Water column monitoring in Massachusetts and Cape Cod Bays: annual report for 1994

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FINAL REPORT

WATER COLUMN MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: ANNUAL REPORT FOR 1994

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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 the 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 in annual reports (Kelly *et al.*, 1993; Kelly and Turner, 1995) for 1992 and 1993.

The purpose of this report is to present a compilation of results for 1994. 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 1994. 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. Furthermore, the report provides an initial summary of interannual trends from 1992-1994.

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. In contrast to previous years of sampling (1992-1993), stations were added in Boston Harbor and along the northeastern open ocean boundary from Cape Ann to Stellwagen Bank. 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. Greater than one-third of ~1130 measurements detected dissolved inorganic nitrogen (DIN = $NH_4 + NO_3 + NO_2$) at low concentrations (<1.8 μM). The overall mean value for farfield measurements was 5.58 μM. Higher DIN and NH_4 concentrations were characteristically found in waters in and around Boston Harbor. As in other years, a decreasing concentration gradient of DIN and NH_4 was observed from the Harbor into western Massachusetts Bay.

Chlorophyll — With respect to chlorophyll, <2% of the farfield survey measurements showed concentrations > 8 $\mu g\ L^{-1}$. In some regions and times, highest chlorophyll concentrations were found at the surface, whereas a subsurface chlorophyll maximum was pronounced during the stratified season in most of the Bays. Seasonally, regions of the Bays had different cycles. A decreasing chlorophyll concentration gradient from the Harbor-edge to the Bay was noted in this year as in previous years. But there was also a region of high mean chlorophyll off Cohasset, east of the Harbor and south of the nearfield. Peak mean annual concentrations at

this off-Cohasset location were ~3.5 $\mu g\ L^{-1}$, compared to in-Harbor averages ~3 $\mu g\ L^{-1}$, nearfield averages ~2 $\mu g\ L^{-1}$, and offshore values ~1.5 to 2 $\mu g\ L^{-1}$.

DO — The principal ecological event that distinguished 1994 from other recent sampling years was lower bottom-water DO concentrations just prior to fall overturn. Some values were below the state standard of 6 mg L^{-1}. Annual DO minima were detected in the nearfield in October.

Plankton — As often observed, the annual cycle showed dominance by diatoms in a winter-spring bloom, a mixed flagellate-diatom community during summer and a fall bloom with typical late-season, chain-forming diatoms (e.g. *Rhizosolenia*) as well as microflagellates and cryptomonads. In Cape Cod Bay during March there was a substantial concentration of the gelatinous alga *Phaeocystis pouchetti*. In contrast to 1993, a huge fall bloom was not observed in the Bays. As observed regularly during 1992-1993, zooplankton were numerically dominated at most locations and sampling times by two small forms, *Oithona similis* and *Paracalanus parvus*.

Net primary production — ^{14}C incubations were performed to assess integrated water column primary production. In contrast to 1992-1993, only two stations were sampled: station F23P at the edge of Boston Harbor and station N16P in the mid-eastern region of the nearfield. There were seasonal differences in rates between these two environments, with the Harbor not showing the rise in production in late spring that was observed in the nearfield. The average production rate for the nearfield station was 1.54 gC $m^{-2}\ d^{-1}$, substantially higher than observed on average at the edge of the Harbor (0.84 gC $m^{-2}\ d^{-1}$). Means for 1994 were more similar to 1992 than to 1993.

The report compares water-quality monitoring results of 1994 across sampling regions and surveys. Specific findings include:

- Statistical testing confirmed that there were differences in water quality among 1994 sampling regions. For example, most surface-water nutrient concentrations were significantly higher in Boston Harbor than other regions. Coastal regions near the Harbor had significantly lower concentrations than the Harbor for DIN, NH_4, Total N, and SiO_4, but not PO_4. Also, water clarity, as measured by beam attenuation, was reduced in Boston Harbor compared to other regions. Although differences were detected between the Harbor and the offshore region with respect to surface-water chlorophyll concentrations, the regions in between were not different; this result reflects a continuum of change from the Harbor to the deeper waters offshore.

- Differences between the Harbor and the nearfield, respectively the sites of the present and future effluent outfall, were highlighted by statistical testing. Detailed graphical and textual description of the overall differences between these environments provided an explicit focus for discussion. The Harbor-nearfield contrast should reinforce the notion that transferring nutrient loads directly to the nearfield does *not* suggest there will be concomitant translation of present conditions in the Harbor to future conditions in the nearfield, for dilution as well as ecological influences on water quality will be expressed quite differently in the two environments.

- Statistical tests confirmed detectable water-quality differences among surveys, a result which confirms an identifiable seasonal cycle in some water quality measures.

- Tests also regularly showed a significant interaction between regions (space) and surveys (time), meaning that some regional environments are different on average and their seasonal cycles differ also. Indeed, a parameter relatively elevated at one place and time may be elevated later in another place. The significant effect of interaction of space and time brings up substantive issues for the monitoring program. For example, regions likely act as poor statistical controls in space and/or time for each other; tests for differences must therefore primarily rely on pre/post diversion comparisons at a given place. On a practical level, these results bring into focus the task of sorting out future changes in average conditions (over some representative space and time), as well as in timing of critical events. Moreover, results enhance the need to examine interannual variability and the ability of the monitoring program to explain interannual differences.

The concluding section thus logically examines interannual variability, using data from 1992-1994 for the intensively sampled nearfield region. Patterns in physical, chemical, and biological measurements related to water quality are presented. A principal focus was the distinctively low DO values experienced in the nearfield during fall 1994.

The main conclusions from interannual comparisons include

- There appears to be a contributing physical basis (temperature, stratification) to the low DO concentrations in bottom-water during fall 1994. Biological and metabolic measurements (plankton, chlorophyll, particulate and dissolved organic carbon, primary production) were not elevated in 1994 compared to other years; in contrast, the year with highly elevated chlorophyll and primary production (1993) did not have unusual bottom-water DO. Thus, while metabolism ultimately regulates DO concentrations, it is apparent that the physical setting and variability therein may determine the potential for the expression of metabolism as a DO change in bottom water.

- DO concentrations in nearfield bottom-waters from 1992 to 1994 could suggest an overall trend of decreasing annual minima for DO. This trend has occurred prior to an outfall diversion. This result should reinvigorate efforts to evaluate whether the monitoring program will provide sufficient data to attribute long-term changes properly and compellingly to their causal mechanisms in the future.

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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. Annual reports separately summarize water column monitoring results in 1992 and 1993 (Kelly *et al.*, 1993; Kelly and Turner, 1995). The 1994 water column monitoring surveys have been presented in a series of five 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 1994. As in previous annual reports, a main objective is to provide a description of the annual cycle of ecological events for 1994 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 and 1993 annual reports. 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; however, some correlation and regression analyses, as well as statistical inference tests, were used to examine time and space patterns in the Bays. The effort should be viewed as prelude to more comprehensive statistical analyses that use results of the baseline monitoring to establish a post-outfall discharge monitoring design.

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, 1993). 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 regional differences , especially between Boston Harbor and the nearfield region in 1994, and summarizes interannual trends (1992-1993) in the nearfield, is presented in Section 5.

2.0 DATA SOURCES, STATIONS, AND SURVEYS

Field sampling equipment and procedures, sample handling and custody, sample processing and laboratory analysis, and instrument performance specifications and data quality objectives are discussed in the water quality monitoring plan (Albro *et al.*, 1993). The plan is detailed and should be consulted for standard survey methods; deviations from standard methods are provided in individual survey reports or periodic reports. Results for 1994 have been presented in periodic water quality monitoring reports and their appendices (Kelly *et al.* 1994a,b; Kelly *et al.*, 1995a,b; and Libby *et al.*, 1995). 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 data used in this report have been submitted to the MWRA Harbor Studies Database.

The MWRA water column sampling stations are located throughout Massachusetts and Cape Cod Bays (Figure 2.1-1). Twenty-five farfield survey stations in 1994 (labeled "F") extend from within Boston Harbor to Cape Ann and beyond Stellwagen Bank to the northeast and to Cape Cod Bay to the south. The combined farfield/nearfield surveys for 1994 represent a continuation of the baseline water quality monitoring conducted in 1992 and 1993 for the MWRA Harbor and Outfall Monitoring Project. Relative to 1992-1993, there were several farfield sampling design modifications. Six new stations, located in Boston Harbor (F30B and F31B) and Massachusetts Bay (F26, F27B, F28, and F29), were added and six previous farfield stations (F04, F08, F09, F11, F20, and F21) were eliminated. The six "P" stations (Figure 2-1) in the nearfield region were also sampled during the farfield survey; thus, on the farfield survey, *in-situ* measurements and dissolved inorganic nutrient samples were obtained at a total of 31 stations plus the 2 repeated productivity stations. In addition, the number of stations where organic nutrients and biological measurements were made was increased from 10 stations to 14 stations. At these biology/productivity stations, additional samples were taken for the analyses of dissolved and particulate organic nutrients, total suspended solids, chlorophyll, and plankton identification and enumeration. At special stations F25 and F24, additional samples were collected for the determination of dissolved and particulate organic nutrients, but not biology. For the four new 1994 biology stations, samples from 1994 have been archived; thus, 1994 biology data presented in this report are for the same stations described for 1992-1993 (Kelly *et al.*, 1993; Kelly and Turner, 1995). Productivity measurements were made at only two stations in 1994 (F23P and N16P). These two stations were sampled twice, once on each of two separate days during the farfield survey.

Twenty-one nearfield stations (labeled "N") are from an area approximately 100 km^2, the center of which is near the midpoint of the future 2-km-long MWRA effluent outfall. On a vertical profiling day of each nearfield survey, *in-situ* measurements and dissolved inorganic nutrient samples were obtained from these 21 nearfield stations. Surface phytoplankton samples were taken at the six biology/productivity stations, and the surface sample from station N10P was analyzed, as in previous years. During both the farfield and nearfield surveys, additional discrete seawater samples were obtained to calibrate the *in-situ* oxygen and fluorescence sensors.

The nearfield stations were sampled on 16 surveys in 1994 (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) implicitly illustrate different frequencies of sampling for different stations.

Figure 2.1-1 also indicates how stations were classified into six regions, by depth and geography. The regions include (1) Boston Harbor (three stations); (2) coastal (six stations near the shoreline in western Massachusetts Bay), (3) nearfield (six stations on a farfield survey, twenty-one stations on a nearfield survey, as defined above, (4) offshore (eight deeper-water stations, three of which are within Stellwagen Basin), (5) boundary (five stations in an arc from Cape Ann to Provincetown, crossing Stellwagen Bank at station F28) and (6) Cape Cod Bay (three stations). 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 stations in Stellwagen Basin in Massachusetts Bay which included stations F22, F19, F17, and F12 (Figure 2.1-1).

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), Quattro Pro (Borland, 1993) and Surfer (1994).

Table 2-1. Schedule of water quality surveys for calendar year 1994.

SURVEY	DATES
W9401 (Combined Farfield/Nearfield)	February 8 and 15-18
W9402 (Combined Farfield/Nearfield)	March 1-2 and 5-7
W9403 (Nearfield)	March 22-23
W9404 (Combined Farfield/Nearfield)	April 5-10
W9405 (Nearfield)	April 27-28
W9406 (Nearfield)	May 22
W9407 (Combined Farfield/Nearfield)	June 21-25
W9408 (Nearfield)	July 7
W9409 (Nearfield)	July 27-28
W9410 (Nearfield)	August 11
W9411 (Combined Farfield/Nearfield)	August 23-27
W9412 (Nearfield)	September 7
W9413 (Nearfield)	September 28-29
W9414 (Combined Farfield/Nearfield)	October 11-15
W9415 (Nearfield)	November 2-3
W9416 (Nearfield)	November 30 - December 1

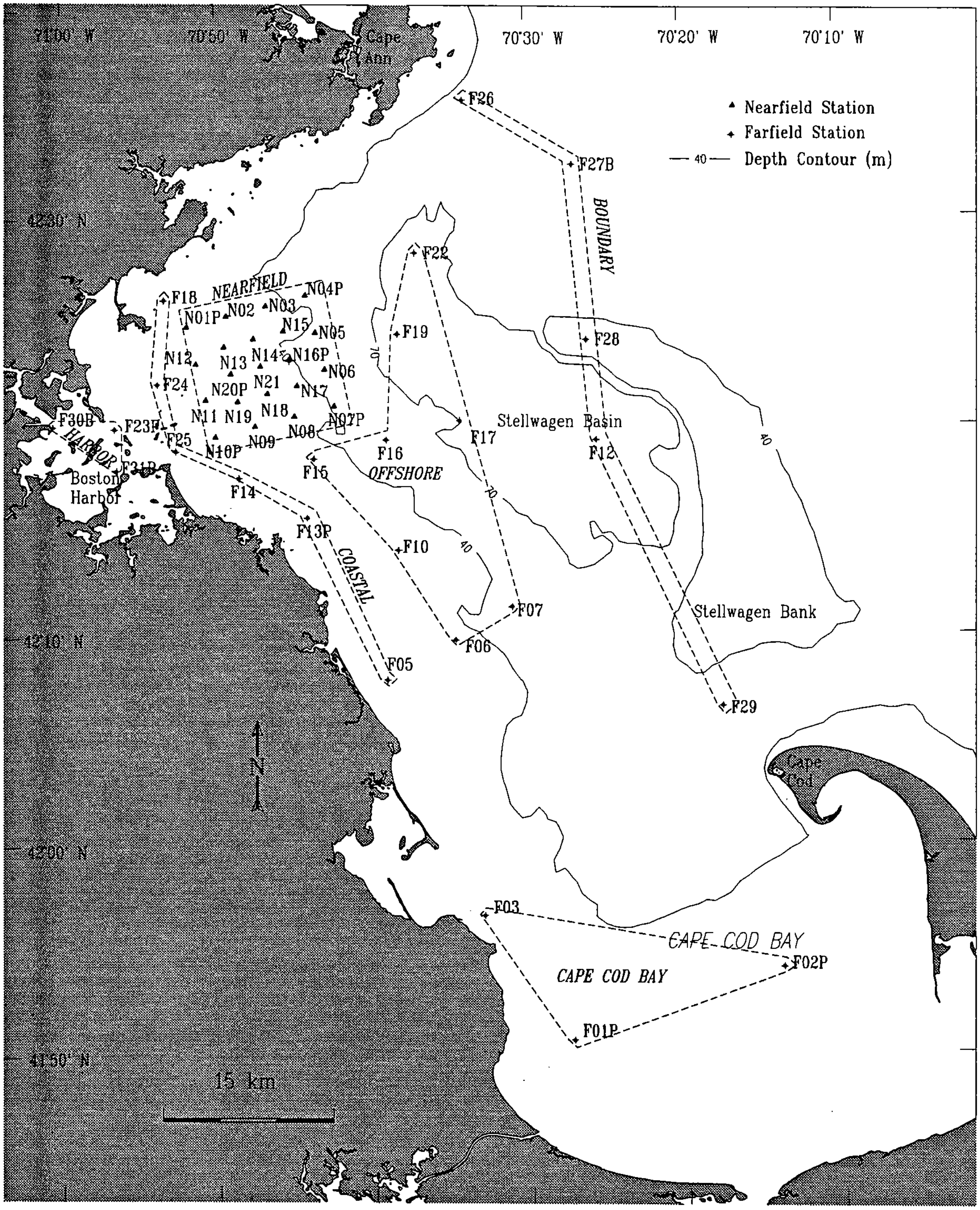


Figure 2.1-1. Water quality sampling stations in Massachusetts and Cape Cod Bays. Station codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Six groups of stations that are referred to in the text and in other figures are identified — Boundary, Offshore, Nearfield, Coastal, Boston Harbor, and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

3.0 FARFIELD SURVEY RESULTS

As described in Section 2, farfield sampling was conducted six times during 1994. 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 included 31 stations, 25 outside the nearfield region. The data set examined here includes a total of 1132 Niskin bottle sampling events. There were no missing data for almost all *in-situ* sensor parameters, however there were 3 missing data points for irradiance. Due to on-deck freezing problems with the DO sensor in the early part of the year (Kelly *et al.*, 1994a) there were only 1044 sensor-based DO values for 1994.

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 1994, there were ≥1130 data values for each of the inorganic nutrients — ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), phosphate (PO_4), and silicate (SiO_4). Summary statistics for each parameter are included in the Appendix (Table A-1). To introduce the 1994 data, frequency distribution plots are presented; these are 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 frequency distribution of samples was skewed to the lowest concentration class, and the distribution shows that over one third of the measured concentrations were below 1.8 μM (Figure 3.1-1). The preponderance of low-concentration data is due to general depletion of DIN in Bay surface waters for the seasonally stratified period, approximately April to October. However, the distribution was bimodal, with a secondary mode at about 9-10 μM. The secondary mode apparently arose because both pre-bloom DIN concentrations in winter, as well as deeper bottom water DIN concentrations in late summer, were often in a similar range. Above the secondary modal concentration, the frequency of observations fell sharply with increasing concentration to a maximum observed concentration of 20.52 μM, which was recorded in Boston Harbor. The overall mean value for DIN was 5.58 μM.

DIN concentrations >12 μM were measured primarily in Boston Harbor proper and in coastal waters receiving export from the Harbor. The mean DIN concentration for Boston Harbor samples was 10.39 μM — almost twice the mean value in other regions of Massachusetts Bay. Regional DIN means (all stations and depths) were 5.88 μM (coastal), 5.55 μM (boundary), 5.16 μM (nearfield), and 5.19 μM (offshore). In contrast, the mean value for Cape Cod Bay was only 2.86 μM.

Most NH_4 concentrations were <1 μM (Figure 3.1-2) and the frequency distribution was unimodal, with decreasing numbers of samples at increasing concentrations. Higher NH_4 concentrations (>4 μM) were almost exclusively found at Boston Harbor and coastal stations.

Spatial Pattern of DIN in Western Massachusetts Bay. A gradient of decreasing surface water DIN and/or NH_4 concentrations with distance from Boston Harbor has repeatedly been demonstrated in recent monitoring (cf. Pandan, 1977; Townsend *et al.*, 1991; Kelly, 1991; Kelly *et al.*, 1993, Kelly, 1993; Kelly and Turner, 1995). Many individual surveys in 1994 displayed the common distance—concentration gradient pattern, and this is evident in the distribution of mean DIN values (n=6 surveys) for surface observations at stations in Massachusetts Bay (Figure 3.1-3a). The mean DIN concentration at three stations in Boston Harbor or at its Bayward edge was ≥11 μM and concentrations graded to about 2-3 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 ≥5 μM at the three Harbor stations and <1 μM at distances >15-20 km from the Harbor. Comparing the figures, one can see that, in the Harbor, NH_4 on average accounted for >50% of the DIN. Along the western edge of the nearfield, NH_4 accounted for about 25% of the DIN, and further seaward, the % of DIN accounted for by NH_4

dropped even lower. 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 or to the north along the coast. This finding repeats the geographical pattern noted in previous years, for example, 1993 (Kelly and Turner, 1995). Linear relationships between NH_4 and salinity frequently have been noted in the area of interaction between the Harbor and the nearfield in western Massachusetts Bay (Kelly, 1993). The 1994 data, like those in 1992-1993, reconfirm NH_4 to be a valuable medium-scale (1s to 10s of kilometers) indicator of discharged effluent and, to an extent, show some of the present dispersion (eastward and southward) of Harbor water into Massachusetts Bay. Some researchers have suggested using stable N isotope analyses to help trace the initial fate of dissolved forms of MWRA effluent. The potential precision and power of a stable isotope analysis for NH_4 seems unnecessary where the present NH_4 signature is so clear, consistent, and distinct against the low baseline signal in waters of the Bay.

Phosphate. Unlike DIN, the lowest (near-zero) concentration class for PO_4 was not the modal class (Figure 3.1-4). PO_4 was normally detectable (>0.05 μM) in all regions, and >80% of the values were in the range of 0.1 to 1.1 μM. Repeatedly, monitoring in the Bays in 1992-1994 has shown that phosphate is present at measurable concentrations even in surface water during summer, when DIN concentrations are virtually undetectable.

Samples with higher PO_4 concentrations (>1 μM) were observed in all regions, but these higher concentrations tended to be more frequent at Boston Harbor stations. One anomalous point (2.84 μM) was from the nearfield region. The overall mean PO_4 concentration for 1994 was 0.64 μM. Regional mean concentrations of PO_4, encompassing data from all depths as included in Figure 3.1-4, suggested a rank ordering of regions similar to that indicated by DIN. For PO_4, the means in Massachusetts Bay regions were 0.87, 0.66, 0.64, 0.60, and 0.58 μM respectively, for Boston Harbor, coastal, nearfield, boundary, and offshore regions. The mean PO_4 concentration for the Cape Cod Bay sampling region was the lowest, 0.52 μM.

Silicate. The frequency distribution of SiO_4 concentrations was bimodal (Figure 3.1-5), a feature also noted for SiO_4 in 1992 and 1993 (Kelly *et al.*, 1993; Kelly and Turner, 1995) and for DIN in 1994 (above). One mode was in the lowest concentration class (<1 μM) and a secondary mode occurred at ~8-11 μM. Samples showing the highest concentrations were often from the offshore or nearfield region, rather than from the coastal or Harbor region. Nevertheless, the mean concentration was highest for the Boston Harbor region. The overall mean SiO_4 concentration for 1994 was 5.31 μM. By region, mean concentrations of SiO_4 were 7.06 μM (Boston Harbor), 5.57 μM (boundary), 5.46 μM (offshore), 5.11 μM (nearfield), 5.14 μM (coastal), and 3.81 μM (Cape Cod Bay).

In summary, for all samples in 1994, the frequency distributions for concentrations of SiO_4 and DIN were relatively similar (cf. Figure 3.1.1 and 3.1.5). The frequency distribution of PO_4 concentrations differed from SiO_4 and DIN. Further comments relative to nutrient ratios are provided below.

3.1.2 Annual Cycle of Nutrients

Nitrogen Forms. The pattern for surface water DIN concentrations (Figure 3.1-6) shows a typical annual pattern (cf. Kelly *et al.*, 1993), with generally higher concentrations when the water column is well-mixed (winter) and lowest concentrations when the water column becomes seasonally stratified (roughly April to October). There was regional variation in the annual cycle for surface and bottom-water DIN concentrations (Figure 3.1-7)and three fundamentally distinct temporal patterns were evident. The boundary, offshore, and nearfield regions all followed one pattern. For these regions, surface-water DIN was low (near detection limits) starting in April (~day 95) and stayed low through October (~day 285), while bottom-water DIN rose slightly from April to October. Thus, bottom-water DIN concentrations were higher than surface water DIN concentrations while stratified. A second pattern was displayed by Cape Cod Bay stations. Here, surface and bottom-water DIN concentrations were both low ($\leq$4 μM) and DIN concentrations in the two layers remained fairly similar for the entire stratified period. A third pattern was exemplified by Boston Harbor stations, but in general mimicked by stations in the coastal region. In this case, the annual cycle of DIN went as follows: concentrations fell to low levels for both surface and bottom water in April and June (~day 175), but then *both* surface and bottom DIN concentrations rose in August and October, nearly to levels seen in winter during pre-bloom winter conditions. High surface-water DIN concentrations in Boston Harbor and adjacent coastal waters, noted as a rise in August well prior to Bay destratification, produced a pattern distinctly different from that seen for other regions of Massachusetts Bay as well as for stations sampled in Cape Cod Bay. Detection of these three identified temporal patterns for DIN suggests there is an inherently different annual cycle of nutrients (and related ecological/biogeochemical events) in shallow inshore waters as compared to deeper (shelf) waters of the open Bay. This difference will be examined and discussed in Section 5.

Sampling for organic forms of nitrogen was limited to a subset of stations, including three from Boston Harbor, three from the coastal region, six from the nearfield region, one from the boundary region, one from offshore, 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." DON concentrations appeared to rise in April as DIN concentrations had fallen, generally decreased in June, and concentrations became widely varying across stations in August and October. Some low DON concentrations were calculated (TDN - DIN), for example, much lower than for 1993 (Kelly and Turner, 1995); it is unknown whether low values (<4 μM) are real or an analytical artifact, but they should be viewed with suspicion. The annual pattern for PON also suggested a slight elevation in concentrations in April, followed by relatively stable concentrations for the remainder of the year (mostly 2-4 μM). Given the time patterns and variability across regions within surveys, a general winter-summer (stratified/unstratified) season distinction, as noted for DIN, was not evident for either DON or PON. In the surface layer, the seasonal cycle for Total N (TN = DIN + DON + PON) was in part driven by seasonal variation in DIN (Figure 3.1-10). But since the sum of the organic forms (DON + PON) was relatively stable and often represented more than 50% of TN, a summer season depletion of water column TN is not as pronounced as DIN.

Further analyses by regions may reveal some spatio-temporal trends in DON, PON, or TN, but the data for a regional analysis is sparse compared to DIN. Like DIN, however, the data in part suggest a gradient of decreasing mean TN concentrations from the Harbor. For 1994, the ranking of regions by annual mean TN was: Boston Harbor (mean = 24.0 μM, max = 42.0 μM, N=45) >> the coastal region (mean = 17.4 μM, max = 25.3 μM, N=30) and the boundary region (mean = 16.4 μM, max = 24.7, N=12) > the nearfield (mean 14.7 μM, max=25.0 μM, N=80), offshore (mean 14.2 μM, max= 18.9 μM, N=12), and Cape Cod Bay regions (mean 13.7 μM, max= 19.4 μM, N=23). This order is similar to the regional ranking obtained for DIN concentrations over all depths (Section 3.1.1), but the relative TN enrichment in Boston Harbor and depletion in Cape Cod Bay is less pronounced than it was for DIN.

Phosphorus Forms. The overall annual cycle for PO_4 was similar to DIN in that a sharp drop in concentrations occurred in April, and mean summer PO_4 concentrations in surface waters stayed low compared to winter concentrations (Figure 3.1-11). 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, annual patterns of total P were probably driven by variability in dissolved inorganic forms, rather than by organic forms.

Although dissolved inorganic N and P had broadly similar annual cycles, the relative changes in DIN and PO_4 did differ, as reflected in temporal variations in DIN relative to PO_4 (i.e., the N/P ratio). As noted in the frequency distributions, there were, consistently, measurable concentrations of PO_4, but not DIN in Bay surface water throughout the summer. Thus, the N/P ratio, generally high and close to the Redfield ratio (16:1), dipped in winter to values in surface water that usually were <2 :1 during the stratified period (Figure 3.1-13). A decrease in the N/P ratio in bottom water was less sharp and more transient. By August and October, the bulk of bottom water N/P ratios were 10-12:1, and near mean values during the mixed water column, pre-bloom conditions in February and March 1994. Temporal patterns for surface and bottom waters in 1994 are highly similar to those seen in 1993 (Kelly and Turner, 1995). Other data on cycling of N and P are needed to fully understand relative nutrient limitations; by itself, the concentration data suggest that relative N limitation occurs in surface water during the entire summer productive season.

Silicate. The annual silicate cycle was broadly similar to the cycles of other inorganic nutrients. Surface water SiO_4 concentrations dropped sharply between winter and summer, but had increased slightly by October (Figure 3.1-14). For comparison, silicate concentrations remained low from late spring *through* October in 1993, and was maintained at low summertime levels because of a very intense September-October 1993 diatom bloom (Kelly and Turner, 1995).

Plots of SiO_4 concentrations for surface and bottom-water in the six major sampling regions (Figure 3.1-15) indicate the same three patterns previously described for DIN. The boundary, offshore, and nearfield regions had a distinct separation of surface and bottom water SiO_4 concentrations during the stratified period, with very low SiO_4 in the surface water. Cape Cod Bay had only a slight difference between surface and bottom water SiO_4 concentrations, and none in October. In contrast, surface and bottom water concentrations were similar in the coastal region and in Boston Harbor; from June to October, concentrations increased throughout the whole water column in these regions, not just in near-bottom water.

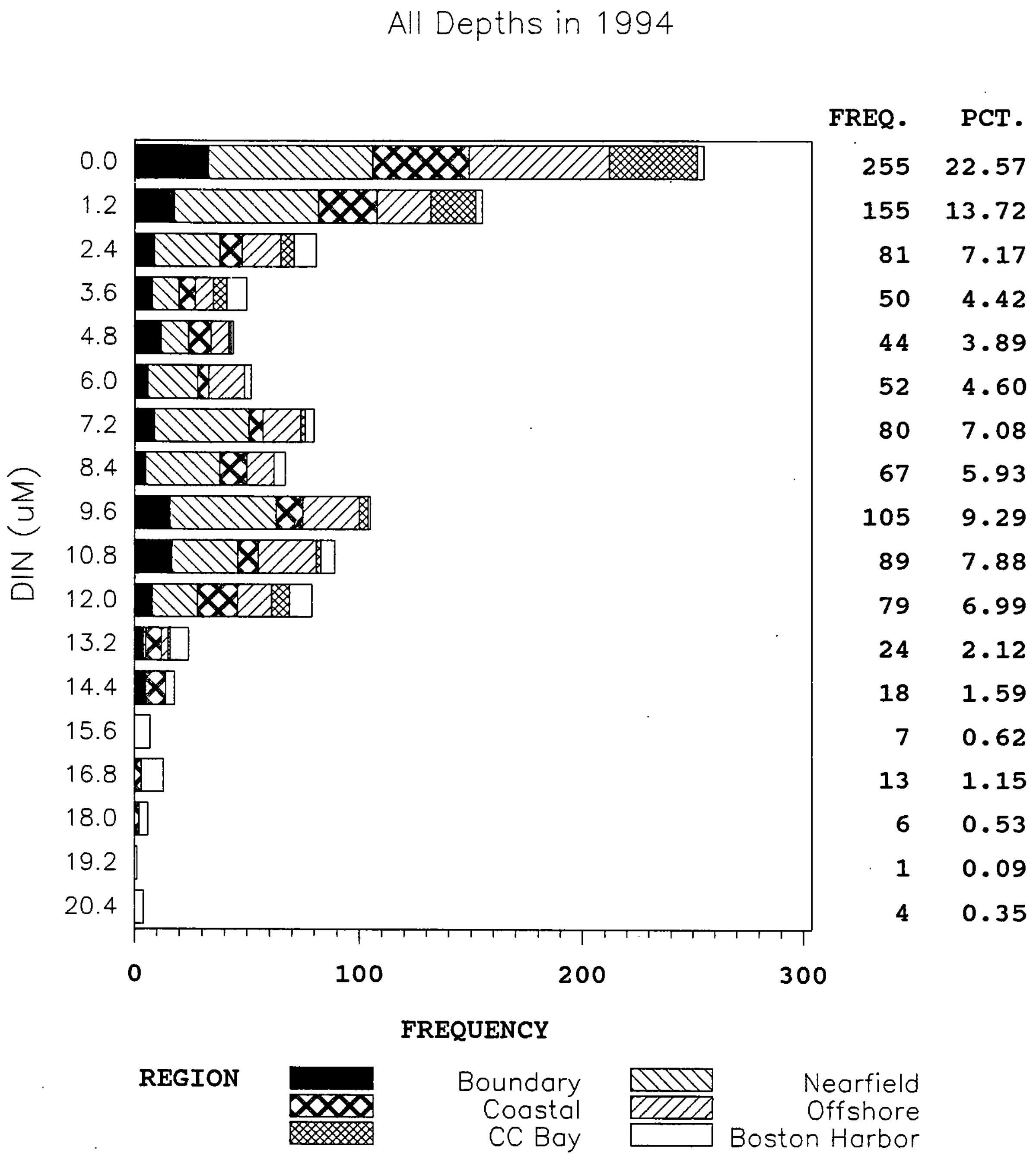


Figure 3.1-1 Frequency distribution of DIN concentrations for all stations sampled in 1994.

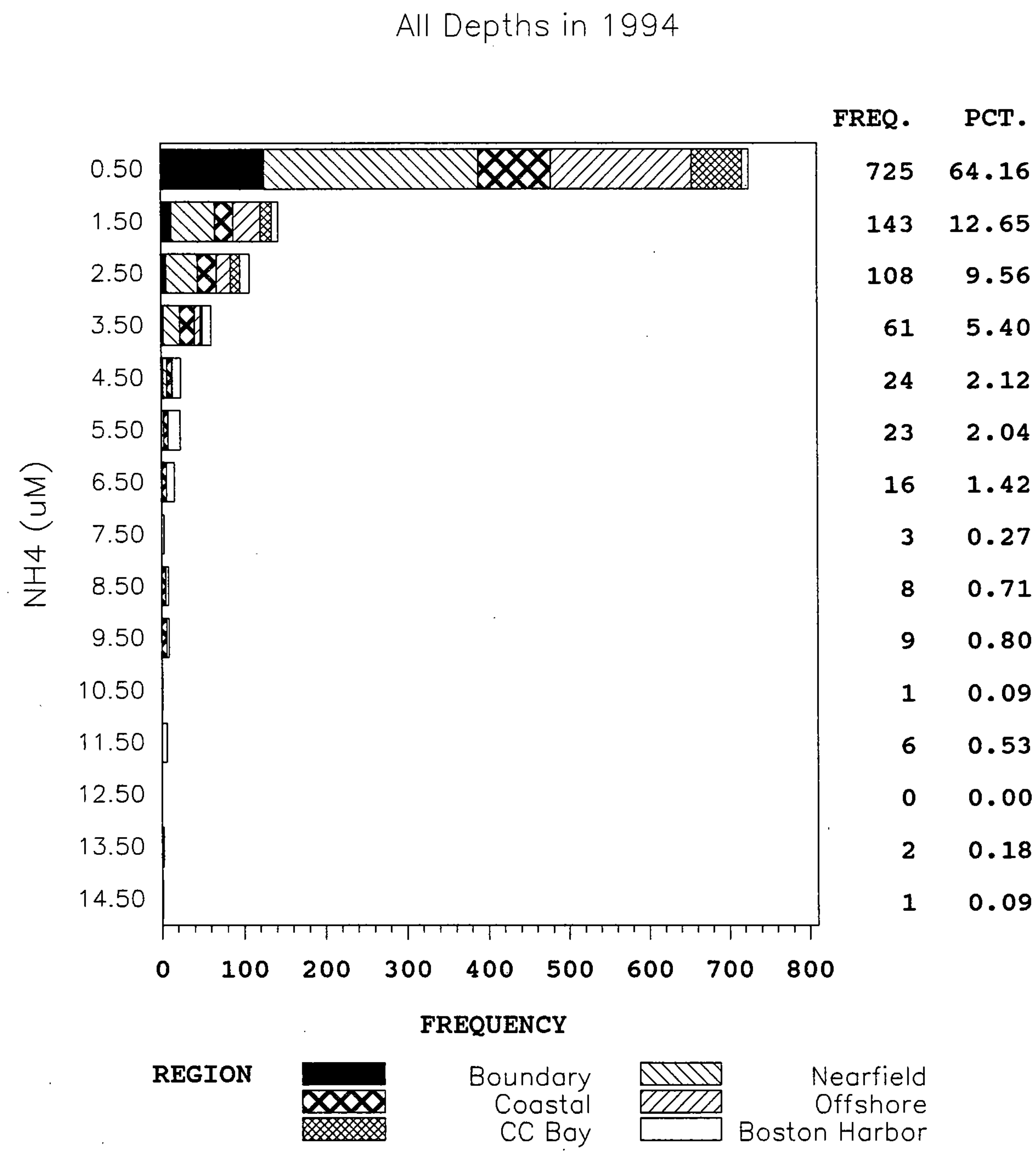


Figure 3.1-2 Frequency distribution of NH_4 concentrations for all stations sampled in 1994.

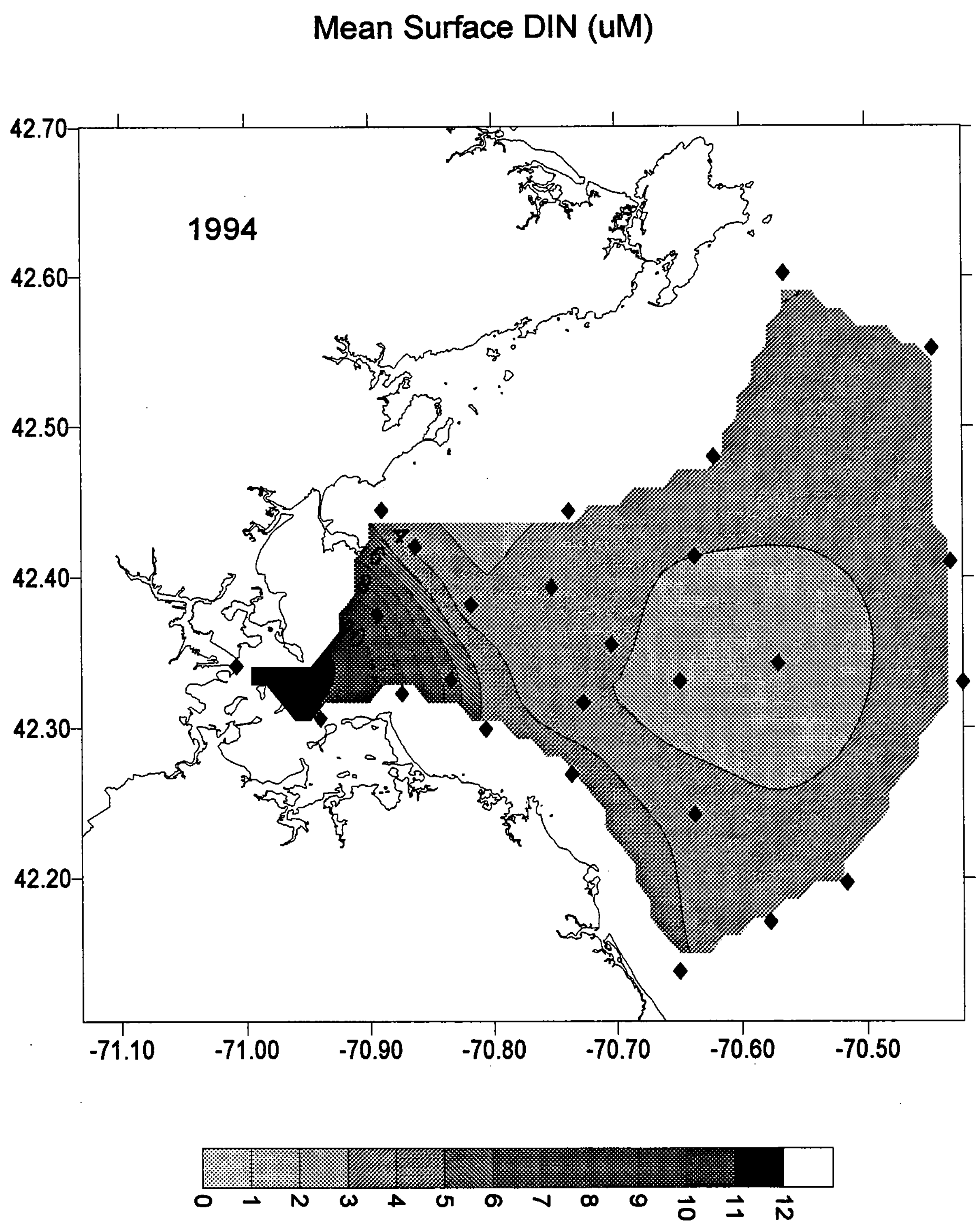


Figure 3.1-3a Spatial pattern of DIN concentrations in Massachusetts Bay. Data are surface water means from six farfield surveys in 1994.

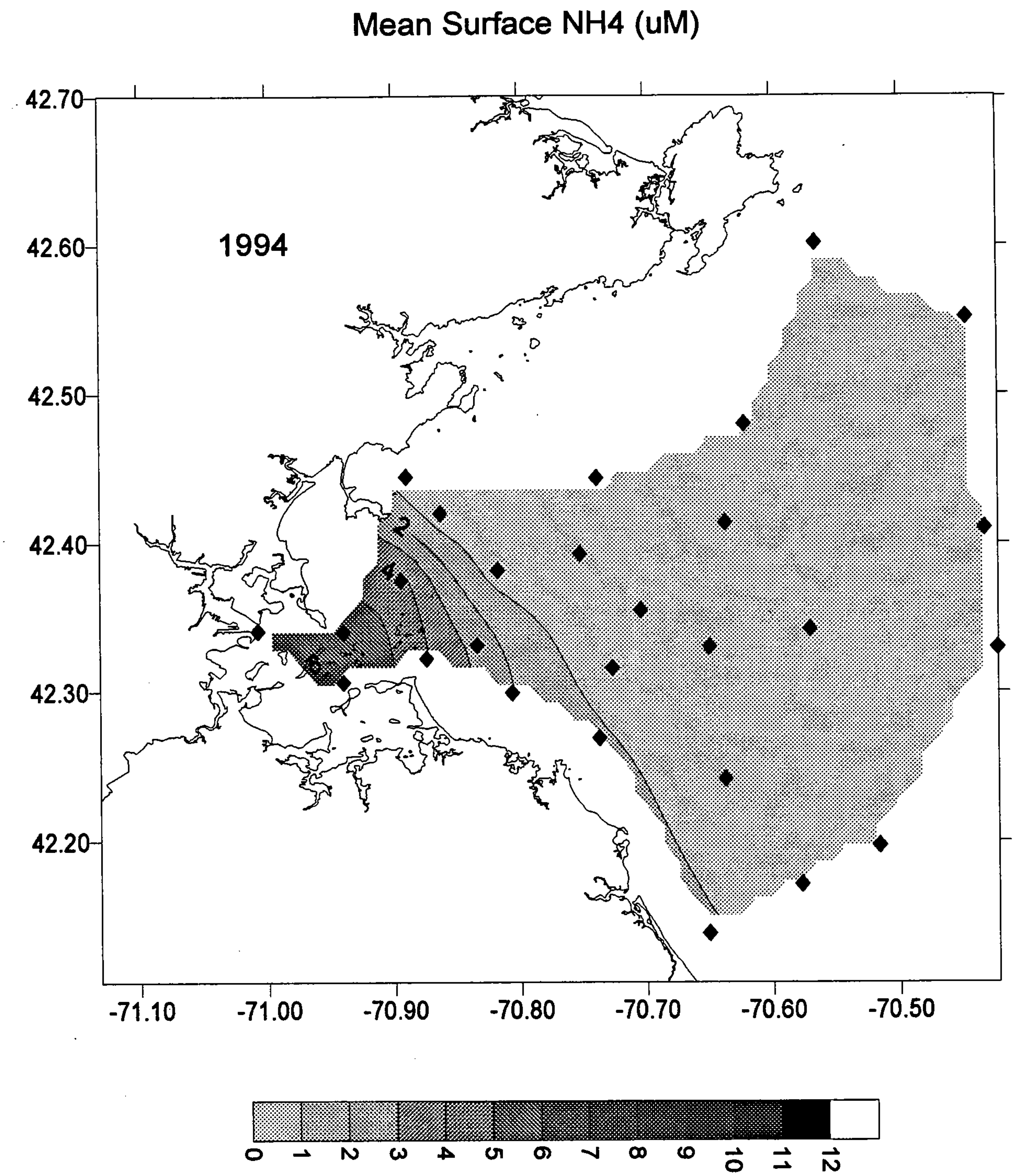


Figure 3.1-3b Spatial pattern of NH_4 concentrations in Massachusetts Bay. Data are surface water means from six farfield surveys in 1994.

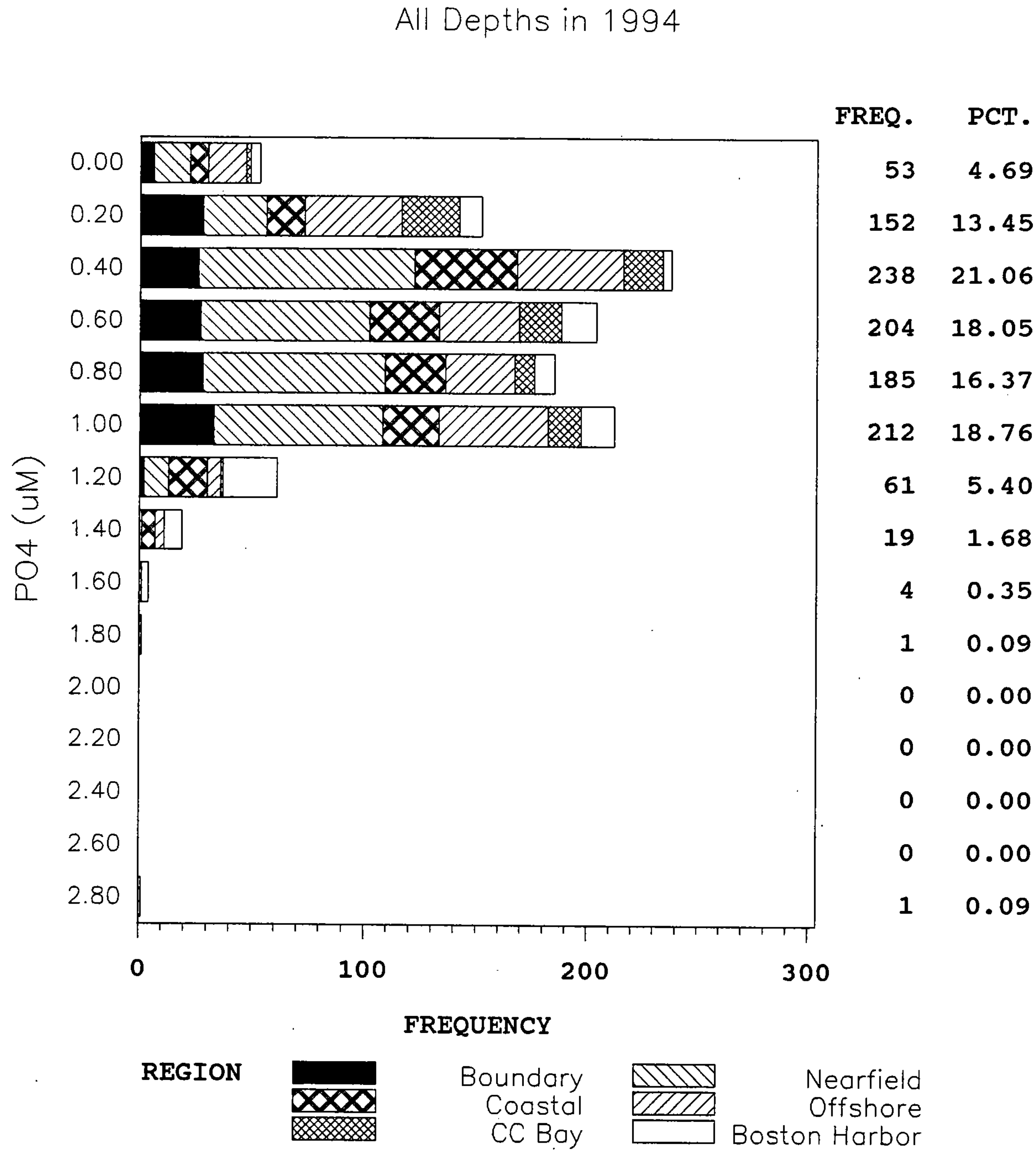


Figure 3.1-4 Frequency distribution of PO_4 concentrations for all stations sampled in 1994.

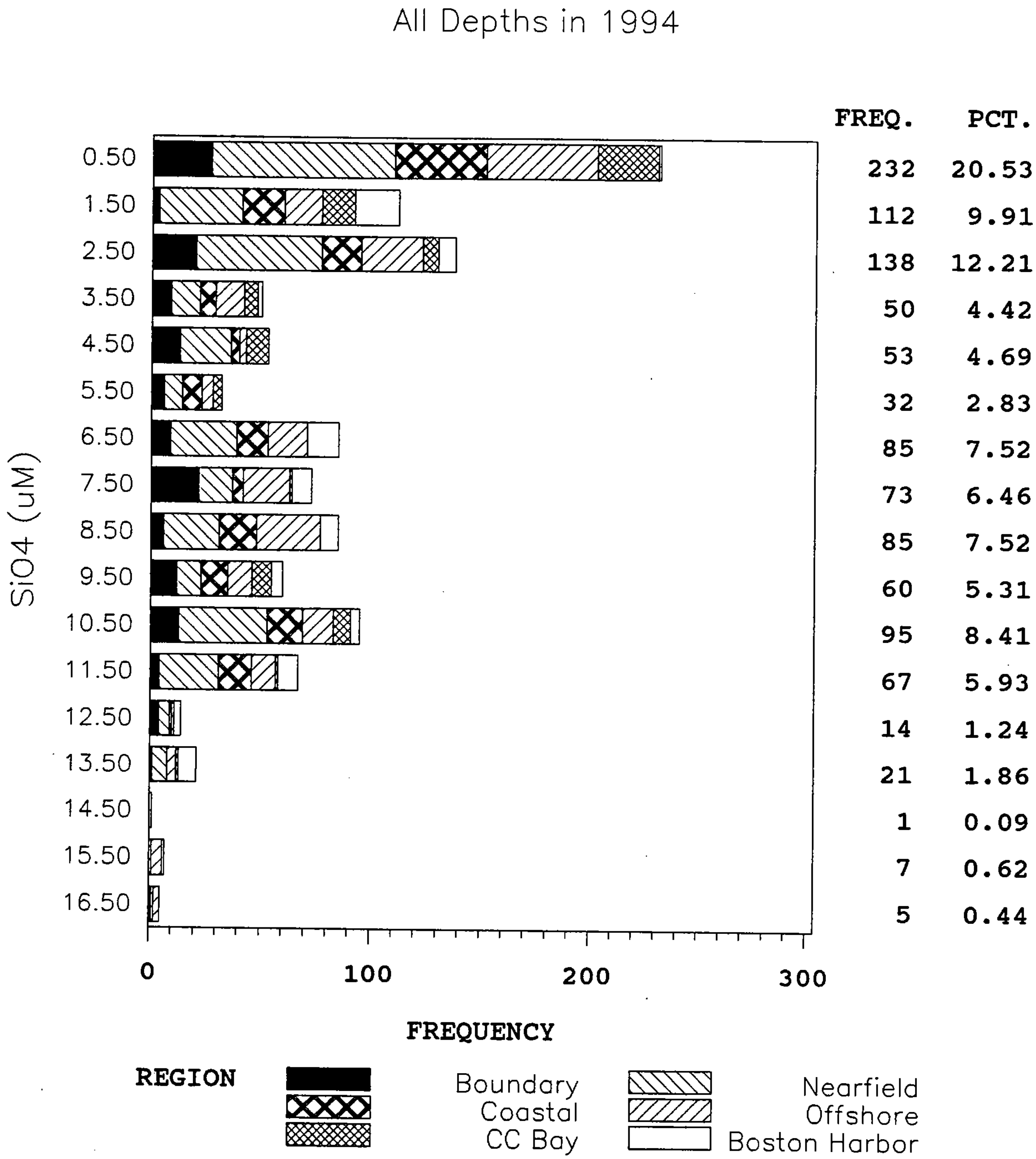


Figure 3.1-5 Frequency distribution of SiO_4 concentrations for all stations sampled in 1994.

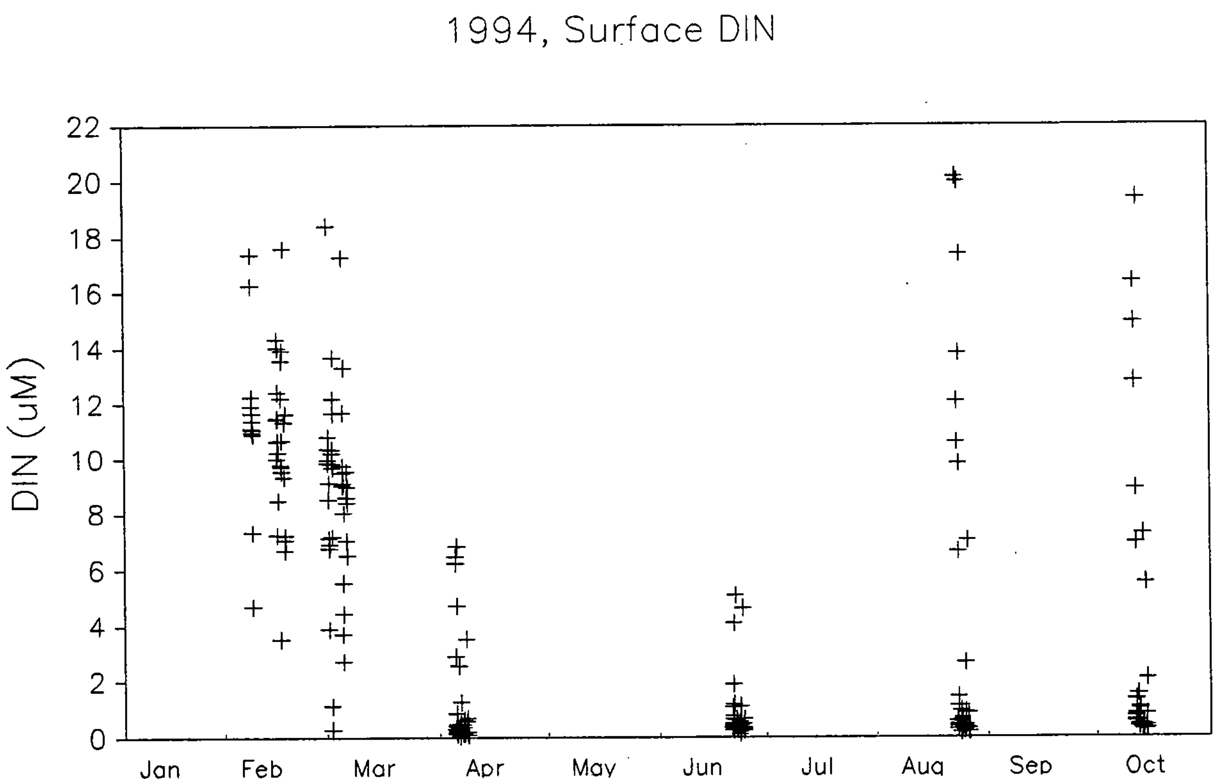


Figure 3.1-6 Annual cycle of DIN concentrations in surface waters of Massachusetts and Cape Cod Bays.

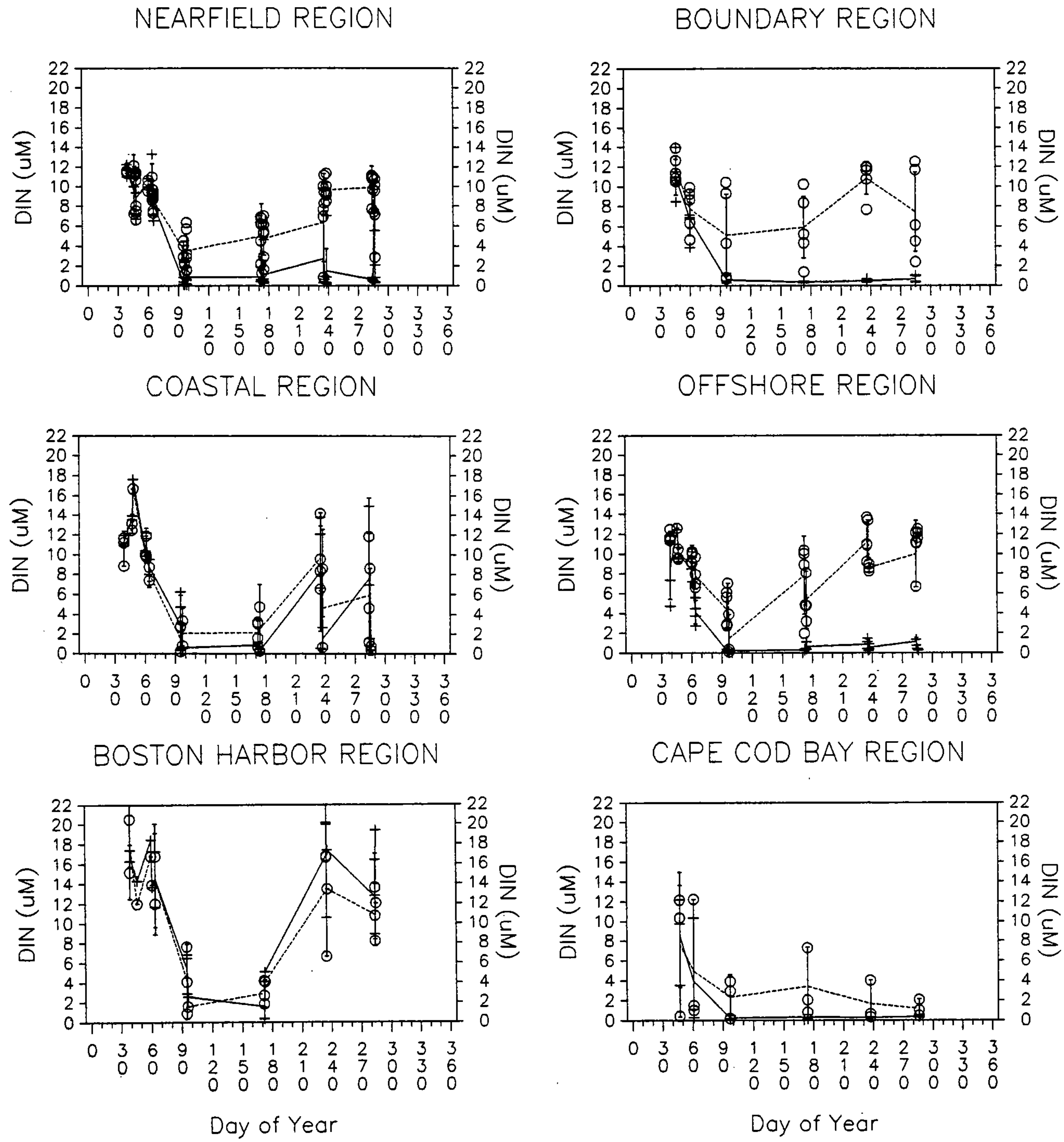


Figure 3.1-7 Comparison of 1994 annual DIN cycles in surface and bottom waters in six sampling regions of Massachusetts and Cape Cod Bays. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling, so sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

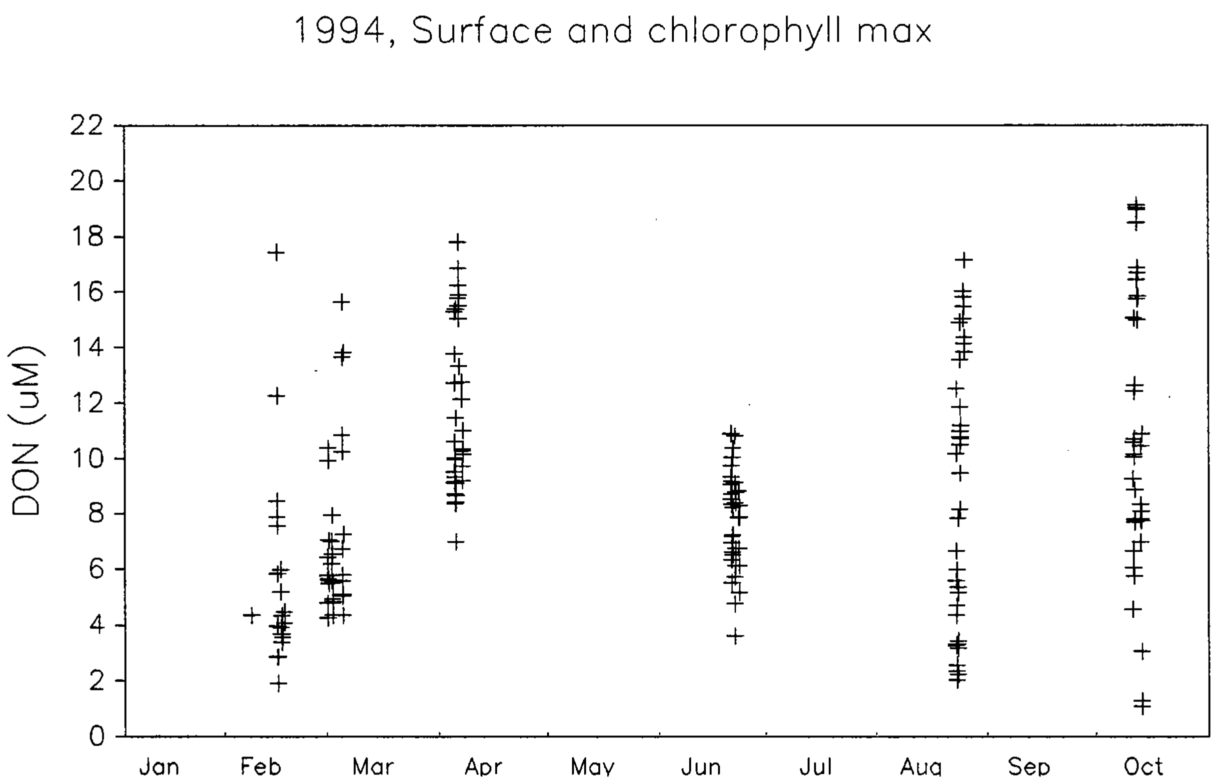


Figure 3.1-8 DON concentrations through the 1994 annual cycle in the surface layer of Massachusetts and Cape Cod Bays. One high point (value = 22.6) not shown.

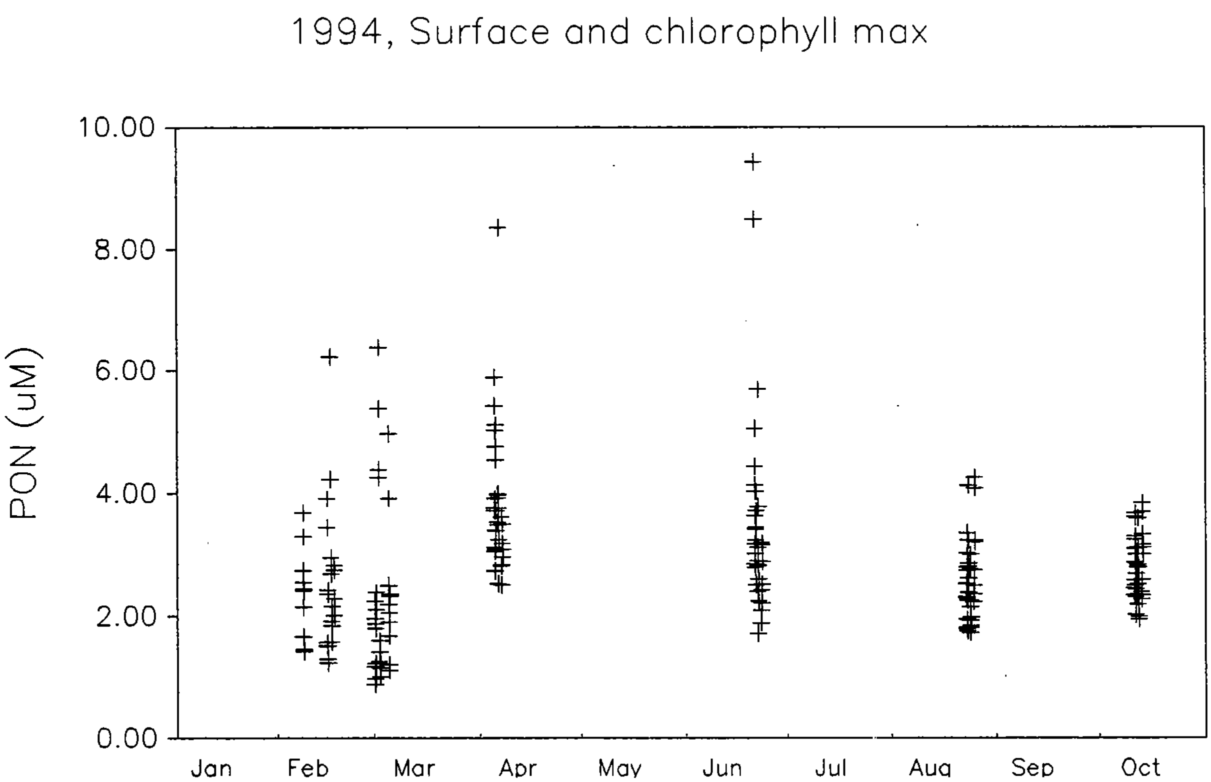


Figure 3.1-9 PON concentrations through the 1994 annual cycle in the surface layer of Massachusetts and Cape Cod Bays.

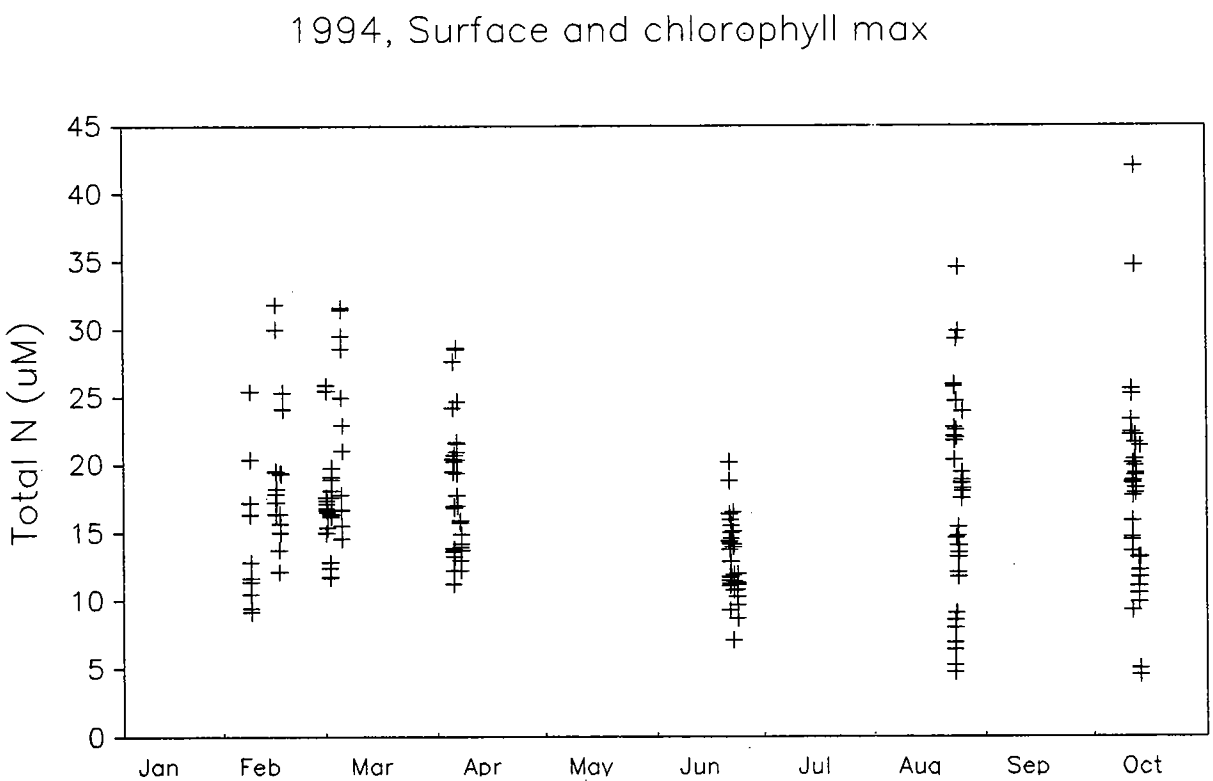


Figure 3.1-10 Total nitrogen (TN) concentrations through the 1994 annual cycle in the surface layer of Massachusetts and Cape Cod Bays.

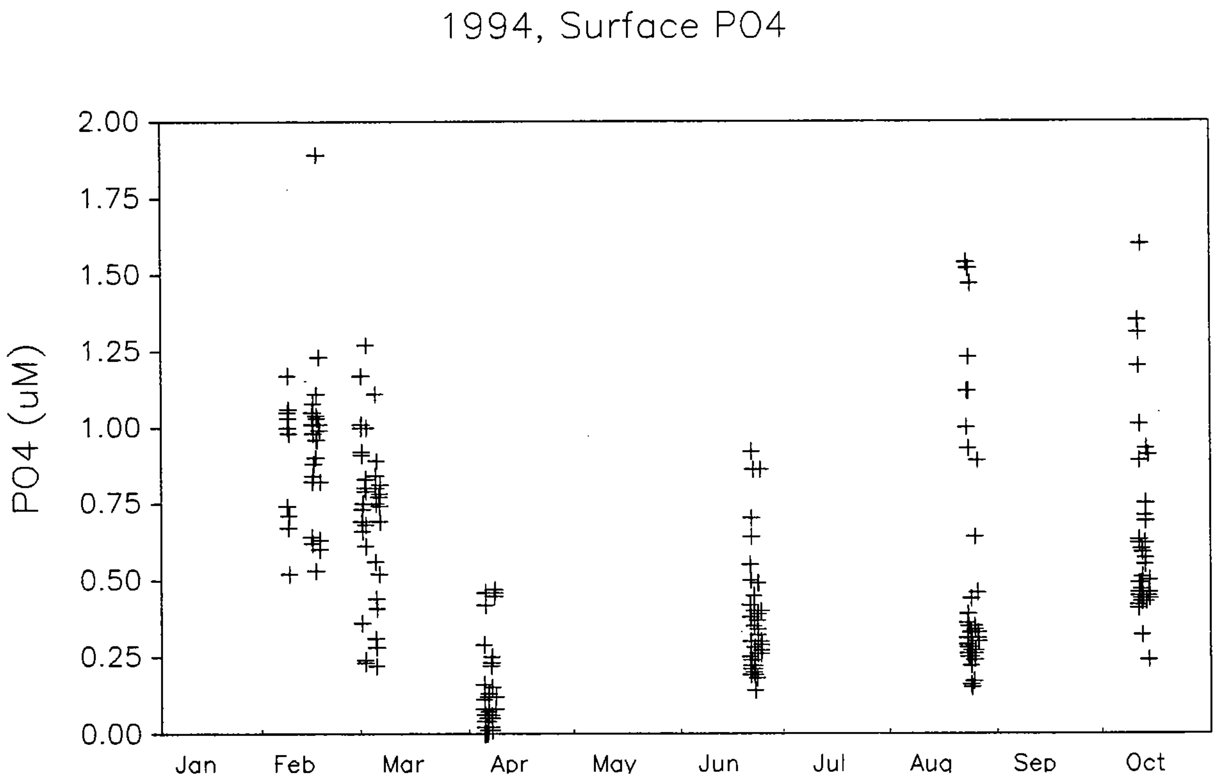


Figure 3.1-11 PO_4 concentrations through the 1994 annual cycle in surface waters of Massachusetts and Cape Cod Bays.

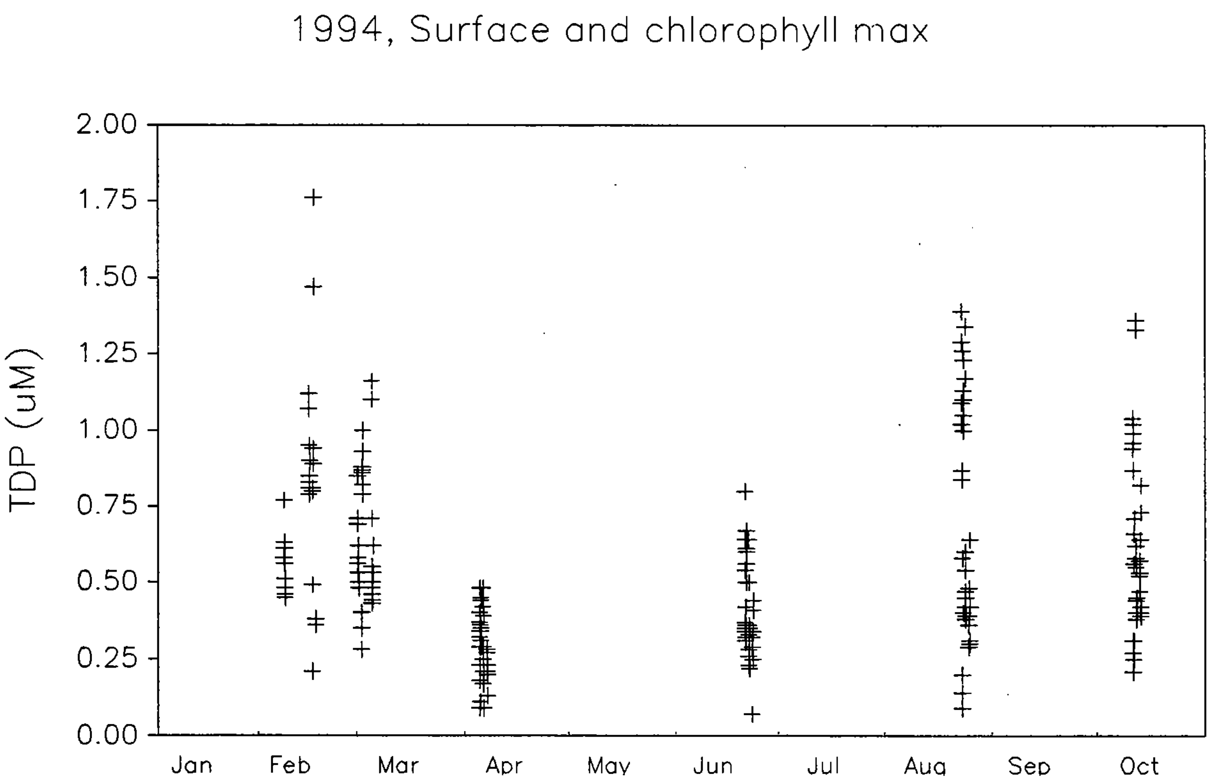


Figure 3.1-12 Total dissolved phosphorus (TDP) concentrations through the 1994 annual cycle in the surface layer in Massachusetts and Cape Cod Bays.

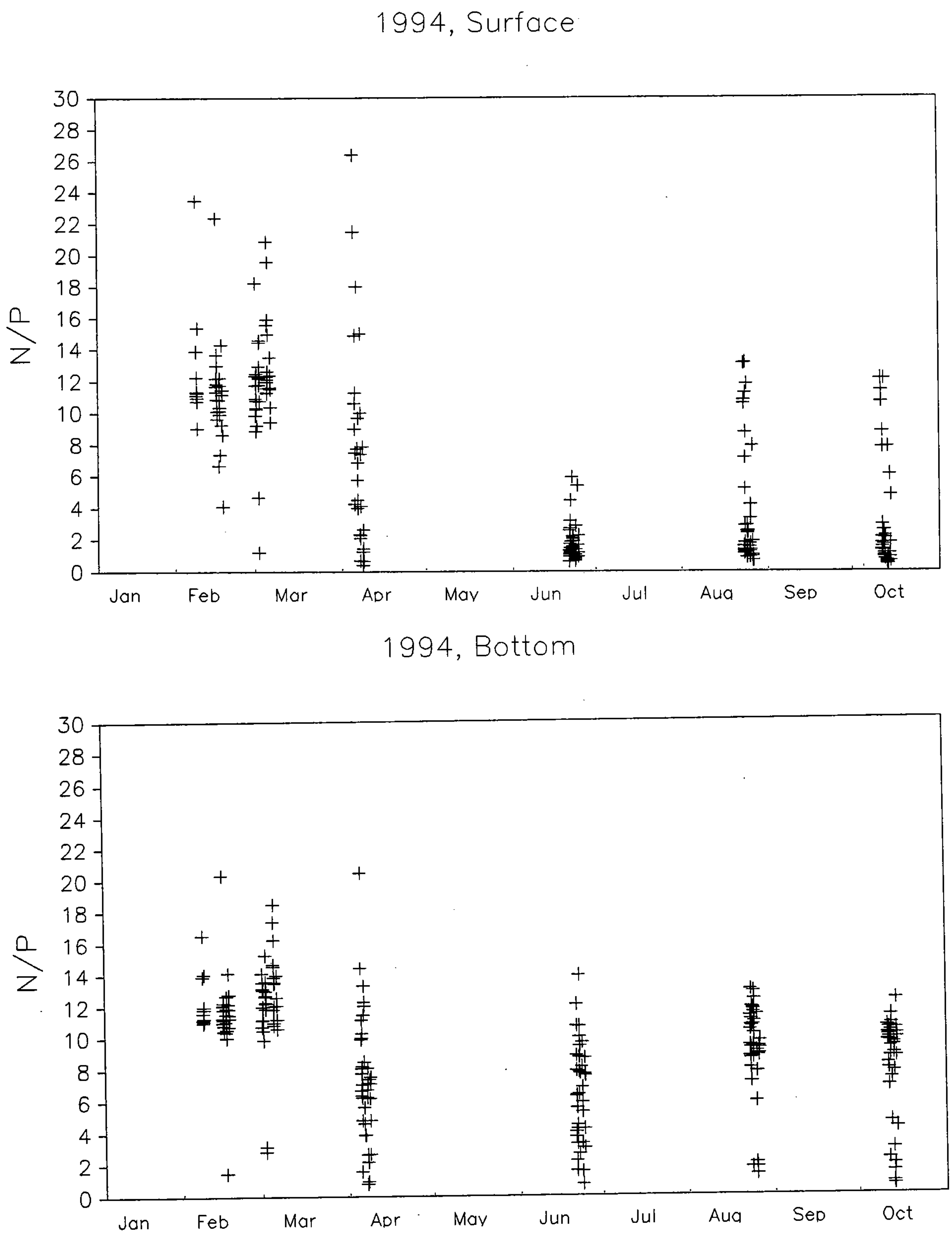


Figure 3.1-13 DIN/PO_4 (N/P) ratios in surface and bottom waters through the 1994 annual cycle in Massachusetts and Cape Cod Bays. Several points above 30:1 are not shown.

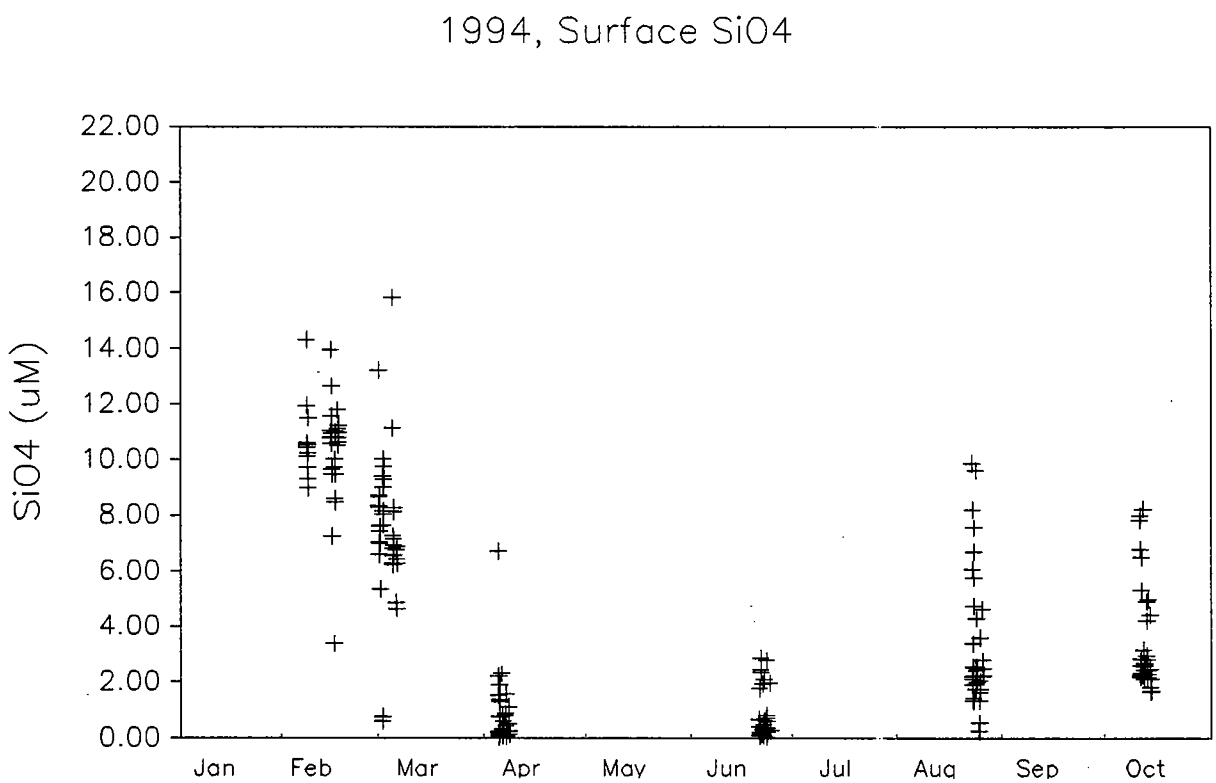


Figure 3.1-14 SiO_4 concentrations through the 1994 annual cycle in surface waters of Massachusetts and Cape Cod Bays.

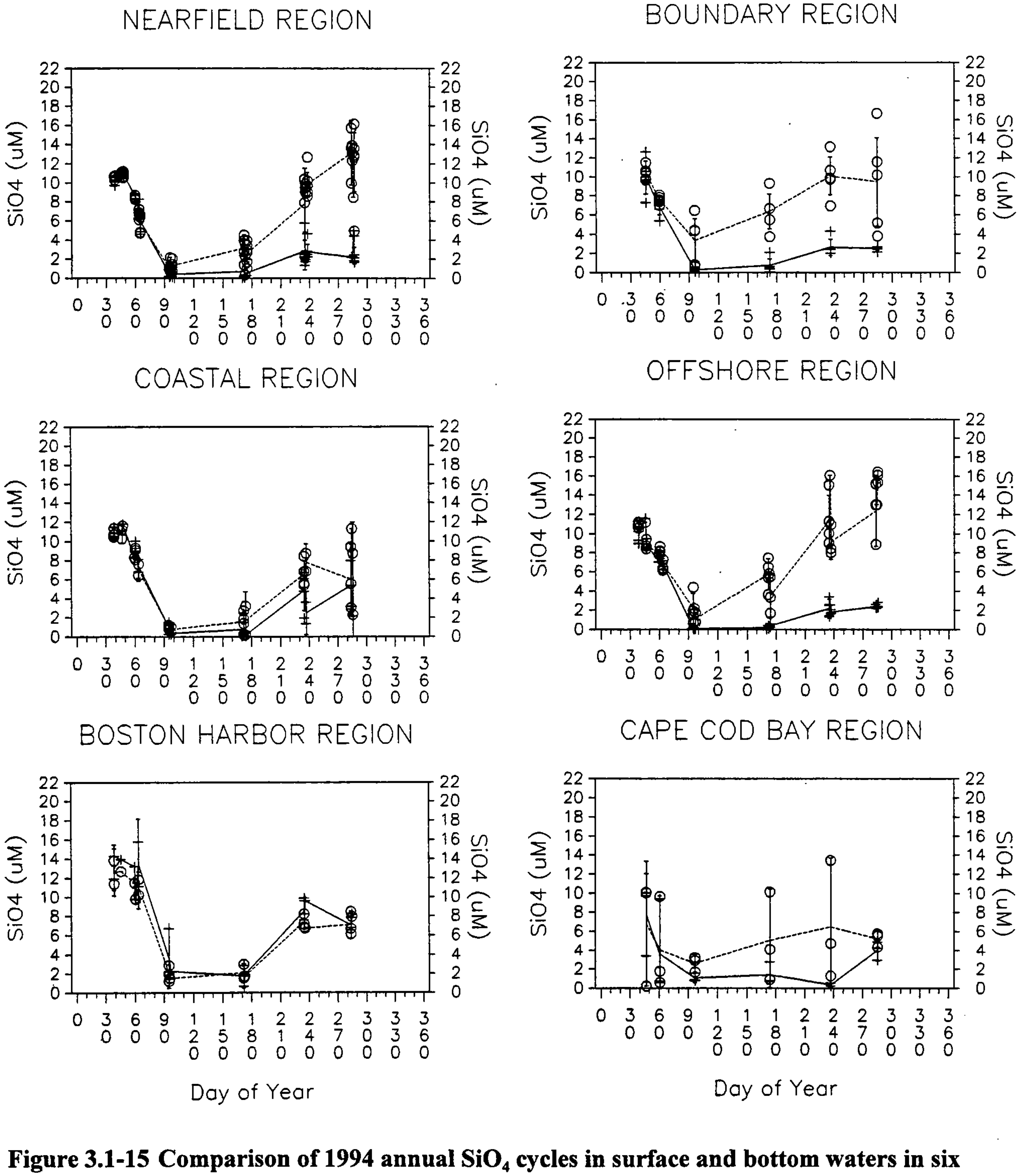


Figure 3.1-15 Comparison of 1994 annual SiO_4 cycles in surface and bottom waters in six sampling regions of Massachusetts and Cape Cod Bays. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values 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

For each survey, *in-situ* 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 post-survey calibrated values. The data used in this report represent readings made at the closing of Niskin bottles on a hydrocast on the 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 1994 water column monitoring reports that are referenced in Section 2.

3.2.1 Frequency Distribution of Chlorophyll

A total of 1132 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 16.9 $\mu g\ L^{-1}$ and was measured in Cape Cod Bay. For comparison, the maximum chlorophyll *a* concentration from standard extraction techniques was 17.6 $\mu g\ L^{-1}$ (N=335 analyses). More than 88% of the samples had concentrations in the four lowest concentration classes (Figure 3.2-1) and thus were below 4.2 $\mu g\ L^{-1}$. In each region, some samples exceeded 6 $\mu g\ L^{-1}$. The overall mean concentration was 2.27 $\mu g\ L^{-1}$ based on fluorescence (N=1132, standard deviation=2.00) and 2.20 $\mu g\ L^{-1}$ based on chlorophyll *a* (N=335, standard deviation=2.11). By region, the mean fluorescence concentrations were 1.85 $\mu g\ L^{-1}$ (offshore region), 2.09 $\mu g\ L^{-1}$ (boundary region), 2.14 $\mu g\ L^{-1}$ (nearfield region), 2.37 $\mu g\ L^{-1}$ (Boston Harbor), 2.56 $\mu g\ L^{-1}$ (coastal region), and 3.58 $\mu g\ L^{-1}$ (Cape Cod Bay).

3.2.2 Distribution of Chlorophyll Over Depth

Figure 3.2-2 provides a regional comparison of 1994 fluorescence measurements. Chlorophyll maxima above 9 $\mu g\ L^{-1}$ were detected below the surface with some frequency in Cape Cod Bay, and occasionally in the boundary region, and at the surface in Boston Harbor. Boston Harbor and the coastal region in general tended to have similar chlorophyll distributions over depth, with higher concentrations often near the surface. From the figure, which incorporates data from all seasons, distinct and persistent mid-depth chlorophyll maximum are not strongly suggested for any region, although a mid-depth chlorophyll maxima was characteristic of much of the eastern nearfield, boundary, and offshore regions during seasonal stratification. Baywide, high concentrations (>6 $\mu g\ L^{-1}$) were unusual at depths >30 m.

3.2.3 Annual Cycle for Chlorophyll in Surface Waters

While there are variations in patterns of chlorophyll over depth across stations and regions, the focus of this section is limited to surface waters. Figure 3.2-3 presents an annual cycle based on surface measurements at stations within the six defined sampling regions. As with the nutrients (Section 2) several regional patterns are evident. To begin, the principal Massachusetts Bay regions (coastal, nearfield, and offshore) had similar, if not exact, surface-water trends. The seasonal pattern showed by this group was low winter chlorophyll, a minor late spring peak, with a general summertime increase in chlorophyll concentrations to an annual maximum in the fall bloom in October. The Massachusetts Bay trend was distinct from the Cape Cod Bay trend, where there were very high winter-spring chlorophyll peaks (the annual maximum), followed by low late spring and summer values. There was a fall bloom in Cape Cod Bay, as well as in Massachusetts Bay, but concentrations (~3 $\mu g\ L^{-1}$) in October were substantially less than in spring and not as high as observed, for example, in the nearfield region's fall bloom. For all baseline water quality sampling years (1992-1994), Cape Cod Bay and Massachusetts Bay have had fundamental differences in timing and in peak concentrations achieved with the major phytoplankton blooms early and late in the year (cf. Kelly *et al.*, 1993; Kelly and Turner, 1995).

The boundary region, to an extent, appeared to have equivalent spring and fall blooms and thus represents almost a mixture of Cape Cod Bay and Massachusetts Bay patterns. The apparent mixed condition may result from the arbitrary grouping of stations that range from northern Massachusetts Bay (and outside Stellwagen Bank) to the tip of Cape Cod, not quite into Cape Cod Bay (station F29).

A uniquely different annual cycle for chlorophyll was suggested by data for Boston Harbor stations. In the Harbor's case, a chlorophyll maximum appeared in late spring and perhaps peaked in mid-summer. In contrast, in the Bays, low chlorophyll concentrations were characteristic of the early winter-spring and fall seasons. Ecological differences, such as the fundamentally different annual cycles for chlorophyll in the Harbor and the Bays in 1994, are discussed more in Section 5.

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

For each station sampled in 1994, the mean chlorophyll concentrations in surface water were calculated (Appendix A). Mean values are displayed for the main region of Massachusetts Bay in Figure 3.2-4. The area shown in Figure 3.2-4 extends north and east of the nearfield to include the boundary region stations as well as stations F22, F19, F17, and F12 overlying Stellwagen Basin, and south to Marshfield (station F05). High concentrations were found within Boston Harbor. The pattern of a general inshore-offshore gradient of decreasing mean chlorophyll concentrations is evident in the figure, as is an apparent extension of higher chlorophyll near the coast some distance south of Boston. This pattern repeats those seen in recent years and matches well with that of 1990 (Townsend *et al.*, 1991 as summarized in

Kelly, 1991), in that it shows a patch with high mean surface chlorophyll concentration in an area off Cohasset, just southeast of Boston Harbor.

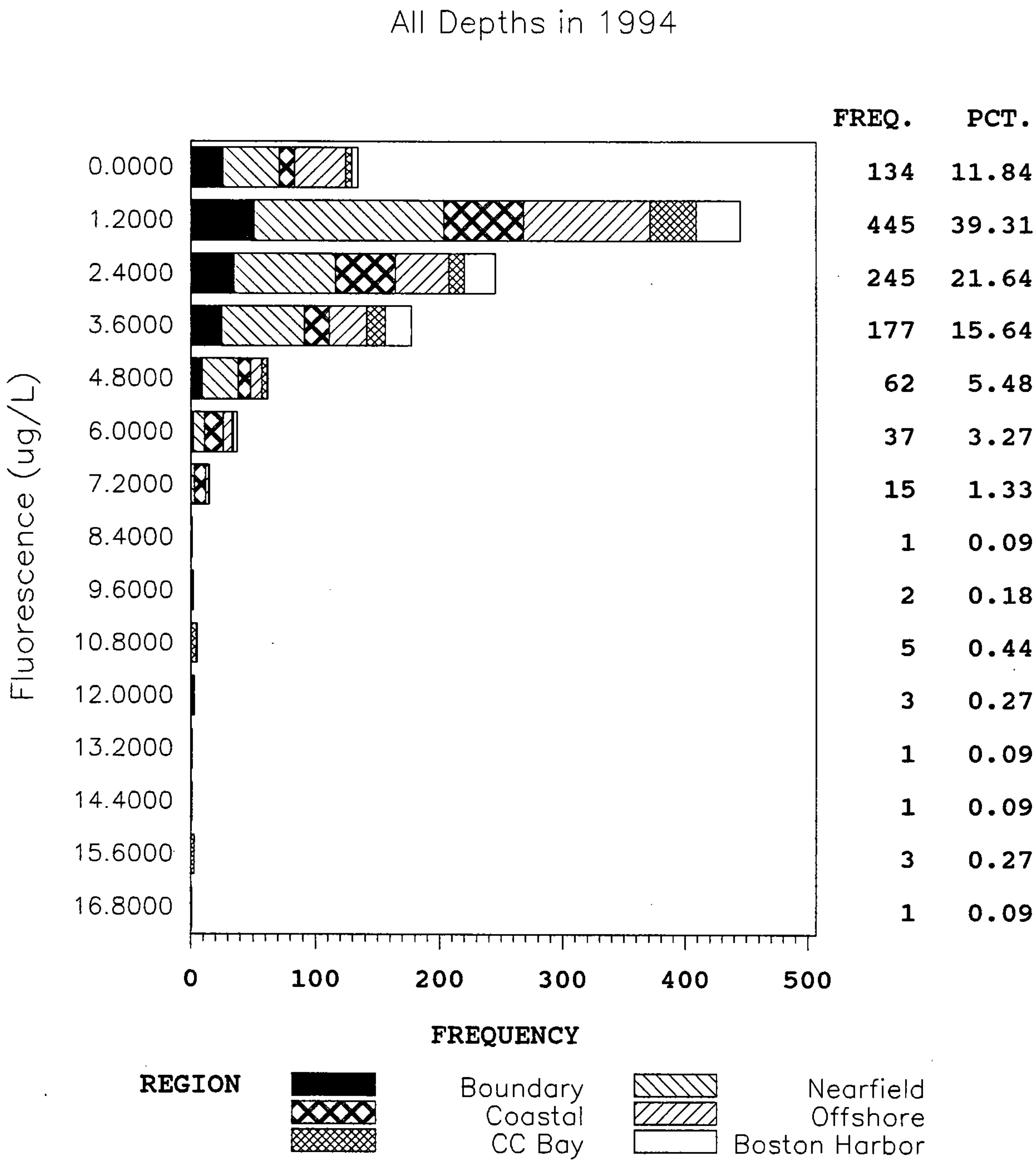


Figure 3.2-1 Frequency distribution of fluorescence for all stations sampled in 1994.

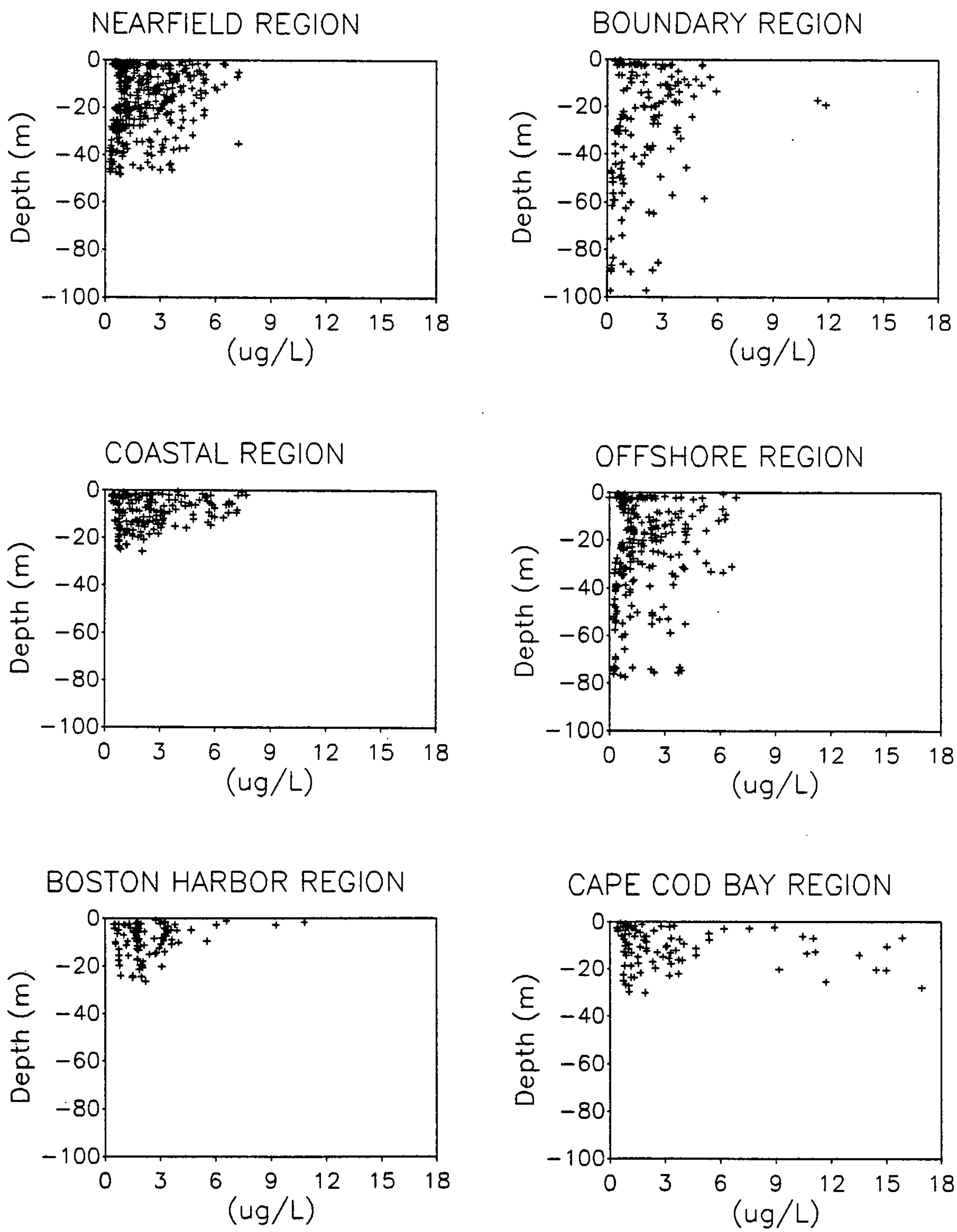


Figure 3.2-2 Fluorescence over depth, by sampling regions, for all surveys in 1994. Two points at depth >100 m are not shown for the boundary region.

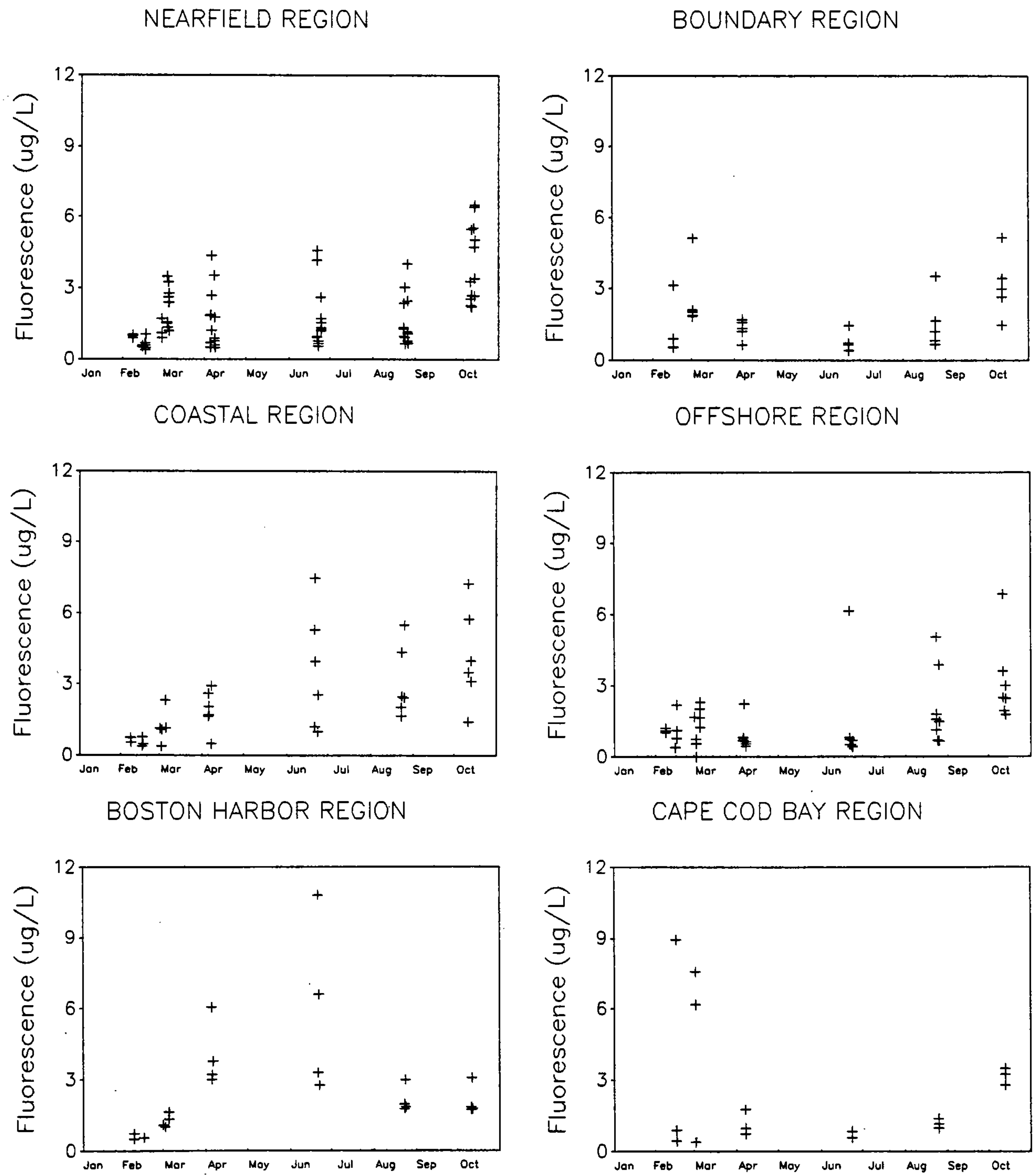


Figure 3.2-3 Fluorescence through the 1994 annual cycle in surface waters for six major sampling regions.

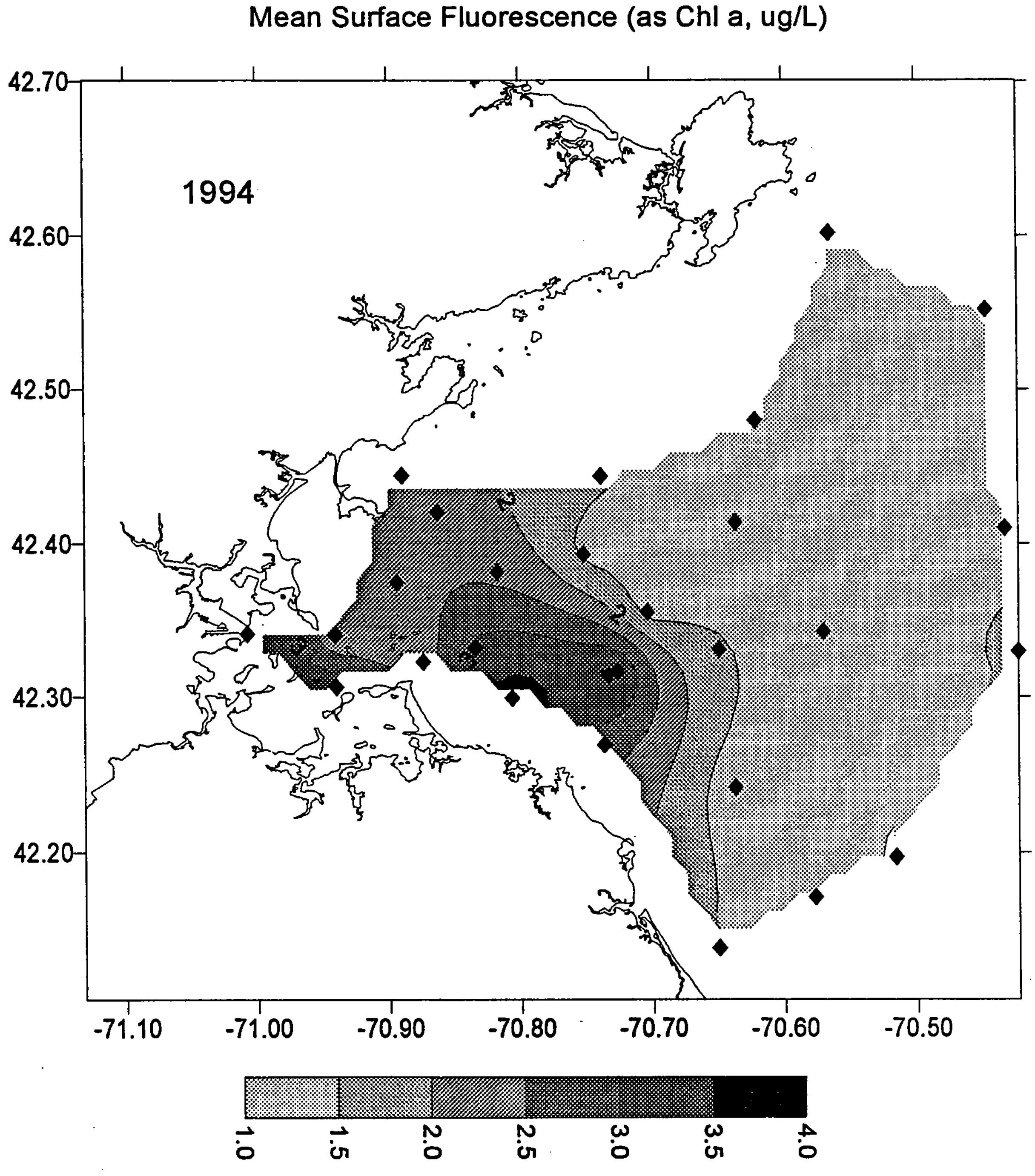


Figure 3.2-4 Spatial pattern of fluorescence in Massachusetts Bay. Data are surface water means from six farfield surveys in 1994.

3.3 DISSOLVED OXYGEN

Dissolved oxygen (DO) concentrations were measured continuously by an *in-situ* sensor during vertical hydrocasts (down and up) at all stations. For each survey, *in-situ* sensor data on the upcast 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. The calibrated DO sensor data that are used in this report are based on the time-averaged readings concurrent with separate Niskin bottle closings at each of five depths during the upcast at each station. These "bottle-closing" data provide the most comprehensive and reliable set of MWRA water column DO. Moreover, 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.

3.3.1 Frequency Distribution of Dissolved Oxygen

For the six farfield surveys, 1044 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 4.82 mg L^{-1}, in bottom water during October. The maximum was 16.85 mg L^{-1} (145% of saturation), but only five individual points exceeded 13 mg L^{-1}, and the mean DO was 9.82 mg L^{-1}. About 5% of the readings were <7 mg L^{-1} and nine (<1%) were <6.0 mg L^{-1}, the state standard. The frequency distribution for the percent saturation (Figure 3.3-2) was centered near 100% saturation; the mean percent saturation was 99%, with a minimum of 55% and a maximum of 145%.

A few regional distinctions are apparent from these plots. For one, compared to other regions, fewer data for Boston Harbor showed supersaturation (e.g., >102%, see Figure 3.3-2). On average, DO was indeed undersaturated (95%) at stations in the Harbor region, whereas most other regions had mean values of 98-100%. Interestingly, the coastal region, which includes stations adjacent to the Harbor, had the highest mean DO (102% of saturation). Secondly, low DO (<68% or <6.0 mg L-1) were restricted essentially to the bottom water of the nearfield region and adjacent deeper water in the offshore region.

3.3.2 Annual Cycle of Dissolved Oxygen

The water column in most sampling regions of the Bays regularly becomes stratified during the summer. A consequence of that stratification is the appearance of a surface productive layer in which photosynthetic activity results in a net production of DO, usually resulting in saturated, or often supersaturated conditions (Figure 3.3-3). In contrast, as a bottom layer becomes seasonally sealed from atmospheric exchange and lies below light levels at which net photosynthesis occurs, respiration dominates and DO declines below saturation. In 1994, the separation of surface and bottom waters, on average, began in April (~day 95) and was notable by June (~day 175).

Figure 3.3-4 contrasts the annual DO cycle for surface and bottom waters of two sampling regions. The offshore region exemplifies the surface and deepwater distinction in DO cycles in those Bay waters which seasonally stratify. From the spring bloom (April) onward through October, the surface productive layer is autotrophic, with a continuous slight supersaturation. In contrast, from April onward, the bottom water progressively declines in terms of percent saturation. In sharp contrast, Boston Harbor is fairly well mixed, except for inner portions of back channels (not sampled in this program, but monitored in MWRA Harbor studies) and the data show little distinction in DO with depth (Figure 3.3-4). In spite of relatively high chlorophyll (see Section 3.2) and considerable primary production (see Section 3.5), the Harbor appears to be a net heterotrophic system in summer, as both surface and bottom waters are undersaturated from June to August. Interestingly, however, note that the bottom water in the offshore region reached lower % DO saturation in late summer/fall 1994 than did the Harbor.

The annual minimum in bottom water DO concentrations for many locations was measured during the October survey (Figure 3.3-5). This pattern is consistent with results of recent years (Kelly, 1993; Kelly and Turner, 1995). Stratified conditions remained at this time in the boundary, offshore, and nearfield regions, and DO concentrations were generally <7 mg L^{-1} at depths below 30 m in these regions. A number of concentrations verged upon the state standard, while two were below it. Notably, a similar plot for DO in October 1993 (cf. Figure 3.3-6 of Kelly and Turner, 1995) showed concentrations centered at about 7.5-8.0 mg L^{-1}, only one below 7.0 mg L^{-1}. Thus, throughout bottom waters of most of Massachusetts Bay, the October 1994 DO values were more than 1 mg L^{-1} lower than the minima for the previous year.

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, 1993). Figure 3.3-6 shows the time trend for DO at stations where water sampling depths were consistently >50 m (stations F12, F17, F19, and F22). Both concentration and percent saturation data approximate a linear decline with time from about April to October. Linear regression analyses of concentration vs. time from April through October indicated a significant decline (Prob>F=0.0001, R^2= 0.95, N=22) in DO at an estimated rate (slope±standard error) of 0.022 (±0.001) mg L^{-1} d^{-1}. DO declines implied from similar analyses of data gathered at these same stations (plus a station, F08, not sampled in 1994) over the same months (April-October) have given similar, but slightly lower rates — 0.015 to 0.018 mg L^{-1} d^{-1} in 1992 and 1993 respectively (Kelly, 1993; Kelly and Turner, 1995). In previous years, the seasonal DO decline at depth within Stellwagen Basin has appeared to increase during the late summer; an increased rate of decline is also suggested from August to October 1994 (Figure 3.3-6).

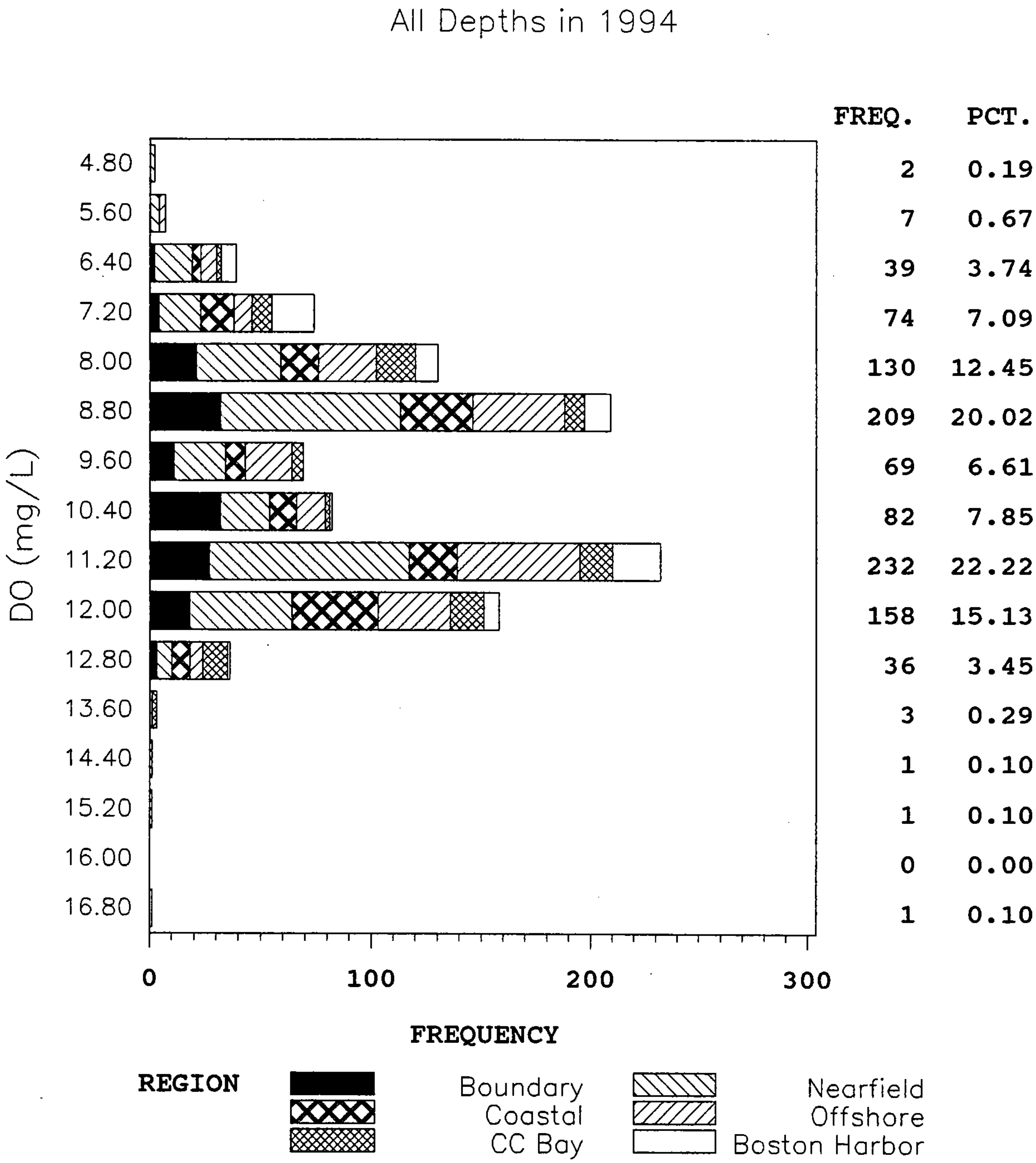


Figure 3.3-1 Frequency distribution of DO concentration for all stations sampled in 1994.

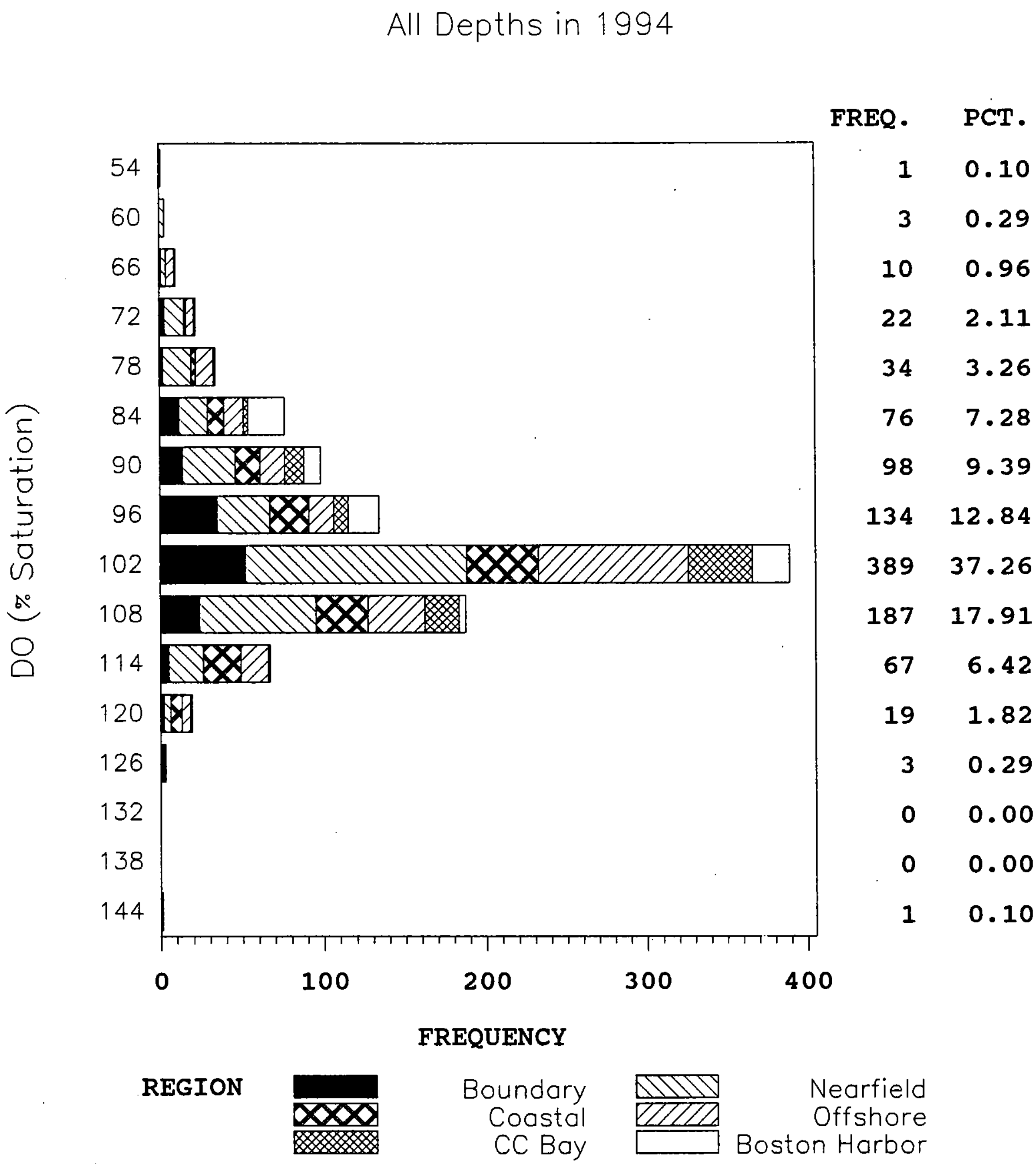


Figure 3.3-2 Frequency distribution of DO saturation for all stations sampled in 1994.

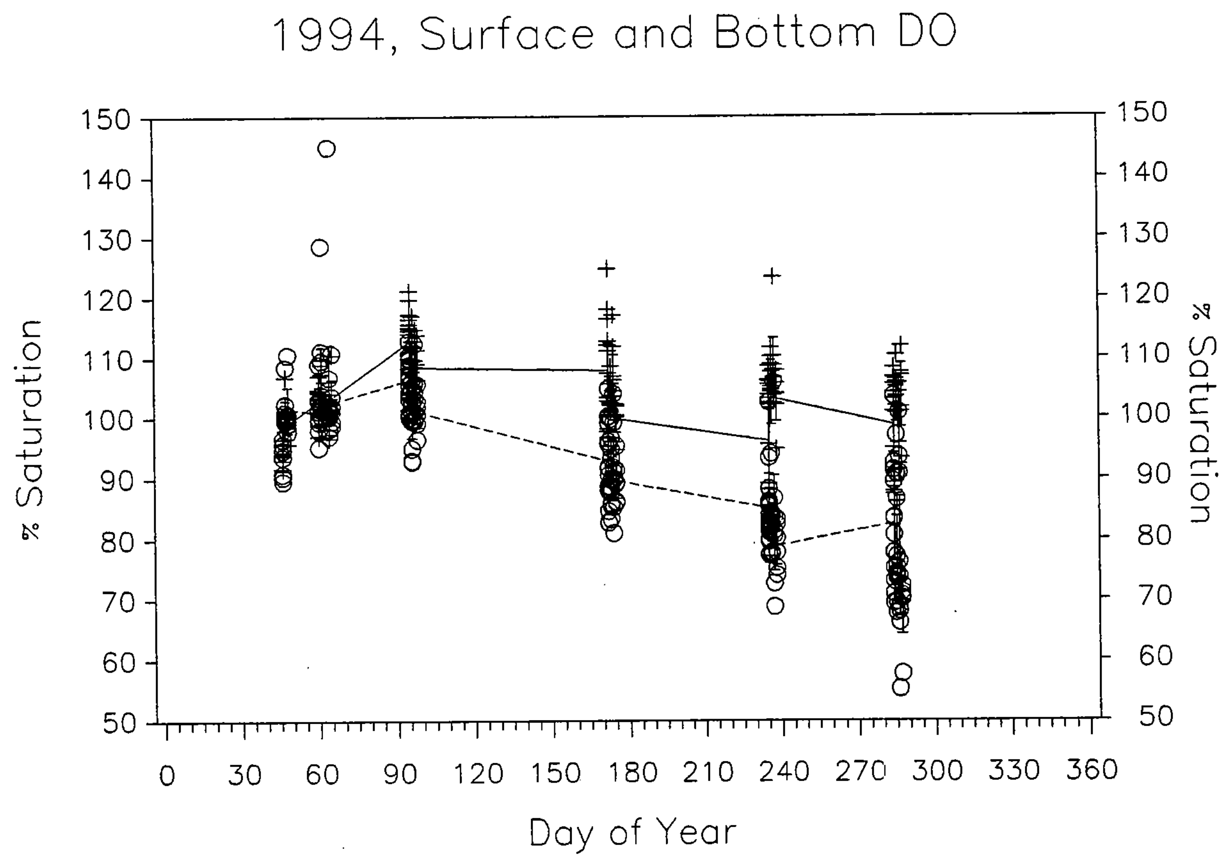


Figure 3.3-3 DO (% saturation) in surface and bottom waters through the 1994 annual cycle in the sampling region. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling. Vertical lines with bars indicate ± standard error of the mean.

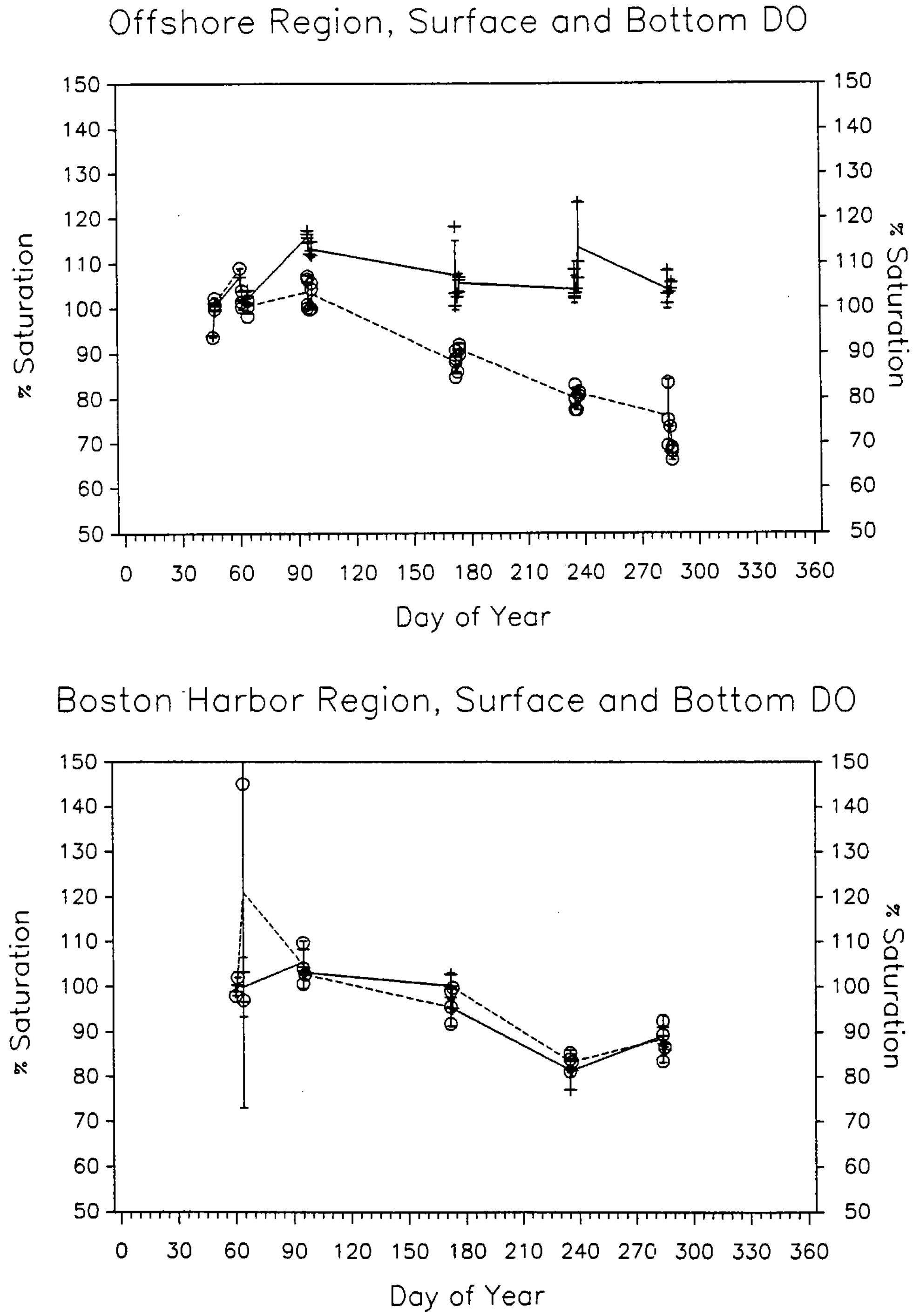


Figure 3.3-4 DO (% saturation) in surface and bottom waters through the 1994 annual cycle in the offshore region and in Boston Harbor. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling. Vertical lines with bars indicate ± standard error of the mean.

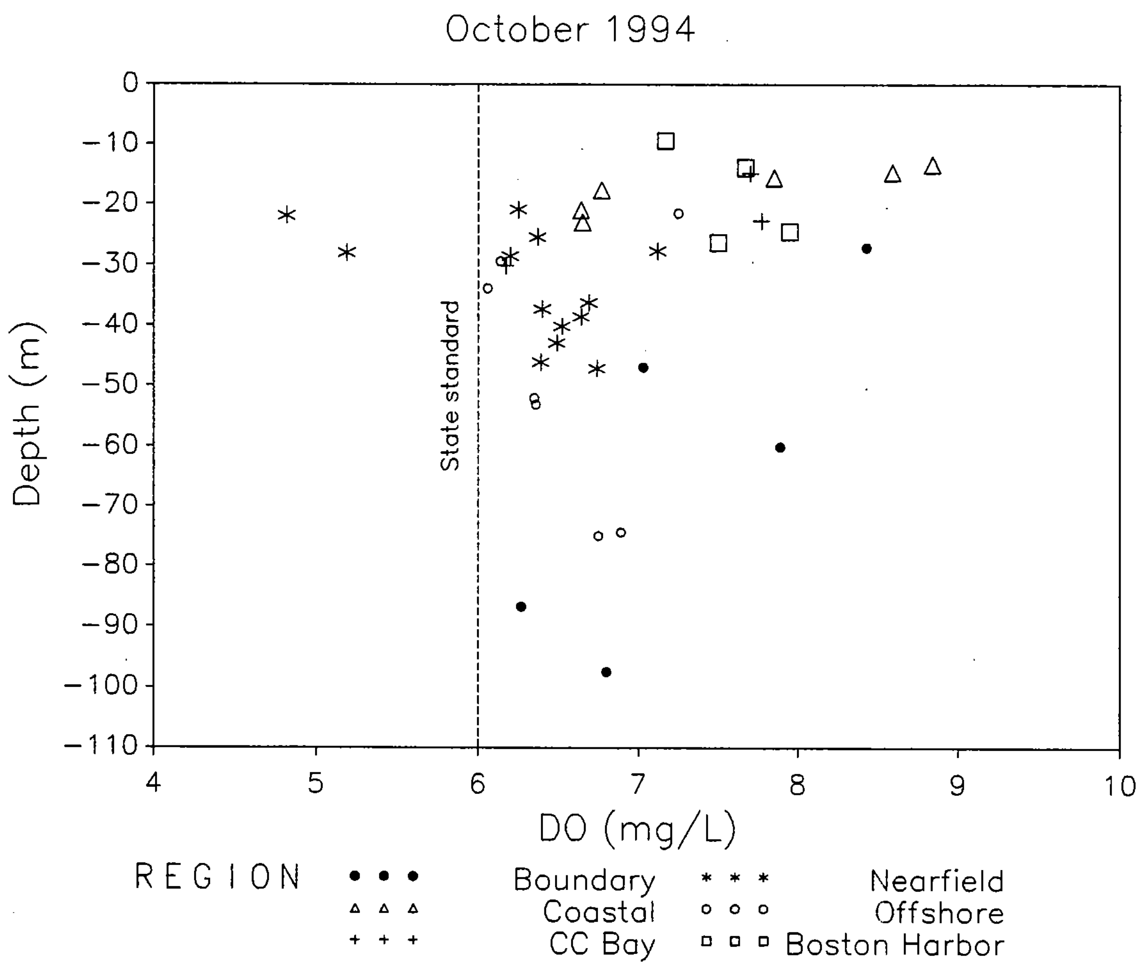


Figure 3.3-5 DO concentration as related to depth of sampling for all bottom waters sampled in October 1994.

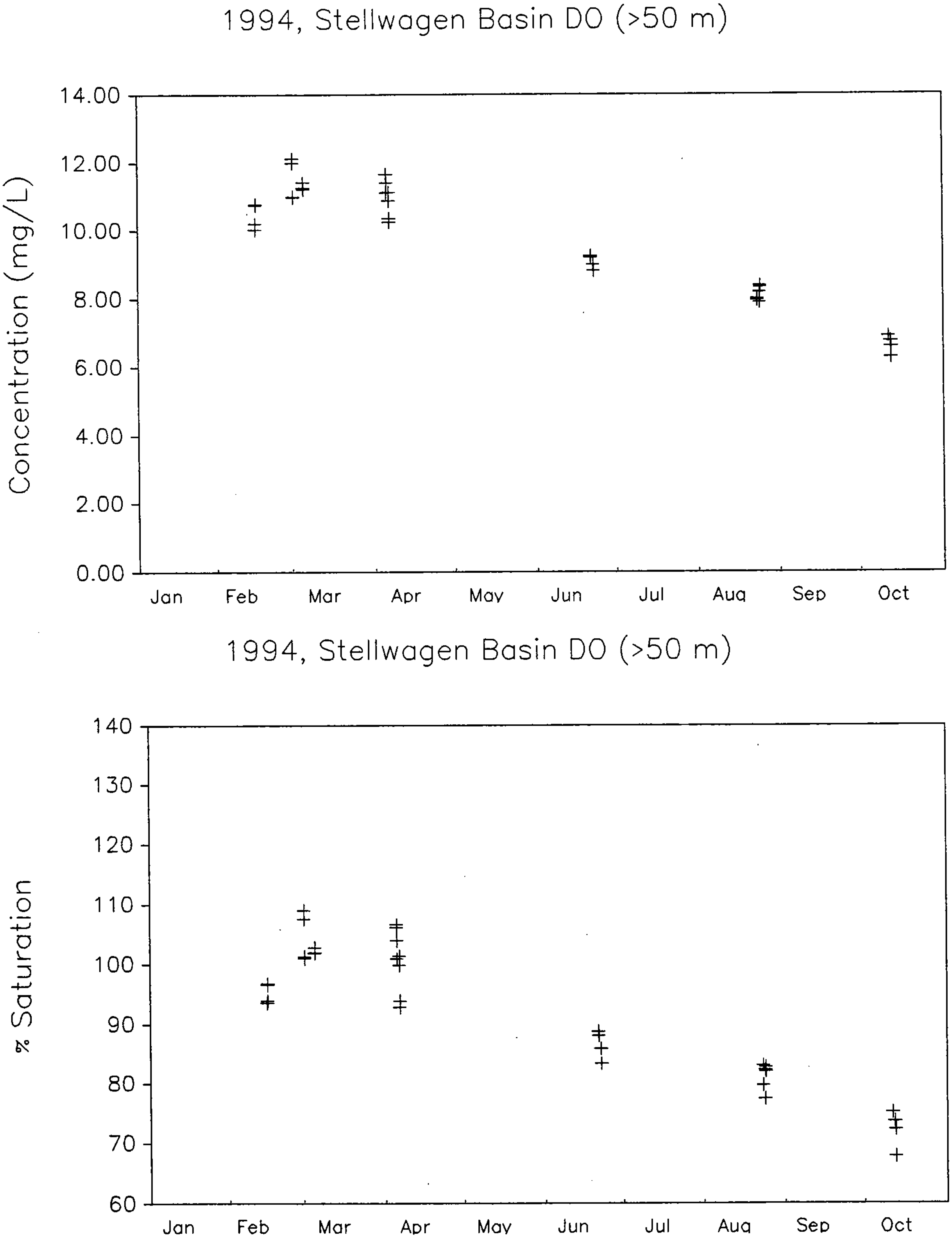


Figure 3.3-6 DO concentration and saturation through the annual cycle in deep water from four Stellwagen Basin stations sampled in 1994.

3.4 PLANKTON

Whole-water samples for phytoplankton counts were analyzed, as for 1992-1993, for samples 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 1994 periodic reports (and appendices). The interested reader should consult those reports for greater 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 basic description of the seasonal progression in abundance, dominant groups, and selected dominant taxa in 1994, within the Bays. A few distinctions are drawn between the biological assemblages in different farfield sampling regions.

3.4.1 Phytoplankton in 1994

In February, 1994 the phytoplankton in whole-water samples was dominated at all stations by microflagellates and cryptomonads, with lesser contributions by a consortium of diatoms. Abundant diatoms included *Skeletonema costatum, Thalassionema nitzschoides,* several species of *Chaetoceros,* and other centric and pennate taxa. Abundances were low (generally <200,000 cells/Liter), except in Cape Cod Bay. There, at station F01P, surface abundance exceeded 800,000 cells/Liter, and at station F02P exceeded 3 million cells/Liter. The bloom in Cape Cod Bay was dominated by microflagellates, cryptomonads, and the diatoms *S. costatum, Chaetoceros compressus,* and at F02P, *Detonula confervacea.* Abundances and taxonomic composition in chlorophyll maximum samples were similar to those at the surface at most stations. Samples collected on 20 µm-mesh screens were dominated by aloricate ciliates and tintinnids (tens to occasionally low hundreds of cells/Liter), but a variety of thecate dinoflagellates and the silicoflagellates *Dictyocha fibula* and *Distephanus speculum* were present at most stations at abundances of single-digits of cells/Liter.

In March, 1994 the phytoplankton in whole-water samples at all stations except Cape Cod Bay was dominated by microflagellates and diatoms (several species of *Thalassiosira: constricta, gravida, rotula, anguste-lineata, nordenskioldii; Thalassionema nitzschoides; Chaetoceros* spp.). Total abundances except in Cape Cod Bay were <100,000 cells/Liter. In Cape Cod Bay, however, in addition to diatoms at levels of approximately a half-million cells/Liter, there was a large bloom of the gelatinous alga *Phaeocystis pouchetti,* with abundances of 2-3 million cells/Liter at the surface and chlorophyll maximum layers. Samples collected on 20 μm-mesh screens were again dominated by aloricate ciliates and tintinnids (tens of cells/Liter) and dinoflagellates and silicoflagellates (single-digits of cells/Liter) except in Cape Cod Bay. There, tintinnids were present in hundreds of cells/Liter, and an unidentified species of the dinoflagellate genus *Protoperidinium* was present at levels exceeding a thousand cells/Liter.

By April 1994, the spring diatom bloom was underway. Phytoplankton in whole-water samples was dominated by several species and size classes of the diatom genera *Chaetoceros* and *Thalassiosira,* and in Cape Cod Bay, *Leptocylindrus minimus.* Microflagellates were still abundant, but proportionately less so than the combinations of diatom taxa. Overall abundance had increased throughout the system relative to previous concentrations, with >200,000 to >800,000 cells/Liter at all stations except station F01P in both surface and chlorophyll maximum strata. Samples collected on 20 μm-mesh screens were again dominated by tintinnids and aloricate ciliates, with a smattering of various dinoflagellates.

In June of 1994 the phytoplankton in whole-water samples was dominated by microflagellates and cryptomonads with lesser contributions by several diatoms of the genus *Chaetoceros.* Dinoflagellates were more prominent at some stations than previously in the year, with subdominant taxa including *Amphidinium* sp., *Ceratium fusus, C. longipes, Dinophysis norvegica, Katodinium rotundatum,* and other unidentified thecate dinoflagellates. Levels of total abundance were higher than earlier in the year, with values >200,000 cells/Liter at most stations, and exceeding 1.0-1.5 million cells/Liter in 40% of both surface and chlorophyll maximum samples. In 20 μm-mesh screened samples, aloricate ciliates and tintinnids were again present in tens to hundreds of cells/Liter at most stations, but thecate dinoflagellates (primarily of the genera *Ceratium, Dinophysis* and *Protoperidinium*) had increased from single-digits to tens of cells/Liter in February through April to tens, hundreds, and occasionally thousands of cells/Liter by June.

In August 1994, the phytoplankton in whole-water samples was dominated by microflagellates and cryptomonads in both surface and chlorophyll maximum samples at virtually all stations. Diatoms such as *Ceratulina pelagica, Chaetoceros* spp., *Cylindrotheca closterium, Nitzschia* spp., *Rhizosolenia delicatula, Skeletonema costatum, Thalassionema nitzschoides,* and *Thalassiosira* spp. were subdominants at various stations, as were the dinoflagellates *Gymnodinium* sp. and *Katodinium rotundatum.* However, patterns of subdominance of these various taxa were patchy between various stations and depths. Similarly, patterns of total abundance varied in surface and chlorophyll maximum samples from less than a half-million cells/Liter in 5 samples, to over a million cells/Liter in 5 samples, with the remaining ten between a half-million and a million cells/Liter.

In August 1994, 20 μm-screened samples contained a wide variety of dinoflagellates. Various species of the genera *Ceratium*, *Dinophysis*, *Gyrodinium*, and *Scrippsiella* were present at abundances of generally tens to hundreds of cells/Liter. An unidentified species of *Protoperidinium* as well as tintinnids and aloricate ciliates were generally present at levels of tens to hundreds of cells/Liter at most stations.

In October 1994, the phytoplankton in whole-water samples was dominated by microflagellates and cryptomonads. Subdominants included various chain-forming diatoms (*Rhizosolenia delicatula, Thalassionema nitzschoides, Skeletonema costatum, Ceratulina pelagica)* and solitary diatom cells of *Cylindrotheca closterium* and an unidentified species of *Thalassiosira*. Also, an unidentified athecate dinoflagellate was a subdominant at most stations. Total abundances in surface and chlorophyll maximum layers from most stations generally ranged from 1.0-2.5 million cells/Liter. Dinoflagellates recorded at most stations in 20μm-mesh samples, generally in tens of cells/Liter, included *Ceratium fuses, longipes, macoceros,* and *tripos, Prorocentrum micans, Dinophysis caudata,* and *Protoperidinium* spp. Tintinnids were again abundant (usually tens to hundreds of cells/Liter) but aloricate ciliates had declined in abundance from August levels.

3.4.2 Zooplankton in 1994

In February 1994, the zooplankton was dominated by copepod nauplii, copepodites and adults. Most copepodites and adults were *Oithona similis* and, secondarily, *Paracalanus parvus.* Total zooplankton abundance was low with all but two stations having <10,000 animals/m^3.

In March 1994, the zooplankton was again dominated by copepod nauplii, copepodites and adults. Again, *O. similis* followed by *P. parvus* were dominant species. Barnacle nauplii were present at most stations, comprising as much as 31% of total zooplankton at Station F23P in Boston Harbor. Polychaete larvae were also present at all stations, comprising as much as 13% of total zooplankton. Total zooplankton abundance increased slightly from February, with most values >10,000 animals/m^3.

In April 1994, copepod nauplii, copepodites and adults dominated, and as usual, most copepodites and adults were *Oithona similis* and *Paracalanus parvus.* However, adults and copepodites of the large copepod *Calanus finmarchicus* were present at all stations, comprising as much as 21% of total abundance at station N07P. Barnacle nauplii were subdominant at all stations, as were polychaete larvae and the appendicularian *Oikopleura dioica.*

In addition to the normally dominant copepod nauplii and adults and copepodites of primarily *O. similis* and *P. parvus,* abundant zooplankters in June included bivalve veligers, echinoderm larvae, and the marine cladoceran *Evadne nordmani.* The copepod *Acartia tonsa* was abundant at station F23P in Boston Harbor, comprising nearly 20% of total zooplankton abundance.

Total zooplankton abundance continued its seasonal increase with levels >30,000 animals/m^3 at all stations, and levels between 60,000-80,000 animals/m^3 at 4 stations.

In August 1994, the zooplankton was dominated by the same taxa at most stations as in June. However, at stations F01P and F02P in Cape Cod Bay, bivalve veligers comprised 32% and 77%, respectively, of the total zooplankton abundance. Total abundance declined somewhat from June levels. The two stations in Cape Cod Bay had <20,000 animals/m^3, and at only two stations (N01P and N04P) abundance exceeded 40,000 animals/m^3.

In October 1994, the zooplankton was dominated by copepod nauplii and copepodites and adults of the copepod *Oithona similis*. However, gastropod veligers usually comprised >20% of all animals collected at most stations. Total zooplankton abundance varied considerably between stations, from <10,000 animals/m^3 at F23P to almost 80,000 animals m^3 at F13P.

3.5 ^{14}C PRIMARY PRODUCTION

Oxygen light-dark bottles were used to estimate primary production during MWRA water column monitoring in 1992, and ^{14}C techniques (e.g., Parsons *et al.*, 1984) were instituted in 1993. In 1994, standard oceanographic methods for ^{14}C were continued , employing shipboard incubations in a (artificial) light box. Whole seawater samples were exposed to a range of irradiance levels to enable modeling of P-I (photosynthesis-irradiance) curves (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. The ^{14}C incubations in 1994 followed the same fundamental procedures (e.g., bottle sizes, incubation times, irradiance levels) used in 1993 (cf. Kelly and Turner, 1995).

Unlike in previous years, there were only two sampling stations in 1994: station F23P, at the edge of Boston Harbor, and station N16P, in the middle of the nearfield in Massachusetts Bay. At each of the farfield surveys, these two stations were occupied twice, so that over the year there was a total of 12 station-visits. At each visit, samples were taken from four depths. Sampling depths were determined by the distribution of fluorescence, but extended beneath a subsurface chlorophyll maximum, if it existed, and in general to the limits of the photic zone. Using P-I curves generated for samples from each depth, a depth-composited profile for volumetric production rates within the water column was derived. This composite rate was integrated to the depth at which PAR (photosynthetically active radiation) was 0.5% of that incident at the surface to arrive at daily rates on an areal basis (either as mg or gC m^{-2} d^{-1}). Individual sample P-I curves have been modeled by simultaneously fitting parameters of one of two models (with and without photoinhibition), and these results have been reported in detail in the series of periodic water column reports for 1994 cited in Section 2. Using the (composite) integrated rates for 1994, drawn directly from tables of individual periodic reports, the focus in this report is on the apparent annual cycle, comparison of the two stations, and the possibility for extrapolation/ projection of primary production rates over space and time.

The time trends for the Harbor-edge station show very similar rates for the two days of sampling within each survey (Figure 3.5-1). Through the year, the pattern was of low rates (<0.5 g C m^{-2} d^{-1}) in winter (February-March), a high rate in April ($\geq$1.5 g C m^{-2} d^{-1}), and intermediate rates (~1 g C m^{-2} d^{-1}) for the summer/fall seasons (June, August, October). Warm-season rates (June-October) averaged above 1 g C m^{-2} d^{-1} for the Harbor-edge station; from the data, the summer-fall period for the Harbor had higher average production than the winter-spring period even though the annual measured maximum was in the spring bloom.

There were two occasions, in March and June, when the production rates at the mid-nearfield stations for the two days within a survey were quite different (Figure 3.5-1). The nearfield also had a different temporal pattern than the Harbor. The annual cycle in the nearfield appeared to consist of an earlier initiation of spring peak production (March) and a fall peak equal to or greater than the spring peak. As in the Harbor, there were intermediate rates during the stratified season (April to August). In contrast to the Harbor, there was similar average production in the cold (February to April) vs. warm (June to October) months in the Bay.

During April to August, the Harbor and nearfield station production rates were alike. During the spring and fall bloom periods, peak production rates in the Bay above 2 g C m^{-2} d^{-1} were measured regularly, making the nearfield at these times distinctly higher than the Harbor in terms of primary production. Over the set of 1994 measurements, the average production rate was 0.86 g C m^{-2} d^{-1} at the edge of the Harbor, compared to 1.54 g C m^{-2} d^{-1} in the nearfield. These rates are within the range of average rates calculated recently in the MWRA monitoring program; they are substantially lower than 1993 rates, but similar to 1992 rates (cf. Kelly and Turner, 1995). Differences in rates, especially across 1994 stations, are further examined in Section 5.

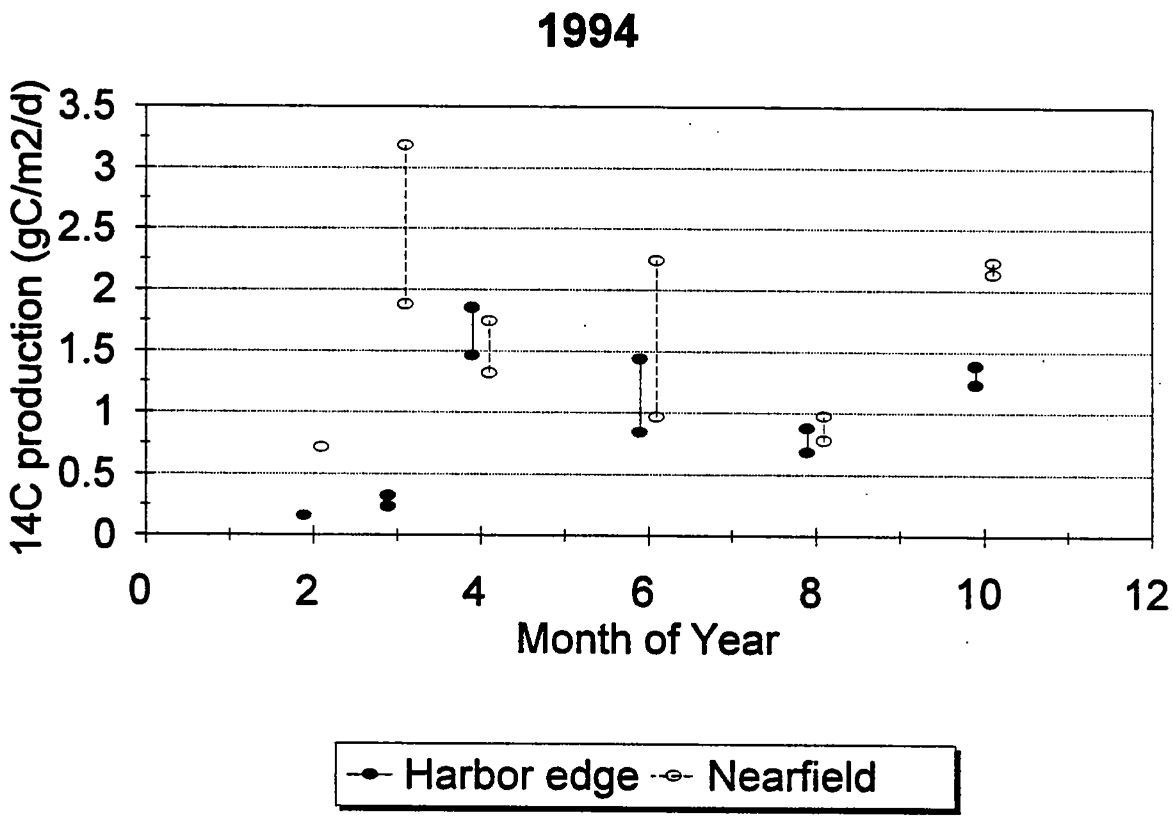


Figure 3.5-1 **^{14}C production rates through the 1994 annual cycle for two sampling stations.**

4.0 NEARFIELD SURVEY RESULTS

The nearfield region was sampled on 16 surveys during 1994; 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 1863 Niskin bottle sampling events, for which there were complete *in-situ* sensor data, except for 140 missing events for DO (due to cold-weather malfunctioning of the sensor). There were 1846 analyses completed for NH_4, and 1854 analyses completed for NO_2, NO_3, PO_4, and SiO_4.

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, provides perspective on the annual cycle of 1994 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 one-third of the measurements, DIN concentrations were <1.5 μM, and nearly three-quarters of NH_4 concentrations were <1.5 μM. In general, the DIN and NH_4 frequencies tailed off exponentially to higher concentration classes, and few (about 5%) of the concentrations were >10 μM for DIN or >3.5 μM for NH_4. For DIN, there was a second mode in the concentration frequency distribution, near 8 μM, and this feature was similar to that noted for the farfield sampling (Section 3). The average DIN concentration was 4.24 μM (standard deviation = 3.56) and the maximum measured concentration was 16.2 μM. The average NH_4 concentration was 1.09 μM (standard deviation = 1.19) and the maximum measured concentration was 8.62 μM.

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 1994 (cf. Appendix Table A-4). The data demonstrate a decreasing DIN concentration gradient seaward, with concentrations at the southwest corner > 6 μM and < 2 μM at some stations on the eastern side of the nearfield . Unlike in Figure 3.1-3, which used data from only six stations included in the 6 farfield surveys, all 21 nearfield stations were included in Figure 4.1-3. The spatial pattern across the nearfield is nevertheless remarkably similar in the two figures. Moreover, the spatial pattern of annual surface means in Figure 4.1-3 for DIN is also a virtual match to 1993 (cf. Figure 4.1-3 of Kelly and Turner, 1995).

Phosphate. Figure 4.1-4 demonstrates that about 95% of the PO_4 concentrations were low, <1 μM. The frequency distribution is similar to that shown for farfield samples. The mean PO_4 concentration was 0.61 μM (standard deviation = 0.27) and the maximum concentration that was measured was 2.84 μM.

Silicate. Figure 4.1-5 illustrates a bimodal frequency distribution for SiO_4 concentrations that has been typical of most locations in the Bay during 1992-1994, as was seen for farfield samples in 1994 (Section 3). The first mode occurs at low concentration and a second mode is at 9-10 μM. The mean SiO_4 concentration was 4.44 μM (standard deviation = 3.40) and the maximum concentration was 16.6 μM.

As expected, the 6-survey/6-station and 16-survey/21-station results for the nearfield in 1994 provide similar overall mean estimates. In comparison to the means just listed for DIN, NH_4,

PO_4, and SiO_4 from 16 surveys, means calculated for the nearfield region based on the farfield sampling (N=384 samples, vs. N =1846 to 1854 for nearfield surveys) were, respectively: 5.16 μM DIN, 1.04 μM NH_4, 0.64 μM PO_4, and 5.11 μM SiO_4. Moreover, the mean nutrient concentrations for the nearfield region, via either sampling frequency and intensity, also have been quite similar across the three years of baseline sampling (1992-1994, see also Section 5.2).

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 for the nearfield region in Figure 3.1-7. The surface and bottom water DIN concentrations were similar through March but thereafter diverged (April, ~day 95) as the surface layer became nutrient-depleted when the water column stratified . The two layers became similar again in the November-December period, when the DIN concentrations in surface waters rose to about 6 μM; note that the November and December surveys showed DIN concentrations that were significantly lower on average than the pre-bloom conditions detected early in 1994. 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.

Particulate nitrogen (PN) concentrations at six nearfield stations primarily ranged from about 2 to 5 μM, with lowest concentrations measured before the spring bloom (Figure 4.1-7). Highest mean PN concentrations across the nearfield occurred in April (~day 95) and concentrations for the rest of stratified period were intermediate. Interestingly, between the two sampling depths (surface and subsurface chlorophyll maximum, generally 2-25 m), there was no real difference in either PN or total nitrogen (TN) concentrations (Figure 4.1-7). TN concentrations appeared to be slightly more constant than DIN concentrations, in part due to a "buffering" effect of PN.

However, there was a decrease in TN concentrations of 10 μM from the spring bloom (March and April) to late summer (August). This difference primarily reflects the seasonal drop of DIN in surface waters (see Section 3). There was also an increase in TN by October, which may reflect a slight seasonal increase in both DIN and PN that accompanied the fall bloom.

Phosphate and Silicate. The seasonal cycle of PO_4 and SiO_4 in nearfield surface and bottom waters showed the same general annual pattern that was observed for DIN (Figure 4.1-8). But there were some subtle differences among the three nutrients (N, P, Si), which suggests that their biogeochemical cycling was, to a degree, independent. For example, in contrast to DIN, PO_4 and SiO_4 concentrations in surface water during the summer stratified season were routinely above detection limits and therefore less depleted than DIN. Like DIN, both PO_4 and SiO_4 concentrations in bottom waters rose progressively during stratification; but there were differences in vertical patterns between nutrients. For PO_4, the difference between surface and bottom-water concentrations was expressed early in the year (April, ~day 95) and the difference was only heightened slightly over the summer — a pattern similar to DIN. In contrast, surface and bottom-water SiO_4 concentrations became distinctly different a bit later in the year (May, ~day 140) and because the bottom-water concentrations nearly doubled over the summer, the concentration difference between layers was amplified over the stratified period. Finally, as noted for DIN, water column concentrations of both PO_4 and SiO_4 were also lower, on average, in December 1994 than in February 1994.

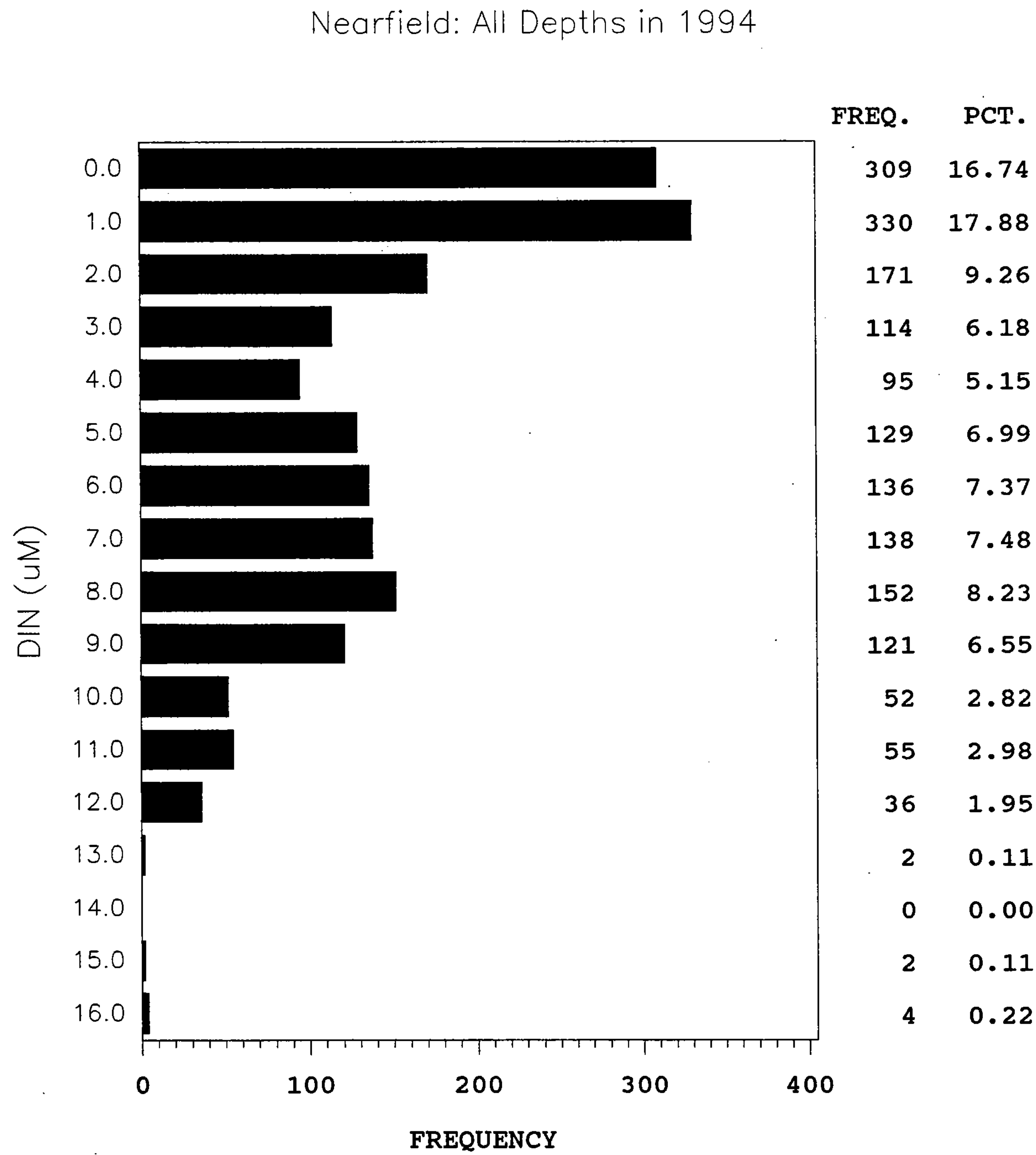


Figure 4.1-1 Frequency distribution of DIN concentrations for all nearfield samples in 1994.

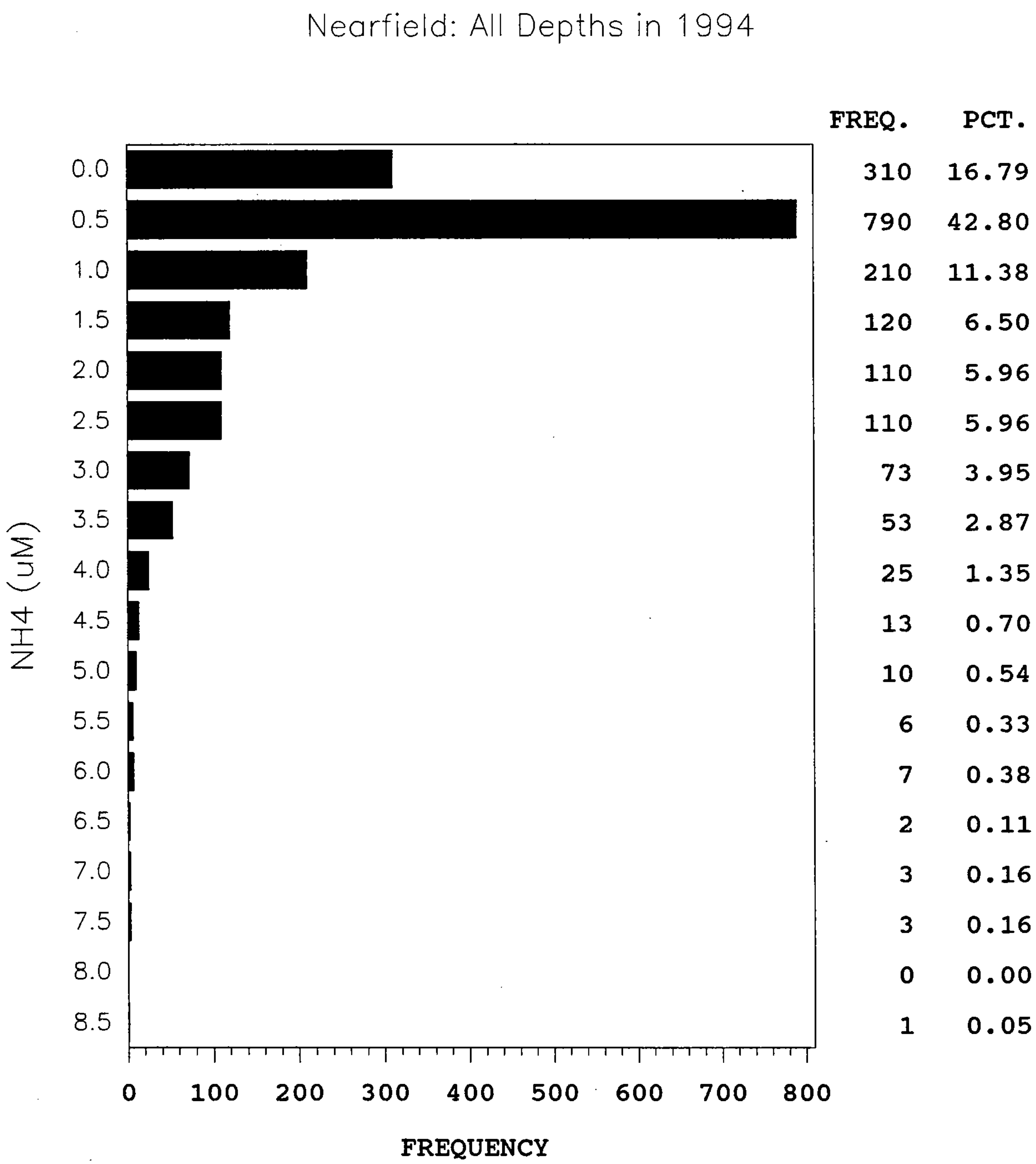


Figure 4.1-2 Frequency distribution of NH_4 concentrations for all nearfield samples in 1994.

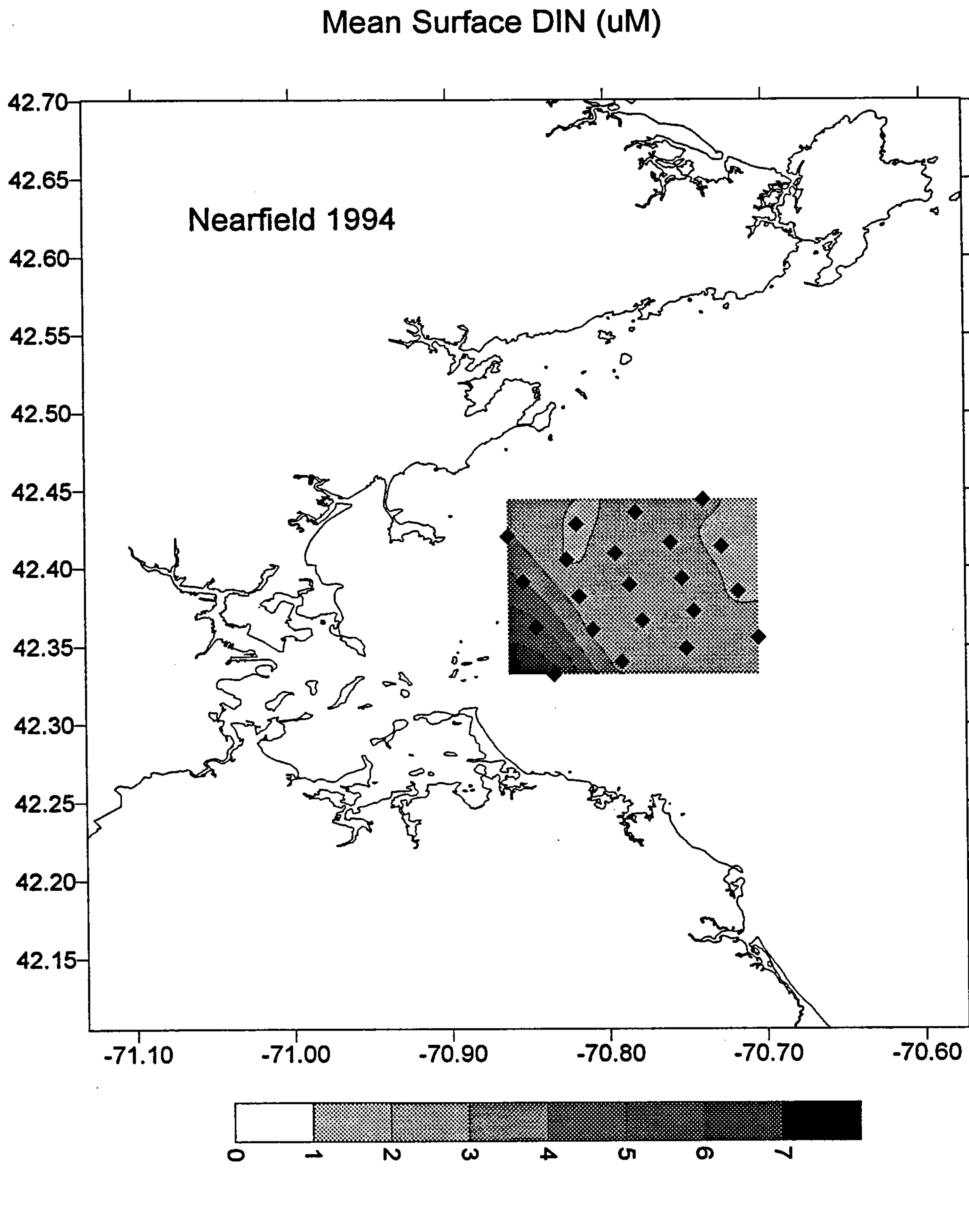


Figure 4.1-3 Spatial pattern of nutrient concentrations in the nearfield region. Data are surface-water means from 16 nearfield surveys in 1994.

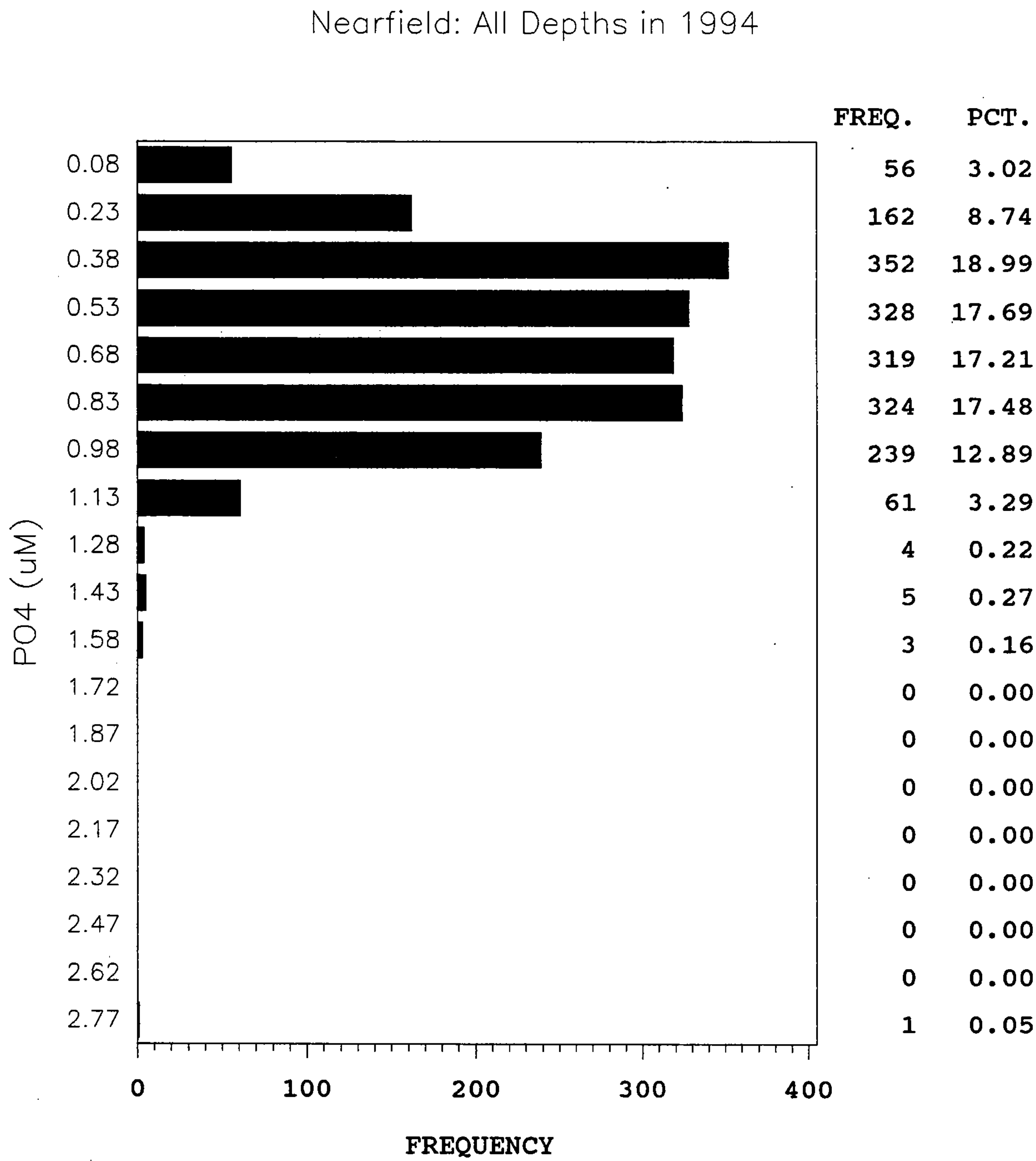


Figure 4.1-4 Frequency distribution of PO_4 concentrations for all nearfield samples in 1994.

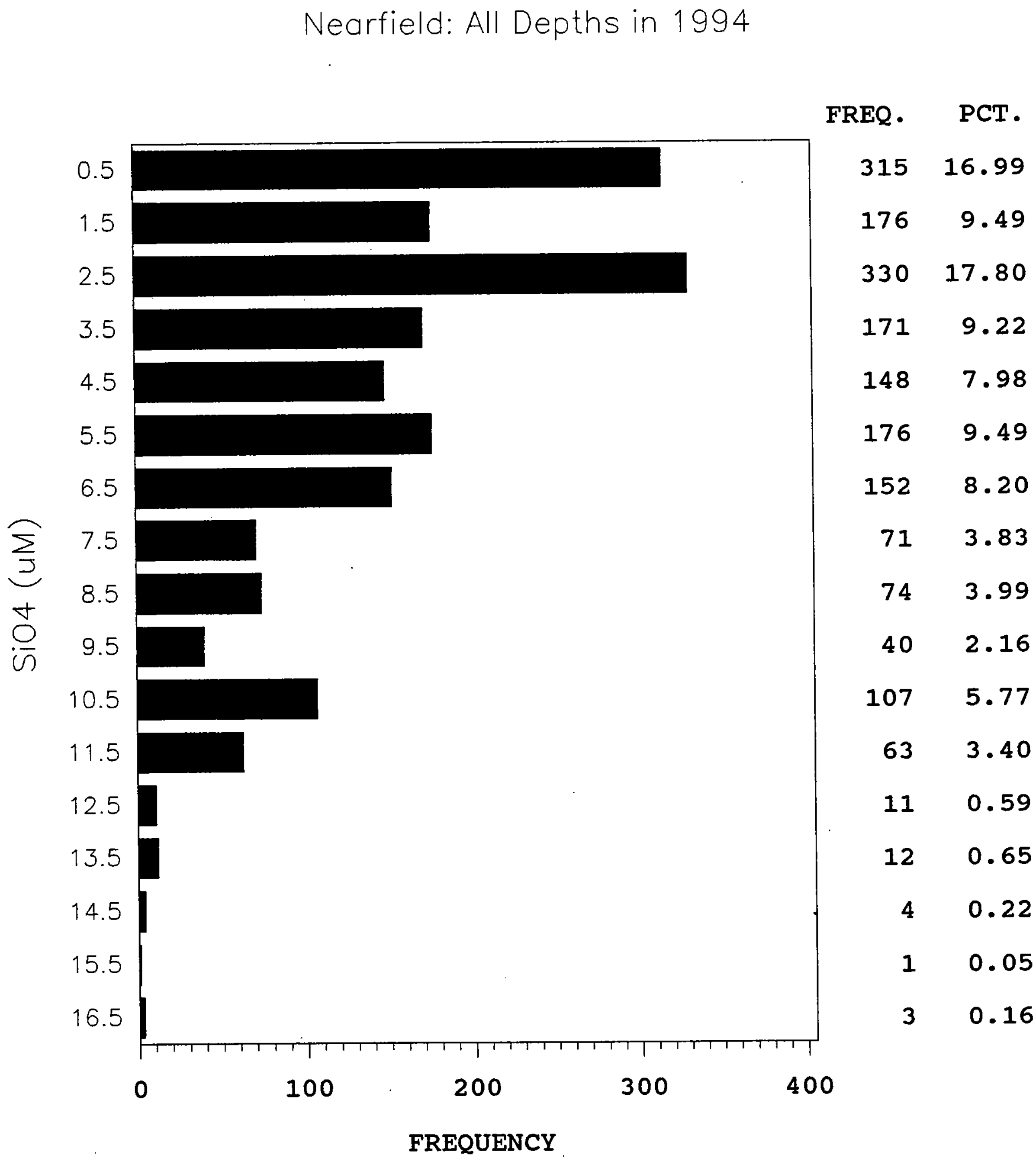


Figure 4.1-5 Frequency distribution of SiO_4 concentrations for all nearfield samples in 1994.

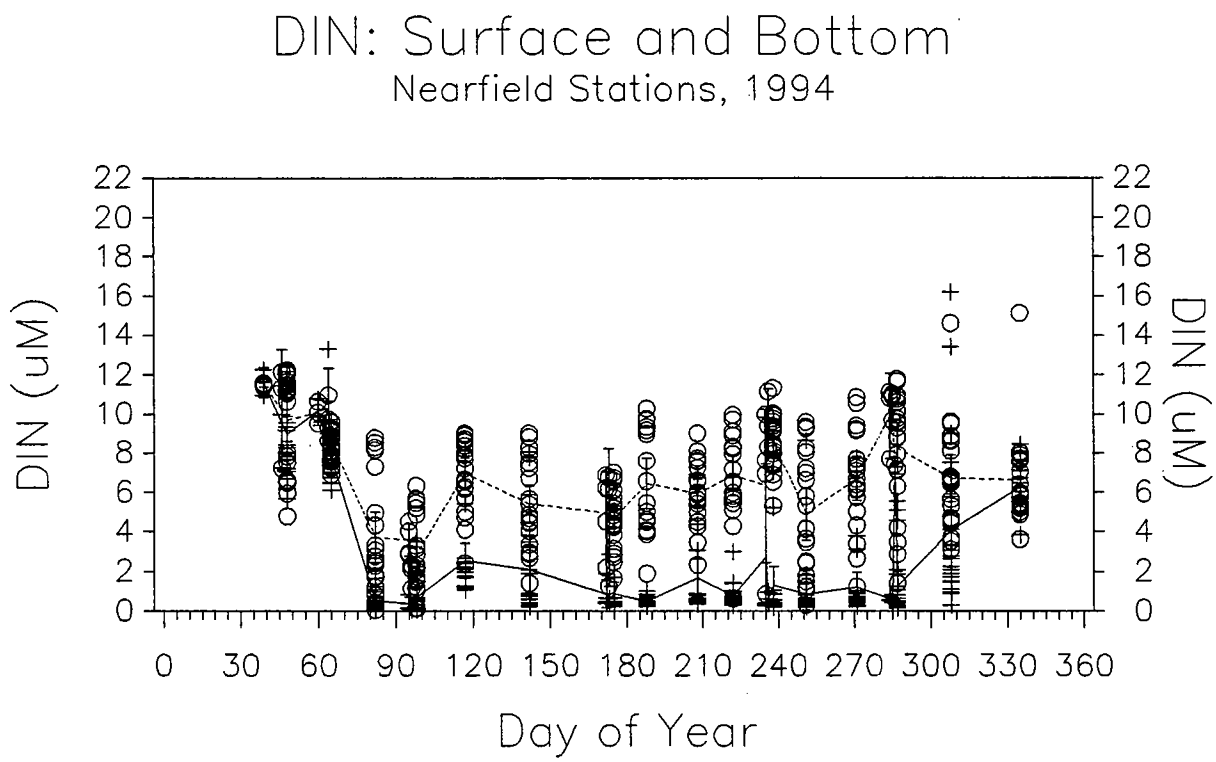
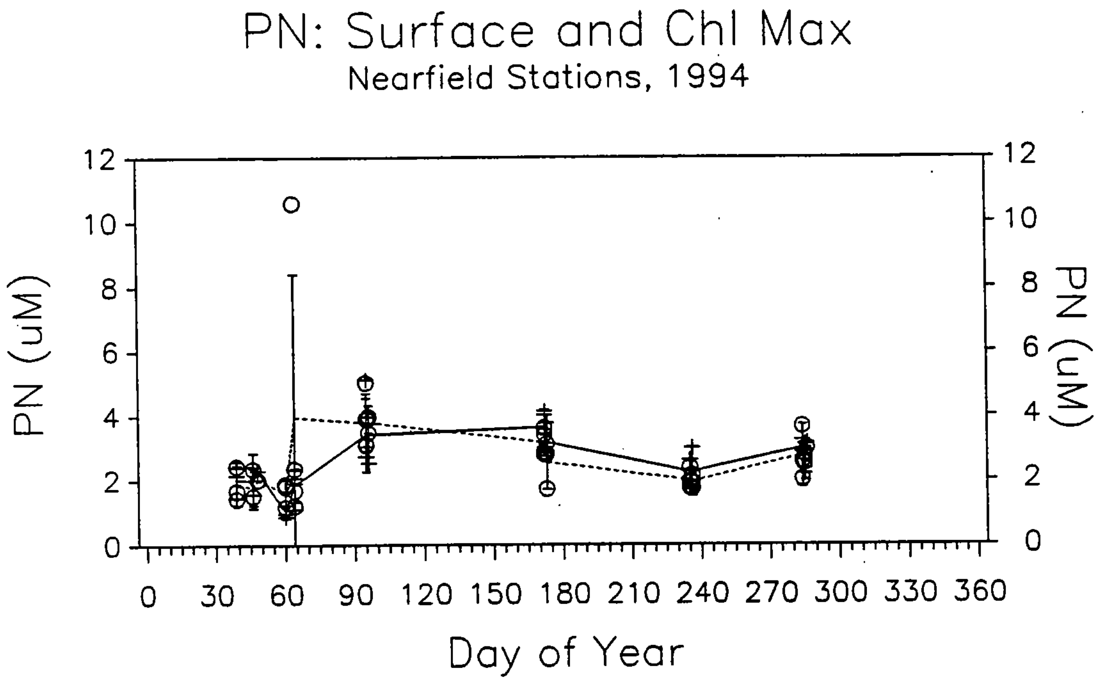


Figure 4.1-6 DIN concentrations in nearfield surface and bottom waters through the 1994 annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.



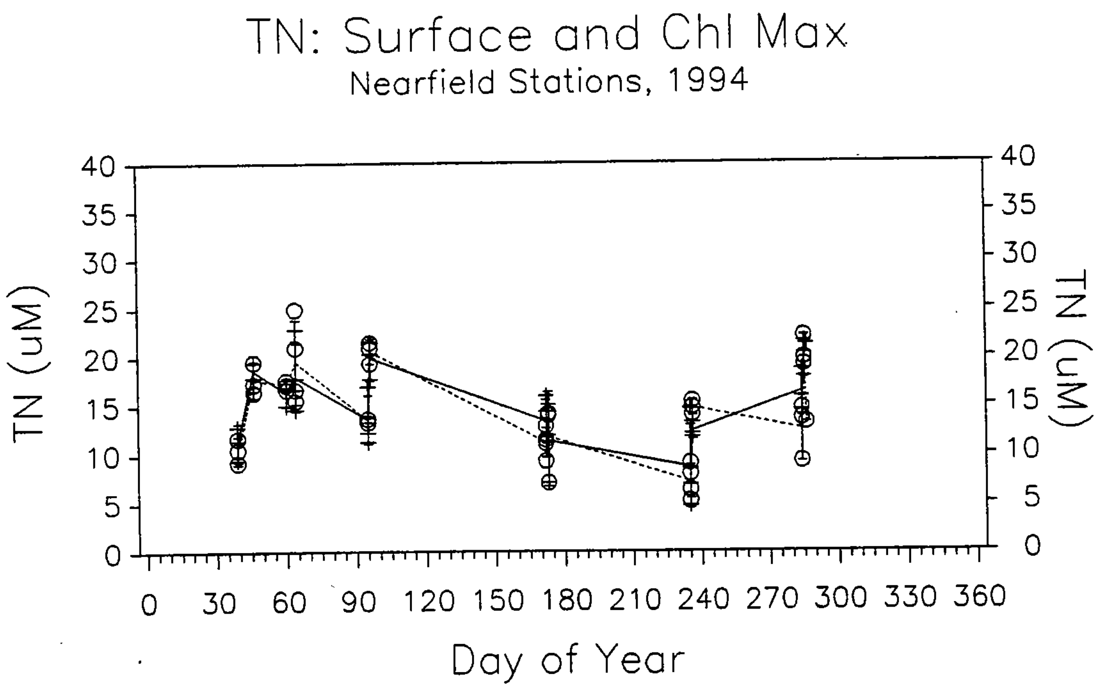
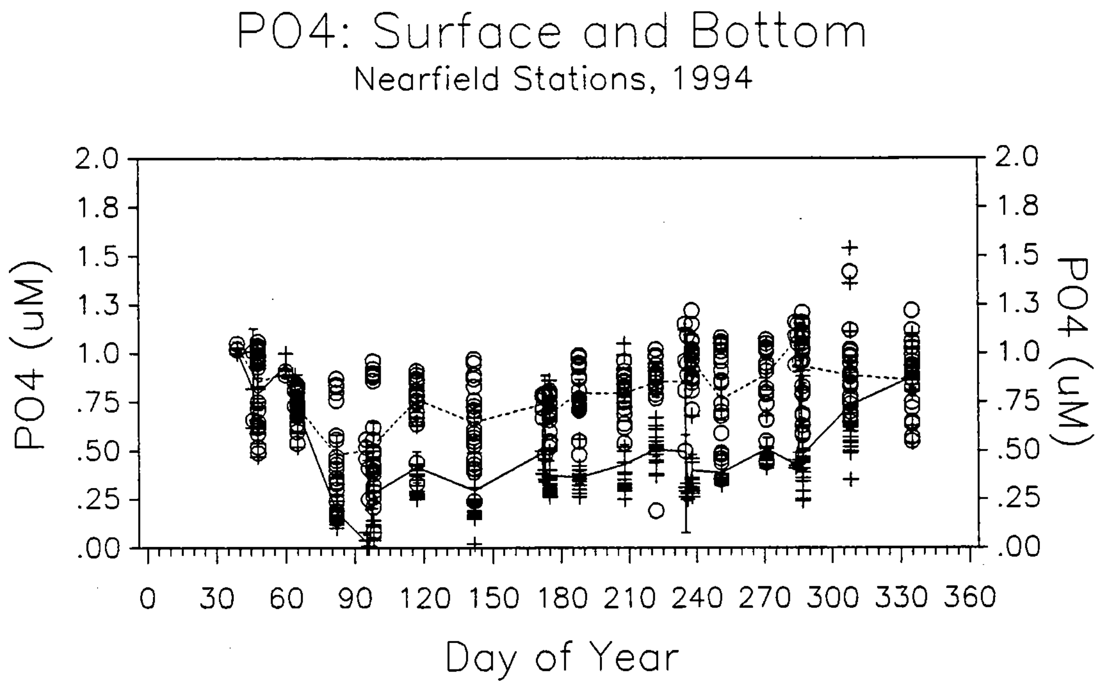


Figure 4.1-7 PN and TN concentrations in nearfield surface and bottom waters through the 1994 annual cycle. These data were collected only on the six farfield surveys. Surface data are represented by the plus symbol and solid lines. Mid-depth chlorophyll maximum data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.



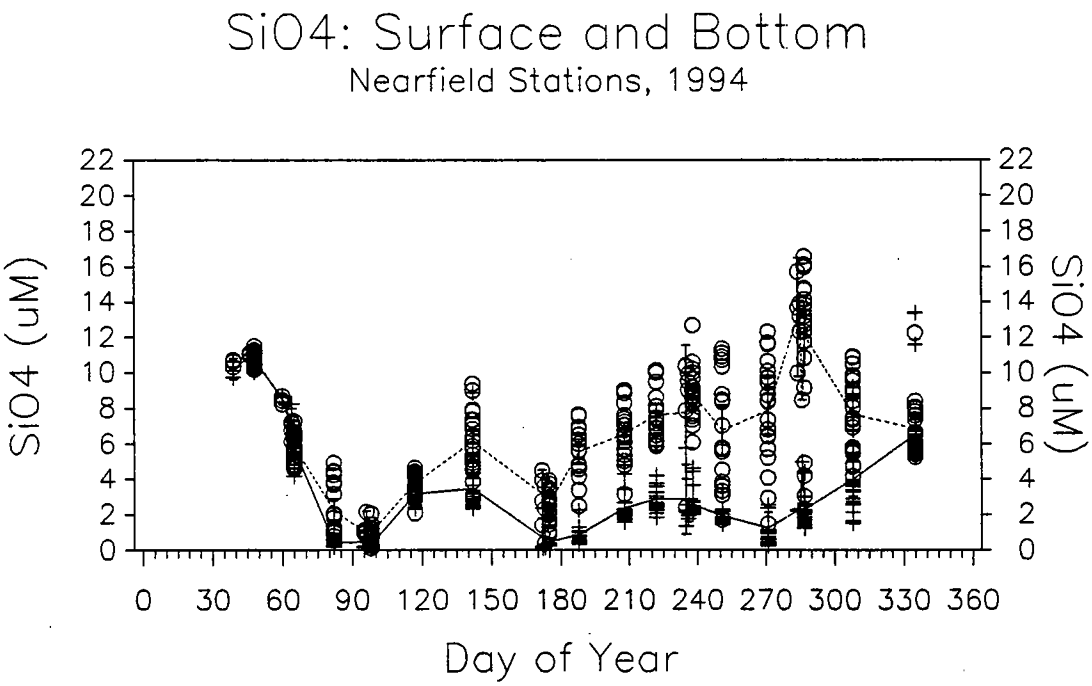


Figure 4.1-8 **PO_4 and SiO_4 concentrations in nearfield surface and bottom waters through the 1994 annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus 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 (~2.8 μM) has been excluded.**

4.2 CHLOROPHYLL

4.2.1 Frequency Distribution of Chlorophyll

Figure 4.2-1 shows the frequency distribution plots for fluorescence measured on the 1994 nearfield surveys. The modal class, with almost more than one-third of the observations, was a low concentration (0.8 μg L^{-1}, interval 0.4-1.2 μg L^{-1}). Frequencies tailed off exponentially to higher concentration classes and few ($\approx$5% or less) of the concentrations of were >5 μg L^{-1}. The average concentration was 1.96 μg L^{-1} (N=1863, standard deviation = 1.48) and the maximum concentration was 13.7 μg L^{-1}. These nearfield survey results are comparable to those obtained from the six nearfield "P" stations occupied during the farfield sampling; based on the six stations, the nearfield mean for fluorescence in 1994 was 2.14 μg 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 286 samples, was 1.86 μg L^{-1}; the maximum concentration was 8.19 μg L^{-1}.

4.2.2 Annual Cycle of Chlorophyll

Figure 4.2-2 shows 1994 temporal patterns of phytoplankton as indicated by fluorescence and extracted chlorophyll measurements for the surface layer of the nearfield. Chlorophyll measurements were not available for late March (cf. Kelly *et al.*, 1994a) but otherwise a set of measurements were available for each survey from stations representing geographic subregions within the nearfield. Fluorescence data have been post-calibrated to those chlorophyll measurements survey by survey, so they generally should, and do, present a similar picture of the annual cycle. The chlorophyll peak measured during winter-spring 1994 occurred during early March to early April (~days 65 and 95), which is a finding comparable to that suggested by near-surface data from farfield sampling (Figure 3.2-3). However, nearly comparable concentration ranges and mean values by survey were observed for the late May to early

September period (~days 140 to 250). In late September and mid-October (~days 270-290) the fall bloom occurred and achieved peak chlorophyll/fluorescence concentrations similar to, but perhaps slightly higher than, those observed during winter-spring. After October, surface chlorophyll concentrations declined, approaching pre-bloom conditions in February 1994.

The annual cycle of chlorophyll (extracted samples) for one nearfield station (N10P) in Figure 4.2-3) shows more variability than shown by the mean nearfield values (cf. Figure 4.2-2). In general, it still displays the nearfield region's overall seasonal pattern: peaks in spring and fall and intermittent, but generally medium to high concentrations throughout most of the summer. At this station, surface sample phytoplankton counts were made for each nearfield survey (N=16), and the subsurface samples analyzed for each farfield survey (N=6). The trend for cell counts demonstrates, as already mentioned for some other parameters (e.g., TN, PN, and chlorophyll), that there were only small differences as a function of depth at all times when both surface and subsurface samples were analyzed (Figure 4.2-3).

Perhaps the most interesting aspect of Figure 4.2-3 is a comparison of trends over the annual cycle. In contrast to variability in chlorophyll concentrations, the clear trend of total phytoplankton counts is one of increasing phytoplankton cell counts, starting in winter-spring, reaching a peak at the fall bloom in October (~day 290), and then being followed by a sharp decrease into December. Clearly, the different trends indicate variations in the chlorophyll (and fluorescence): cell count ratio over the year, with the most strikingly different ratios being expressed for the winter-spring bloom period compared to the summer and fall periods. By the total counts measure, it could be judged that there was no spring bloom whatsoever, and the overall phytoplankton community instead defined by an increasing abundance over the summer, leading to a fall bloom crescendo. Further inspection of the nearfield data, not displayed here, indicates that station N10P did not have an anomalous disjunction between chlorophyll and cell count trends; instead patterns at station N10P reasonably reflected the typical situation for the nearfield region as a whole.

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 4.2-4). This gradient regularly exists and it is noticeable using either the nearfield or farfield sampling designs (cf. Figure 4.2-5 and Figure 3.2-4). In this area, the distribution of chlorophyll over horizontal and vertical space has substantial fine-scale variability, and has been observed to change in days and hours (e.g., Kelly and Albro, 1994). Nevertheless, on an annual basis, the pattern is persistent and the pattern for 1994 is much like the pattern for 1993 (cf. Figure 4.2-5 of Kelly and Turner, 1995).

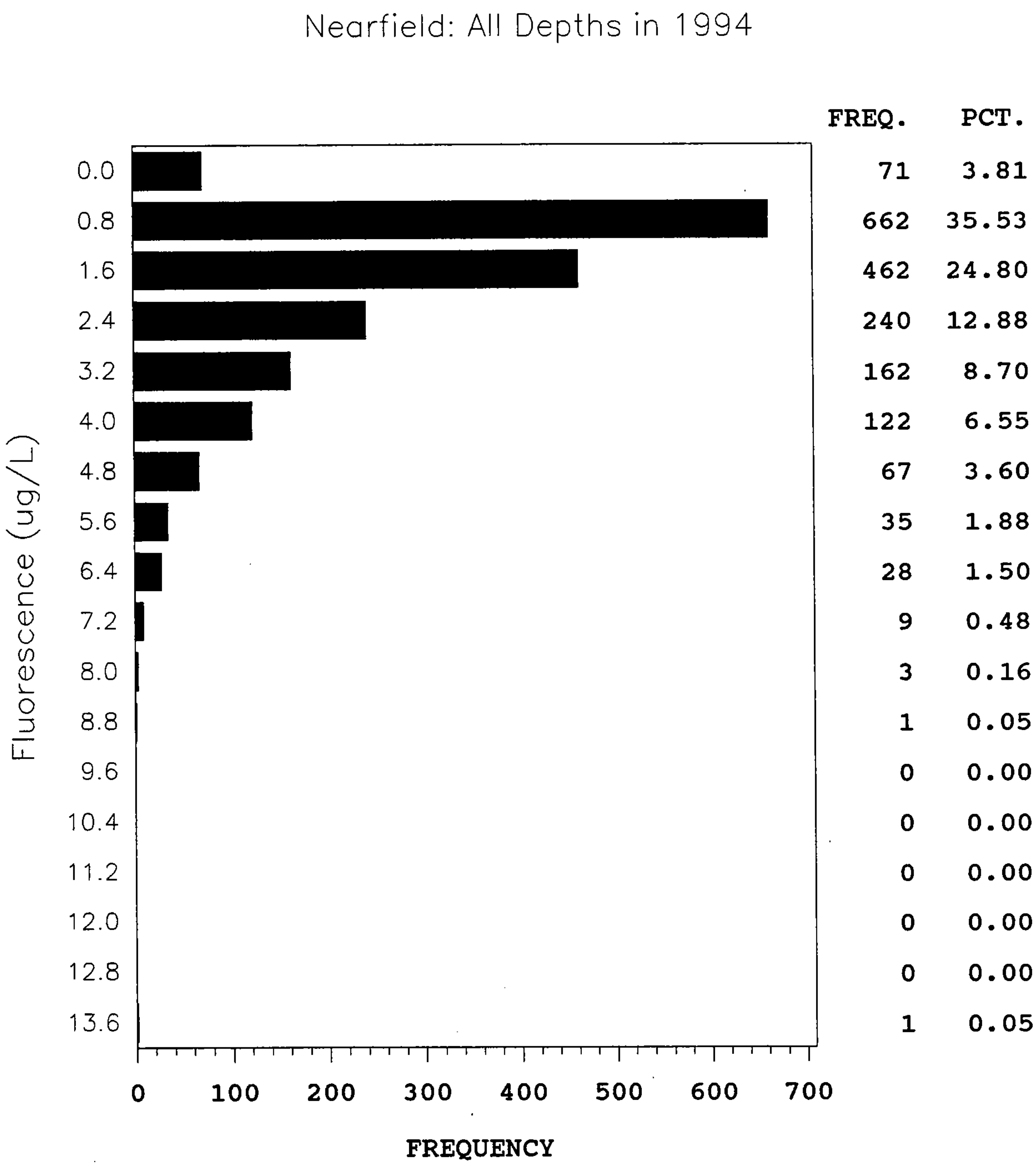


Figure 4.2-1 Frequency distribution of fluorescence concentrations for all nearfield samples in 1994.

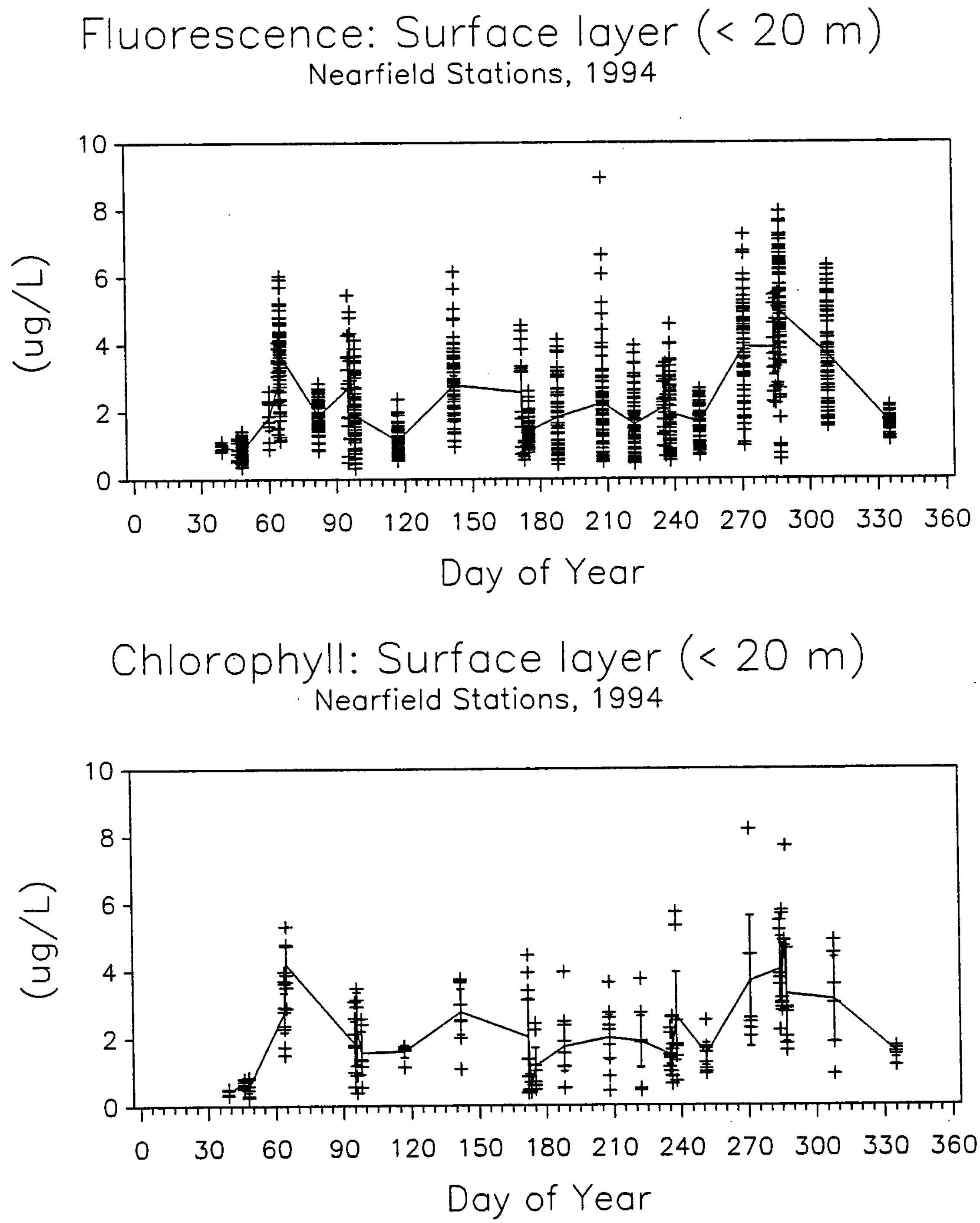


Figure 4.2-2 Fluorescence and chlorophyll concentrations in the nearfield surface layer through the 1994 annual cycle. Lines pass through mean values for each day of sampling; thus sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

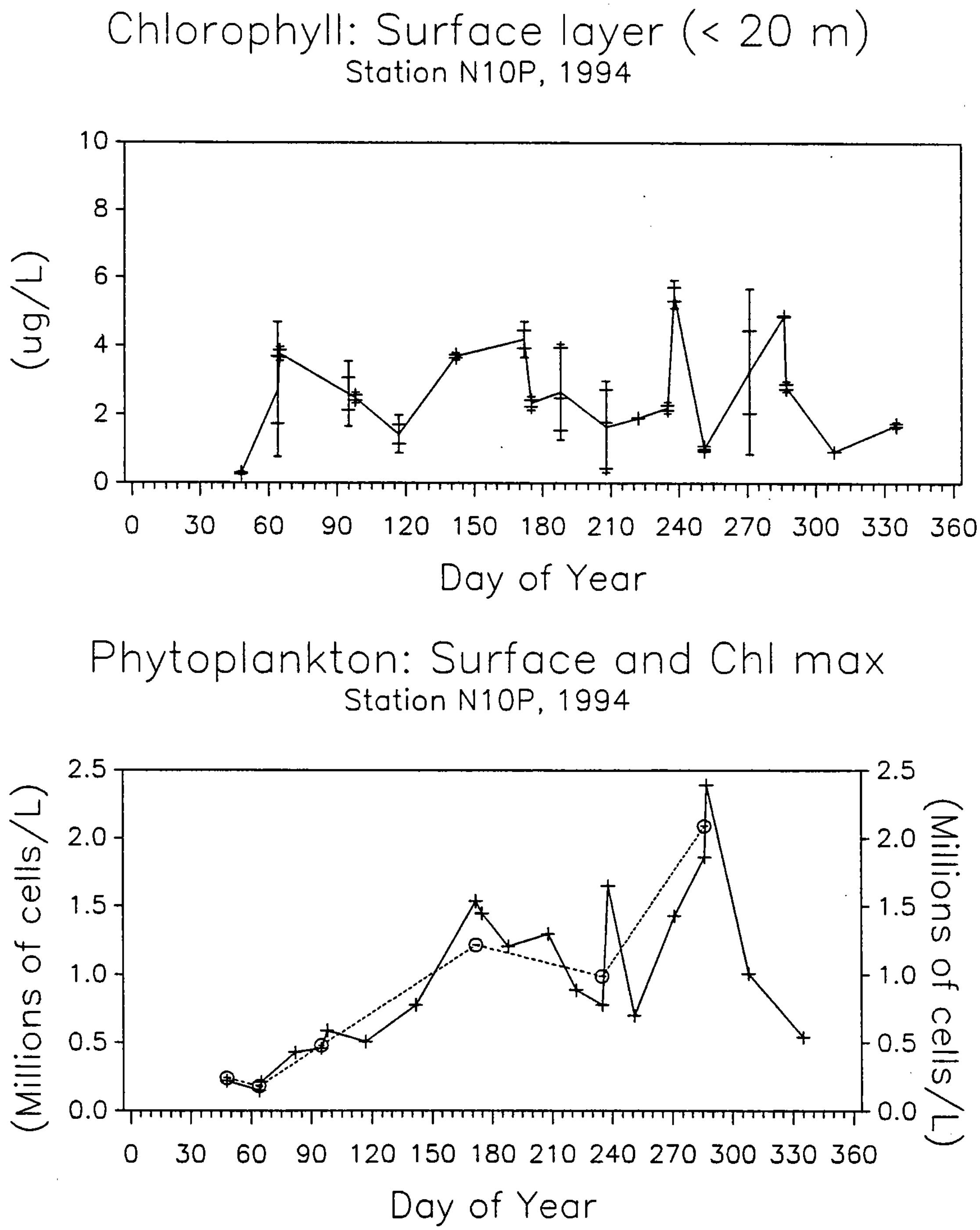


Figure 4.2-3 Chlorophyll concentrations and total phytoplankton cell counts at nearfield station N10P through the 1994 annual cycle. For cell counts (bottom), surface data are represented by the plus symbol and solid lines. Mid-depth chlorophyll maximum data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

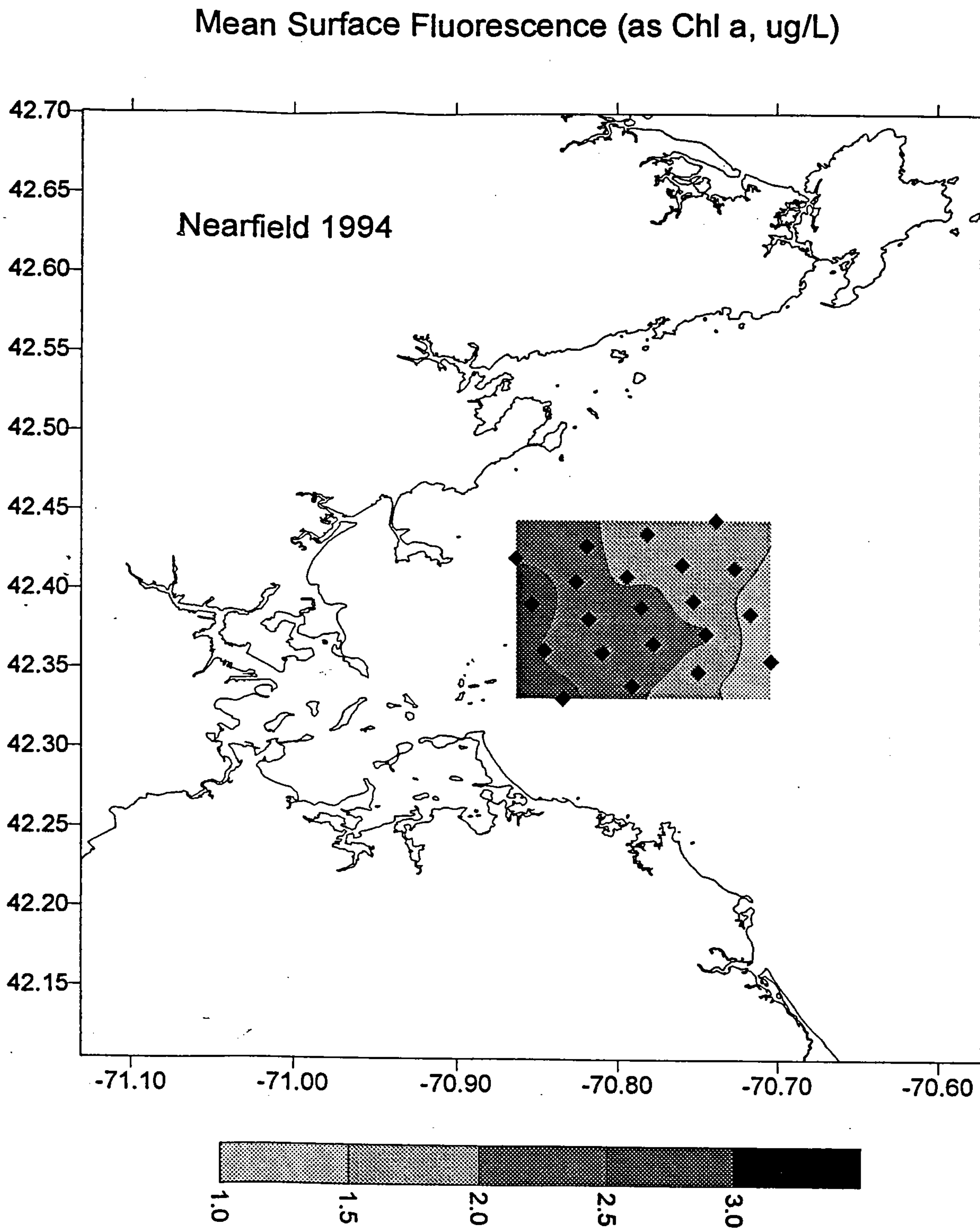


Figure 4.2-4 **Spatial pattern of fluorescence in the nearfield. Data are surface water means from 16 nearfield surveys in 1994.**

4.3 DISSOLVED OXYGEN

4.3.1 Frequency Distribution in Bottom Waters

The frequency distribution of all nearfield DO concentrations (N=1723) is shown in Figure 4.3-1. DO concentrations ranged from 4.82 to 17.37 mg L^{-1}, with a mean of 9.36 mg L^{-1}. There were 16 data points (<1 % of the total) with DO concentrations below the state standard of 6.0 mg L^{-1}. In comparison, the minimum and maximum concentrations for this region, based on the six farfield surveys, were 4.82 and 13.26 mg L^{-1}, respectively, with a mean of 9.73 mg L^{-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 and spatial coverage of the nearfield provided significant detail. Interestingly, the difference between surface and bottom waters, in terms of absolute DO concentration, is quite slight except during the late August (~day 235) to November (~day 310) period (Figure 4.3-2). Owing to the difference in temperature, the surface layer being significantly warmer than the bottom layer during stratification, the percent saturation is a better indicator of differences between surface and bottom waters. A persistent difference in the mean degree of saturation of surface and bottom waters occurred from about April (≈day 95) to December (day 330). The period between April and mid-October 1993 (≈day 290) encompassed the period of stratification for most of the nearfield; during almost this entire period there were supersaturated DO concentrations in the surface water (Figure 4.3-2) and this period seems to define the biologically productive season in the nearfield area in 1994. Notably, 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); this undersaturation defines periods of net respiration in the nearfield area in 1994.

Bottom Water Dissolved Oxygen Near the End of the Stratified Period in 1994. The annual DO minima in bottom waters of the nearfield occurred in mid-October (Figure 4.3-2). There was significant short-term variability at some stations in the nearfield. For example, the lowest DO reading of the year (4.82 mg L^{-1}) occurred at 21.9 m depth at station N10P on the farfield day of the survey (see also Figure 3.3-5); the next day at this location a value of 6.25 mg L^{-1} was recorded at 20.9 m. Some short-term variability may be due to tidal excursion or bottom-water advection and there also may be sharp near-bottom DO gradients; given these features, the precise depth above the bottom at which samples are taken could significantly affect results.

In October on the nearfield sampling day, most of the nearfield bottom-water had DO concentrations in the range 6-7 mg L^{-1} (Figure 4.3.3). However, near-bottom DO values were 5-6 mg L^{-1} at a group of three stations (N01P, N02, N03) along the northern edge of the nearfield. Thus, as described previously, the nearfield region had the lowest DO at this time. We suspect that an irregular bathymetry in the nearfield area may allow semi-isolation of bottom-waters for periods long enough to cause spatial variability and perhaps create patches of bottom-water with slightly more depressed DO concentrations.

Over the broader Baywide scale, a general trend of decreasing bottom-water DO concentrations with increasing depth was apparent in October as a strong correspondence of DO with bathymetry (cf. Figure 2.1-1 and Figure 4.3-3). At shallow stations fringing the shoreline, bottom-water DO was regularly >7 or 7.5 mg L^{-1}. The middle sampling region of the Bay encompasses much of the deeper water (>70 m) in Stellwagen Basin; here, DO concentrations were similar to the deep (>50 m) eastern nearfield and generally 6-7 mg L^{-1}. At station F28 (about 42.40° N, -70.40° W) along the easternmost line of farfield sampling, DO concentration >8 mg L^{-1} was noted; this is a shallow Stellwagen Bank station. Stations just north and south of station F28 lie in deepwater basins (>80 m), and DO was <6.5-7 mg L^{-1} at both of these locations. Although not displayed, virtually the same correspondence between bottom-water DO and water depth results when percent DO saturation, rather than DO concentration (as in Figure 4.3-3), was contoured over the Massachusetts Bay sampling region.

As described for 1993 (Kelly and Turner, 1995), a shore-to-sea progression of destratification in western Massachusetts Bay generally occurs in fall. For the nearfield in 1994, based on hydrographic profiles and a general increase in bottom-water DO in early November (Figure 4.3-2), we know that the nearfield had generally become well-mixed at that time. Without further late fall season sampling of the farfield and particularly the deeper basins, we do not know when fall overturn occurs in those regions; subsequently, the sampling in October may not have captured the annual DO minima in deep Bay bottom-waters.

4.3.3 Rates of Dissolved Oxygen 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=0.90, N=226). The slope (and standard error) of the decline indicates a rate of decrease as 0.027 (± 0.001) mg L^{-1} d^{-1}. When the time period was restricted to June through mid-October, the estimate of the rate was unchanged (0.028 ± 0.001 mg L^{-1} d^{-1}, R^2=0.81, N=184). The decrease in DO during the latter part of the summer (Figure 4.3-1) appeared to be slightly higher; indeed, if the time period of the analysis was restricted to August and September, a significantly higher estimate was obtained (0.046 ± 0.003 mg L^{-1} d^{-1}, R^2=0.77, N=90). Thus, as in previous years (e.g. Kelly and Turner, 1995), we noted a non-linear decline in DO during the stratified period, with increasing DO decrease late in the summer.

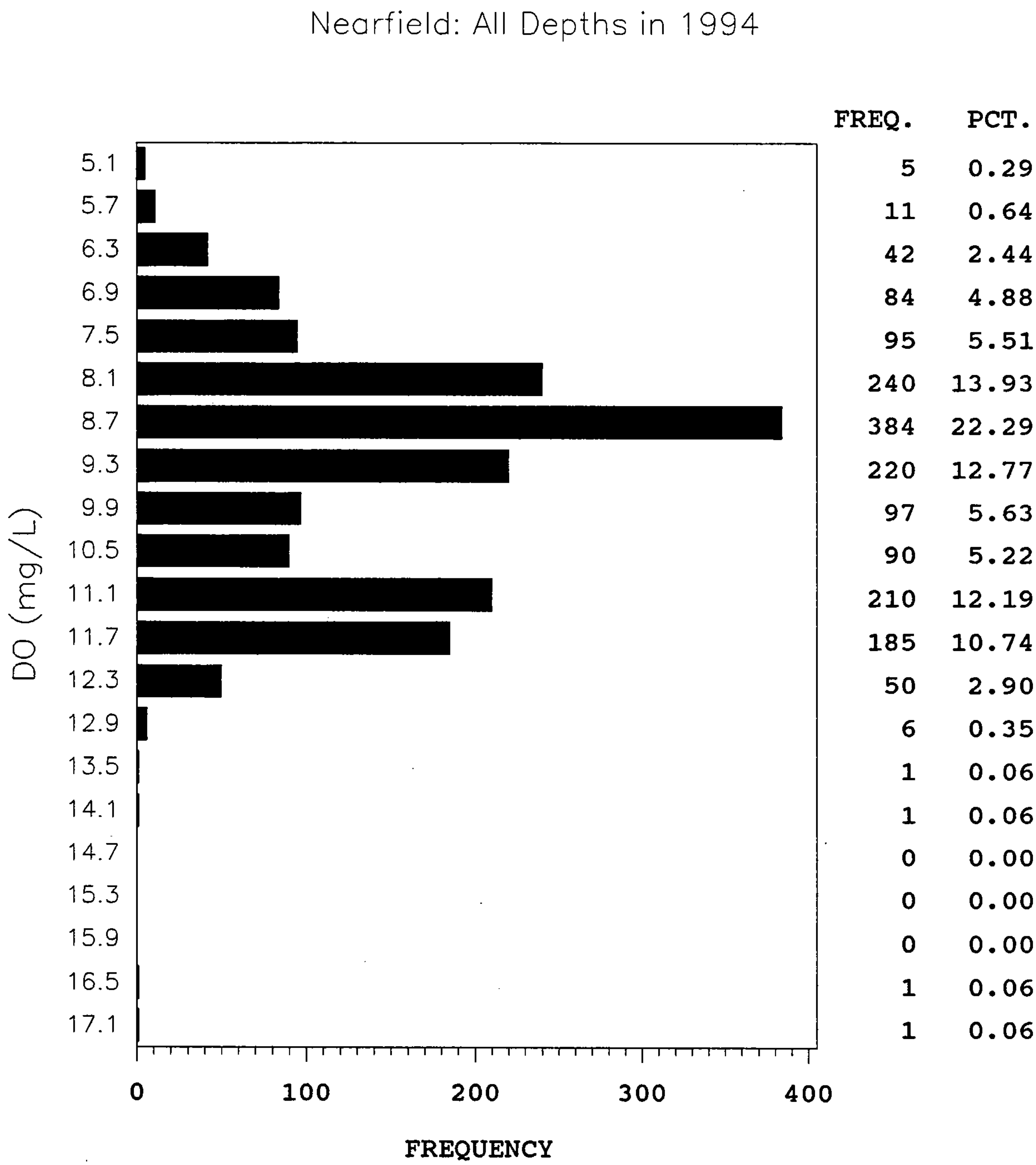


Figure 4.3-1 Frequency distribution of DO concentrations for all nearfield samples in 1994.

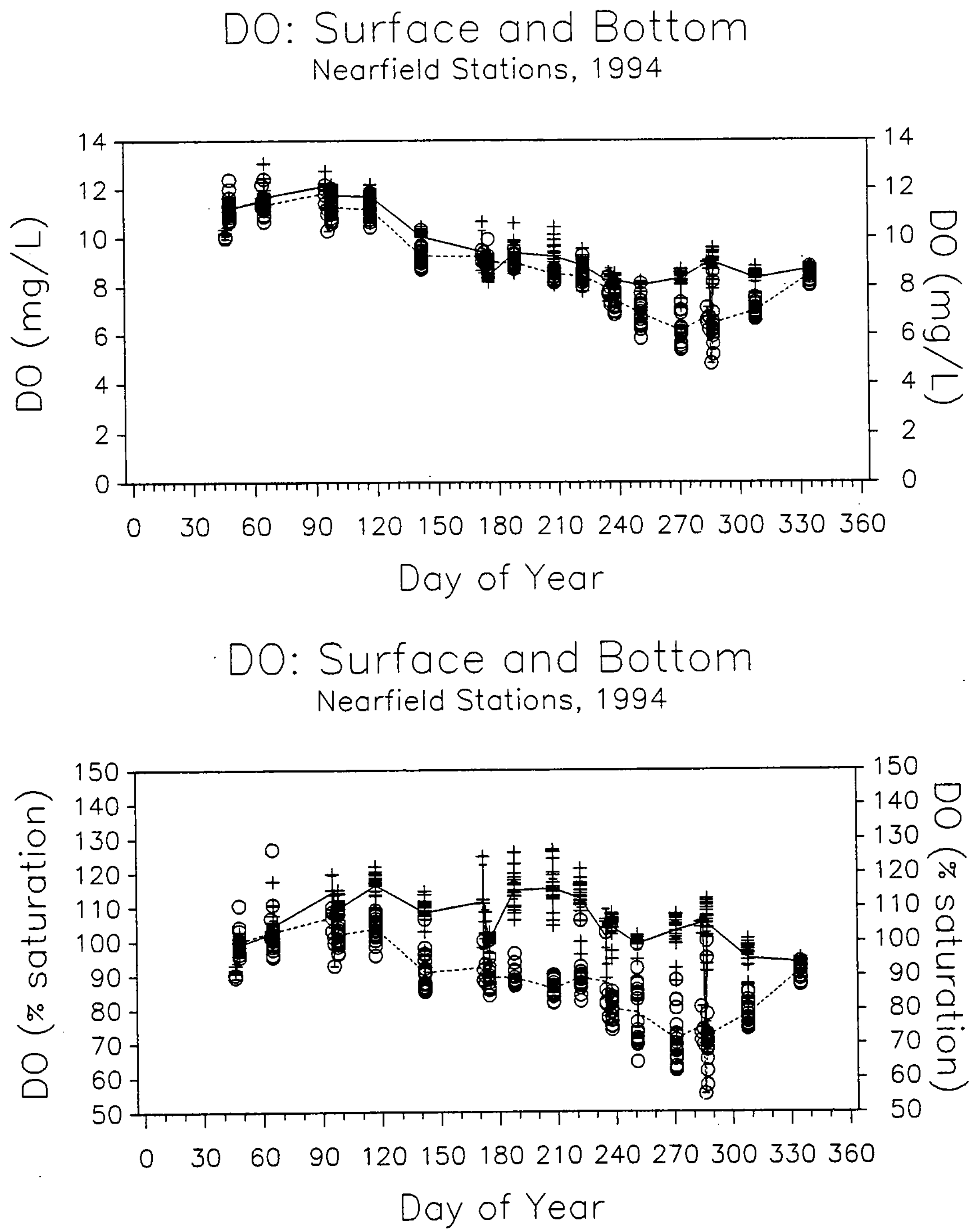


Figure 4.3-2 DO concentrations (top) and % saturation (bottom) in nearfield surface and bottom water through the 1994 annual cycle. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus some variations within a combined farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

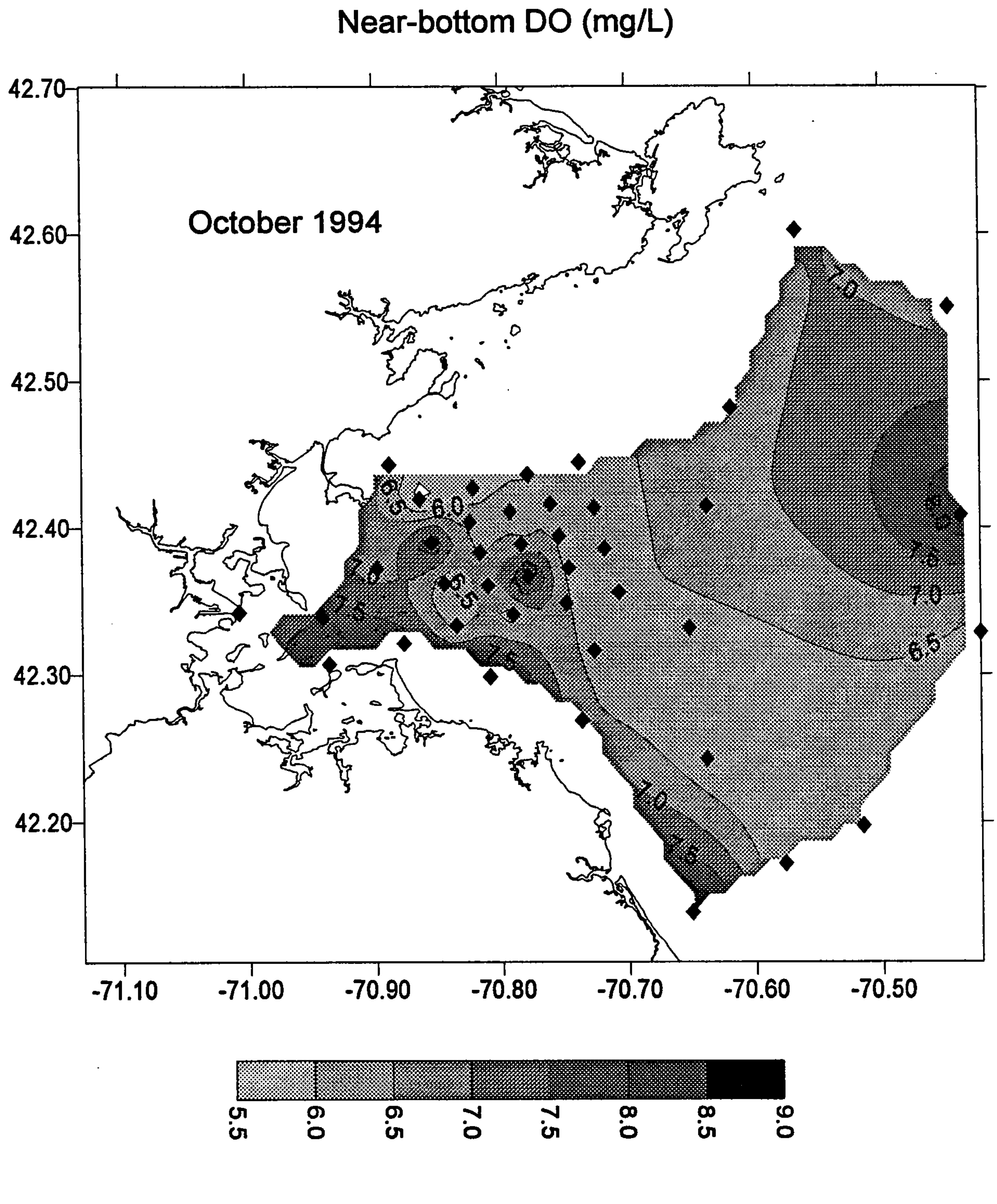


Figure 4.3-3 Spatial pattern of DO (concentration) in near-bottom water in the nearfield and farfield of Massachusetts Bay in October 1994. Data for twenty-one nearfield stations are from the deepest sample taken on the nearfield survey on October 14. Similar sampling of near-bottom water from surrounding farfield stations occurred from October 11-13.

5.0 DISCUSSION

At the farfield scale of sampling, 1994 water column monitoring results suggested there were a number of water-quality differences among regions. Initial discussion focuses on confirmation of differences by statistical inference tests. Following an extended comparison of water-quality similarities and differences (in 1994) between the present (Boston Harbor) and future (nearfield region) receiving waters for MWRA effluent, brief concluding comments address how the understanding gained from 1994 results offers guidance for continued monitoring and prediction efforts.

At the nearfield scale of sampling, a principal and defining result from 1994 water column monitoring was the occurrence of DO concentrations that were considerably lower than in recent years. Interannual comparisons of water-quality in the nearfield during 1992 to 1994 are developed in an effort to identify factors contributing to the unusually low DO in bottom waters. Again, brief concluding comments highlight some possible lessons for continued monitoring and prediction efforts.

5.1 FARFIELD/REGIONAL COMPARISONS

5.1.1 Differences in Surface Water Concentrations

Statistical Testing. An effort was made to determine how regions differed statistically during 1994. Using surface water concentrations, a variety of parameters were evaluated using two-way (space and time) analysis of variance (ANOVA) tests of means, followed by multiple comparison tests (SAS, 1988a,b)[1].

[1]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.

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 many additional statistical tests could be conducted. For example, testing might employ a multivariate rather than univariate mode, use different data transformations, or include depth strata in designing tests, and ANOVA using repeated measures may be an appropriate test in some cases.

Regions, Surveys, and Interaction. Table 5-1 shows that generally there were significance differences for the chosen parameters across regions and surveys. Table 5-1a presents results for all six sampling regions for routinely measured parameters, including fluorescence and beam attenuation (a measure of turbidity) from *in-situ* sensors as well as dissolved inorganic nutrients. In general, the total number of surface sampling events for this set was 231 and the number of data points varied from about 18 to 77 depending on the region and the parameter. Table 5-1a presents results for four sampling regions (Boston Harbor, coastal, nearfield, and Cape Cod Bay regions) that had two or more special sampling stations at which organic nutrients, chlorophyll, and phytoplankton counts were sampled and analyzed. In general, the number of data points was much reduced and varied from 6 to 62 depending on the region and the parameter.

Tests for most parameters indicated significance of the interaction of region and survey. This result may confound interpretation of the difference across regions or surveys alone. The significance of the interaction term is expected. Actually, it represents a primary result that supports the contention made from observing gradients over space at different times and inspecting comparative plots of regions over time and depth (Section 3) — there are differing annual cycles across sampling regions much as there are differing concentration levels. Consequently, two regions may be similar at some times and not at other times; for a given parameter, the relationship among values across the six regions varies somewhat over time.

Most parameters tested showed significant differences over regions and surveys. Exceptions were found only for the more limited data sets, including chlorophyll *a* (region), total suspended solids (TSS) (survey and interaction), DON (region), POC (survey) and DOC (survey and interaction). Despite possible confoundment of region and survey trends, planned comparisons are a useful initial guide and are provided in Tables 5-2 (regions) and 5-3 (surveys) for those parameters showing a significant difference in 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 and the regions connected by horizontal lines were not significantly different from each other. Comparisons look at each group vs. the rest, so in this scheme, there can be overlapping subsets of regions similar to each other, such as is shown for fluorescence. In the case of fluorescence, the extremes (Boston Harbor—high; offshore —low) are significantly different from each other.

Results were analogous to those from similar testing presented by Kelly and Turner (1995) for the 1993 sampling year, where the coastal region occasionally stood out as elevated for some parameters. Note that for 1993 testing, station F23P was included in a coastal group, whereas in 1994, it was included in the Harbor group. A difference between sampling in 1993 and 1994 was the addition of other stations within Boston Harbor proper, as well as boundary stations along the northeastern edge of Massachusetts Bay. Indeed, it is the Harbor in the 1994 data set which is most unique compared to other regions [Table 5-2 (e.g., DIN, NH_4, SiO_4, beam attenuation, total N)].

The ranking of regions usually follows the spatial gradients we have described previously, where concentrations generally diminish with distance from Boston Harbor into the Bay and the common pattern of overlapping subsets is indicative of a gradient or continuum. The coastal region often ranks second and is sometimes distinct from other regions (e.g., DIN, NH_4), while the group of nearfield, Cape Cod Bay, offshore, and boundary regions (or subsets thereof) are usually indistinct.

Perhaps the most striking observation from Table 5-2 is a difference in results across parameters, which illustrates a basic difference between the location of the present outfall in Boston Harbor and the future location in Massachusetts Bay. For the nutrients that are readily assimilated and likely limiting to phytoplankton, Boston Harbor was significantly enriched. The parameters which we generally think of as primary response variables to nutrient enrichment — fluorescence, chlorophyll *a*, and phytoplankton abundance — were not significantly elevated. Of these three parameters, there were most frequent measurements of fluorescence. It is known in theory, but we also have shown empirically that the frequency of sampling affects the ability to detect significant differences (cf. Kelly and Turner, 1995). Boston Harbor was indeed ranked first in fluorescence (2.75 $\mu g\ L^{-1}$) , but was not different from most other regions (ranging from 2.4 [coastal] to 1.7 [boundary] $\mu g\ L^{-1}$) and the fluorescence is much less than expected based on the elevated nutrient concentrations alone (see Kelly, 1993). Turbidity (beam attenuation) was highest in the Harbor, no doubt due to higher suspended solids as well dissolved organics, and this factor may strongly influence phytoplankton through its influence on light availability. The sharp distinction of a different water quality in Boston Harbor, although neither unexpected or new, is made clear by the extension of sampling to include additional stations within the Harbor in 1994.

The Harbor, as well as other regions (e.g., Cape Cod Bay) have semi-unique seasonal patterns, a fact suggested previously and supported by significance of the region by survey interaction term in ANOVA testing (Table 5-1). Even so, for the bulk of the stations (i.e., Massachusetts Bay) there are some overriding norms for annual cycles, and these fundamental patterns are suggested by results in Table 5-3. Principal among these is a trend in fluorescence, mimicked in part by beam attenuation, chlorophyll *a*, and total phytoplankton — all indicators of the activity of primary producers. The fluorescence testing results indicate peak annual values characteristic of the fall phytoplankton bloom. October concentrations were elevated and distinct from those during the period of the spring bloom through the summer. In turn, the summer values were themselves elevated and distinct from the annual minima (February), which occurred prior to initiation of the spring bloom in most of the sampling region (Cape Cod Bay being the exception). This result for 1994 is virtually the same as for 1993, even though the fall bloom in 1994 was a minor event compared to 1993 (see Kelly and Turner, 1995). Actually, during the entire 1992-1994 baseline water quality monitoring program we have observed late September-October peaks in fluorescence, and these peaks have been higher on average than those occurring in the winter-spring bloom in Massachusetts Bay.

As expected, the cycle for each of the dissolved inorganic nutrients (DIN, NH_4, PO_4, SiO_4) in 1994 was somewhat opposite to the basic fluorescence trend. This, too, is a consistent result for the entire 1992-1994 water quality monitoring. For nutrients, there are some subtle differences in seasonal trends among forms, but in general the annual maxima were found in early winter pre-bloom conditions, intermediate concentrations occurred in late summer and early fall, and lowest values were recorded during the late spring bloom to early summer period. In contrast to the dissolved inorganic nutrient forms, the organic nutrients as a group had indistinct seasonal patterns and broad overlap in similarity of concentrations among surveys. Often, only the extreme surveys were different and the months of highest and lowest average concentrations differed across nutrient forms.

5.1.2 Regional Contrast: Boston Harbor and the Nearfield in Massachusetts Bay

A number of previous reports (e.g., Kelly *et al.*, 1993; Kelly and Turner, 1995; Turner, 1994) have drawn distinctions between Massachusetts Bay and Cape Cod Bay in terms of their pelagic ecology, such as in the seasonal timing of phytoplankton blooms, nutrient concentrations, nutrient ratios, and composition of plankton communities. There were again some of these differences noted between these two Bay in 1994, as presented in Section 3 and also as strongly emphasized in the series of periodic reports covering the 1994 farfield surveys (cited in Section 2). There were also occasional differences, some subtle, within regions of Massachusetts Bay itself, particularly as a function of depth. But given the distinctiveness of Boston Harbor shown by the above statistical testing, we thought it useful to focus on the 1994 annual cycle in the Harbor and contrast this with conditions in the mid-nearfield in Massachusetts Bay. This is also a natural contrast because the entire basis for the extensive MWRA monitoring is the planned diversion of MWRA effluent from the Harbor to the nearfield.

We chose to develop the contrast using data for two stations near the locations of the present and future MWRA outfalls. Station F23P is near Deer Island at the edge of Boston Harbor and the available data are most extensive for this Harbor station. Although at the Harbor edge, it exemplifies the fundamental seasonal characteristics of the nutrient-enriched, well-mixed, and relatively turbid environment of the shallow inshore Harbor ecosystem. Station N16P in the nearfield is located near the eastern end of the future 2-km outfall diffuser track in the Bay. It is distant enough from the Harbor to have minimal direct influence of Harbor export within its surface water. It is a relatively clear-water, seasonally-stratified ecosystem with lower surface layer nutrient concentrations.

Contrasting physical environments (Figure 5.1-1). From minimum winter temperatures below 0°C in February to maximum temperatures near 16°C in August, the Harbor had minor differences in temperature between surface and bottom waters. The nearfield had a similar seasonal pattern for its surface water, but the extreme temperatures were about 2°C higher. A bottom-water layer in the nearfield was slightly warmer than the surface layer in winter and progressively warmed from about April, reaching an annual maximum near 11 °C at fall overturn, rather than mid-summer. The Harbor does not receive a large freshwater load. It had some differences in salinity between surface and bottom water that were expressed during periods of spring runoff and wet weather, but there were periods throughout the year when surface and bottom salinities were similar. The nearfield in general had salinities about 1-2 PSU greater than the Harbor. Once thermal and density stratification of the nearfield began (by mid-April), bottom waters remained about 0.5 to 1.5 PSU greater than surface water. In the nearfield, variability in surface water salinity was as large between three-day periods as it was over several months, but lowest salinities were noted in April and gradually rose from then to October. The bottom layer in the nearfield was very stable in terms of salinity over the entire year, varying within the range of 32 to 32.5 PSU.

Contrasting DO patterns (Figure 5.1-2). The Harbor DO cycle basically follows the temperature cycle, falling in August to an annual minimum below 7 mg L^{-1}. Note that station F30B at the entrance to the inner Harbor had a concentration near 6 mg L^{-1} in August 1994 and even more interior portions of the Harbor have lower DO depression in mid-summer (Lavery and Coughlan, 1995). Interestingly, the Harbor shows slightly supersaturated DO in April and perhaps June; the supersaturation coincides with the period of highest chlorophyll and primary production (see below). The Harbor otherwise was undersaturated with respect to DO and on balance may be seen as undersaturated. This typically indicates a heterotrophic (consumer) ecosystem, where *in situ* production of organic matter (and oxygen) is exceeded by consumption of organic matter (and oxygen).

The nearfield DO cycle shows the separation of surface and bottom waters, by late summer in terms of concentration, but by April in terms of percent saturation. Interestingly, the bottom-water DO minimum in 1994 at station N16P was between 6 and 7 mg L^{-1} and therefore similar to the Harbor, but was found in October, at the nearfield's annual bottom-water temperature maximum. Percent saturation in surface and bottom layers in the nearfield distinguishes a productive (autotrophic) surface layer (supersaturated from April to October) from its underlying heterotrophic layer (undersaturated from April to October).

Contrasting nutrient concentration levels and cycles of nutrients and plankton (Figure 5.1-3). The DIN cycle in the Harbor shows similarity between surface and bottom water concentrations throughout the year. There were high concentrations prior to a fully-developed spring bloom in April. Concentrations were low in April and June, but had risen by August and October to levels similar to early in winter (~12 to 20 μM). Fluorescence, like chlorophyll, shows essentially the inverse of the nutrient cycle, rising by April and falling by late summer. In contrast to many parameters, there appears to be a difference between surface and bottom water fluorescence, with higher concentrations at the surface in the biologically productive season in the Harbor (late spring to mid-summer).

In the nearfield, differences in surface and bottom layer DIN patterns reflect autotrophic vs. heterotrophic conditions. Surface water DIN concentrations were virtually exhausted by the spring bloom and, unlike in the Harbor, did not even begin to increase again until fall. Bottom-water DIN was reduced, but not depleted by the spring bloom, and then increased progressively into October, nearly reaching concentrations (~10-12 μM) in pre-bloom conditions early in winter 1994. In the nearfield, instead of late spring and summer peaks in fluorescence like in the Harbor, there were early spring (March) and fall (October) peaks. Moreover, in late spring, high fluorescence (and chlorophyll) in bottom layers suggested sinking of the remnants of the spring bloom. Note that in summer in the nearfield, instead of high surface chlorophyll concentrations, there tended to be subsurface chlorophyll maxima that are not represented in Figure 5.1-3.

As shown by the statistical tests, the nutrient levels and cycles differ between Harbor and nearfield surface and bottom waters. Interestingly, some differences, especially seasonal lags in the annual cycle, may lead to strong interactions of the two regions. For example, it is reasonable to speculate that the mid-summer/early fall increase in nutrients in the Harbor helps fuel a fall surface water bloom in the western nearfield through an export of readily available dissolved nutrients, especially NH_4 (cf. Kelly, 1993; Libby *et al.*, 1995).

Contrasting turbidity and light attenuation (Figure 5.1-4). Water clarity is reduced in Boston Harbor, as shown by *in situ* transmissometry measurements throughout the year (see, for example, Table 5-2). The effect of high turbidity in the Harbor is to reduce the depth of penetration of incident light used in photosynthesis (termed photosynthetically active radiation, PAR). The photic zone, calculated as the depth at which PAR is reduced to 0.5% of the surface-incident PAR, varied from about 10-20 m at station F23P and was about 20-40 m at station N16P in the nearfield throughout 1994.

A comparison of primary production rates in the differing environments of the Harbor and the nearfield. The primary production measurements in 1994 were designed to examine rates for these two different environments which could be affected by a diversion of MWRA effluent to the Bay. A goal was to investigate if primary production fundamentally could be described from similar underlying principles or following empirical formulation schemes developed elsewhere (e.g., Cole and Cloern, 1987).

Production rates are in part dependent upon the number of organisms and/or their biomass — at a constant rate of doubling, the growing phytoplankton population starting with twice the cells will have twice the production. Thus, it was not surprising to find that the annual pattern in production rates was broadly similar to the pattern in fluorescence (expressed as a chlorophyll concentration and averaged over the photic zone) (Figure 5.1-5). We have described this same result in previous reports (e.g., Kelly and Turner, 1995).

With greater light penetration in the nearfield, primary production profiles with depth in 1994 typically showed significant production to significantly greater depth at the nearfield station. Given the differences between photic zone depths in the two environments, the integrated photic zone chlorophyll biomass (as mg m^{-2}) thus may be a more useful metric than concentration [following Cole and Cloern (1987), and others]. Figure 5.1-6 shows the nearfield condition to have greater chlorophyll mass than the Harbor at virtually all sampling events, and thus is consistent with the nearfield nearly always having higher measured primary production. Figure 5.1-7 shows that there was a significant correlation between the chlorophyll biomass in the photic zone and the integrated ^{14}C production rate for each station averaged at each survey ($R^2 = 0.58$, N=12) and the pattern was much stronger than obtained when production was regressed on average chlorophyll *concentration* ($R^2 = 0.26$, N=12). A single general relationship (Figure 5.2-7) seems adequate to describe *both* nearfield and Harbor results, implying that the interaction of the light regime and the standing stock of chlorophyll biomass are basic factors that can similarly influence primary production in spite of the many ecological differences just chronicled for these two environments (e.g., nutrient status, temperature, seasonal cycles). Importantly, the result also explains how production can be higher in the present nearfield than in the Harbor and confirms that production rates are strongly influenced by light as well as nutrients in these two environments (cf. Kelly, 1993).

Conclusions. Besides a compelling description of differences in the environments, what does the Harbor-nearfield contrast tell us? First, the contrast graphically illustrates a principal finding of statistical tests that showed a significant interaction of space and time — the environments are different on average, as well as in their seasonal cycles, and a concentration that is high in one place at a given time may be higher later in the other. This knowledge should help shape further details of monitoring and designs to test for change. As an example, the outfall diversion effects testing design primarily must be limited to pre-/post comparisons of the same areas, as regions seem a poor control in space and/or time for each other. The result therefore brings into focus intra-regional variability, over space, within seasons, and across years (see next section). On a practical level, the task of detecting changes in water quality in the future will be to sort out changes in average conditions (averaged over some specified space or time) as well as in timing of events. As yet, we do not know fully, in terms or ecology or water quality, what acute events or chronic conditions are most critically important to populations and communities residing in the ecosystem.

Secondly, the Harbor-nearfield contrast should reinforce the notion that transferring nutrient loads directly to the nearfield (in contrast to indirectly, as they are now — see Kelly, 1993) does not suggest there will be concomitant translation of present conditions in the Harbor to future conditions in the nearfield, for dilution as well as ecological influences on water quality will be expressed quite differently in the two environments. Accordingly, it is highly appropriate to enlist the aid of linked hydrodynamic and water quality models (e.g. Hydroqual, 1995) to provide at least coarse-scale predictions of future conditions. The result offered here, that production in both Harbor and nearfield environments appears to follow general, rather than specific, rules, may bolster confidence in the use of these complex models, for their fundamental underpinnings are generalized formulations including the interaction of plankton and light.

Table 5-1a. Type III ANOVA Significance Levels (Pr>F) for 1994 Farfield Survey Surface Water Data: Parameters Across Six Regions[a]

Parameter	Region	Survey	Region*Survey Interaction
Fluorescence	0.017	0.0001	0.0001
DIN	0.0001	0.0001	0.0002
NH_4	0.0001	0.0001	0.023
PO_4	0.0001	0.0001	0.0001
SiO_4	0.0001	0.0001	0.0001
Beam attenuation	0.0001	0.0001	0.0001

[a]Regions = boundary, nearfield, coastal, offshore, Cape Cod Bay, and Boston Harbor.

Table 5-1b. Type III ANOVA Significance Levels (Pr>F) for 1994 Farfield Survey Surface Water Data: Parameters Limited to Four Regions[a]

Parameter	Region	Survey	Region*Survey Interaction
Chlorophyll *a*	0.82	0.0001	0.0001
Total phytoplankton	0.0008	0.0001	0.0001
TSS	0.0001	0.511	0.41
PON	0.0003	0.0011	0.0004
DON	0.179	0.0046	0.052
Total N	0.0001	0.044	0.007
POC	0.0001	0.243	0.0002
DOC	0.0042	0.067	0.646

[a]Regions = nearfield, coastal, Cape Cod Bay, and Boston Harbor.

Table 5-2. Results of Tukey's Multiple Comparisons Test to Note Significant Differences Among Surface Waters in Regions of the Bays in 1994

	Parameter						
Six Regions	Fluorescence	BH	COA	CCB	NEA	BOU	OFF
	DIN	BH	COA	NEA	BOU	OFF	CCB
	NH_4	BH	COA	NEA	OFF	BOU	CCB
	PO_4	BH	COA	NEA	CCB	BOU	OFF
	SiO_4	BH	COA	BOU	NEA	CCB	OFF
	Beam attenuation	BH	COA	CCB	NEA	BOU	OFF
Four Regions	Total phytoplankton	CCB	COA	BH	NEA		
	TSS	BH	COA	CCB	NEA		
	PON	BH	CCB	COA	NEA		
	Total N	BH	COA	NEA	CCB		
	POC	BH	COA	CCB	NEA		
	DOC	BH	COA	CCB	NEA		

BOU = boundary
COA = coastal
NEA = nearfield
OFF = offshore
CCB = Cape Cod Bay
BH = Boston Harbor

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 1994

	Parameter						
Six Regions	Fluorescence	OCT	MAR	AUG	JUN	APR	FEB
Six Regions	DIN	FEB	MAR	OCT	AUG	JUN	APR
Six Regions	NH_4	FEB	MAR	OCT	AUG	JUN	APR
Six Regions	PO_4	FEB	MAR	OCT	AUG	JUN	APR
Six Regions	SiO_4	FEB	MAR	OCT	AUG	JUN	APR
Six Regions	Beam attenuation	OCT	AUG	MAR	JUN	FEB	APR
Four Regions	Chlorophyll *a*	OCT	MAR	AUG	APR	JUN	FEB
Four Regions	Total phytoplankton	OCT	AUG	JUN	APR	FEB	MAR
Four Regions	PON	JUN	APR	OCT	AUG	FEB	MAR
Four Regions	DON	APR	OCT	JUN	AUG	MAR	FEB
Four Regions	Total N	MAR	OCT	APR	FEB	AUG	JUN
Four Regions	POC	APR	JUN	OCT	AUG	MAR	FEB

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

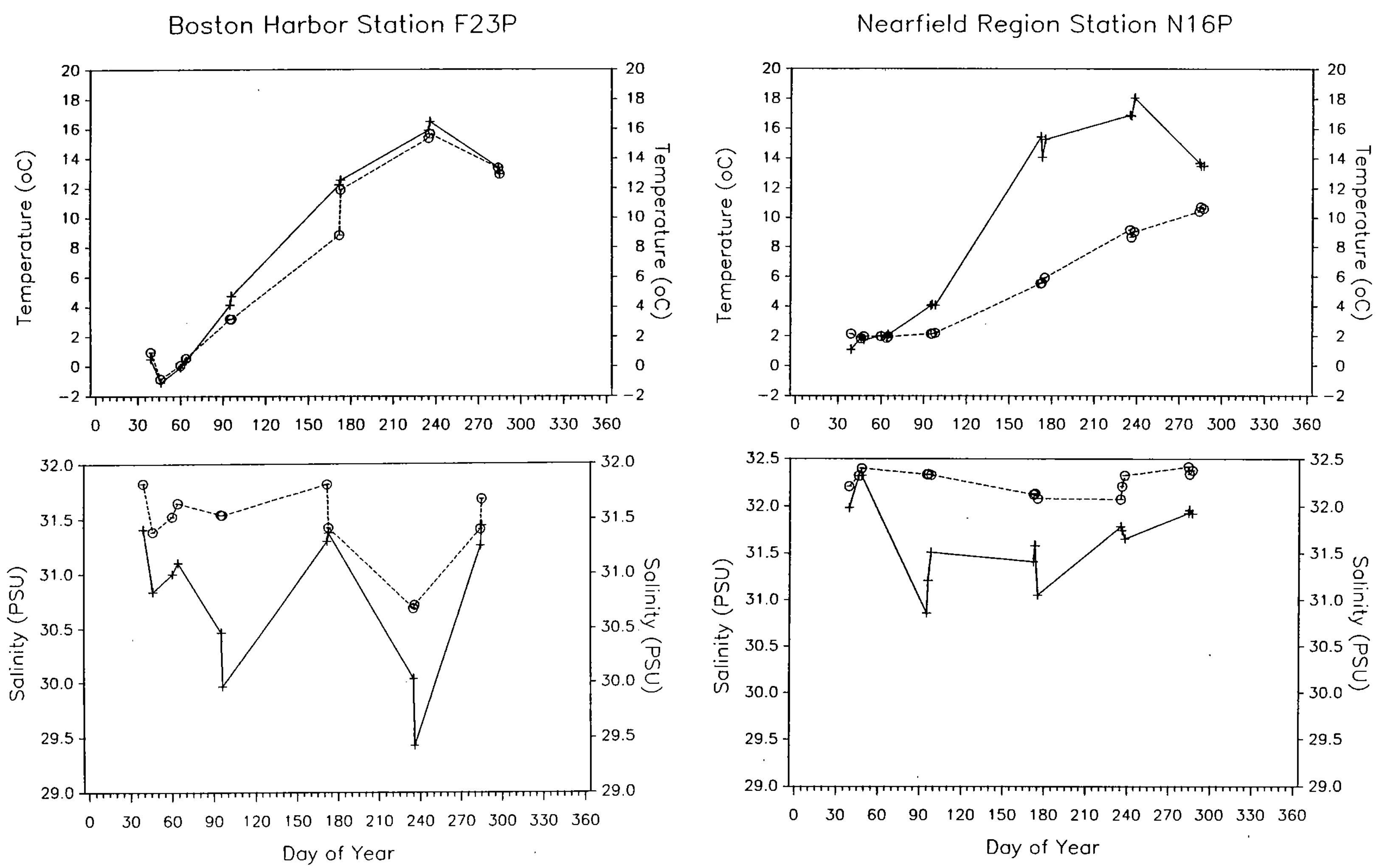


Figure 5.1-1 Annual cycle of temperature and salinity at stations F23P (Harbor) and N16P (nearfield). Data are from repeated sampling on each farfield survey. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines.

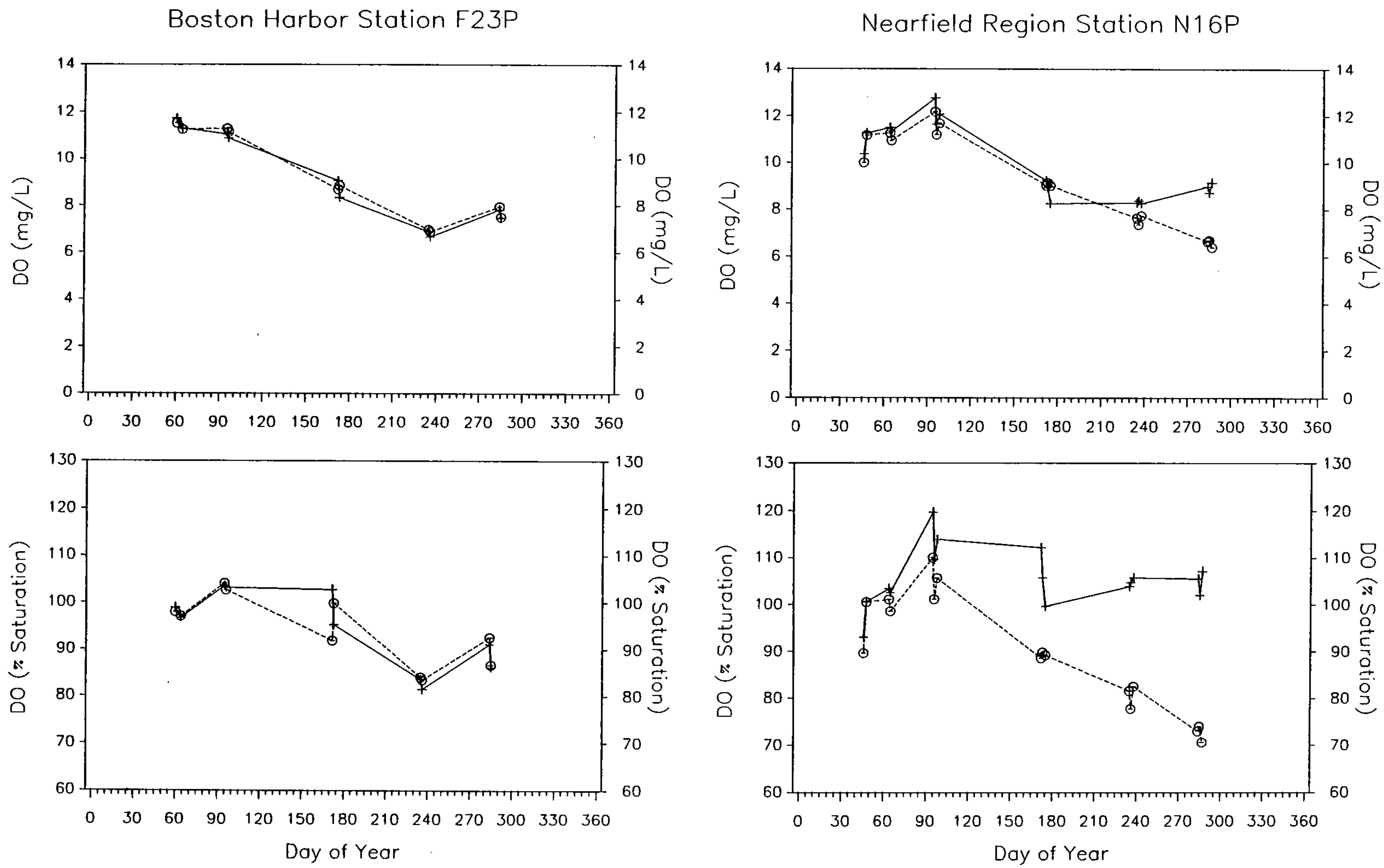


Figure 5.1-2 Annual cycle of DO (mg L^{-1} and % saturation) at stations F23P (Harbor) and N16P (nearfield). Data are from repeated sampling on each farfield survey. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines.

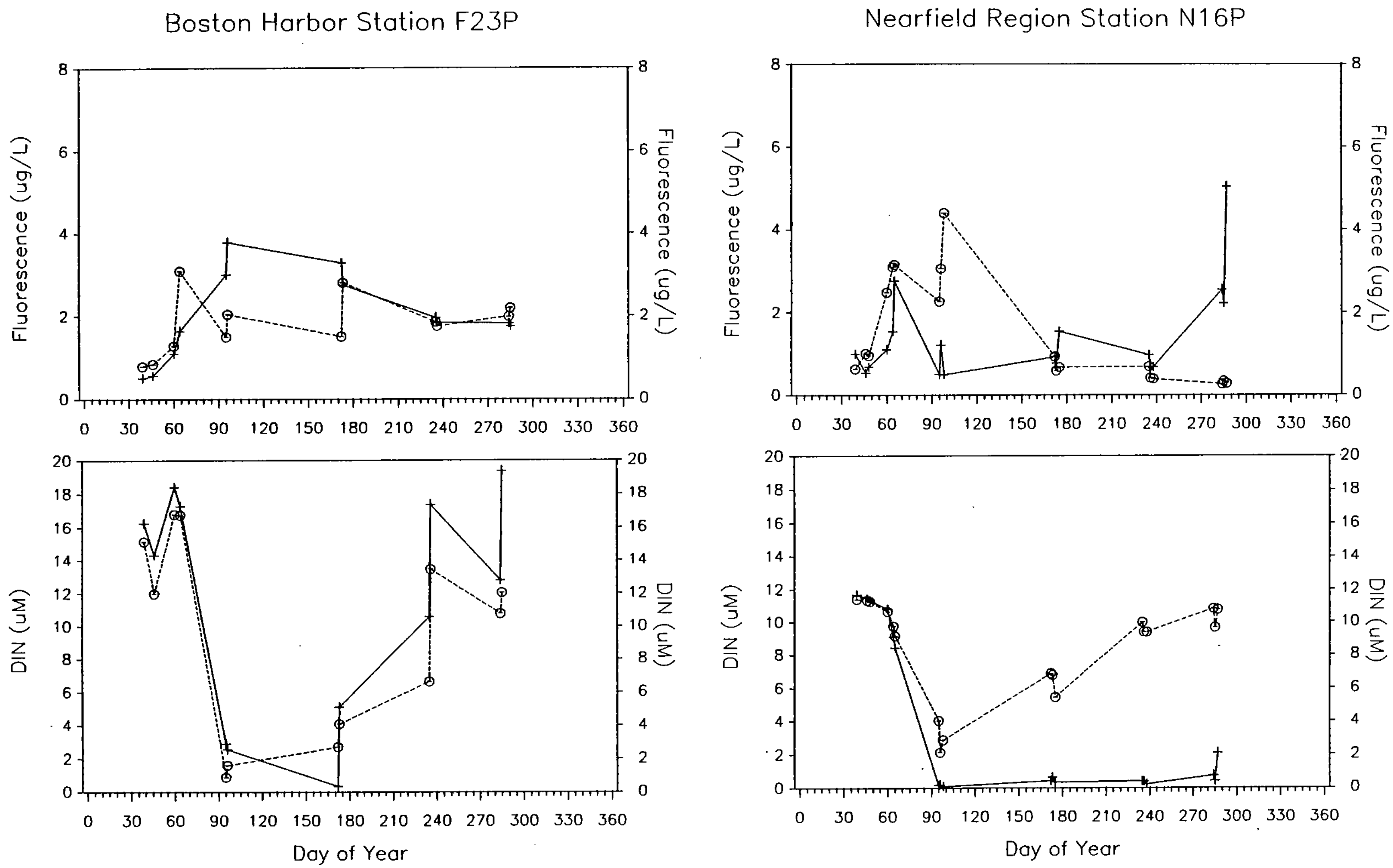


Figure 5.1-3 Annual cycle of fluorescence (as chlorophyll *a*) and DIN at stations F23P (Harbor) and N16P (nearfield). Data are from repeated sampling on each farfield survey. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines.

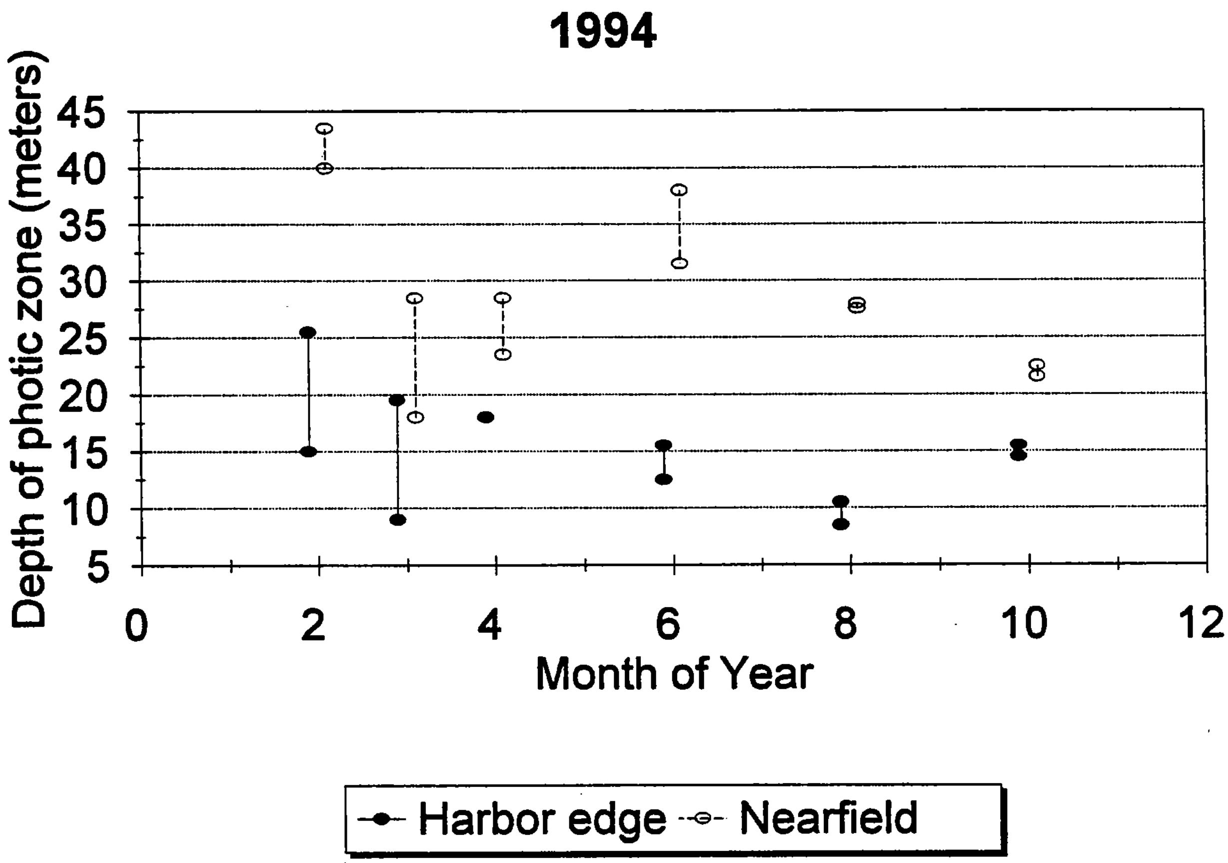
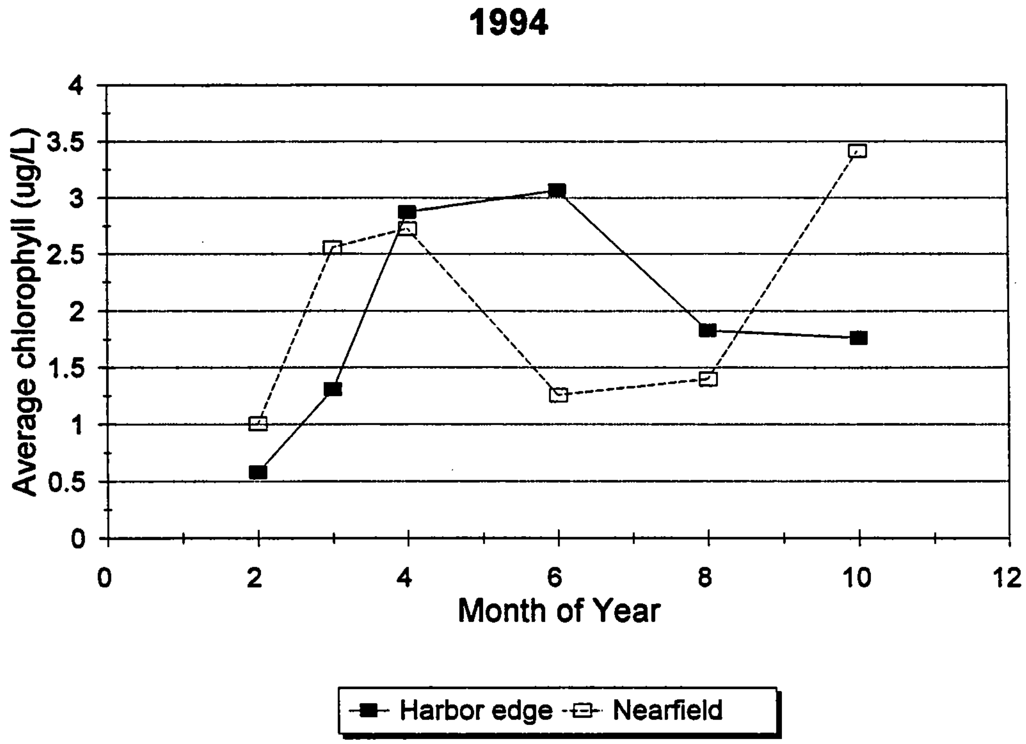


Figure 5.1-4 Annual cycle of the photic zone depth (0.5% PAR) at stations F23P (Harbor) and N16P (nearfield). Ranges within a month show data from repeated sampling on each farfield survey.



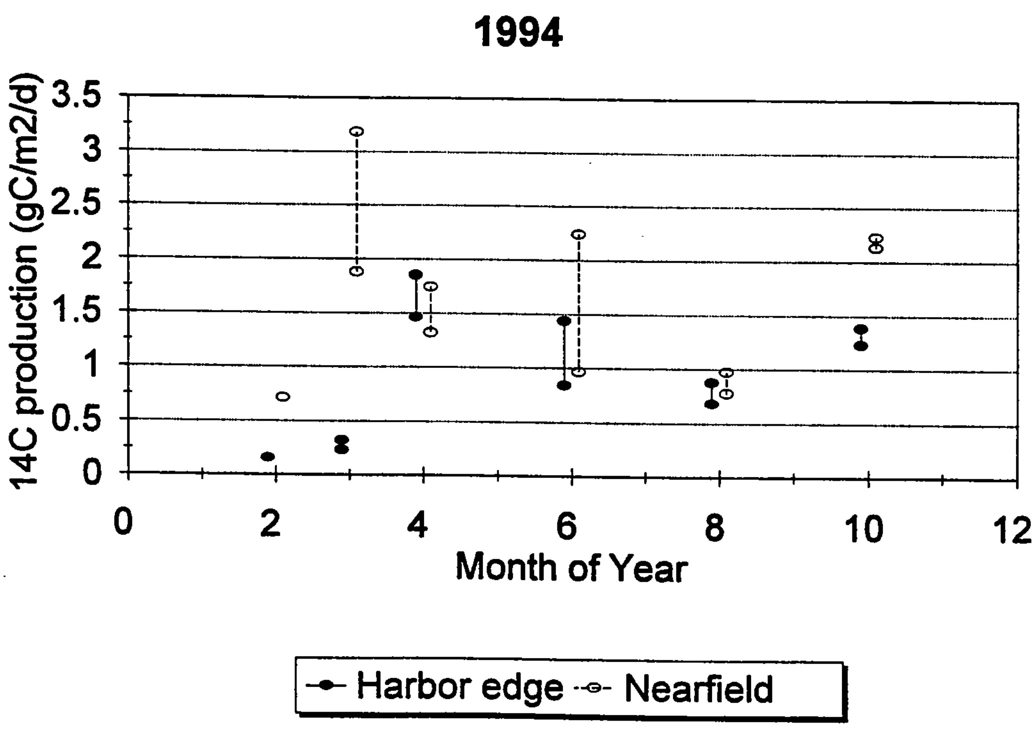


Figure 5.1-5 Annual cycle of the average photic zone chlorophyll concentration (top) and ^{14}C net production (bottom) at stations F23P (Harbor) and N16P (nearfield). Ranges for production within a month show repeated sampling on each farfield survey. Chlorophyll (from bin-averaged fluorescence) was averaged by survey.

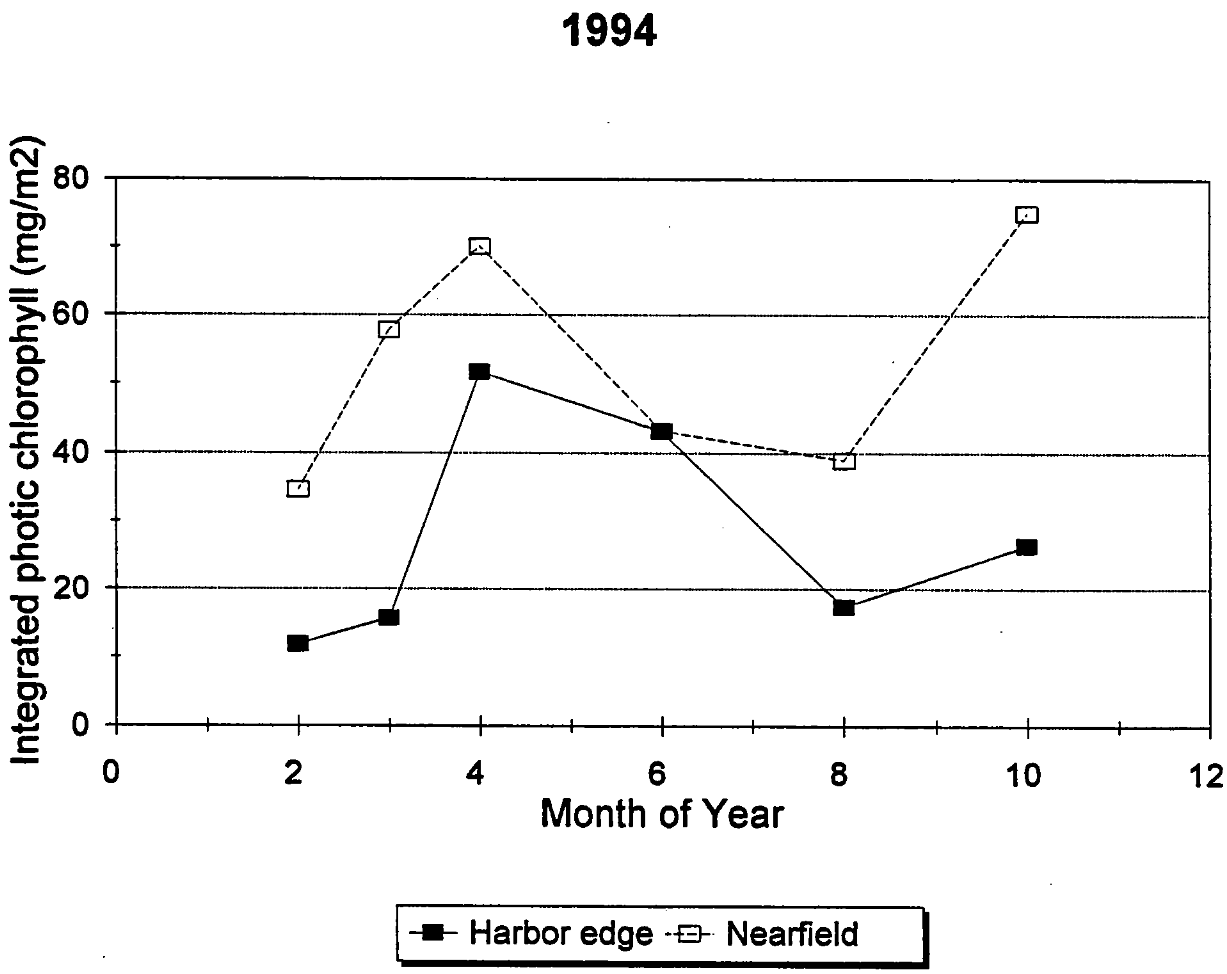


Figure 5.1-6 Annual cycle of the average chlorophyll biomass (mg/m²) integrated over the photic zone at stations F23P (Harbor) and N16P (nearfield). Chlorophyll (from bin-averaged fluorescence) was averaged by survey.

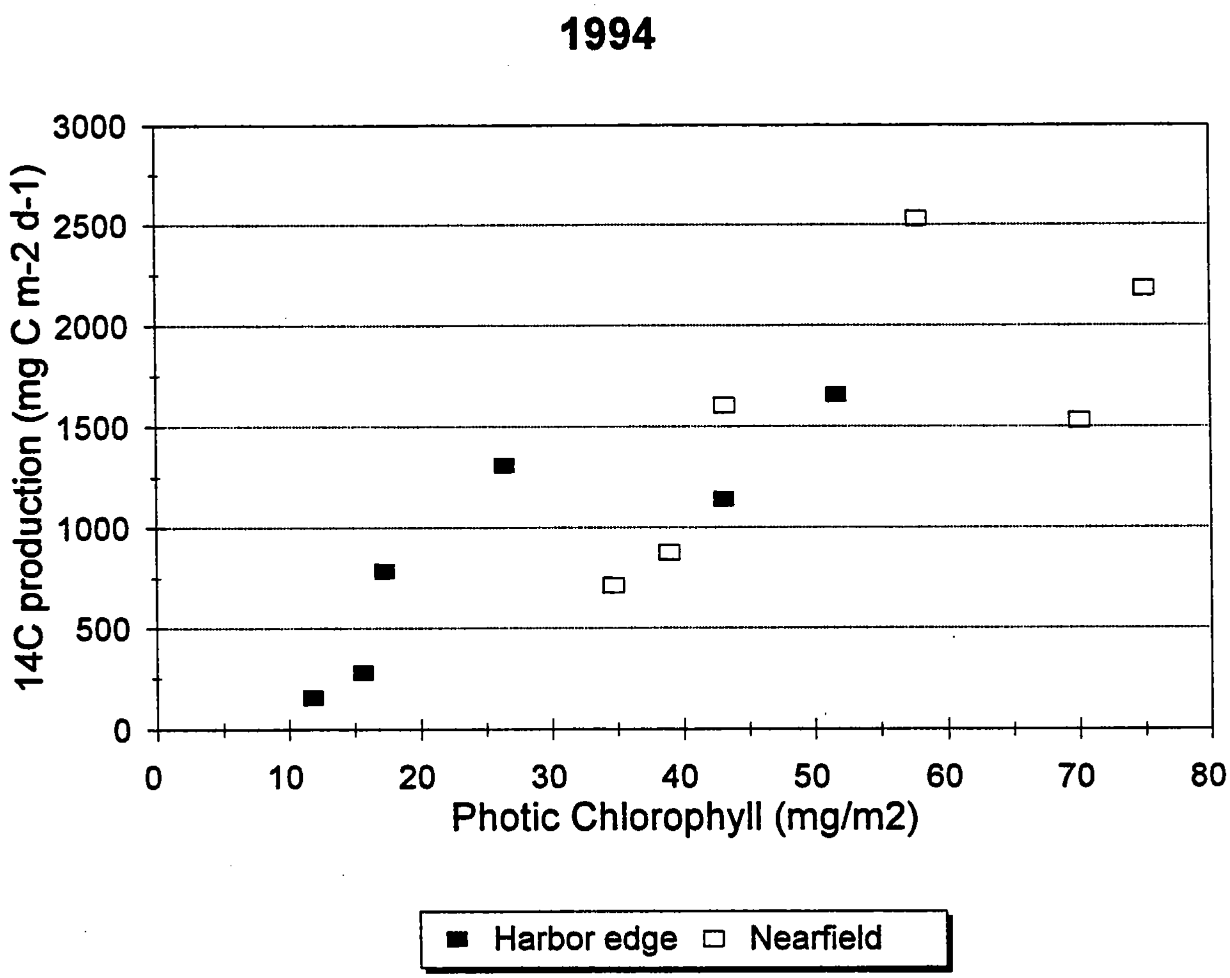


Figure 5.1-7 Comparison of ^{14}C production with average chlorophyll biomass integrated over the photic zone at stations F23P (Harbor) and N16P (nearfield). Production and chlorophyll (from bin-averaged fluorescence) were averaged by survey.

5.2 THE NEARFIELD REGION IN 1994

A defining ecological feature for nearfield water quality for the 1994 sampling year was the observation of DO concentrations in fall that were distinctly lower than in the two previous years (Figure 5.2-1). Kelly *et al.* (1995a) noticed that bottom-water DO concentrations were low in June-July 1994 compared to the same period in 1992 and 1993, and had commented that values below 6 mg L^{-1} were possible in fall 1994 if rates of DO decline during summer were similar to previous years. Actual rates of DO decline (Section 4) were indeed similar, if not higher, than in previous years. Subsequently, the *mean* nearfield DO concentration for bottom water approached 6 mg L^{-1}, while individual measurements $\leq$5 mg L^{-1} were recorded. We have confidence in the 1994 DO readings (to an expected mean precision of $\pm$0.5 mg L^{-1}). Moreover, there were independent measurements of near-bottom DO by Winkler titrations at three benthic flux stations (33-36 m) in the nearfield on October 20, six days after the October 1994 nearfield survey — the measured DO concentrations confirmed low values detected in water column monitoring and values ranged from 5.38 to 5.89 mg L^{-1} (Giblin *et al.*, 1995).

The annual bottom-water DO minima each fall (1992-1994) has been notable as % saturation as well as absolute concentration (Figure 5.2-2). A clear separation of surface and bottom-water layers, in terms of % saturation, was evident much earlier in 1994 than in 1992, and perhaps 1993 as well. Interestingly, the DO concentration and % saturation minima in bottom waters (~October) has reached progressively lower values each year from 1992 to 1994. The full reason for the lower DO values in 1994 remains uncertain, but a brief comparison of trends in other water-quality parameters in the nearfield serves well to illustrate the nearfield during the three-year baseline period of MWRA monitoring as well as provide some insight on factors that can influence DO concentrations in Massachusetts Bay in the area of the proposed MWRA outfall.

Patterns in physical parameters. The temperature cycle has varied over the three years in a number of ways (Figure 5.2-3). In terms of bottom-water, temperature was on average much higher in 1994 during the stratified period. The differences between years was most pronounced in the late summer and fall (August to November, ~days 220 to 310), but may have begun as early as May-June (~days 140 to 180). Water temperature influences water and sediment metabolism rates, and this could have contributed to lower DO in 1994.

There has been considerable variability in surface salinity during 1992-1994, and this is most pronounced during the spring runoff period (April-May, ~days 90 to 150). In this respect, 1994 and 1992 were somewhat similar, but 1993 had significantly lower surface salinity (Figure 5.2-4). For the entire summer-fall, there characteristically has been a relatively small difference in salinity between surface and bottom waters. From about June onward, both surface and bottom-water salinity in the nearfield tended to increase slightly in each year of monitoring. The surface-bottom salinity difference generally makes only a minor contribution to density stratification (Figure 5.2-5), which is more regulated by thermal effects on density. From Figure 5.2-5, it is apparent that surface and bottom layers are formed sometime in spring and persist until about October-November. In 1992, stratification appears to have been delayed substantially compared to 1993 and 1994. Earlier stratification could enhance DO depletion in 1993 and 1994 relative to 1992, in part by sealing the bottom water from atmospheric exchange and surface production for a longer period. However, this would not explain fully the DO difference in bottom water between 1993 and 1994 because the timing of the spring initiation of density stratification does not appear to differ strongly between 1993 and 1994. Results in Figure 5.2-5 do not preclude the possibility that there were differences in the details of water column layering (e.g., depths of distinct layers, sharpness of vertical gradients), either in the spring or throughout the summer-fall.

Patterns in chemical parameters. The annual cycles of DIN have shown similar patterns across years (Figure 5.2-6), but there are differences in the timing of separation of DIN concentrations in surface and bottom layers and in the nature of temporal changes in bottom-water concentrations during the stratified period. 1994 stands out as having an early and abrupt distinction between surface and bottom layers (~day 80) in terms of DIN concentrations, a rapid increase in bottom-water DIN concentrations by late April (~day 120), and relatively stable DIN (~6-8 μM) during the summer. Silicate cycles offer an additional perspective

(Figure 5.2-7), for the patterns across years are more dissimilar than DIN. As for DIN, surface and bottom-waters become distinct during stratification, with low SiO_4 concentrations in the surface and enrichment at depth. In 1992 and 1993, silicate was not depleted by a spring bloom, whereas in 1994 it was depleted by April. It is hard to assess the relationship of DIN or SiO_4 with bottom-water DO, but the data seem consistent with the notion of earlier setup of seasonal stratification, especially in 1994 compared to 1992.

Patterns in biological features. There are several indicators of plankton in the monitoring program. These are gathered at different time-space scales, and the trends for 1992-1994 are displayed in Figure 5.2-8 to 5.2-10 for fluorescence (*in situ* sensors, calibrated survey-by-survey to chlorophyll), chlorophyll *a* (extracted measurements at surface and the subsurface chlorophyll maximum), and total phytoplankton cell counts (whole-water samples). Judged by fluorescence (Figure 5.2-8) and confirmed by more limited data on chlorophyll *a* (Figure 5.2-9), the surface layer in 1994 had a mild fall bloom and even milder spring bloom, whereas 1993 had an indistinct spring peak but a strong fall bloom (cf. Kelly and Turner, 1995). In 1992 there were higher peak concentrations in spring and fall blooms than in 1994. Cell counts at the depth of the surface and subsurface chlorophyll maxima display interannual pattern differences similar to those just described (cf. Figures 5.2-8 to 5.2-10). A notable feature in Figure 5.2-10 is the high phytoplankton counts at mid-depth in April 1992; this was a time of sinking of a major bloom of *Phaeocystis pouchetti* (Kelly *et al.*, 1993). Sinking of this bloom may have contributed to a bottom-water depression of DO in late spring 1992, which, while a phenomenon observed as a transient feature each year, was more extreme than observed in subsequent years (cf. Figures 5.2-1 and 5.2-2). However, with respect to chronically lower DO in summer and fall 1994, the compelling result is the lack of any indication that phytoplankton bloom periods or nominal concentrations in the water column during 1994 were unusually high compared to other years. In fact, the opposite seems to be true: plankton concentrations in 1994 were relatively low during the major seasonal bloom periods and similar during most of the summer.

Besides phytoplankton indicators, the concentration of particulate organic carbon (POC) has been measured at the nearfield stations throughout the MWRA monitoring program (Figure 5.2-11). POC measures carbon biomass in plankton, combined with that in seston (detritus). The striking result of comparing 1992 to 1994 results for POC is that 1994 had relatively low POC concentrations. Thus, like the previous plankton indicators, there is no evidence that POC concentrations in 1994 were elevated relative to 1992 and 1993 at any time during the sampling year.

Concentrations are not a perfect indicator of biological activity and carbon flow. To provide an understanding of the carbon supply (as the source for metabolism and DO consumption) from surface to bottom water layers, one would like to have direct measurements of POC settling. Unfortunately, there are technical problems with making direct measurements of POC settling. As a surrogate indicator of the potential strength of carbon supplies from the photic surface layer, net primary production was included in the monitoring program. Net production rates for the nearfield averaged about 1.13 gC m^{-2} d^{-1} (oxygen-based, 6 nearfield stations — Kelly *et al.*, 1993) in 1992 and 2.38 gC m^{-2} d^{-1} (^{14}C-based, six nearfield stations — Kelly and Turner, 1995) in 1993. Results for station N16P in 1994 (^{14}C-based, 12 occupations — this report, Section 3.5) were intermediate to 1992 and 1994, averaging 1.54 gC m^{-2} d^{-1}. Seasonal patterns and annual averages of production rates are difficult to compare with the limited data set (see Kelly and Turner, 1995, for caveats on comparisons of production data), but the available data suggest that peak rates during spring, summer, and fall periods of 1994 were comparable to or less than the same periods in 1992 and 1993. Thus, from all plankton, biomass, and production measures of the monitoring program, there seems no strong evidence that *in situ* organic matter sources for metabolism in 1994 were unusually high over the biologically productive period of the year. Consequently, there appears no directly demonstrable correspondence between plankton activity and low bottom-water DO in 1994.

From the patterns we have summarized for a variety of parameters during 1992-1994, the distinctly low DO in bottom waters during September-November 1994 appear to have more of a physical basis than a biological or biogeochemical basis. The ecological coupling of surface carbon production to bottom layer and sediment metabolism and the resultant DO concentrations in the nearfield of Massachusetts Bay *may be* somewhat weak but *certainly* is imperfectly known (cf. Kelly, 1993). These interannual comparisons (Figures 5.2-1 to 5.2-11) therefore are a valuable addition to the set of information by which to examine the interaction of surface and bottom layers in this seasonally stratified environment. The comparisons suggest that a combination of relatively early initiation of stratification — also persistent and prolonged until at least mid-October — and unusually high summer-fall bottom-water temperatures may be major contributing factors to the DO decline in nearfield bottom waters in 1994.

Conclusions. The inference of a contributing physical basis for lower DO concentrations in 1994 is highly significant for at least two reasons, one serving as a reminder and one serving as a caution. First, the finding reminds us that water quality is structured by the ecosystem, which includes abiotic as well as biotic factors. Metabolism ultimately regulates DO, but the physical setting determines the potential for DO changes. Interpretation of trends over time in Massachusetts Bay must remain attentive to physical-biological-chemical interactions, and significant interactions (relative to water quality) can occur at a great variety of scales. Indeed, the baseline water quality monitoring during 1992 to 1994 has been very successful at elucidating, if not fully explaining, a number of ecological interactions at time scales from tidal to interannual and space scales from less than meters to nearly hundreds of kilometers. At the level of understanding we now have, to dismiss interactions at any of these scales as not relevant to the ecology and water quality of Massachusetts Bay would be folly.

Second, the finding of low bottom-water DO concentrations in 1994 culminates a 1992-1994 trend of progressive decrease in the annual DO minima (Figure 5.2.1 and 5.2-2). Had this period been the initial one after the Bay outfall commissioning, a natural inclination, without compelling alternative evidence, would be to implicate the outfall. This points to the complexity of finding causal signals among the noise of natural variability. Moreover, it should provide the cautionary note on trends, reinvigorating efforts to examine not only the statistical power of the post-discharge monitoring program design to detect future ecosystem change, but also its ability to provide data sufficient for attributing changes properly and compellingly to their causal mechanisms.

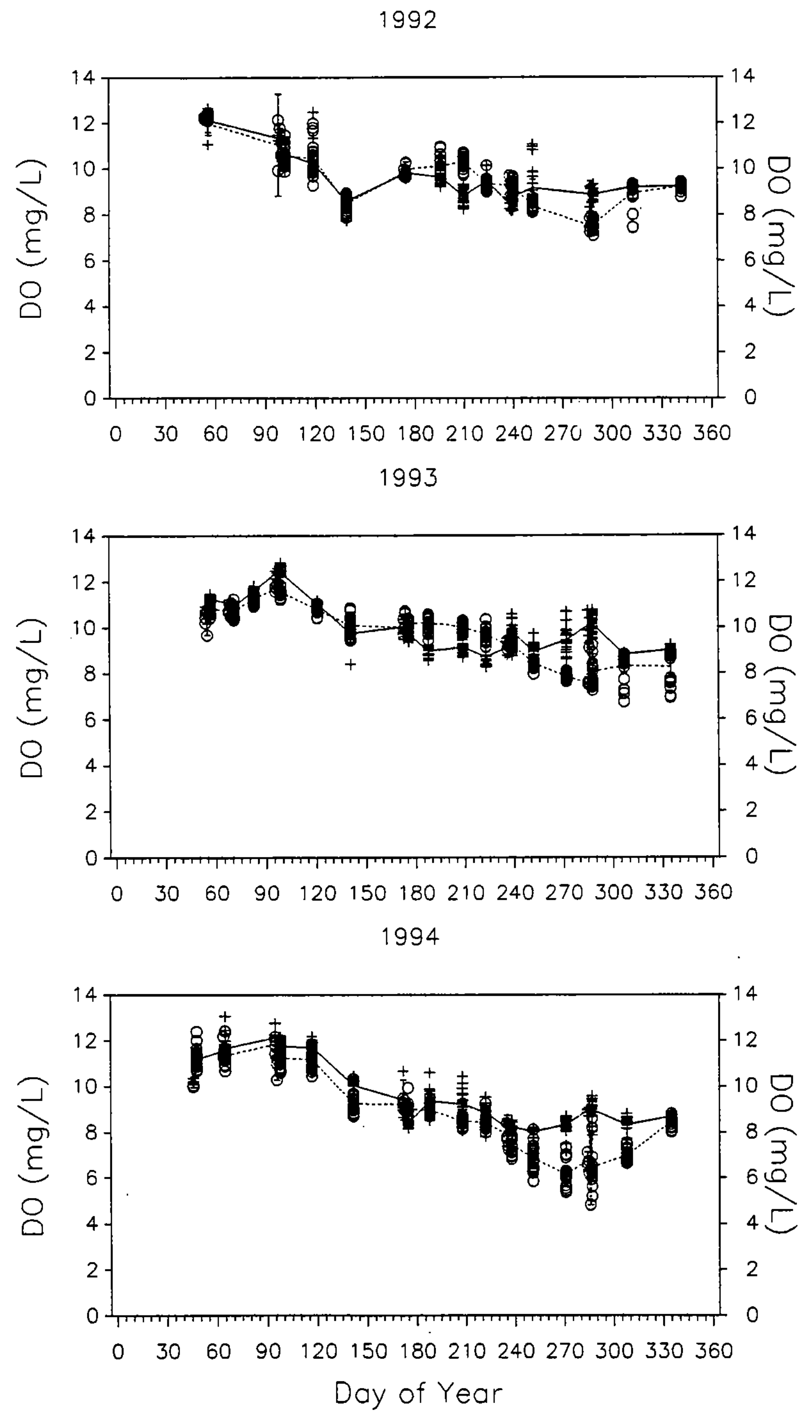


Figure 5.2-1 Comparison of 1992-1994 annual cycles of DO concentrations in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

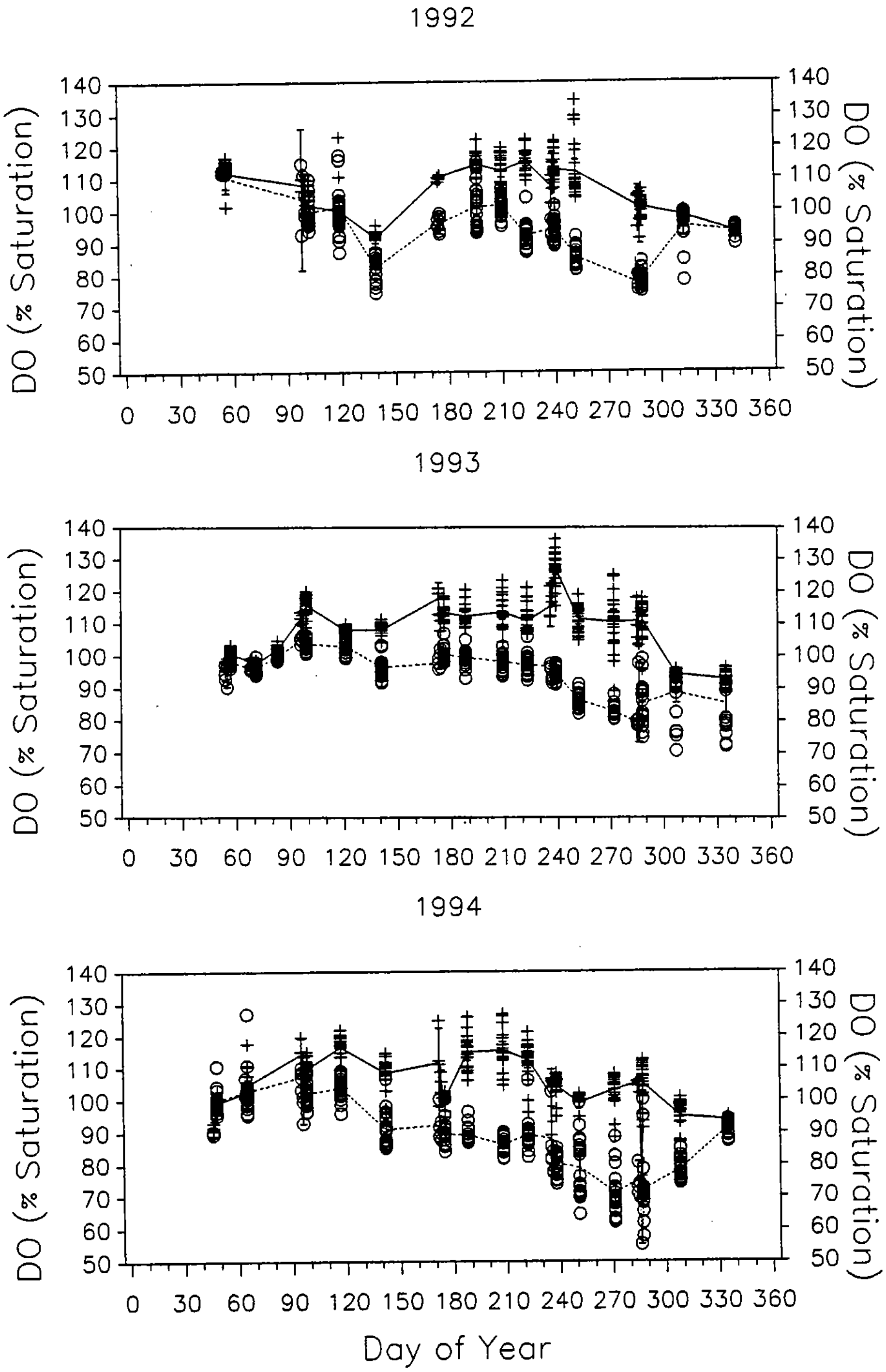


Figure 5.2-2 Comparison of 1992-1994 annual cycles of DO (% saturation) in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

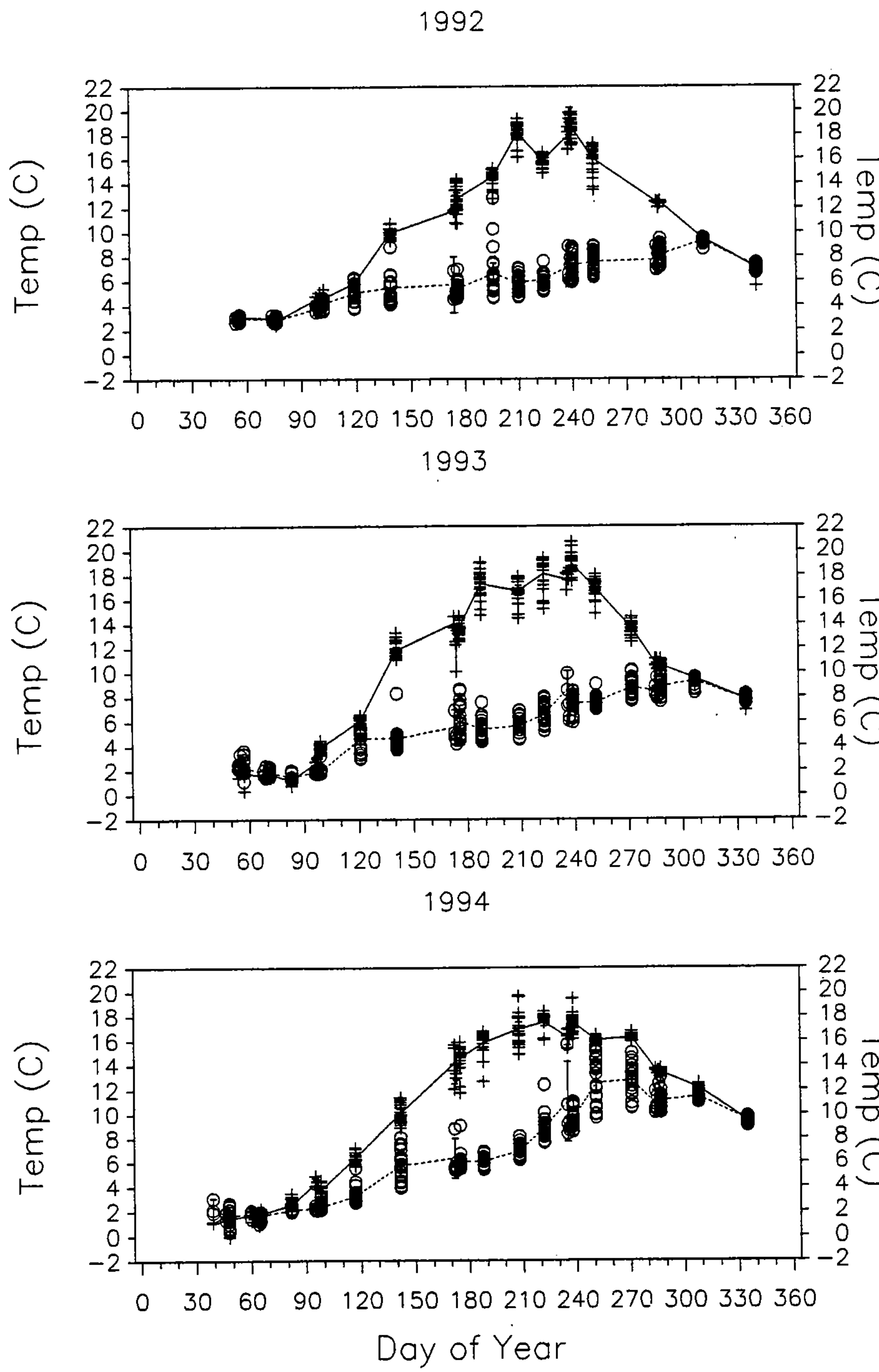


Figure 5.2-3 Comparison of 1992-1994 annual cycles of temperature in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

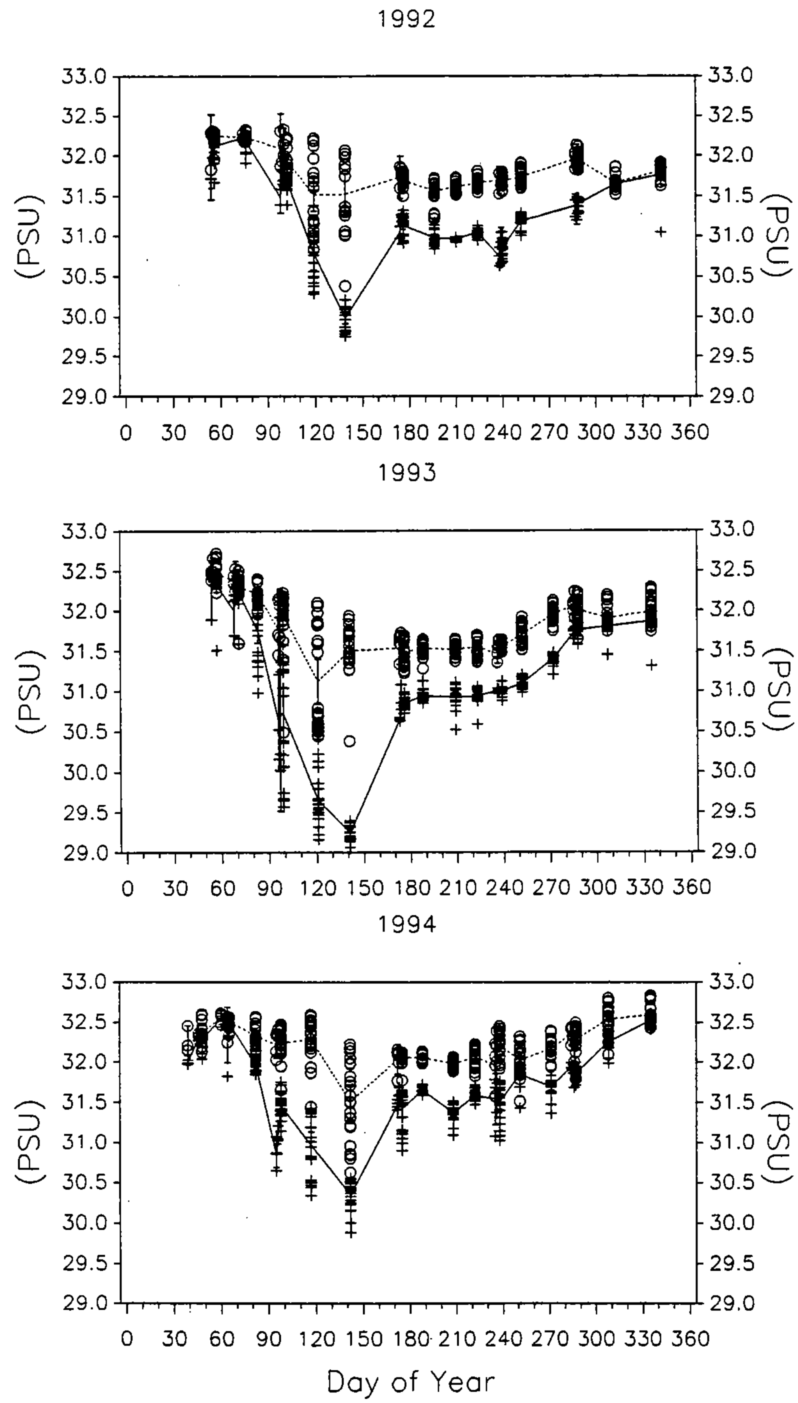


Figure 5.2-4 Comparison of 1992-1994 annual cycles of salinity in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

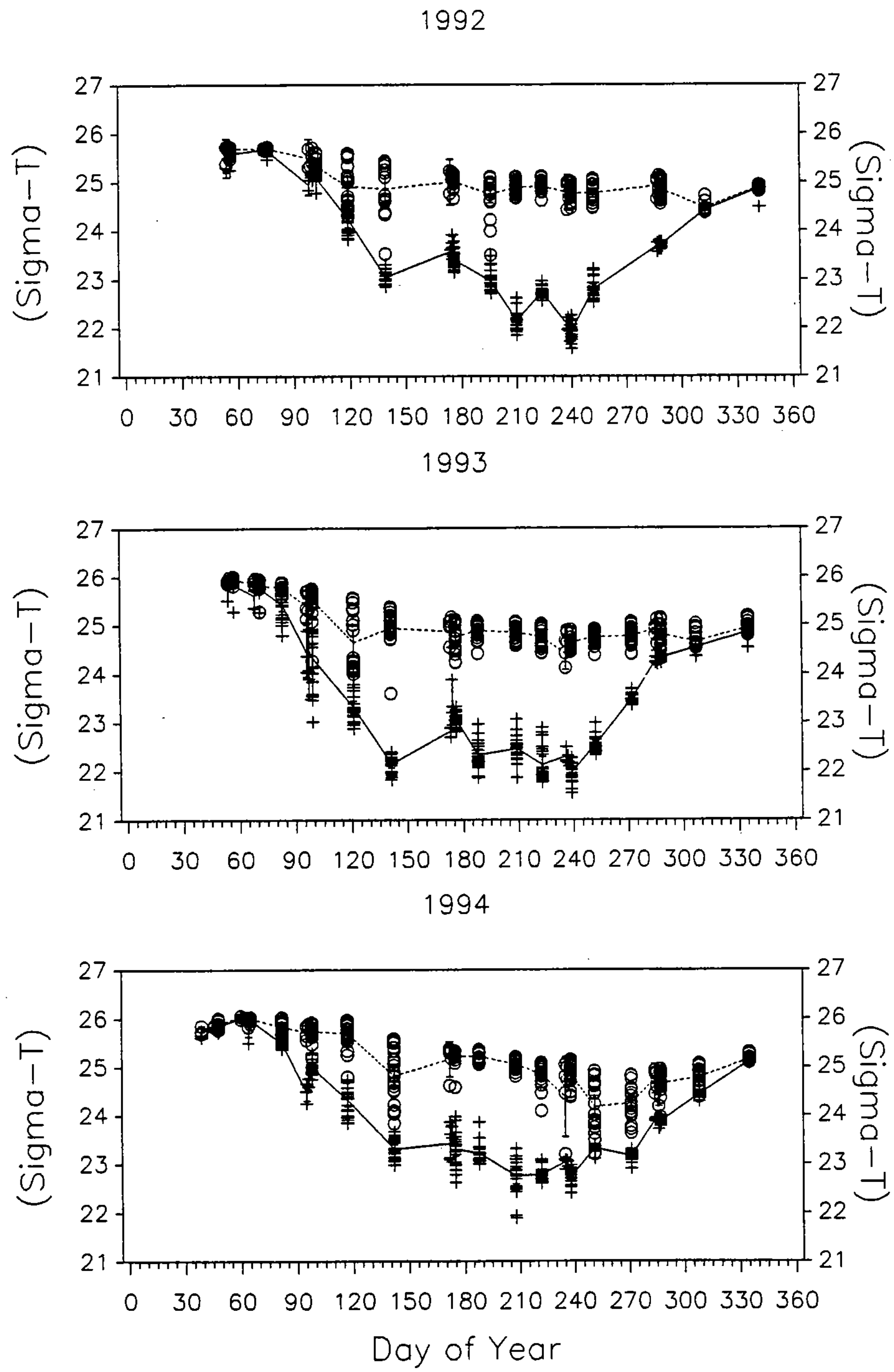


Figure 5.2-5 Comparison of 1992-1994 annual cycles of density in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

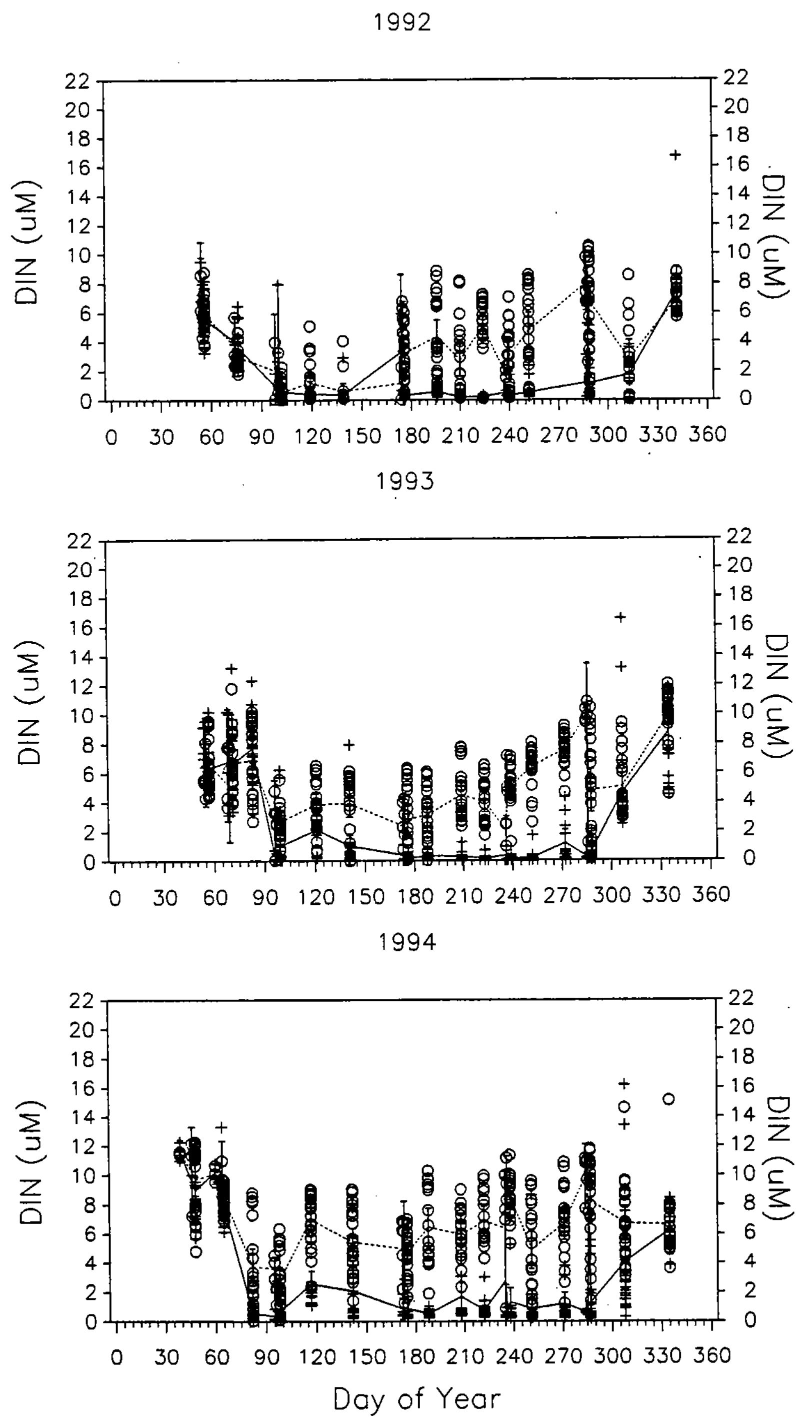


Figure 5.2-6 Comparison of 1992-1994 annual cycles of DIN concentrations in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

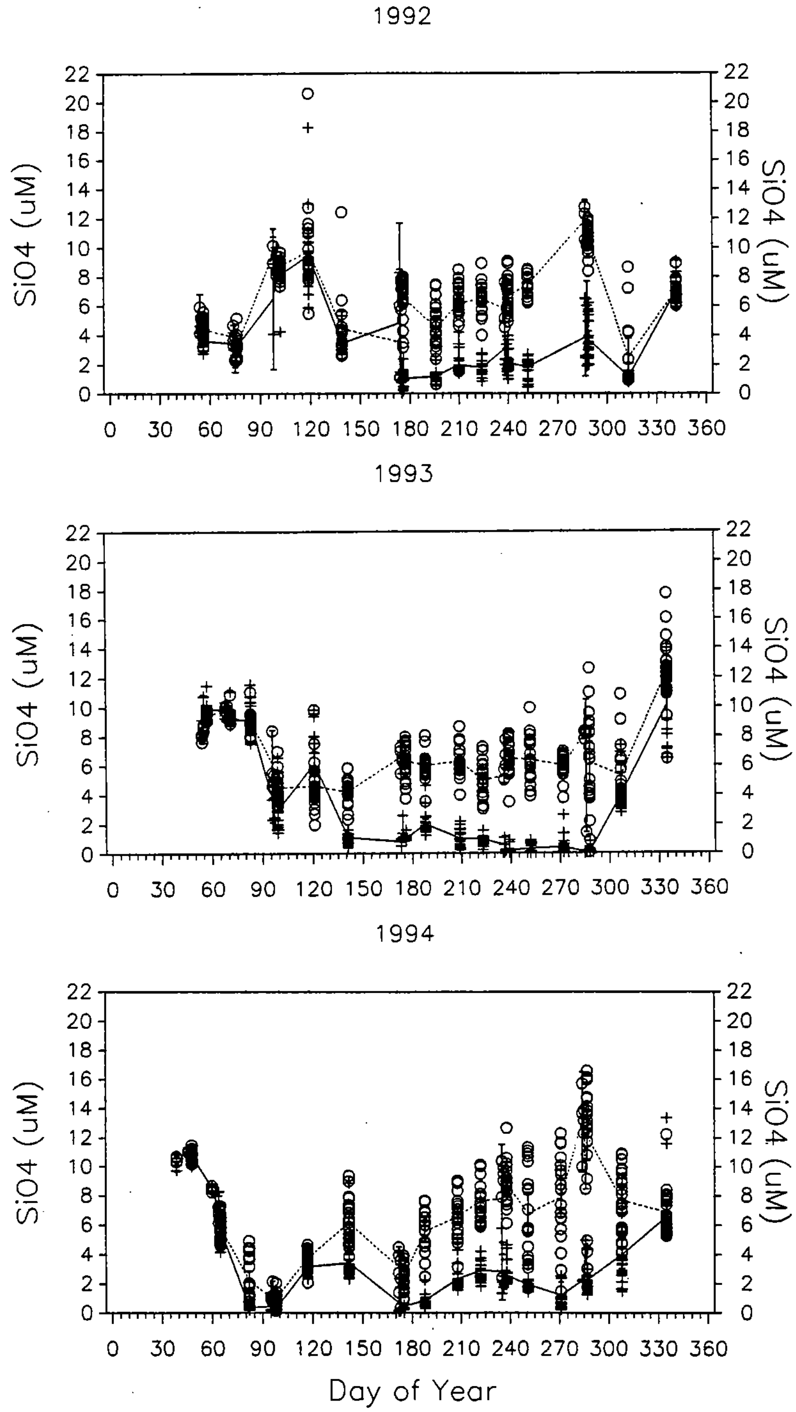


Figure 5.2-7 Comparison of 1992-1994 annual cycles of SiO_4 concentrations in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Bottom data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

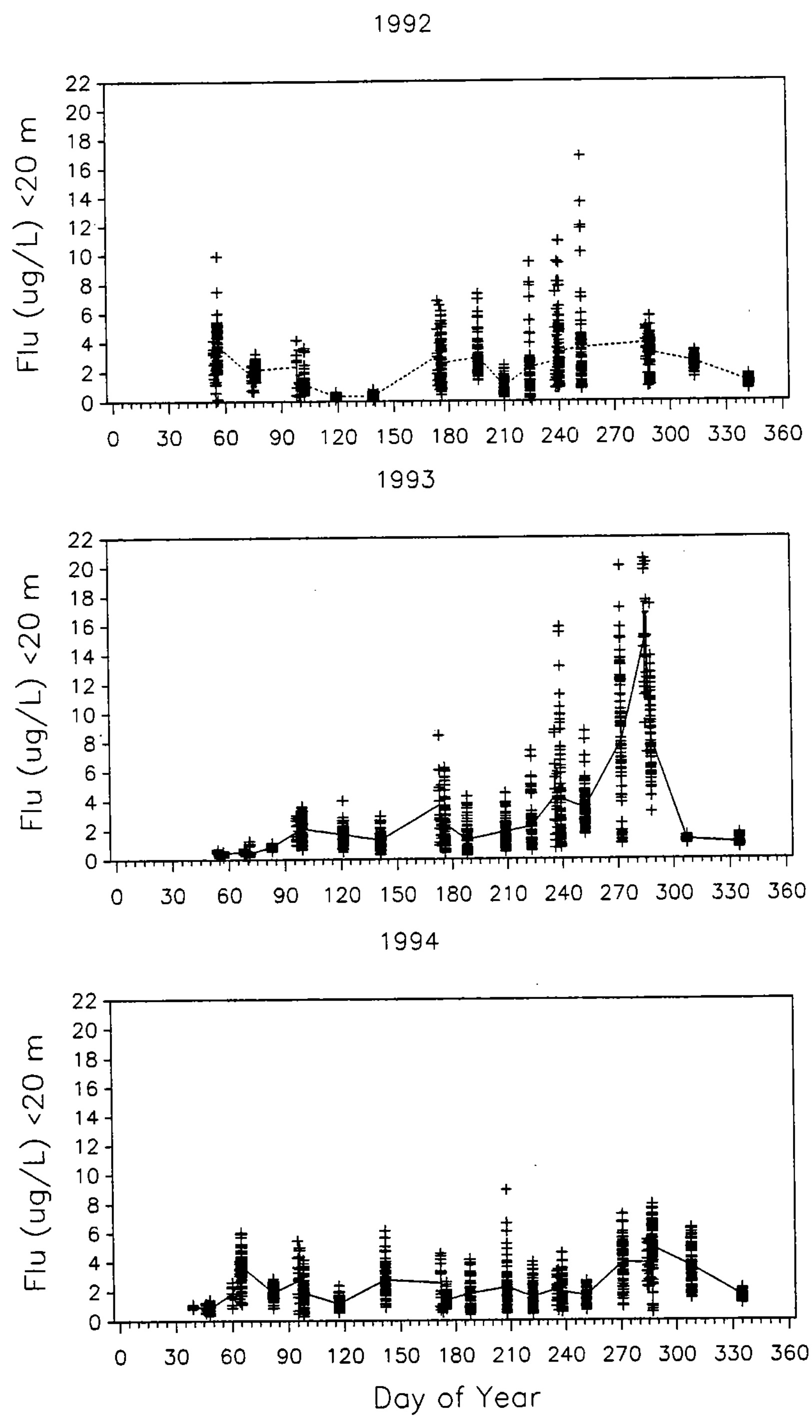


Figure 5.2-8 Comparison of 1992-1994 annual cycles of fluorescence in the nearfield. Surface layer (<20 m) data are represented by the plus (+) symbol and solid lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

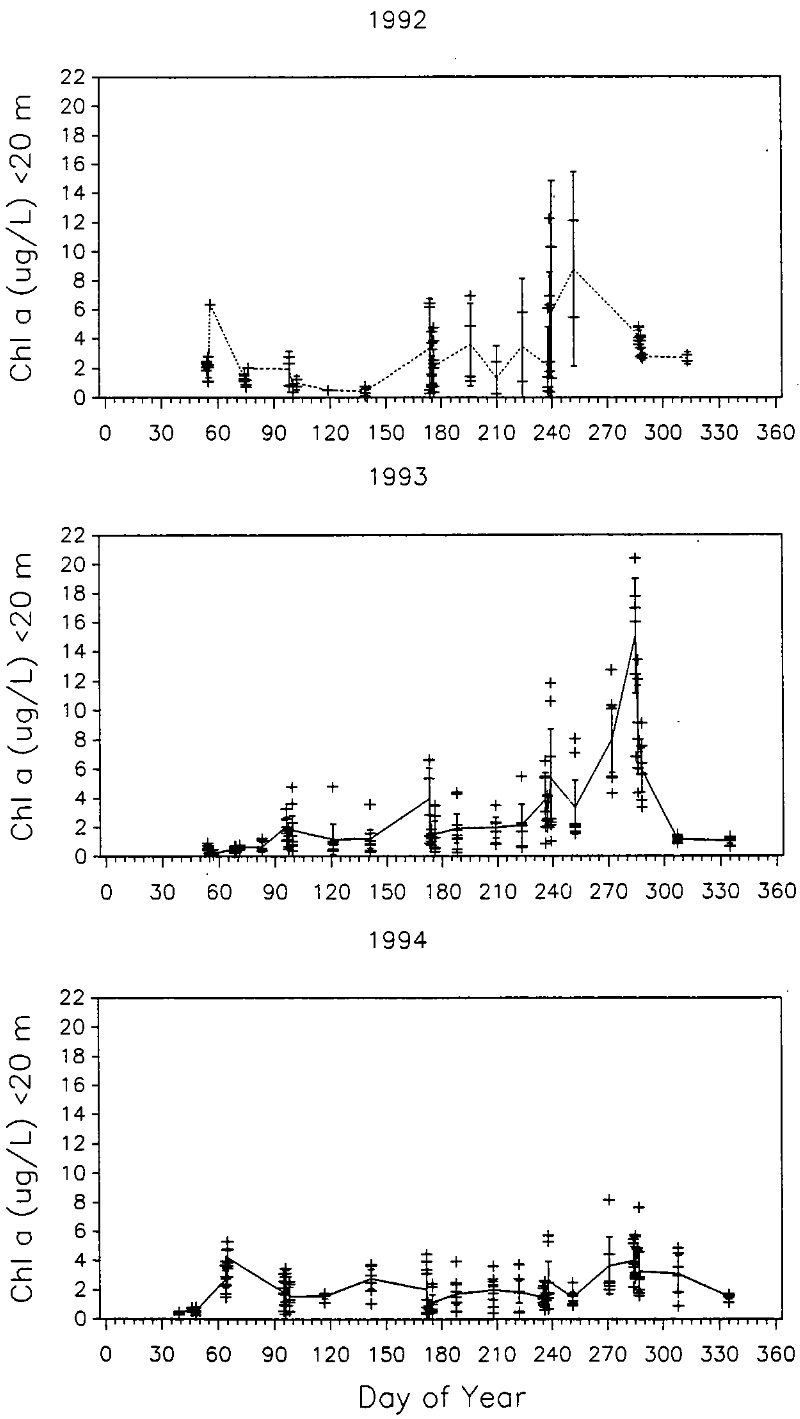


Figure 5.2-9 Comparison of 1992-1994 annual cycles of chlorophyll *a* in the nearfield. Surface layer (<20 m) data are represented by the plus (+) symbol and solid lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

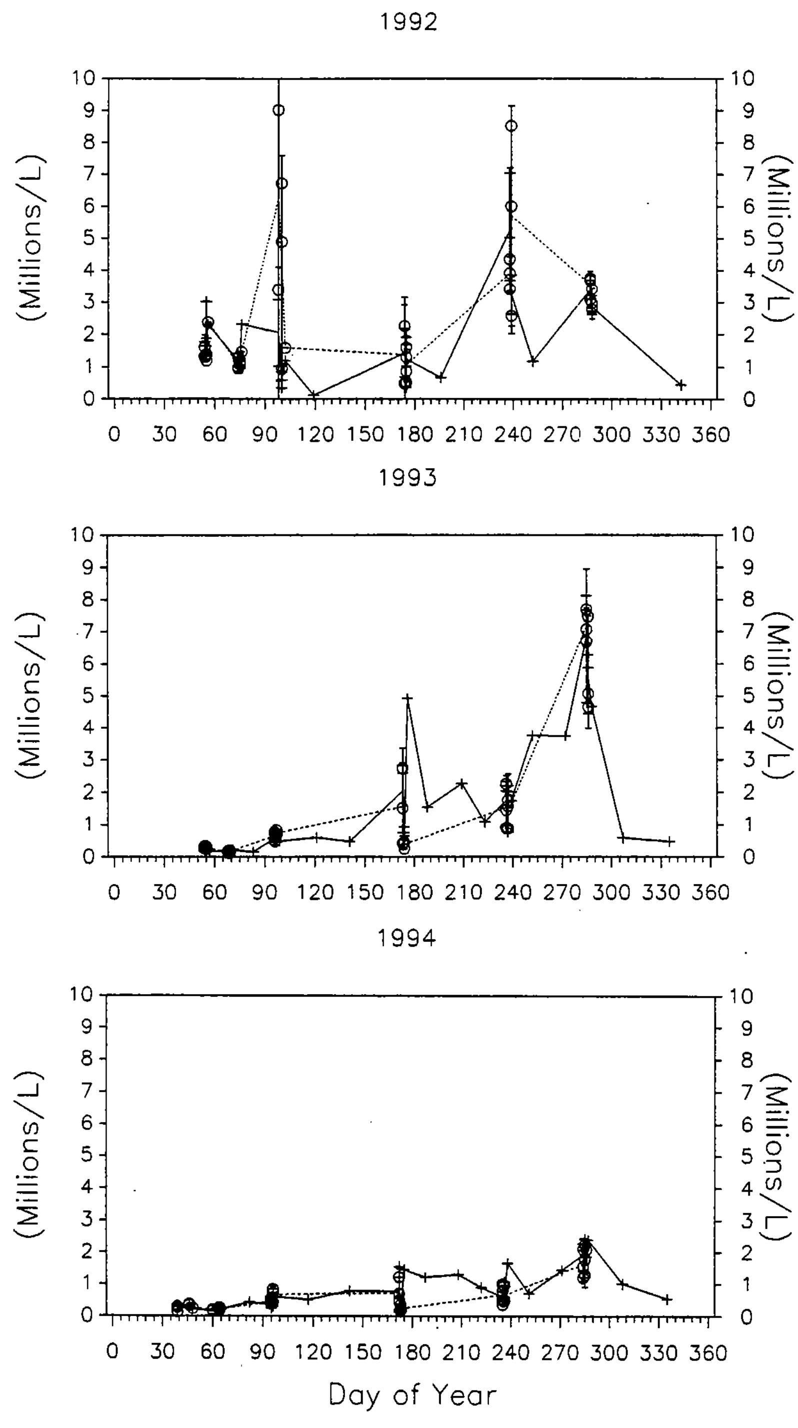


Figure 5.2-10 Comparison of 1992-1994 annual cycles of total phytoplankton abundance in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Chlorophyll maximum data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

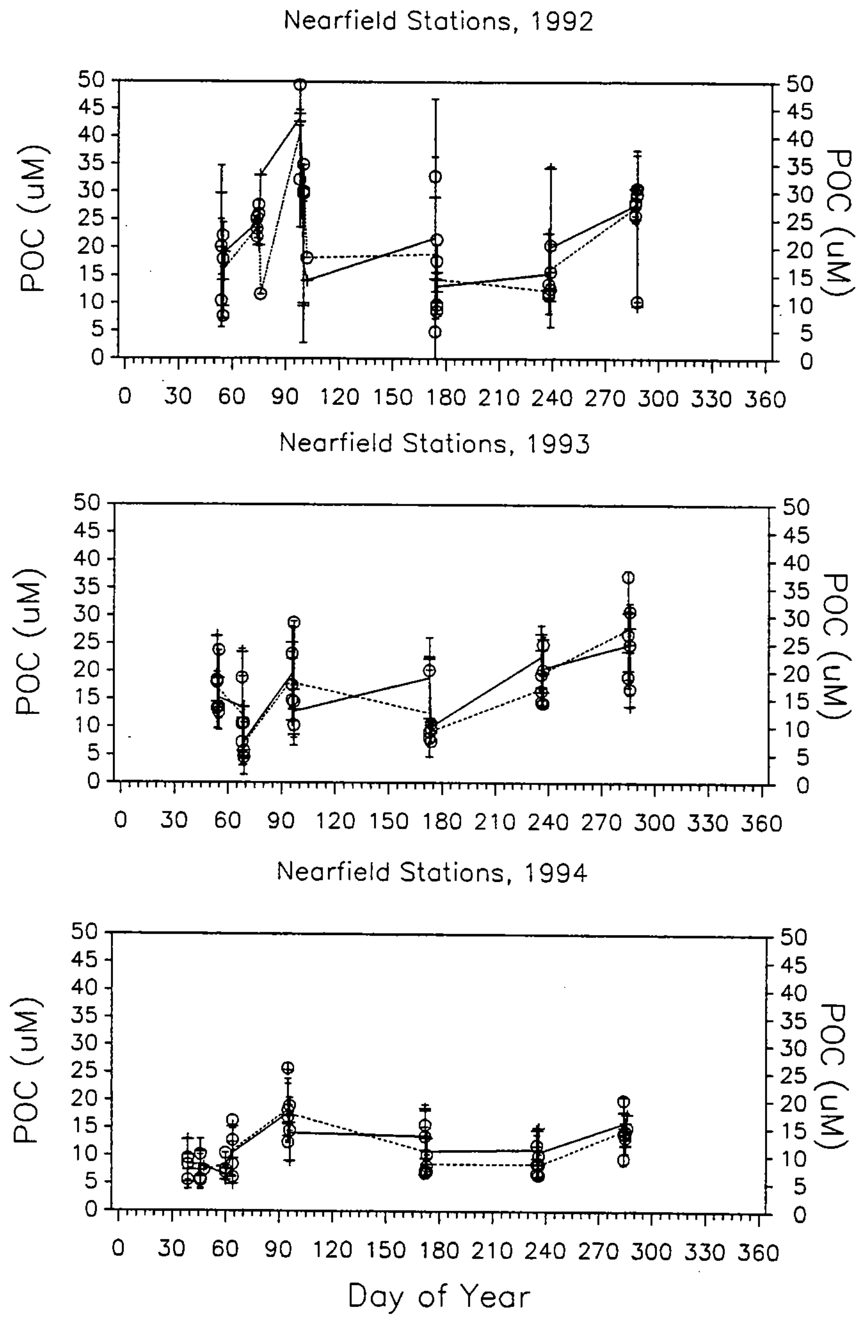


Figure 5.2-11 Comparison of 1992-1994 annual cycles of particulate organic carbon (POC) in the nearfield. Surface data are represented by the plus (+) symbol and solid lines. Chlorophyll maximum data are represented by the circles and dotted lines. Lines pass through mean values for each day of sampling; thus sharp variations within a farfield/nearfield survey (≈3 days) are indicated. Vertical lines with bars indicate ± standard error of the mean.

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APPENDIX

Data Summaries for 1994
Water Column Monitoring in Massachusetts
and Cape Cod Bays

TABLE A-1

Table A-1: Statistics by parameter for farfield surveys in 1994. Data include each visit to six nearfield stations (P stations) during combined farfield/nearfield survey

All Depths in 1994

Variable	N	Mean	Std Dev	Minimum	Maximum
LATITUDE	1131	42.3452357	0.9092412	41.8496700	72.4423300
LONGITUD	1131	-70.6900665	0.1804880	-71.0092000	-70.2277000
DEPTH	1132	17.5008392	17.3885324	0.3100000	104.4800000
JUL_DAY	1132	149.5839223	89.0812077	39.0000000	287.0000000
DAYTIME	1132	0.4822615	0.1385047	0.2300000	0.7900000
TEMP	1132	7.0184284	5.7159695	-1.1310000	18.7380000
SAL	1132	31.8977014	0.5251785	28.0770000	32.9280000
SIGMA_T	1132	24.7935848	1.0402327	20.2750000	26.2070000
TRANS	1132	1.1569136	0.5507797	0.5087200	5.8092400
FLU	1132	2.2716965	1.9950045	0	16.9390000
DO	1044	9.8255268	1.8172696	4.8200000	16.8500000
OXSAT	1044	9.8909557	1.2629838	7.8120408	12.0608223
SATUR	1044	98.9998373	10.6922926	55.2344169	145.1052954
COND	1132	32.5734311	4.7341133	25.0500000	41.9960000
PRES	1132	17.3251148	17.3865126	0.3100000	103.7300000
SURFACE_	1129	1355.52	810.5150526	0.0300000	3551.14
LIGHT	1129	131.5854207	284.1014533	0	3534.95
DEP_CODE	462	2.0000000	1.0010840	1.0000000	3.0000000
REGION	1132	3.0079505	1.4618425	1.0000000	6.0000000
NH4	1130	1.4184159	1.9852373	0	14.7000000
NO3	1132	4.0116784	4.0793268	0	13.5000000
NO2	1130	0.1407434	0.1507301	0	0.9100000
PO4	1130	0.6365487	0.3421424	0	2.8400000
SIO4	1130	5.3068938	4.1623916	0.0100000	16.6600000
CHLA	335	2.2015224	2.1097449	0.0700000	17.6200000
PHA	335	1.4739104	0.7647104	0.4500000	3.9400000
DOC	204	133.3516176	42.2359832	82.5000000	312.9200000
POC	207	14.4032367	7.9665102	3.4000000	56.3900000
PON	207	2.9413527	1.3524785	0.8800000	10.5900000
TDN	206	14.1724272	5.9230141	1.4200000	38.4200000
TDP	206	0.5621359	0.3162390	0.0700000	1.7600000
TSS	183	1.3503005	0.8550340	0.1300000	4.6800000
TOT_PHY	145	0.8698621	0.8037732	0.1200000	3.7000000
NDEPTH	1132	-17.5008392	17.3885324	-104.4800000	-0.3100000
TOTALN	202	17.1302475	6.0999161	4.5400000	42.0100000
DIN	1130	5.5779381	4.8516232	0.0400000	20.5200000
DP	207	8.6428986	5.7014283	2.0100000	24.1100000

File 94fargch.lst

TABLE A-2

TABLE A-2: Means by station for surface water samples based on farfield/nearfield surveys in 1994

1994 Surface - Farfield Surveys

STATION	_TYPE_	_FREQ_	FLU	TRANS	NH4	DIN	PO4	SIO4	PON	TDN	TOTALN
	0	321	2.0361	1.17131	1.17	4.2736	0.54	4.09	2.96	14.30	17.2455
F01P	1	6	2.2916	1.29743	0.42	1.9017	0.45	3.10	3.41	10.27	13.6783
F02P	1	6	3.7279	1.30750	0.31	0.9200	0.29	1.45	3.12	10.25	13.3750
F03	1	6	1.1647	1.28054	0.60	4.0033	0.59	4.54	.	.	.
F05	1	6	1.4518	1.45333	1.11	4.1500	0.54	4.13	.	.	.
F06	1	6	1.5092	1.23481	0.52	3.0683	0.50	3.56	2.83	11.40	14.2333
F07	1	6	0.9328	0.99836	0.44	3.5950	0.52	3.56	.	.	.
F10	1	6	1.1847	0.99087	0.46	3.7150	0.53	3.66	.	.	.
F12	1	6	1.6342	0.98930	0.33	3.5217	0.48	3.74	.	.	.
F13P	1	6	2.6656	1.36590	1.12	4.9500	0.73	4.40	2.79	12.35	15.1350
F14	1	6	3.7441	1.61128	2.06	4.6017	0.50	4.69	.	.	.
F15	1	6	3.6875	1.31122	0.51	2.9483	0.41	3.35	.	.	.
F16	1	6	1.5783	0.91769	1.06	2.0867	0.31	3.36	.	.	.
F17	1	5	1.2336	0.80843	0.40	2.3440	0.32	4.17	.	.	.
F18	1	6	2.0934	1.00572	0.36	4.0500	0.59	4.03	.	.	.
F19	1	6	1.2632	0.83529	0.69	3.0000	0.39	3.67	.	.	.
F22	1	6	1.2372	0.87145	0.32	3.7183	0.45	3.98	.	.	.
F23P	1	12	1.9982	1.79900	5.68	11.4383	0.90	7.61	3.41	22.24	25.6500
F24	1	6	2.3470	1.55322	4.38	9.2883	0.84	5.56	3.69	16.46	20.3833
F25	1	6	2.2654	1.47685	4.07	9.4100	0.90	6.14	3.24	14.65	17.8925
F26	1	6	1.4108	1.15917	0.38	2.8467	0.38	4.45	.	.	.
F27B	1	6	1.1454	0.88238	0.37	3.8033	0.45	3.75	2.19	13.49	15.6767
F28	1	6	1.3344	0.84327	0.28	3.2967	0.46	3.80	.	.	.
F29	1	6	3.1735	1.14447	0.49	3.0483	0.42	3.32	.	.	.
F30B	1	6	3.7346	1.94277	5.63	12.0617	0.77	9.20	4.31	20.76	25.0667
F31B	1	5	3.3754	1.84342	6.14	10.6960	1.04	5.72	3.13	17.94	21.0700
N01P	1	12	2.3917	1.11262	0.39	3.5900	0.67	3.84	2.53	13.42	15.9417
N02	1	6	2.0898	1.07631	0.41	2.3867	0.46	3.38	.	.	.
N03	1	6	1.5596	0.99045	0.27	3.3017	0.52	3.68	.	.	.
N04P	1	12	1.5918	0.94911	0.52	3.0050	0.47	3.94	2.63	14.18	16.6820
N05	1	6	1.2693	0.94083	0.28	2.8033	0.45	3.76	.	.	.
N06	1	6	1.4145	0.91171	0.45	3.2117	0.50	3.83	.	.	.
N07P	1	12	1.2903	0.93119	0.53	3.3900	0.49	3.59	2.44	9.73	12.1733
N08	1	6	1.3952	1.01570	0.26	3.3050	0.49	3.30	.	.	.
N09	1	6	2.0823	1.26429	0.34	2.5700	0.47	3.54	.	.	.
N10P	1	11	3.1313	1.62233	2.69	6.5736	0.78	4.74	3.26	14.91	18.3620
N11	1	6	2.5502	1.33928	2.85	6.0717	0.73	4.52	.	.	.
N12	1	6	2.8115	1.18545	1.44	5.3600	0.65	4.07	.	.	.
N13	1	6	2.1182	1.10255	0.47	2.5850	0.42	3.37	.	.	.
N14	1	6	2.0218	1.04598	0.37	3.4400	0.48	3.34	.	.	.
N15	1	6	1.7260	0.98877	0.46	3.3600	0.48	3.61	.	.	.
N16P	1	18	1.3902	0.93442	0.52	3.8200	0.49	3.73	2.24	12.23	14.4758
N17	1	6	2.0830	0.96896	0.32	2.9233	0.44	3.52	.	.	.
N18	1	6	2.4688	1.07844	0.75	3.0300	0.43	3.31	.	.	.
N19	1	6	2.3022	1.24262	0.51	3.1950	0.48	3.66	.	.	.
N20P	1	12	2.3677	1.23121	0.51	3.1775	0.46	3.48	2.82	10.19	13.0117
N21	1	6	2.4286	1.00718	0.53	3.5283	0.45	3.36	.	.	.

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

From 94farsum.lst

TABLE A-3

TABLE A-3: Selected parameter statistics by all stations, for surface water samples based on combined farfield/nearfield surveys in 1994

1994 Surface - Farfield Surveys

STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
F01P	6	FLU	6	2.2916000	2.7059474	0.5716000	7.5743000
		TRANS	6	1.2974267	0.5067630	0.6474500	2.0457800
		NH4	6	0.4166667	0.4964541	0.1400000	1.4200000
		DIN	6	1.9016667	3.8503840	0.2700000	9.7600000
		PO4	6	0.4483333	0.2642284	0.2200000	0.9000000
		SIO4	6	3.1016667	3.5691815	0.2600000	9.7200000
		PON	6	3.4066667	1.4776829	2.5000000	6.3800000
		TDN	6	10.2716667	3.8090598	6.4600000	16.1300000
		TOTALN	6	13.6783333	3.2612968	9.8800000	18.6300000
F02P	6	FLU	6	3.7279167	3.2277189	0.8365000	8.9373000
		TRANS	6	1.3074950	0.4752128	0.7400500	1.8909700
		NH4	6	0.3050000	0.2821170	0.0700000	0.7700000
		DIN	6	0.9200000	1.3312400	0.1200000	3.5300000
		PO4	6	0.2883333	0.2035109	0.0600000	0.5500000
		SIO4	6	1.4483333	1.3537860	0.2400000	3.3800000
		PON	6	3.1233333	1.0883872	1.8900000	4.3900000
		TDN	6	10.2516667	2.9988892	7.3100000	15.3000000
		TOTALN	6	13.3750000	2.8670595	10.5400000	17.5300000
F03	6	FLU	6	1.1646500	1.0788285	0.3862000	3.2443000
		TRANS	6	1.2805433	0.4471013	0.6942600	1.8438900
		NH4	6	0.5983333	0.9158475	0.1100000	2.4500000
		DIN	6	4.0033333	5.6686036	0.1600000	12.2100000
		PO4	6	0.5850000	0.3234038	0.2300000	1.0400000
		SIO4	6	4.5400000	4.2993860	0.5400000	10.0200000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F05	6	FLU	6	1.4518333	1.4723956	0.3906000	3.9994000
		TRANS	6	1.4533267	0.5051821	0.5748900	1.9338800
		NH4	6	1.1066667	1.3419935	0.1600000	3.3400000
		DIN	6	4.1500000	5.9557737	0.2100000	13.5500000
		PO4	6	0.5350000	0.3309834	0.2500000	1.1100000
		SIO4	6	4.1250000	4.9279438	0.0400000	10.8000000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F06	6	FLU	6	1.5092333	1.5229113	0.4206000	3.8676000
		TRANS	6	1.2348100	0.6503029	0.5439200	2.0569300
		NH4	6	0.5216667	0.5517397	0.1700000	1.6100000
		DIN	6	3.0683333	4.2454748	0.3400000	9.7200000
		PO4	6	0.4950000	0.3381568	0.0500000	0.9600000
		SIO4	6	3.5583333	3.6681626	0.0700000	8.6000000
		PON	6	2.8300000	1.1981653	1.2600000	4.2600000
		TDN	6	11.4033333	3.4865150	6.4600000	15.1200000
		TOTALN	6	14.2333333	3.5059188	8.6700000	18.8500000
F07	6	FLU	6	0.9328333	0.8508768	0	2.1882000

1994 Surface - Farfield Surveys

STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
F07	6	TRANS	6	0.9983583	0.4277642	0.5528800	1.7624500
		NH4	6	0.4383333	0.3340908	0.1600000	1.0400000
		DIN	6	3.5950000	4.8713150	0.2000000	10.2100000
		PO4	6	0.5150000	0.3663195	0.0200000	0.9600000
		SIO4	6	3.5583333	3.7958842	0.0400000	8.4800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F10	6	FLU	6	1.1846500	0.6990581	0.6305000	2.4495000
		TRANS	6	0.9908683	0.5290753	0.5821100	1.9769600
		NH4	6	0.4616667	0.3931115	0.1300000	0.9700000
		DIN	6	3.7150000	5.0249488	0.1500000	10.6800000
		PO4	6	0.5300000	0.3743795	0.0100000	1.0300000
		SIO4	6	3.6600000	4.0648936	0.0800000	9.4600000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F12	6	FLU	6	1.6342167	1.0503460	0.4178000	3.4212000
		TRANS	6	0.9892967	0.5536812	0.6155500	1.9389000
		NH4	6	0.3333333	0.1326147	0.1600000	0.5100000
		DIN	6	3.5216667	4.7734743	0.2700000	10.2200000
		PO4	6	0.4750000	0.3633043	0.0600000	1.0100000
		SIO4	6	3.7416667	3.8716065	0.0700000	9.4600000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F13P	6	FLU	6	2.6655500	1.6928847	0.7816000	5.5002000
		TRANS	6	1.3659017	0.4942108	0.8398600	1.9797400
		NH4	6	1.1216667	1.1695711	0.1700000	3.1200000
		DIN	6	4.9500000	6.1736083	0.3800000	13.9200000
		PO4	6	0.7333333	0.6070475	0.1500000	1.8900000
		SIO4	6	4.4033333	4.5599635	0.2600000	11.0100000
		PON	6	2.7850000	0.9267308	1.6000000	4.0800000
		TDN	6	12.3500000	6.7633749	1.6600000	19.8300000
		TOTALN	6	15.1350000	6.6491075	4.9900000	23.9100000
F14	6	FLU	6	3.7440833	3.0803840	0.5508000	7.4570000
		TRANS	6	1.6112833	0.5363701	0.7467000	2.0586300
		NH4	6	2.0583333	1.8072788	0.1900000	4.1200000
		DIN	6	4.6016667	4.5166156	0.4500000	10.9100000
		PO4	6	0.4950000	0.3201718	0.0600000	0.9300000
		SIO4	6	4.6900000	4.4239123	0.1600000	11.5100000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F15	6	FLU	6	3.6875000	2.6718199	0.6681000	6.8539000
		TRANS	6	1.3112167	0.5345581	0.6823400	1.9300400

1994 Surface - Farfield Surveys

STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
F15	6	NH4	6	0.5066667	0.4322345	0.1000000	1.0700000
		DIN	6	2.9483333	4.2903959	0.1400000	11.0600000
		PO4	6	0.4100000	0.3458323	0	0.9800000
		SIO4	6	3.3466667	3.7695712	0.1000000	9.3000000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F16	6	FLU	6	1.5782500	1.0537766	0.8141000	3.5993000
		TRANS	6	0.9176900	0.2859425	0.6958000	1.4018400
		NH4	6	1.0633333	1.0136995	0.1900000	2.6100000
		DIN	6	2.0866667	2.4042851	0.2300000	5.5500000
		PO4	6	0.3133333	0.1965367	0	0.5200000
		SIO4	6	3.3566667	3.7817597	0.1300000	8.9800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F17	5	FLU	5	1.2336200	0.5483804	0.7439000	2.0197000
		TRANS	5	0.8084300	0.1951752	0.6697300	1.0886300
		NH4	5	0.3980000	0.3285118	0.1300000	0.9300000
		DIN	5	2.3440000	2.9652875	0.1800000	7.3400000
		PO4	5	0.3200000	0.2386420	0.0200000	0.6700000
		SIO4	5	4.1700000	4.3856413	0.1300000	10.2200000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F18	6	FLU	6	2.0934333	1.8478708	0.7514000	5.7560000
		TRANS	6	1.0057183	0.4076861	0.5991100	1.7438400
		NH4	6	0.3600000	0.1964688	0.1800000	0.6400000
		DIN	6	4.0500000	5.2018228	0.3000000	11.1000000
		PO4	6	0.5850000	0.4357866	0	1.1700000
		SIO4	6	4.0250000	4.3468644	0.0900000	10.4400000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F19	6	FLU	6	1.2632167	0.7180791	0.5194000	2.4918000
		TRANS	6	0.8352883	0.2537537	0.5708300	1.2135500
		NH4	6	0.6866667	0.5718275	0.1600000	1.5800000
		DIN	6	3.0000000	4.2993674	0.2800000	11.3900000
		PO4	6	0.3883333	0.3659189	0	1.0600000
		SIO4	6	3.6650000	4.0153991	0.0400000	10.5200000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F22	6	FLU	6	1.2371500	0.8051920	0.3878000	2.2404000
		TRANS	6	0.8714500	0.2327360	0.6260500	1.2562500
		NH4	6	0.3233333	0.2534298	0.0200000	0.7500000

1994 Surface - Farfield Surveys

STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
F22	6	DIN	6	3.7183333	5.3754941	0.1900000	12.4300000
		PO4	6	0.4450000	0.3745264	0.0400000	1.0500000
		SIO4	6	3.9800000	4.4853316	0.1100000	11.5800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F23P	12	FLU	12	1.9981750	1.0368540	0.5005000	3.7864000
		TRANS	12	1.7989958	0.6123993	0.9241800	3.1043300
		NH4	12	5.6841667	3.9905695	0.2000000	13.6400000
		DIN	12	11.4383333	6.9428876	0.3400000	19.3800000
		PO4	12	0.8975000	0.4845077	0.0500000	1.6000000
		SIO4	12	7.6091667	4.5908832	1.7800000	13.9600000
		PON	12	3.4075000	0.9321639	2.2500000	5.7000000
		TDN	12	22.2425000	8.4491174	10.8200000	38.4200000
		TOTALN	12	25.6500000	8.2249697	14.4100000	42.0100000
F24	6	FLU	6	2.3470333	1.5910761	0.7531000	5.3021000
		TRANS	6	1.5532217	0.5274459	0.6590900	2.1385000
		NH4	6	4.3816667	3.8914595	0.9400000	9.3300000
		DIN	6	9.2883333	4.9652771	1.0800000	14.9300000
		PO4	6	0.8383333	0.4055326	0.2900000	1.3100000
		SIO4	6	5.5566667	3.8854944	0.4000000	10.5400000
		PON	3	3.6900000	0.7133723	3.0200000	4.4400000
		TDN	4	16.4575000	5.0461693	9.7800000	21.5700000
		TOTALN	3	20.3833333	5.6063565	14.2200000	25.1800000
F25	6	FLU	6	2.2653667	1.3433879	0.4844000	3.9537000
		TRANS	6	1.4768517	0.4827032	0.8719100	2.1834100
		NH4	6	4.0733333	3.1358486	0.4300000	9.2500000
		DIN	6	9.4100000	6.1578275	1.1800000	17.5900000
		PO4	6	0.9016667	0.3243095	0.4200000	1.2300000
		SIO4	6	6.1400000	4.0019345	1.2900000	11.8000000
		PON	4	3.2400000	0.4169732	2.8000000	3.7200000
		TDN	4	14.6525000	3.2702128	11.5700000	19.1600000
		TOTALN	4	17.8925000	2.9396868	15.0100000	21.9600000
F26	6	FLU	6	1.4108167	0.8953872	0.5230000	2.9908000
		TRANS	6	1.1591717	0.4240337	0.6720400	1.8479000
		NH4	6	0.3833333	0.2378795	0.2300000	0.8600000
		DIN	6	2.8466667	4.4511107	0.3300000	11.4800000
		PO4	6	0.3816667	0.2512701	0.1200000	0.8400000
		SIO4	6	4.4450000	4.6852353	0.3100000	12.6500000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F27B	6	FLU	6	1.1454333	0.5972843	0.5229000	1.8637000
		TRANS	6	0.8823800	0.1623046	0.6264700	1.1313300
		NH4	6	0.3716667	0.1511842	0.2000000	0.6100000
		DIN	6	3.8033333	5.6751023	0.3800000	14.0100000

1994 Surface - Farfield Surveys

STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
F27B	6	PO4	6	0.4533333	0.3754286	0.0800000	1.0800000
		SIO4	6	3.7466667	4.1738312	0.0800000	10.5800000
		PON	6	2.1900000	0.6357987	1.3000000	3.2400000
		TDN	6	13.4866667	2.7002494	9.1800000	16.2800000
		TOTALN	6	15.6766667	2.6177369	11.4200000	18.2700000
F28	6	FLU	6	1.3344167	0.8918960	0.3998000	2.6448000
		TRANS	6	0.8432650	0.3113637	0.5814700	1.4044800
		NH4	6	0.2750000	0.1061603	0.1700000	0.4400000
		DIN	6	3.2966667	4.3755487	0.3800000	10.6500000
		PO4	6	0.4583333	0.3301767	0.0700000	0.9800000
		SIO4	6	3.8016667	3.8735587	0.1400000	9.6600000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F29	6	FLU	6	3.1735167	1.8595921	0.6424000	5.1694000
		TRANS	6	1.1444700	0.4548249	0.5087200	1.8764200
		NH4	6	0.4883333	0.3460299	0.1300000	1.1000000
		DIN	6	3.0483333	3.6524480	0.2700000	8.4800000
		PO4	6	0.4166667	0.3336865	0.1300000	0.8800000
		SIO4	6	3.3216667	2.4838149	0.5900000	7.2600000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
F30B	6	FLU	6	3.7345500	3.9582605	0.7252000	10.8167000
		TRANS	6	1.9427733	0.7440215	1.2086100	3.3092300
		NH4	6	5.6266667	5.0650160	0.2600000	13.7300000
		DIN	6	12.0616667	7.4978941	0.3300000	20.1500000
		PO4	6	0.7666667	0.5686358	0.1600000	1.5400000
		SIO4	6	9.1983333	5.4948464	0.6700000	15.8100000
		PON	6	4.3066667	2.8803796	2.1900000	9.4300000
		TDN	6	20.7600000	6.0291326	9.3800000	27.3300000
		TOTALN	6	25.0666667	3.7258109	18.8100000	29.5200000
F31B	5	FLU	5	3.3753600	2.0115132	1.0139000	6.5906000
		TRANS	5	1.8434220	0.7971792	1.0376300	2.9103000
		NH4	5	6.1380000	4.8430383	2.8600000	14.7000000
		DIN	5	10.6960000	6.2584926	4.1000000	19.9800000
		PO4	5	1.0360000	0.3984093	0.4600000	1.5200000
		SIO4	5	5.7200000	3.2815926	1.9000000	9.7500000
		PON	5	3.1340000	1.4126146	1.2300000	4.7700000
		TDN	5	17.9360000	4.6937544	12.3200000	25.1600000
		TOTALN	5	21.0700000	5.0234002	15.5500000	29.2900000
N01P	12	FLU	12	2.3917000	1.8732091	0.5767000	6.4144000
		TRANS	12	1.1126183	0.4540673	0.6665000	1.9678200
		NH4	12	0.3900000	0.2202891	0.0500000	0.7600000
		DIN	12	3.5900000	4.5784237	0.0800000	11.6500000
		PO4	12	0.6666667	0.7297737	0	2.8400000

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STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
N01P	12	SIO4	12	3.8425000	4.0042594	0.1300000	10.9600000
		PON	6	2.5250000	1.0774182	0.8800000	3.7600000
		TDN	6	13.4166667	5.6157623	4.2500000	17.8900000
		TOTALN	6	15.9416667	5.6308274	7.0800000	21.6500000
N02	6	FLU	6	2.0897833	1.4259478	0.9499000	4.6067000
		TRANS	6	1.0763100	0.4293884	0.6768600	1.7496800
		NH4	6	0.4066667	0.1955164	0.2200000	0.7600000
		DIN	6	2.3866667	3.0533173	0.2800000	6.4500000
		PO4	6	0.4583333	0.1092551	0.3500000	0.5900000
		SIO4	6	3.3816667	4.0354203	0.2700000	11.0600000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N03	6	FLU	6	1.5596000	0.6443931	0.8726000	2.4608000
		TRANS	6	0.9904467	0.3681089	0.6709900	1.5630000
		NH4	6	0.2733333	0.1388044	0.0600000	0.4000000
		DIN	6	3.3016667	4.4609793	0.3000000	9.5500000
		PO4	6	0.5216667	0.2132995	0.3300000	0.8300000
		SIO4	6	3.6766667	4.2313528	0.2200000	11.0900000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N04P	12	FLU	12	1.5918167	1.2018780	0.4735000	4.3446000
		TRANS	12	0.9491067	0.3187471	0.6362600	1.6856900
		NH4	12	0.5208333	0.5936399	0.0900000	2.3300000
		DIN	12	3.0050000	3.9124591	0.1300000	9.9500000
		PO4	12	0.4725000	0.2602490	0	0.9100000
		SIO4	12	3.9358333	4.2508533	0.2200000	11.2200000
		PON	5	2.6280000	1.2071537	1.2300000	3.9700000
		TDN	6	14.1766667	2.2347766	11.3100000	16.3700000
		TOTALN	5	16.6820000	2.7104557	13.2300000	20.3400000
N05	6	FLU	6	1.2692500	0.7476979	0.4506000	2.3701000
		TRANS	6	0.9408283	0.3847948	0.6352700	1.6350400
		NH4	6	0.2766667	0.1367723	0.1500000	0.5300000
		DIN	6	2.8033333	3.8752376	0.2000000	8.7700000
		PO4	6	0.4516667	0.1869135	0.2700000	0.7600000
		SIO4	6	3.7633333	4.3617229	0.1500000	11.2300000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N06	6	FLU	6	1.4144833	1.3318693	0.5202000	4.0419000
		TRANS	6	0.9117050	0.3792702	0.6188400	1.6400000
		NH4	6	0.4450000	0.2829664	0.2200000	1.0100000
		DIN	6	3.2116667	4.1480859	0.2400000	9.2100000
		PO4	6	0.4966667	0.2212389	0.2700000	0.8000000
		SIO4	6	3.8250000	4.3805879	0.1200000	11.1500000

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STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
N06	6	PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N07P	12	FLU	12	1.2902500	0.8185257	0.5825000	3.4191000
		TRANS	12	0.9311867	0.3473987	0.6024700	1.8056300
		NH4	12	0.5333333	0.3741495	0.1100000	1.1500000
		DIN	12	3.3900000	4.3923777	0.1700000	10.9600000
		PO4	12	0.4900000	0.2766685	0.0400000	1.0000000
		SIO4	12	3.5908333	3.9544393	0.1200000	10.7800000
		PON	6	2.4400000	0.7063427	1.4600000	3.4200000
		TDN	6	9.7333333	3.3646733	6.2600000	14.7900000
		TOTALN	6	12.1733333	3.3690691	8.5200000	16.7000000
N08	6	FLU	6	1.3951833	1.3225186	0.3603000	3.8620000
		TRANS	6	1.0157033	0.5717610	0.5709600	2.1228600
		NH4	6	0.2583333	0.1538072	0.1100000	0.4700000
		DIN	6	3.3050000	4.9219783	0.1600000	11.4100000
		PO4	6	0.4866667	0.3096880	0.2500000	1.0100000
		SIO4	6	3.2950000	3.9978732	0.1100000	10.4100000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N09	6	FLU	6	2.0823000	1.9489583	0.3657000	5.5717000
		TRANS	6	1.2642850	0.6021739	0.6513200	2.2172700
		NH4	6	0.3433333	0.1652473	0.2100000	0.6400000
		DIN	6	2.5700000	3.2884464	0.2700000	7.7400000
		PO4	6	0.4666667	0.1242041	0.3200000	0.6800000
		SIO4	6	3.5350000	3.9530634	0.2300000	10.4700000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N10P	11	FLU	11	3.1313182	1.5168300	0.6757000	5.5231000
		TRANS	11	1.6223318	0.3889754	0.9304300	2.1313600
		NH4	11	2.6900000	1.7715417	0.2800000	6.4900000
		DIN	11	6.5736364	3.8383467	0.3800000	13.3100000
		PO4	11	0.7754545	0.3101730	0	1.1200000
		SIO4	11	4.7436364	2.9831067	1.1100000	10.5100000
		PON	6	3.2566667	1.1216714	2.2900000	5.1200000
		TDN	5	14.9120000	4.1524535	11.8500000	20.5600000
		TOTALN	5	18.3620000	3.5619545	14.6500000	22.8900000
N11	6	FLU	6	2.5501833	1.0922732	0.7245000	3.6402000
		TRANS	6	1.3392750	0.3504406	0.8912200	1.7537600
		NH4	6	2.8483333	1.7048333	1.1200000	5.3900000
		DIN	6	6.0716667	2.4056551	2.2400000	8.4800000
		PO4	6	0.7266667	0.2186016	0.3200000	0.9000000
		SIO4	6	4.5200000	3.4151427	0.6300000	10.2900000
		PON	0	.	.	.	.

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STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
N11	6	TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N12	6	FLU	6	2.8114500	1.5129784	1.2002000	4.8609000
		TRANS	6	1.1854533	0.4388266	0.7064300	1.6887500
		NH4	6	1.4366667	1.3955596	0.3900000	4.1700000
		DIN	6	5.3600000	3.9421872	1.5200000	12.1600000
		PO4	6	0.6466667	0.2463872	0.2900000	1.0000000
		SIO4	6	4.0733333	3.6700391	0.4300000	10.4800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N13	6	FLU	6	2.1182167	2.3948891	0.4686000	6.8326000
		TRANS	6	1.1025533	0.5300132	0.6738900	2.0850900
		NH4	6	0.4650000	0.6171791	0.1000000	1.7100000
		DIN	6	2.5850000	3.6380970	0.2100000	8.2900000
		PO4	6	0.4183333	0.2705119	0.0800000	0.8200000
		SIO4	6	3.3650000	3.7645916	0.2700000	10.3100000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N14	6	FLU	6	2.0217667	1.7897694	0.5631000	5.1607000
		TRANS	6	1.0459767	0.4713762	0.6529200	1.9276500
		NH4	6	0.3716667	0.2715450	0.0700000	0.8400000
		DIN	6	3.4400000	4.9987278	0.1800000	11.6900000
		PO4	6	0.4800000	0.3404703	0.1100000	1.0300000
		SIO4	6	3.3416667	3.7661302	0.2300000	9.9800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N15	6	FLU	6	1.7259667	1.5120002	0.6125000	4.5837000
		TRANS	6	0.9887717	0.4262599	0.6665000	1.7916300
		NH4	6	0.4550000	0.3659918	0.0300000	1.1200000
		DIN	6	3.3600000	4.5608113	0.0900000	11.1500000
		PO4	6	0.4800000	0.3186848	0.1100000	0.9400000
		SIO4	6	3.6066667	4.1815244	0.2100000	10.8700000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N16P	18	FLU	18	1.3901556	1.1455470	0.4827000	5.0326000
		TRANS	18	0.9344211	0.3517103	0.6089300	1.8444500
		NH4	18	0.5177778	0.5338380	0.0300000	1.9800000
		DIN	18	3.8200000	4.9085148	0.0800000	11.6700000
		PO4	18	0.4927778	0.3401004	0	1.0300000
		SIO4	18	3.7327778	4.0455797	0.1200000	11.1000000
		PON	12	2.2416667	0.6746559	0.9700000	3.0100000
		TDN	12	12.2341667	4.2576849	5.0900000	19.3900000

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STATION	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
N16P	18	TOTALN	12	14.4758333	4.1766090	6.9000000	21.5800000
N17	6	FLU	6	2.0830333	2.2919999	0.3227000	6.1966000
		TRANS	6	0.9689550	0.5152033	0.5489500	1.9486800
		NH4	6	0.3166667	0.1677697	0.0800000	0.5000000
		DIN	6	2.9233333	3.9967470	0.1500000	8.1700000
		PO4	6	0.4416667	0.2290342	0.1400000	0.7600000
		SIO4	6	3.5200000	4.1625089	0.1100000	10.7600000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N18	6	FLU	6	2.4687833	2.5314084	0.4479000	6.7784000
		TRANS	6	1.0784400	0.5598757	0.6961700	2.1707000
		NH4	6	0.7483333	1.0495031	0.0900000	2.8600000
		DIN	6	3.0300000	4.1224119	0.1500000	9.1700000
		PO4	6	0.4316667	0.2595702	0.0500000	0.7300000
		SIO4	6	3.3083333	4.0513919	0.1400000	10.6500000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N19	6	FLU	6	2.3021833	2.0495038	0.4456000	6.1898000
		TRANS	6	1.2426167	0.5615275	0.7723200	2.1384400
		NH4	6	0.5100000	0.2587663	0.1000000	0.8700000
		DIN	6	3.1950000	3.6191201	0.1500000	7.9600000
		PO4	6	0.4800000	0.2804282	0.0400000	0.7500000
		SIO4	6	3.6600000	3.8921048	0.1900000	10.4800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.
N20P	12	FLU	12	2.3676583	1.7336990	0.3865000	6.5077000
		TRANS	12	1.2312142	0.5019860	0.6910500	2.0893600
		NH4	12	0.5100000	0.4962770	0.1100000	1.9400000
		DIN	12	3.1775000	4.2617434	0.2100000	12.2600000
		PO4	12	0.4616667	0.2792143	0.0800000	1.0000000
		SIO4	12	3.4775000	3.8173006	0.1000000	10.6200000
		PON	6	2.8216667	0.8098251	2.0600000	4.1400000
		TDN	6	10.1900000	4.3120204	2.4200000	15.7400000
		TOTALN	6	13.0116667	4.3958681	4.7100000	17.8000000
N21	6	FLU	6	2.4285667	2.3188107	0.5470000	6.3606000
		TRANS	6	1.0071817	0.4876014	0.6499100	1.9634300
		NH4	6	0.5266667	0.5919347	0.0900000	1.7000000
		DIN	6	3.5283333	4.6418592	0.1800000	11.2100000
		PO4	6	0.4450000	0.3359613	0.0800000	0.9800000
		SIO4	6	3.3583333	3.8717408	0.2700000	10.2800000
		PON	0	.	.	.	.
		TDN	0	.	.	.	.
		TOTALN	0	.	.	.	.

TABLE A-4

Table A-4: Selected parameter statistics by all nearfield stations

for surface water samples based on all 1994 surveys

Parameter means for nearfield surface water

STATION=N01P

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	22	3.1131818	3.8297487	0.0700000	11.6500000
NH4	22	0.5968182	0.5507431	0.0500000	2.5500000
FLU	22	2.4447773	1.8136447	0.5767000	7.2478000

STATION=N02

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	1.8668750	2.3810298	0.2300000	6.4500000
NH4	16	0.4025000	0.2349610	0.1900000	1.1200000
FLU	16	2.0905625	1.3564442	0.7568000	5.1959000

STATION=N03

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	2.1218750	3.1261035	0.3000000	9.5500000
NH4	16	0.3631250	0.1793216	0.0600000	0.6500000
FLU	16	1.8277188	1.0119003	0.6998000	4.1175000

STATION=N04P

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	22	2.1627273	3.1979773	0.0400000	9.9500000
NH4	22	0.4472727	0.4597844	0.0400000	2.3300000
FLU	22	1.7315045	1.1883261	0.4735000	4.3962000

STATION=N05

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	1.7068750	2.7701714	0.2000000	8.7700000
NH4	16	0.2887500	0.1676455	0.1000000	0.6300000
FLU	16	1.6223250	1.3216014	0.4506000	5.6231000

Parameter means for nearfield surface water

STATION=N06

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	1.9056250	2.9000298	0.2400000	9.2100000
NH4	16	0.3806250	0.2092038	0.1800000	1.0500000
FLU	16	1.3535125	0.9383333	0.4137000	3.8301000

STATION=N07P

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	22	2.3359091	3.5639714	0.1100000	10.9600000
NH4	22	0.4454545	0.3232974	0.1000000	1.1500000
FLU	22	1.2715227	0.7701575	0.4400000	3.4191000

STATION=N08

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	2.4906250	3.5934653	0.1500000	11.4100000
NH4	16	0.5443750	0.8136663	0.1100000	3.4300000
FLU	16	1.5559500	0.9850186	0.3603000	3.8620000

STATION=N09

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	2.5200000	2.7493611	0.2400000	7.7400000
NH4	16	0.6112500	0.7133290	0.1000000	2.6300000
FLU	16	2.0491563	1.4463485	0.3657000	5.5717000

STATION=N10P

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	21	6.4761905	4.1748670	0.1800000	16.2000000
NH4	21	3.2709524	2.3054607	0.1800000	7.7200000
FLU	21	2.7563238	1.3847976	0.6757000	5.5231000

Parameter means for nearfield surface water

STATION=N11

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	5.4400000	3.4599807	0.8600000	13.4200000
NH4	16	2.8875000	1.9541699	0.6300000	6.1500000
FLU	16	2.4404000	1.2330657	0.7245000	4.9330000

STATION=N12

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	4.0725000	3.5324373	0.2700000	12.1600000
NH4	16	1.5100000	1.5493483	0.1700000	4.5200000
FLU	16	2.8854125	1.7735328	1.1266000	6.7432000

STATION=N13

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	15	1.9040000	2.5967832	0.2100000	8.2900000
NH4	15	0.4793333	0.4907206	0.1000000	1.7100000
FLU	15	2.3053600	2.0438165	0.4686000	6.8326000

STATION=N14

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	14	2.5085714	3.6173872	0.1800000	11.6900000
NH4	14	0.4092857	0.2327582	0.0700000	0.8400000
FLU	15	1.8925800	1.3355386	0.4648000	5.1607000

STATION=N15

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	14	2.0921429	3.1664666	0.0900000	11.1500000
NH4	14	0.4107143	0.2738743	0.0300000	1.1200000
FLU	15	1.8768867	1.2671401	0.4789000	4.5837000

Parameter means for nearfield surface water

STATION=N16P

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	28	2.8789286	4.1997534	0.0800000	11.6700000
NH4	28	0.4607143	0.4464090	0.0300000	1.9800000
FLU	28	1.5591179	1.2296640	0.4546000	5.0326000

STATION=N17

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	15	2.0240000	2.8350480	0.1500000	8.1700000
NH4	15	0.3873333	0.3567606	0.0800000	1.3500000
FLU	15	2.0992933	1.7619030	0.3227000	6.1966000

STATION=N18

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	2.1250000	2.8227174	0.1500000	9.1700000
NH4	16	0.6425000	0.8198414	0.0900000	2.8600000
FLU	16	2.4876500	1.9324045	0.4479000	6.7784000

STATION=N19

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	2.6450000	2.8058558	0.1500000	7.9600000
NH4	16	0.8462500	0.9697826	0.1000000	4.3000000
FLU	16	1.9489500	1.4417777	0.4456000	6.1898000

STATION=N20P

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	22	2.5390909	3.5271274	0.2100000	12.2600000
NH4	22	0.5436364	0.4282361	0.1100000	1.9400000
FLU	22	2.0186091	1.4411056	0.3865000	6.5077000

Parameter means for nearfield surface water

STATION=N21

Variable	N	Mean	Std Dev	Minimum	Maximum
DIN	16	2.2412500	3.1417211	0.1800000	11.2100000
NH4	16	0.4931250	0.4051126	0.0900000	1.7000000
FLU	16	2.3238063	1.7854037	0.5470000	6.3606000

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