | SIO4 | 6 | 0.4400000 | 9.2600000 | 4.5783333 | 4.2655101 |
| | | DIN | 6 | 0.0400000 | 9.4700000 | 2.8066667 | 3.7486193 |
| | | NH4 | 6 | 0 | 1.7000000 | 0.6850000 | 0.6848284 |
| | | PON | 0 | . | . | . | . |
| | | TDN | 0 | . | . | . | . |
| | | DP | 0 | . | . | . | . |
| | | TOTALN | 0 | . | . | . | . |
| F23P | 6 | FLU | 6 | 0.8100000 | 8.1448000 | 3.6747500 | 2.8558475 |
| | | TRANS | 6 | 2.1060000 | 3.4500000 | 2.5748100 | 0.4711215 |
| | | PO4 | 6 | 0.3000000 | 1.0600000 | 0.6200000 | 0.3240370 |
| | | SIO4 | 6 | 0.9600000 | 12.9000000 | 7.2300000 | 5.9628383 |
| | | DIN | 6 | 0.0500000 | 21.0800000 | 8.8300000 | 8.0857133 |
| | | NH4 | 6 | 0.0200000 | 9.0200000 | 3.8233333 | 3.2719760 |
| | | PON | 6 | 2.2857100 | 4.8928550 | 3.9393025 | 0.9442243 |
| | | TDN | 6 | 10.3600000 | 28.4400000 | 20.0066667 | 7.3240014 |
| | | DP | 6 | 4.0396450 | 23.3657100 | 12.7693025 | 7.7672833 |
| | | TOTALN | 6 | 14.3496450 | 32.2057150 | 23.9459692 | 7.2613823 |
| F24 | 6 | FLU | 6 | 0.7800000 | 11.4162000 | 4.9548833 | 4.6640922 |
| | | TRANS | 6 | 1.6770000 | 3.4900000 | 2.4736500 | 0.7794226 |
| | | PO4 | 6 | 0.1200000 | 0.6900000 | 0.4450000 | 0.2432077 |

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                          1993 Surface- Farfield surveys

STATION     N Obs  Variable    N        Minimum        Maximum           Mean        Std Dev
-----------------------------------------------------------------------------------------------
F24             6  SIO4        6      0.4900000     11.2500000      5.7866667      4.9524001
                   DIN         6      0.1400000     13.0600000      6.1783333      5.1925809
                   NH4         6      0.1000000      5.7000000      3.3283333      2.3173642
                   PON         0              .              .              .              .
                   TDN         0              .              .              .              .
                   DP          0              .              .              .              .
                   TOTALN      0              .              .              .              .

F25             6  FLU         6      0.7000000      7.1289000      2.2455167      2.4285088
                   TRANS       6      1.1225300      3.3800000      2.0257200      0.8468715
                   PO4         6      0.0600000      1.1500000      0.6066667      0.4250490
                   SIO4        6      0.5200000     11.4100000      5.3866667      5.0720634
                   DIN         6      0.0500000     14.3300000      6.7550000      6.3249656
                   NH4         6              0      4.4000000      2.1766667      1.8989330
                   PON         5      2.1978250      5.0589650      3.1727880      1.1731605
                   TDN         5      9.6850000     23.7550000     15.3510000      5.9980386
                   DP          5      2.3878250     16.5442900      8.4787880      5.7545032
                   TOTALN      5     12.2328250     25.9692900     18.5237880      5.8431896

N01P           12  FLU        12      0.2700000     13.8426000      3.3738250      4.0451346
                   TRANS      12      0.6529400      2.8800900      1.4632042      0.6961231
                   PO4        12      0.0700000      0.9300000      0.3366667      0.3051180
                   SIO4       12      0.0300000      9.8300000      4.0341667      4.0271272
                   DIN        12              0     10.0200000      2.6241667      3.8867946
                   NH4        12              0      4.0600000      0.5991667      1.1808199
                   PON         6      1.9642850      4.1199300      3.0746917      1.1060935
                   TDN         6      6.0500000     18.0600000     11.7416667      4.5145816
                   DP          6      2.0042850     11.9842900      6.1330250      4.0162317
                   TOTALN      6     10.1639300     20.0242900     14.8163583      3.8723673

N02             6  FLU         6      0.3100000      6.8577000      2.3350000      2.7610678
                   TRANS       6      0.6270800      2.8337500      1.2856950      0.8067072
                   PO4         6      0.1300000      0.8200000      0.3450000      0.2890502
                   SIO4        6      0.0600000      9.6600000      3.8350000      4.3822175
                   DIN         6              0      9.6900000      2.7050000      4.0896296
                   NH4         6              0      1.3900000      0.4150000      0.5075333
                   PON         0              .              .              .              .
                   TDN         0              .              .              .              .
                   DP          0              .              .              .              .
                   TOTALN      0              .              .              .              .

N03             6  FLU         6      0.3700000      5.4346000      1.6314500      1.9493068
                   TRANS       6      0.6318500      1.9932900      1.1140300      0.4884861
                   PO4         6      0.1300000      0.6100000      0.2900000      0.1972815
                   SIO4        6      0.0600000     10.1500000      3.9550000      4.5046454
                   DIN         6              0      6.3900000      1.9950000      2.8790606
                   NH4         6              0      4.8000000      0.9466667      1.8921064
                   PON         0              .              .              .              .
                   TDN         0              .              .              .              .
                   DP          0              .              .              .              .
                   TOTALN      0              .              .              .              .
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                         1993 Surface- Farfield surveys

STATION      N Obs  Variable    N      Minimum      Maximum         Mean      Std Dev
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N04P            12  FLU        12    0.1500000   13.7040000    2.4769500    3.9210561
                    TRANS      12    0.6428600    2.0600500    1.2184600    0.3886833
                    PO4        12            0    0.6500000    0.2250000    0.2363164
                    SIO4       12    0.0200000   10.0400000    4.1891667    4.2069844
                    DIN        11    0.0400000    6.8800000    2.1754545    3.0370228
                    NH4        11    0.0300000    1.4100000    0.3336364    0.4530844
                    PON         5    1.0000000    3.7826400    2.2408130    1.0657159
                    TDN         6    6.6550000   19.3300000   11.5408333    5.0124778
                    DP          4    1.7285700    4.1300000    3.1760163    1.1186148
                    TOTALN      5    9.1785700   20.3300000   12.9198130    4.3610533

N05              6  FLU         6    0.2700000    5.7137000    1.4607333    2.0990682
                    TRANS       6    0.7207900    1.2252000    1.0149017    0.2109255
                    PO4         6    0.0400000    0.7700000    0.3033333    0.3214758
                    SIO4        6    0.0100000   10.2000000    4.2816667    4.5276149
                    DIN         6    0.0700000    8.2700000    2.5900000    3.8052438
                    NH4         6    0.0400000    0.5200000    0.1933333    0.2050041
                    PON         0            .            .            .            .
                    TDN         0            .            .            .            .
                    DP          0            .            .            .            .
                    TOTALN      0            .            .            .            .

N06              6  FLU         6    0.1800000    5.1071000    1.4528167    1.8606426
                    TRANS       6    0.7360000    1.4804800    1.0764050    0.2776051
                    PO4         6    0.0800000    0.5100000    0.2783333    0.1806008
                    SIO4        6    0.1600000    9.9500000    3.7000000    4.5503055
                    DIN         6    0.0900000    5.0100000    1.6716667    2.2877187
                    NH4         6    0.0700000    1.5700000    0.3566667    0.5955054
                    PON         0            .            .            .            .
                    TDN         0            .            .            .            .
                    DP          0            .            .            .            .
                    TOTALN      0            .            .            .            .

N07P            12  FLU        12    0.2400000    7.2239000    1.8203500    2.2954019
                    TRANS      12    0.6740000    2.1347400    1.1768067    0.4340462
                    PO4        12    0.0300000    1.1100000    0.2866667    0.3057133
                    SIO4       12    0.0700000   10.7800000    3.7941667    4.4456955
                    DIN        12    0.0300000    9.5100000    2.0166667    2.9912002
                    NH4        12    0.0300000    1.2400000    0.3441667    0.3551813
                    PON         6    1.0357150    3.4642850    2.1983217    0.8524031
                    TDN         6    6.6300000   16.6950000   10.7508333    4.1511148
                    DP          6    2.0657150   11.0814300    4.5666550    3.3489624
                    TOTALN      6    9.2805000   17.7307150   12.9491550    3.4827014

N08              6  FLU         6    0.2600000    7.0460000    2.0587000    2.5381650
                    TRANS       6    0.8350000    2.1380300    1.2755550    0.4583666
                    PO4         6    0.0400000    0.6400000    0.2900000    0.2689238
                    SIO4        6    0.0700000   10.0300000    3.7250000    4.7270615
                    DIN         6    0.0400000    6.1300000    2.0250000    2.6608777
                    NH4         6    0.0200000    1.1100000    0.2866667    0.4141819
                    PON         0            .            .            .            .
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                          1993 Surface- Farfield surveys

STATION      N Obs  Variable    N      Minimum      Maximum         Mean      Std Dev
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N08              6  TDN         0            .            .            .            .
                    DP          0            .            .            .            .
                    TOTALN      0            .            .            .            .

N09              6  FLU         6    0.3200000    8.3837000    2.3599667    3.0579040
                    TRANS       6    0.8370000    2.2194700    1.4260367    0.5092427
                    PO4         6    0.0700000    0.8600000    0.3883333    0.3059030
                    SIO4        6    0.2100000   10.1000000    3.9566667    4.5036193
                    DIN         6    0.0400000    8.7000000    2.8366667    3.4497691
                    NH4         6    0.0100000    1.0700000    0.4933333    0.3526849
                    PON         0            .            .            .            .
                    TDN         0            .            .            .            .
                    DP          0            .            .            .            .
                    TOTALN      0            .            .            .            .

N10P            12  FLU        12    0.4700000   14.4450000    3.4987333    3.9292652
                    TRANS      12    1.1340000    3.4200000    2.0817558    0.6574402
                    PO4        12    0.1100000    0.9100000    0.4625000    0.2975086
                    SIO4       12    0.1300000   11.4800000    4.8733333    4.6199908
                    DIN        12            0   13.2000000    4.5250000    4.8793153
                    NH4        12            0    4.6500000    1.7908333    1.9104376
                    PON         6    2.8571400    4.3928550    3.8701250    0.5517822
                    TDN         6    8.5200000   24.0400000   13.8050000    6.3924205
                    DP          6    4.1573600   13.9657150    6.9434583    4.1707346
                    TOTALN      6   12.5373600   27.8257150   17.6751250    6.0719264

N11              6  FLU         6    0.2800000    7.6697000    2.6711500    2.7956038
                    TRANS       6    0.9865200    2.0882700    1.4670683    0.4450743
                    PO4         6    0.0400000    0.6700000    0.3383333    0.2560794
                    SIO4        6    0.0900000    9.8400000    4.3283333    4.4512758
                    DIN         6    0.0200000    6.3600000    3.1383333    2.9831153
                    NH4         6    0.0100000    3.3400000    1.3950000    1.4926587
                    PON         0            .            .            .            .
                    TDN         0            .            .            .            .
                    DP          0            .            .            .            .
                    TOTALN      0            .            .            .            .

N12              6  FLU         6    0.3600000    9.4623000    3.5758833    3.8339301
                    TRANS       6    0.7987700   17.3366000    3.8301983    6.6220237
                    PO4         6    0.0600000    0.6800000    0.2900000    0.2780647
                    SIO4        6    0.0200000    9.3500000    4.0500000    4.2416412
                    DIN         6    0.0300000    5.9600000    2.5400000    2.8536853
                    NH4         6            0    1.7200000    0.7216667    0.7858096
                    PON         0            .            .            .            .
                    TDN         0            .            .            .            .
                    DP          0            .            .            .            .
                    TOTALN      0            .            .            .            .

N13              6  FLU         6    0.2800000    4.9125000    1.8856833    2.2128354
                    TRANS       6    0.6285100    2.8192400    1.2566217    0.7974245
                    PO4         6    0.0900000    0.6200000    0.3016667    0.2495930
--------------------------------------------------------------------------------------
```

```
                         1993 Surface- Farfield surveys

STATION      N Obs  Variable     N      Minimum       Maximum          Mean        Std Dev
--------------------------------------------------------------------------------------------
N13              6  SIO4         6    0.0200000    10.0100000     3.7266667      4.5841190
                    DIN          6    0.0300000     5.7100000     2.0083333      2.6351730
                    NH4          6    0.0300000     2.8900000     0.6700000      1.1075198
                    PON          0            .             .             .              .
                    TDN          0            .             .             .              .
                    DP           0            .             .             .              .
                    TOTALN       0            .             .             .              .

N14              6  FLU          6    0.3200000     4.2726000     1.5097167      1.5349010
                    TRANS        6    0.7330000     2.2038100     1.1846217      0.5284281
                    PO4          6    0.0300000     0.9100000     0.3150000      0.3281920
                    SIO4         6    0.0300000     9.9500000     3.6300000      4.5356808
                    DIN          6    0.0200000     9.6900000     2.8216667      4.2352351
                    NH4          6    0.0200000     0.8700000     0.2616667      0.3046583
                    PON          0            .             .             .              .
                    TDN          0            .             .             .              .
                    DP           0            .             .             .              .
                    TOTALN       0            .             .             .              .

N15              6  FLU          6    0.4000000     3.2111000     1.5244667      1.2660311
                    TRANS        6    0.7720000     2.4750900     1.2077133      0.6382910
                    PO4          6    0.0700000     0.5900000     0.2883333      0.2127361
                    SIO4         6    0.0800000     9.9400000     3.6683333      4.5226648
                    DIN          6    0.0700000     5.5200000     1.9083333      2.6048372
                    NH4          6    0.0200000     0.5600000     0.2566667      0.1904381
                    PON          0            .             .             .              .
                    TDN          0            .             .             .              .
                    DP           0            .             .             .              .
                    TOTALN       0            .             .             .              .

N16P            12  FLU         12    0.3300000    11.1616000     2.2628083      3.1084434
                    TRANS       12    0.6980000     2.2345400     1.2775467      0.4959246
                    PO4         12            0     0.9100000     0.2758333      0.2959870
                    SIO4        12    0.0300000    10.0800000     3.5166667      4.1729068
                    DIN         12    0.0200000     9.1100000     2.3816667      3.5026246
                    NH4         12            0     0.5400000     0.1975000      0.1868458
                    PON          6    1.1785750     5.1071400     2.7312550      1.4091400
                    TDN          6    5.5400000    15.2000000    10.0908333      4.0424861
                    DP           6    2.1157150    10.8957100     4.9729217      3.1409163
                    TOTALN       6    8.3969650    16.3785750    12.8220883      3.4006783

N17              6  FLU          6    0.3900000     6.2586000     1.7664333      2.2465729
                    TRANS        6    0.7840000     2.0659600     1.2073933      0.4582600
                    PO4          6    0.0700000     0.5700000     0.2466667      0.2216905
                    SIO4         6    0.0200000     9.8300000     3.5650000      4.5752541
                    DIN          6    0.0900000     5.2700000     1.5266667      2.2520184
                    NH4          6    0.0400000     3.3300000     0.6900000      1.2993229
                    PON          0            .             .             .              .
                    TDN          0            .             .             .              .
                    DP           0            .             .             .              .
                    TOTALN       0            .             .             .              .
--------------------------------------------------------------------------------------------
```

```
                          1993 Surface- Farfield surveys

STATION     N Obs  Variable    N      Minimum       Maximum          Mean       Std Dev
-----------------------------------------------------------------------------------------

N18             6  FLU         6    0.4000000     5.1289000     1.7537000     1.7397769
                   TRANS       6    0.7830000     2.0093800     1.2506683     0.4087103
                   PO4         6    0.1000000     0.7500000     0.3216667     0.2955954
                   SIO4        6            0     9.7300000     3.5983333     4.5922954
                   DIN         6            0     7.6700000     2.3266667     3.4579223
                   NH4         6            0     0.6700000     0.1933333     0.2472785
                   PON         0            .             .             .             .
                   TDN         0            .             .             .             .
                   DP          0            .             .             .             .
                   TOTALN      0            .             .             .             .

N19             6  FLU         6    0.2900000     9.6357000     2.2736500     3.6441377
                   TRANS       6    0.8380000     1.9798400     1.2375517     0.4241294
                   PO4         6    0.0400000     0.8000000     0.3466667     0.3119402
                   SIO4        6            0     9.7000000     3.9600000     4.4828339
                   DIN         6    0.0400000     8.5100000     2.5333333     3.7627525
                   NH4         6    0.0300000     0.3500000     0.1550000     0.1367845
                   PON         0            .             .             .             .
                   TDN         0            .             .             .             .
                   DP          0            .             .             .             .
                   TOTALN      0            .             .             .             .

N20P           12  FLU        12    0.3100000    20.0351000     3.1566667     5.6040656
                   TRANS      12    0.7520000     2.1759600     1.4125800     0.5010915
                   PO4        12    0.0500000     1.2100000     0.3633333     0.3698730
                   SIO4       12            0     9.7400000     3.7183333     4.1401358
                   DIN        12            0     9.0600000     2.5933333     3.3645190
                   NH4        12            0     1.0600000     0.4741667     0.3643040
                   PON         6    1.5000000     4.9480750     3.1101967     1.4544508
                   TDN         6    5.8400000    18.2600000    11.2291667     5.0440167
                   DP          6    3.3800000     8.5714300     5.7268633     2.0443775
                   TOTALN      6   10.7880750    19.7600000    14.3393633     3.7834017

N21             6  FLU         6    0.3500000     5.6285000     1.8660833     1.9521587
                   TRANS       6    0.7370000     1.9513200     1.2026667     0.4001426
                   PO4         6    0.0900000     0.6300000     0.2683333     0.2308607
                   SIO4        6            0     9.9900000     3.6616667     4.6309931
                   DIN         6    0.0100000     6.4400000     2.0283333     2.9316304
                   NH4         6    0.0100000     1.5500000     0.4016667     0.5765559
                   PON         0            .             .             .             .
                   TDN         0            .             .             .             .
                   DP          0            .             .             .             .
                   TOTALN      0            .             .             .             .
-----------------------------------------------------------------------------------------

From file 93tstnh4.sas/*.log/*.lst
```

### *TABLE A-4*

Table A-4: Selected parameter statistics by nearfield stations, for surface water samples based on nearfield surveys in 1993.

```
------------------------------------------------------------ STATION=N01P ------------------------------------------------------------

              N Obs  Variable   N      Minimum       Maximum          Mean       Std Dev
              ----------------------------------------------------------------------------
                 22  DIN       22            0    11.2400000     2.8063636     3.8195220
                     NH4       22            0     4.0600000     0.7227273     1.0699274
                     FLU       22    0.2700000    13.8426000     3.1264227     3.4900254
              ----------------------------------------------------------------------------

------------------------------------------------------------ STATION=N02 ------------------------------------------------------------

              N Obs  Variable   N      Minimum       Maximum          Mean       Std Dev
              ----------------------------------------------------------------------------
                 16  DIN       16            0    11.2200000     2.5768750     3.7388139
                     NH4       16            0     2.6700000     0.5962500     0.7437103
                     FLU       16    0.3100000     8.1883000     2.0360688     2.3990273
              ----------------------------------------------------------------------------

------------------------------------------------------------ STATION=N03 ------------------------------------------------------------

              N Obs  Variable   N      Minimum       Maximum          Mean       Std Dev
              ----------------------------------------------------------------------------
                 16  DIN       16            0     7.3700000     2.1393750     2.7756980
                     NH4       16            0     4.8000000     0.6162500     1.1595279
                     FLU       16    0.3700000    11.8043000     1.9110688     2.9306468
              ----------------------------------------------------------------------------

------------------------------------------------------------ STATION=N04P ------------------------------------------------------------

              N Obs  Variable   N      Minimum       Maximum          Mean       Std Dev
              ----------------------------------------------------------------------------
                 22  DIN       21    0.0200000     7.2000000     2.0542857     2.7083419
                     NH4       21            0     2.0500000     0.4185714     0.5505932
                     FLU       22    0.1500000    13.7040000     2.0917591     3.2143651
              ----------------------------------------------------------------------------

------------------------------------------------------------ STATION=N05 ------------------------------------------------------------

              N Obs  Variable   N      Minimum       Maximum          Mean       Std Dev
              ----------------------------------------------------------------------------
                 16  DIN       16            0     8.2700000     2.1968750     2.9726772
                     NH4       16            0     1.2300000     0.2656250     0.3401366
                     FLU       16    0.2700000     6.4731000     1.4227937     1.8620161
              ----------------------------------------------------------------------------
```

```
                              Parameter means for nearfield surface water

----------------------------------------------- STATION=N06 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16             0     9.2700000     1.9218750     2.6949811
                     NH4        16             0     2.8700000     0.4793750     0.7722734
                     FLU        16     0.1800000     8.9381000     1.6300437     2.2620405
              ------------------------------------------------------------------------------

----------------------------------------------- STATION=N07P -----------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 22  DIN        22     0.0300000     9.5100000     1.7936364     2.5692922
                     NH4        22             0     2.0300000     0.3550000     0.4996165
                     FLU        22     0.2400000     7.2239000     1.5701045     1.8941535
              ------------------------------------------------------------------------------

----------------------------------------------- STATION=N08 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16     0.0100000     7.8200000     1.9000000     2.5376525
                     NH4        16             0     1.1100000     0.3206250     0.3868586
                     FLU        16     0.2600000     7.0460000     1.4766625     1.5963776
              ------------------------------------------------------------------------------

----------------------------------------------- STATION=N09 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16     0.0200000    10.1000000     3.1225000     3.6246591
                     NH4        16     0.0100000     3.4000000     0.8250000     0.8759224
                     FLU        16     0.3200000     8.3837000     1.9139687     2.1821163
              ------------------------------------------------------------------------------

----------------------------------------------- STATION=N10P -----------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 22  DIN        21             0    22.4200000     6.0885714     6.3483102
                     NH4        21             0    12.4400000     3.1261905     3.5612322
                     FLU        22     0.4700000    14.4450000     3.2755273     3.1203042
              ------------------------------------------------------------------------------
```

```
                         Parameter means for nearfield surface water

------------------------------------------------ STATION=N11 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16     0.0200000    13.1500000     3.6893750     4.5299867
                     NH4        16     0.0100000     8.8700000     1.6700000     2.3685101
                     FLU        16     0.2800000     9.2994000     3.0465875     2.5894050
              ------------------------------------------------------------------------------

------------------------------------------------ STATION=N12 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16     0.0100000    11.7200000     3.0012500     3.7622952
                     NH4        16             0     3.7500000     0.9356250     1.1156640
                     FLU        16     0.3600000    13.6576000     3.4626750     3.7484459
              ------------------------------------------------------------------------------

------------------------------------------------ STATION=N13 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16             0    11.4700000     2.3350000     3.3681944
                     NH4        16             0     3.4400000     0.7756250     1.1156222
                     FLU        16     0.2800000    15.8253000     2.3162500     3.8530136
              ------------------------------------------------------------------------------

------------------------------------------------ STATION=N14 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16     0.0100000    10.1900000     2.5631250     3.5269528
                     NH4        16             0     1.6100000     0.3962500     0.4445353
                     FLU        16     0.3200000    14.1744000     2.0082188     3.3918593
              ------------------------------------------------------------------------------

------------------------------------------------ STATION=N15 ------------------------------------------------

              N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
              ------------------------------------------------------------------------------
                 16  DIN        16     0.0100000     7.4800000     1.9406250     2.5217546
                     NH4        16             0     0.7200000     0.3462500     0.2813272
                     FLU        16     0.3221000    13.4633000     2.0502375     3.1654051
              ------------------------------------------------------------------------------
```

```
                              Parameter means for nearfield surface water

------------------------------------------------------------ STATION=N16P -----------------------------------------------------------

                   N Obs  Variable     N        Minimum        Maximum           Mean        Std Dev
                   -----------------------------------------------------------------------------------
                      22  DIN         22      0.0100000      9.2900000      2.1400000      3.1834782
                          NH4         22              0      1.4100000      0.2722727      0.3462442
                          FLU         22      0.2976000     11.1616000      2.0068409      2.6178662
                   -----------------------------------------------------------------------------------

------------------------------------------------------------ STATION=N17 ------------------------------------------------------------

                   N Obs  Variable     N        Minimum        Maximum           Mean        Std Dev
                   -----------------------------------------------------------------------------------
                      16  DIN         16      0.0200000      9.2800000      1.8700000      2.7648388
                          NH4         16      0.0100000      3.3300000      0.4937500      0.8334977
                          FLU         16      0.2755000      6.2586000      1.7017875      1.6061175
                   -----------------------------------------------------------------------------------

------------------------------------------------------------ STATION=N18 ------------------------------------------------------------

                   N Obs  Variable     N        Minimum        Maximum           Mean        Std Dev
                   -----------------------------------------------------------------------------------
                      15  DIN         15              0     10.2700000      2.6100000      3.5924862
                          NH4         15              0      2.3000000      0.4853333      0.6730407
                          FLU         15      0.4000000      6.6332000      1.9455733      1.9201461
                   -----------------------------------------------------------------------------------

------------------------------------------------------------ STATION=N19 ------------------------------------------------------------

                   N Obs  Variable     N        Minimum        Maximum           Mean        Std Dev
                   -----------------------------------------------------------------------------------
                      16  DIN         16      0.0400000     10.7200000      2.8493750      3.9347231
                          NH4         16      0.0300000      3.4100000      0.6962500      0.9986182
                          FLU         16      0.2900000      9.6357000      2.0507750      2.6308879
                   -----------------------------------------------------------------------------------

------------------------------------------------------------ STATION=N20P -----------------------------------------------------------

                   N Obs  Variable     N        Minimum        Maximum           Mean        Std Dev
                   -----------------------------------------------------------------------------------
                      22  DIN         22              0     10.9300000      2.5668182      3.5237674
                          NH4         22              0      2.8700000      0.5745455      0.6708965
                          FLU         22      0.3100000     20.0351000      2.6476591      4.2686501
                   -----------------------------------------------------------------------------------
```

```
                              Parameter means for nearfield surface water

------------------------------------------------------------ STATION=N21 ----------------------------------------------------------


                   N Obs  Variable    N       Minimum       Maximum          Mean       Std Dev
                   ---------------------------------------------------------------------------
                      16  DIN        16             0    10.7700000     2.2893750     3.2993605
                          NH4        16             0     2.6300000     0.5537500     0.7539750
                          FLU        16     0.3500000    10.6630000     2.2145562     2.6302604
                   ---------------------------------------------------------------------------

                   From file 93nrsur.sas/*.log/*.lst
```

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