Water quality monitoring in Massachusetts and Cape Cod Bays: annual report for 1992

Massachusetts Water Resources Authority

Environmental Quality Department
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WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: ANNUAL REPORT FOR 1992

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority began a baseline environmental monitoring program (MWRA, 1991) to determine 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 conducted throughout 1992, with surveys every month from February to December. Results of surveys have been presented in a series of reports, each focusing on the surveys conducted within a season (Kelly *et al.*, 1992; Kelly *et al.*, 1993a,b).

The purpose of this report is to present a compilation of results for all of 1992. The 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 of the space and time distribution of these parameters and thereby describe the annual cycle of ecological events in Massachusetts and Cape Cod Bays for 1992. Brief consideration is given to the scales of resolution possible with the monitoring design, but this descriptive effort is prelude to more comprehensive statistical testing.

Water column parameters described in the report include: nutrients (nitrogen, phosphorus, and silicate), chlorophyll, dissolved oxygen (DO), phytoplankton and zooplankton species and abundances, net primary production. A brief description of results follows.

Nutrients — The majority of measurements of dissolved nutrients showed low nutrient concentrations. For example, for dissolved inorganic nitrogen (DIN), almost one-half of the measured concentrations were ≤ 1 μM. The mean for all measurements was 2.43 μM and the maximum value was slightly above 16 μM. An annual cycle for DIN was indicated in western Massachusetts Bay, with bottom waters having higher concentrations than surface waters during the stratified season from about May to October. Total nitrogen (TN) concentrations, e.g., the sum of all inorganic and organic forms, showed a seasonal pattern in the surface layer, which in part paralleled DIN concentrations. Different patterns of nutrient concentrations in different regions of the Bays are illustrated.

Chlorophyll — The annual average for measurements of chlorophyll concentrations (either all measurements or surface layer only) was slightly over 2 $\mu g\ L^{-1}$. Seasonal peaks in chlorophyll (10-17 $\mu g\ L^{-1}$) occurred in winter (Cape Cod Bay) and in fall (Massachusetts Bay). Seasonal lows in chlorophyll were apparent in late spring and early winter. Patterns of vertical chlorophyll distribution over time varied across regions; there tended to be higher surface values inshore at coastal stations.

DO — There were no striking geographic differences in DO frequency distributions in surface waters. Most surface-water DO readings were in the 100 to 125% saturation range during the year, until November. The lowest DO values, not necessarily in terms of absolute values, but in terms of percent saturation, were generally from the deepest waters

sampled in a survey. Samples collected at depths greater than 50 m exhibited a DO decrease (concentration and percent saturation) from February to October.

Plankton — Total phytoplankton cell counts for all samples ranged from about 0.3 million cells L^{-1} to as high as about 9 million cells L^{-1}. Some regional distinctions were suggested, with the Cape Cod Bay stations having relatively high counts in winter-spring, low counts in mid-summer, and high counts in early fall. Total zooplankton abundance was relatively similar within all stations of a survey (usually less than a factor of five variation), but the variation across surveys through the year was about two orders of magnitude. Patterns for selected taxa illustrate some seasonal changes in plankton communities. In 1992, two major events were a Baywide *Phaeocystis pouchetii* bloom in April and the appearance of a dinoflagellate, *Ceratium longipes,* in Cape Cod Bay in June at very high cell counts at the subsurface chlorophyll maximum.

Net primary production — Rates were measured by oxygen changes in bottles incubated across a range of irradiance level. Integrated water column rates were modeled from these data and expressed as carbon. Sensitivity analyses have not been conducted to determine a level of uncertainty that may be attached to calculated rates; such analyses are recommended for there are a variety of assumptions and inherent uncertainties associated with the technique and the calculations. Rates overall ranged from essentially zero (net respiration in the water column in two cases in April) to >9 g C m^{-2} d^{-1}. Some of the highest rates were calculated at stations in Cape Cod Bay during the Baywide dominance of *Phaeocystis* in April. Rates above 3 g C m^{-2} d^{-1} were also calculated for several nearfield stations, especially in August when Massachusetts Bay station net production rates appeared to be higher than Cape Cod Bay stations. The overall average for all estimates (n= 102) was 1.25 g C m^{-2} d^{-1} for the period of late February to mid-October. On average, the two Cape Cod Bay stations had higher rates (1.91 g C m^{-2} d^{-1}, or 1.61 g C m^{-2} d^{-1} if a suspect June data point is omitted) than the nearfield set of stations (1.13 g C m^{-2} d^{-1}) or the two coastal stations (0.96 g C m^{-2} d^{-1}).

Several variability and scale issues are examined as they relate to monitoring design or prospective analyses of change. Preliminary suggestions from the data, which need confirmation by further analyses, are as follows:

(1) Because of a seasonal cycle of stratification that depletes nutrients in surface layers while enriching bottom waters, future increases of DIN into surface waters may be more easily detectable than in deep water. Moreover, with the high degree of physical and chemical variability within the nearfield, analyses of change due to effluent diversion may be best examined on a regional average basis, rather than on the basis of pre/post comparisons at individual stations.

(2) Graphical comparisons were developed to show the perception and reality of variability in some key parameters. Spatially, comparisons were made of *in situ* high-resolution towing measurements vs. standard *in situ* vertical hydrocasts.

Temporally, comparisons showed how different perceptions of annual cycles can be produced by different sampling frequencies. The question for further assessment and for the monitoring program is what level of change should be detectable? This is not purely a statistical question, but statistical analyses may be helpful to address this issue quantitatively.

Several regional contrasts were developed from the data set. One contrast highlighted nutrient and chlorophyll differences in annual patterns across nearshore (more enriched) to offshore (less enriched) stations. For the offshore region, the pattern of development of deepwater DO concentrations during stratification was similar at several stations and DO measurements showed an annual low at the October 1992 survey. A final contrast summarized some of the observed differences in annual cycles of nutrients, chlorophyll, productivity, and plankton species composition between Massachusetts Bay and Cape Cod Bay stations. Over the year, Cape Cod Bay stations showed high winter-spring chlorophyll, had high levels of primary production, developed an intense dinoflagellate bloom, and maintained a summer plankton community with a lower diatom component than many northern Massachusetts Bay stations. Although the mechanisms promoting the Bay to Bay differences are not fully known, the Cape Cod Bay stations, rather than Massachusetts Bay stations (which are nearer major nutrient sources), exhibit more of the classical list of eutrophication symptoms. Continued examination of this regional contrast should sustain a great deal of interest.

In summary, the water column monitoring in 1992 provided an extremely valuable data set for Massachusetts and Cape Cod Bays, and there are more ecological contrasts and insights to be developed than could be included in an annual report. With respect to the basic design of the monitoring program and its emphasis on nutrient enrichment, the major seasonal features of key parameters are well covered, as are the principal spatial scales of interest. A remaining task, with these comprehensive data now in hand, is to use the data in assessing the potential of the present monitoring design to detect change. As initial steps, determining the statistical significance of the suggested regional and station differences in biology, chlorophyll, and nutrients is recommended along with an explicit consideration of the scale of sampling required to meet monitoring objectives (MWRA, 1991).

CONTENTS

APPENDIX

Note to reader: The Appendix contains time plots for selected stations and parameters and is bound separately from this technical report. To request the Appendix, contact the MWRA and ask for the MWRA Miscellaneous Publication entitled "APPENDIX TO WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: ANNUAL REPORT FOR 1992"

LIST OF FIGURES

1.0 INTRODUCTION

The Massachusetts Water Resources Authority began a baseline environmental monitoring program (MWRA, 1991) to determine 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 conducted throughout 1992, with surveys every month from February to December. Results of surveys have been presented in a series of reports, each focusing on the surveys conducted within a season (Kelly *et al.*, 1992; Kelly *et al.*, 1993a,b).

The purpose of this report is to present a compilation of results for all of 1992. The spatial and temporal variability are described for selected parameters that are viewed as key to monitoring objectives. A main objective, focusing on these parameters, is to provide a description of the annual cycle of ecological events for 1992. Secondarily, consideration is given to the scales of resolution possible with the monitoring design. This descriptive effort is prelude to more comprehensive statistical testing to suggest differences among geographic areas during the baseline period and to determine the power of the design to detect change in key parameters.

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

- Nutrients (nitrogen, phosphorus, and silicate)
- Chlorophyll
- Dissolved oxygen
- Phytoplankton and zooplankton
- Net primary production

The rationale behind the focus on these key parameters is given in MWRA (1991). Briefly, the distribution and concentration of nutrients is 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 and Nowicki, 1993). The loading and concentration of nutrients is 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. The level of chlorophyll and net primary production can influence dissolved oxygen concentrations, the main concern being development of low oxygen concentrations in bottom water layers.

This report is organized as follows:

- Presentation of data for each of five key monitoring categories
- Overview of annual cycles
- Perspective of scales of resolution possible with monitoring data
- Suggestions for further analyses of these data.

2.0 DATA SOURCES, STATIONS, AND SURVEYS

The data used in this report are from the MWRA Harbor Studies Database, and have been presented in previous water quality monitoring reports and their appendices (Kelly *et al.*, 1992; 1993a,b). Any data manipulations are described in the appropriate section of this report. Plots were generated using Battelle Ocean Sciences (BOS) propriety software or SAS (1988a,b).

The stations are located throughout Massachusetts and Cape Cod Bays (Figure 2-1). Twenty-one nearfield stations (labeled "N") are from a roughly 100-km^2 area, the center of which is near the mid-point of the planned 2-km-long MWRA effluent diffuser. Twenty-five farfield stations (labeled "F") are spread from the edge of Boston Harbor to Stellwagen Basin to the east and, in the north—south direction from Cape Cod Bay to the east of Salem in deep offshore water. Ten stations (labeled "P") are the subject of more extensive measurements including organic nutrients, biology, and productivity.

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

The nearfield stations were sampled on 14 surveys in 1992. Some of the stations were visited several times during the course of six of these surveys, during which all the farfield stations were sampled. Various time plots will illustrate some of the different frequencies of sampling for different stations.

The reader may note in temporal contour plots that the depth of a station appears to vary. There were depth differences over time, due to time-of-tide differences and position differences at sampling that create differences in water depth because of the irregularity of the bottom in some areas. The plots (e.g., Figure 3-23) do not show the water depth, but rather show the data collected to the bottom of vertical profile casts. The target depth for the bottom of profiling was 5 meters above bottom, but the actual depth achieved at different surveys varied slightly.

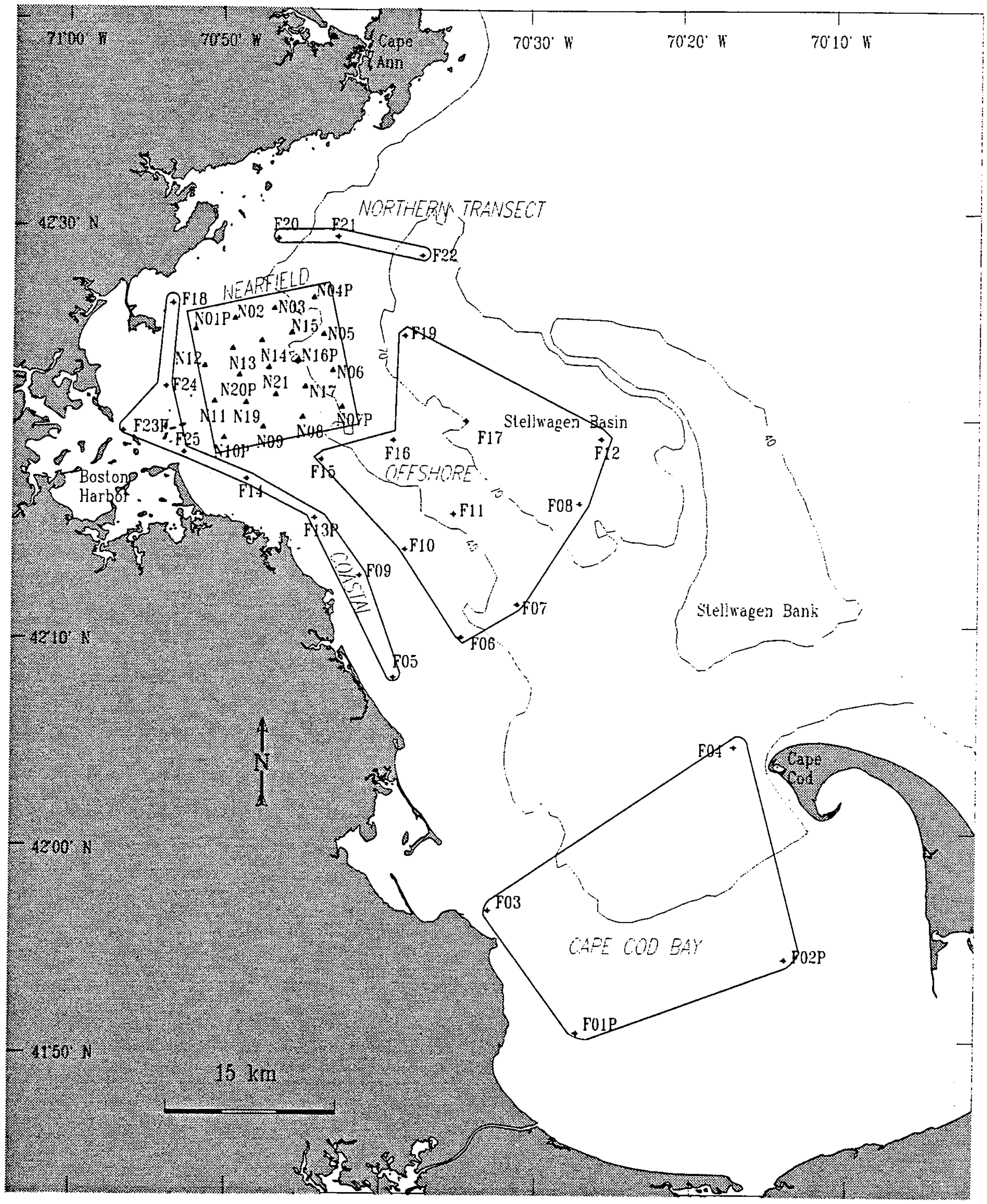


Figure 2-1. Water quality sampling stations in Massachusetts and Cape Cod Bays. Stations codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Five groups of stations that are referred to in text and other figures are identified — Northern Transect, Nearfield, Coastal, Offshore, and Cape Cod Bay.

3.0 NUTRIENTS

Data for dissolved inorganic nutrients, including ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), phosphate (PO_4), and silicate (SiO_4), are available for all stations (21 nearfield and 25 farfield). Data for organic nutrients are available for a subset of stations (6 nearfield and 5 farfield, comprising the 10 Biology/Productivity stations plus station F25 — see Figure 2-1).

3.1 Frequency Distribution of Nutrients, Including Selected Regional Contrasts

In all, about 2200 analyses for dissolved inorganic nutrients were completed in 1992. Frequency plots were developed to describe how the samples (nutrients and other parameters) were distributed by concentration class intervals and are labeled according to the highest concentration in the class, e.g., 1, 2, 3, etc., for the respective interval series, $0 < x \leq 1$, $1 < x \leq 2$, $2 < x \leq 3$, etc. Each class thus may be referred to in abbreviated form, respectively, as >0-1, >0-2, >2-3, etc. The maximum interval for each parameter was chosen to include the highest value observed for the data set with all stations; for regional subsets, the same range of frequency class intervals was retained to allow direct comparison. In each of these frequency plots, we have listed some elementary statistics for the distribution: the number of analyses (N), the average concentration (mean), and the standard deviation (s).

For dissolved inorganic nitrogen ($DIN = NH_4 + NO_3 + NO_2$), the distribution for all stations and depths showed that nearly one-half of measured concentrations were ≤ 1.0 μM (Figure 3-1). The frequency distribution of samples fell sharply with increasing concentration and the maximum value was > 16 μM. No concentration interval above 1 μM constituted 10% and no concentration interval above 8 μM constituted even 5% of the total number of measurements. Most of the samples (over 1400) were from the nearfield region, for which the frequency distribution is also given in Figure 3-1. The distribution of the "surface" samples only (roughly 2-5 m, the depth of the uppermost hydrocast bottle at each station) shows a sharper falloff from the lowest concentration interval (Figure 3-2). There were several samples with surface concentrations of DIN > 7 μM in the nearfield region.

Two other regional groups of stations are included in Figure 3-3. Fewer samples were collected from these farfield stations, but the regional contrasts in DIN seem clear. The coastal stations' distribution is skewed — relative to other regions there are greater numbers of samples at higher concentrations. The surface samples at Cape Cod Bay stations, with only one exception, were low in DIN. If sampling had been conducted earlier in 1992, prior to the development of the winter-spring bloom (earlier in Cape Cod Bay), or later in the year after fall overturn, a few higher points might have been expected for Cape Cod Bay stations.

The distribution of NH_4 shows that over 95% of the samples had a concentration ≤ 2.0 μM (Figure 3-4). Higher concentration samples occurred infrequently at the surface in the nearfield (Figure 3-5) and more frequently at the surface of the coastal stations (Figure 3-6), especially those near the mouth of Boston Harbor. NH_4 is a good medium-scale ($\approx$1-10 km) tracer for the present MWRA effluent because the signal-to-background "noise" ratio is favorable.

For phosphate (Figures 3-7, 3-8, 3-9), the modal concentration class was not the lowest. For most plots the mode was the second interval (>0.2-0.4 μM), but for the surface values in the coastal region it was shifted to the next higher class (Figure 3-9). Infrequent, but higher concentrations were measured in both the nearfield and coastal regions, but not in Cape Cod Bay. It was previously noted (Kelly *et al.*, 1992; 1993a,b) that surface phosphate was usually detectable when DIN was at or near detection limits; the differences between N and P frequency distributions offer a different perspective that also suggests N, rather than P, limitation.

The frequency distribution for silicate was similar to phosphate in that the mode was not the lowest class (Figures 3-10, 3-11, 3-12); similarly, we previously noted that silicate was usually present when DIN was virtually undetectable. For silicate, concentration classes neighboring the mode had similar frequencies and thus, the distribution around the mode was broad, rather than sharp, like phosphate. This distribution was more apparent with data over all depths than it was with surface concentrations alone (cf. Figure 3-10 and 3-11). As for other nutrients, high silicate concentrations (> 6 μM) were observed in surface samples from the nearfield and coastal regions, but the maximum at the four stations in Cape Cod Bay was in the 5-6 μM interval.

3.2 Annual Cycle of Nutrients

Examining the trend in surface-water concentration of DIN for all stations (Figure 3-13), it was readily apparent that the pattern is very strong, in spite of station-to-station variability. Higher nutrient concentrations in late winter fell to low levels by April and generally stayed low until about October, when fall overturn occurs; the concentrations rose again at the end of the year. With a few exceptions, the high values at any date throughout the year occurred at either station F23P, F24, F25, or N10P — those nearest Boston Harbor (see Figure 2-1).

Figure 3-14 displays the DIN trend for deep water in Massachusetts Bay. There is certainly variability within a given survey, but there is also a gradual trend from lower to higher values through the year. Note that this plot, compared to the previous one, only encompasses February through October because the stations are generally from the farfield surveys.

Organic nitrogen forms were measured only during the February to October period. Total dissolved nitrogen (TDN), particulate organic nitrogen (PON), and total nitrogen (TN = TDN + PON) are given in Figures 3-15 to 3-17. The measurements, made near the surface and at a mid-water "chlorophyll maximum", represent primarily the upper 10-20 m of the water column. TDN includes dissolved organic nitrogen (DON) as well as DIN. There is a seasonal cycle in TDN with lowest values in mid-year. This cycle is primarily driven by DIN (cf. Figure 3-13). During late spring to early fall TDN is mostly DON, at concentrations of 5-10 μM, when upper water column DIN is low and often ear zero. PON was quite variable across stations (Figure 3-16). The data did not suggest a strong seasonal cycle; highest values were associated with high plankton and chlorophyll in April, and at the subsurface chlorophyll maximum of several stations in June. TN can vary with station, region, and time of year (e.g., Kelly *et al.*, 1992). Figure 3-17 suggests a broad time trend with TN concentrations on average being higher in winter-spring and lower in summer-early fall. The TN trend parallels the DIN cycle, which suggests that TN variability results from the strong seasonal utilization and remineralization cycle for DIN more than seasonal trends in organic forms.

The surface water phosphate cycle in the bays was evident and PO_4 paralleled the average trend for DIN (Figure 3-18), although the change from winter to summer was not as pronounced. The deep water trend for PO_4, like DIN, suggested a gradual increase from early spring to fall (Figure 3-19). Total dissolved phosphorus (TDP) includes dissolved organic phosphorus (DOP) and PO_4. A strong seasonal cycle was less evident for TDP than for PO_4 (Figure 3-20).

The annual silicate cycle in surface water differed somewhat from DIN and PO_4 (Figure 3-21). On average, highest values were observed in spring later than February and March. Regional differences were pronounced at this time — Cape Cod Bay surface water silicate concentrations were much lower than in Massachusetts Bay (Kelly *et al.*, 1993a). Silicate concentrations were low in summer in Massachusetts Bay, but Cape Cod Bay stations were higher in June (Kelly *et al.*, 1993a,b). Silicate concentrations generally appeared to rise again late in the year. In deep water, the trend of a gradual increase in silicate was similar to DIN and PO_4 (Figure 3-22).

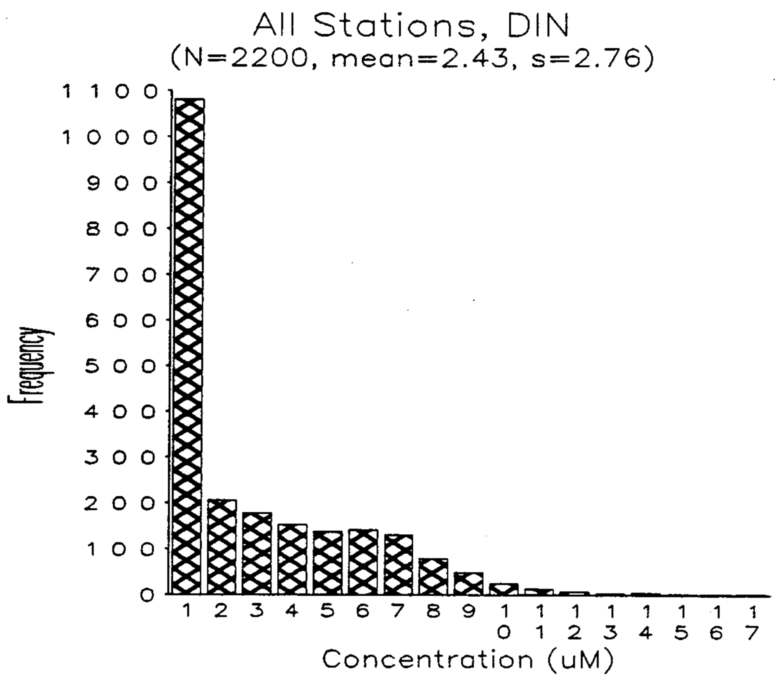
3.3 Annual Cycle of Nutrients at Selected Stations

Plots were developed to show the distribution of water properties over depth and over the year for a selection of stations (Figures 3-23 through 3-34). Four stations from different regions are shown. A larger set of stations is provided in the Appendix to this report. The sequence of stations presented is F02P in Cape Cod Bay, F23P at the edge of Boston Harbor off Deer

Island, F17 in deep water in Stellwagen Basin, and N16P near the center of the nearfield. The farfield station plots are based on five or six surveys (station F17 was not sampled in March due to weather) and the nearfield station plot is based on 14 surveys, so it is richer in detail. For each station, a sequence of plots is presented: (1) temperature to indicate the thermal structure (or lack thereof, station F23P), (2) DIN concentration, and (3) silicate concentration. On the figures, note that the dots indicate where and when sampling occurred. Note also that temperature represents 0.5-m averages and nutrients represent about 5 samples distributed through the water column.

The plots illustrate some variations from the generalized seasonal cycle patterns and facilitate comparison of station by station, as well as regional differences. A few points are suggested here, but many nuances of variability can be examined. For example, thermal stratification (F02P, F17, N16P) regulates the vertical distribution of nutrients (cf. F23P). Additionally, short-term variability in thermal structure appears to influence nutrient variability during summer (e.g., N16P).

The DIN concentrations at F23P near the present effluent source are generally higher than in surface waters elsewhere, and the length of the summer period of DIN depletion is shorter than at other stations. Sub-thermocline bottom water (20-40 m) concentrations in the nearfield during summer can be equal to or higher than the summer DIN concentrations at the edge of the Harbor. Differences between DIN and silicate cycles, and differences in their phasing between regions (e.g., Cape Cod Bay vs. Massachusetts Bay stations), as discussed above, are evident from inspection and comparison of the plots.



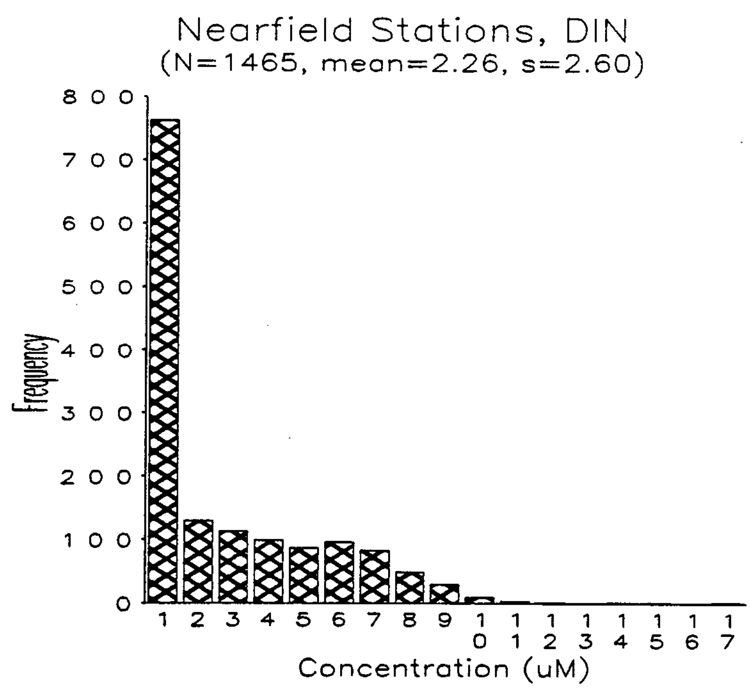
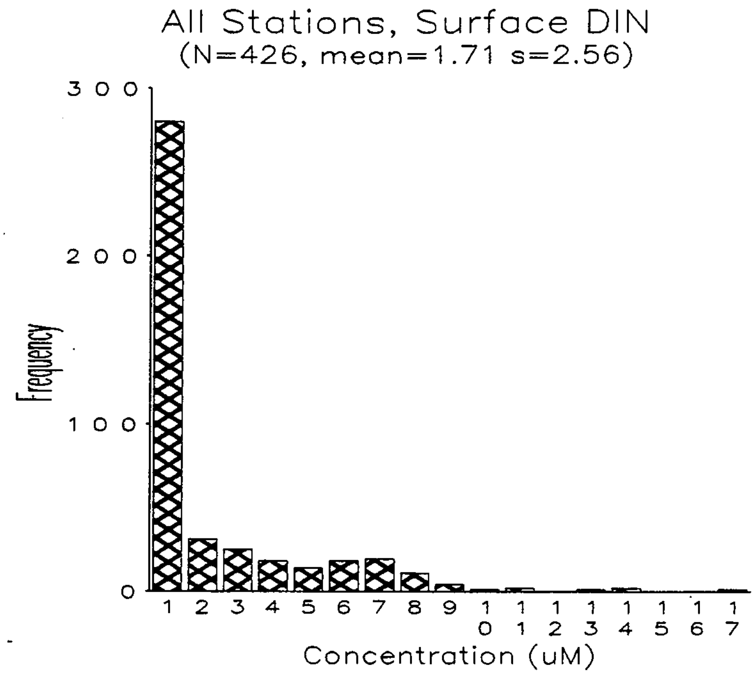


Figure 3-1. DIN frequency distribution for all 1992 data, all stations and nearfield stations.



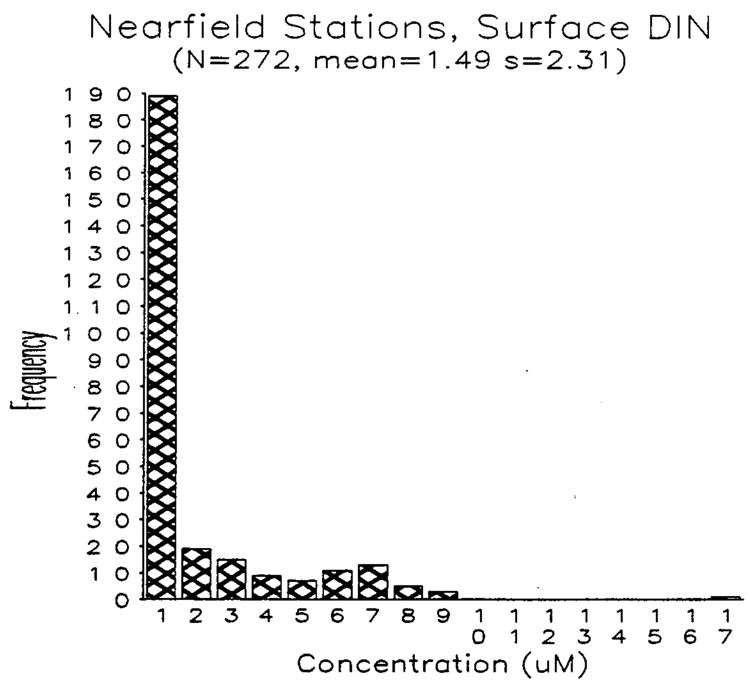
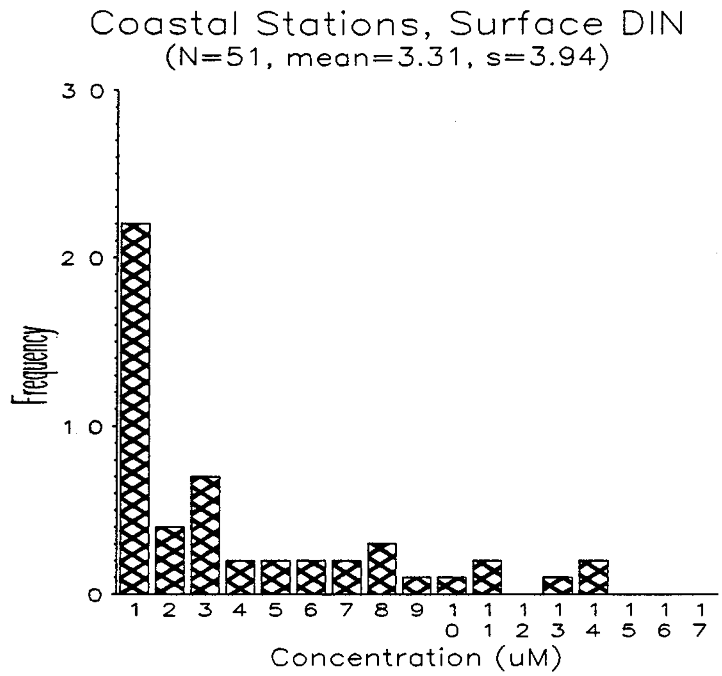


Figure 3-2. DIN frequency distribution for surface samples, all stations and nearfield stations.



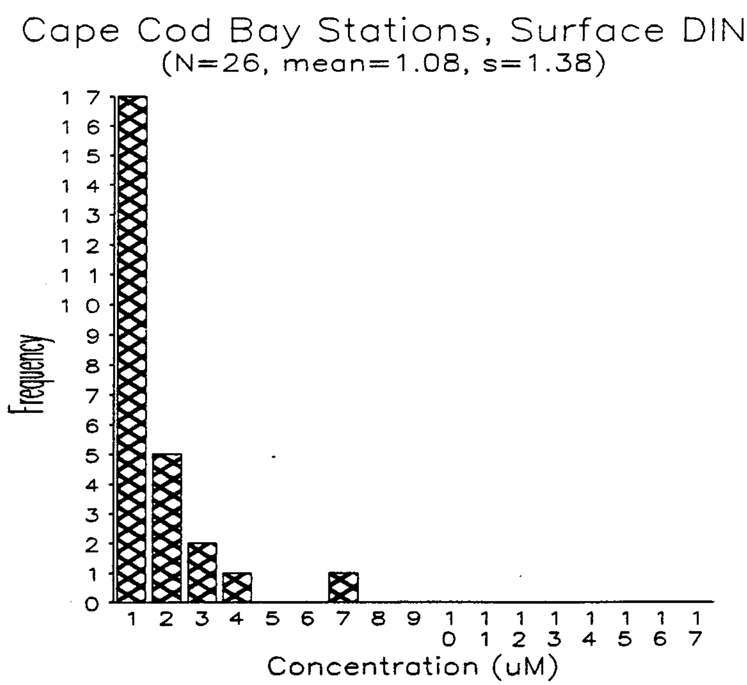
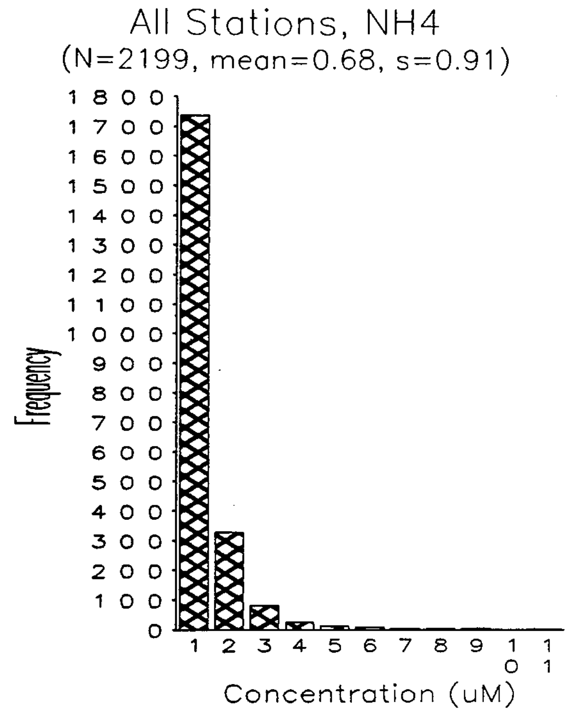


Figure 3-3. DIN frequency distribution for surface samples at coastal stations (F5, F9, F13P, F14, F18, F23P, F24, F25) and Cape Cod Bay stations (F01P, F02P, F03, F04).



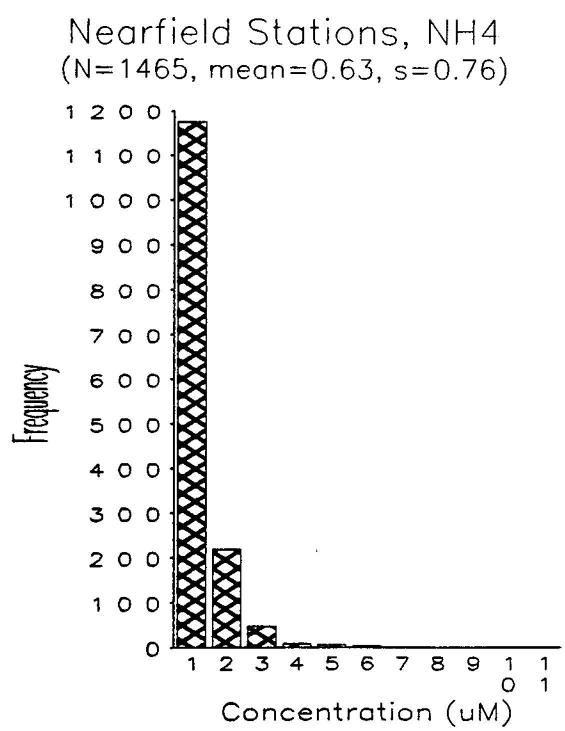
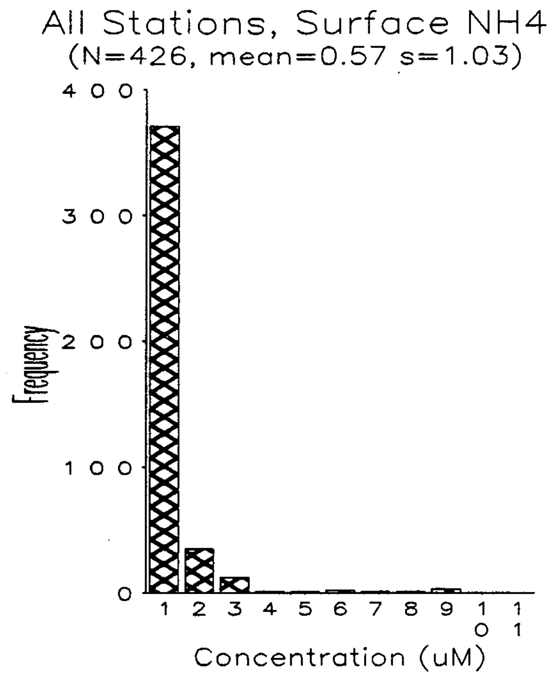


Figure 3-4. NH_4 frequency distribution for all 1992 data, all stations and nearfield stations.



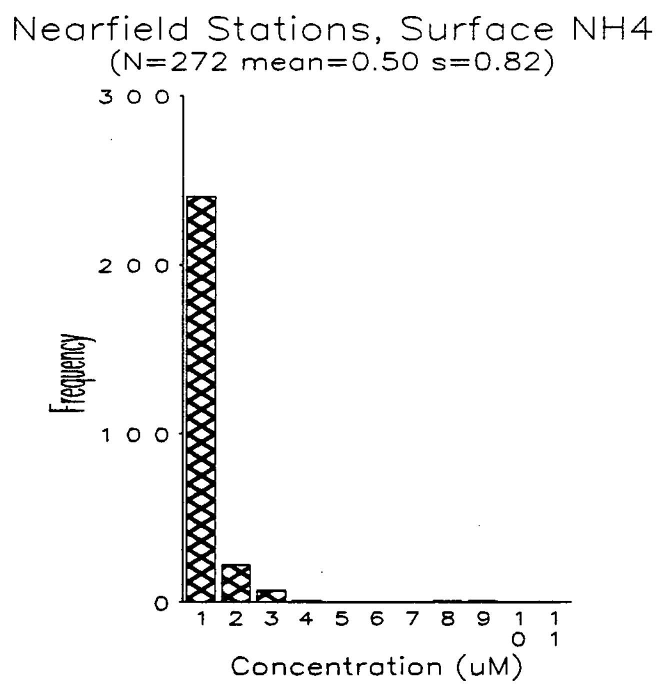
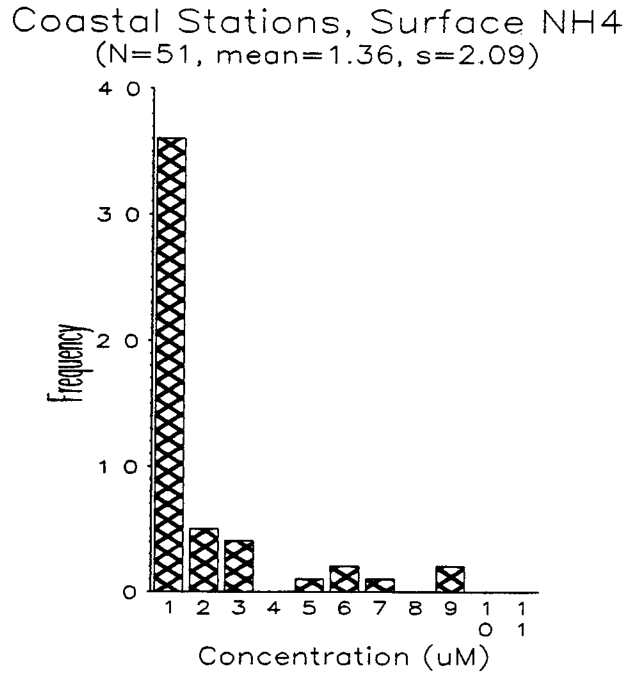


Figure 3-5. NH_4 frequency distribution for surface samples, all stations and nearfield stations.



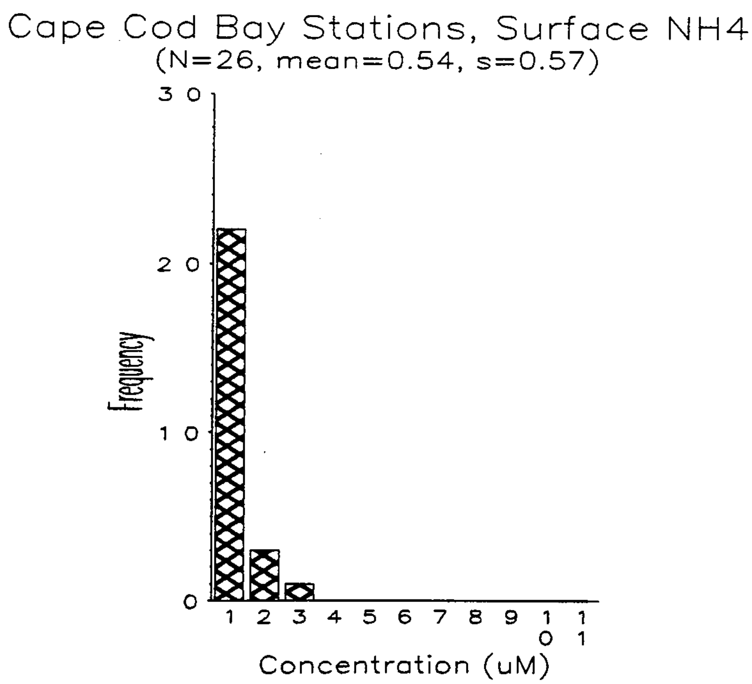
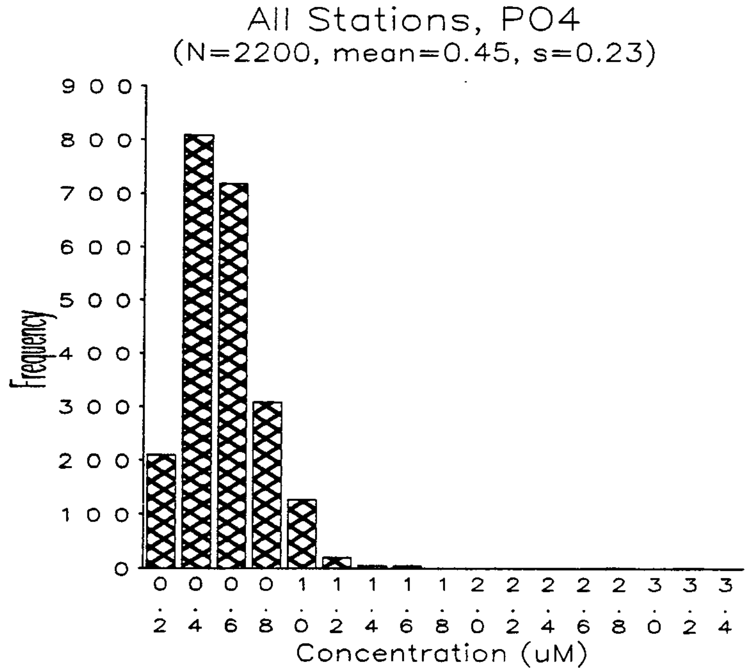


Figure 3-6. NH_4 frequency distribution for surface samples at coastal stations (F5, F9, F13P, F14, F18, F23P, F24, F25) and Cape Cod Bay stations (F01P, F02P, F03, F04).



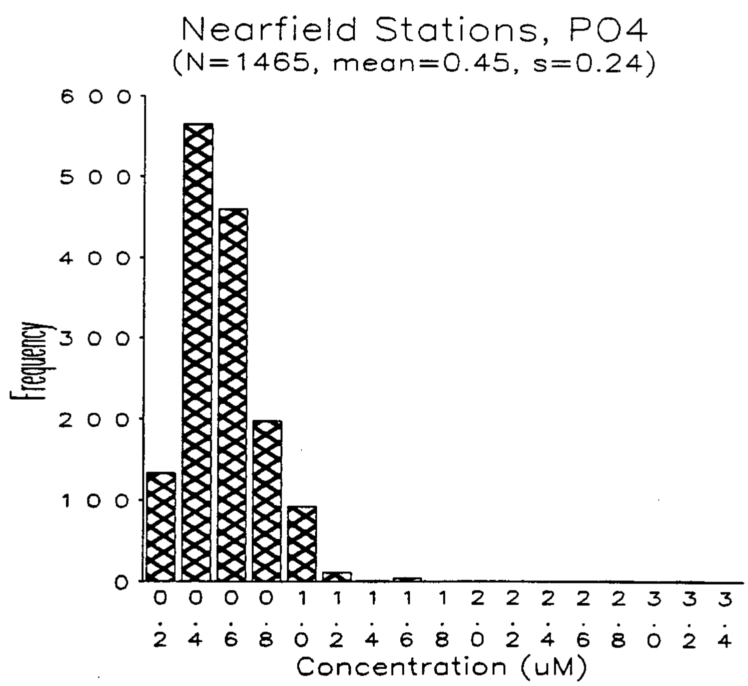
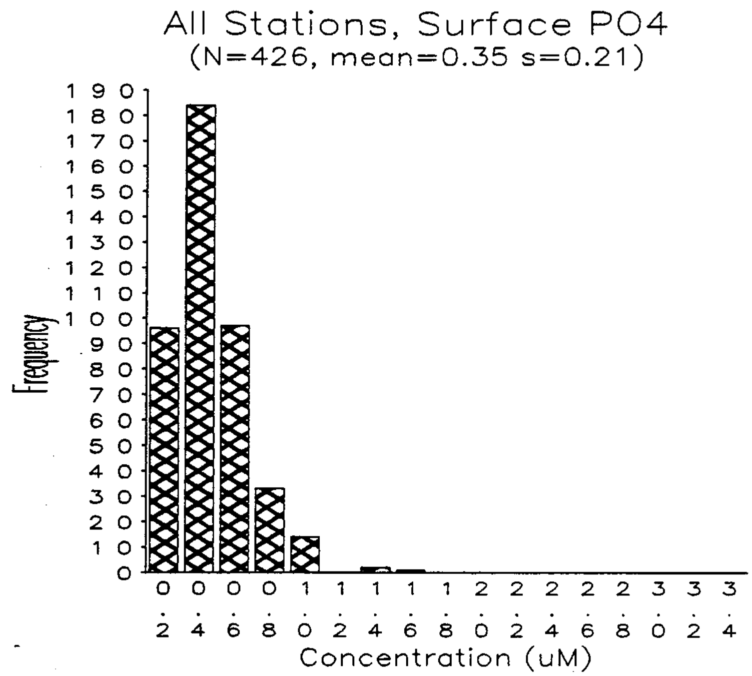


Figure 3-7. PO_4 frequency distribution for all 1992 data, all stations and nearfield stations.



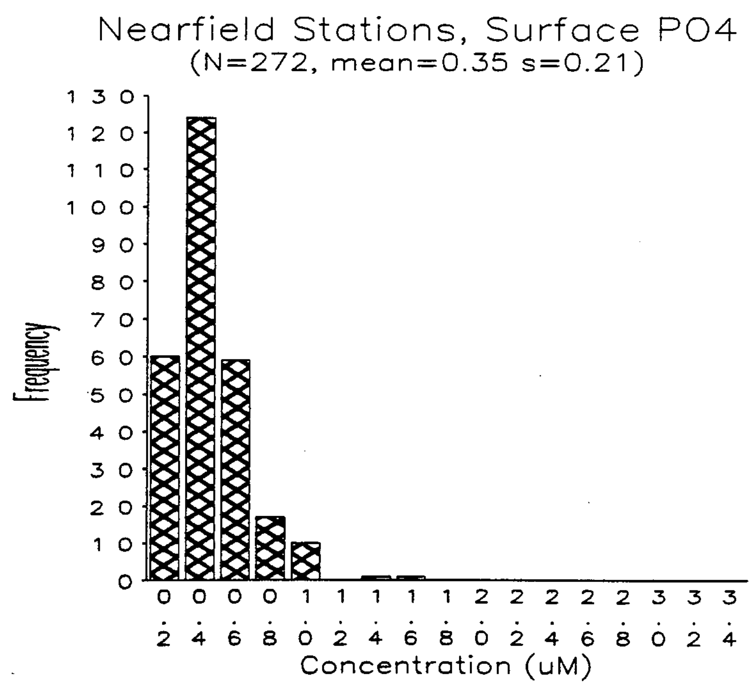
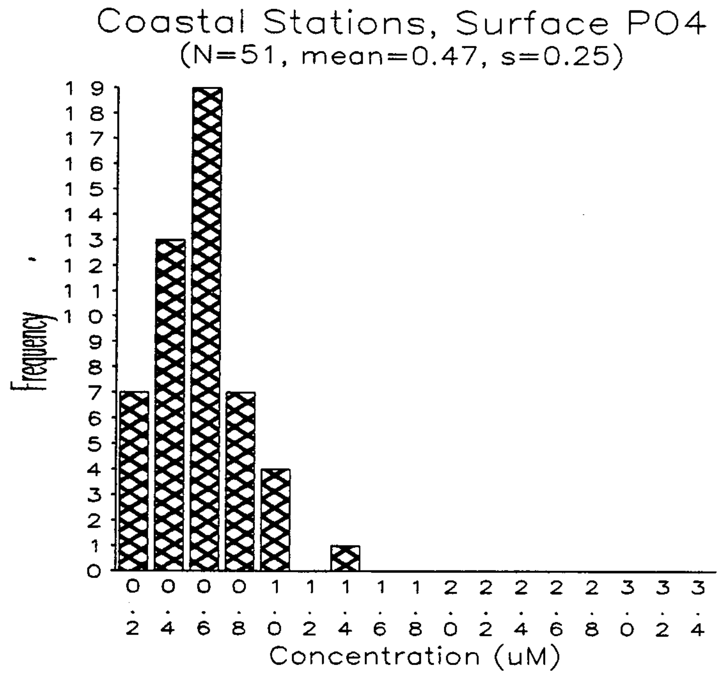


Figure 3-8. PO_4 frequency distribution for surface samples, all stations and nearfield stations.



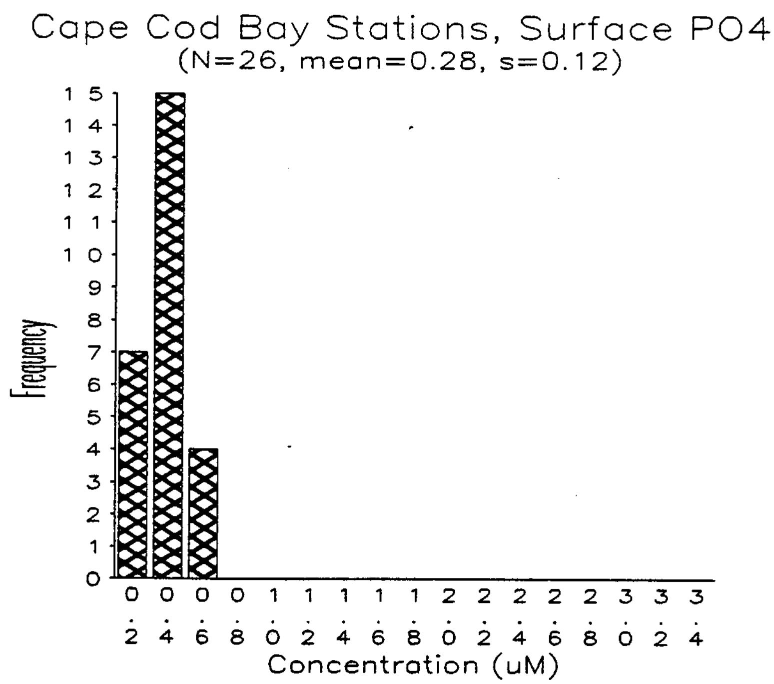
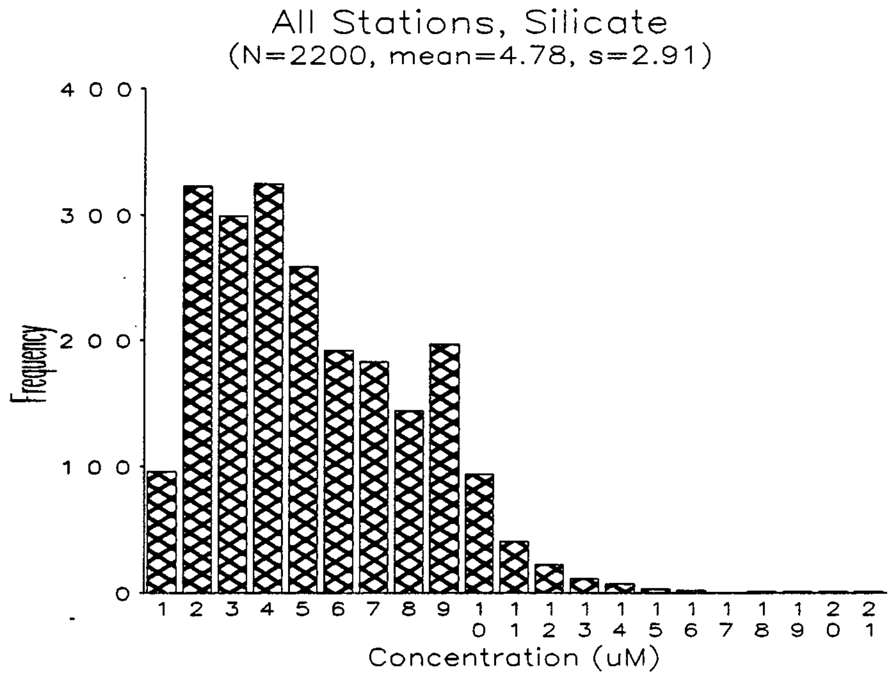


Figure 3-9. PO_4 frequency distribution for surface samples at coastal stations (F5, F9, F13P, F14, F18, F23P, F24, F25) and Cape Cod Bay stations (F01P, F02P, F03, F04).



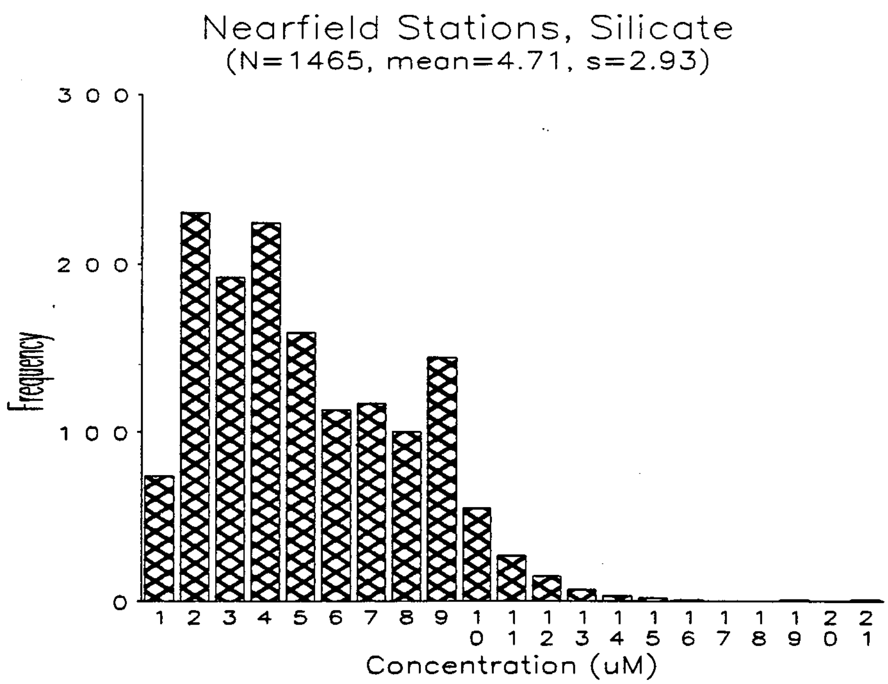
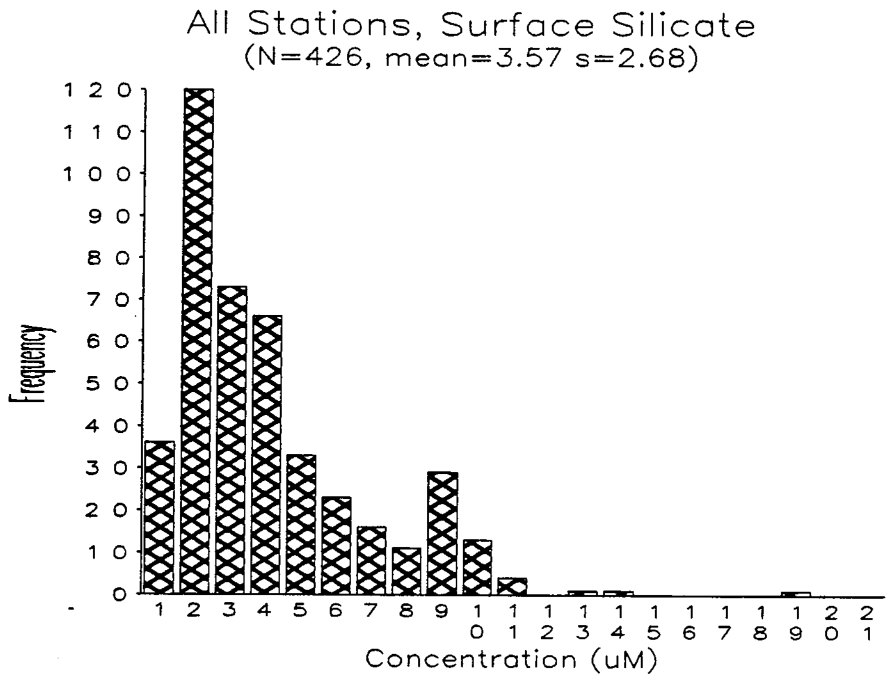


Figure 3-10. Silicate frequency distribution for all 1992 data, all stations and nearfield stations.



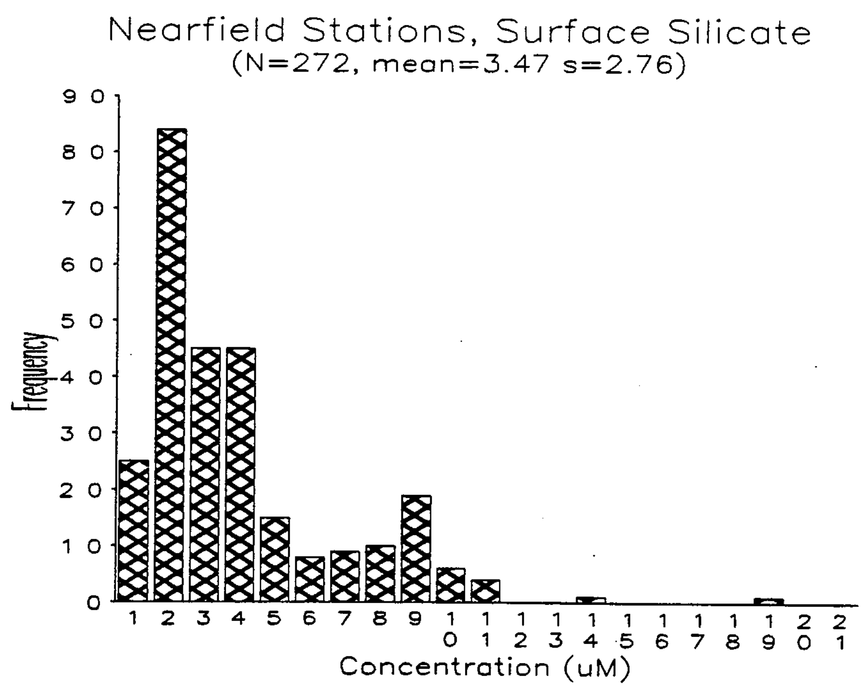
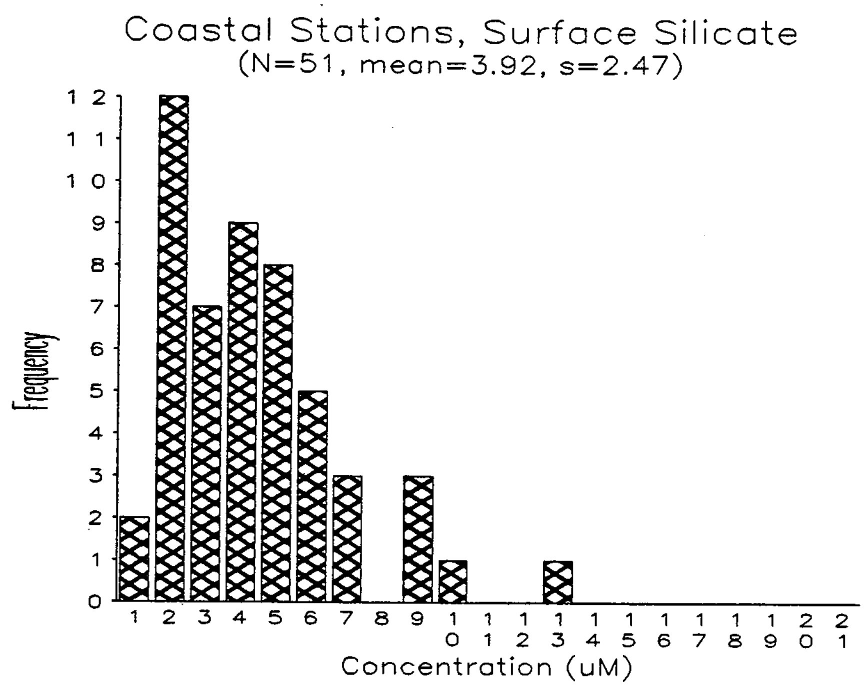


Figure 3-11. Silicate frequency distribution for surface samples, all stations and nearfield stations.



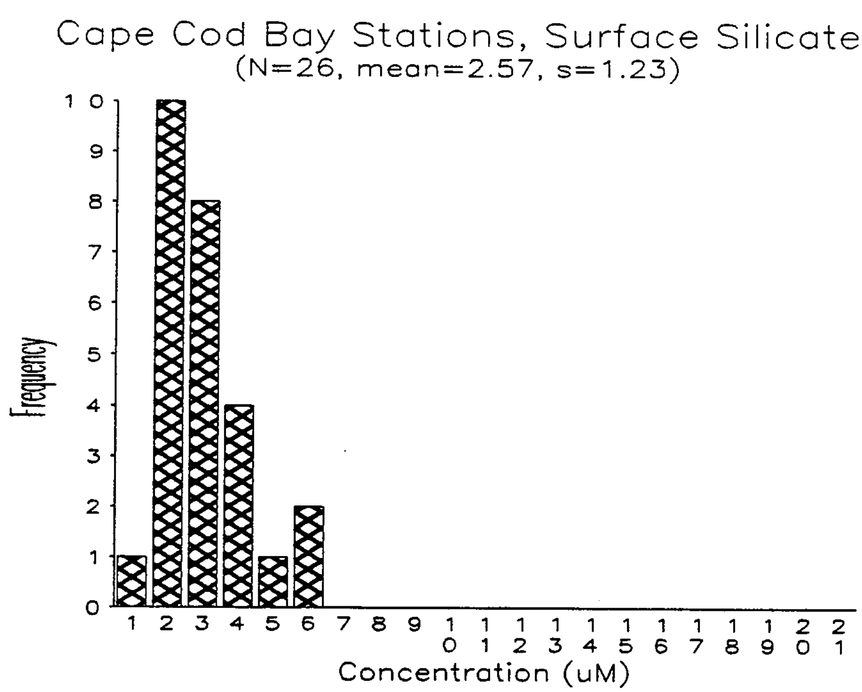


Figure 3-12. Silicate frequency distribution for surface samples at coastal stations (F5, F9, F13P, F14, F18, F23P, F24, F25) and Cape Cod Bay stations (F01P, F02P, F03, F04).

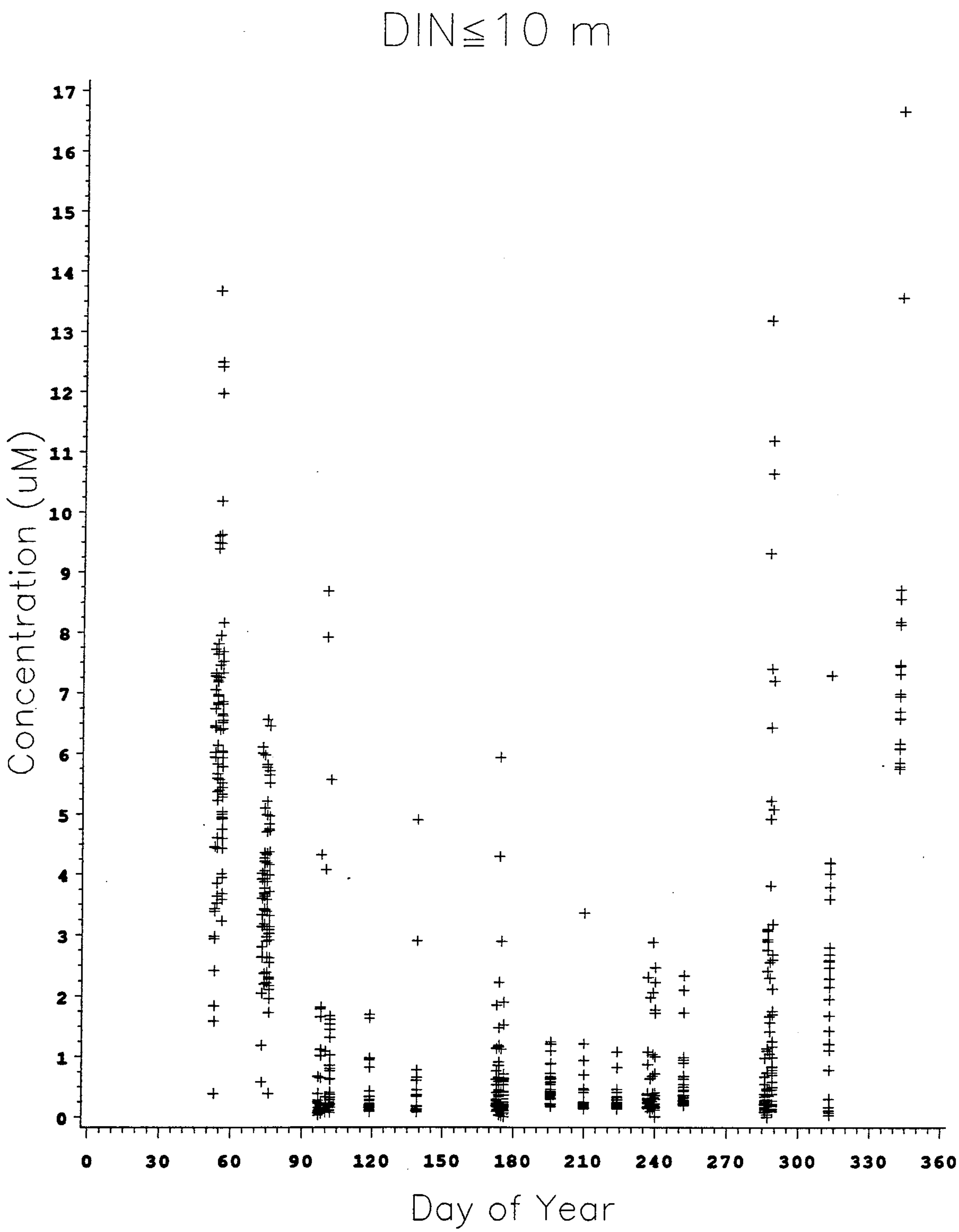


Figure 3-13. Annual DIN cycle in surface water at Massachusetts and Cape Cod Bay stations.

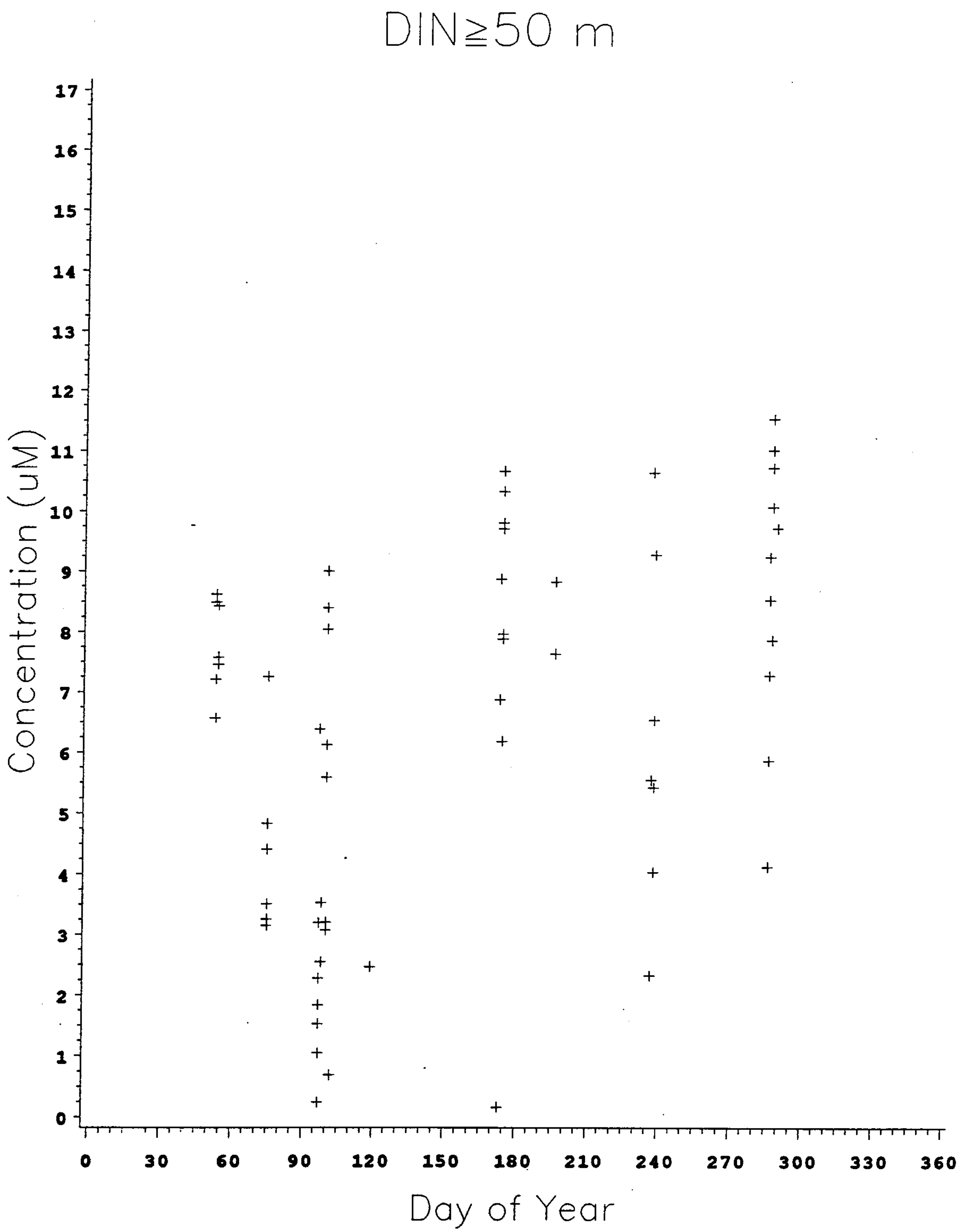


Figure 3-14. Annual DIN cycle in deep water at Massachusetts and Cape Cod Bay stations.

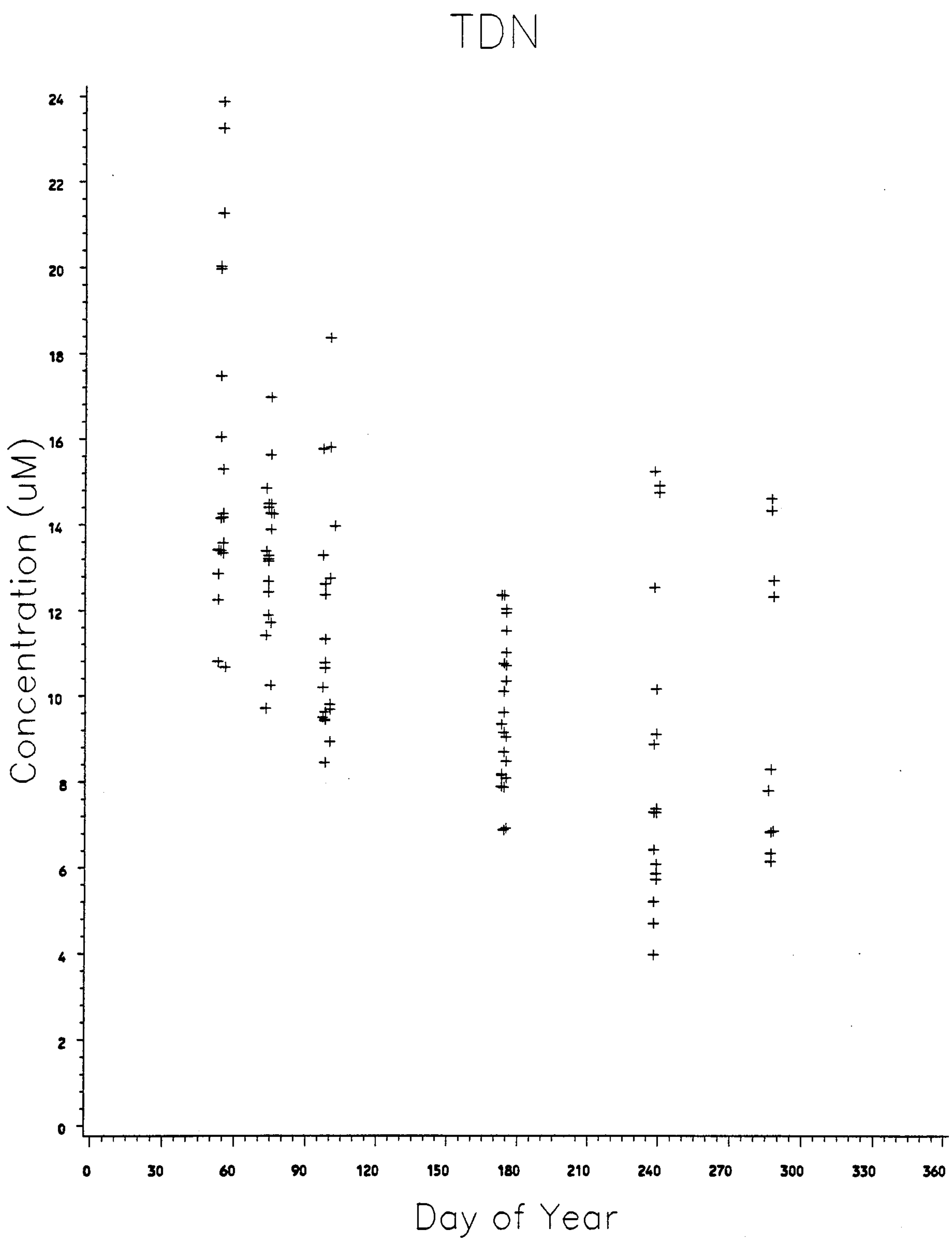


Figure 3-15. Annual TDN cycle at Massachusetts and Cape Cod Bay stations.

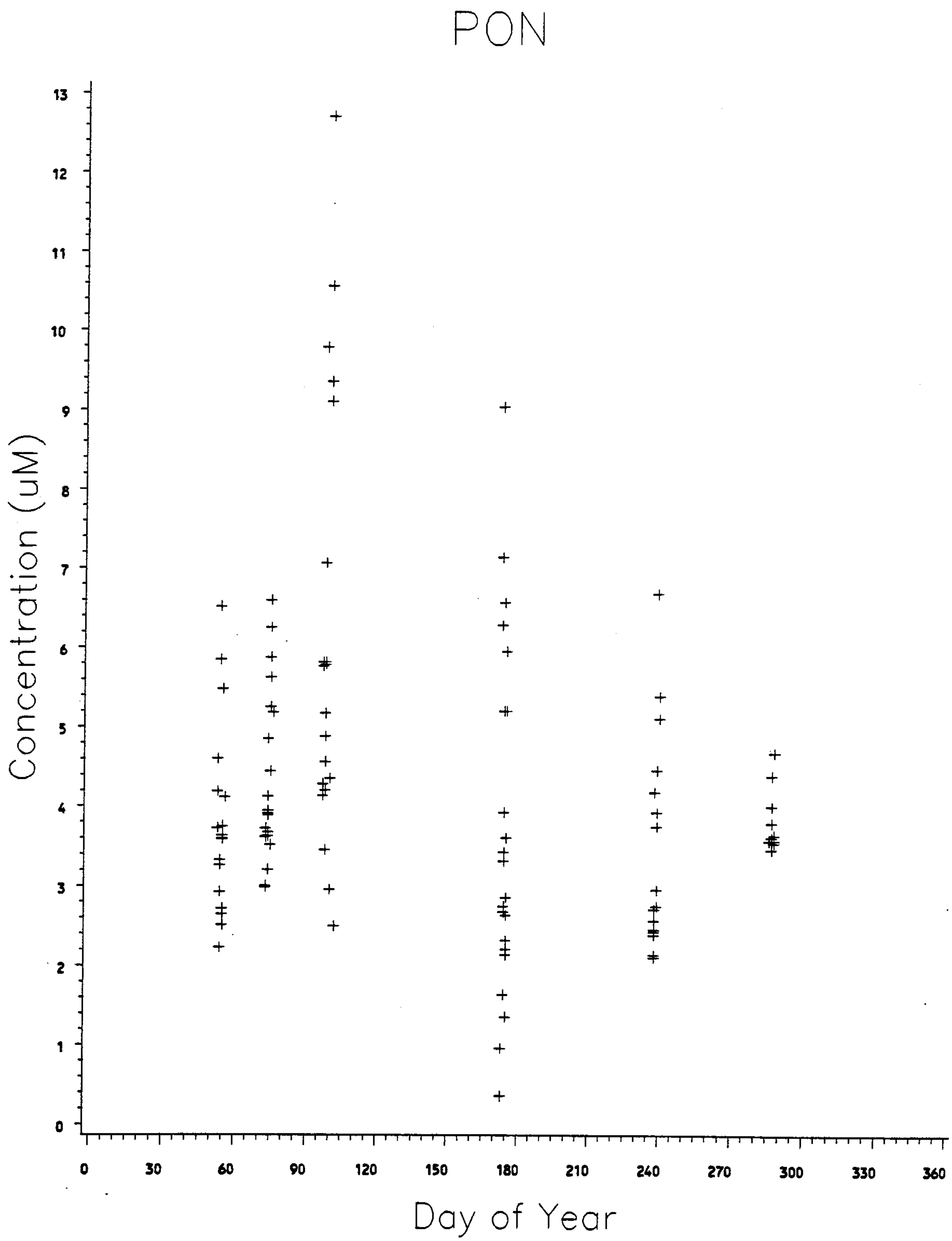


Figure 3-16. Annual PON cycle at Massachusetts and Cape Cod Bay stations.

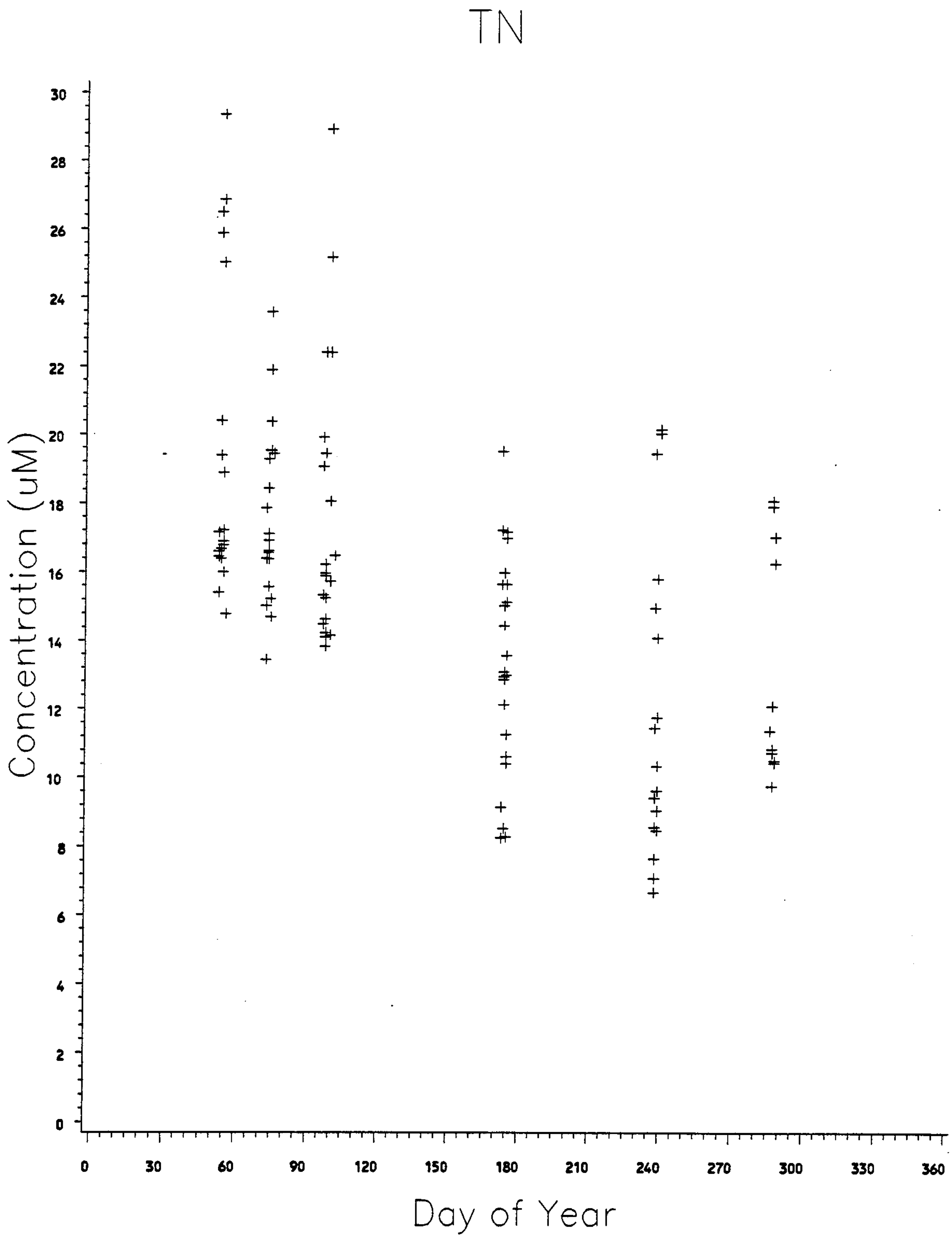


Figure 3-17. Annual TN cycle at Massachusetts and Cape Cod Bay stations.

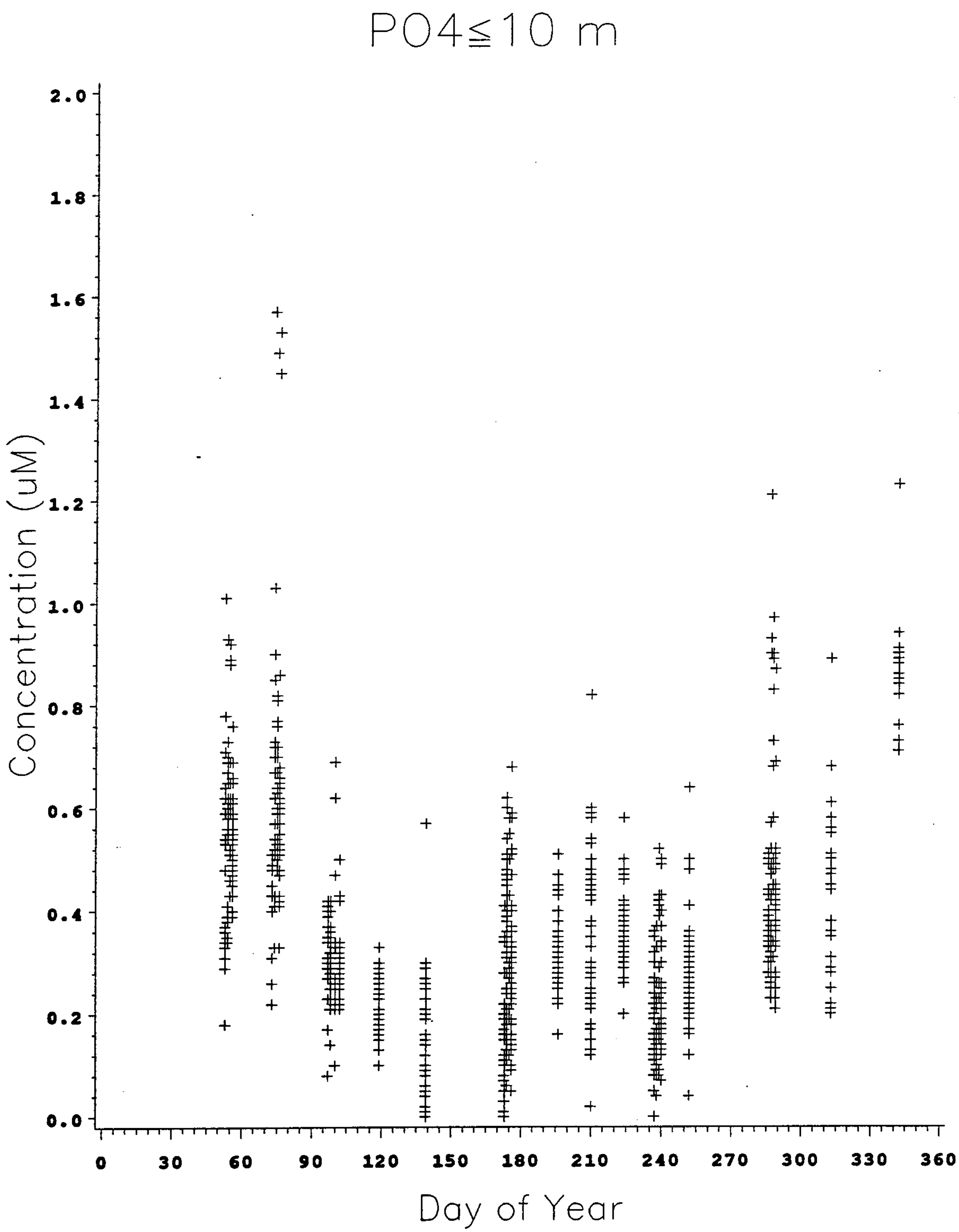


Figure 3-18. Annual PO_4 cycle in surface water at Massachusetts and Cape Cod Bay stations.

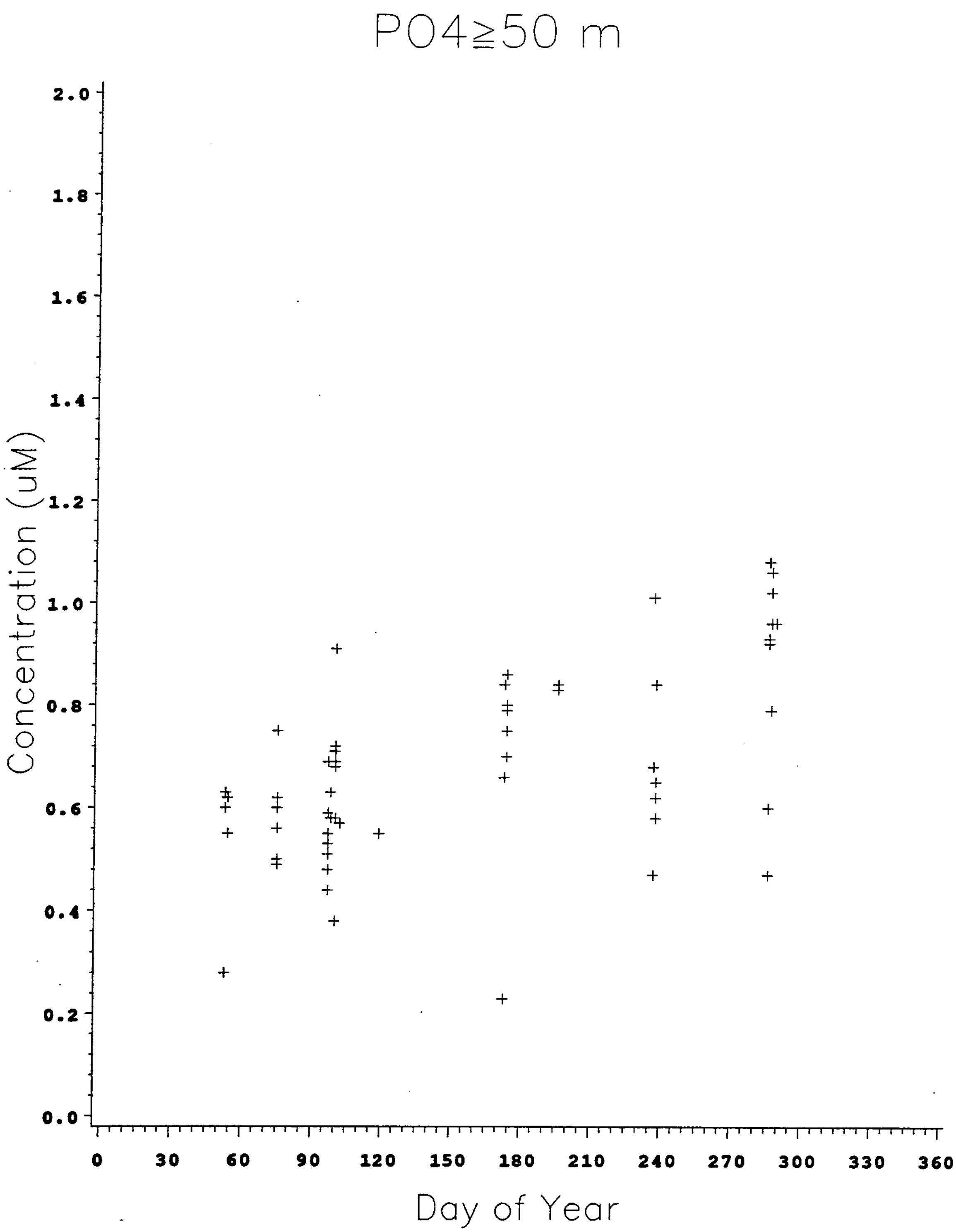


Figure 3-19. Annual PO_4 cycle in deep water at Massachusetts and Cape Cod Bay stations.

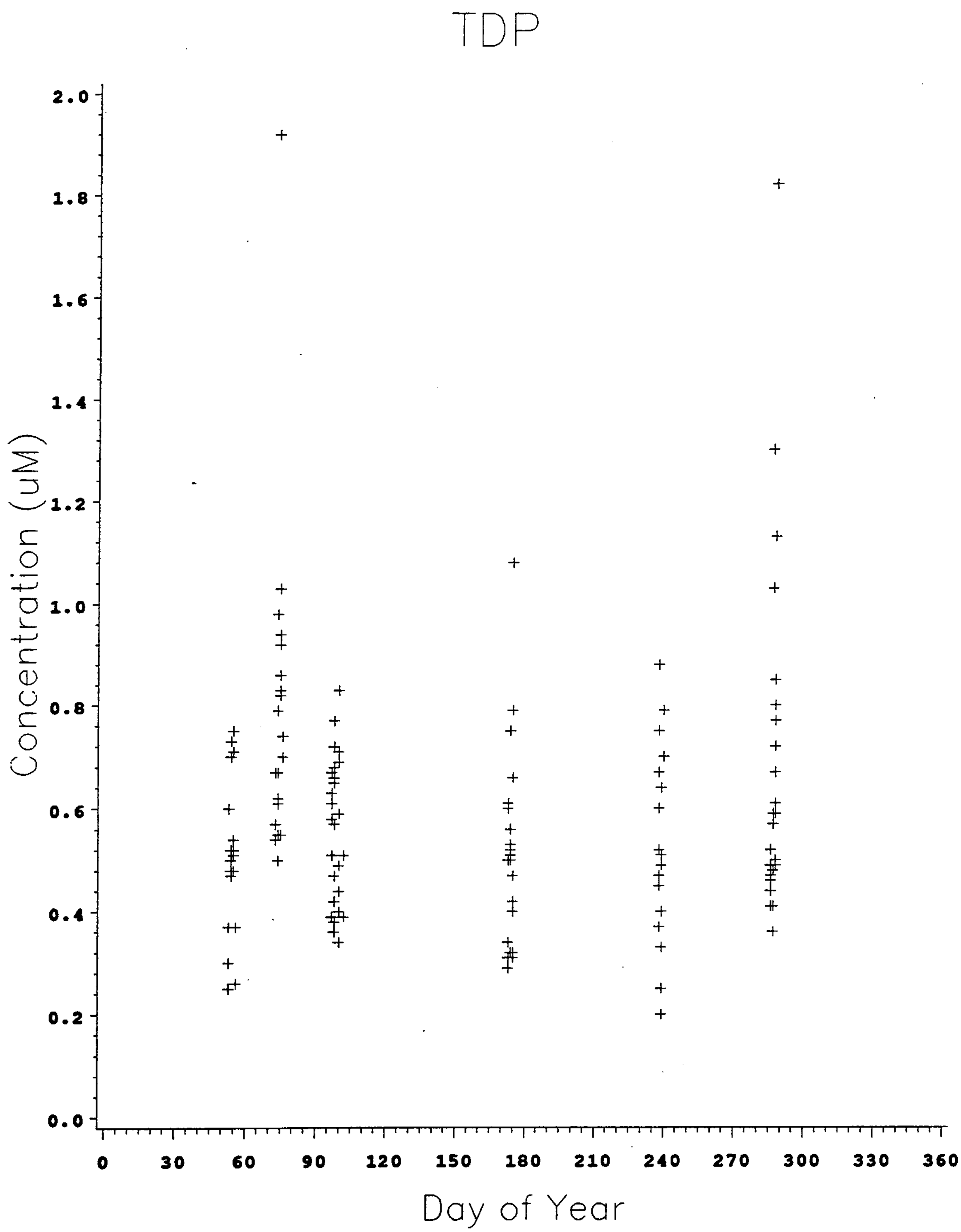


Figure 3-20. Annual TDP cycle at Massachusetts and Cape Cod Bay stations.

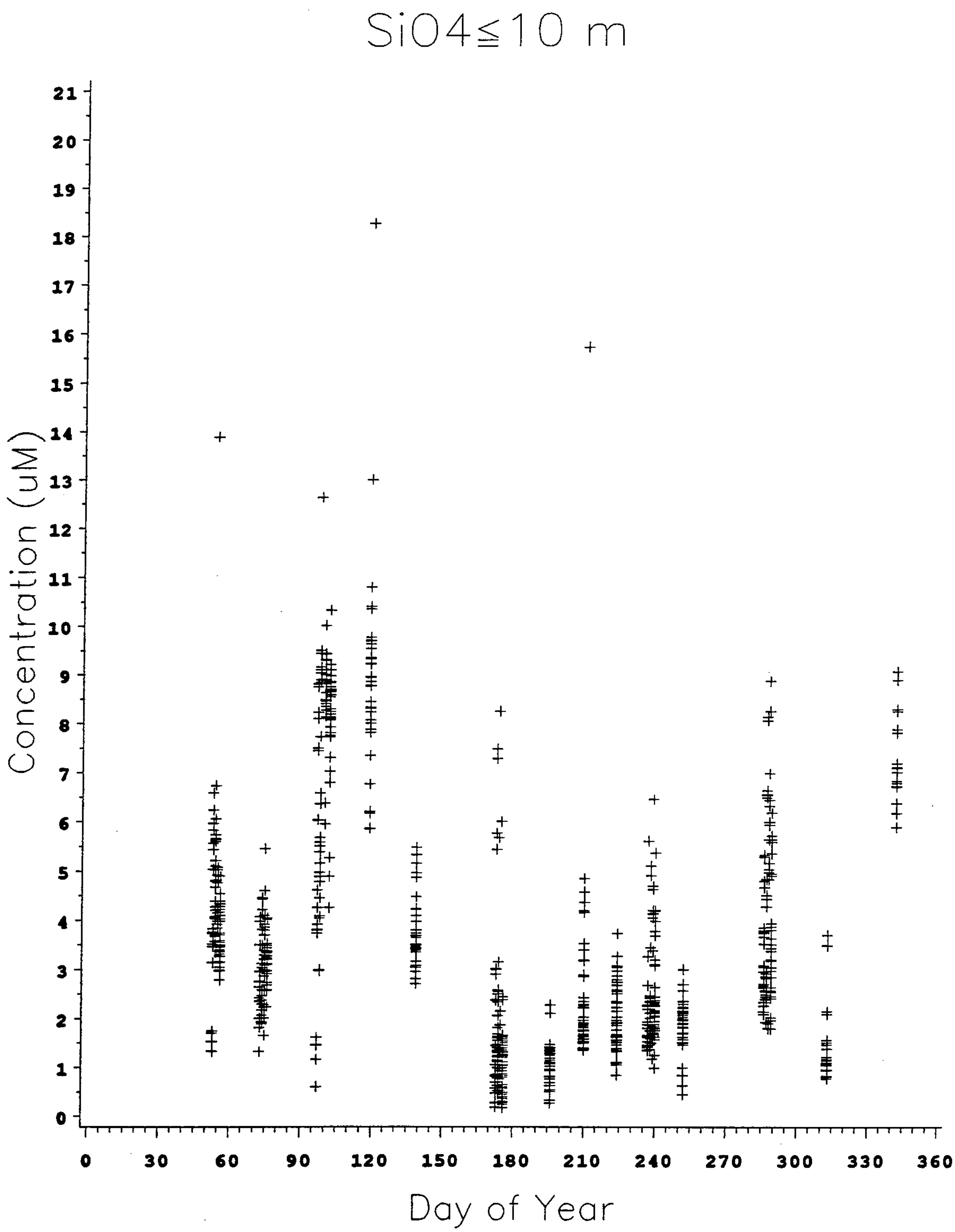


Figure 3-21. Annual SiO_4 cycle in surface water at Massachusetts and Cape Cod Bay stations.

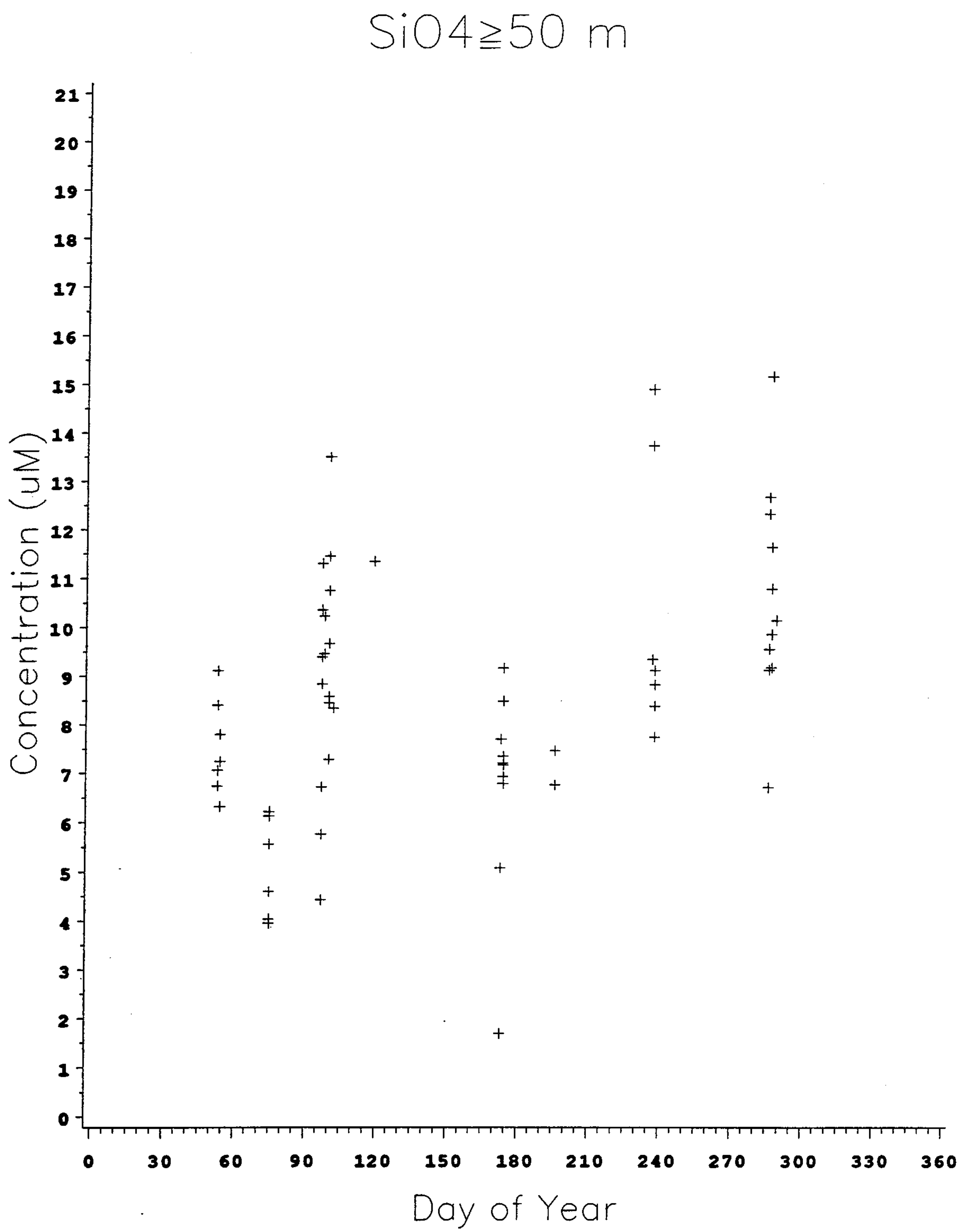


Figure 3-22. Annual SiO_4 cycle in deep water at Massachusetts and Cape Cod Bay stations.

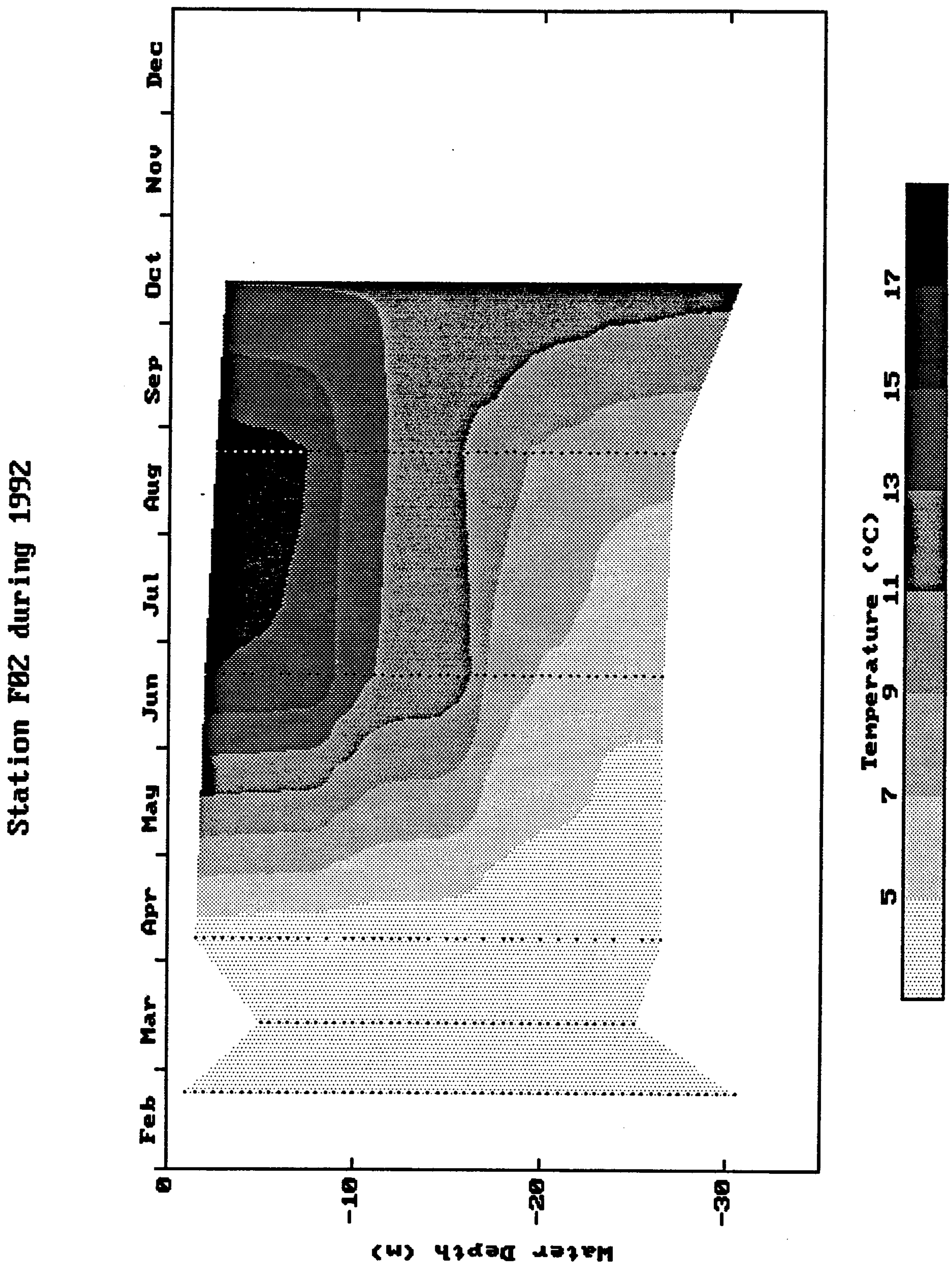


Figure 3-23. Temperature at station F02P (Cape Cod Bay) during 1992.

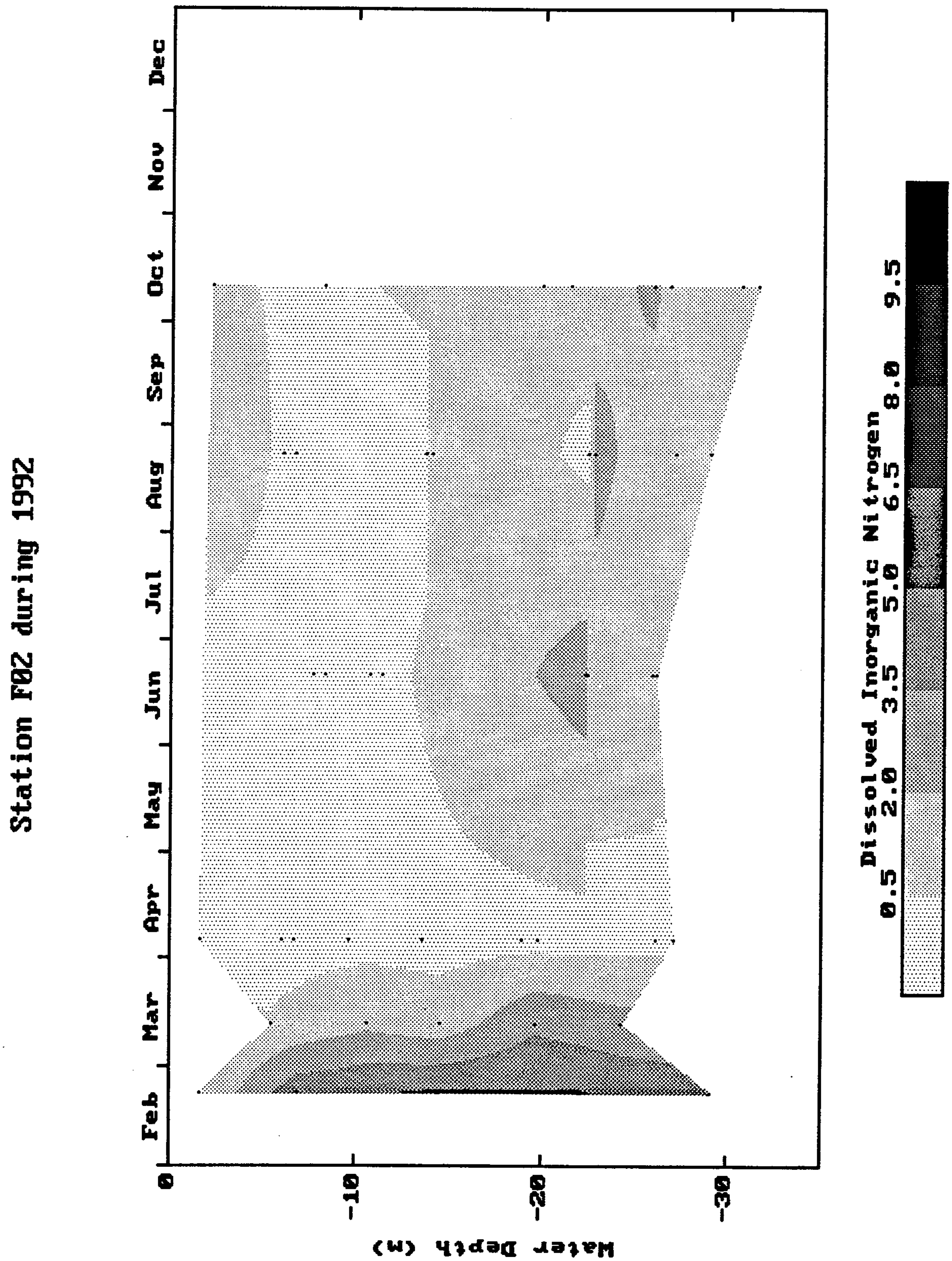


Figure 3-24. DIN at station F02P (Cape Cod Bay) during 1992.

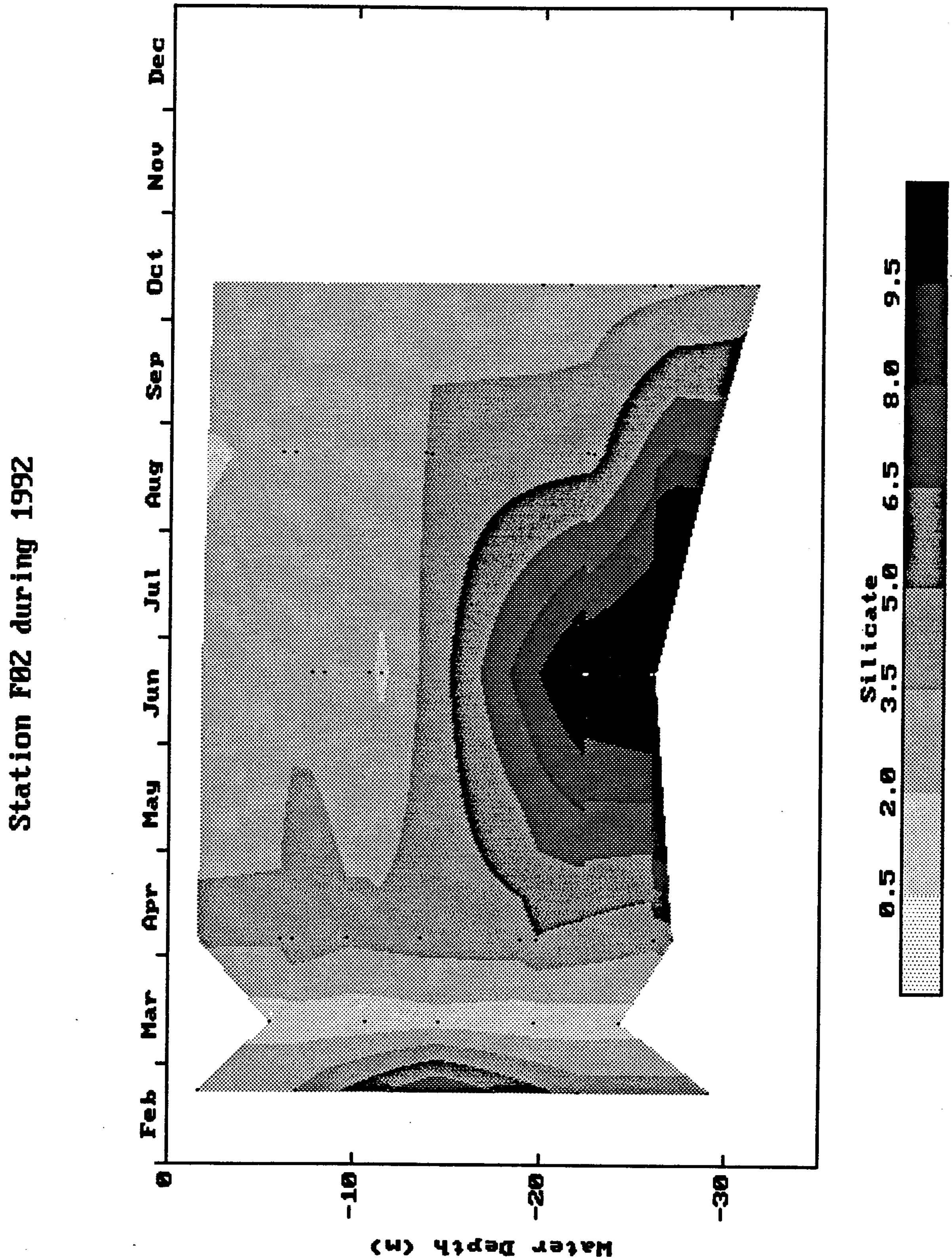


Figure 3-25. Silicate at station F02P (Cape Cod Bay) during 1992.

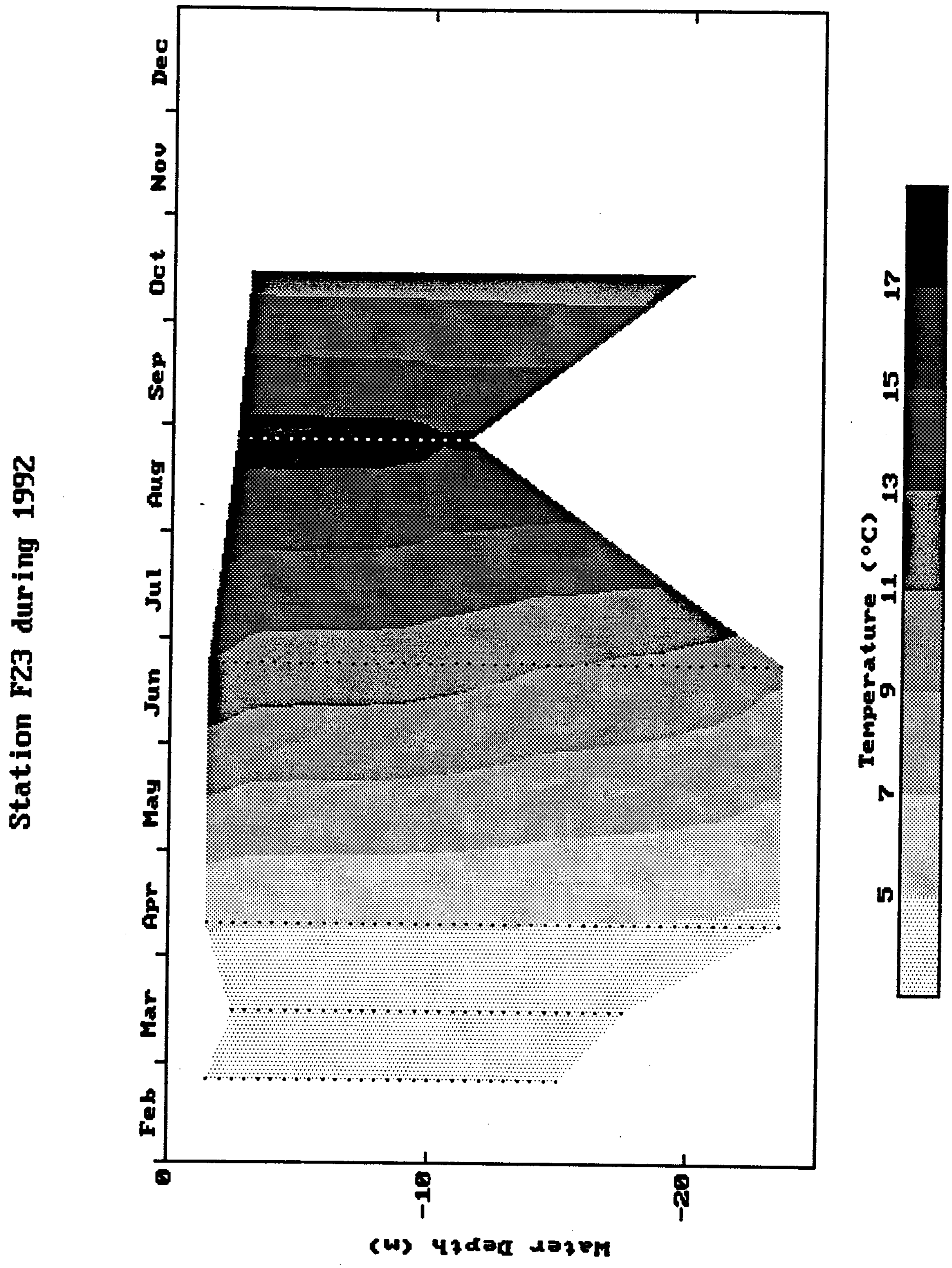


Figure 3-26. Temperature at station F23P (Boston Harbor edge) during 1992.

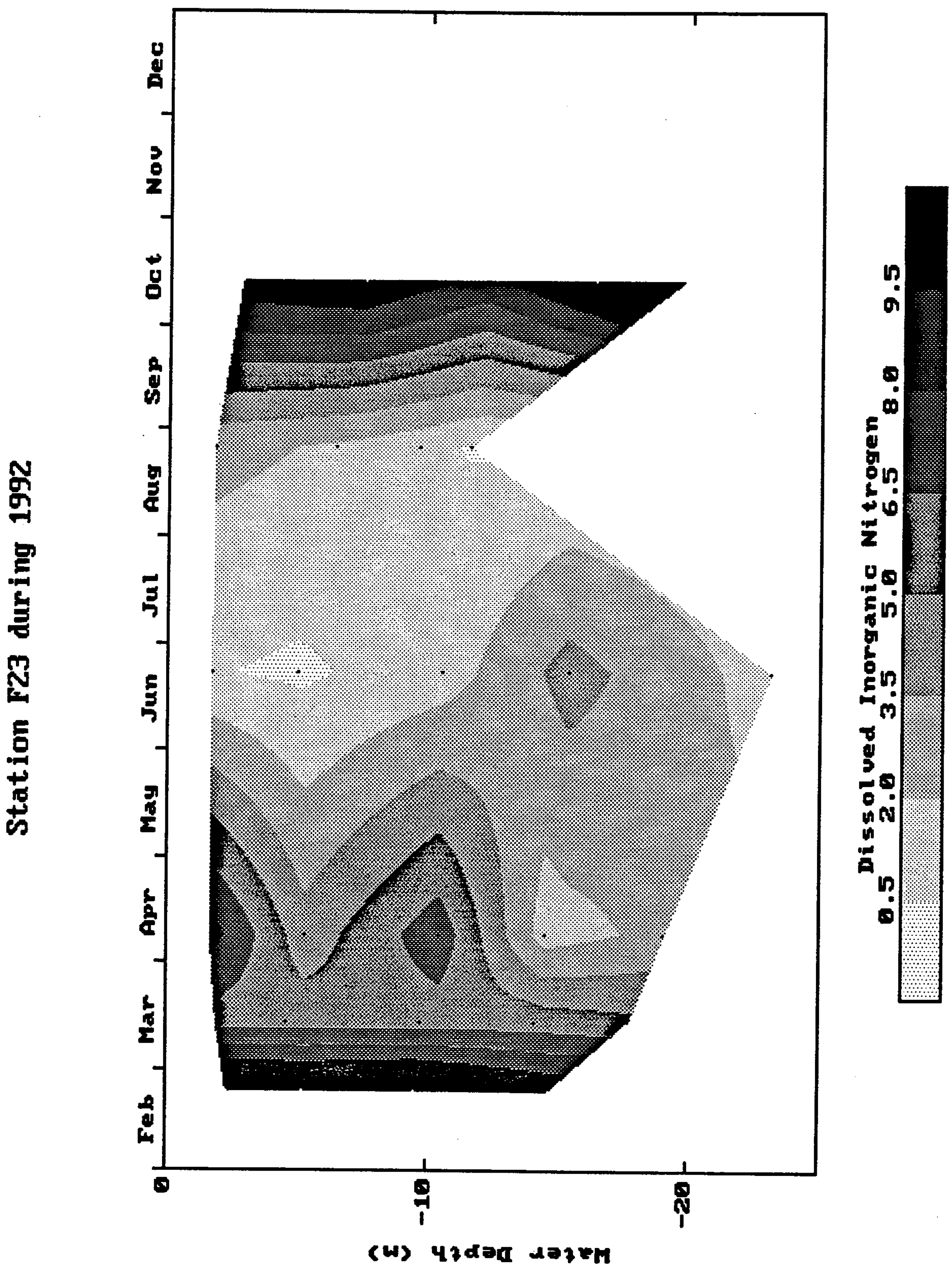


Figure 3-27. DIN at station F23P (Boston Harbor edge) during 1992.

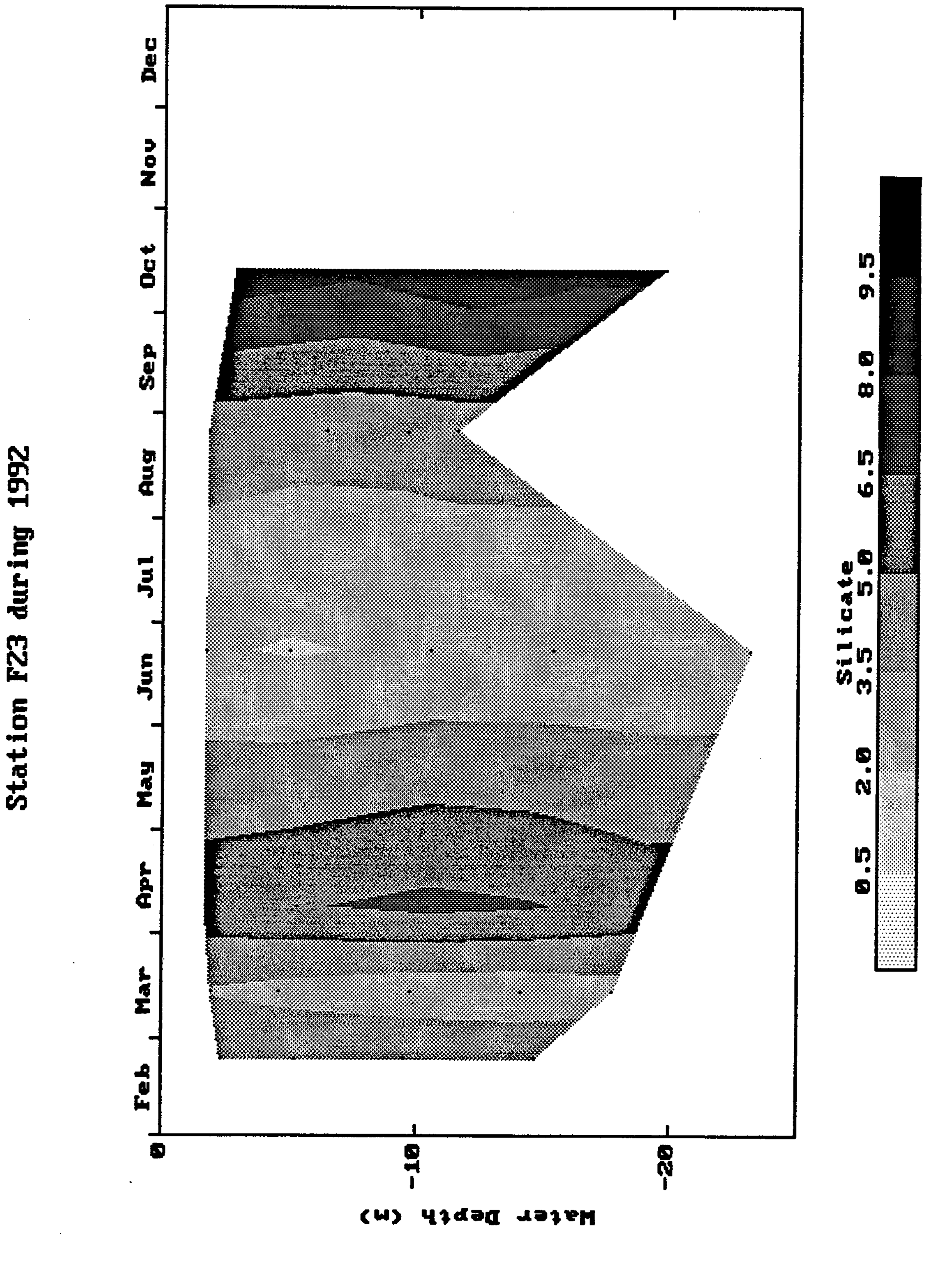


Figure 3-28. Silicate at station F23P (Boston Harbor edge) during 1992.

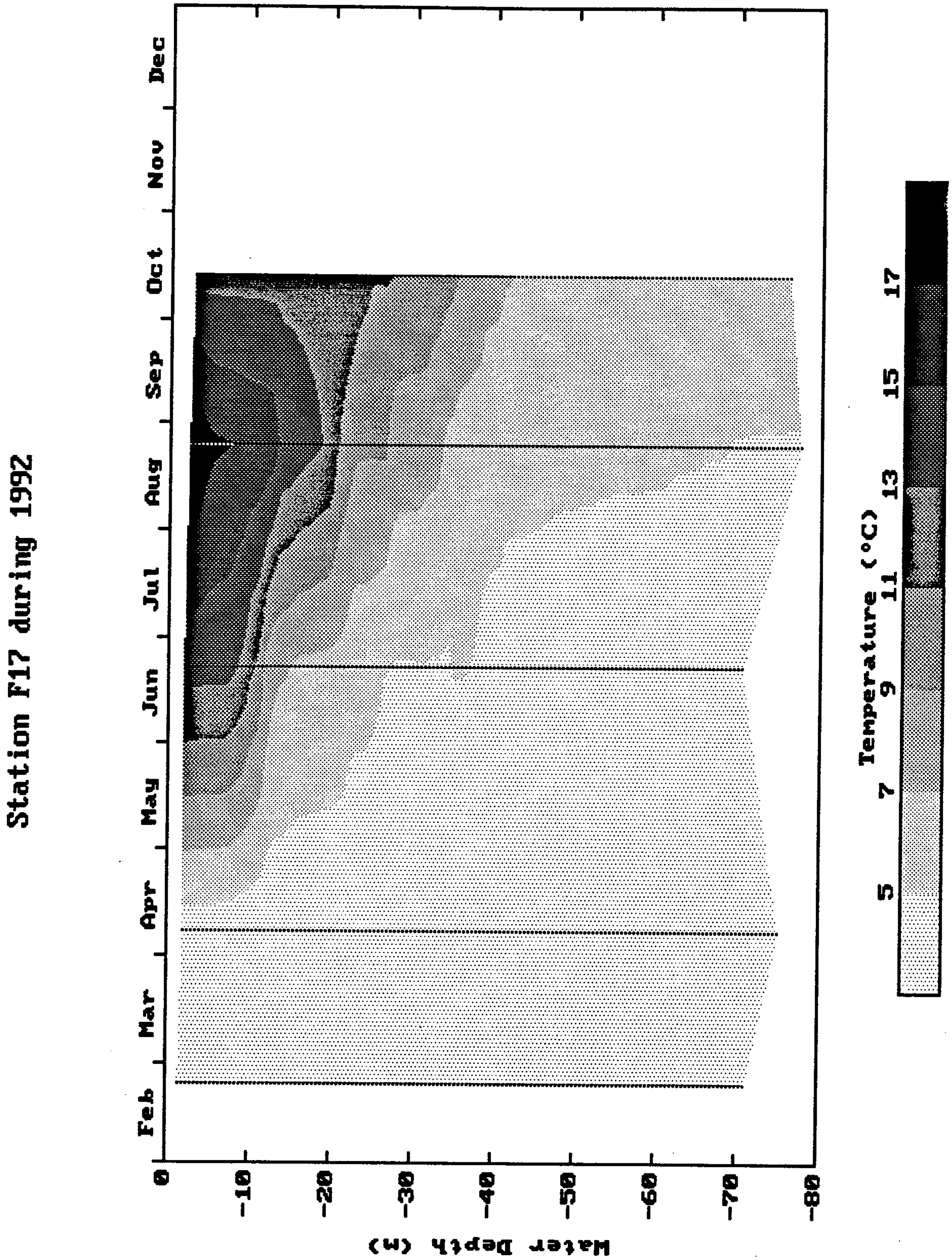


Figure 3-29. Temperature at station F17 (Massachusetts Bay) during 1992.

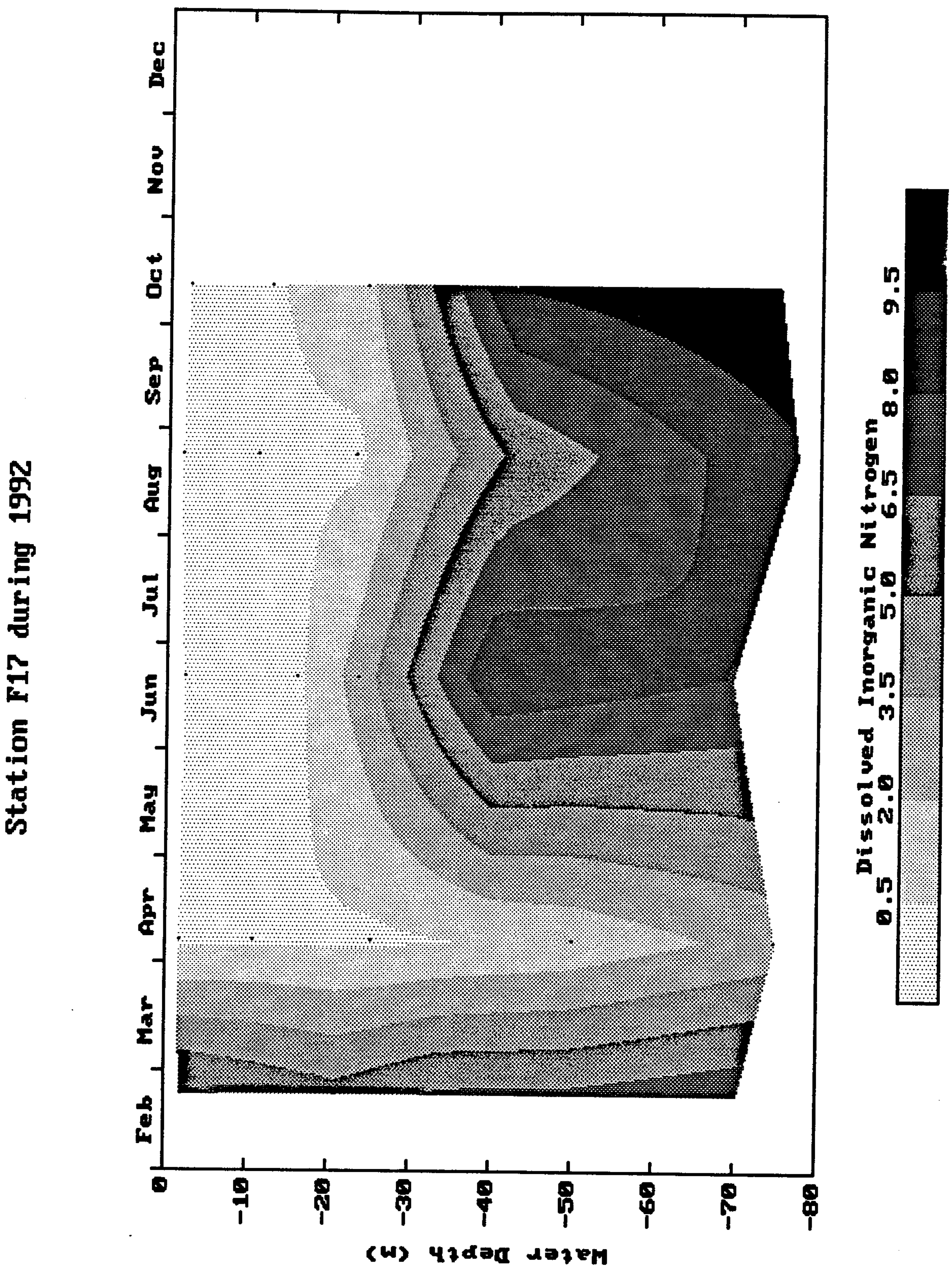


Figure 3-30. DIN at station F17 (Massachusetts Bay) during 1992.

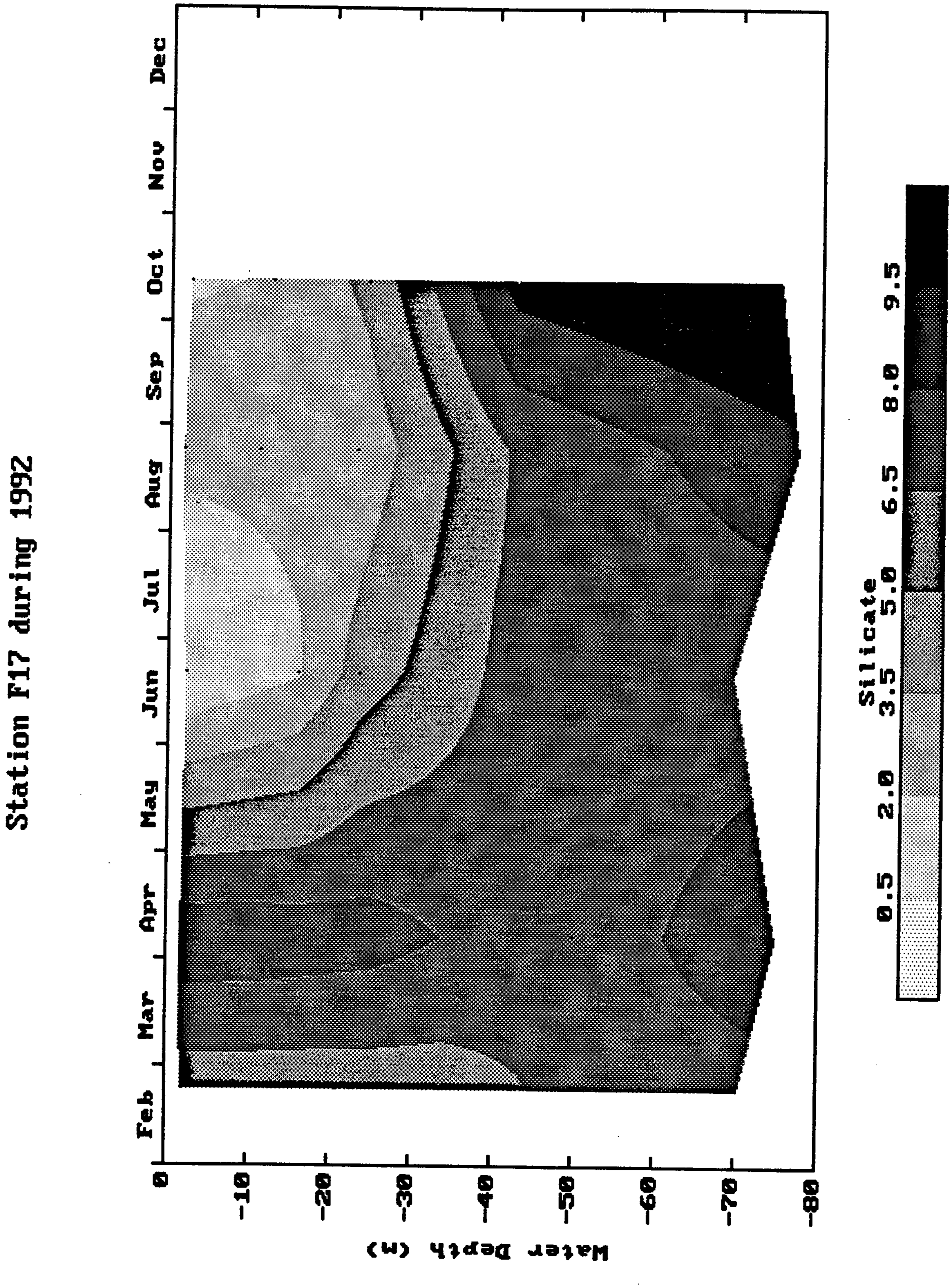


Figure 3-31. Silicate at station F17 (Massachusetts Bay) during 1992.

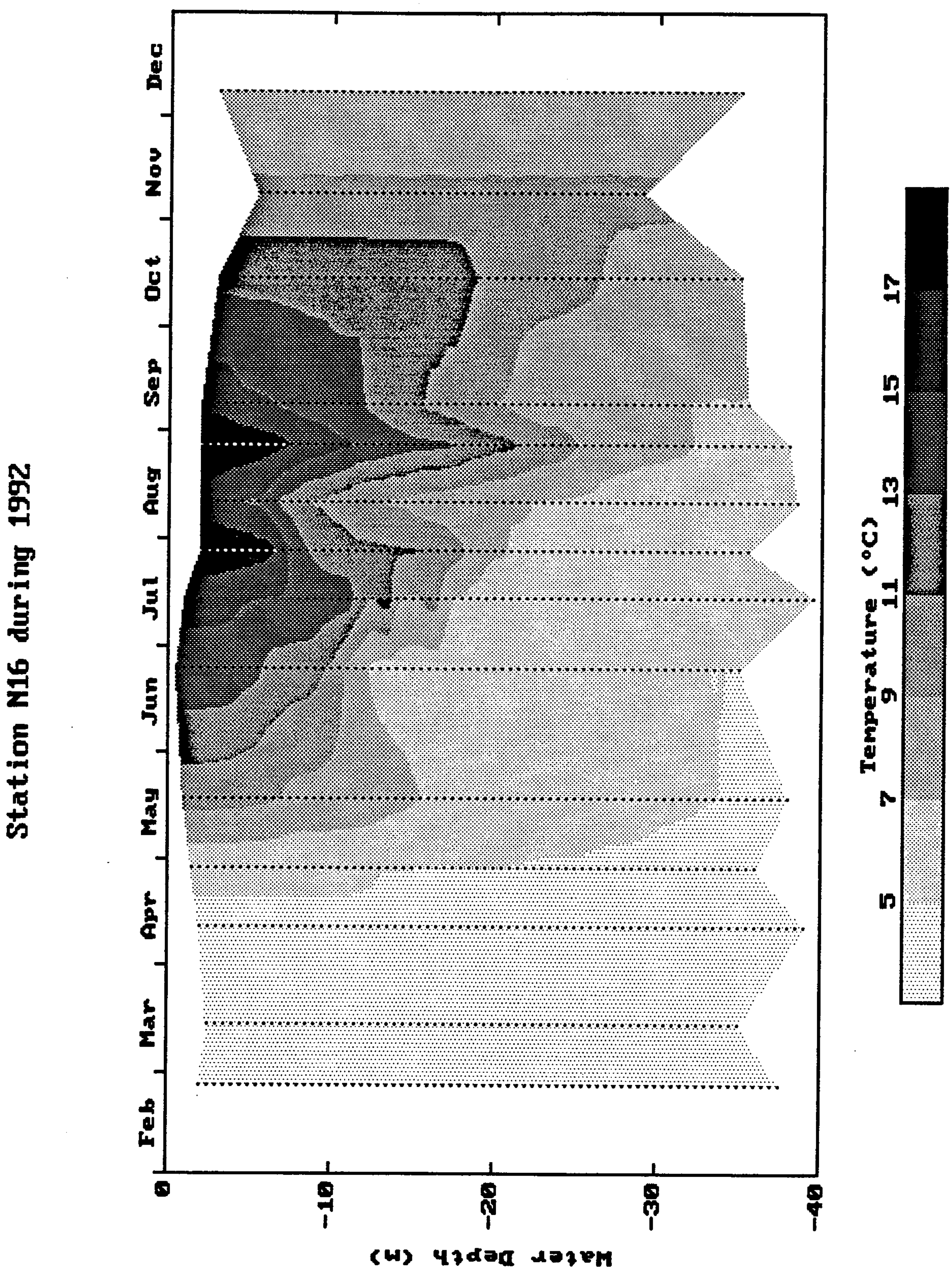


Figure 3-32. Temperature at station N16P (Nearfield) during 1992.

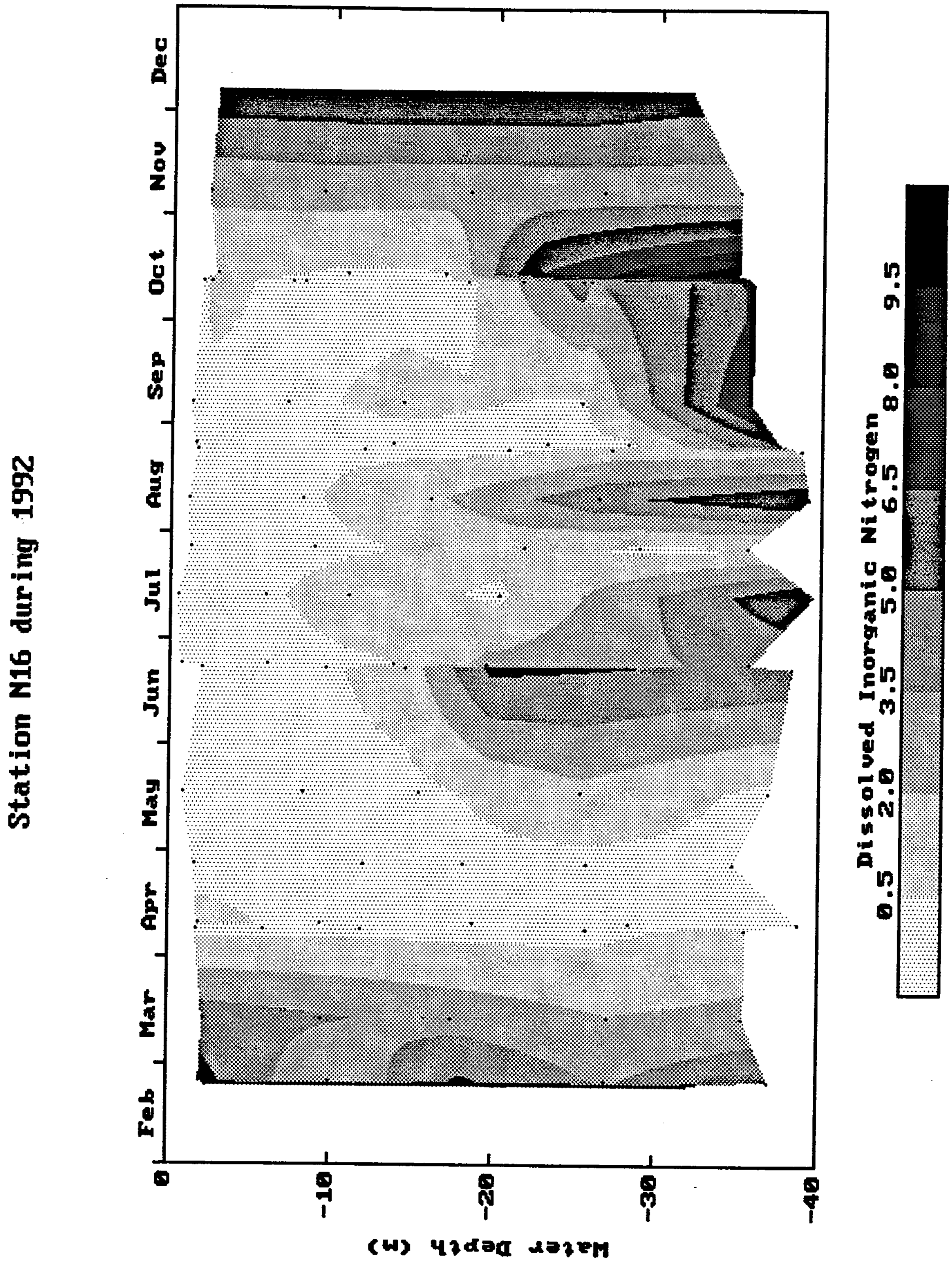


Figure 3-33. DIN at station N16P (Nearfield) during 1992.

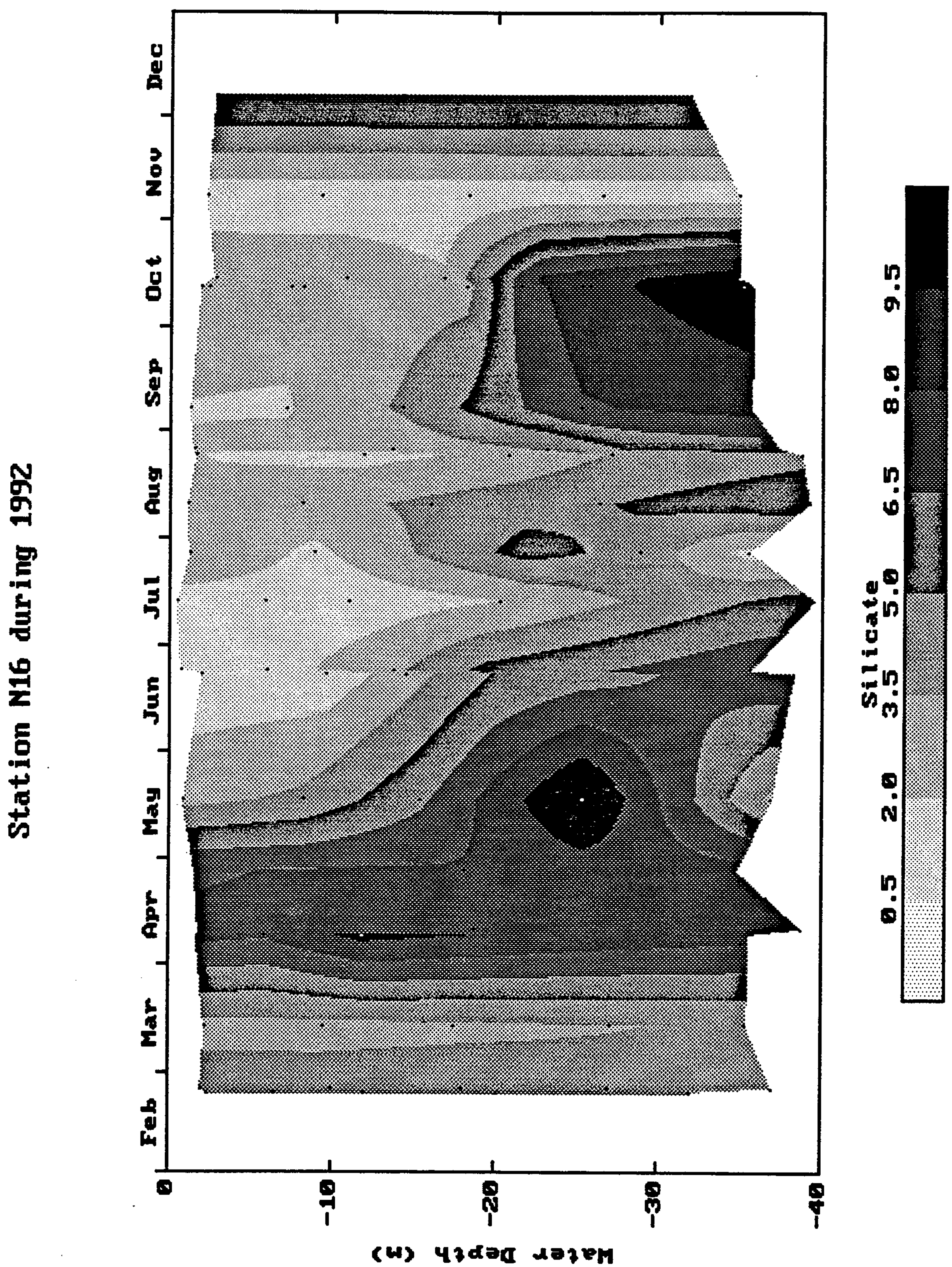


Figure 3-34. Silicate at station N16P (Nearfield) during 1992.

4.0 CHLOROPHYLL

Chlorophyll data are available for all stations (21 nearfield and 25 farfield). Measurements were made as *in situ* fluorescence. For each survey, a small set of chlorophyll *a* measurements was made by standard extraction methods and the *in situ* readings were post-calibrated to derive the reported values (Kelly *et al.*, 1992; 1993a,b). The terms fluorescence and chlorophyll are used interchangeably in this report, and refer to these post-calibrated values. The data described in Section 4.1 and 4.2 represent readings made at the time of closing of the hydrocast bottles for nutrients, so they are directly comparable to the nutrient data series discussed in Section 3. For the station contour plots discussed in Section 4.3, the 0.5-m bin-averaged data from the vertical profile were used.

4.1 Frequency Distribution of Chlorophyll, Including Selected Regional Contrasts

About 2200 fluorescence data points were used in the frequency distribution analysis of 1992 sampling data. Frequency plots were developed to describe samples distribution by concentration class intervals (e.g., 0-1 μg/L, >1-2 μg/L, >2-3 μg/L, etc.).

For the data set that includes all stations, the highest chlorophyll concentrations were >13 μg/L and most (≈75%) samples were in the 0-3 μg/L range (Figure 4-1). About 15-20% of the samples were in the >3-5 μg/L range. Values >5 μg/L were relatively rare, but were observed at the surface of some stations (Figure 4-2). The distribution for surface samples, compared to data from all depths, was more skewed to the lowest concentration class (see mode shift comparing Figures 4-1 and 4-2).

There were some regional differences in surface concentrations (Figures 4-2 and 4-3). For example, the distribution for coastal stations appeared to be shifted to higher concentrations compared to the nearfield stations. Fewer measurements were made in Cape Cod Bay, yet the extremes, both high and low concentrations, for the total data set were observed there.

4.2 Annual Cycle of Chlorophyll

Was an annual cycle evident for chlorophyll? There is considerable variability, with some higher values above 6 μg/L detected from February through October if data over all depths are examined (Figure 4-4). High values occurred at the surface, even during the summer period (Figure 4-5). On average, it appears that a seasonal cycle was evident at the surface, with the relatively high winter-spring concentrations diminished by April, variable but mostly low during the summer, and a fall peak associated with breakdown of thermal stratification in October. The data in Figure 4-5 suggest that extreme high concentrations may occur briefly in winter, but more frequently during the late summer/early fall period (August-September).

Fluorescence was generally low, as expected, in deep waters in the Bay (Figure 4-6), but there may be a seasonal signature influenced by activity in the euphotic surface waters. In March, and particularly in April, sinking of plankton cells was suggested by profiles at many stations (Kelly *et al.*, 1993a). Samples with higher fluorescence were detected at this time in deep waters, most likely signaling some seasonal input to the bottom that occurs as stratification begins, as nutrients are depleted to limiting levels, and as the winter-spring bloom terminates.

4.3 Annual Cycle of Chlorophyll at Selected Stations

As presented in Section 3, the same selection of four stations from different regions is used to illustrate chlorophyll distribution. These stations are F02P in Cape Cod Bay, F23P at the edge of Boston Harbor off Deer Island, F17 in deep water in Stellwagen Basin, and N16P near the center of the nearfield. Also included are plots for stations N10P and N12, along the western edge of the nearfield and influenced by the Harbor, as well as station N20P, only a short distance from N16P to the west near the center of the nearfield. Again, the farfield station plots (Figures 4-7 through 4-9) are based on six surveys, whereas the nearfield station plots (Figures 4-10 through 4-13) are based on 14 surveys, so the latter are richer in detail.

The regional contrasts are interesting. Note that the Cape Cod Bay and offshore stations are reasonably representative of their respective regions even though each region had some station-to-station variability. The Boston Harbor edge (station F23P) was continuously high in chlorophyll throughout the summer, always higher than during winter-spring and fall. Having a strong and consistent nutrient source, this area is arguably more light limited and, thus, the chlorophyll distribution throughout the year, in part, reflects seasonal variation in irradiance. In contrast, both F02P in Cape Cod Bay and F17 in Stellwagen Basin show classical winter-spring and fall bloom dynamics with higher chlorophyll throughout a well-mixed water column. In June, between these blooms, both Cape Cod Bay stations had a mid-depth chlorophyll maximum which was especially intense at station F02P and occurred near the base of a well-developed pycnocline (Appendix). In contrast, a relatively intense subsurface chlorophyll maximum (about 25 m) in April at station F17 offshore occurred during well-mixed conditions and a pycnocline was lacking (Appendix); some apparent deepening and intensification of subsurface chlorophyll concentrations were noted in April (Kelly *et al.*, 1993a) and the higher concentrations at depth (based on fluorescence may be a patch of sinking cells rather than a resident deepwater community of phytoplankton. For the nearfield region (Figures 4-10 to 4-13) in general, the stations toward the west (N10P, N12, and N20P) tended to have high chlorophyll throughout much of the water column during summer and fall. Station N16P is in the eastern half of the nearfield at one end of the proposed diffuser track. Although chlorophyll distributions at N16P had a broadly similar time pattern to N20P (near the other, western, end of the proposed diffuser track), concentrations at N16P did not reach peak levels observed at N20P, N10P, and N12. When one begins to examine the data in detail, a notable feature of the nearfield is the large variability in time-space patterns across stations of the nearfield region.

As suggested by the time trends with all data (Section 4.2), chlorophyll distributions tend to be patchy in time and this was shown in many nearfield station plots. But chlorophyll also was patchy in space as can be seen by comparing some stations within the nearfield that are close to each other. For example, stations N10P and N12, separated by only several kilometers and both apparently influenced by Harbor nutrient outflows, show approximately the same general time pattern, punctuated by intense events, but the concentrations and time patterns reveal a number of differences that are obvious when the plots are more closely inspected. The difference between stations N16P and N20P, the latter being only kilometers to the west of the former, are perhaps more striking. This area seems to be the location of sporadic offshore and inshore water-mass fronts (Townsend *et al.*, 1991; Kelly, 1991; Kelly *et al.*, 1992; 1993a,b), and N20P is more subject to advection and mixing of water and nutrients from Boston Harbor. More frequent and intense chlorophyll events throughout the water column in summer appear at station N20P.

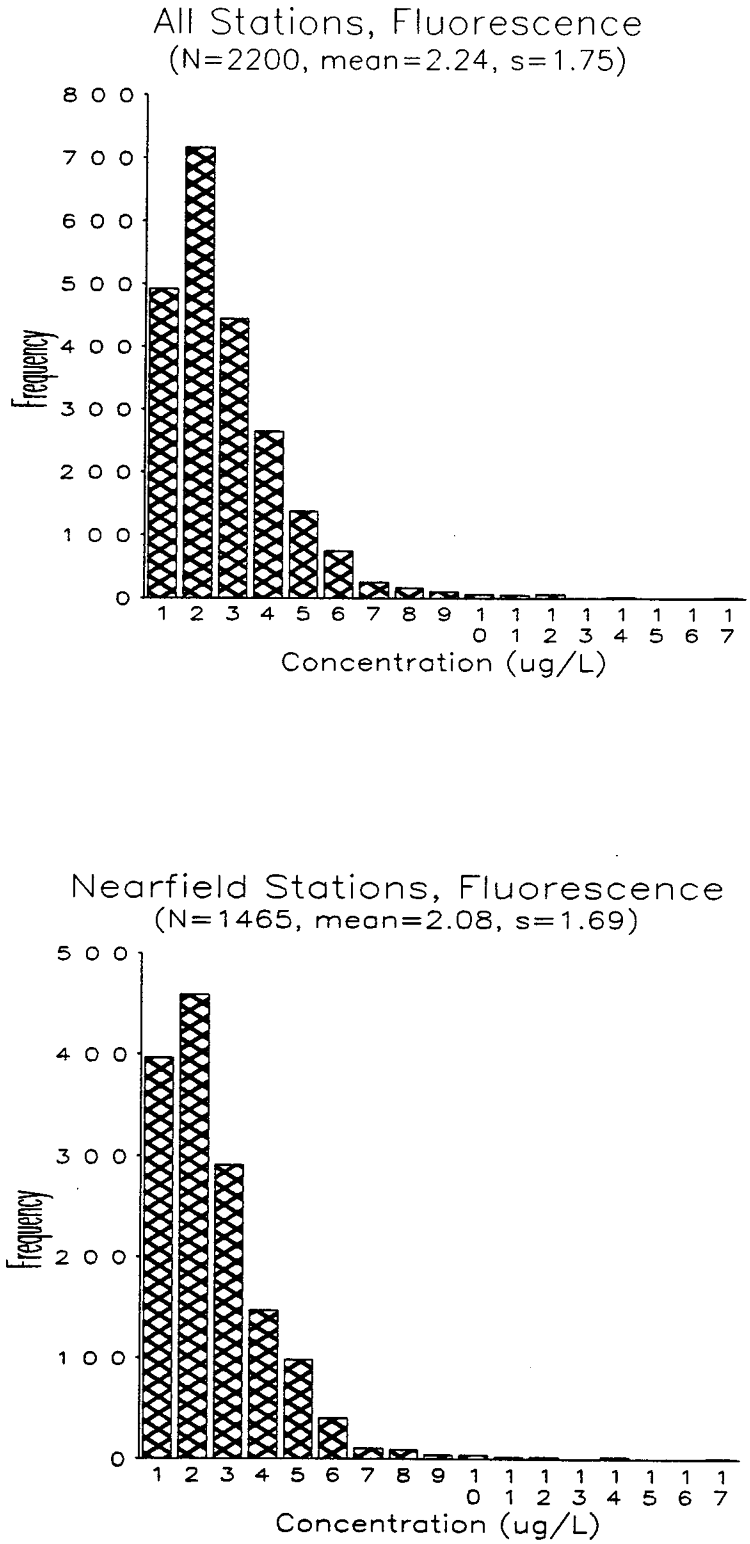
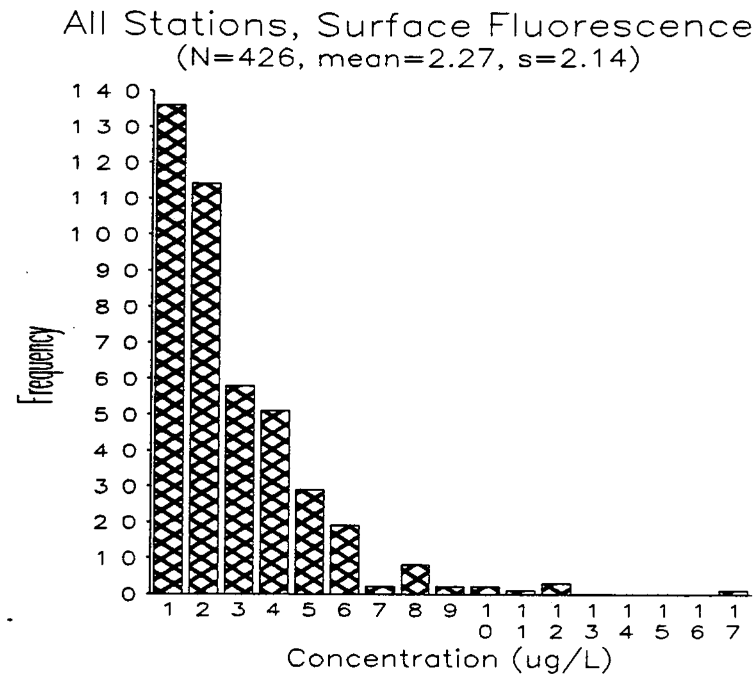


Figure 4-1. Chlorophyll frequency distribution for all 1992 data, all stations and nearfield stations.



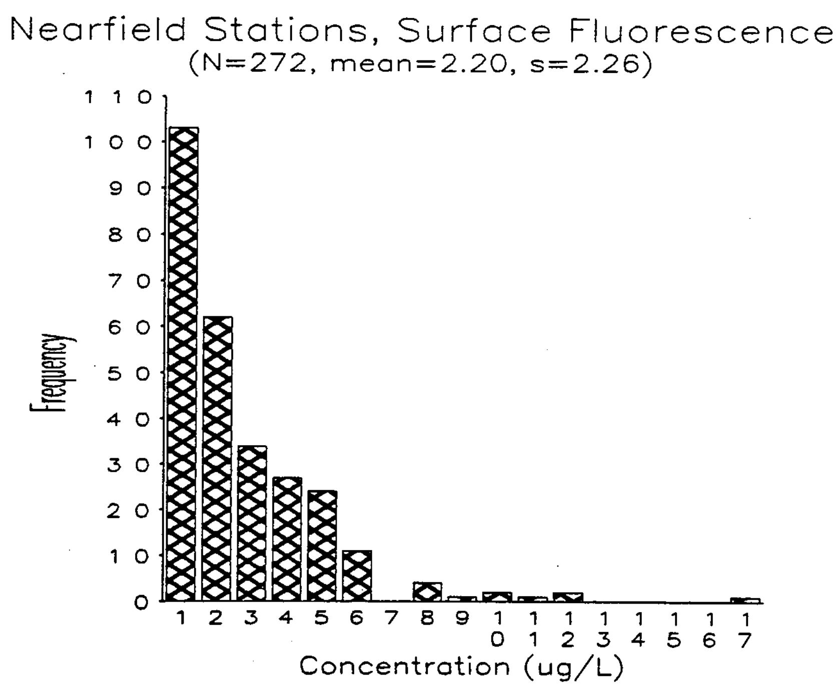
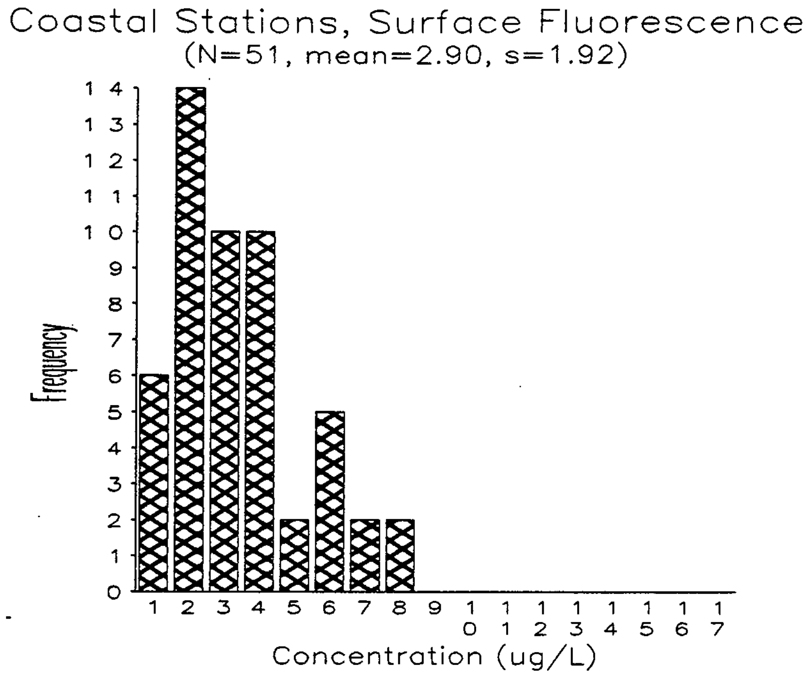


Figure 4-2. Chlorophyll frequency distribution for surface samples, all stations and nearfield stations.



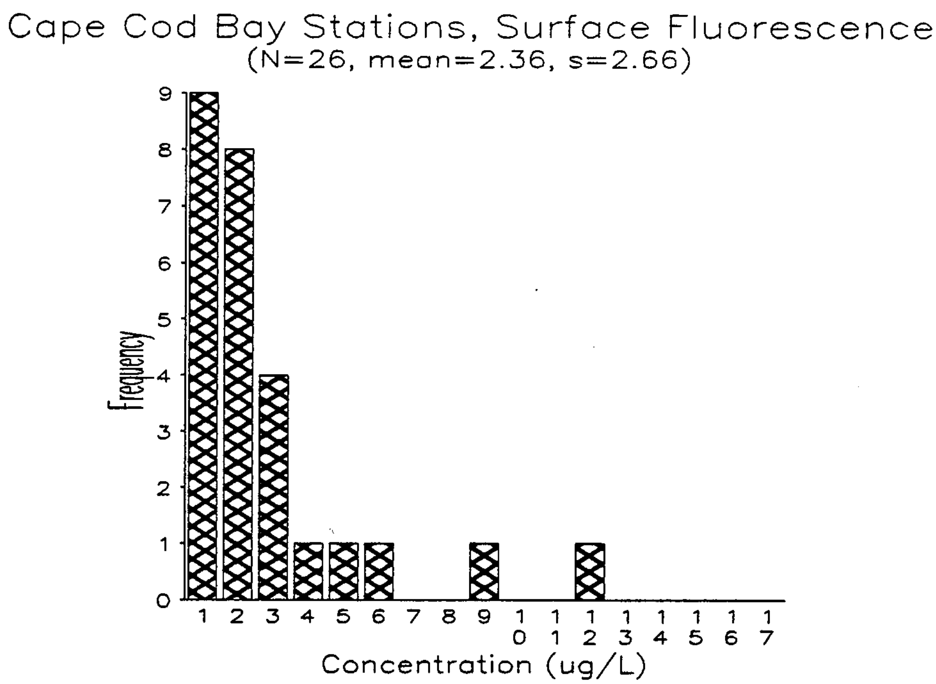


Figure 4-3. Chlorophyll frequency distribution for surface samples at coastal stations (F5, F9, F13P, F14, F18, F23P, F24, F25) and Cape Cod Bay stations (F01P, F02P, F03, F04).

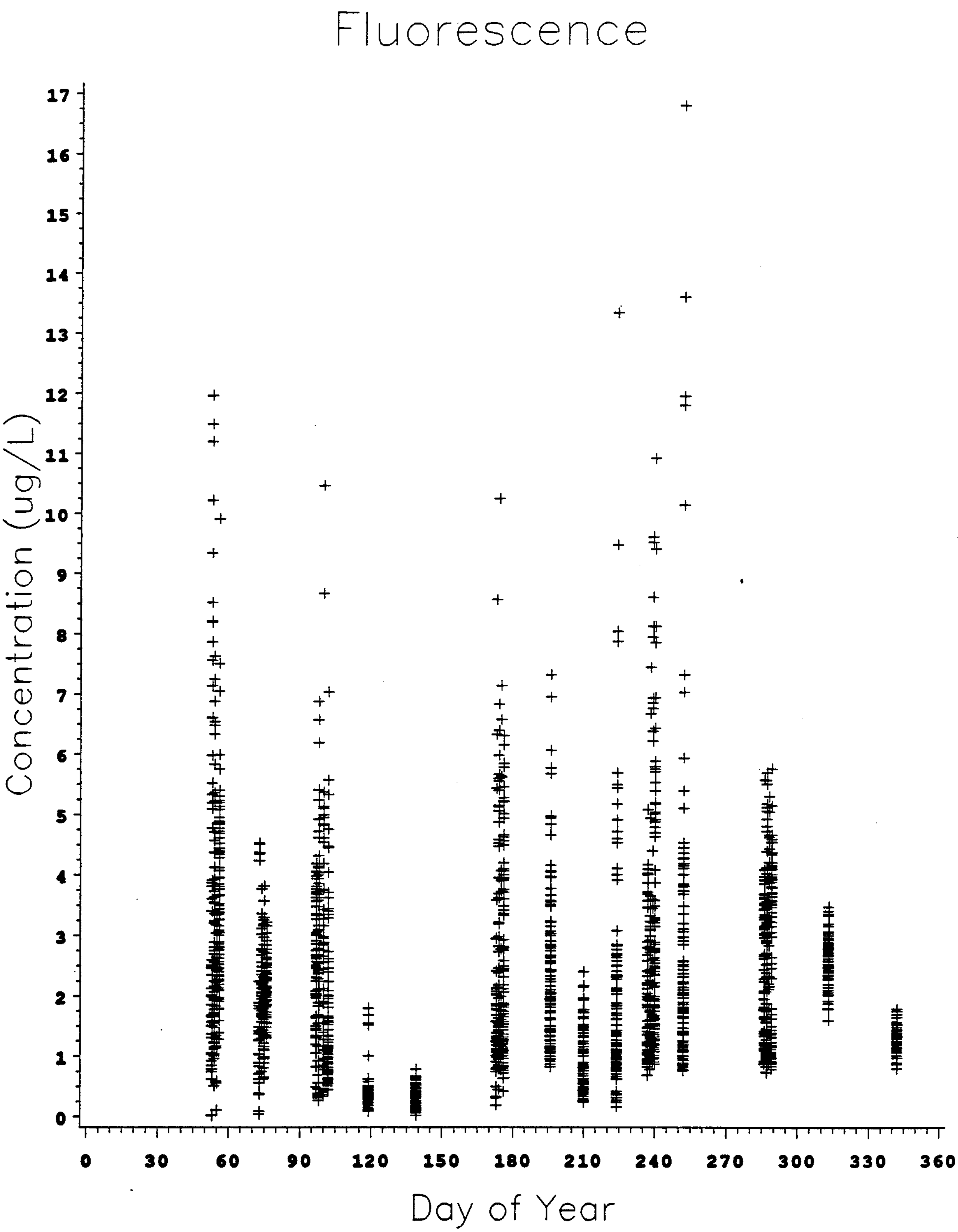


Figure 4-4. Annual fluorescence (chlorophyll) cycle over all depths at Massachusetts and Cape Cod Bay stations.

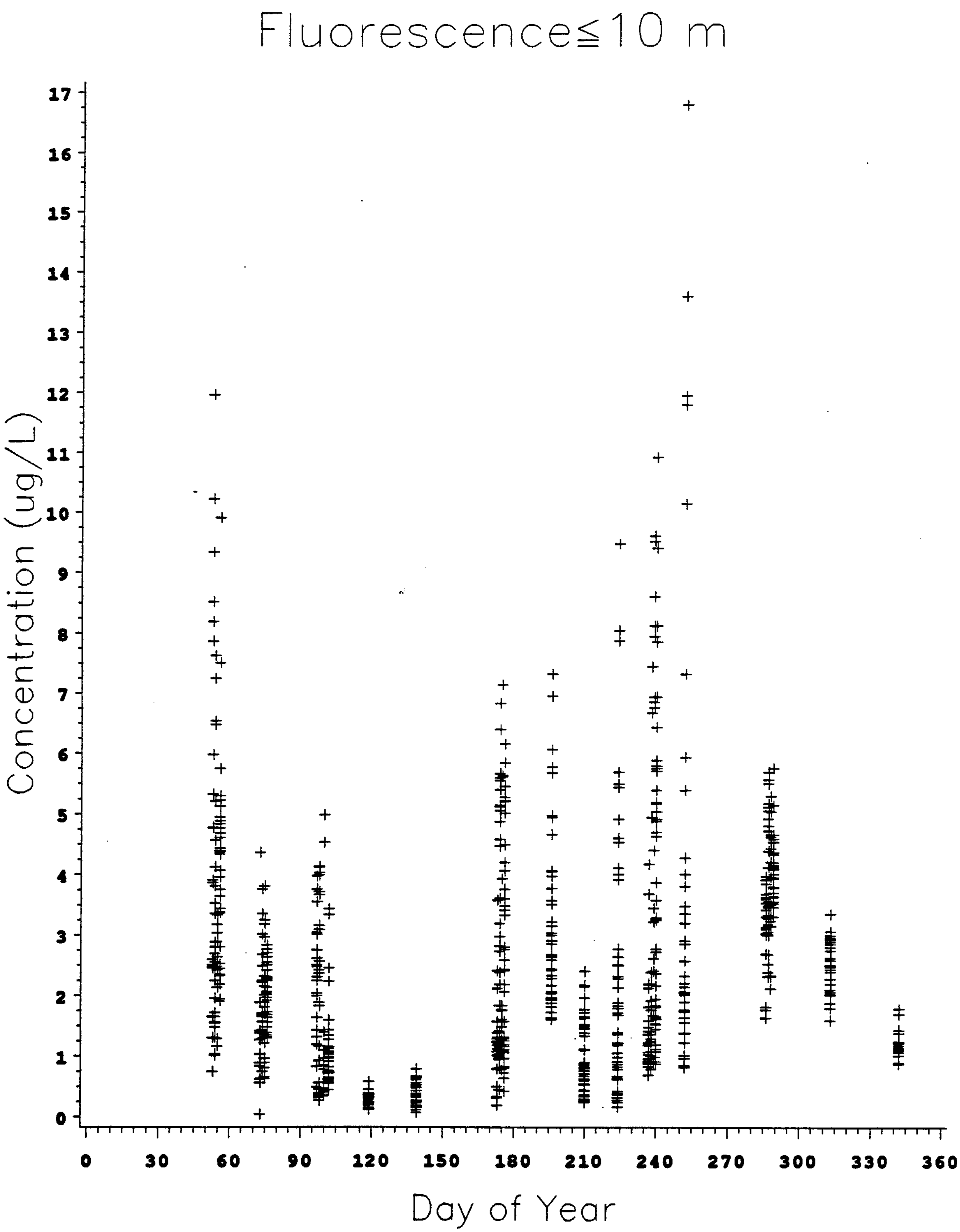


Figure 4-5. Annual fluorescence (chlorophyll) cycle in surface water at Massachusetts and Cape Cod Bay stations.

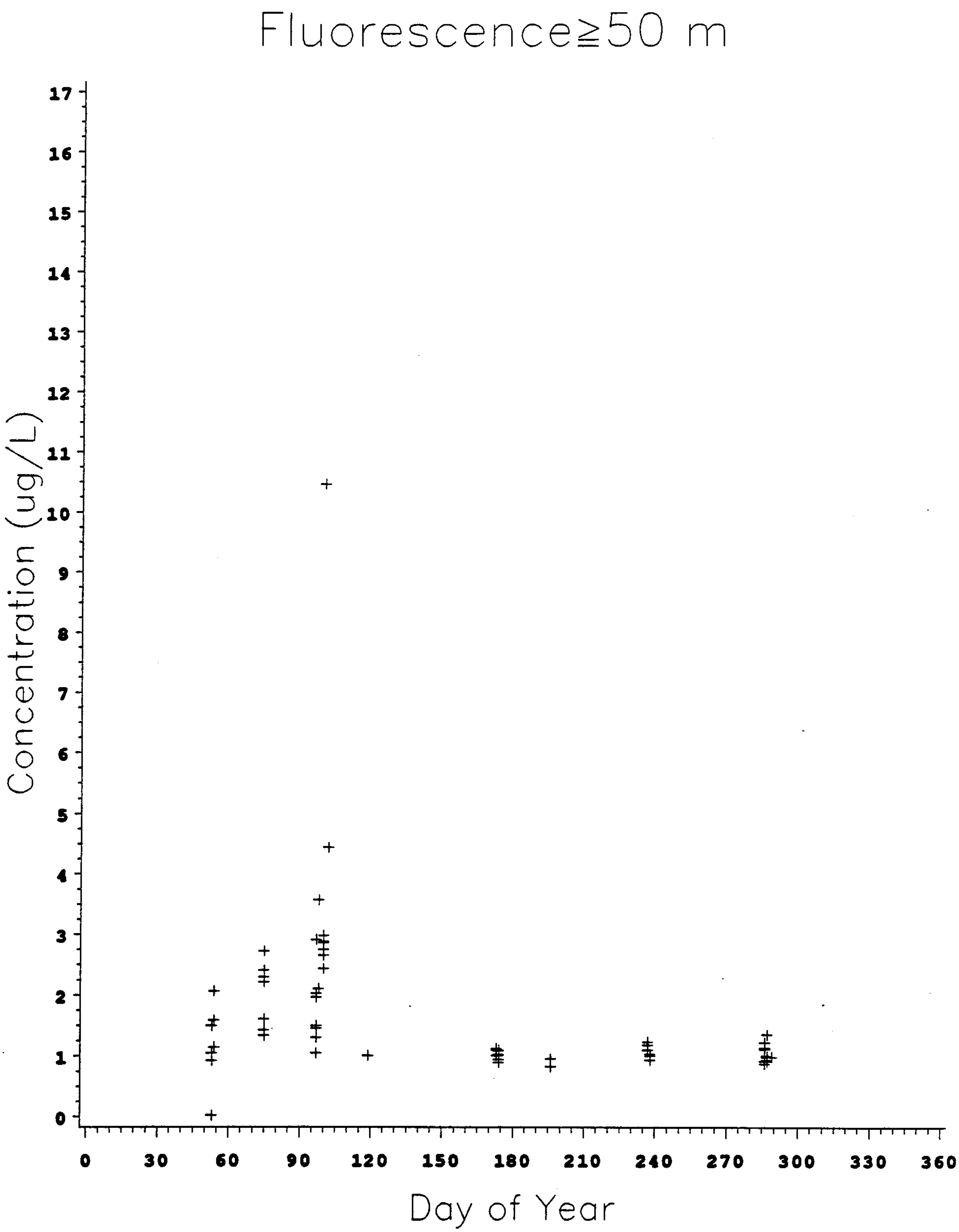


Figure 4-6. Annual fluorescence (chlorophyll) cycle in deep water at Massachusetts and Cape Cod Bay stations.

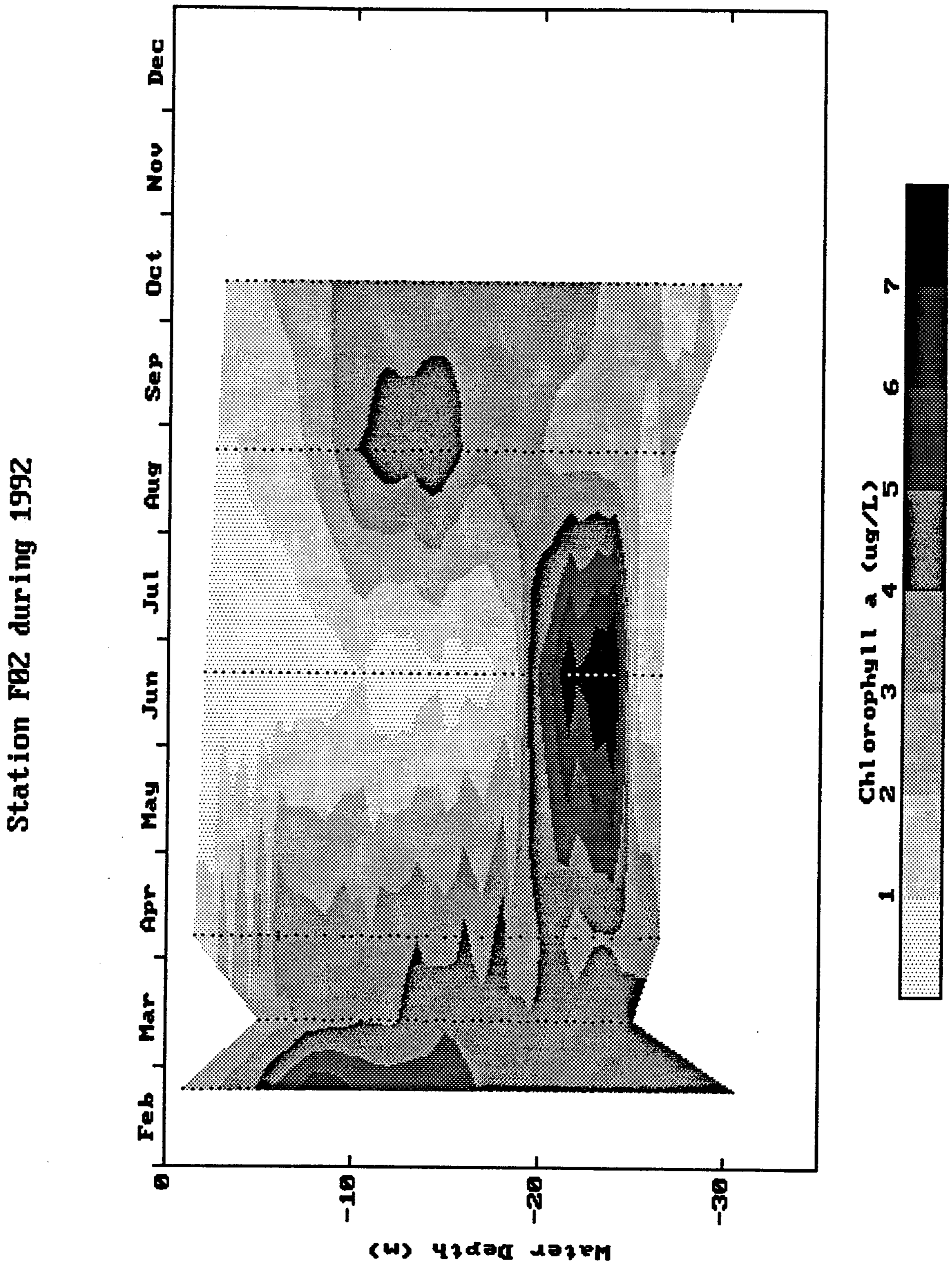


Figure 4-7. Chlorophyll at station F02P (Cape Cod Bay) during 1992.

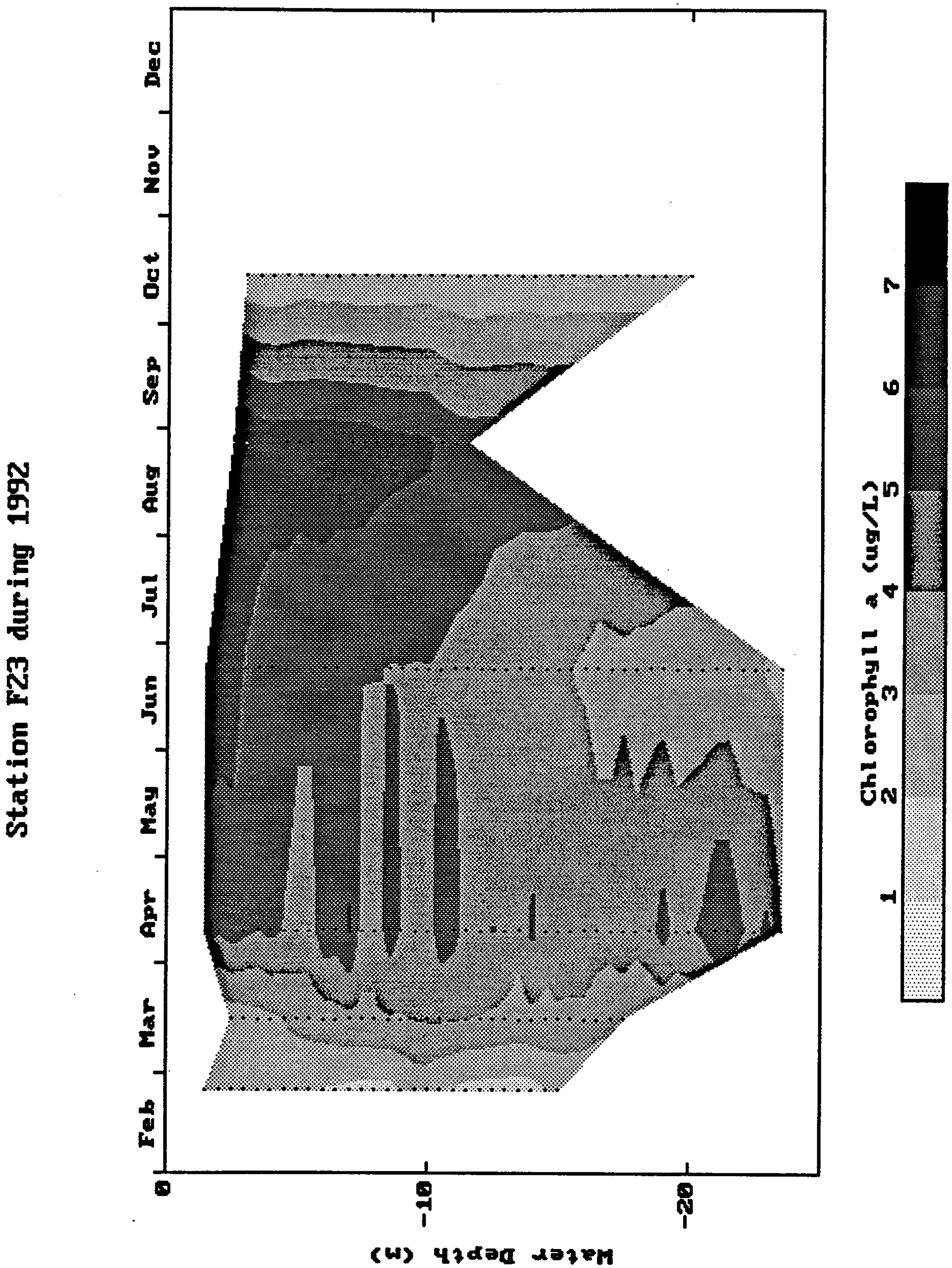


Figure 4-8. Chlorophyll at station F23P (Boston Harbor edge) during 1992.

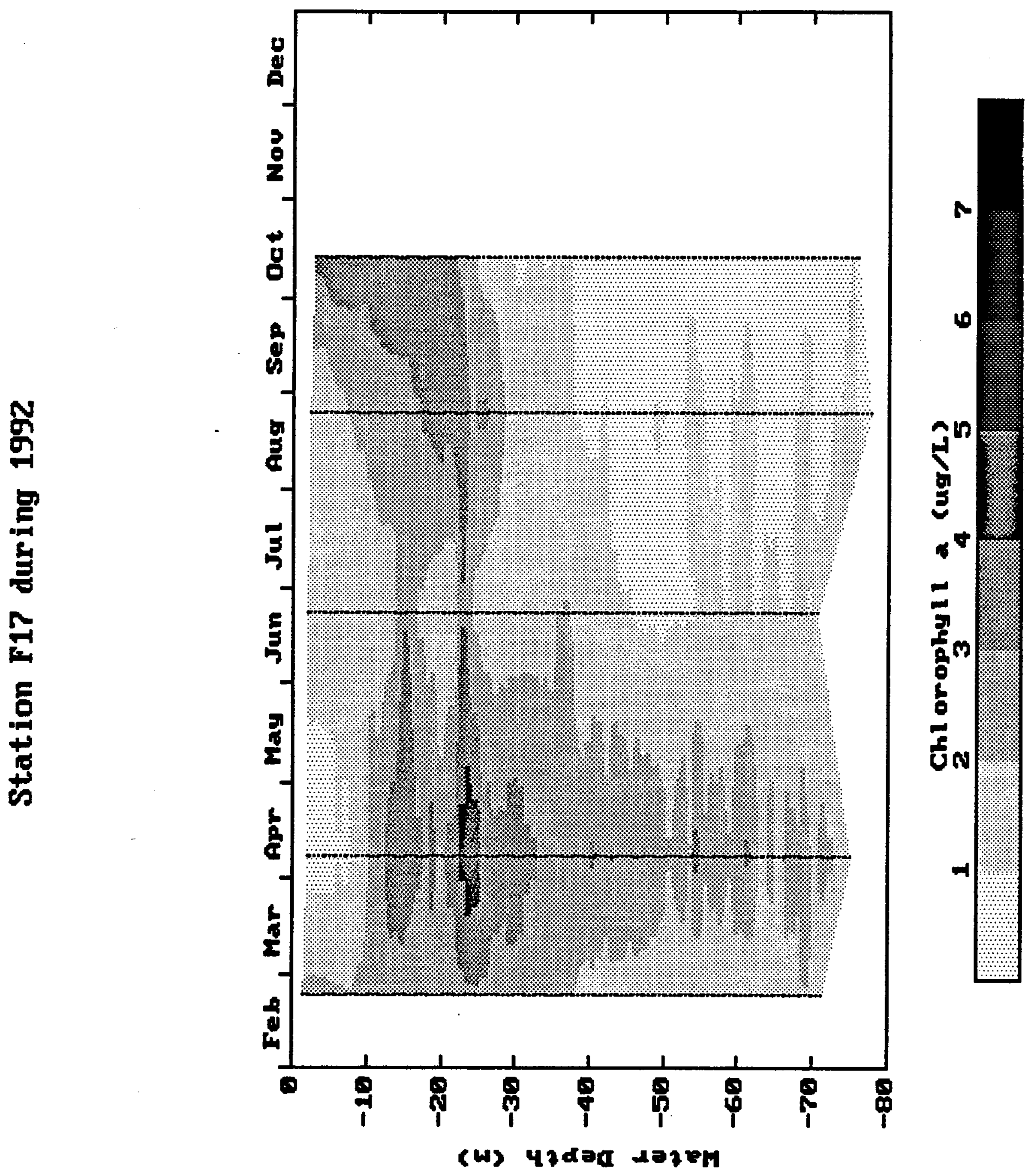


Figure 4-9. Chlorophyll at station F17 (Massachusetts Bay) during 1992.

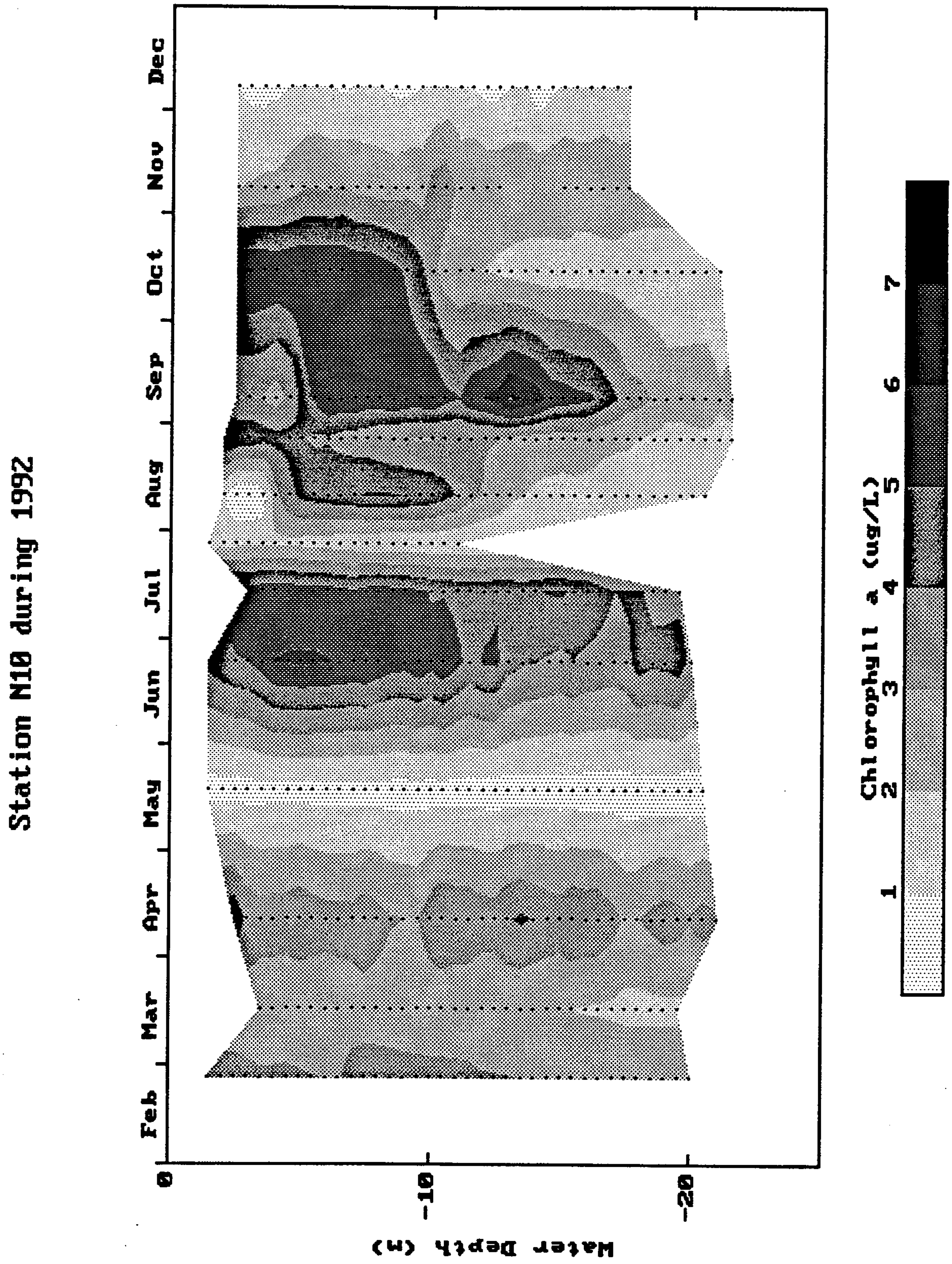


Figure 4-10. Chlorophyll at station N10P (Nearfield) during 1992.

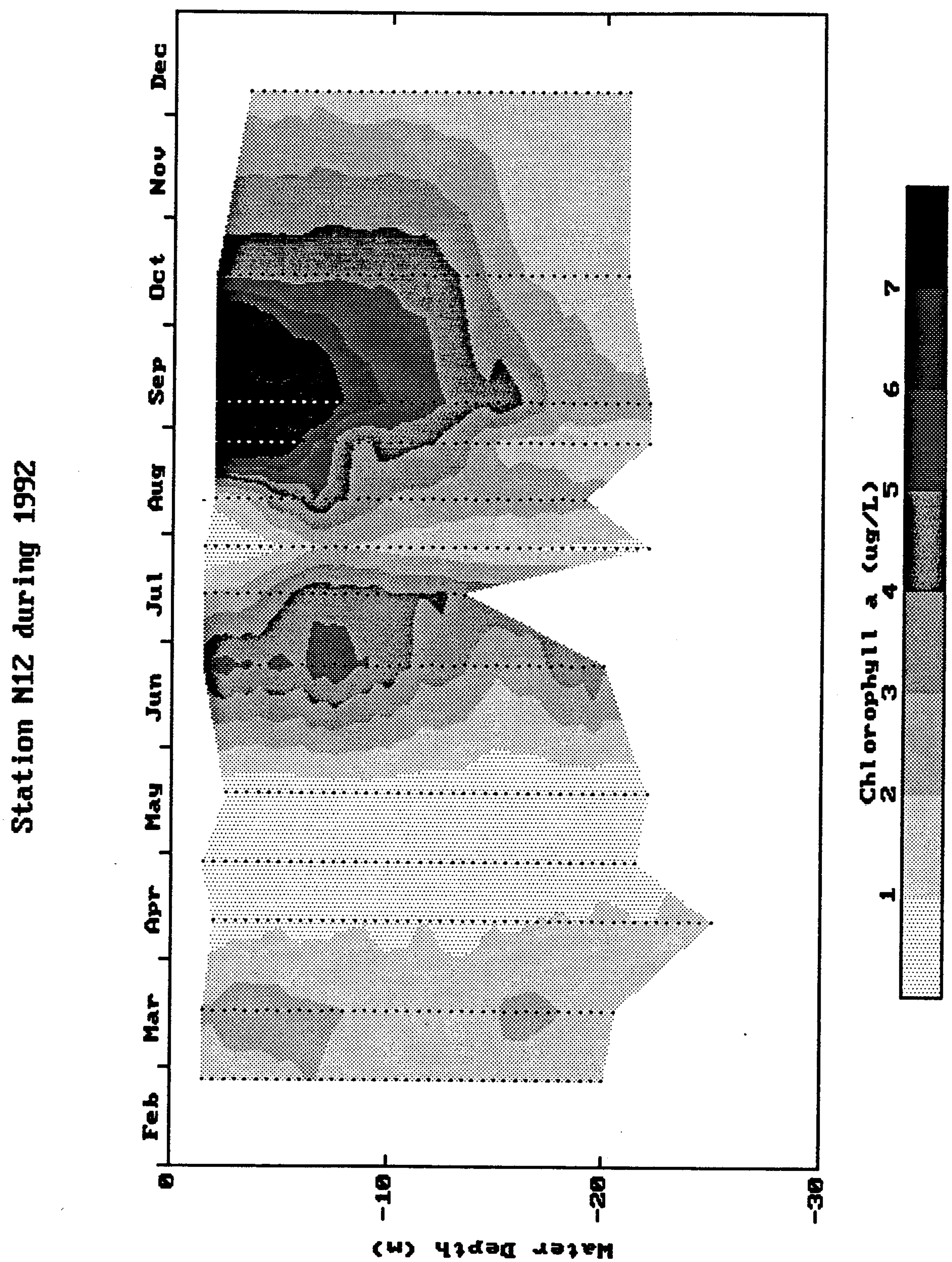


Figure 4-11. Chlorophyll at station N12 (Nearfield) during 1992.

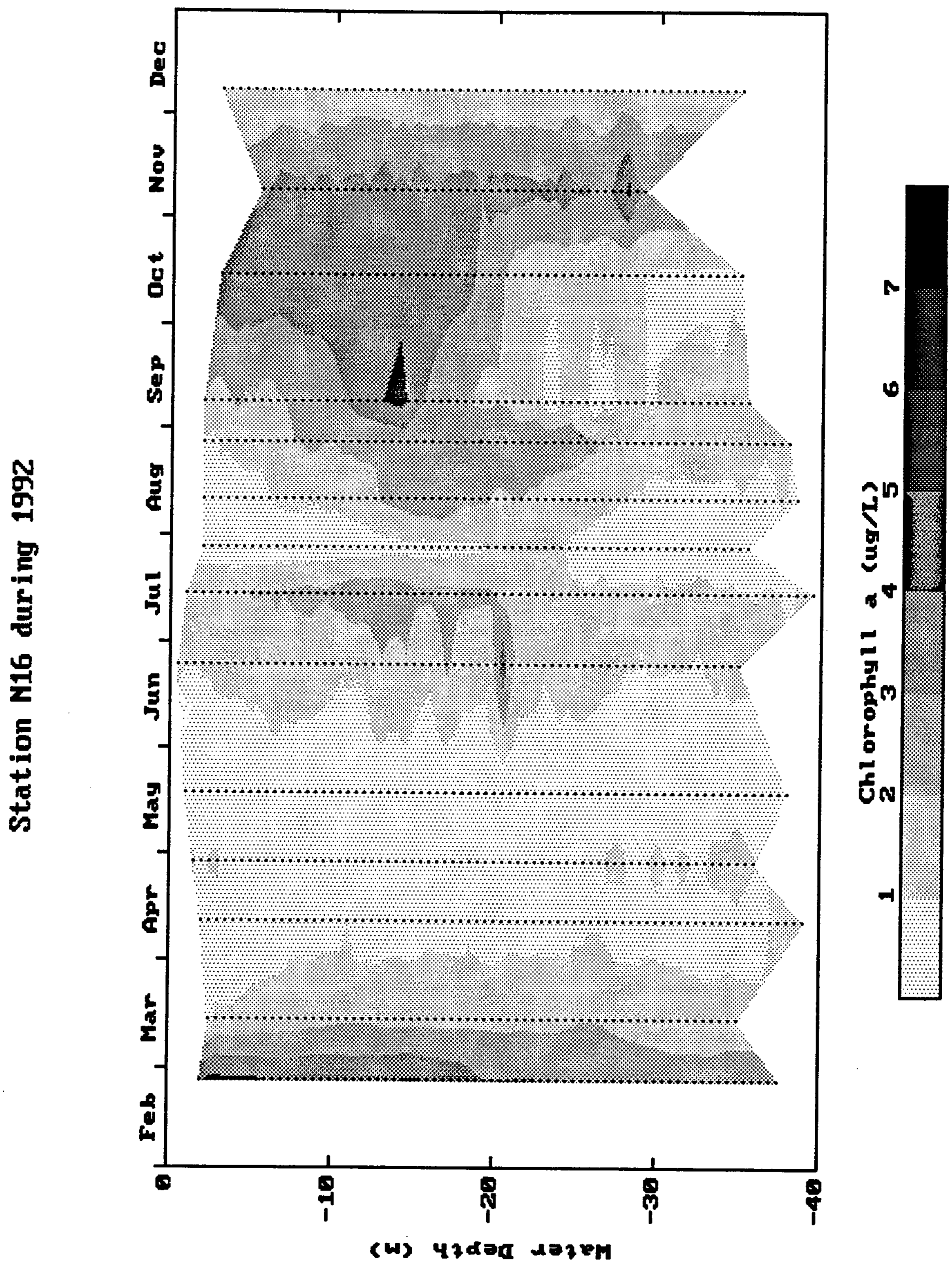


Figure 4-12. Chlorophyll at station N16P (Nearfield) during 1992.

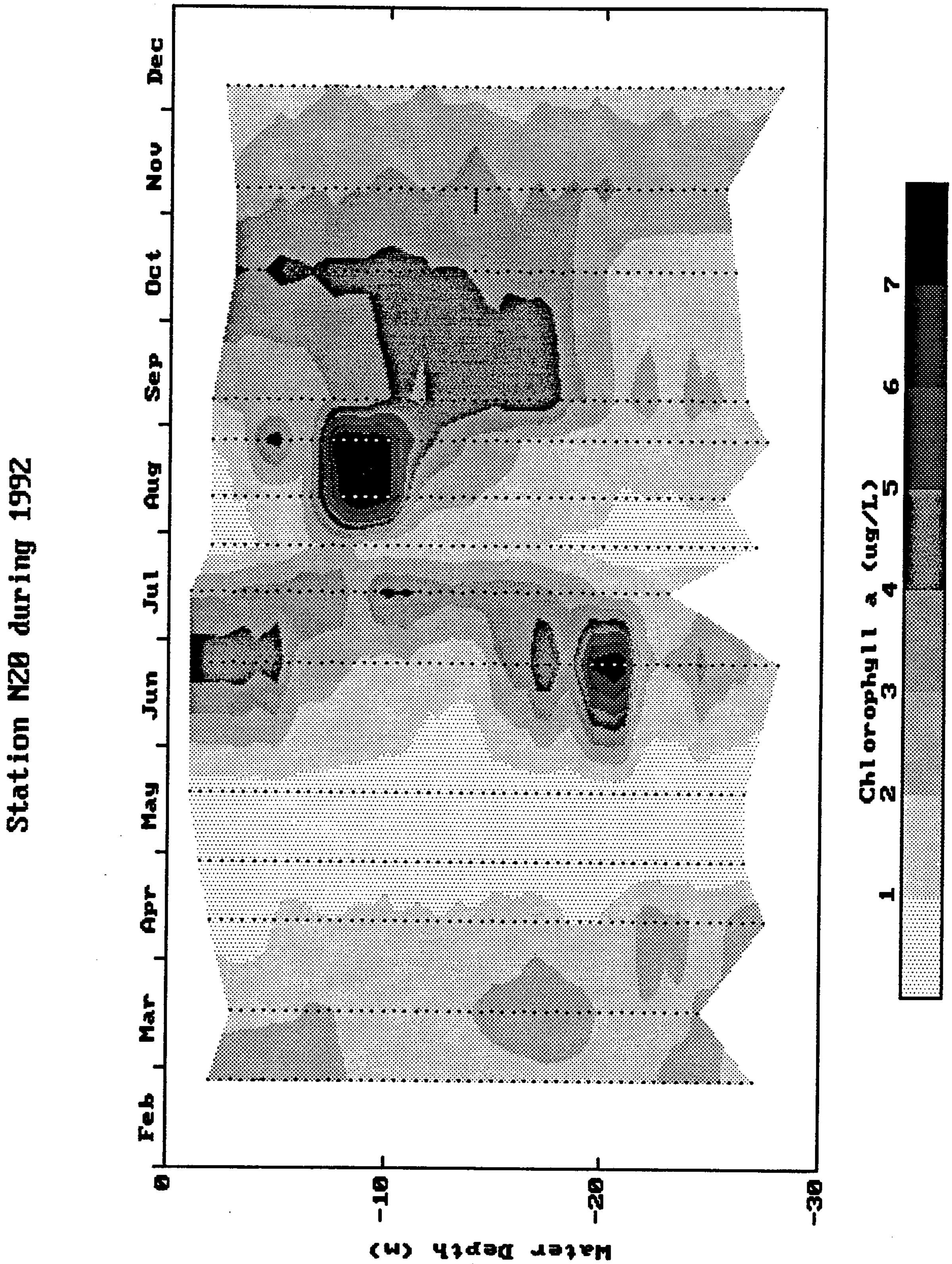


Figure 4-13. Chlorophyll at station N20P (Nearfield) during 1992.

5.0 DISSOLVED OXYGEN

Dissolved oxygen (DO) data are available for all stations (21 nearfield and 25 farfield). Measurements were made with *in situ* sensors. For each survey, a small set of measurements was made by standard Winkler titration and the *in situ* readings were post-calibrated to derive the values reported here (Kelly *et al.*, 1992; 1993a,b). During the March survey the sensors were not functioning and no data are available. For the May nearfield survey no titration data were available; those data were post-calibrated using the late April survey calibration, which was within about 10% of the June survey data. The data represent readings made at the time of closing of the hydrocast bottles for nutrients, so they are directly comparable with the nutrient and chlorophyll series discussed previously. For the station contour plots discussed in Section 5.3, the 0.5-m averaged data from the vertical profile were used.

5.1 Frequency Distribution of Dissolved Oxygen

About 2200 DO data points were used in the frequency distribution analysis of 1992 sampling results. For each point, the percent saturation was calculated based on simultaneous measurements of temperature and salinity, as described in Kelly *et al.* (1992; 1993a,b). Frequency plots were then developed to describe how the samples were distributed by percent saturation intervals in 5% increments (e.g., >75-80%, >80-85%, >85-90%, etc.).

For all stations and depths of bottle measurement, the lowest class was the >70-75% interval (Figure 5-1), but values up to 135% saturation were noted. More than 50% of the values were in the 95-115% saturation range, with the mean just over 100%. Fewer samples were below 95% than above it for both the nearfield subset and the entire data set. There were no striking geographic differences in DO frequency distributions in surface water.

5.2 Annual Cycle of Dissolved Oxygen

Figures 5-2 and 5-3 respectively display oxygen in concentrations of mg/L and as percent saturation for surface samples at all stations. The decreasing trend in DO values over the year is primarily driven by the seasonal temperature cycle, as suggested the relative consistency of the percent saturation data, which showed little noticeable decrease from February to late summer. Apparent slight decreases in the fall may be partially the result of vertical mixing with bottom water, but also may be due to less autotrophic activity at that time. Interestingly, most surface readings were in the 100 to 125% saturation range until November. This would indicate a net autotrophic surface water, where the values can be maintained in excess of saturation value by primary production, even under free atmospheric exchange. There was an interesting dip in percent saturation in May which, if real (see above) may suggest that in the nearfield there is some rapid feedback from the winter-spring bloom, the termination of which was accompanied by sinking chlorophyll in April. It is also interesting to note that, if real, this was a transient depression of DO and percent saturation values were again above 100% in most cases in June. Previously we noted that a subsurface DO maximum was frequently associated with subsurface, sub-pycnocline chlorophyll maxima through the stratified summer period (Kelly *et al.*, 1993a).

The pattern for all stations and depths (not shown) was not markedly different from the pattern of the surface samples. However, the lowest values, not necessarily in terms of absolute values, but in terms of percent saturation, were generally from the deepest waters sampled in a survey. This is expected because the deep waters, after stratification, are essentially sealed from atmospheric exchange and are heterotrophic — receiving and processing organic matter and reducing DO, rather than producing it. In Figures 5-4 and 5-5, representing samples collected at depths greater than 50 m, a decrease in DO, as both concentration and percent saturation, was apparent from February to October. Note that the decrease in DO in these bottom waters was associated with a gradual increase in dissolved nutrients (the products of decomposition and heterotrophic processes), as shown in previous sections.

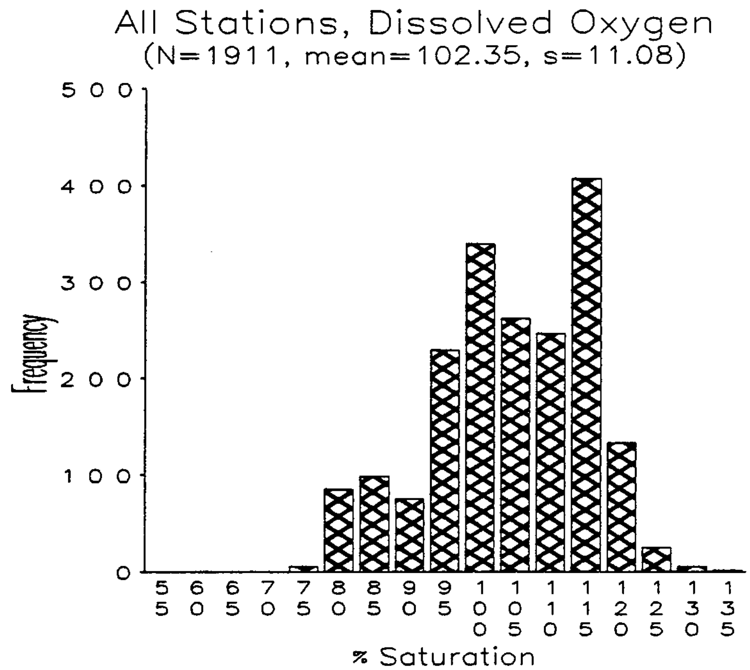
5.3 Annual Cycle of Dissolved Oxygen at Selected Stations

The same selection of four stations from different regions are given here as were shown in Section 3, including F02P in Cape Cod Bay, F23P at the edge of Boston Harbor off Deer Island, F17 in deep water in Stellwagen Basin, and N16P near the center of the nearfield. Also included, are plots for stations N10P and N12, along the western edge of the nearfield and influenced by the Harbor, as well as for station N20P, only a short distance from N16P to the west near the center of the nearfield. The farfield station plots (Figures 5-6 through 5-8) are based on five surveys (March was unsuccessful), whereas the nearfield station plots (Figures 5-9 through 5-12) are based on 13 surveys and are richer in detail.

Of interest for the farfield stations plots are the generally well-mixed conditions at F23P and slightly more vertical structure at F02P (including a spot of higher percent saturation at depth in June). A much more graded vertical structure progressively emerged during stratification at the offshore deep water station (F17), which also showed a mid-depth peak in April, where >120% saturation was evident.

For the nearfield, the temporal sequence is interesting. Station N10P was essentially vertically uniform from February to July, but some vertical structure developed in bottom waters during August-October. At the other three stations, slightly lower bottom water DO values were detected in May, a noticeable subsurface maximum was detected in late July and/or early August, and markedly lower percent saturation was found in bottom water about a month later, prior to water column overturn between October and November.

It was interesting that the high degree of temporal and spatial patchiness observed for chlorophyll was not as visibly evident in the plots for dissolved oxygen. This can occur arise for several reasons. One relates to instrumentation: the response time for the DO sensor is slower than the fluorometer, which in part, could contribute to the perception of smoother vertical distributions in DO relative to chlorophyll. The apparent differences may also be, in part, a reflection of the nature of particle vs. dissolved distributions in nature. Particles (e.g. chlorophyll) often tend to be more highly aggregated and heterogeneously distributed, but also they are moved by different some fundamentally different physical and biological forces than dissolved substances (e.g. gravitational settling, buoyant rising, metazoan grazing and defecation). In principal, dissolved substances are often more easily homogeneously distributed.



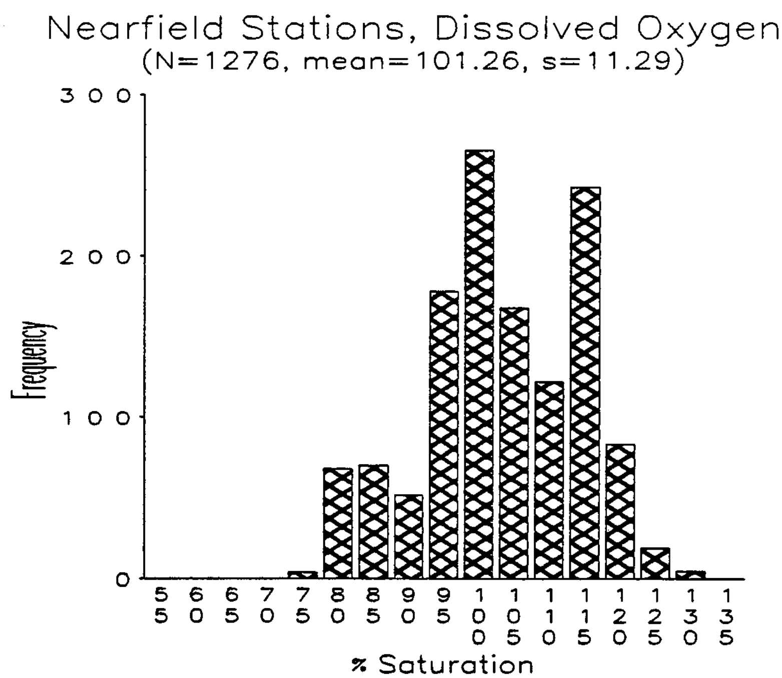


Figure 5-1. DO frequency distribution for all 1992 data, all stations and nearfield stations.

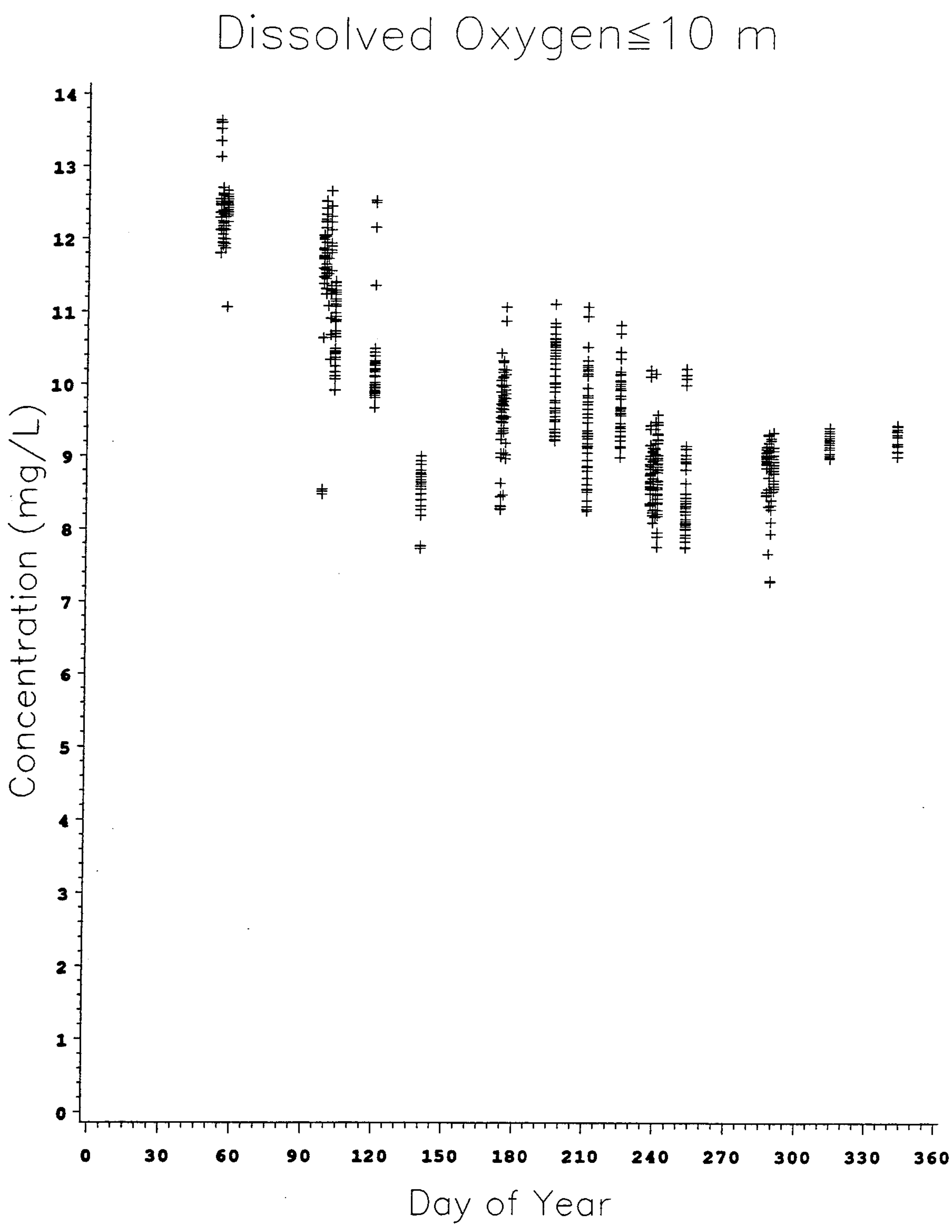


Figure 5-2. Annual DO (mg/L) cycle in surface water at Massachusetts and Cape Cod Bay stations.

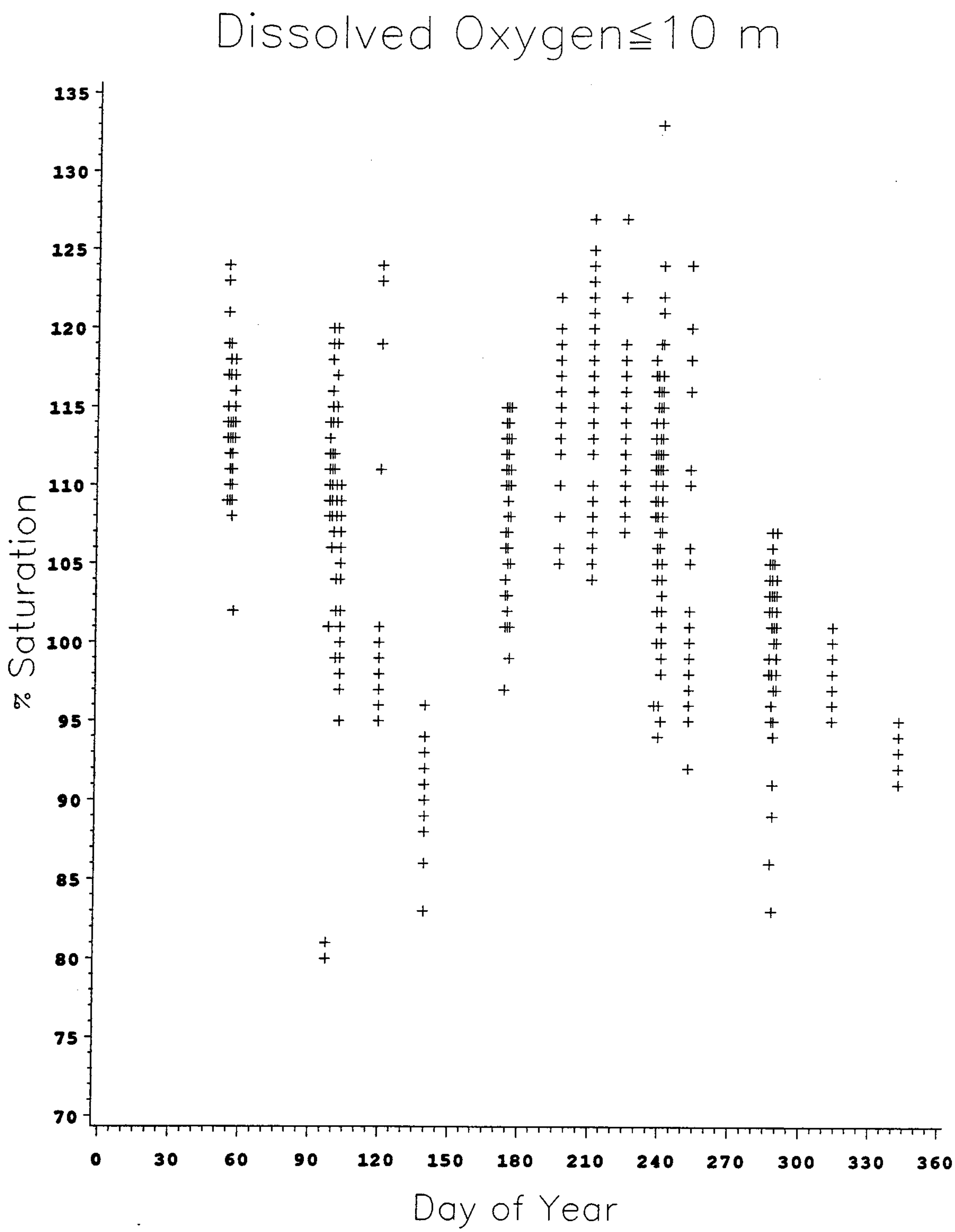


Figure 5-3. Annual DO (percent saturation) cycle in surface water at Massachusetts and Cape Cod Bay stations.

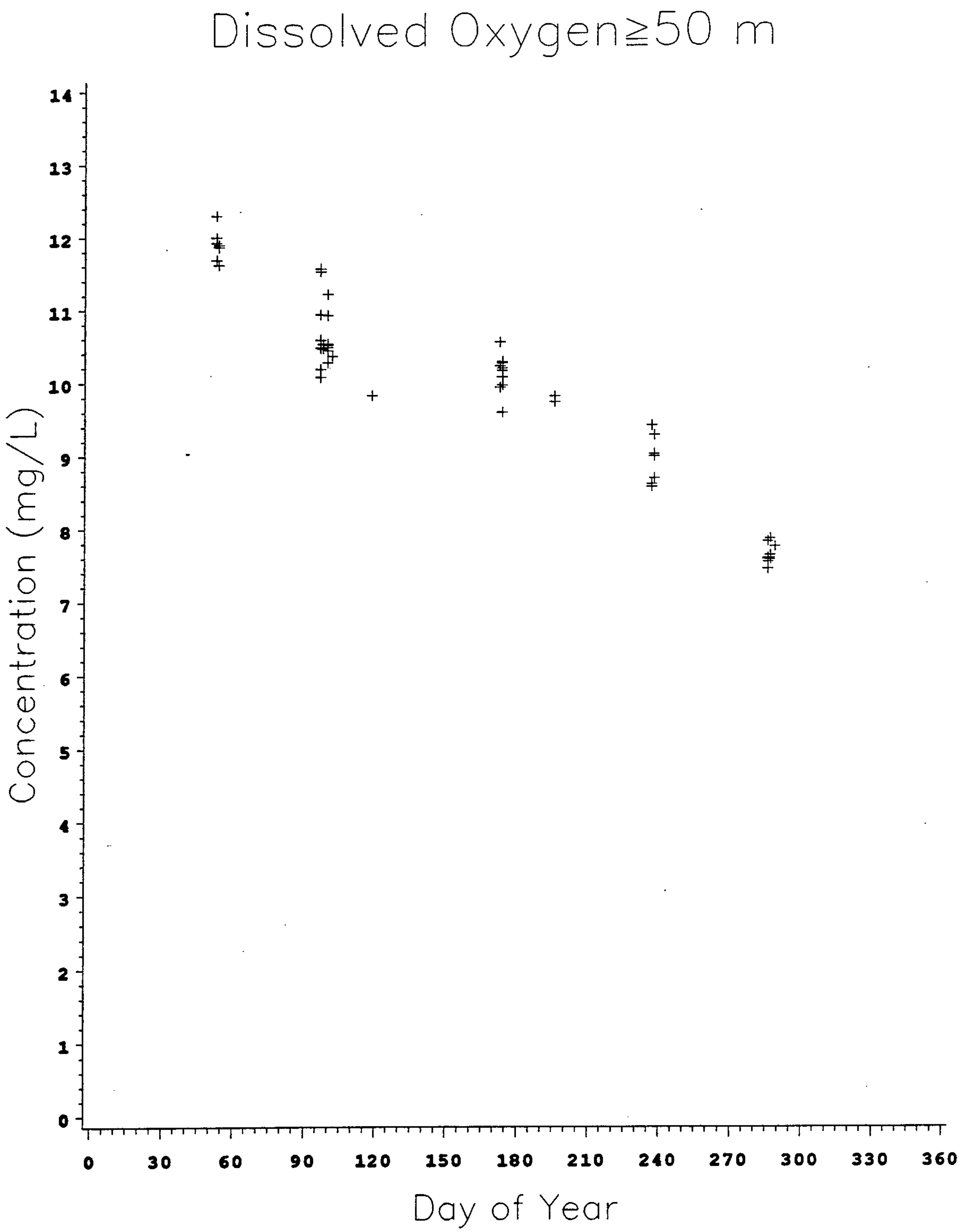


Figure 5-4. Annual DO (mg/L) cycle in deep water at Massachusetts and Cape Cod Bay stations.

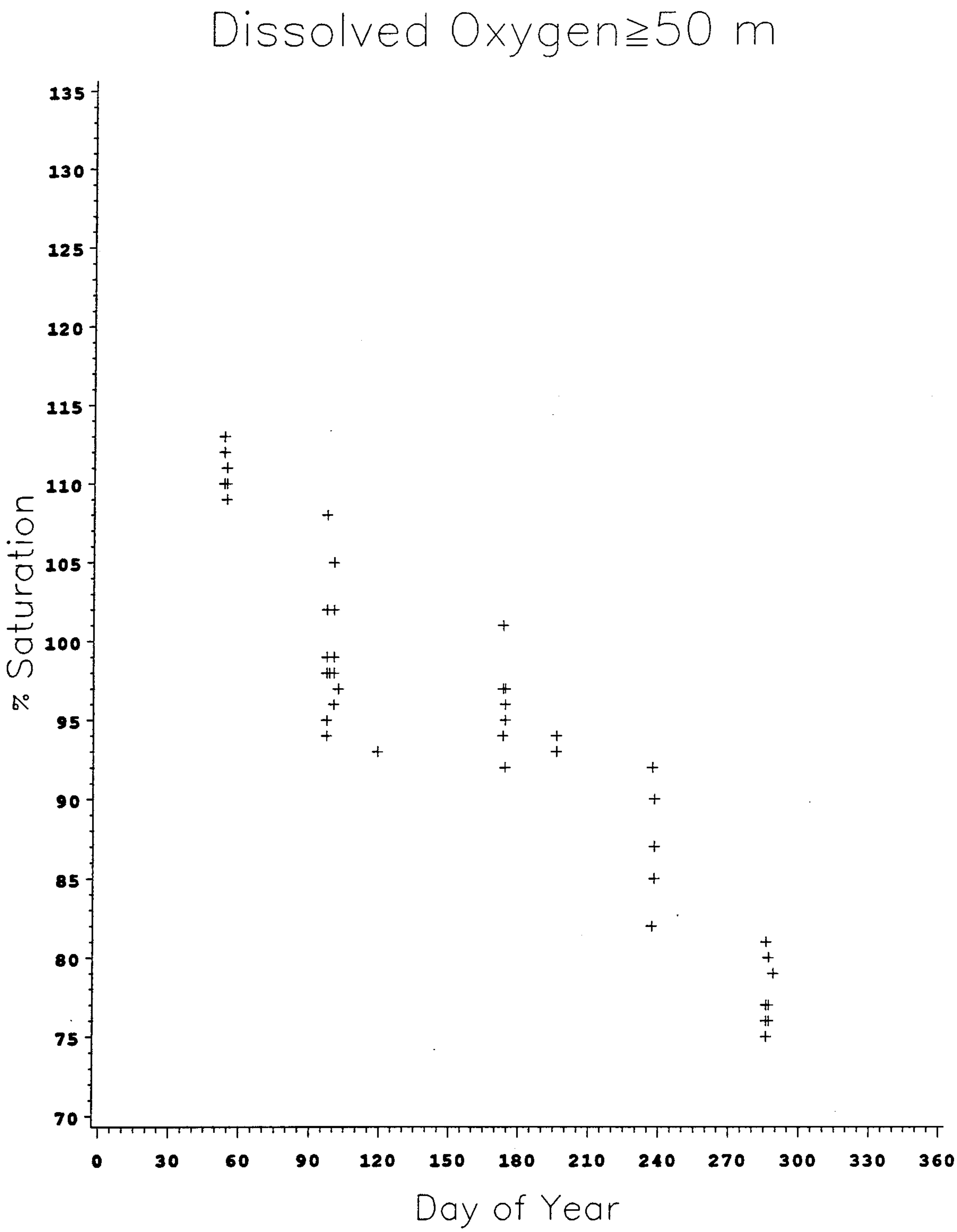


Figure 5-5. Annual DO (percent saturation) cycle in deep water at Massachusetts and Cape Cod Bay stations.

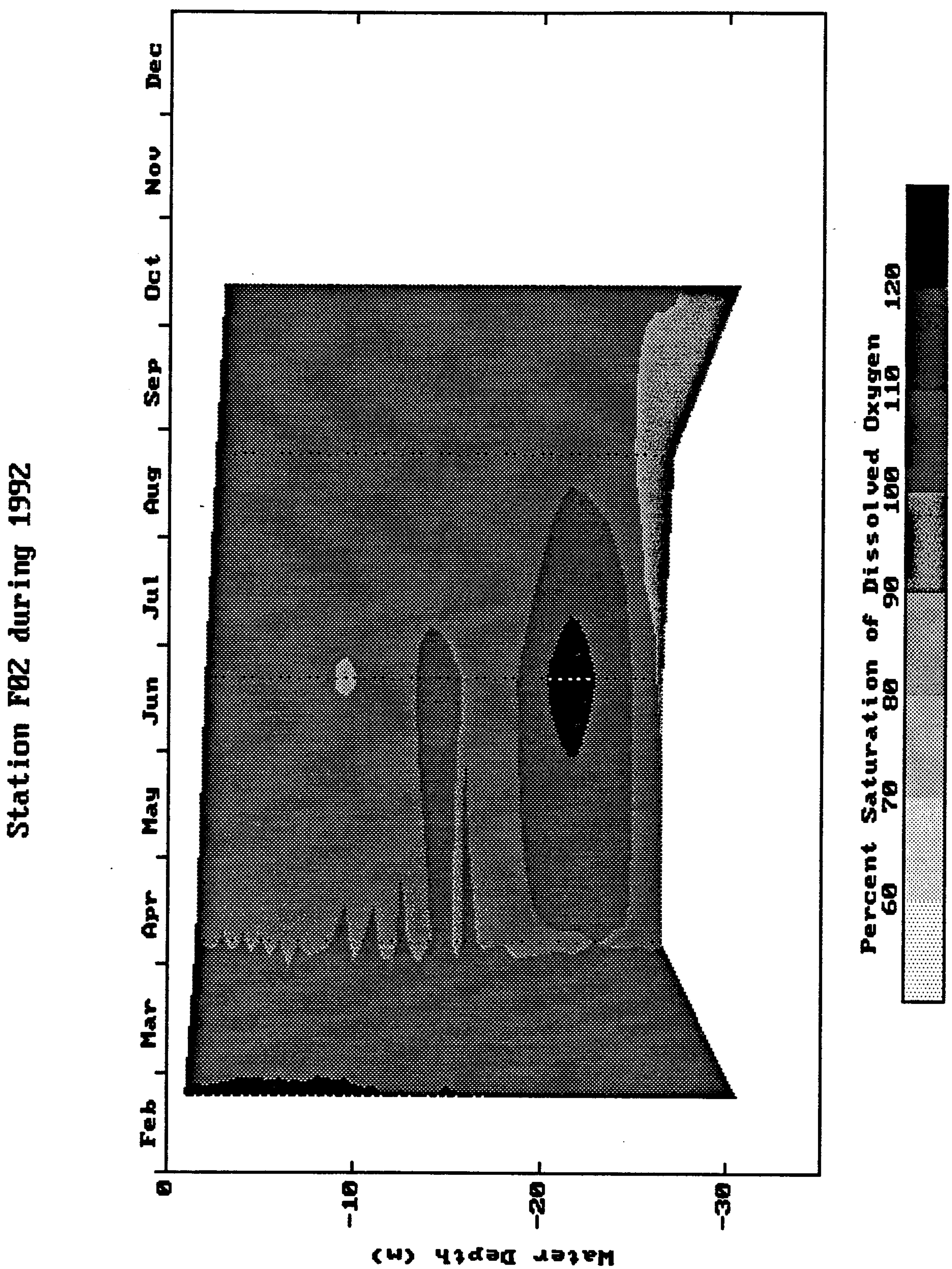


Figure 5-6. DO (percent saturation) at station F02P (Cape Cod Bay) during 1992.

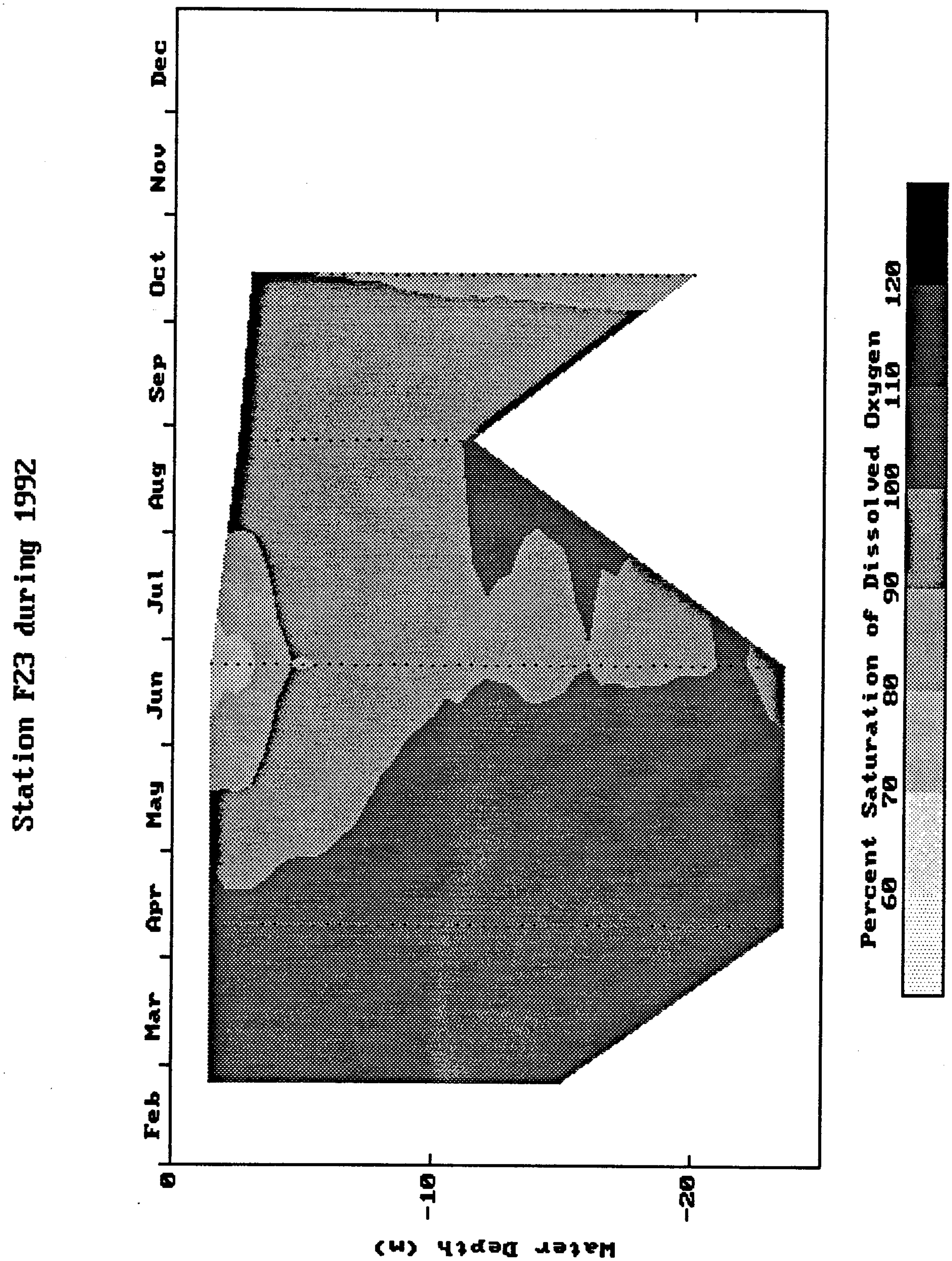


Figure 5-7. DO (percent saturation) at station F23P (Boston Harbor edge) during 1992.

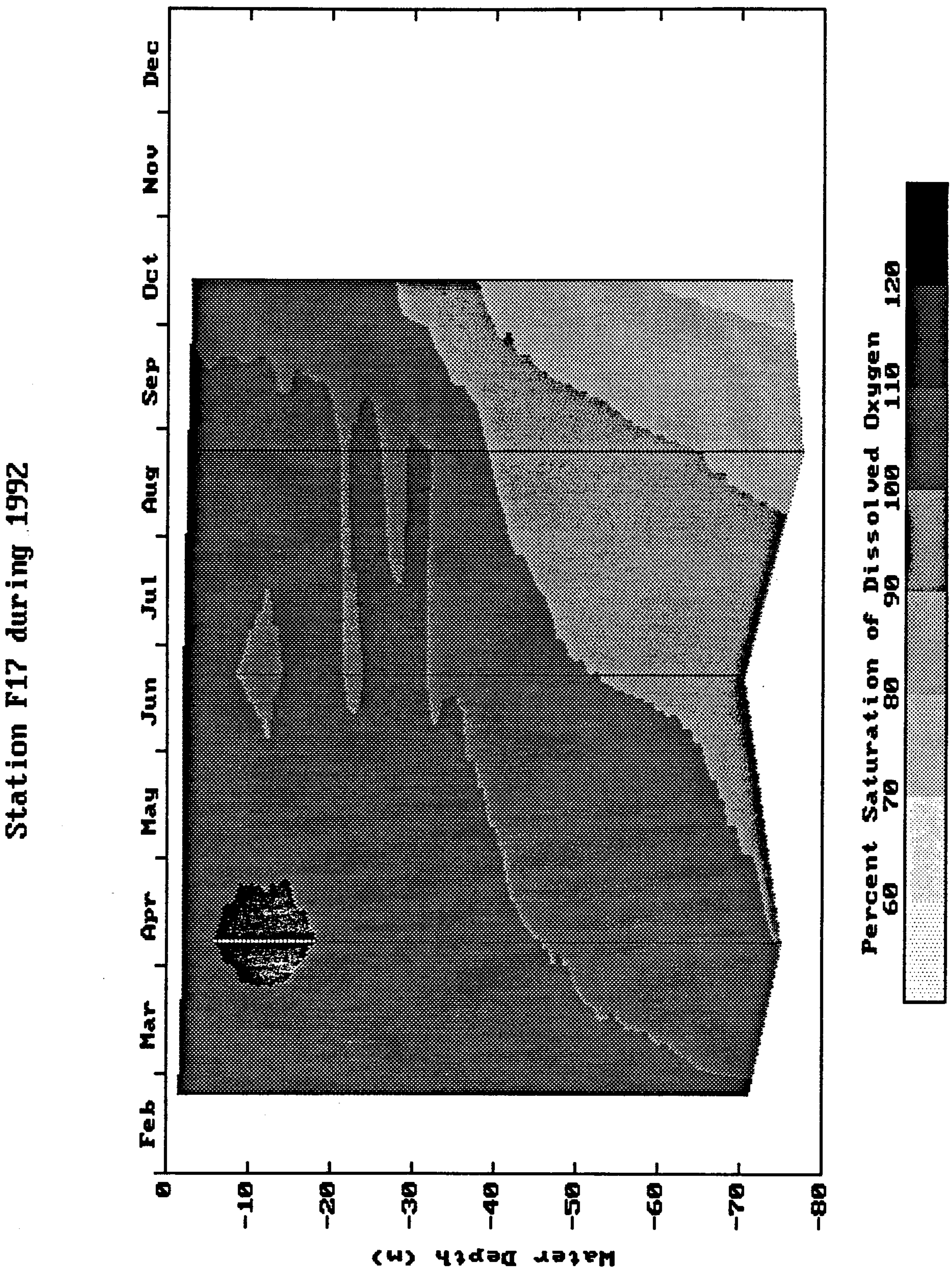


Figure 5-8. DO (percent saturation) at station F17 (Massachusetts Bay) during 1992.

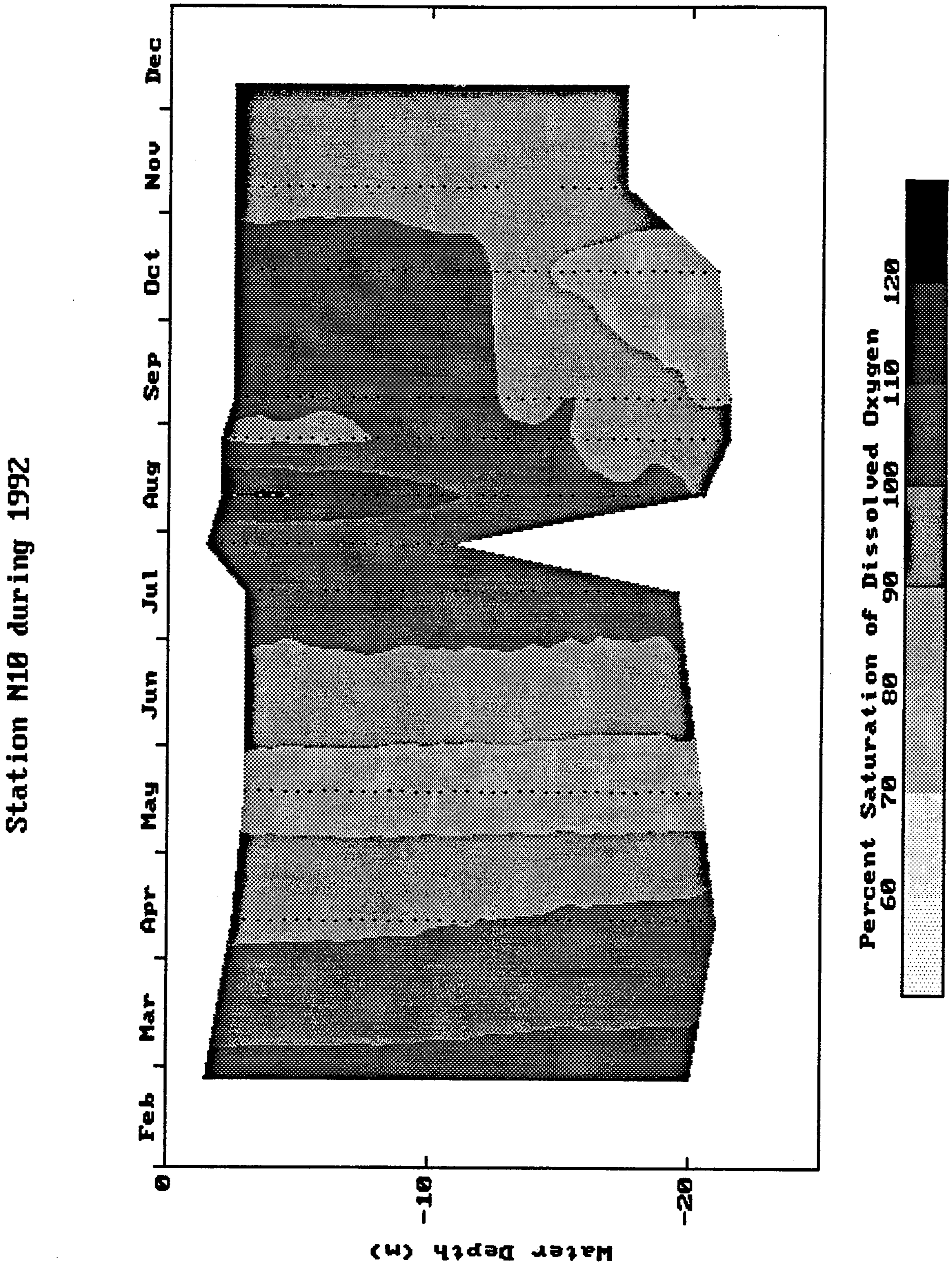


Figure 5-9. DO (percent saturation) at station N10P (Nearfield) during 1992.

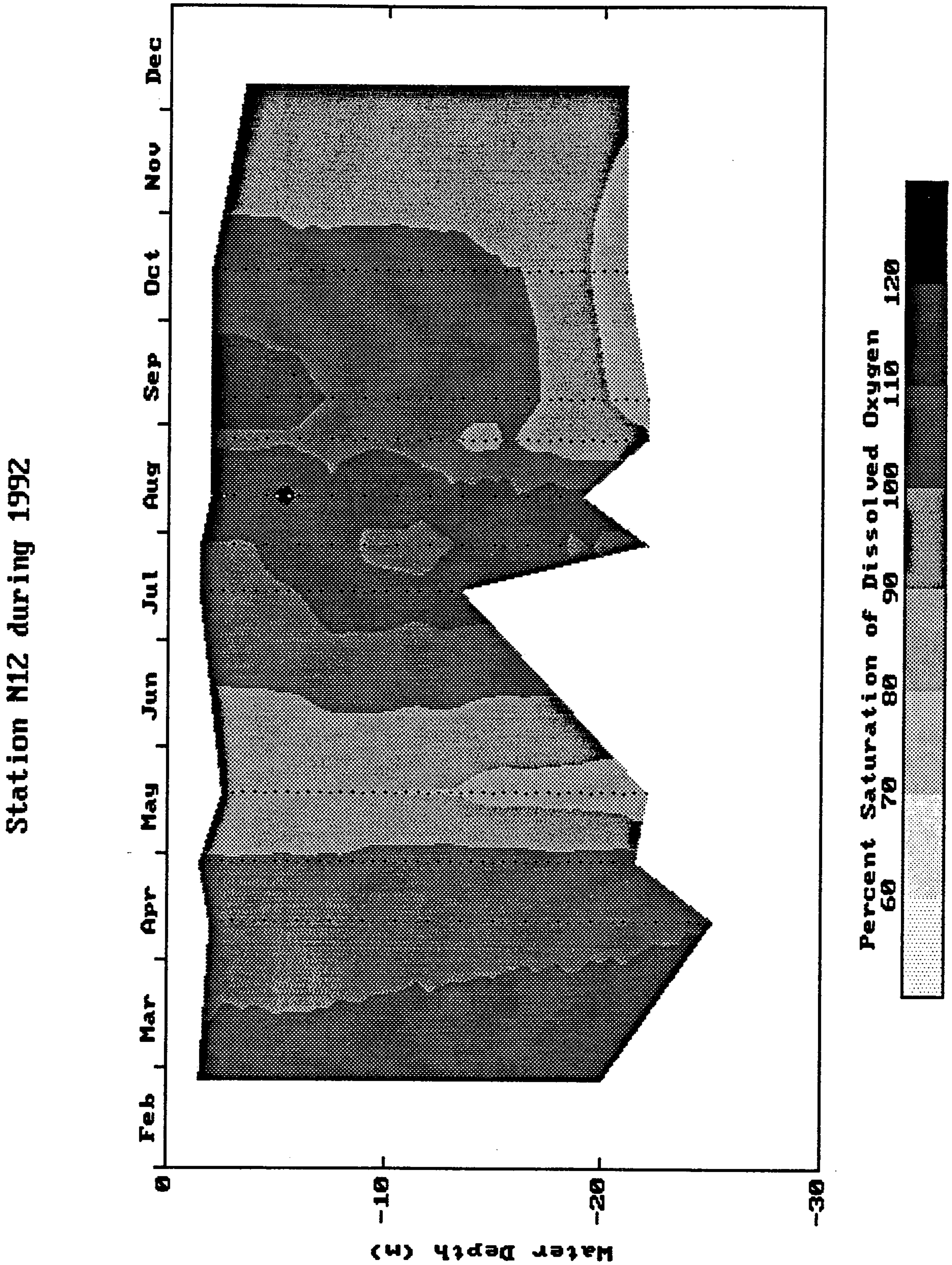


Figure 5-10. DO (percent saturation) at station N12 (Nearfield) during 1992.

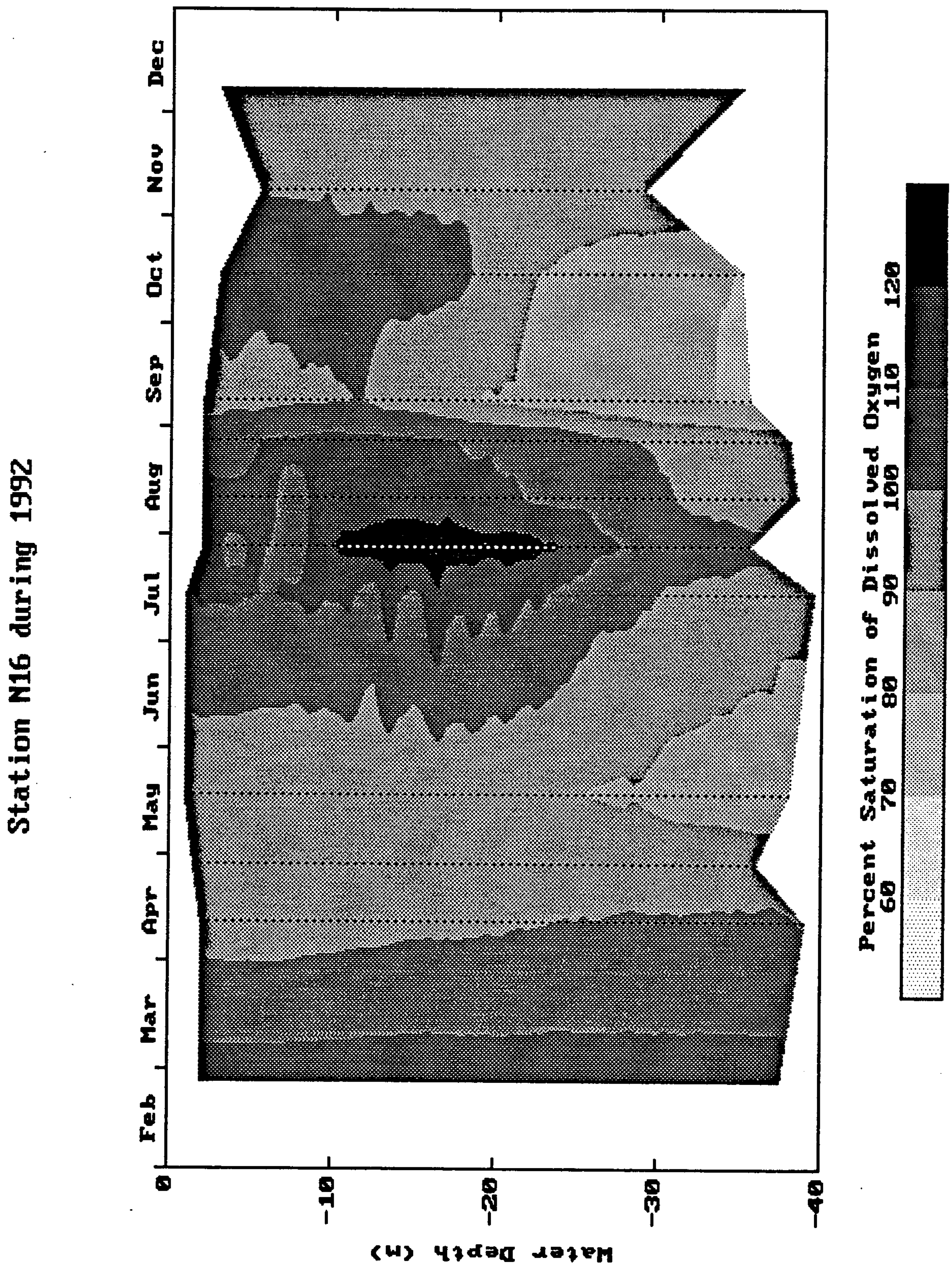


Figure 5-11. DO (percent saturation) at station N16P (Nearfield) during 1992.

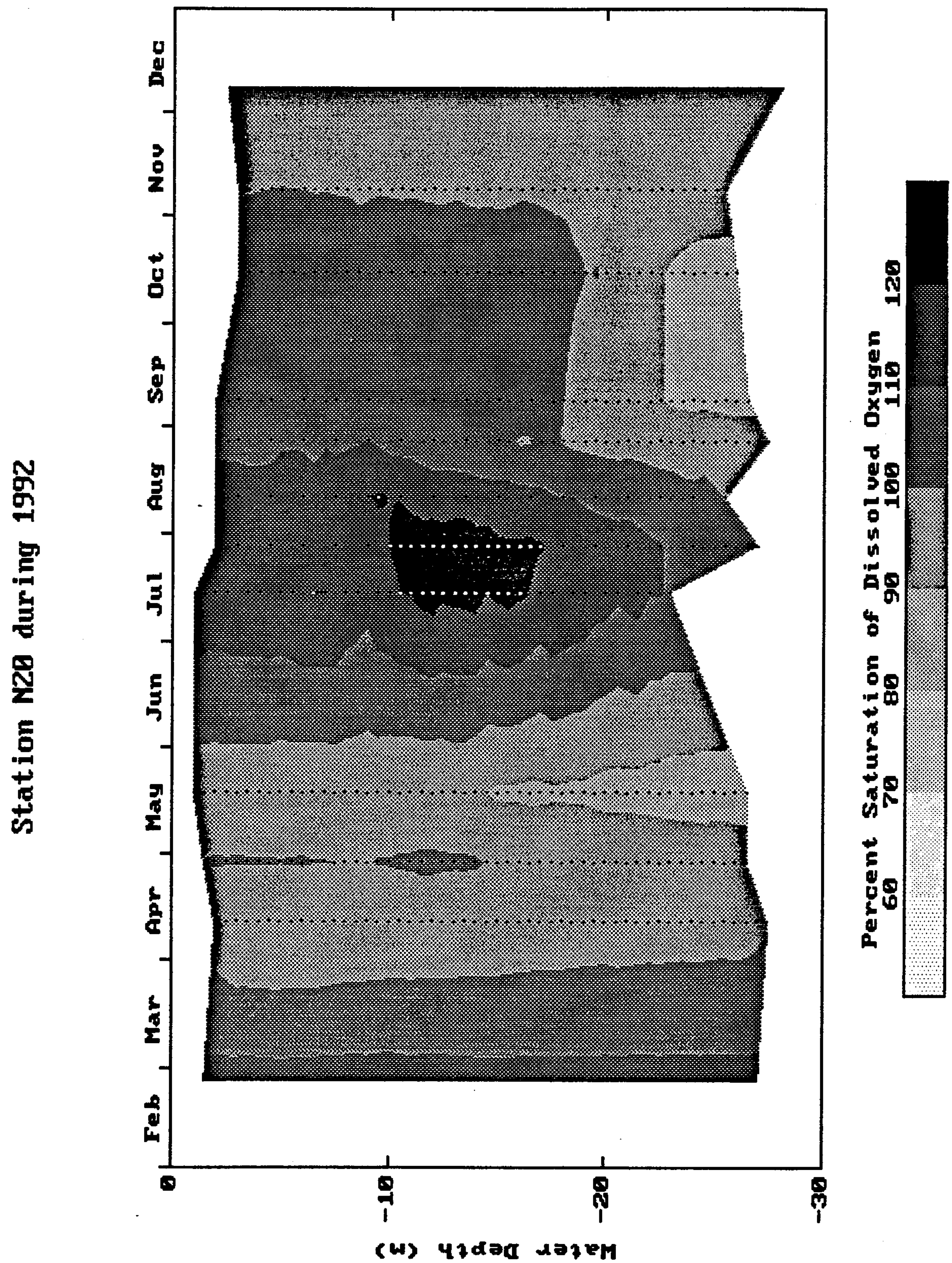


Figure 5-12. DO (percent saturation) at station N20P (Nearfield) during 1992.

6.0 PLANKTON

For phytoplankton and zooplankton, data are available for 10 stations (6 nearfield and 4 farfield). Phytoplankton samples are from two depths, a "surface" and a subsurface "chlorophyll maximum." Two types of phytoplankton samples were collected, a whole-water sample and a screened sample. In the whole water sample, all taxa were identified to lowest level possible and cells were enumerated. These samples for 10 stations were analyzed for all six farfield surveys; additionally, whole-water samples were taken near the surface at station N10P on eight nearfield surveys and these data are reported separately in Kelly *et al.* (1994). The screened (>20 μm-mesh) sample, collected only on three farfield surveys, (June to October), retained larger, less abundant organisms which were identified and enumerated. Zooplankton samples were collected in a single vertical-oblique tow (102 μm-mesh) at each phytoplankton sampling station. Copepods were identified to species and other forms were identified to major groups (e.g., barnacle nauplii, polychaete larvae, etc.), with several exceptions (e.g., *Oikopleura dioica*, an appendicularian). Detailed field and laboratory methods are presented in Kelly *et al.* (1992; 1993a,b).

6.1 Total Abundance of Plankton From February to October

Total cell counts of phytoplankton over the year are given in Figure 6-1. Figures 6-2 and 6-3 illustrate the abundance of groups of species (diatoms, microflagellates, dinoflagellates, and "other") for the surface samples.

The variation across the stations at each survey was often nearly as much as an order of magnitude. Total counts for all samples were as low as about 0.3 million cells/L to as high as about 9 million cells/L. There was no apparent average trend over the year for the whole group of stations, but total counts may have been slightly higher in April and August. Some regional distinctions were suggested, with the Cape Cod Bay stations having relatively high counts in winter-spring, low counts in mid-summer, and high counts in early fall. Total phytoplankton counts at coastal and nearfield stations, all in western Massachusetts Bay, were not distinct from each other.

With minor exceptions (see Kelly *et al.*, 1992; 1993a,b), the species composition varied over depth but, overall, the species and taxonomically related groups found at a station were detected at both sampled depths. The patterns among groups from the surface sample (Figures 6-2 and 6-3) are, therefore, similar to those in the deeper samples.

Generally, for all regions, the diatoms fell from high levels early in the year to low levels as the winter-spring bloom terminated, then rebounded slightly in summer-fall. Microflagellates showed a similar pattern, but in summer and fall the counts rose to higher levels than in winter-spring. Dinoflagellates were most prominent in early summer, especially at mid-depth in some locations (Cape Cod Bay stations, see Section 6.2). Counts in the "other" plankton category were high in April due to *Phaeocystis* (see Section 6.2), and generally were higher in summer than in winter. The main regional distinctions for phytoplankton groups were differences in concentration and successional progression between the Cape Cod Bay and Massachusetts Bay stations. This trend is similar to that observed for fluorescence measurements (Section 4); moreover, the trend in fluorescence of a low during late April/May was also apparent in cell counts at station N10P (Kelly *et al.*, 1994).

Total numbers of zooplankton fell sharply in April, when the Bays were dominated by *Phaeocystis,* and, at all stations, rose to highest levels in late summer (Figure 6-4). Zooplankton abundance was relatively similar within all stations of a survey (usually less than a factor of five variation), but the variation across surveys through the year was about two orders of magnitude. Thus, in contrast to phytoplankton trends, there may be a more Baywide zooplankton cycle that is less obscured by individual stations or regional variability.

Interestingly, of all the phytoplankton groups, the annual cycle for total zooplankton abundance most nearly mirrored the annual cycle shown for microflagellates, although it was also similar to the pattern for diatoms (cf. Figures 6-2 and 6-4). The net mesh size (102 μM) retains smaller zooplankton and, not surprisingly, the main two species observed were microzooplankton (see next section). The similarity of zooplankton abundance trends with the smaller phytoplankton species perhaps suggests that the strong and consistent trophic linkage among small-sized organisms is a significant feature. Turner (1994) has further examined the zooplankton and offers a more comprehensive perspective on the nature of the trophic structure in the Bays.

The total zooplankton counts were separated into component groups (Figures 6-5 and 6-6). The numerical dominance of copepods and their nauplii is apparent throughout the year, and both show the same time trends with no obvious regional distinctions. Generally, the "other" zooplankton category is a minor, but relatively constant, component. In contrast, the barnacle nauplii obviously are a seasonal component of the plankton and fall off in abundance with the winter-spring bloom.

6.2 Patterns of Selected Taxa

Some of the dominant phytoplankton identified to species level (i.e., the diatoms; microflagellates and cryptomonads were not identified) and some of the dominant zooplankton (i.e., copepods) were chosen to show some of the seasonal succession and variability in distribution. The phytoplankton species are shown in Figures 6-7 through 6-9 (diatoms) and 6-10 (one dinoflagellate). The plots are sequenced to show some of the early season species (*Thalassiosira*, *Phaeocystis*, *Chaetoceros*), followed by those species that were present, sometimes in high numbers, through most of the year (*Leptocylindrus*, *Skeletonema*), to one which became the dominant fall diatom (*Rhizosolenia*).

The brief burst of *Phaeocystis* in 1992 is indeed a remarkable feature that followed a mixed succession of diatoms, including *Thalassiosira* and many others. Turner (personal communication) also observed *Phaeocystis* in Buzzards Bay in this year. From region to region some of the most dominant taxa differ, but the major groups were generally quite similar and the annual patterns of diatoms and other groups represent fairly classical expectations for a temperate shelf community.

A principal ecological distinction, most evident in the Cape Cod Bay station data, was the appearance of a dinoflagellate, *Ceratium longipes,* (Figure 6-10) in June in high numbers at the subsurface chlorophyll maximum. Sampling for dinoflagellates did not start until June so the lack of data before that does not indicate absence of the organism. It is unknown whether this species became dominant at other stations in Massachusetts Bay just prior to or after the extremely high numbers were noted in June, but from the samples taken, the clear trend at all stations was a secular decrease of this species into the fall.

Two, small-sized numerically dominant zooplankton were *Oithona similis* and *Paracalanus parvus,* present during the entire year (Figure 6-11). Two of the principal larger copepods are shown in Figure 6-12; the counts for these species were usually about an order of magnitude lower than the two small dominants. Both of the larger species (Figure 6-12) seemed to have higher numbers in late summer, especially when the Cape Cod Bay stations had higher abundances of *Calanus* than other regions.

Finally, as was the case for diatom species, there appeared to be some regional distinctions in zooplankton at the level of copepod species. Turner (1994) more thoroughly describes interstation variability, but one situation is illustrated in Figure 6-13, showing two species of *Acartia, A. hudsonica* preferring the cold season and *A. tonsa* preferring the warm season. *A. tonsa,* the more numerically important of the two, was often high at station F23P at the edge of Boston Harbor. This genus is more characteristic of estuarine, than shelf, waters so a presence at slight lower salinity near the Harbor is unsurprising.

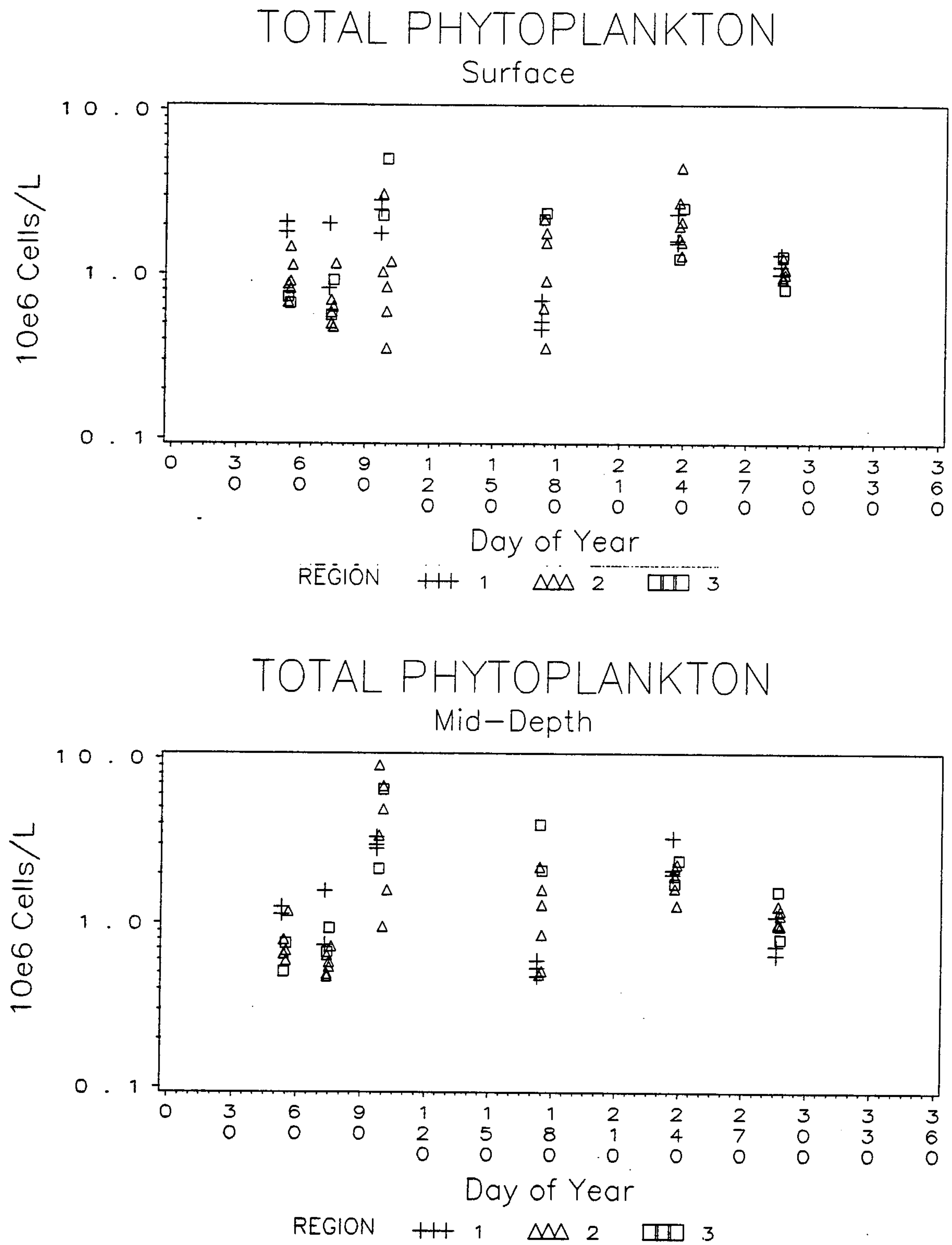
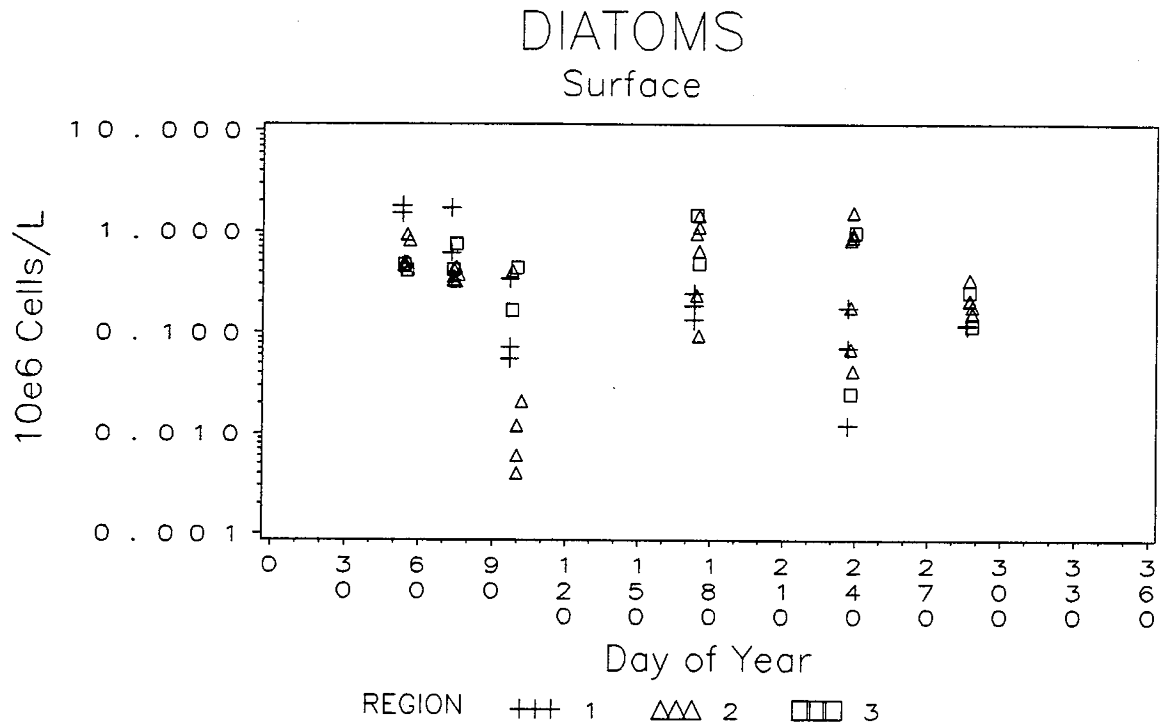


Figure 6-1. Total phytoplankton cells at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



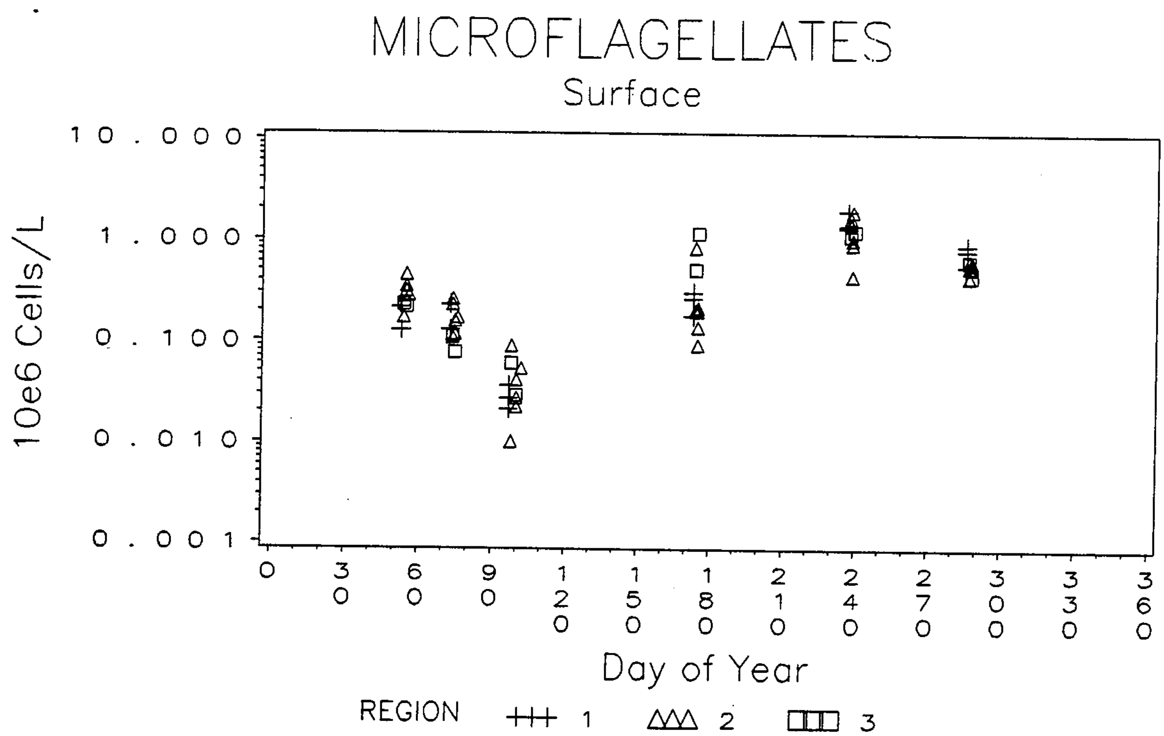


Figure 6-2. Phytoplankton groups at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal

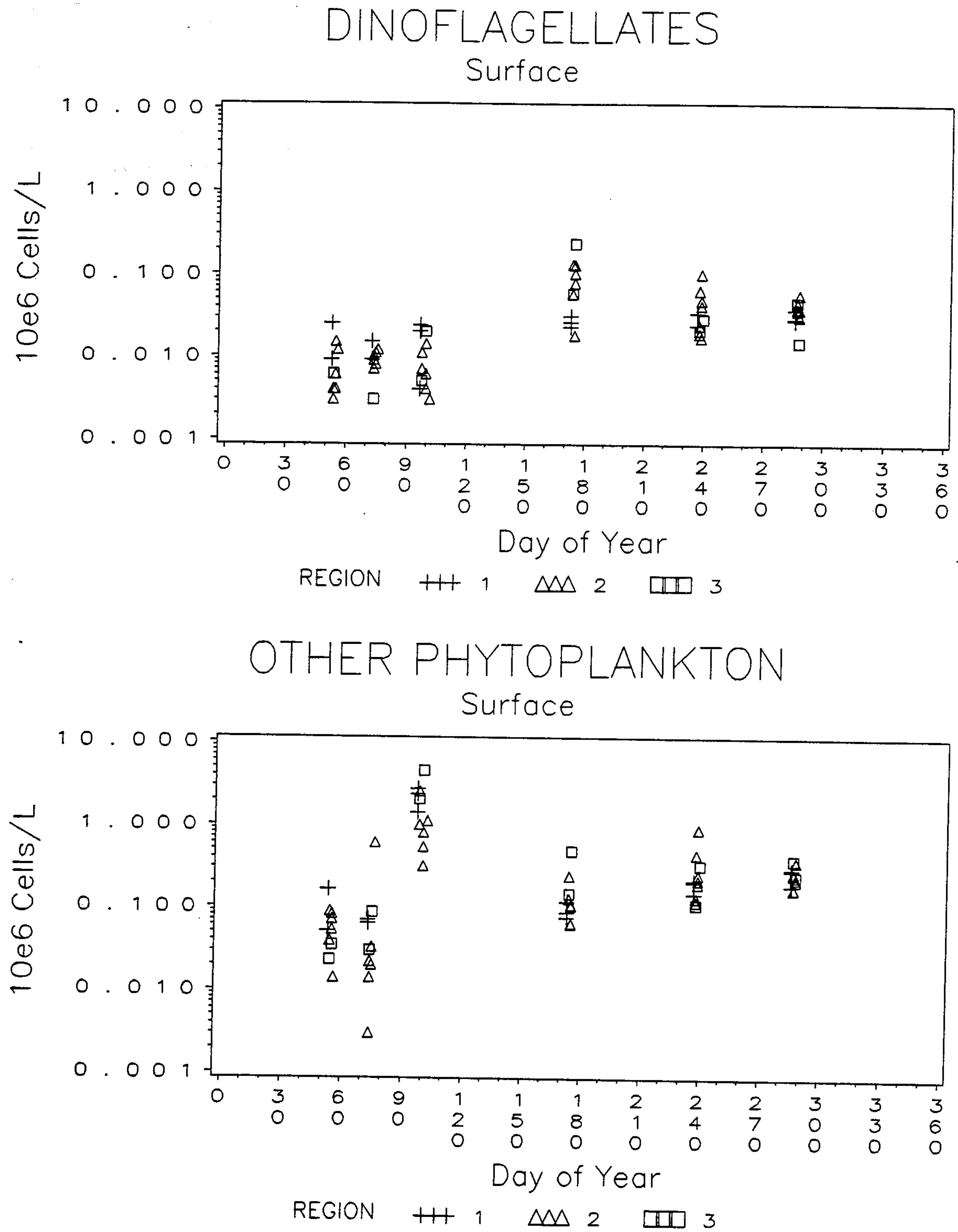


Figure 6-3. Phytoplankton groups at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal

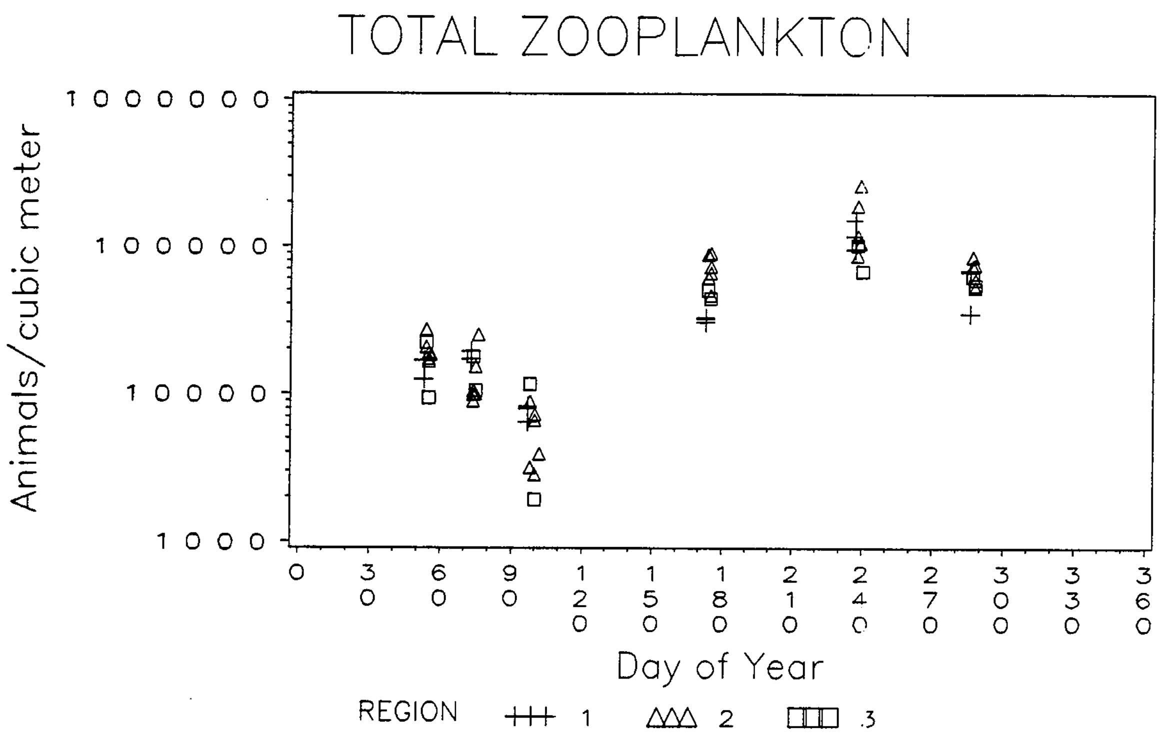
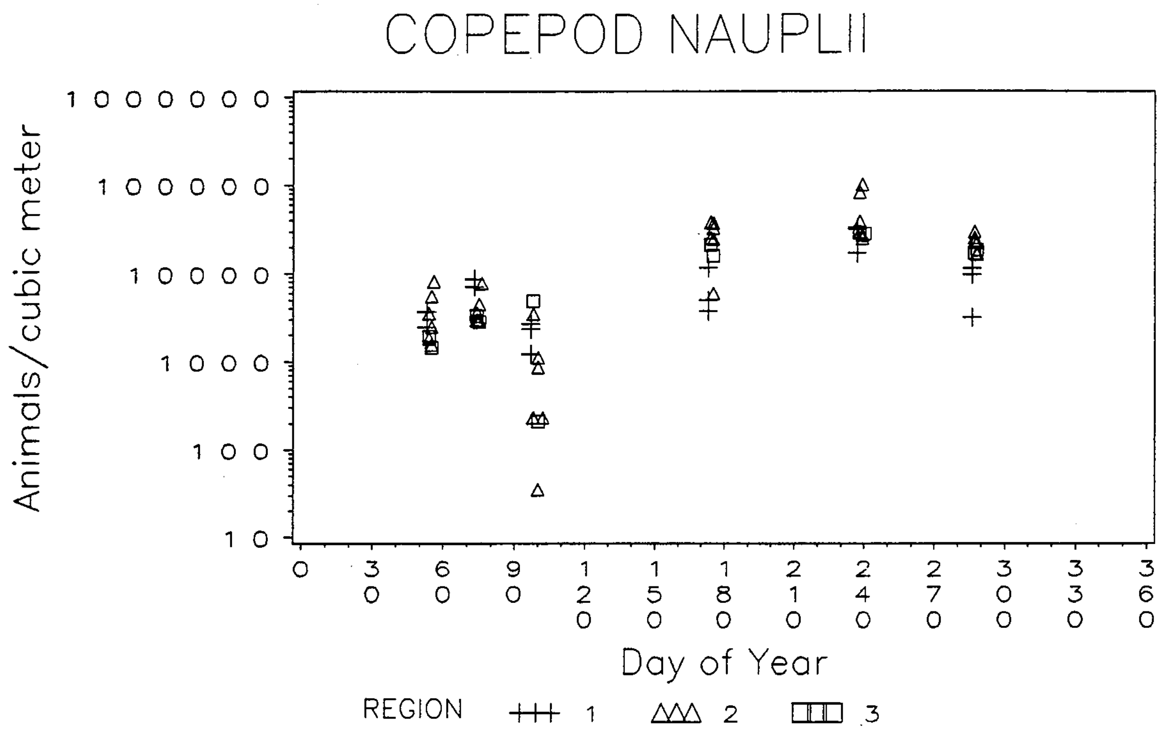


Figure 6-4. Total zooplankton abundance at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



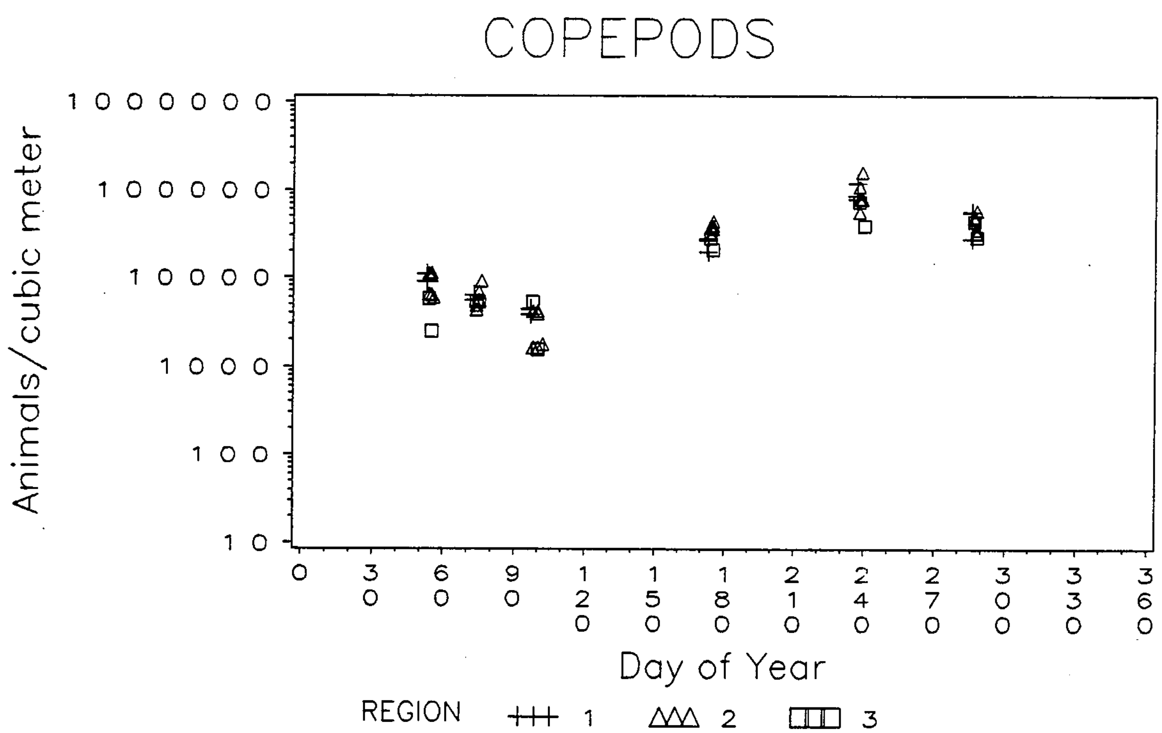
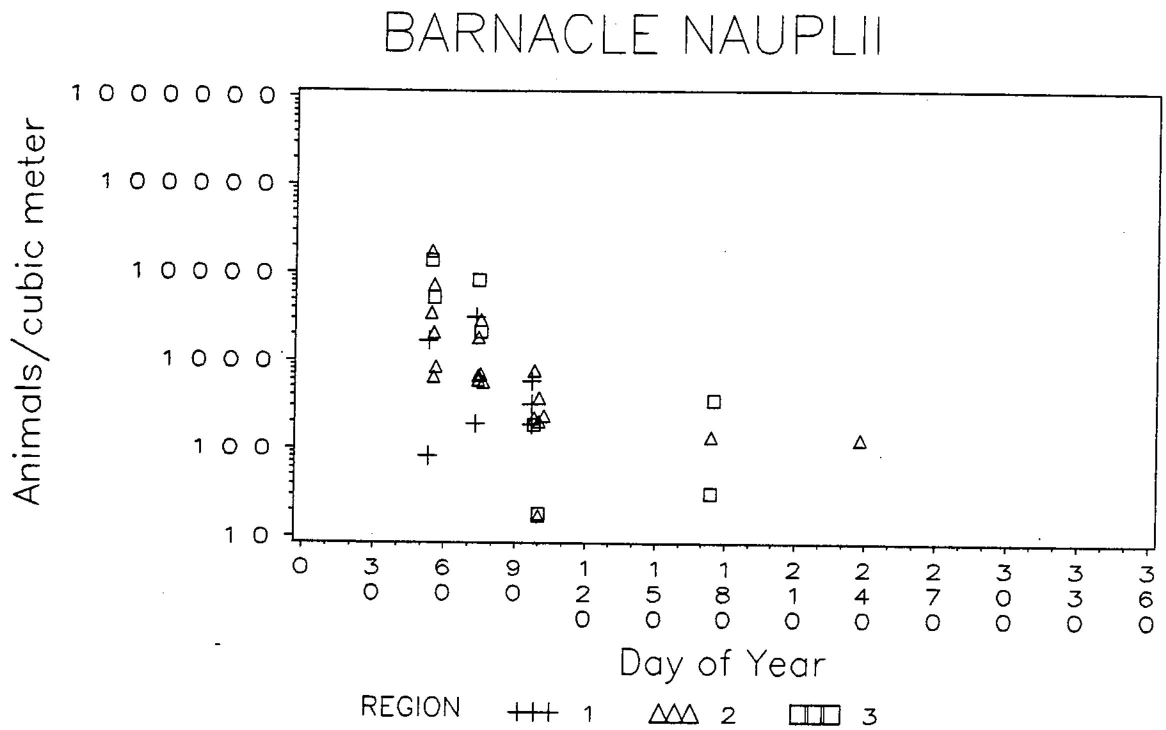


Figure 6-5. Zooplankton groups at different regions in 1992.
Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



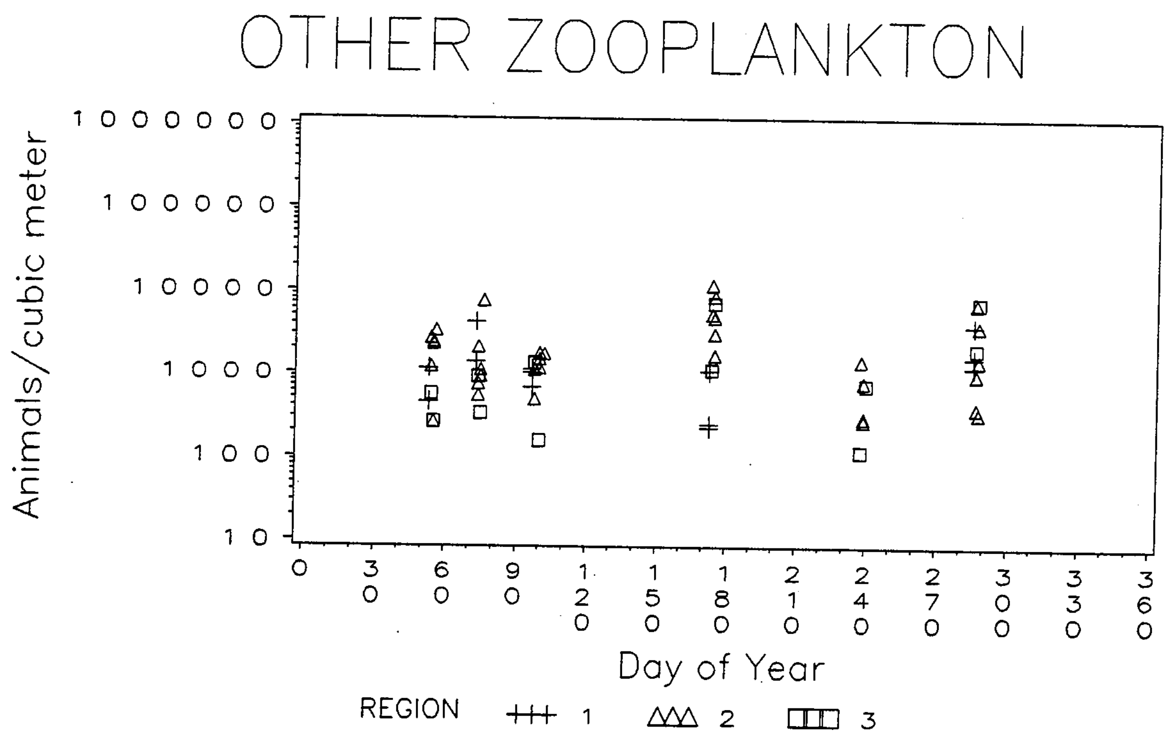
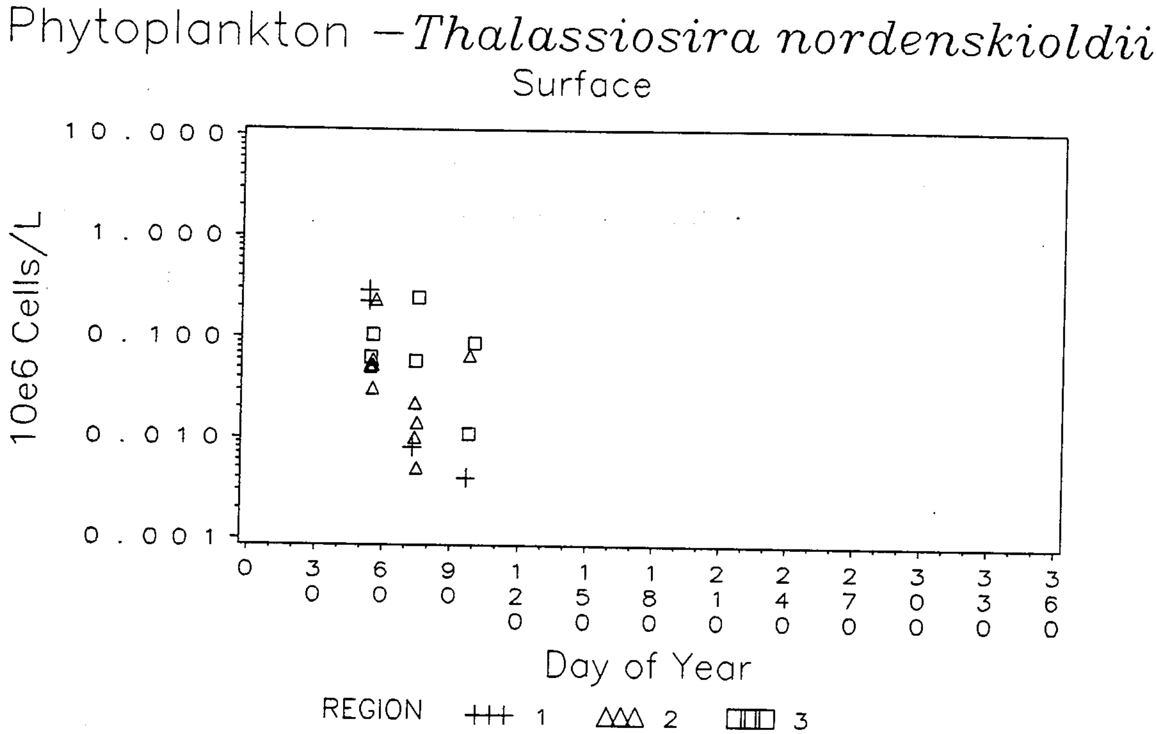


Figure 6-6. Zooplankton groups at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



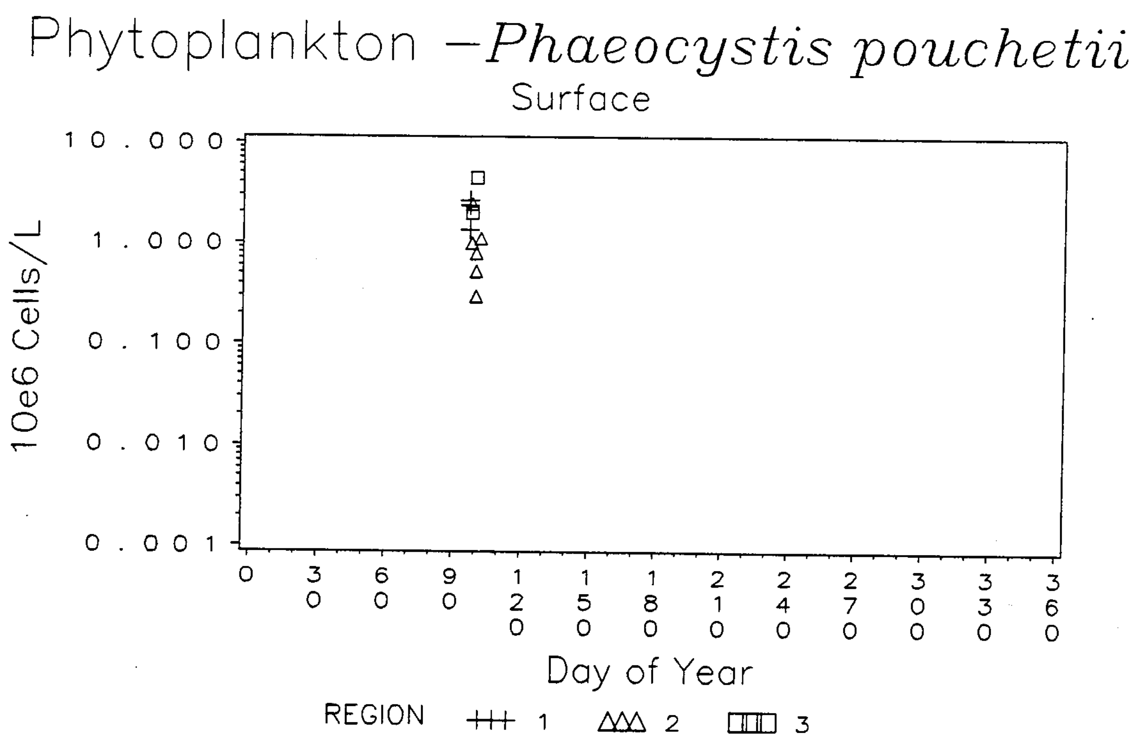
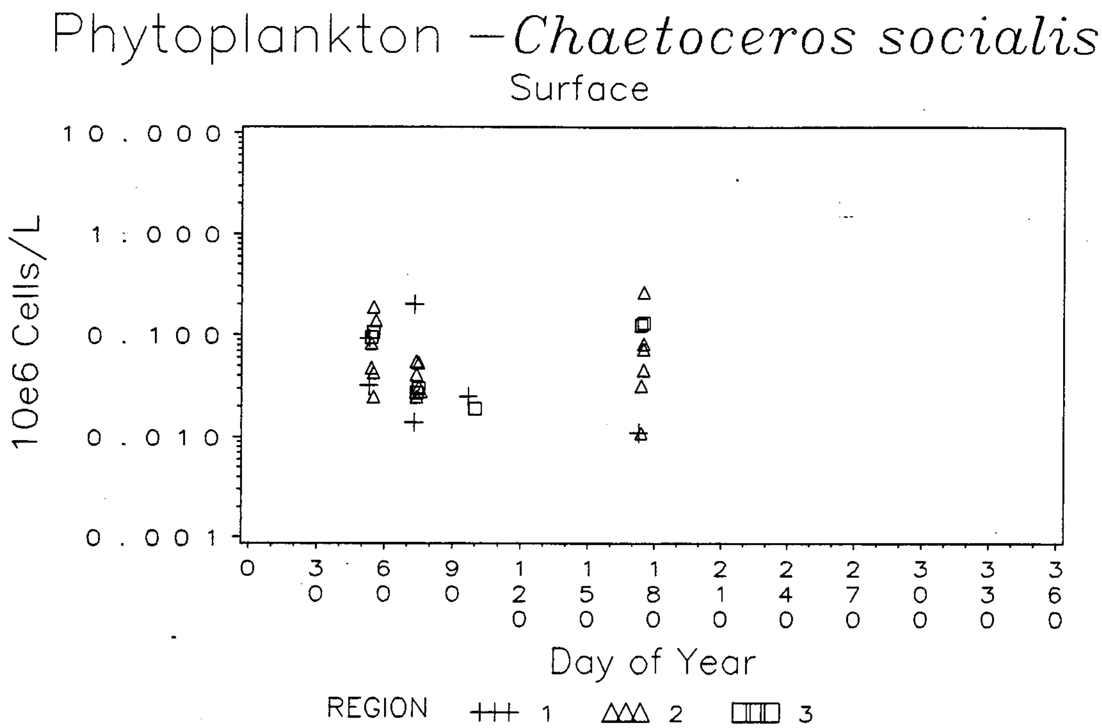


Figure 6-7. Selected diatom species at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



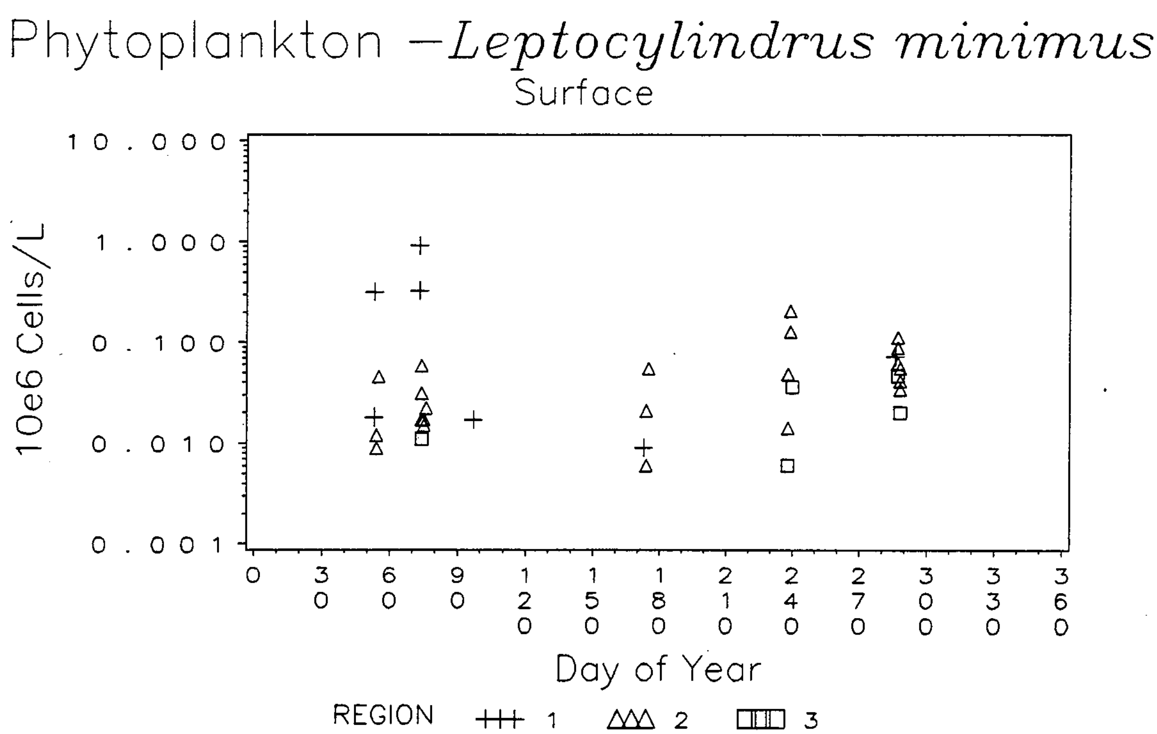
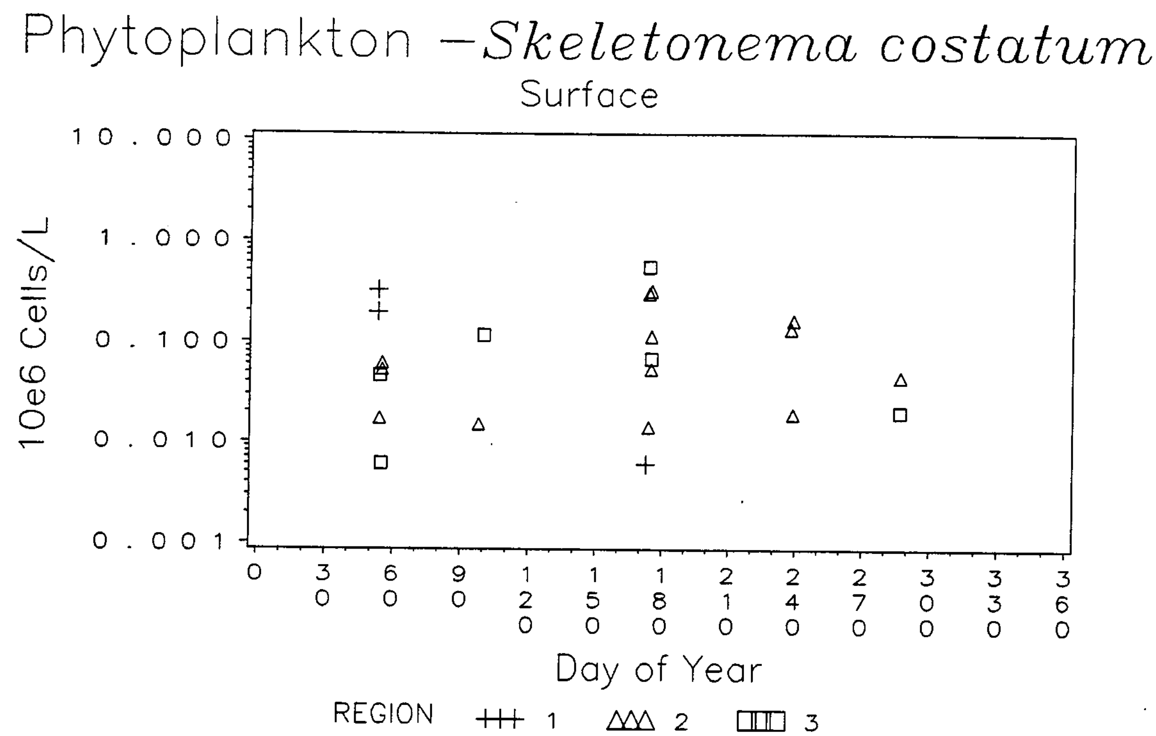


Figure 6-8. Selected diatom species at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



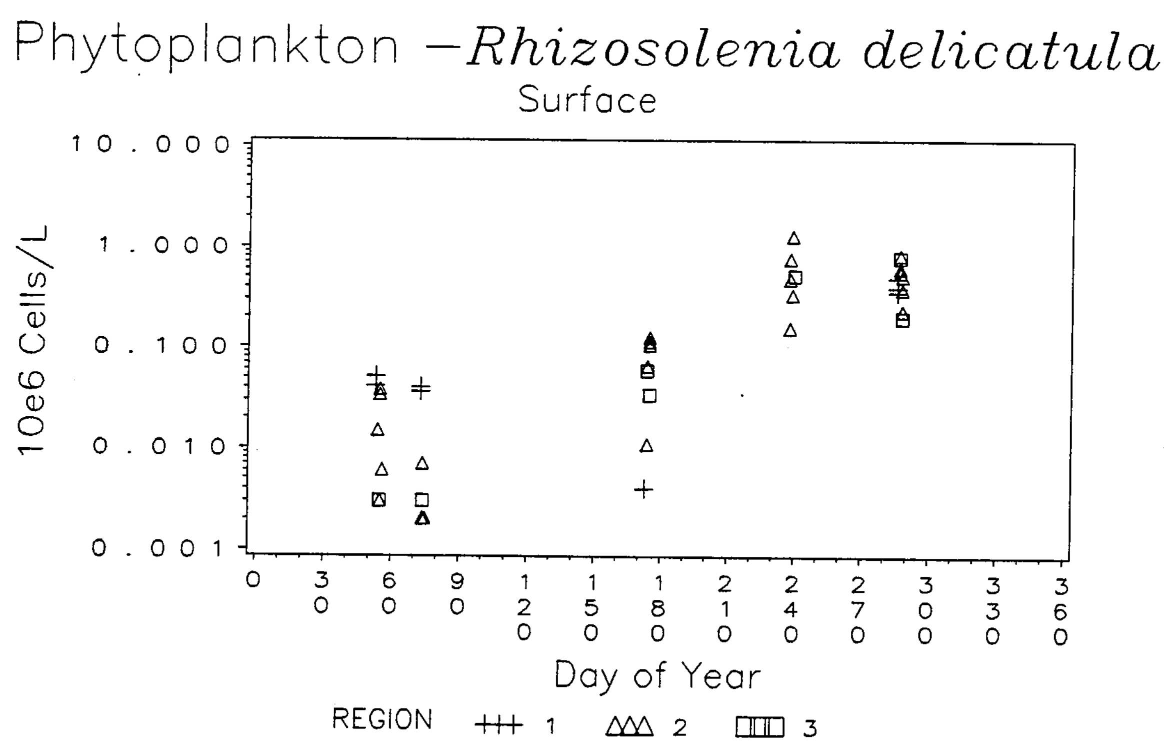
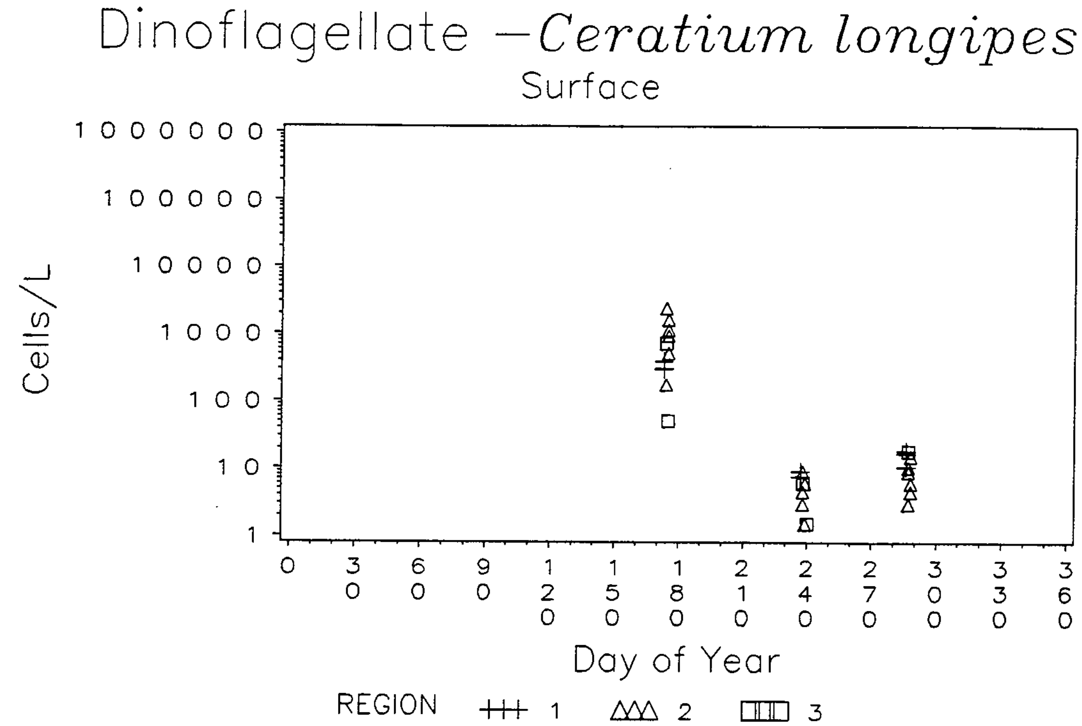


Figure 6-9. Selected diatom species at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



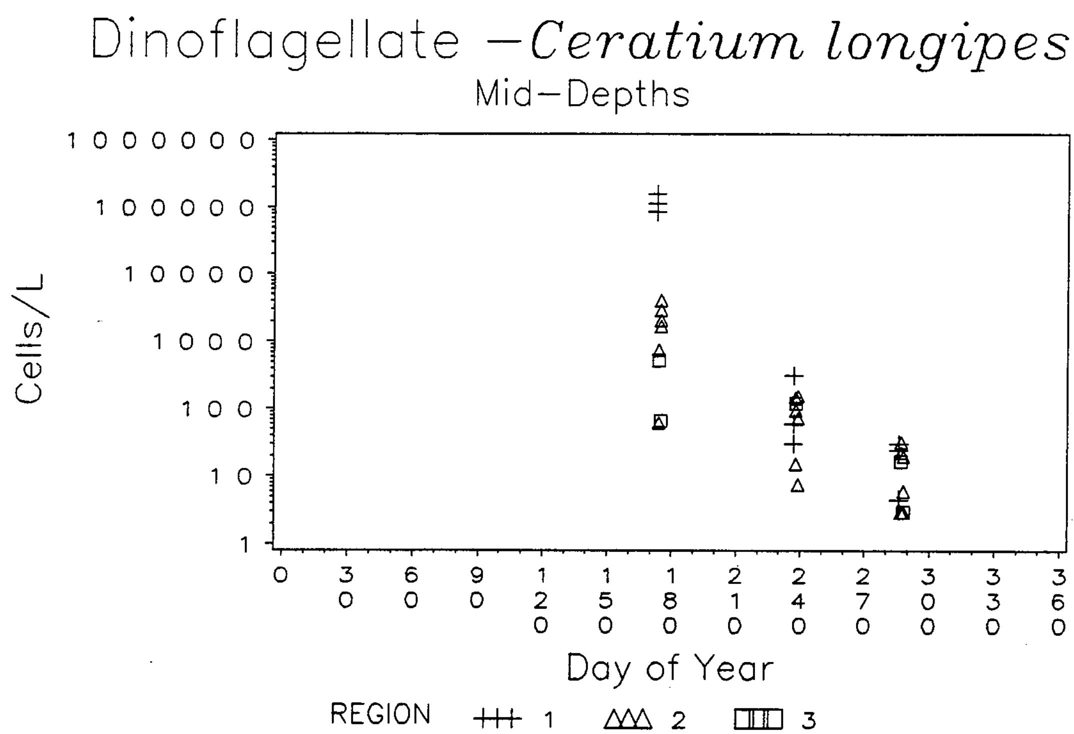
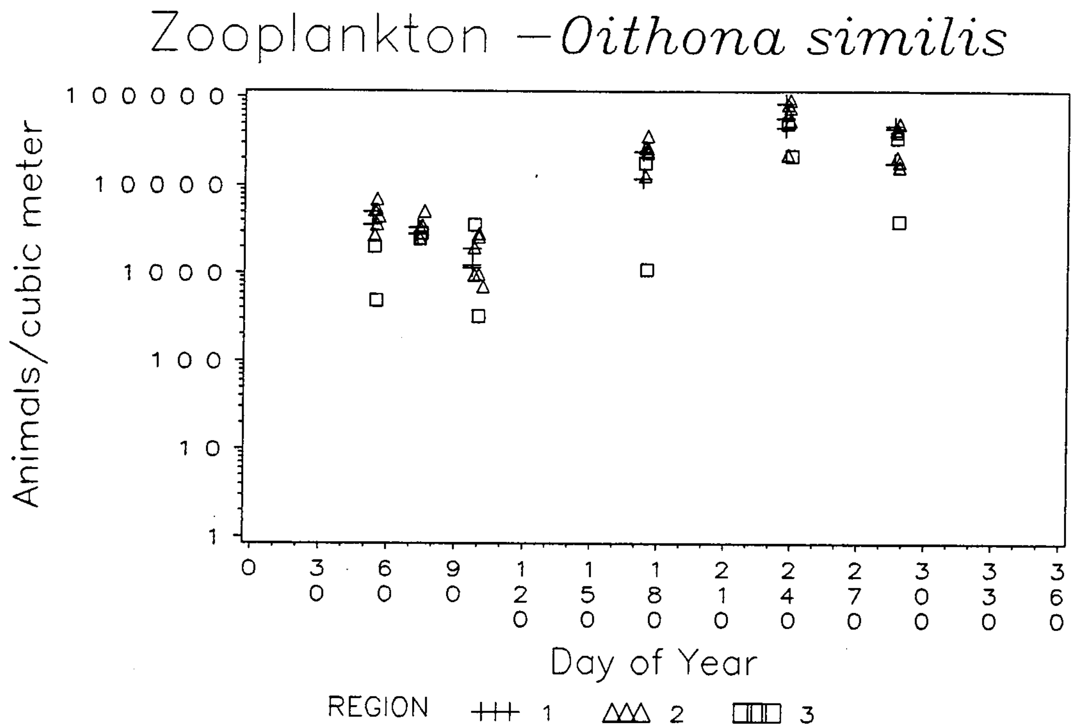


Figure 6-10. ***Ceratium longipes*** **at different regions in 1992.**
Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



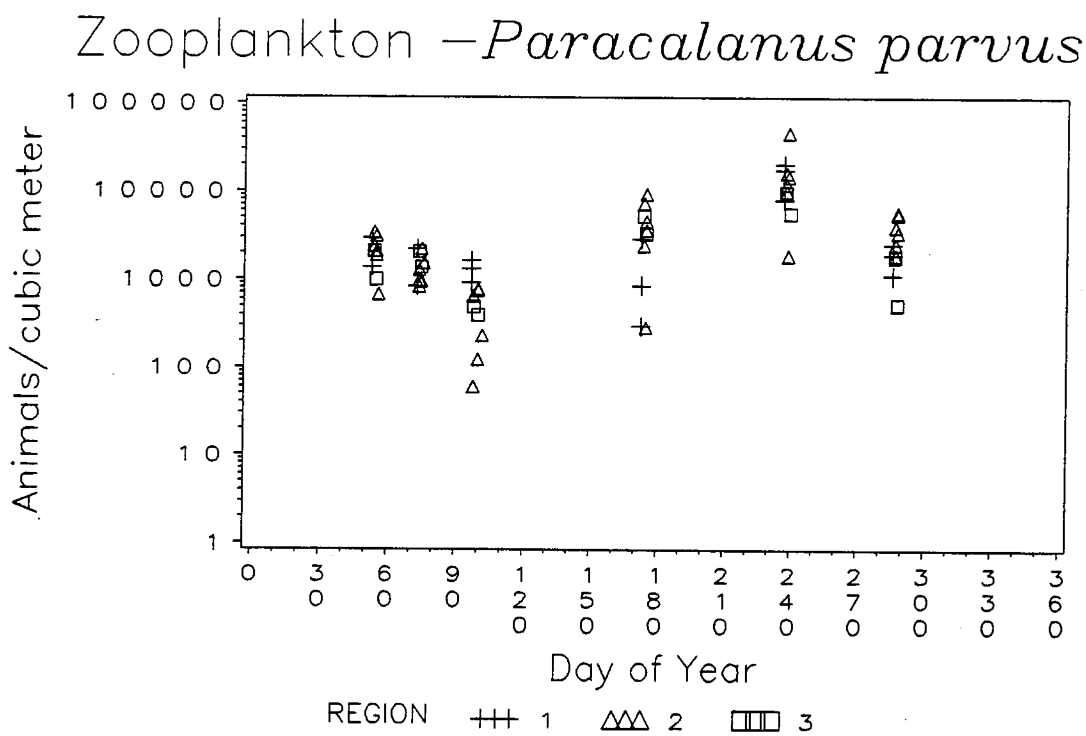


Figure 6-11. Selected copepod species at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal

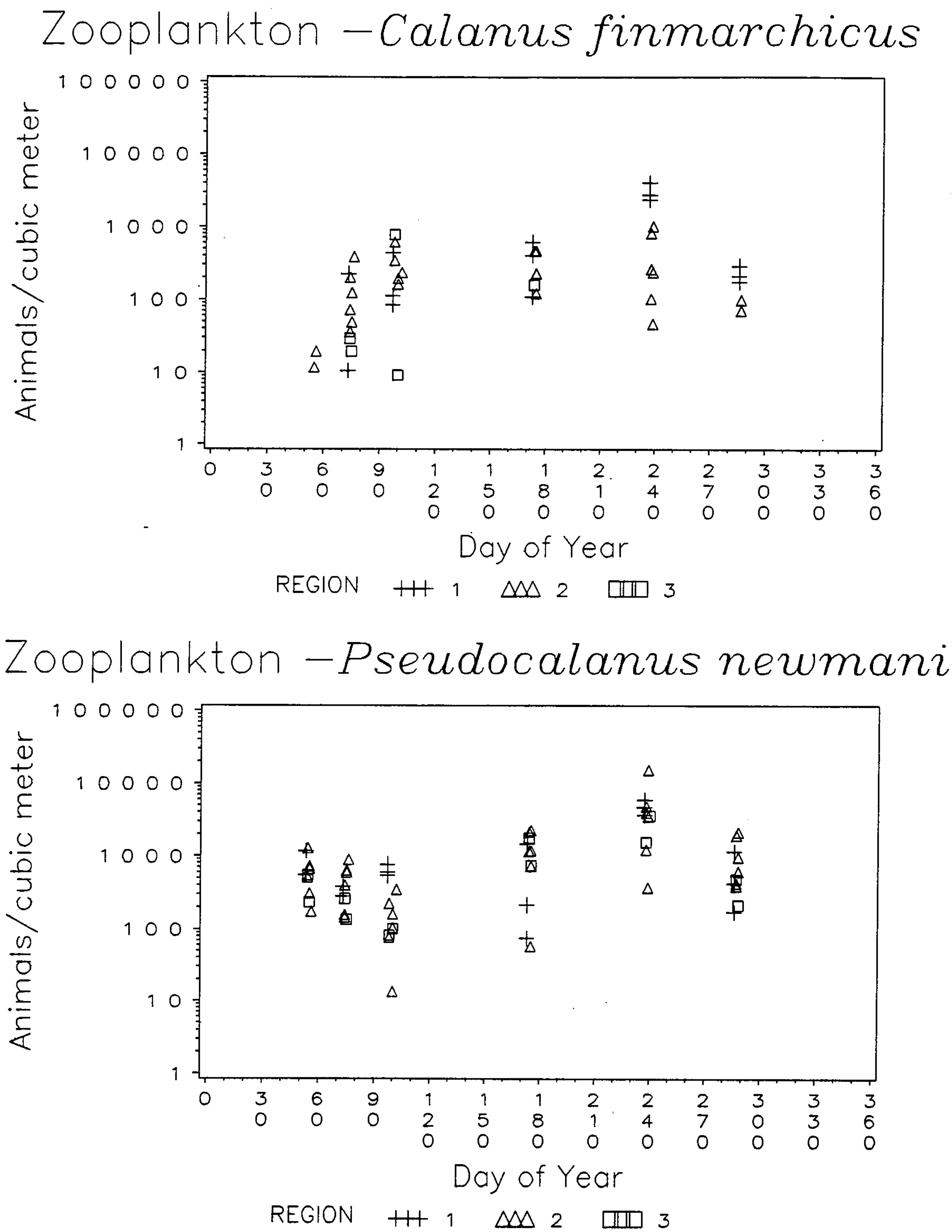
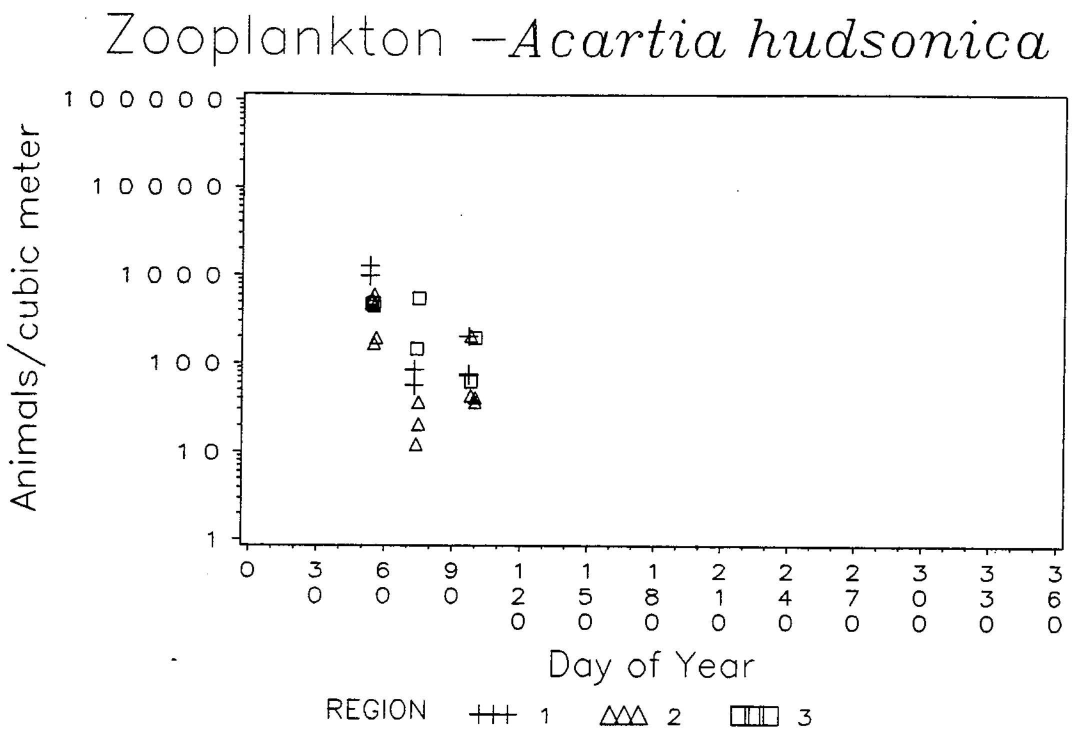


Figure 6-12. Selected copepod species at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal



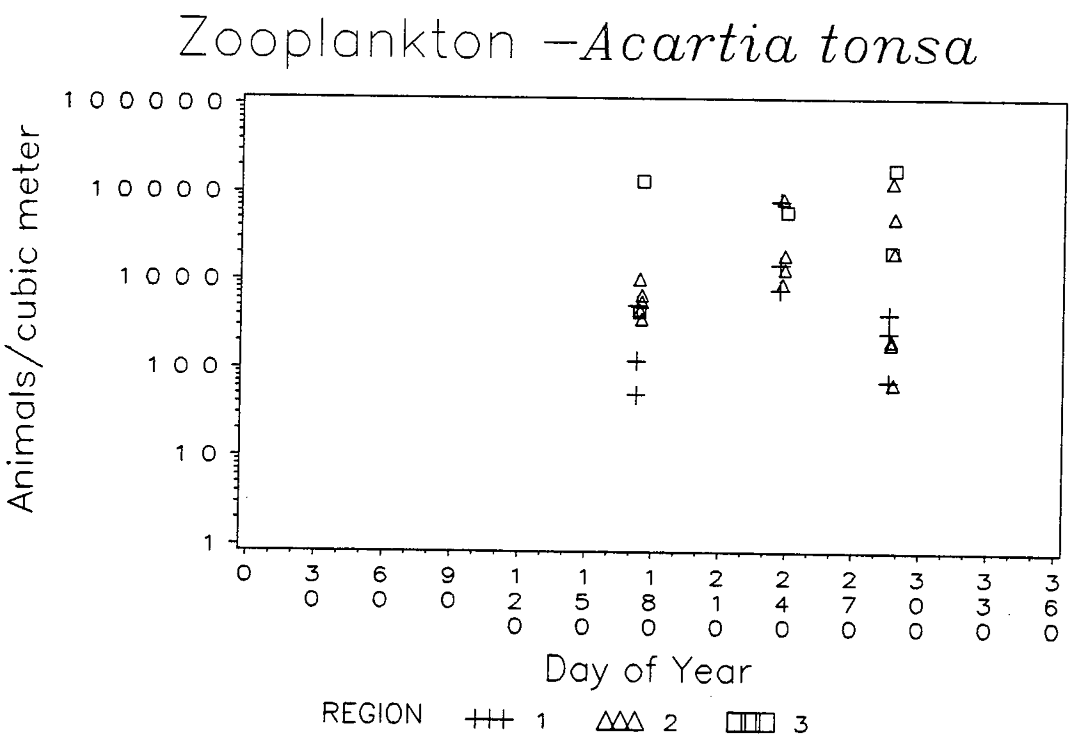


Figure 6-13. Selected copepod species at different regions in 1992. Region 1 = Cape Cod Bay, Region 2 = Nearfield, Region 3 = Coastal

7.0 NET DAYTIME PRIMARY PRODUCTION

To estimate water column primary production, several types of data must be combined in a modeling exercise. The modeling requires many assumptions, including those described below.

Suitable data were collected at 10 stations to make production calculations (see Kelly *et al.*, 1992 and 1993a,b for method details). Data include: (1) irradiance profile measurements with depth (all were sampled during daylight hours); (2) P-I curves generated from collection of water and subsequent bottle incubations (~4 to 6 h) at a range of irradiance levels in a temperature-controlled incubator, and (3) chlorophyll (based on fluorescence, see Section 4) concentrations with depth. P-I incubations were performed by measuring oxygen changes in the bottles, and fitting the data (if possible) to one of three assumed model formulations to describe photosynthetic activity as a function of light. To extrapolate and provide estimates of *in situ* rates, one must assume that conditions of the incubation (bottle sizes, length of incubations, spectral quality of the light source, turbulence level, etc.) and use of oxygen, 14-C, or other measures do not bias results. Those issues are significant but not of concern here, where the focus is on the assumptions necessary to provide a standardized estimate of integrated water column rates that allows comparison across stations, especially within a survey.

Because irradiance varies throughout the day and stations are sampled at different times, the light conditions were standardized to allow comparison. The average incident irradiance (I_o) (for all sampling days within a survey) measured by the deck cell during a mid-day period (~0900 to 1300 h) was used to standardize conditions. Then, for each station an extinction coefficient (k) was determined by regressing $\ln(I_z/I_o)$ vs. depth, where I_z is the irradiance at depth z, and the slope of the resultant line estimates k. The coefficient (k) was then used with the average survey I_o to generate the standardized light profile using the model $I_o = I_z e^{-kz}$.

Next, for each station and each incubation series ("surface" or "chlorophyll maximum" sample), the fitted P-I model was combined with the standardized light profile to yield chlorophyll-normalized production rates ($\mu g\ O_2\ \mu g\ Chl^{-1}\ h^{-1}$), generally at 0.5-m intervals to coincide with 0.5-m bin-averaged chlorophyll values generated from a vertical cast. For each incubation-modeled series, the model output may indicate a depth (with low light level) where the rate becomes negative (i.e., where respiration exceeds production) so there is no *net* production. In a number of cases, net production was positive to the bottom of the hydrocast (normally about 5 m from the bottom). To calculate depth-integrated rates, the predicted hourly, chlorophyll-normalized rate to the bottom of the profile, or where it became negative, was then multiplied by the chlorophyll fluorescence at each depth interval from the surface to either the point where net production became zero or the bottom of the profile. The values were then appropriately summed over depth and units were converted to m^{-2} from a volumetric basis.

The above procedure estimates hourly mid-day rates ($\mu g\ O_2\ m^{-2}\ h^{-1}$). It is desirable to extrapolate to a full day because daylength varies across the surveys and the most valid rate for comparison is production over the course of a complete day. Conversion to full day rates can be made by multiplying by a factor (7) which recognizes that about 55-60% of the production generally occurs during a 4-hour mid-day period when the irradiance is highest (Vollenweider, 1966). Finally, because many researchers are accustomed to rates expressed in carbon units, the rates presented were converted to C assuming a PQ (moles of O_2 produced/mole of CO_2 consumed) of 1.25. Thus, final modeled rates provide an estimate of net daytime primary production as $g\ C\ m^{-2}\ d^{-1}$.

The same procedure was applied to both surface and chlorophyll-maximum samples at a station. All P-I curves that could be fit (Kelly *et al.*, 1992; 1993a,b) were used; no statistical criteria were used for goodness of model fit to exclude points of a P-I series to obtain a fit. However, in several cases where model fitting failed for both samples of a station (usually for an anomalous point or two), the model parameters were estimated visually. In two cases, no light profiles were available and the extinction coefficient from a proximal station was used to produce the standardized light profile for that day. There are two estimates per station where each sample was fit by a P-I curve; no attempt was made to use the two samples of a station in a vertical series to model sequentially the upper and lower portions of the water column, respectively. In all, there were 102 estimates for the 10 stations (i.e., of a possible 120), because model parameters for 8 cases were not fit and could not be estimated visually.

7.1 Temporal and Spatial Variability

Net daytime production rates (g C m^{-2} d^{-1}) are given in Figure 7-1. Stations labels are indicated but groupings also separate those in Cape Cod Bay (F01P, F02P), coastal (F23P, F13P), and six in the nearfield region (N's). There is a considerable range of rates within each group, especially noticeable with the nearfield stations — probably because this set has more observations. Rates overall ranged from essentially zero (net respiration in the water column in two cases in April) to >9 g C m^{-2} d^{-1}. There is no obvious indication that a particular station was consistently high or low. Overall, the estimates centered around 1 g C m^{-2} d^{-1} (Figure 7-1) and the overall average for all estimates (n= 102) was 1.25 g C m^{-2} d^{-1} for the period of late February to mid-October. On average, rates were higher for the surveys between March and August when mid-day I_o values were all above 1000 μE m^{-2} sec^{-1}.

Some of the highest rates were calculated at stations in Cape Cod Bay during the Baywide dominance of *Phaeocystis* in April. A high value for F02P at the surface in June is suspect and not confirmed by the estimate from the deeper sample at that station where chlorophyll (*Ceratium*) was highly concentrated (Figure 7-2). Rates above 3 g C m^{-2} d^{-1} were also calculated for several nearfield stations, especially in August when Massachusetts Bay stations seemed to have higher rates than Cape Cod Bay stations.

On average, the two Cape Cod Bay stations had higher rates (1.91 g C m^{-2} d^{-1}, or 1.61 g C m^{-2} d^{-1} if the suspect June data point is omitted) than the nearfield set of stations (1.13 g C m^{-2} d^{-1}) or the two coastal stations (0.96 g C m^{-2} d^{-1}).

Comparing across surveys involves comparing short periods of time that may have had distinctly different sky conditions. The temporal pattern of results, because survey-specific light conditions were used, are sensitive to such atmospheric anomalies. Nevertheless, the relative pattern among groups should be conserved by the procedures used; results suggest that the annual cycle of net daytime production rates may be slightly different in regions of the Bays, particularly between the Cape Cod Bay stations and the Massachusetts Bay stations (Figures 7-1 and 7-2).

7.2 Sensitivity of Estimates

Statistical testing for differences among regions and stations could be conducted, but the estimates are based on so many assumptions that the sensitivity of results to some of these should be examined prior to such testing. Sensitivity analyses have not been conducted to determine a level of uncertainty that may be attached to calculated rates. At a minimum these analyses should include: (1) varying the P-I model coefficients within their 95% confidence intervals produced by curve-fitting, and (2) similarly varying the irradiance extinction coefficient for each station, and (3) using the vertical density/thermal structure and the descriptions of phytoplankton species at the two sample depths (Kelly *et al.*, 1992; 1993a,b) to adjust the exclusive depth intervals over which that model outputs derived from incubating either "surface" and "chlorophyll- maximum" samples should be applied.

Short-term variability in fluorescence at a station is highly influential on the estimates of net production rate. For example, the data from N01P in February were used to illustrate this. The station was sampled on 25-FEB-92 for profiles and for P-I incubations. It was sampled again 26-FEB-92 for profiles. The first day had relatively low chlorophyll fluorescence (<1 $\mu g\ L^{-1}$), but values were in excess of 4 $\mu g\ L^{-1}$ through the upper water column on the second day (Kelly *et al.*, 1992). If the P-I and irradiance data from 25-FEB-92 are used with the same day chlorophyll data, the integrated net production is calculated as 0.12 $g\ C\ m^{-2}\ d^{-1}$. In comparison, using the same P-I and irradiance data, but the 26-FEB-92 chlorophyll profile, the resulting calculation yields a net production estimate of 1.67 g C m^{-2} d^{-1}. It may be unwise to use P-I curves and irradiance with chlorophyll gathered on different days; nevertheless, for heuristic purposes, the calculation suggests that the magnitude of short-scale variability can be large. Indeed, this same point seems well illustrated by the considerable range of rates in the group of nearfield stations (all from a roughly 100 km^2 area) at any of the six surveys (Figure 7-1).

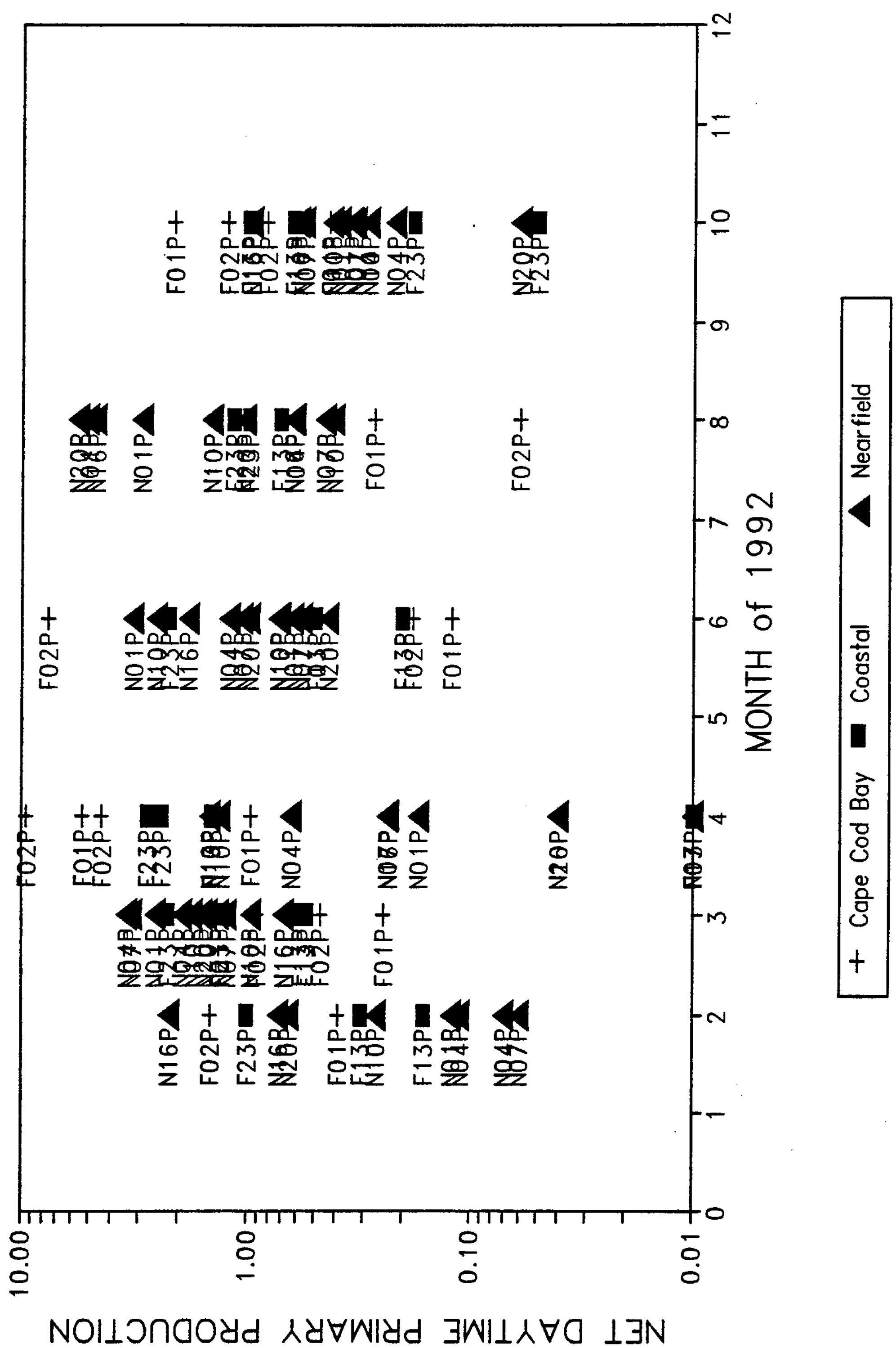


Figure 7-1. Primary production (g C m^{-2} d^{-1}) for all ten stations in 1992.

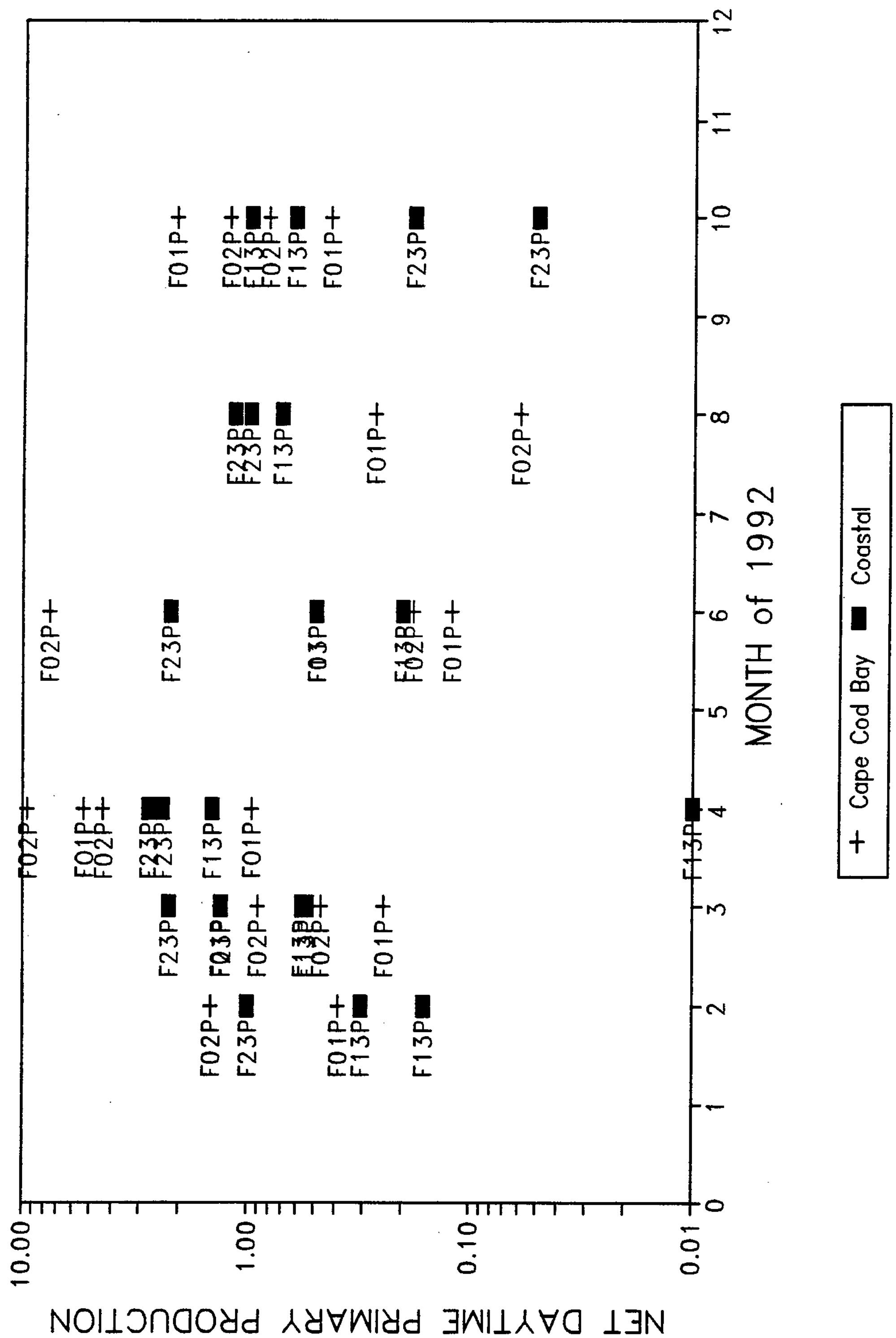


Figure 7-2. Primary production (g C m^{-2} d^{-1}) for coastal and Cape Cod Bay stations in 1992.

8.0 SOME VARIABILITY AND SCALE ISSUES

Much of the substance of this annual report revolves around an effort to convey major patterns, trends over time, and some of the apparent variability between groups of stations in similar geographic regions or individual stations at very different geographic locations. For explicit questions regarding the adequacy of monitoring design and statistical power, additional analyses must be conducted. This section begins to raise issues relative to such questions by giving some initial illustrations of statistical variability among stations intensely sampled in the nearfield region and by assessing some of the pattern variability that is strictly a function of the temporal and spatial scales of the observations.

8.1 Nearfield Variability of Nutrients in Surface and Bottom Waters

The nearfield region grades from a water depth of about 20 m inshore to about 50 m offshore, with considerable bathymetric variability throughout. From the data set, the surface and near bottom samples taken for nutrients were used to provide a plot of mean surface and bottom water concentrations for all stations, independent of bottom depth (Figures 8-1a,b). The seasonal cycle discussed previously also emerges. DIN concentrations start out high throughout the well-mixed water column and are depleted by late spring-early summer. At the end of that period the surface and bottom water DIN concentrations begin to diverge, the surface staying virtually everywhere at very low levels and the bottom waters "growing" in DIN as a consequence of being sealed off to become a heterotrophic system. From May to June there was an initially sharp increase in bottom-water DIN concentrations. From June to October, there was a large range in bottom-water DIN concentrations, but a slow, progressive increase, on average, is suggested. In October, just prior to mixing and equalization of surface and bottom water concentrations, the mean difference in DIN between surface and bottom was highest, but variability was also high, probably because some of the inshore stations were starting to mix and/or a consequence of the higher DIN water coming from the Harbor. For the November and December, while the water column was well-mixed, so surface and bottom-water DIN concentrations were not different.

Given the high degree of physical and chemical variability within the nearfield (e.g. Figure 8-1b), analyses of change may be examined most appropriately on a regional average basis, rather than on the basis of pre/post comparisons at individual stations. In any event, it is relatively clear that increases of DIN into surface waters will be more easily detectable than in deep water. Given the smaller variability at the surface in summer, a signal would be more apparent relative to *both* background concentrations *and* spatio-temporal variability.

8.2 Spatial Scale of Sampling

In the nearfield, two types of sampling were conducted. On one day, standard vertical profiles at discrete points ("stations") were performed. On a second day, profiling was accomplished by "tow-yos," with sensors mounted on a towfish towed from a ship (4-6 kts) and oscillated from near surface to near bottom along tracks covering the same stations as were vertically profiled the day before. The latter method obviously provides higher resolution and can be performed faster. Moreover, it is a straightforward exercise to extract a series of individual, discrete (near-)vertical profiles from the tow-yos to make a direct comparison of information from a continuous high-resolution sampling strategy vs. discrete profile sampling. Figure 8-2 compares vertical profile data (top), complete tow-yo data (bottom), and extracted profiles from the tow-yo (middle).

Comparison of the top and middle panels in Figure 8-2 shows the daily variability that has been observed in this area off Boston Harbor throughout 1992. On the first day (top panel, Figure 8-2), a large continuous "patch" of chlorophyll in the middle of the track is inferred from contouring the data. On the following day (middle panel, Figure 8-2), the same resolution of sampling suggests two discrete "patches" were across this track.

Comparison of the middle and bottom panels in Figure 8-2 reveals the advantages of higher resolution. In the bottom panel, the contours are wavy and the patches nicely defined. The middle panel has less spatial resolution and therefore has a distribution more inferred by contouring; the resulting pattern is smoother and less reflects the inherent variability observed with the high resolution sampling. Most importantly, with the high resolution (tow-yo) sampling, the spatial distributions are described with greater confidence and less extrapolation over space. If regional descriptions are required to assess change, the higher resolution clearly offers some advantages. The question for further assessment is what level of change should be detectable?

8.3 Temporal Scale of Sampling

As the spatial scale may be altered to allow comparisons by extracting partial information from an existing high-resolution data set, comparisons of different frequencies of sampling may be developed by data manipulation from existing sampling. Such a comparison is presented in Figures 8-3 and 8-4, where time-depth contours based on data from all 14 surveys are compared with those generated using data from a subset that includes only the six farfield surveys.

Results indicate that the principal features of the annual cycle are well captured by sampling during the months chosen for the six farfield surveys. Higher frequency (weeks-month) and more extreme events may or may not be captured, depending on the synchrony of sampling and events. Again, the principal question is what level of resolution is required. We can design analyses using the 1992 data set to address this issue explicitly and quantitatively.

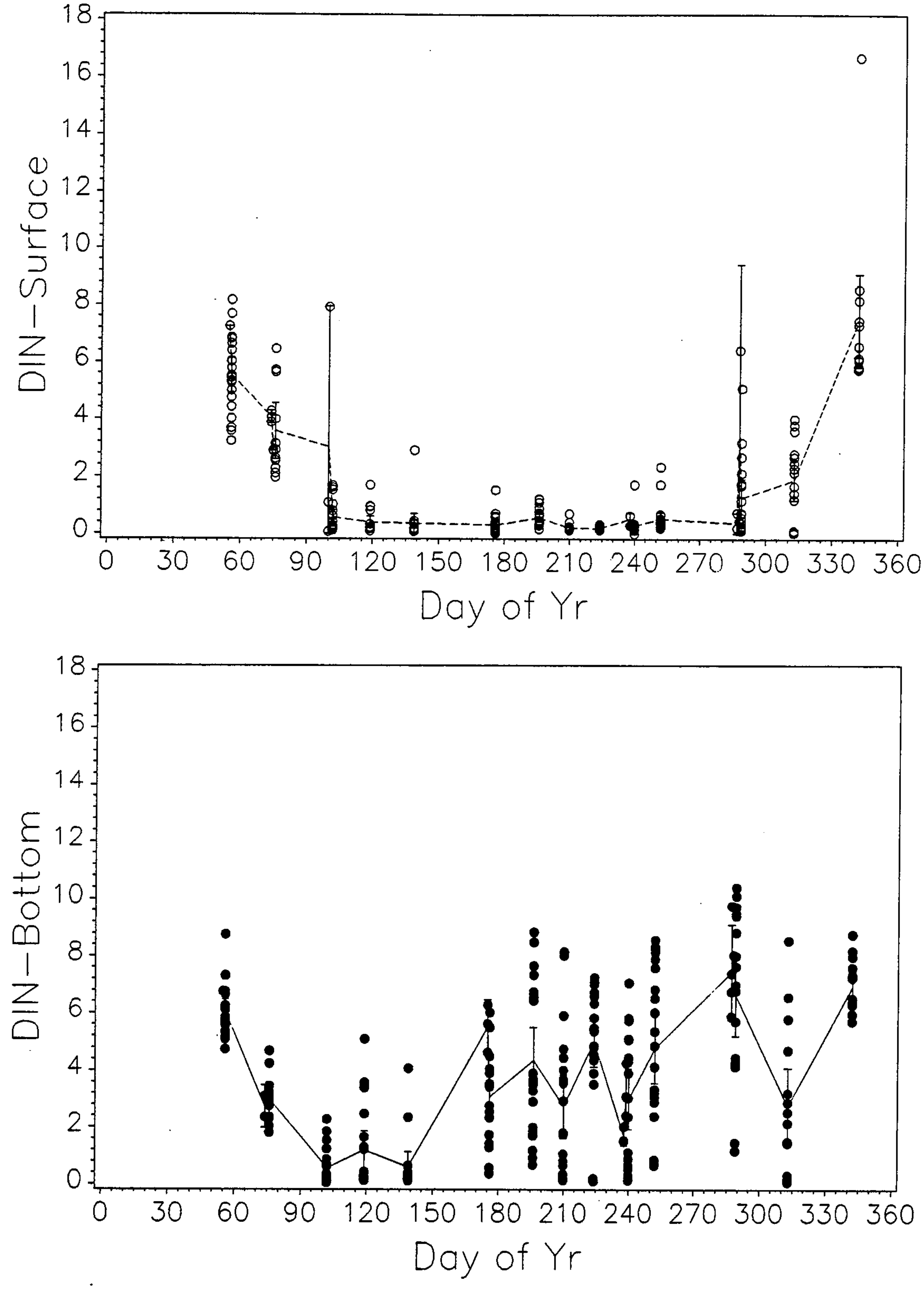


Figure 8-1a. DIN (μM) in surface and bottom water at all nearfield stations throughout 1992. Data points are for each sampling of nearfield stations (farfield or nearfield surveys) for surface (top panel) and bottom water (bottom panel). Lines join the means for each sampling day and the range bars show ± 1 standard error of the mean.

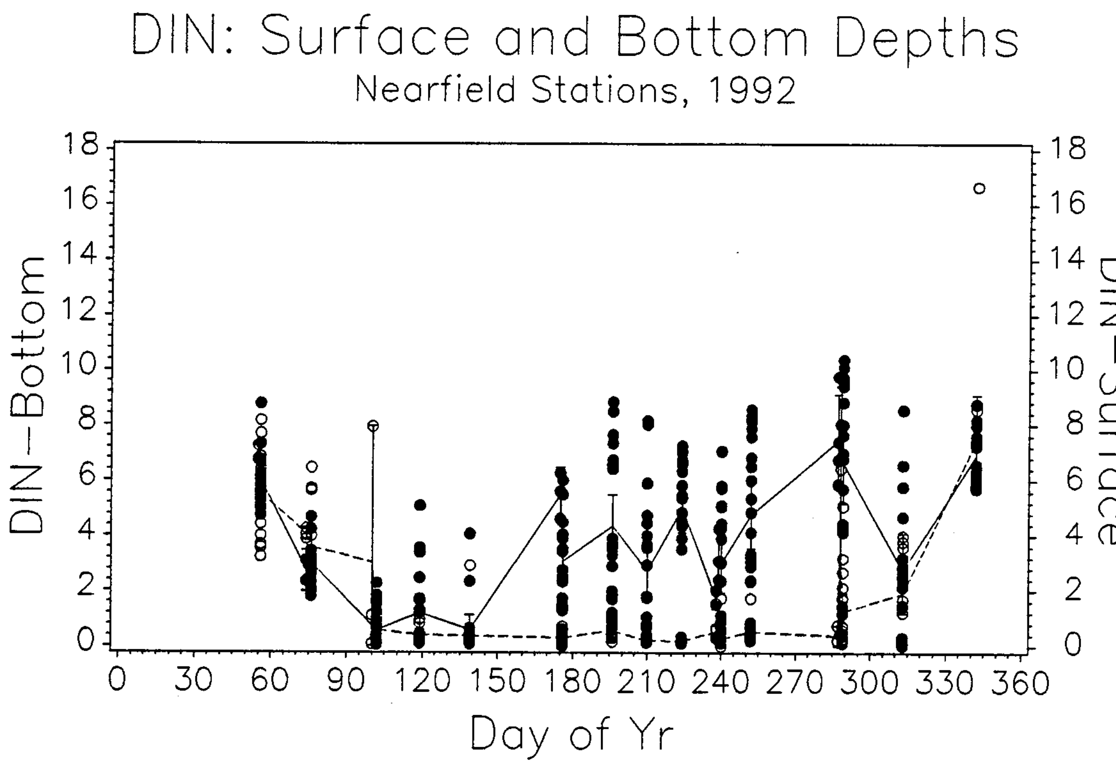


Figure 8-1b. DIN (μM) in surface and bottom water at all nearfield stations throughout 1992. Overlay of panels in Figures 8-1a. Open circles connected by dashed lines = surface samples. Closed circles connected by solid lines = bottom samples.

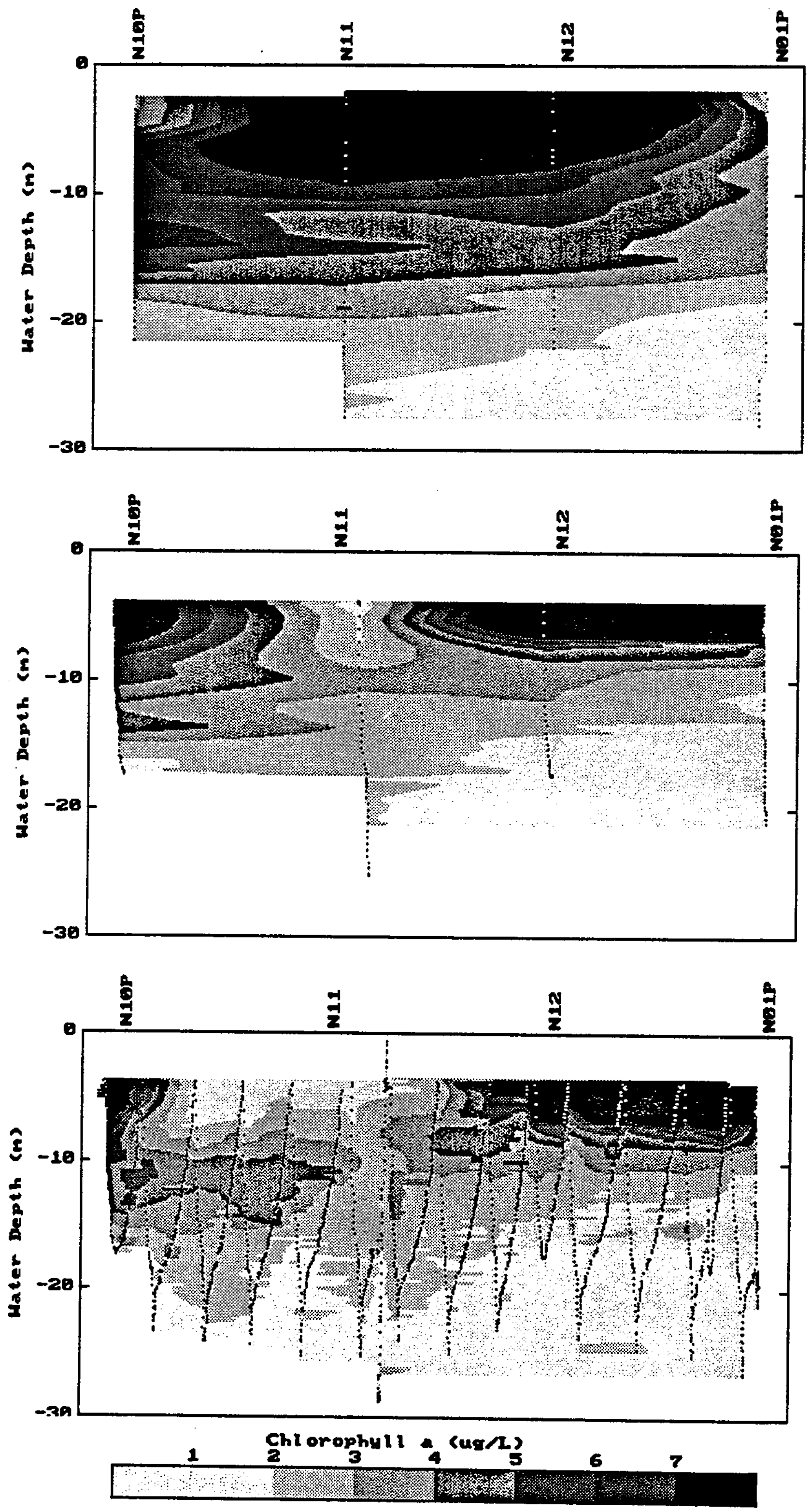


Figure 8-2. Scales of resolution in the western nearfield transect closest to Boston Harbor. Top shows vertical profiles from day 1. Bottom shows tow-yo from day 2. Middle shows profiles at four stations stripped from tow-yos shown in bottom graph. Data are from the nearfield survey in September.

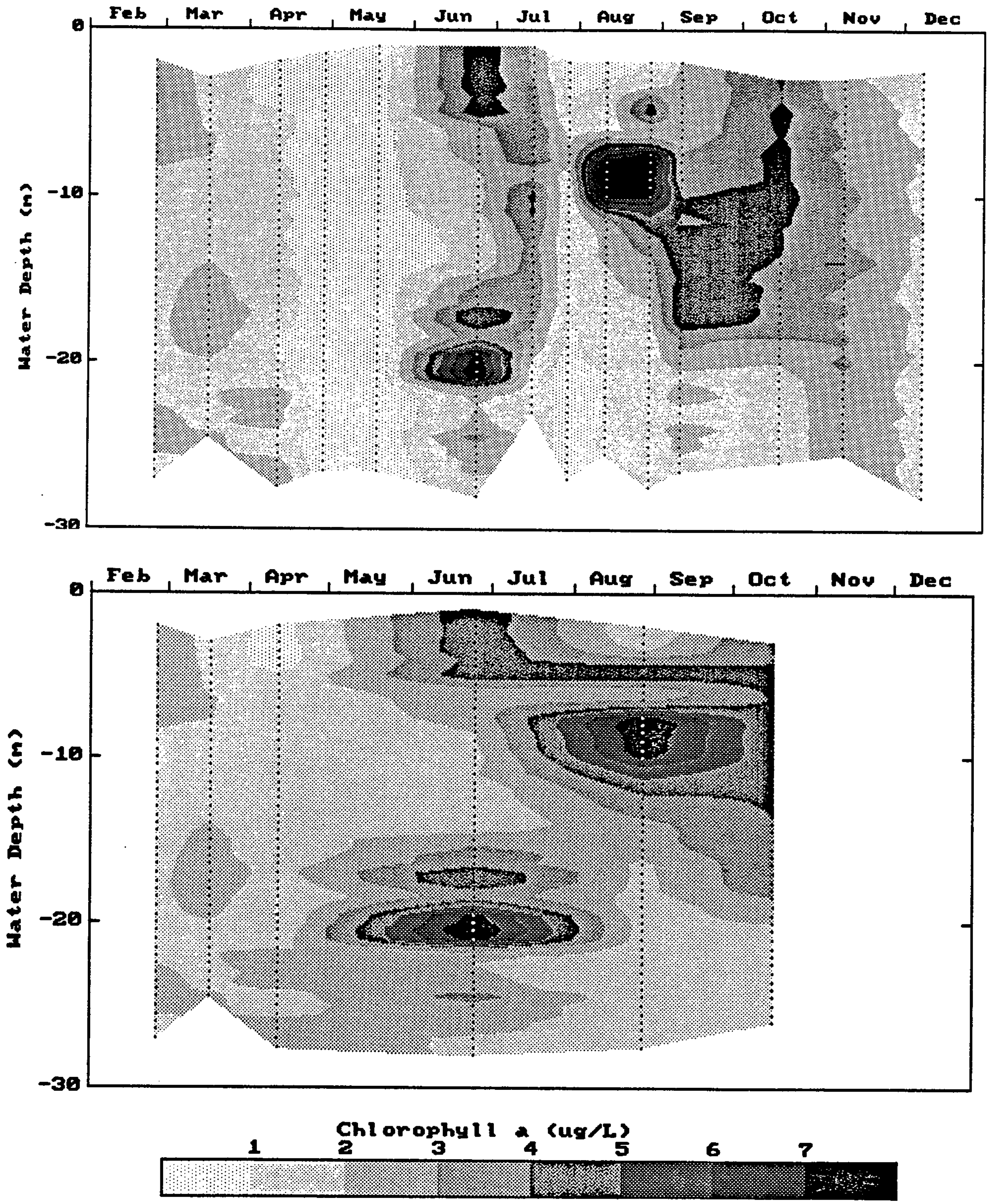


Figure 8-3. Comparison of patterns generated from 14 vs. 6 surveys per year at nearfield station N20P.

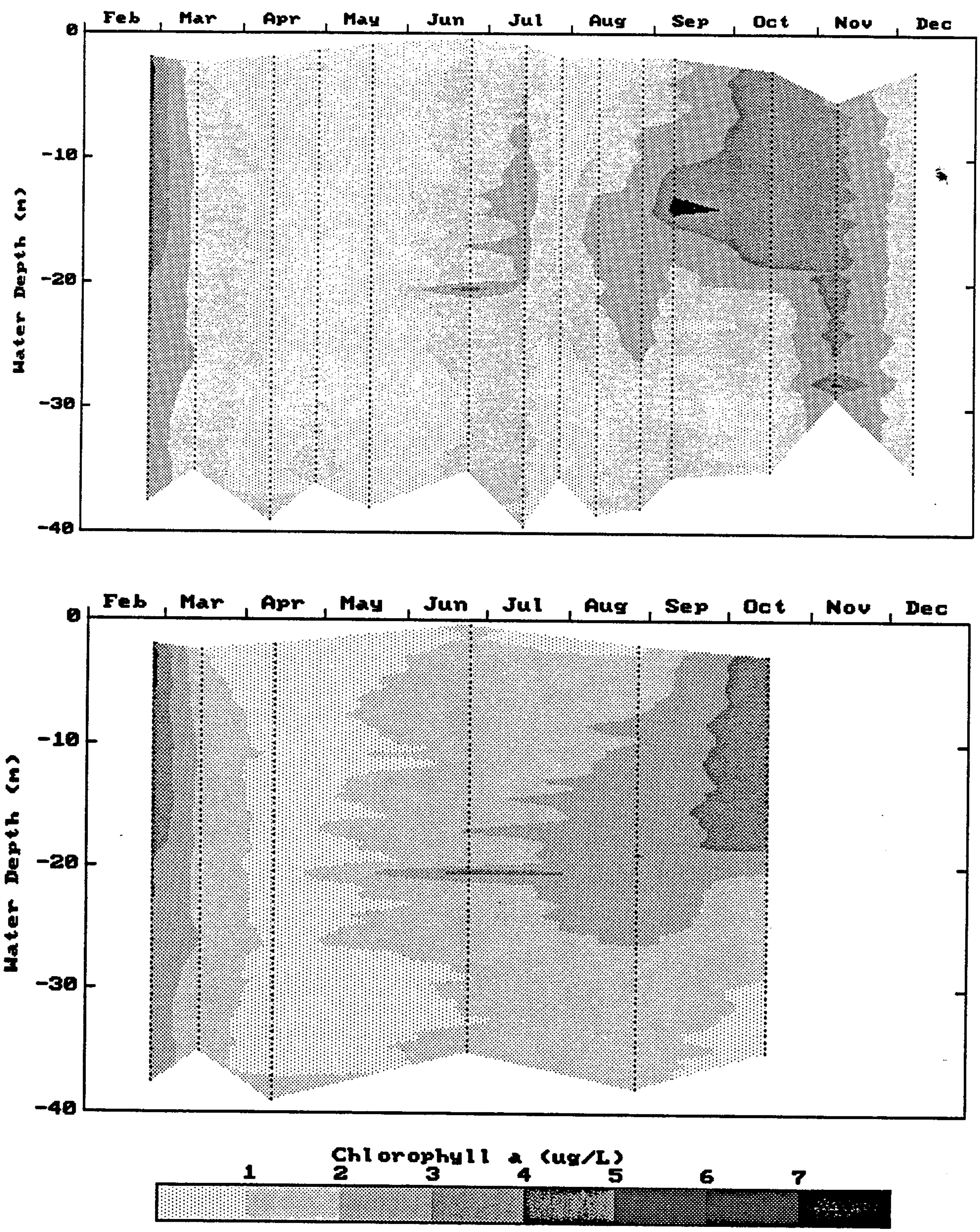


Figure 8-4. Comparison of patterns generated from 14 vs. 6 surveys per year at nearfield station N16P.

9.0 CONCLUDING PERSPECTIVE ON SOME REGIONAL PATTERNS

9.1 Pattern From Nearshore to Offshore in 1992

Three stations, from Broad Sound (F24) through the center of the nearfield (N20P) to deep water in Stellwagen Basin (F19), form a "transect" that suggests some seasonal, geographic and depth-related differences in DIN (Figure 9-1) and chlorophyll (Figure 9-2) through the year. The early spring and fall DIN concentrations at station F24 are high and reflect the proximity to Boston Harbor but, as noted, there was still surface-water depletion of DIN during the summer when primary production activity was high and chlorophyll was continuously high (Figure 9-2). Note that during summer there were sporadic periods of high bottom-water DIN, perhaps reflecting development of strong stratification and rapid benthic regeneration processes.

Moving offshore to station N20P, the early and late periods of the year are highest in DIN, but less than at the Harbor; these periods of high concentration may be shorter than at locations near the Harbor nutrient source. In between, during summer, the surface waters were generally low in DIN, but were punctuated by brief bursts of chlorophyll either at the surface or in mid-waters (Figure 9-2). The bottom water DIN was highly variable over time and perhaps some time-lag relationships between DIN at depth and chlorophyll are suggested. For example, August-October chlorophyll precedes high bottom-water DIN in October.

Even in Stellwagen Basin, some variability in bottom-water DIN was suggested at some stations, including F19 (Figure 9-1). In April, the subsurface chlorophyll maximum was very deep (30-40 m) and may have caused the relative depletion of DIN from the surface to this depth. Similarly, it is possible that the mid-water chlorophyll event in late August helped to reduce nutrient concentrations in deep water. Interestingly, the subsurface chlorophyll maximum in August (at 15-20 m) appeared to produce a subsurface dissolved oxygen (DO) concentration maximum (Figure 9-3); however, there was a relatively continuous decline in dissolved oxygen concentration in deep water that appeared unaffected by deep-water DIN or subsurface DO fluctuations. At this offshore station (F19), the fall-winter rebound of surface DIN concentrations that is typically initiated by mixing of the entire water column and thereafter promoted by declining productivity had not yet occurred by mid-October 1992, a situation which contrasts with shallower areas of the Bay.

9.2 Bottom Waters Along the Axis of Stellwagen Basin in 1992

It was only the deepest waters sampled that showed a strong seasonal decrease in percent saturation of dissolved oxygen. From an examination of the pattern in bottom waters at three of the Stellwagen Basin stations, it was apparent that the chronological development of undersaturated values was very similar. The deeper the water, the lower the percent saturation that had been reached by October.

9.3 Massachusetts Bay and Cape Cod Bay Nutrient and Plankton Cycles in 1992

Differences in nutrients and plankton during spring and summer at the Cape Cod Bay stations relative to most Massachusetts Bay stations have been extensively described in previous reports (Kelly *et al.* 1992; 1993a). Basin- or region-specific differences were also reported by Geyer *et al.* (1992) and Becker (1992). As a summary contrast, 1992 annual cycles for a station in Massachusetts Bay in the center of the nearfield (N20P) and in western Cape Cod Bay (F01P) illustrate some of the differences (Figures 9-4 and 9-5). The comparison follows mid-depth samples for phytoplankton, and shows the pattern of DIN and silicate concentration from three mid-depth samples (including the depth of the plankton sample).

The total cells counts of $\approx$ 1 million cells L^{-1} were similar for both stations and relatively constant throughout the year. At both stations, the high concentrations of diatoms in February and March (through day 90) were replaced by *Phaeocystis* ("Other" category in the plots) in April. At station N20P, the June data showed a recovery of diatoms and a mixed diatommicroflagellate-cryptomonad community for the remainder of yearly sampling. In contrast, an intense *Ceratium* (dinoflagellate) bloom occurred during the June sampling period in Cape Cod Bay (both station F01P, shown in Figures 9-4 and 9-5, and station F02P). For the remainder of the year in Cape Cod Bay, flagellates became less significant, but diatoms were also less prominent than at station N20P.

At these two stations, the major difference in nutrient cycles was silicate. Station F01P was nearly depleted in silicate by April due to vigorous diatom growth, whereas station N20P was fairly high in silicate. By June, silicate levels at station F01P had rebounded, in part because *Ceratium* does not require silicate like diatoms. In contrast, by this time, when diatom concentrations had increased again at station N20P, silicate was again drawn down to a lower concentration. By late summer, concentrations of both silicate and DIN were similar at the two stations.

The contrast between these two stations suggests that a succession of biological events can be established by preferential use of nutrients. Moreover, the contrast also demonstrates that it is inadequate and probably misleading to interpret the ecological condition (or potential condition) of a bay from nutrient concentrations alone, without full knowledge of the biology and its own dramatic influence on those nutrients.

The final point raises an interesting notion. Over the year, Cape Cod Bay stations showed high winter-spring chlorophyll, had high levels of primary production, developed an intense dinoflagellate bloom, and maintained a summer plankton community with a lower diatom component than many northern Massachusetts Bay stations. These conditions are all part of the classical list of eutrophication "symptoms". It is fascinating that these observations are being made far from the perceived major sources (Boston Harbor and the Merrimack River) of loading to the Massachusetts Bay-Cape Cod Bays system. It is possible that Cape Cod Bay has some unknown nutrient sources or that the basin's shallowness begets more efficient recycling. Whatever the reason, the continued examination of this regional contrast should sustain a great deal of interest.

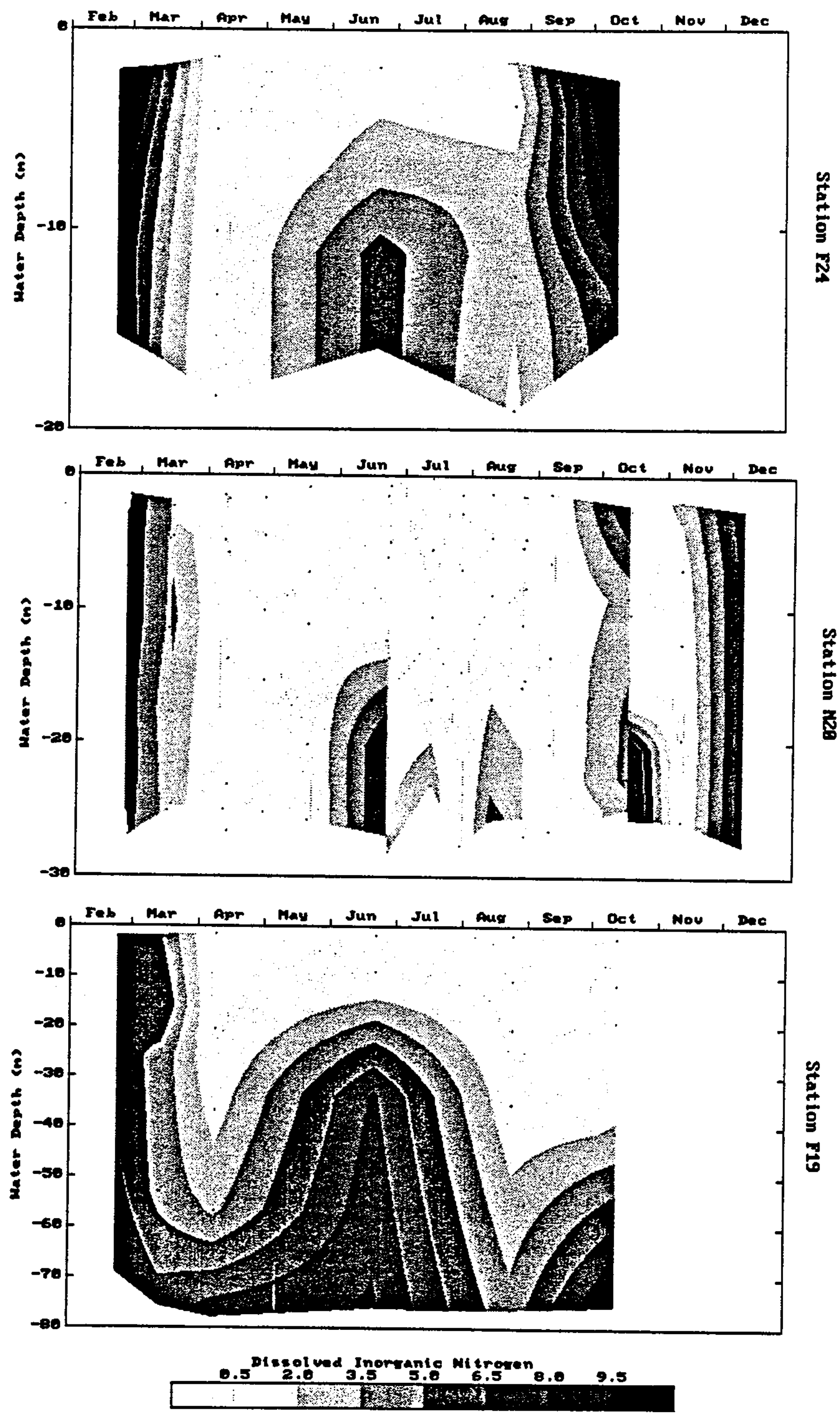


Figure 9-1. DIN transect from Broad Sound to Stellwagen Basin. Note different depth scales.

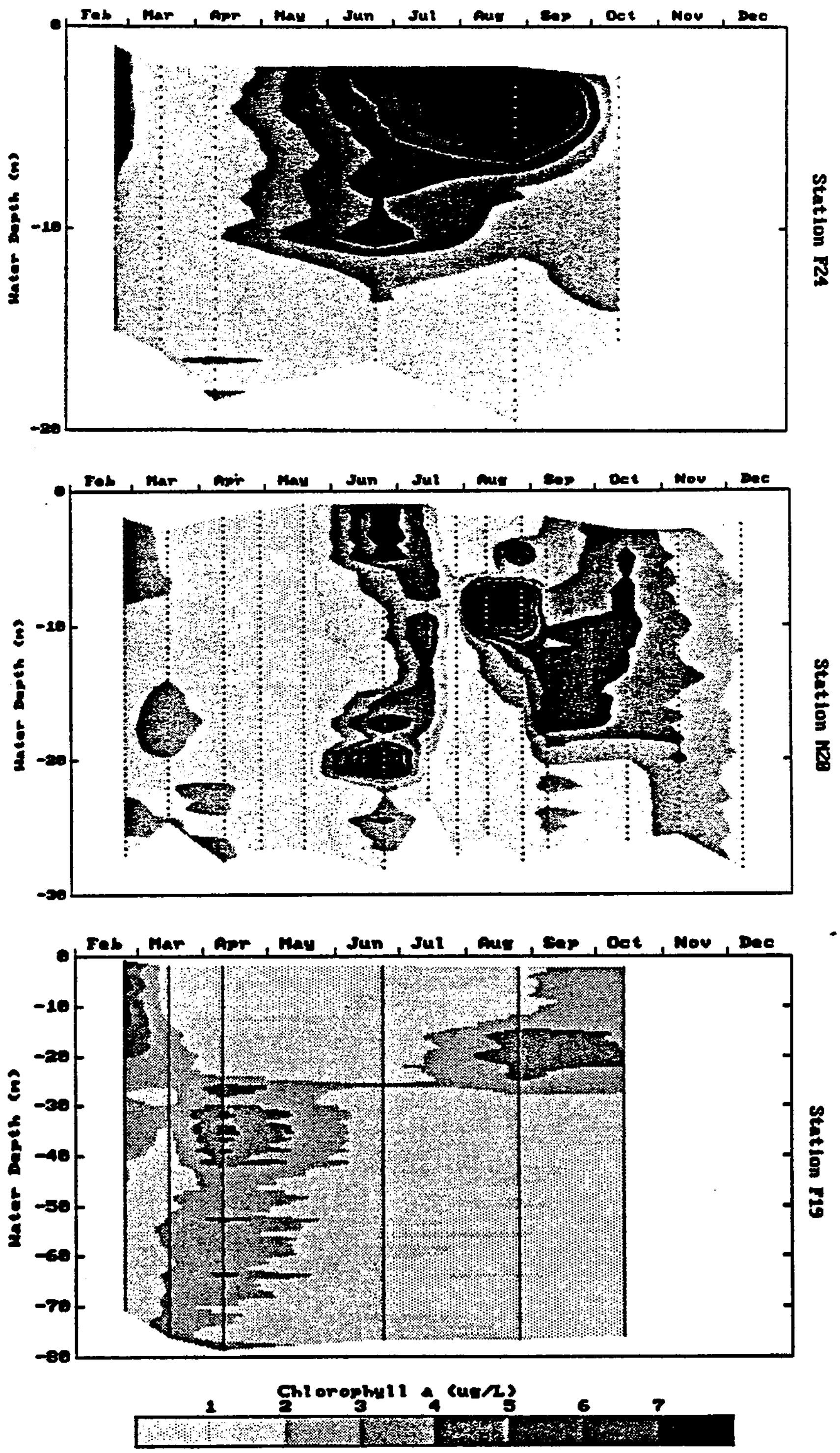


Figure 9-2. Chlorophyll transect from Broad Sound to Stellwagen Basin. Note different depth scales.

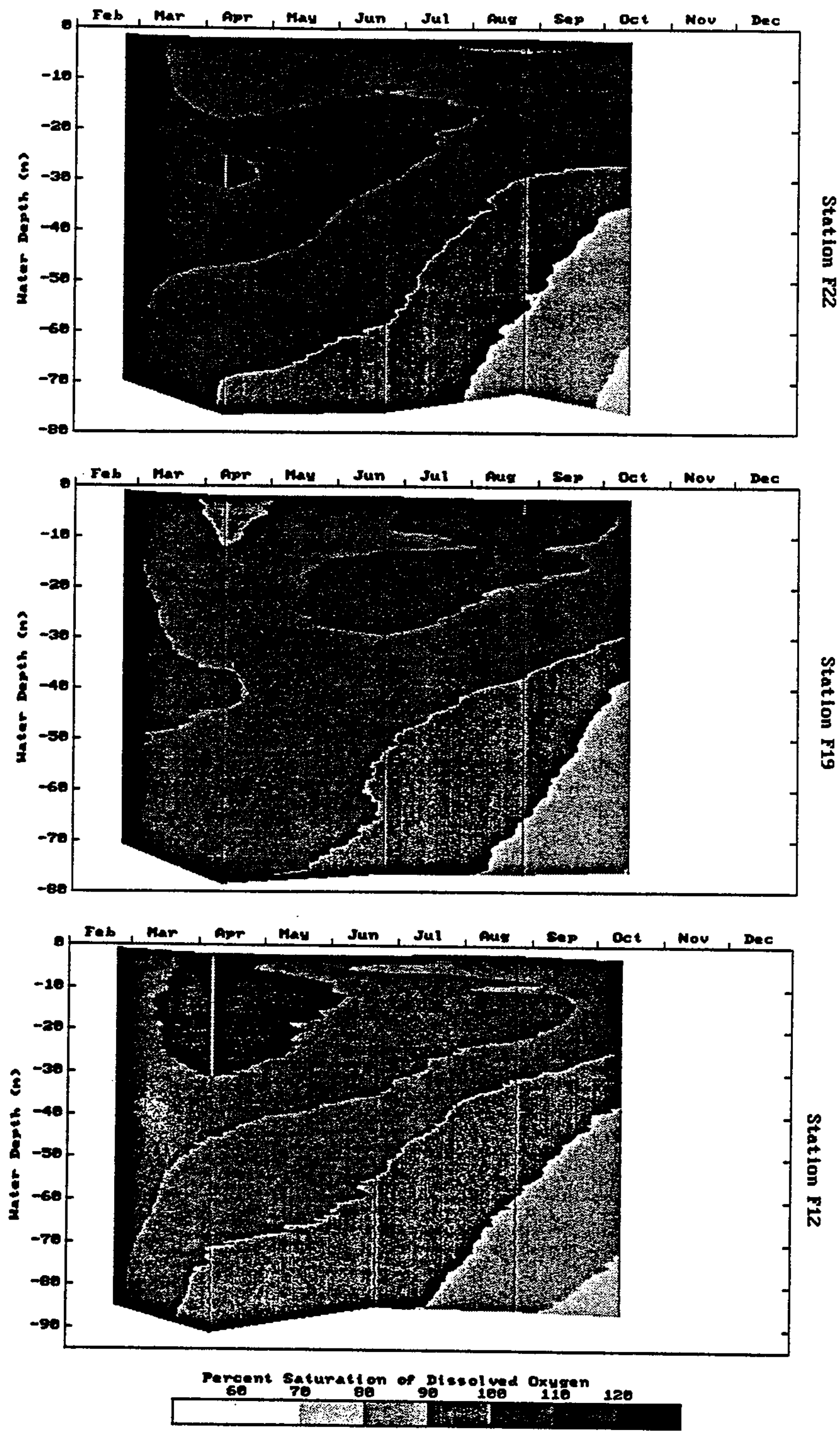


Figure 9-3. Dissolved oxygen (percent saturation) transect from northern- to mid-Stellwagen Basin.
Note different depth scales.

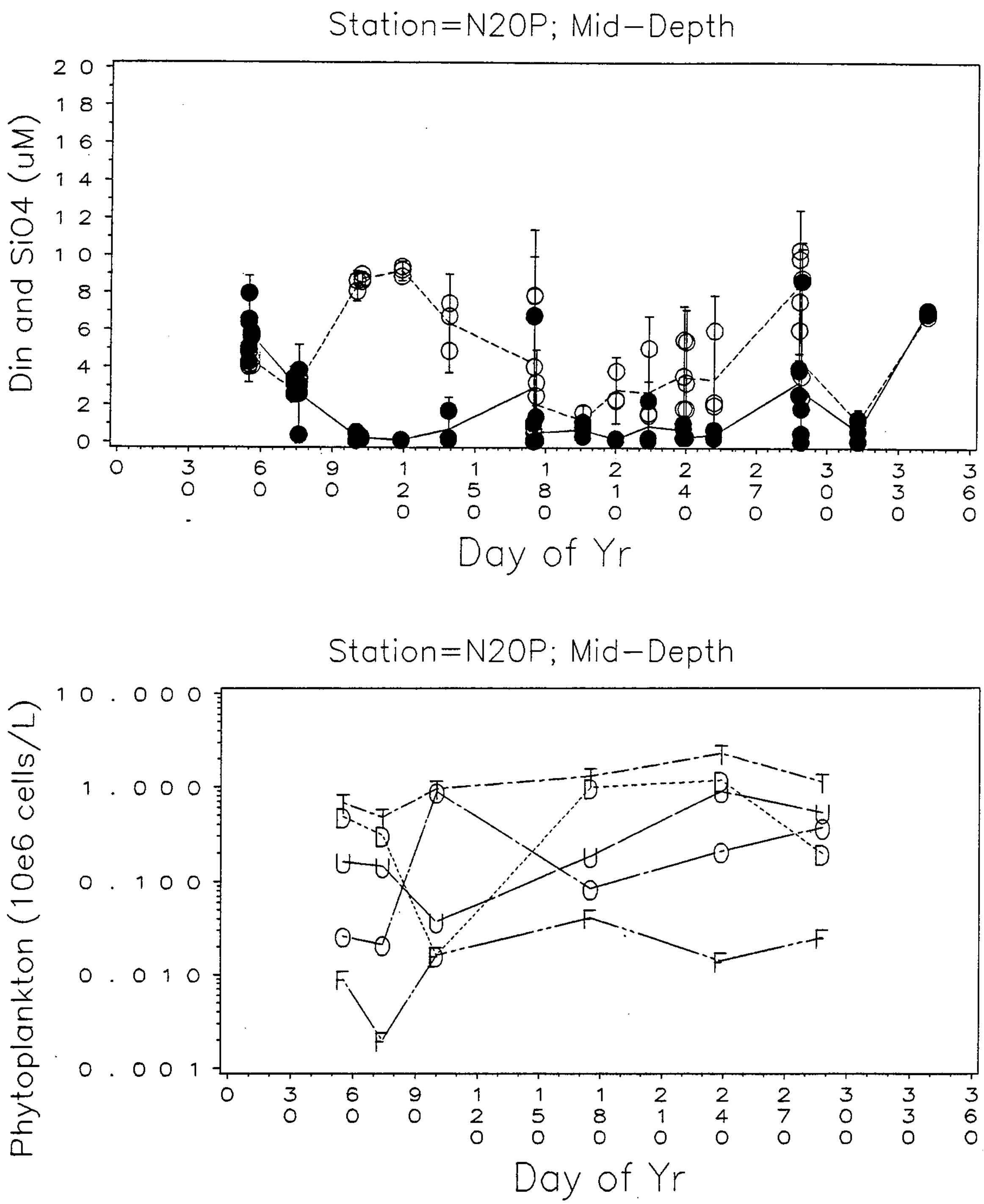
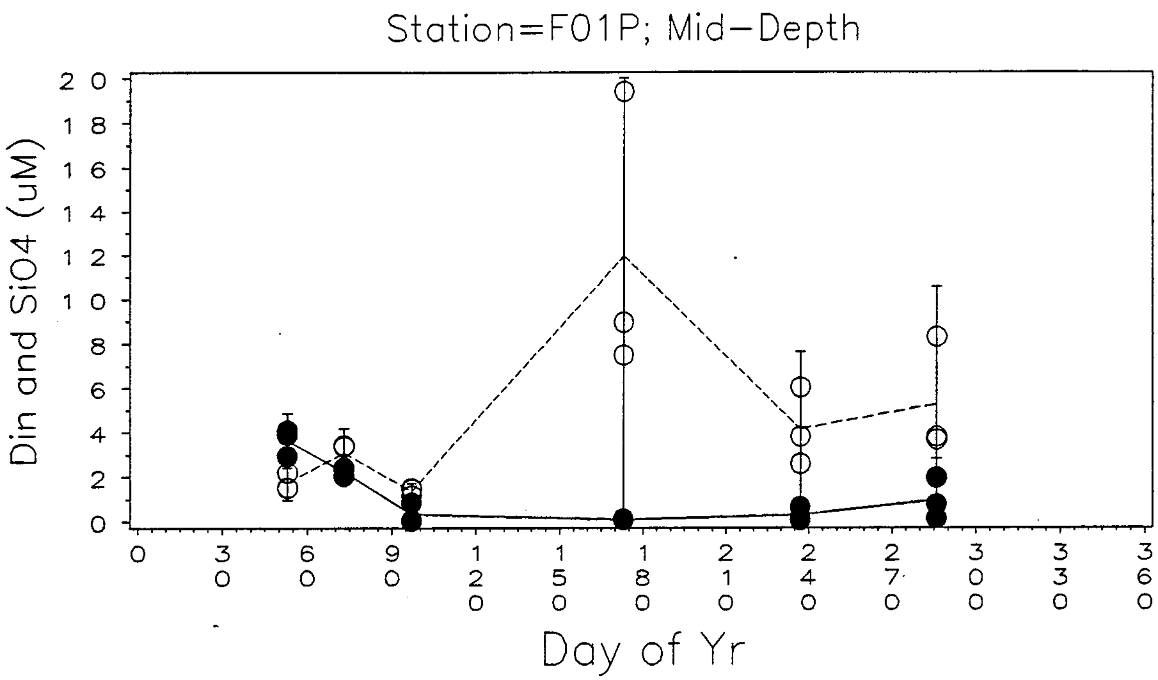


Figure 9-4. Nutrients and phytoplankton near the center of the nearfield in 1992.
Top: Dots = DIN, Circles = SiO_4, and Mean ± σ is indicated.
Bottom: T = total, D = diatoms, U = microflagellates, F = dinoflagellates, and O = other.



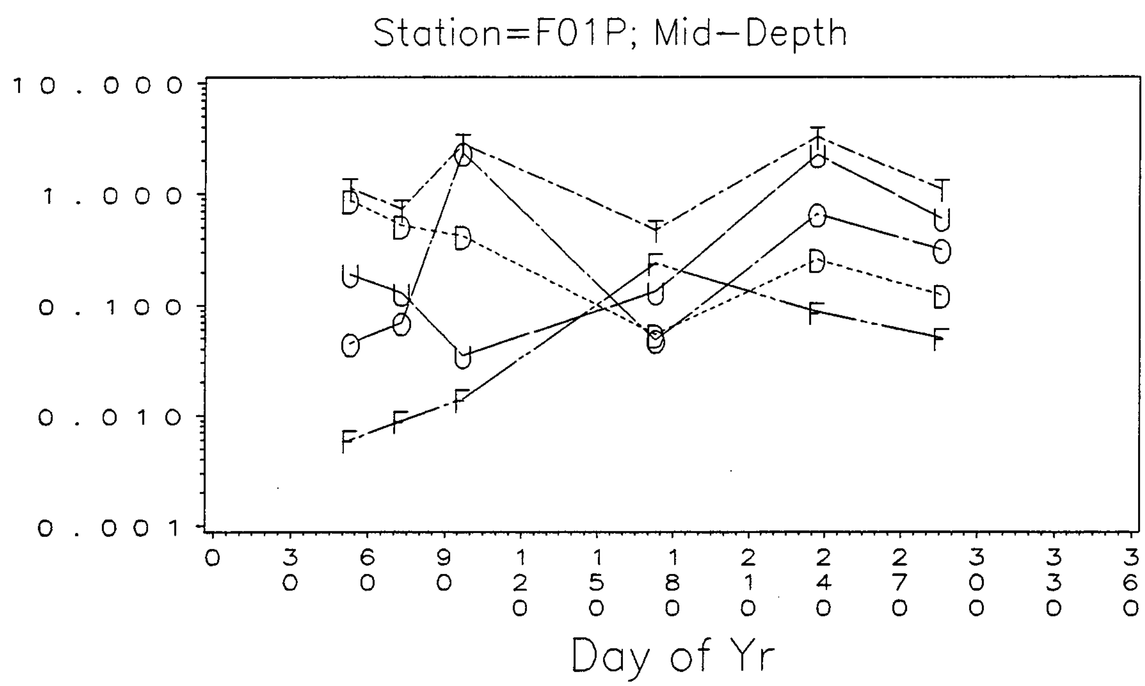


Figure 9-5. Nutrients and phytoplankton at a station in western Cape Cod Bay in 1992. Top: Dots = DIN, Circles = SiO_4, and Mean ± σ is indicated. Bottom: T = total, D = diatoms, U = microflagellates, F = dinoflagellates, and O = other.

10.0 SUMMARY

The water column monitoring in 1992 provided an extremely valuable data set for Massachusetts and Cape Cod Bays, and there are more ecological contrasts and insights to be developed than could be included in an annual report. But, with respect to the basic design of the monitoring program, it is obvious that the major seasonal features of key parameters of interest with respect to nutrient enrichments are well covered, as are the principal spatial scales of interest. Fine tuning the station locations and sampling frequency can be done, but this should be driven by specific hypotheses and done to meet specified objectives.

A remaining task, with these comprehensive data now in hand, is to use the data in assessing the potential of the present design to detect change. With some extensive understanding and quantitative description of variability from scales of meters to hundreds of kilometers and hours to seasons, specific tests can be designed. For initial steps, determining the statistical significance of the suggested regional and station differences in biology, chlorophyll, and nutrients is recommended along with an explicit consideration of the scale of sampling required to meet monitoring objectives (MWRA, 1991).

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