1999 annual water column monitoring report

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) has collected water quality data in Massachusetts and Cape Cod Bays for the Harbor and Outfall Monitoring (HOM) Program since 1992. This monitoring is in support of the HOM Program mission to assess the potential environmental effects of the relocation of effluent discharge from Boston Harbor to Massachusetts Bay. The data are being collected to establish baseline water quality conditions and ultimately to provide the means to detect significant departure from that baseline. The surveys have been designed to evaluate water quality on both a high-frequency basis for a limited area in the vicinity of the outfall site (nearfield surveys) and a low-frequency basis over an extended area throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay (farfield). This annual report evaluates the 1999 water column monitoring results, assesses spatial and temporal trends in the data, and compares these results and trends for 1999 with previous baseline monitoring years (1992-1998).

The most outstanding meteorological characteristics of 1999 were the dry conditions during the summer and fall drought. The drought conditions contributed to high salinity in nearfield bottom waters. The lack of significant storm events directly affects bottom water salinity by weakening vertical mixing or indirectly by decreasing Merrimack River flow and diminishing the freshet plume. A significant relationship between Merrimack River flow, bottom water salinity and bottom water dissolved oxygen at the outfall site was revealed in regression analyses of the parameters. In 1999, the anomalously high salinity resulting from the drought conditions and low flow was correlated to the low bottom water dissolved oxygen conditions. This connection may reflect the variability of residence time of water in the Western Maine Coastal Current.

In general, 1999 temporal trends in nutrient, chlorophyll and dissolved oxygen concentrations were typical for the nearfield area in comparison to previous baseline monitoring years. The values observed for many of these parameters in 1999, however, were baseline maxima or minima. A review of annual mean nutrient concentrations showed a significant trend of increasing nutrients across Cape Cod and Massachusetts Bays from 1992 to 1999. In Boston Harbor, ammonium (NH_4) concentrations increased by 5 μM over the baseline period (primarily due to increased discharge of NH_4 from the Deer Island Facility in 1998 and 1999). The increase in NH_4 concentrations was coincident with an increase in annual mean chlorophyll at the Boston Harbor stations. Nearfield chlorophyll concentrations also increased in 1999 and exceeded 1992-1998 winter/spring (2.51 μgL^{-1}), fall (4.03 μgL^{-1}) and annual (3.45 μgL^{-1}) warning threshold values. Annual mean chlorophyll concentrations for areas throughout the bays achieved baseline maxima in 1999. No significant trend in annual mean chlorophyll over the baseline period was established, but there was a very strong trend of increasing chlorophyll from 1997 to 1999. The factors controlling this increase in annual mean chlorophyll concentrations are likely related to the regional and local factors affecting nutrient concentrations. One effect of the increase in chlorophyll (as an indicator of biomass) from 1997 to 1999 may have been an increase in the flux of organic material to bottom waters and contributed to the low DO concentrations in 1998 and 1999.

The 1999 nearfield survey mean bottom water DO minimum (5.93 mgL^{-1} in early September) was the lowest observed during for the baseline monitoring program and was lower than the proposed warning threshold of 6.0 mgL^{-1} for the nearfield bottom water mean. A baseline minimum concentration was also measured in Stellwagen Basin with a survey mean DO minimum concentration of 6.26 mgL^{-1} in October 1999. Low bottom water DO concentrations observed at 'setup' in June, the additional flux of organic material to bottom waters following the late summer bloom and the lack of re-aeration events contributed to the rapid DO decline and extremely low survey mean value observed in early September 1999. A storm event in late September reset the system with higher DO concentration and prevented even lower DO concentrations from being reached in the nearfield. Physical mechanisms related to the residence time of water in the coastal zone or diffusion/mixing of DO (and lower salinity water) into nearfield bottom waters during substantial storm events may also play an important direct or indirect role in controlling bottom water DO concentrations in Massachusetts Bay.

The biological trends in production and plankton in 1999 generally followed trends observed during previous baseline monitoring years. In 1999, a winter/spring phytoplankton bloom was observed in the nearfield and much of the farfield from early February to April. During the bloom, phytoplankton assemblages were comprised primarily of microflagellates and a mixed assemblage of diatoms, mainly of the genus *Chaetoceros*. It is interesting that although the winter/spring nearfield chlorophyll concentrations were unprecedented (high) for the baseline monitoring, program phytoplankton abundance was not substantially different than previous years and actually rather low in comparison to previous winter/spring blooms. The reason for this may be because the abundant taxa during the winter/spring bloom were large, chain-forming diatoms (*Chaetoceros* spp.). Although the total abundances were not substantially higher than previous years, the large cell size and higher chlorophyll per cell ratio for *Chaetoceros* spp. may have led to this apparent disconnect between chlorophyll concentration and total phytoplankton abundance. Davis and Gallager (2000) noticed a similar disconnect between chlorophyll concentrations and *Chaetoceros* abundance, but attributed the high chlorophyll concentrations to the presence of smaller phytoplankton that were not measured using the Video Plankton Recorder. At the HOM stations, this was not the case as total phytoplankton counts (which include smaller phytoplankton species) were not substantially elevated in comparison to previous years and were dominated by *Chaetoceros* spp.

Bottom water respiration rates in the nearfield were substantially higher in the spring of 1999 compared to previous baseline monitoring results, in response to the availability of organic material from the bloom. These abnormally high respiration rates contributed to the unprecedented low DO concentrations that were observed during the fall of 1999.

An atypical late summer phytoplankton bloom was observed in the nearfield and throughout most of Massachusetts Bay in August and September. Levels of chlorophyll, primary productivity and phytoplankton cell abundance did not parallel each other as clearly as observed during the winter/spring bloom. Nearfield phytoplankton abundance peaked in early August, productivity in mid-August and chlorophyll concentrations, though increasing in August, did not reach maximum levels until September. The August phytoplankton bloom was comprised primarily of microflagellates and the diatom *Leptocylindrus danicus*. Although total phytoplankton counts decreased in the nearfield later in August, the abundance of *L. danicus* increased and may have resulted in the increase that was observed in primary production and chlorophyll. An increase in *Ceratium* spp. from August through October also likely contributed disproportionately to the increase in chlorophyll in September. A fall bloom was also observed in 1999 in the nearfield and western Massachusetts Bay in October, evidenced by increases in chlorophyll, primary productivity and cell abundance. The phytoplankton increase during this period was primarily diatoms of the genus *Thalassiosira*.

Zooplankton abundance exhibited the typical pattern of increases through the winter and spring, high levels in the summer, followed by declines in the fall. The typical dominants for the Massachusetts Bay system, *Oithona similis* and *Pseudocalanus* spp., comprised most assemblages. In Boston Harbor, meroplankton pulses dominated abundance at some stations and resulted in the highest total zooplankton abundances for the entire 1992-1999 baseline. Area means revealed that 1999 was also uncharacteristic of other baseline years in that low abundance of copepods of the genus *Acartia tonsa* were found in Boston Harbor. The decrease in abundances of *Acartia* in Boston Harbor appears to be a continuing trend with substantial declines in 1998 and 1999, compared to peak years of 1995-1997. The extremely low 1999 abundance of *Acartia* spp. in their primary habitat of Boston Harbor could be related to the drought during the first half of 1999 because of species intolerance for salinity >25 ppt. It is also of note that the decrease in *Acartia* abundance in 1999 occurred despite increased

NH_4 concentrations and unprecedented high chlorophyll concentrations within Boston Harbor. At one time, it was thought that increases in *Acartia* abundance would be indicative of increased nutrient concentration. The 1999 *Acartia*, nutrient and chlorophyll data support the elimination of the *Acartia* warning threshold for the nearfield.

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1.0 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) has implemented a long-term Harbor and Outfall Monitoring (HOM) Program for Massachusetts and Cape Cod Bays. The objective of the HOM Program is to (1) verify compliance with NPDES permit requirements; (2) evaluate whether the impact of the discharge on the environment is within the bounds projected by the SEIS; and (3) determine whether change within the system exceeds the Contingency Plan thresholds. To help establish the present water quality conditions, Battelle was contracted by MWRA to conduct baseline water quality surveys in Massachusetts and Cape Cod Bays in 1999. This was the eighth consecutive year of MWRA baseline monitoring.

The 1999 water column monitoring data have been reported in a series of survey reports, data reports, and semi-annual interpretive reports (Libby *et al.* 1999a and 2000). The purpose of this report is to present a compilation of the 1999 results in the context of the seasonal trends and the annual cycle of ecological events in Massachusetts and Cape Cod Bays. The data have been evaluated based on a variety of spatial and temporal scales that are relevant to understanding environmental variability in the bays. *In situ* vertical profiles and discrete water samples provide the data with which to examine spatial variability whether it is vertically over the water column, locally within a particular region (i.e. nearfield or harbor) or regionally throughout the Bays. The temporal variability of each of the parameters provides information on the gross seasonal trends on a regional scale and allows for a more thorough characterization of trends in the nearfield area. The 1999 data have also been compared to previous baseline monitoring data to evaluate interannual variability and to characterize trends.

The water column data presented in this report include physical characteristics – temperature, salinity, and density (Section 3), water quality parameters – nutrients, chlorophyll, and dissolved oxygen (Section 4), production and respiration (Section 5), and phytoplankton and zooplankton (Section 6). In each of these sections, a preliminary attempt has been made to integrate across disciplines when interpreting the data. The final section of this report completes this integration and summarizes the major themes from the 1999 water column data.

2.0 1999 WATER COLUMN MONITORING PROGRAM

This section provides a summary of the 1999 HOM Program. The sources of information and data discussed in this report are identified and a general overview of the monitoring program is provided.

2.1 Data Sources

A detailed presentation of field sampling equipment and procedures, sample handling and custody, sample processing and laboratory analysis, and instrument performance specifications and data quality objectives are discussed in the Combined Work/Quality Assurance Project Plan (CW/QAPP) for Water Quality Monitoring: 1998-2000 (Albro *et al*., 1998). Details on any deviations from the methods outlined in the CW/QAPP have been provided in individual survey reports and the semiannual reports. For each water column survey, the survey objectives, station locations and tracklines, instrumentation and vessel information, sampling methodologies, and staffing were documented in a survey plan. Following each survey, the activities that were accomplished, the actual sequence of events and tracklines, the number and types of samples collected, a preliminary summary of *in situ*, phytoplankton, and whale watch data, and any deviations from the plan were reported in a survey report.

Results for 1999 water column surveys have been presented in nutrient (including calibration information, sensor and water chemistry data), plankton (phytoplankton and zooplankton), and productivity/respiration data reports. These data reports were submitted to the MWRA five times per year. The 1999 results have also been presented in semi-annual water column reports that provide full descriptions of physical, chemical, and biological conditions in the Bays over the course of the year (Libby *et al*. 1999a and 2000). The semi-annual reports also provide an initial interpretation of the results on various spatial and temporal scales. The data that have been submitted in the data reports, presented in the semi-annual reports, and are discussed in this report are available in the MWRA HOM Program Database.

2.2 1999 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 17 surveys that were conducted in 1999 (Table 2-1). The surveys have been designed to evaluate water quality on both a high-frequency basis for a limited area (nearfield surveys) and a low-frequency basis for an extended area (farfield). A total of 48 stations are distributed throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay in a strategic pattern that is intended to provide a comprehensive characterization of the area (Figures 2-1 and 2-2). The nearfield stations, located in Massachusetts Bay in the vicinity of the outfall site, were sampled during each of the 17 surveys. The farfield stations, located throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay, were sampled during the 6 combined farfield/nearfield surveys.

The 21 nearfield stations are located in a grid pattern covering an area of approximately 100 km^2 centered on the MWRA outfall site (Figure 2-1). The 28 farfield stations are located throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay (Figure 2-2). This includes stations F32 and F33 that were added to the monitoring program in 1998 to better characterize zooplankton variability in Cape Cod Bay. Stations F32 and F33 are sampled during the winter/spring farfield surveys that are conducted in February through April. Station N16 is sampled twice during the combined surveys as both a farfield and a nearfield station. The stations for the farfield surveys have been further separated into regional groupings according to geographic location to simplify regional data comparisons. These regional groupings include Boston Harbor (three stations), coastal (six stations along the coastline from Nahant to Marshfield), offshore (eight deeper-water stations in central

Massachusetts Bay), boundary (five stations in an arc from Cape Ann to Provincetown, all stations are in or adjacent to the Stellwagen Bank National Marine Sanctuary), and Cape Cod Bay (five stations, two of which are only sampled for zooplankton during the first three combined surveys). The regional nomenclature is used throughout this report and regional comparisons are made by partitioning the total data set. For this report, a subset of the data has also been grouped to focus on the deep-water stations in Stellwagen Basin (F12, F17, F19 and F22 – see Figure 2-2).

Vertical profiles of *in situ* data were collected during the downcast at all stations. *In situ* data were also recorded during the upcast coincident with water sampling events. Discrete water samples are generally collected at five depths at each station (surface, mid-surface, mid-depth, mid-bottom, and bottom). Only three depths are sampled at the shallow, harbor stations F30 and F31 and, at stations F32 and F33, only hydrographic profiles of *in situ* data and zooplankton net tow samples were collected.

Station designations were assigned according to the type of analyses performed at that station, with each type distinguished by a letter code (Tables 2-2 and 2-3). At E type stations, only dissolved inorganic nutrient (DIN) samples were collected. DIN and dissolved oxygen (DO) samples were collected at type F stations and, at station F19, which is both an F and R type station, additional samples were collected for respiration measurements. DIN, other dissolved and particulate nutrients, chlorophyll, total suspended solids (TSS) and DO were collected at type A and D stations with additional samples collected at type D stations for plankton and urea analyses. The type G stations are similar to the type D stations except that samples were only collected at three depths at these shallow stations. The full suite of analyses, including productivity and respiration measurements, was conducted at the three type P stations. In 1998, stations F32 and F33 (type Z) were added to the monitoring program to better capture the winter/spring spatial variability of zooplankton assemblages in Cape Cod Bay.

Table 2-1. Water quality surveys for 1999 (WF991-WN99H).

Survey #	Type of Survey	Survey Dates
WF991	Nearfield/Farfield	February 2 – 8
WF992	Nearfield/Farfield	February 23 – 28
WN993	Nearfield	March 20
WF994	Nearfield/Farfield	April 1 – May 6[a]
WN995	Nearfield	April 29[b] & May 5
WN996	Nearfield	May 12
WF997	Nearfield/Farfield	June 14 – 19
WN998	Nearfield	July 7
WN999	Nearfield	July 20
WN99A	Nearfield	August 2
WF99B	Nearfield/Farfield	August 16 - 19
WN99C	Nearfield	September 8
WN99D	Nearfield	September 24
WF99E	Nearfield/Farfield	October 6, 8, 22, 28[c]
WN99F	Nearfield	October 27
WN99G	Nearfield	November 23
WN99H	Nearfield	December 20

[a] Due to severe weather, the WF994 survey was completed over the course of six days in April and May – nearfield samples were collected April 11th and farfield samples were collected April 1, 6, 11, 26, and May 6.
[b] Productivity samples were collected on April 29 prior to postponement of survey due to weather conditions.
[c] Due to severe weather, the WF99E survey was completed over the course of three weeks in October – nearfield samples were collected October 8th and farfield samples were collected October 6, 22, and 28.

Table 2-2. Station types, applicable analyses, and number of depths sampled.

Station Type	A	D	E	F	G	P	R[4]	Z
Number of Stations	**5**	**8**	**26**	**3**	**2**	**3**	**1**	**2**
Dissolved inorganic nutrients (NH_4, NO_3, NO_2, PO_4, and SiO_4)	5	5	5	5	3	5		
Other nutrients (DOC, TDN, TDP, PC, PN, PP, Biogenic Si)[1]	3	3			3	3		
Chlorophyll [1]	3	3			3	3		
Total suspended solids [1]	3	3			3	3		
Dissolved oxygen	5	5		5	3	5		
Phytoplankton, urea [2]		2			2	2		
Zooplankton[3]		1			1	1		1
Respiration [1]						3	3	
Productivity, DIC						5		

[1]Samples collected at bottom, mid-depth, and surface
[2]Samples collected at mid-depth and surface
[3]Vertical tow samples collected
[4]Respiration samples collected at type F station F19

Table 2-3. Distribution of stations by station types.

Station Type	Number	Station Number
A	5	N01, N07, N10, N16, and N20
D	8	F01, F02, F06, F13, F24, F25, F27, and N16 (on farfield survey day)
E	26	F03, F05, F07, F10, F14-F18, F22, F26, F28, N02, N03, N05, N06, N08, N09, N11-N15, N17, N19, and N21
F	3	F12, F19, and F29
G	2	F30 and F31
P	3	F23, N04, and N18
R[1]	1	F19
Z	2	F32 and F33

[1]Respiration samples collected at type F station F19

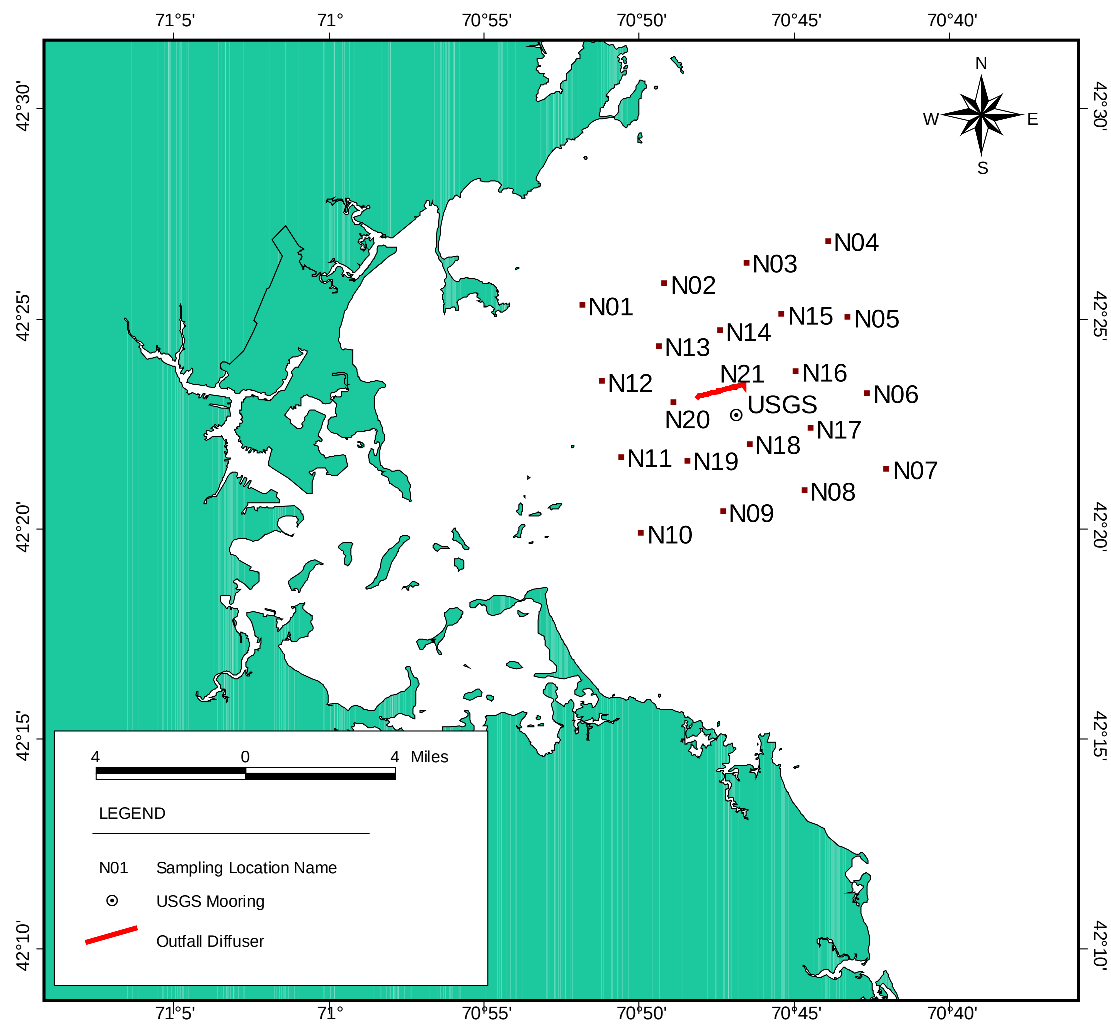


Figure 2-1. Locations of nearfield stations, MWRA offshore outfall, and USGS mooring.

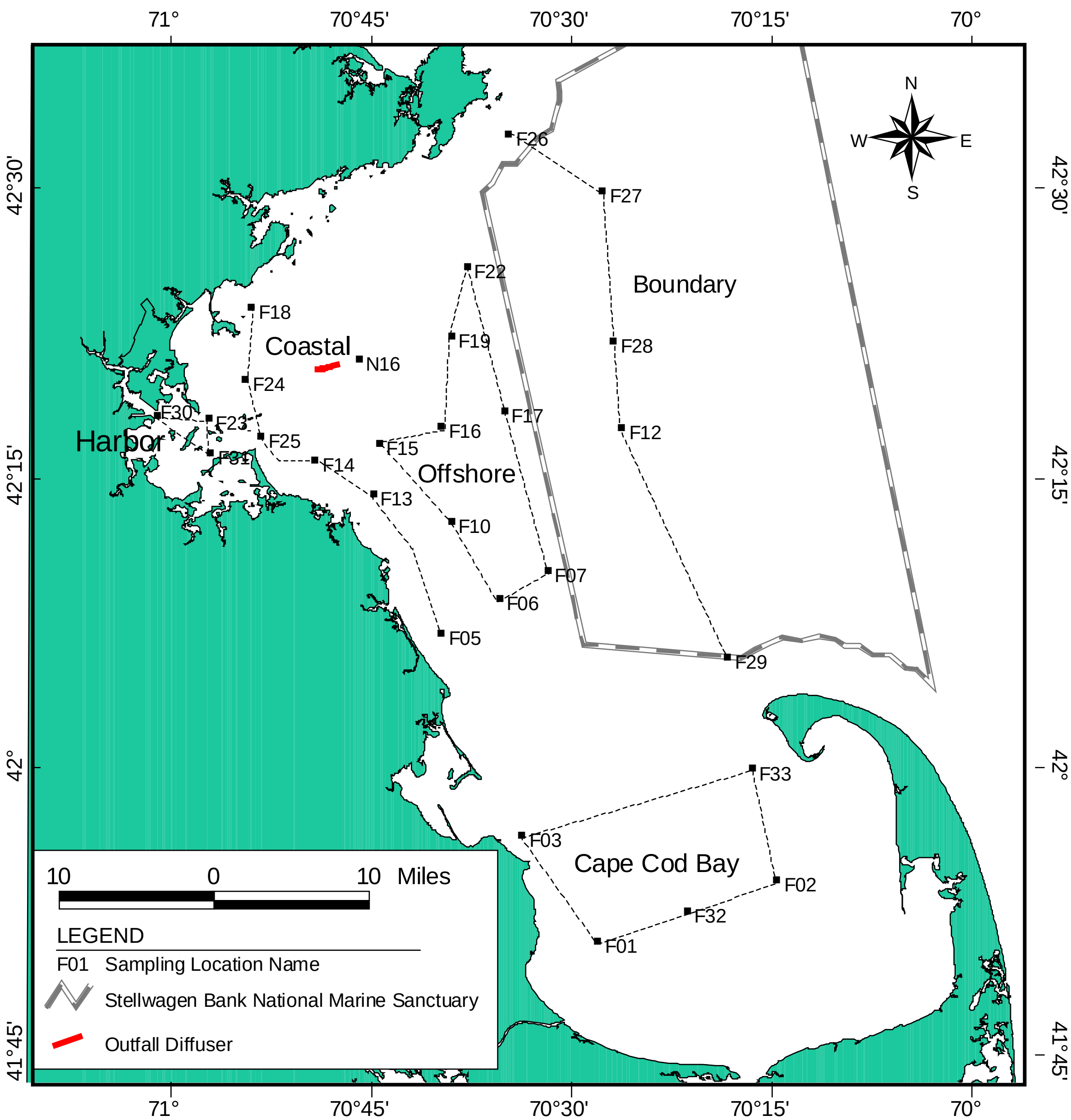


Figure 2-2. Locations of farfield stations and geographic regional classifications.

3.0 PHYSICAL CHARACTERIZATION

3.1 Meteorological Overview

The primary variables affecting the physical regime in western Massachusetts Bay are freshwater inputs, winds, and seasonal variations in surface heat flux.

The freshwater inflows come locally from the Charles River, the MWRA outfalls, and direct precipitation, with comparable magnitudes from each (approximately 10 $m^3 s^{-1}$ long-term average). The Merrimack River is a much larger source of freshwater (250 $m^3 s^{-1}$ long-term average), but its plume only intermittently enters Massachusetts Bay. The surface salinity near the outfall site is more highly correlated with the Charles River than the Merrimack (Figure 3-1). The Merrimack, however, is found to have an important influence on deepwater salinity during the fall, as discussed in Section 3.3.2.

The freshwater inflow in 1999 was below average (Figure 3-2 and Table 3-1), particularly during the period from mid-April to September. The flow in the Merrimack was the lowest since the drought of 1995, although the Charles was only slightly below average (Table 3-1). The local input from the Charles River and the MWRA are generally comparable in magnitude. In 1999, however, due to low river flow conditions during the summer, there was significantly more input from the MWRA discharge than the Charles (Figure 3-3). The timeseries record over the last decade (Figure 3-4) indicates that the freshet peak during 1999 was smaller than average but not extremely small.

Winds have three important effects on Massachusetts Bay. First, they cause upwelling and downwelling, which promotes vertical exchange and transport between the coast and waters further offshore (Geyer *et al*., 1992). Second, they drive the circulation through Massachusetts Bay (Geyer *et al*., 1992). Third, strong winds during the fall in combination with cold air temperatures cause the destratification of the water column.

Table 3-2 indicates the average upwelling-directed wind-stress on a seasonally averaged basis, from 1990 to 1999. The N-S wind stress was close to its climatological mean for most of 1999 (Figure 3-5 and Table 3-2), indicating that there should have been average upwelling and downwelling conditions. Wind speeds for 1999 were typical of the decadal average (Table 3-3). The relationship between the wind forcing and the near-bottom dissolved oxygen levels at the outfall site are discussed below.

The winter of 1999 was more than 1°C warmer than normal, as were the previous two winters (Table 3-4). The wintertime mean air temperature determines the water temperature at the onset of stratification. As in 1998, the bottom temperatures were warmer than average during the spring, owing in part to the mild winter.

Table 3-1. River discharge summary for the Charles and Merrimack Rivers, 1990-1999. Data from USGS gauging stations in Waltham (Charles River) and Lowell (Merrimack River), MA.

Year	Jan.-March	April-June	July-Sept.	Oct.-Dec.	Mean
Charles River Discharge (m^3s^{-1})					
1990	13	13	7	13	12
1991	13	7	3	10	8
1992	10	8	2	9	7
1993	15	15	1	5	9
1994	15	11	3	7	9
1995	11	5	1	7	6
1996	16	12	4	16	12
1997	12	13	1	4	8
1998	21	21	8	7	14
1999	**18**	**7**	**4**	**9**	**10**
mean	14	11	3	9	9
Merrimack River Discharge (m^3s^{-1})					
1990	333	366	164	331	298
1991	289	237	117	295	234
1992	254	266	100	174	199
1993	200	393	51	198	211
1994	253	380	74	164	218
1995	295	154	45	292	196
1996	409	487	127	401	356
1997	296	404	70	123	257
1998	401	451	122	116	273
1999	**328**	**175**	**103**	**180**	**197**
mean	306	332	97	239	239

Table 3-2. North-south component of wind stress, 1990-1999. Estimated seasonally averaged stress in Pascals*10^3 at the Boston Buoy (USGS). Estimated using relationship of Large and Pond (1981). Positive values indicate upwelling favorable winds.

Year	Jan.-March	April-June	July-Sept.	Oct.-Dec.
1990	-0.0	1.4	0.8	0.1
1991	-1.6	-0.2	1.0	-4.2
1992	-3.8	-0.4	1.0	-3.4
1993	-4.5	-0.0	1.3	-1.3
1994	-3.5	1.0	0.4	-1.7
1995	-0.1	0.0	-0.0	-0.9
1996	-2.8	0.5	-0.2	-1.3
1997	-0.1	-0.8	0.5	-2.2
1998	-4.3	-0.8	0.9	-0.5
1999	**-2.1**	**-0.2**	**0.7**	**0.2***
mean	-2.3	0.1	0.6	-1.5

*Incomplete data set: limited data for November and no data for December 1999.

Table 3-3. Wind speed, 1990-1999. Seasonally averaged speed in m s^{-1} at the Boston Buoy (USGS).

	Jan.-March	April-June	July-Sept.	Oct.-Dec.
1990	7.0	5.8	4.4	7.9
1991	7.6	5.8	5.3	7.5
1992	7.9	5.8	5.1	7.0
1993	7.7	5.8	4.9	6.9
1994	7.4	5.9	5.6	6.8
1995	6.6	4.6	4.6	7.2
1996	7.3	5.1	4.5	6.6
1997	7.6	5.3	5.1	6.6
1998	6.9	4.6	3.9	6.8
1999	**7.3**	**4.5**	**4.3**	**6.8**
mean	7.3	5.3	4.8	7.0

Table 3-4. Winter air temperature, 1993-1999. Average temperature in °C at the Boston Buoy. Data from NOAA National Data Buoy Center (http://seaboard.ndbc.noaa.gov/data).

Year	Dec. 1 - Feb. 28
1992-1993	-0.4
1993-1994	-1.4
1994-1995	1.7
1995-1996	-0.4
1996-1997	2.3
1997-1998	2.6
1998-1999	**2.2**
mean	0.9

3.2 Temperature

3.2.1 Nearfield Description

The temperature variation in the nearfield in 1999 (Figure 3-6) was similar to other years, being strongly controlled by the seasonal cycle of heat flux. Minimum temperatures of surface and bottom water occurred in March, followed by rapid warming of the surface waters. Warming of the bottom water was much more modest, as is typical of the spring warming period. The bottom water followed a typical warming trend until mid-September, then becoming warmer than average in late September and October. This warming was coincident with an intense storm event, Hurricane Floyd passed through the area on September 15-17, that mixed warmer surface waters into the bottom waters and also re-aerated the bottom waters leading to an increase in DO concentrations from the early September minima.

3.2.2 Interannual Comparisons

Comparison of the temperature variation in the nearfield with other years indicates relatively warm winter temperatures, similar to the warm winters in 1995, 1997, and 1998 (cf. Table 3-4). The maximum surface water temperature was typical of other years. The maximum bottom water temperature was slightly warmer than average, but not as warm as 1994, when low dissolved oxygen had been observed in the near-field bottom water. The best indicator of the maximum fall bottom temperature was found to be the average north-south wind stress for the month of September (r=0.8).

3.2.3 Spatial Temperature Structure

The spatial variability of temperature is exemplified by cross-sections along the Boston-Nearfield transect from the mouth of Boston Harbor across Stellwagen Basin to the Gulf of Maine (Figure 3-7). Stratification was absent and there was slightly warmer water offshore in February. By June the strong seasonal thermocline had been established, with water less than 5°C in the deep waters of Stellwagen Basin and greater than 16°C at the surface. The same conditions were evident in August, with continued, gradual warming of the deep waters. By the end of October, fall cooling had erased the thermal stratification in the upper 20-m of the water column, but there was still temperature variation between 20 and 40-m depth.

3.3 Salinity

3.3.1 Nearfield Description

The surface and bottom salinity were relatively high in western Massachusetts Bay during 1999 due to low river flows (Figure 3-8). Surface salinity reached its minimum of 30.4 PSU in early May and rose through the rest of the year. The minimum bottom salinity of 31.5 PSU also occurred in early May and increased to 32.5 PSU in late October.

3.3.2 Interannual Comparisons

Salinity was lower than the climatological average through April, but by November it was about 0.5 PSU higher than average, due to the low river discharge conditions. The deep salinity at the end of October was the highest that has been observed in the 8 years of the monitoring program. Regression between the autumn near-bottom salinity and Merrimack River discharge indicates a significant correlation (r=0.7, based on the average flow between January and September; Figure 3-9). The deep salinity is weakly correlated with the Charles River input. This suggests that the bottom salinity depends mainly on the regional influence of the river inflow over relatively long (9 month) time scales.

3.3.3 Spatial Salinity Structure

The salinity structure across Massachusetts Bay (Figure 3-10) showed a strong E-W gradient in February, due to local freshwater inputs into Boston Harbor. By June, the influence of dry conditions was already apparent. There was little horizontal structure to salinity and slight vertical variation. This trend continued through August. In late October, unusually high-salinity water (>32.5 PSU) was present in Stellwagen Basin and in a thin, near-bottom layer at the outfall site (station N21).

3.4 Stratification

3.4.1 Nearfield Description

The stratification showed a typical annual cycle during 1999 (Figure 3-11). There were large fluctuations in stratification in October, due in part to the timing of observations relative to the passage of storms.

3.4.2 Spatial Variations in Stratification

The stratification early in 1999 reflected the salinity structure (Figure 3-12), with strong stratification near Boston Harbor and weak stratification further offshore. By June, the stratification was dominated by the temperature structure, which produced strong stratification throughout Massachusetts Bay. This condition persisted through the August observations. By October, surface cooling eliminated the stratification above 20-m depth, but there was still stratification between 20 and 40-m depth due both to temperature and salinity variations.

3.5 Temperature and Salinity Impact on Dissolved Oxygen

The near-bottom dissolved oxygen (DO) concentrations at the outfall site (station N21) dropped below 6 mgL^{-1} in October 1999 (Figure 3-13). This was the lowest value during the monitoring program, comparable to the low values observed in the fall of 1994 and 1995. The spatial structure of DO shows that dissolved oxygen values were below 7 mgL^{-1} in Stellwagen Basin at this time (Figure 3-14), and the vertical gradient of dissolved oxygen was coincident with the seasonal pycnocline. Note that the values at station N21 are comparable to the average of the nearfield values at stations around the future outfall. Stations N13 to N21 are situated in a ~5-km box around the outfall diffuser (see Figure 2-2). Comparison of the average DO concentration at nearfield stations N13–N21 with N21 shows a correlation coefficient r=0.99, i.e., station N21 is representative of the region of the outfall, but the inner box of nearfield stations are used in the evaluation below.

Regression analysis between the interannual variations of autumn dissolved oxygen and other variables indicates significant correlation with both salinity and temperature (Figure 3-15). For each baseline monitoring year, the average value of near-bottom dissolved oxygen at nearfield stations N13-N21 for the months of September and October was regressed against the average value of salinity and temperature at the same location, with correlation coefficients r = -0.78 and r = -0.68, respectively. Thus, dissolved oxygen was lower when the salinity was higher and when the temperature was warmer. Surprisingly, there was insignificant correlation between interannual variations of temperature and salinity for the same data set. Stratification was correlated with dissolved oxygen, but not as strongly as either temperature or salinity, and it appears that its correlation is due mainly to the covariance of temperature and stratification.

Based on these high correlations, a statistical model for the deep dissolved oxygen variations (Figure 3-16) was constructed according to the formula

$$DO = A - B \times T' - C \times S'$$

where T' and S' are the near-bottom temperature and salinity anomalies (relative to the 8-year mean for September-October, A=7.46 mg/l, B=1.9, and C=0.22. The model explains 85% of the variance of autumn DO over the 8-year period and is significant at the 95% level (Figure 3-17). The lower panel of Figure 3-16 indicates that in 1999, the salinity effect was much more pronounced than the temperature effect, whereas in 1994, both effects were comparable.

The main factor controlling the interannual variations of near-bottom salinity appears to be the regional riverine inflow. High river flow causes a decrease in near-bottom salinity in Massachusetts

Bay (see Figure 3-9). According to this model, it should also cause an increase in the dissolved oxygen levels. The connection between river flow and dissolved oxygen might be related to water residence time. When there is more freshwater inflow, the along-coast transport in the Western Maine Coastal Current is stronger (Geyer *et al*., submitted), which causes a shorter residence time of water in the coastal environment. This shorter residence time might, in turn, result in less depletion of dissolved oxygen due to local respiration of organic matter. However, this connection to residence time is speculative at this point and further data analysis and modeling is required to clarify the causality of the correlation between salinity and dissolved oxygen.

The north-south wind stress is the main variable controlling the deep temperature variation. Northward-directed winds cause upwelling, which results in lower bottom water temperatures. It is not obvious that there should be a direct, physical connection between the upwelling process and variations in dissolved oxygen, however. There is no evidence that upwelling should transport higher dissolved oxygen during the fall; if anything the vertical structure of dissolved oxygen suggests the opposite (Figure 3-14). Thus it appears most likely that the connection between temperature and dissolved oxygen is biological—i.e., that the uptake of oxygen is greater when the bottom water is warmer.

3.6 Summary

The most outstanding characteristics of 1999 were dry conditions during the summer and fall and low dissolved oxygen in the near-bottom waters. These two variables appear to be related. The dissolved oxygen in the deep water at the outfall site varies with both the local salinity and temperature variation. In 1999, the anomalously high salinity resulting from low river flow apparently contributed to the low dissolved oxygen conditions. This connection may be related to the variability of residence time of water in the Western Maine Coastal Current.

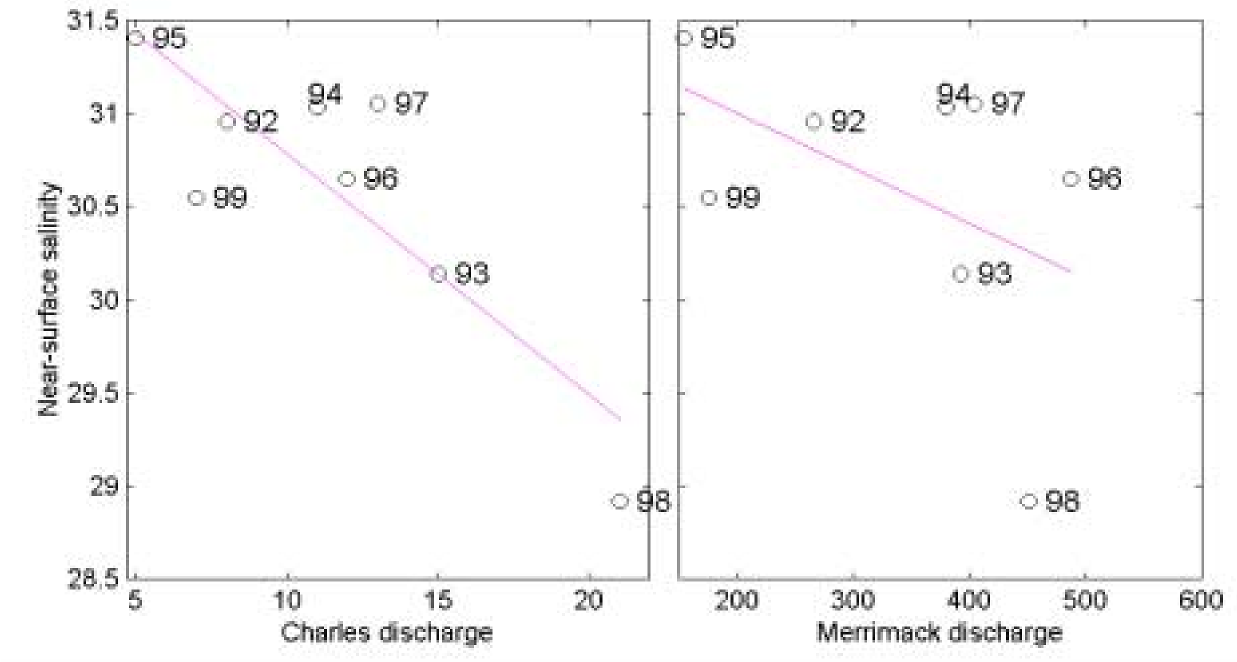


Figure 3-1. Surface salinity at the Outfall Site (nearfield stations N12-N21) during April-June compared with Charles and Merrimack River discharge for the same period. The regression coefficients are r=0.85 for the Charles and r=0.48 for the Merrimack. River discharge data come from the USGS gauging stations in Waltham (Charles River) and Lowell (Merrimack River), Massachusetts.

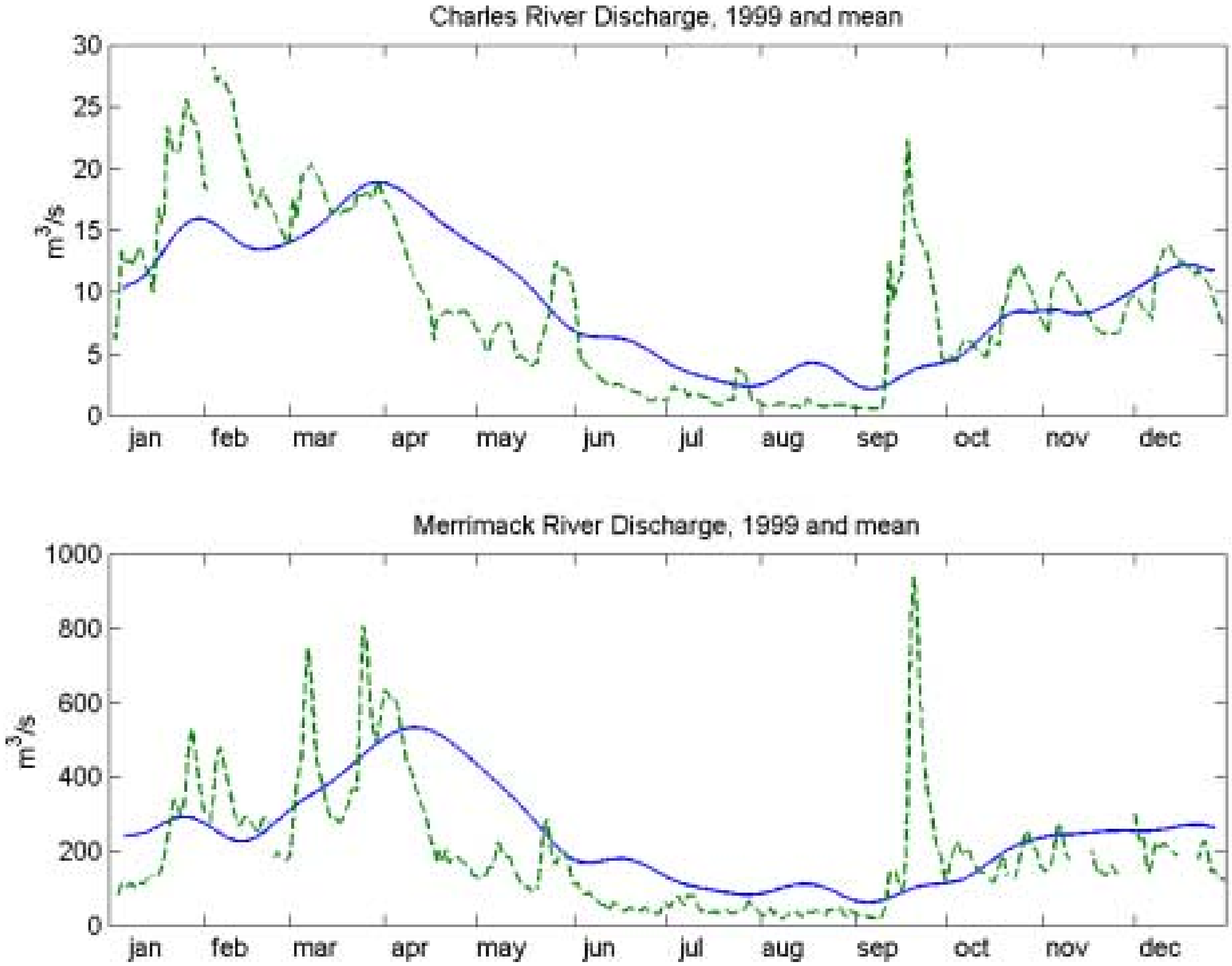


Figure 3-2. Comparison of daily Charles and Merrimack River discharge for 1999 to 10-year average annual cycle (smoothed by a 30-day running mean).

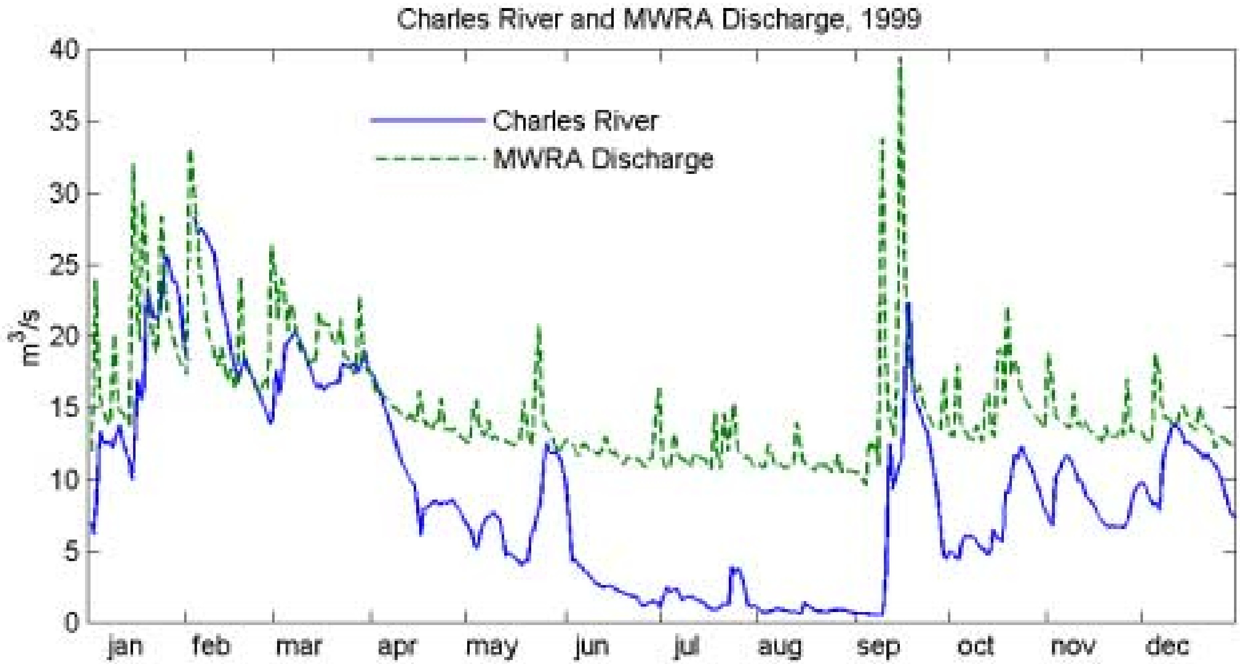


Figure 3-3. Comparison of Charles River (at USGS gauging station in Waltham, MA) and MWRA daily average discharge (Deer Island) for 1999. Since mid-1998, all effluents from the south system have been pumped from Nut Island to Deer Island for treatment and discharge.

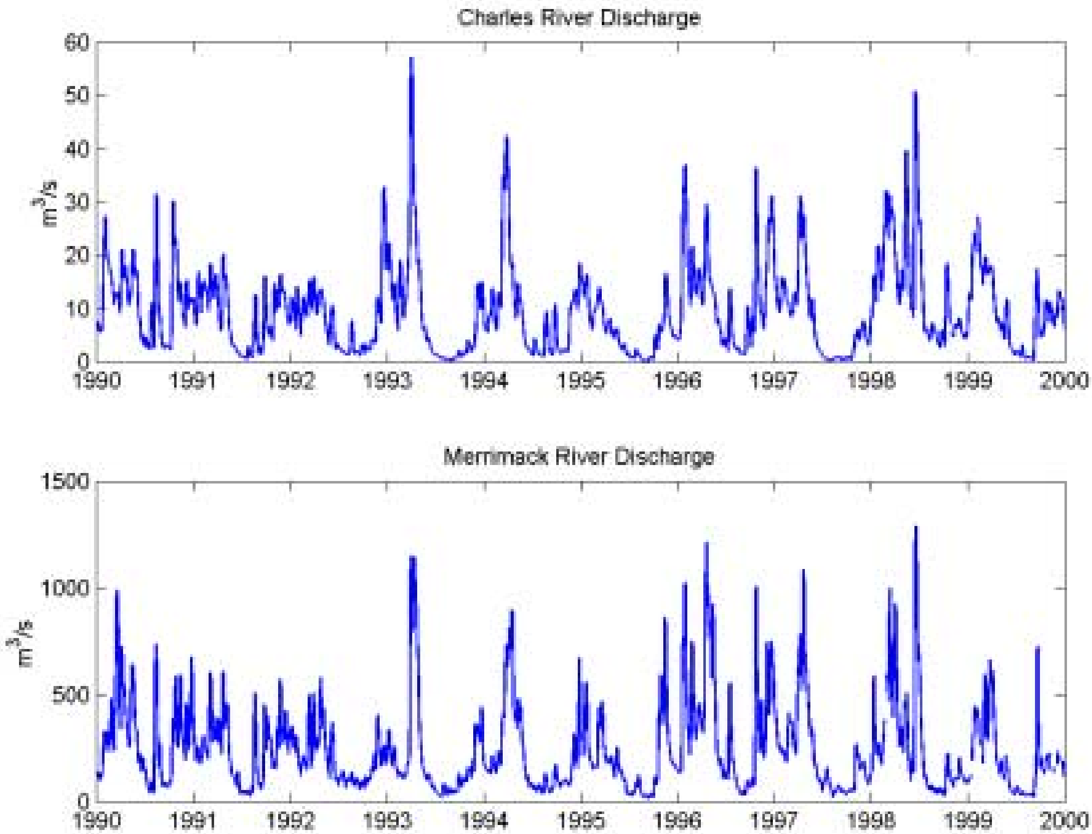


Figure 3-4. Charles River (at Waltham) and Merrimack River (at Lowell) discharge, 1990–2000 (5 day running mean).

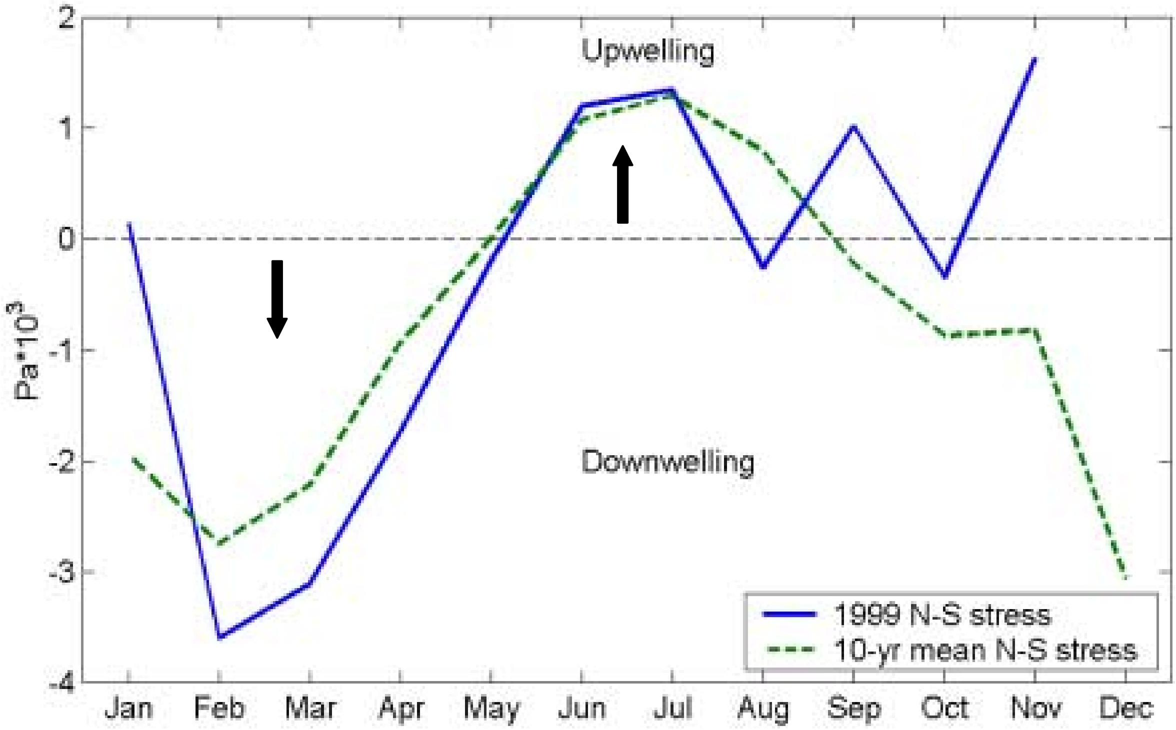


Figure 3-5. Monthly average N-S wind stress at Boston Buoy for 1999 compared with 10-year average. Positive values indicate northward-directed, upwelling-favorable wind stress. The winds were close to climatology for most of the year. (Note: The November data set was incomplete and no December data were available.)

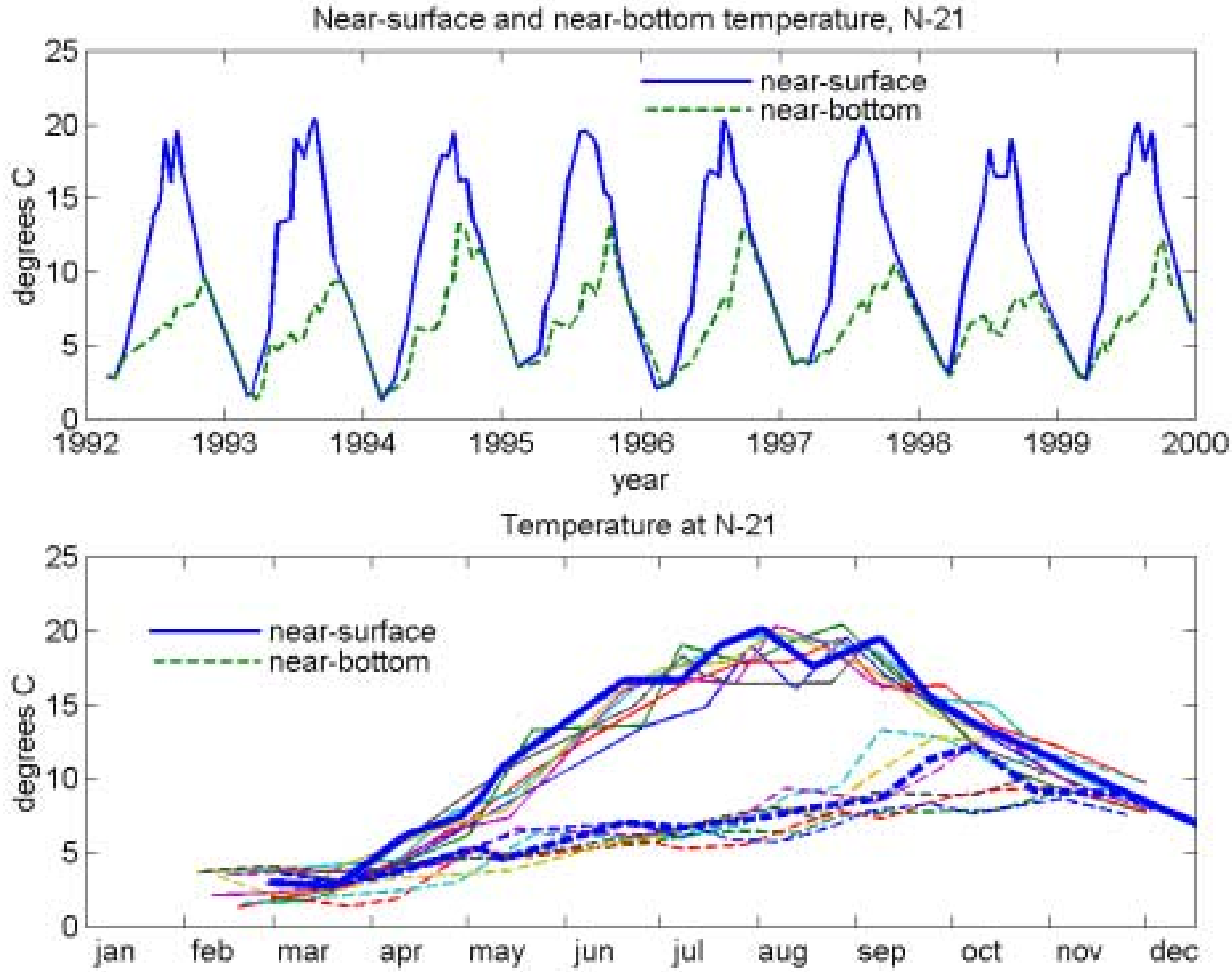


Figure 3-6. Near-surface and near-bottom temperature at nearfield station N21, 1992–1999. The lower panel shows the annual cycle for each year, with 1999 shown in bold lines.

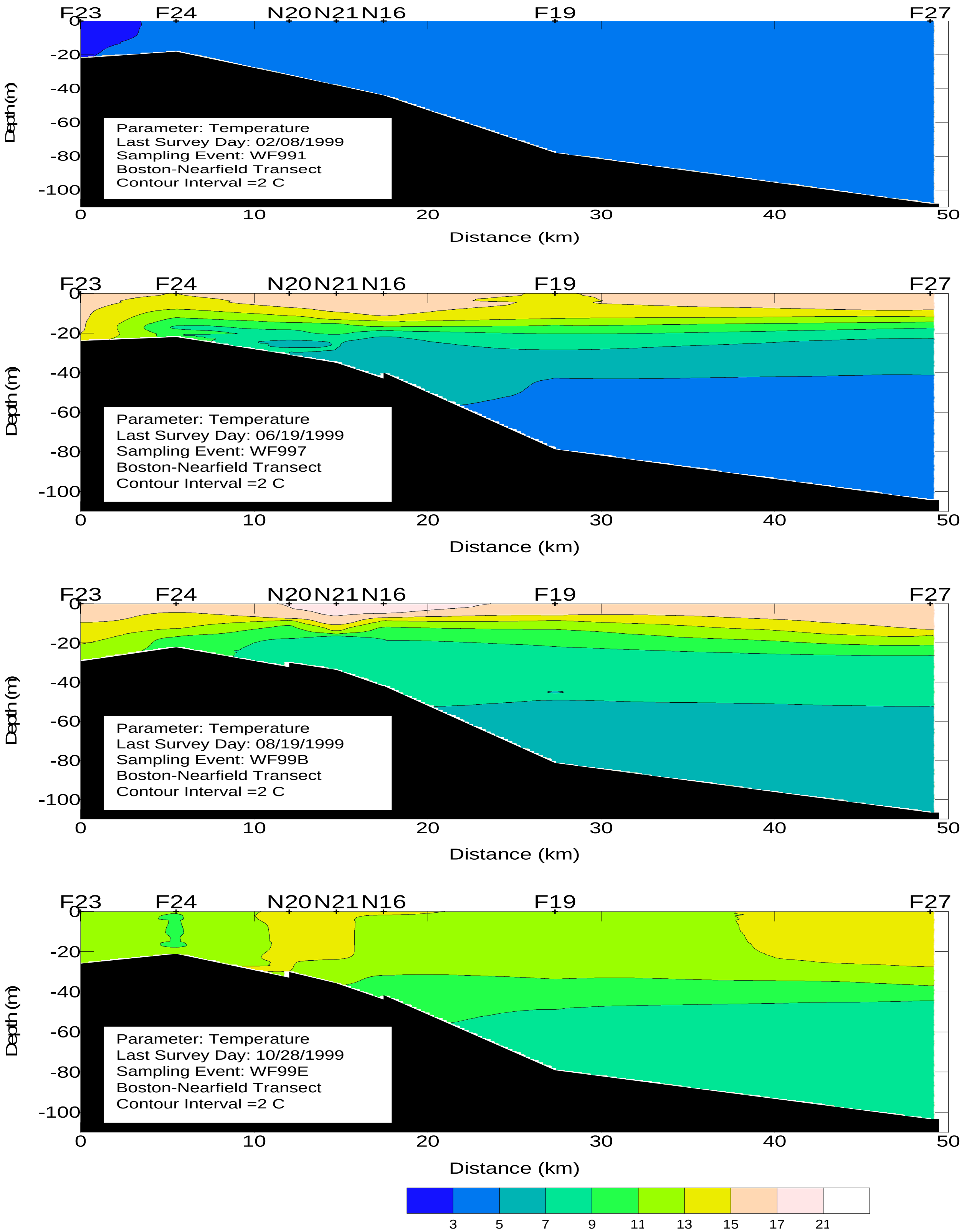


Figure 3-7. Temperature contour along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine in February, June, August and October 1999.

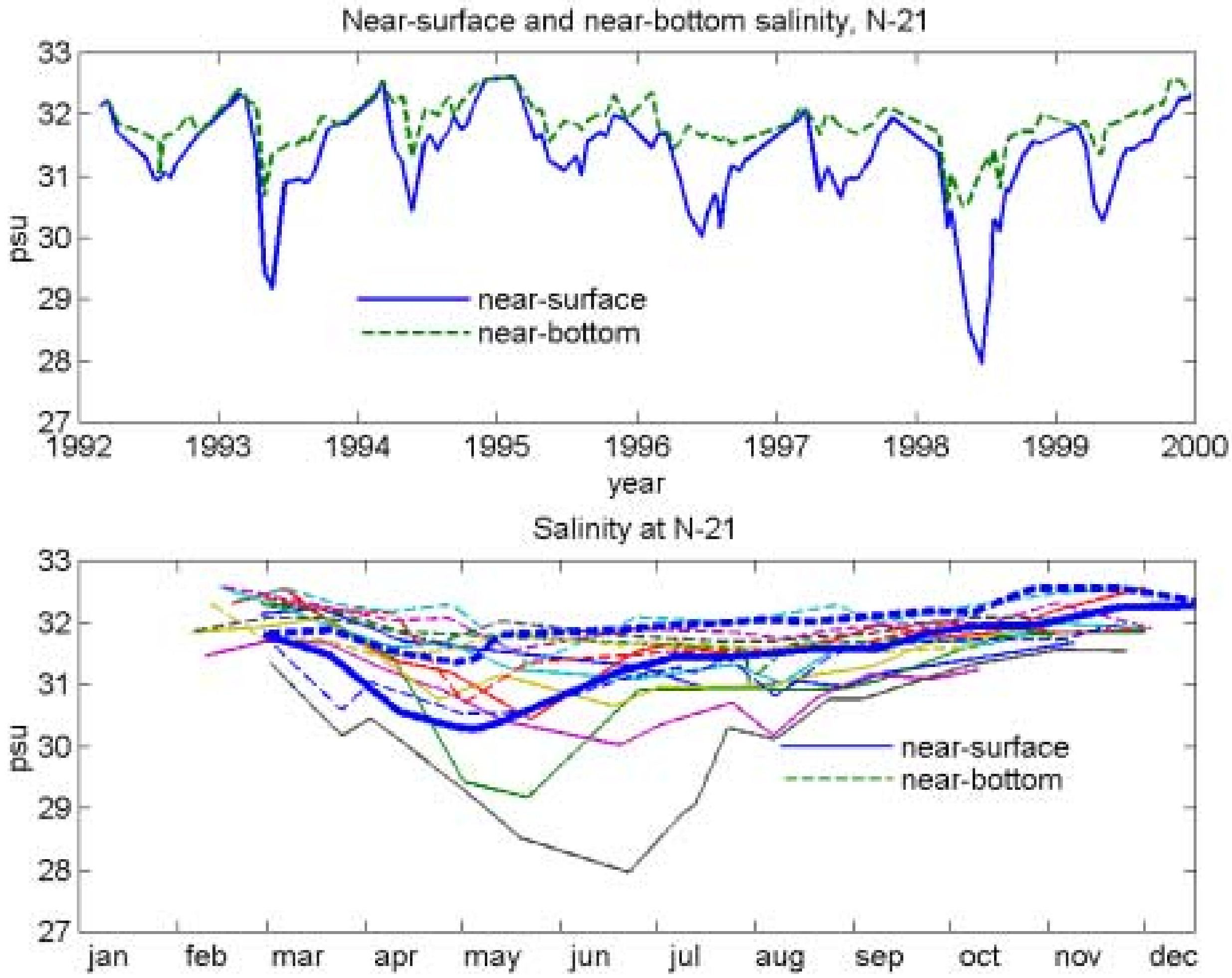


Figure 3-8. Near-surface and near-bottom salinity at nearfield station N21, 1992–1999. The lower panel shows the annual cycle for each year, with 1999 shown in bold lines.

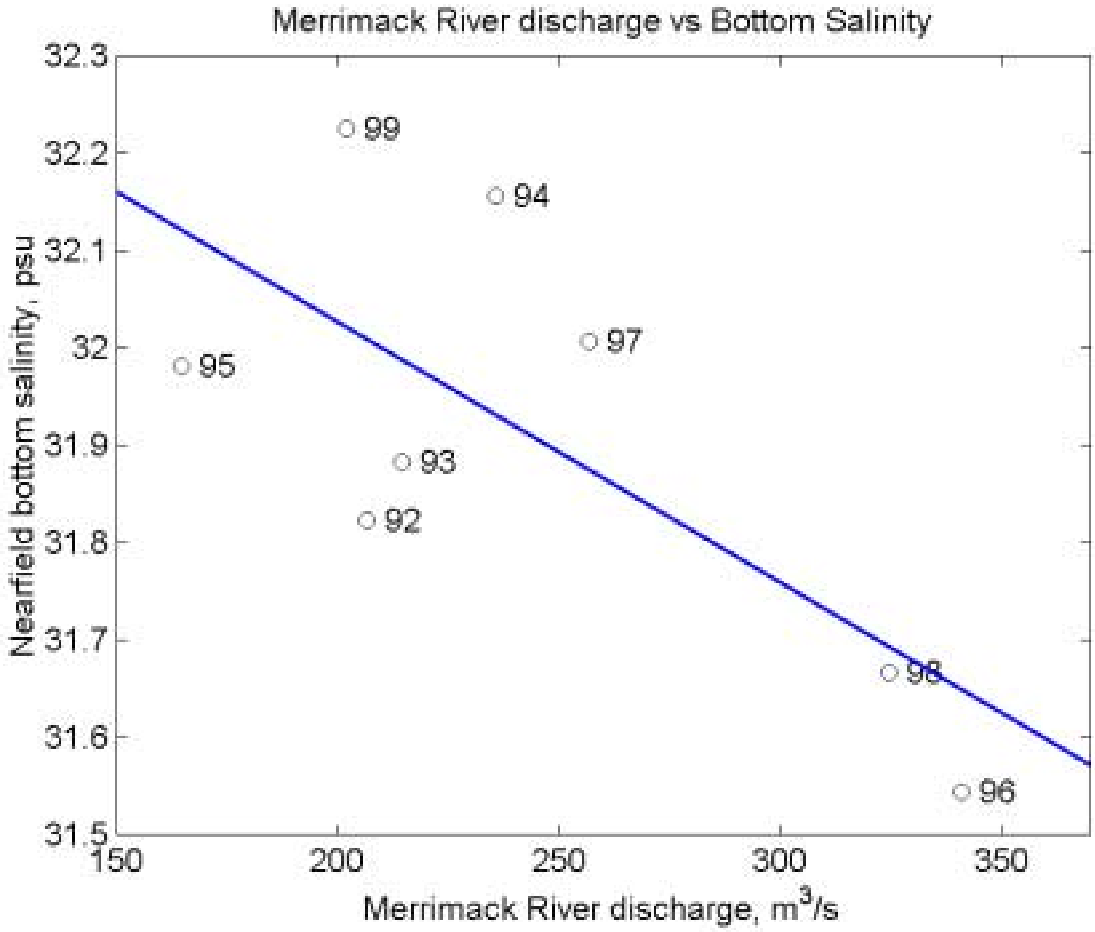


Figure 3-9. Near-bottom salinity at station N21 during autumn (September–October) compared with the average Merrimack River discharge (averaged between January and September). The correlation coefficient r=0.7 is significant at the 95% level. The years of each observation are indicated.

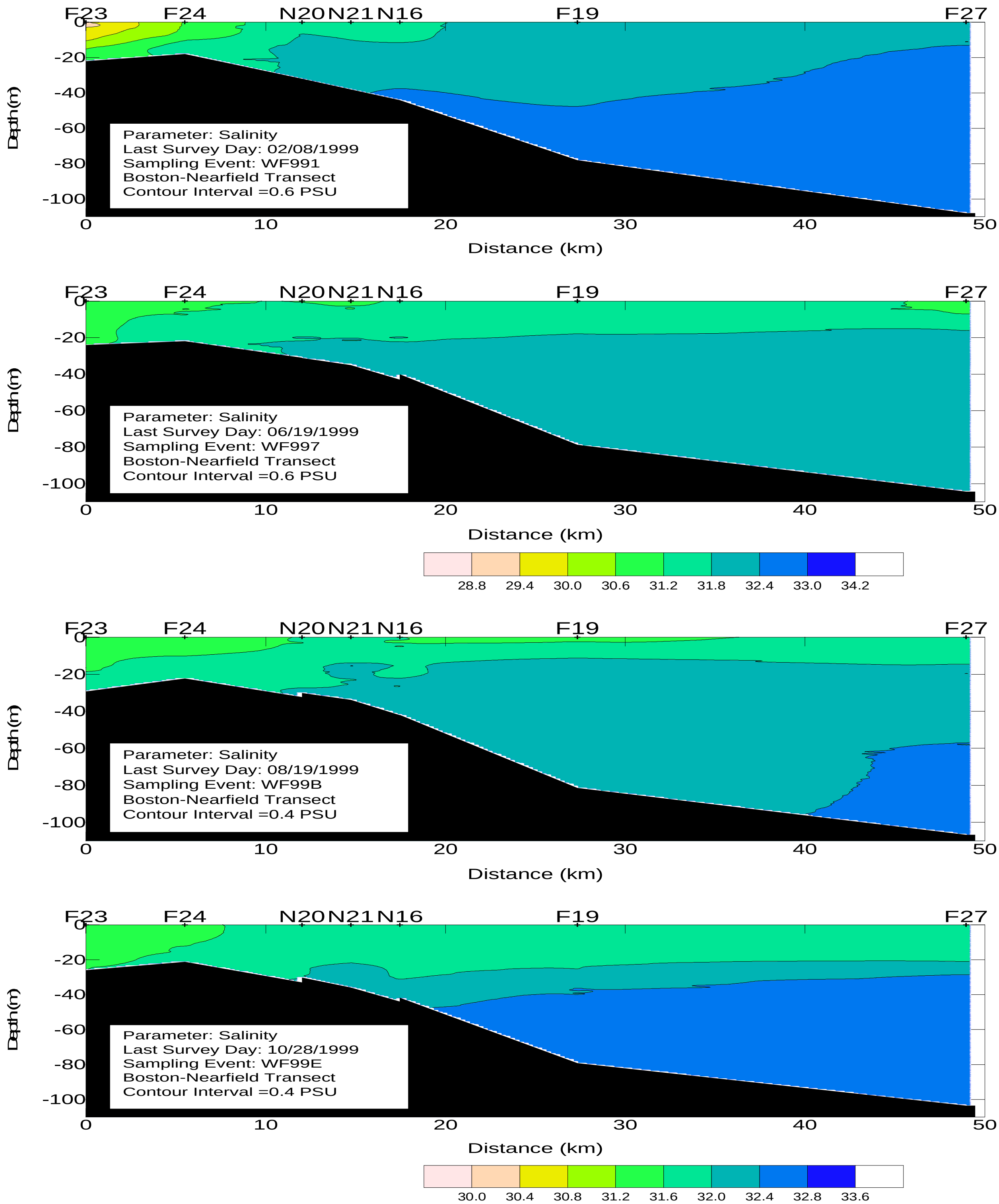


Figure 3-10. Salinity along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine in February, June, August and October 1999.

Note: Two scales used to provide detail for summer and fall surveys.

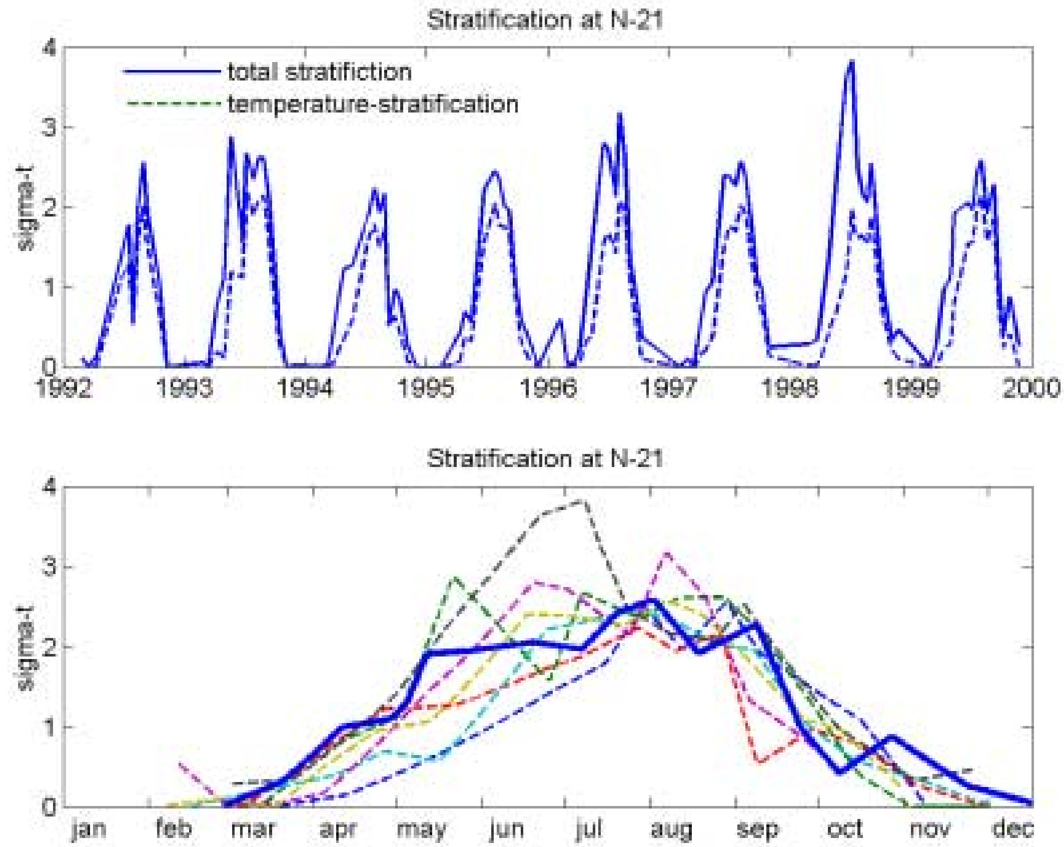


Figure 3-11. Stratification (density difference between near-bottom and near-surface) at nearfield station N21, 1992–1999. The dashed line in the upper panel shows the stratification due only to temperature variation, and the solid line includes both salinity and temperature effects. The bottom panel shows the annual cycle for 1999 in a bold trace, and the other years with dashed lines.

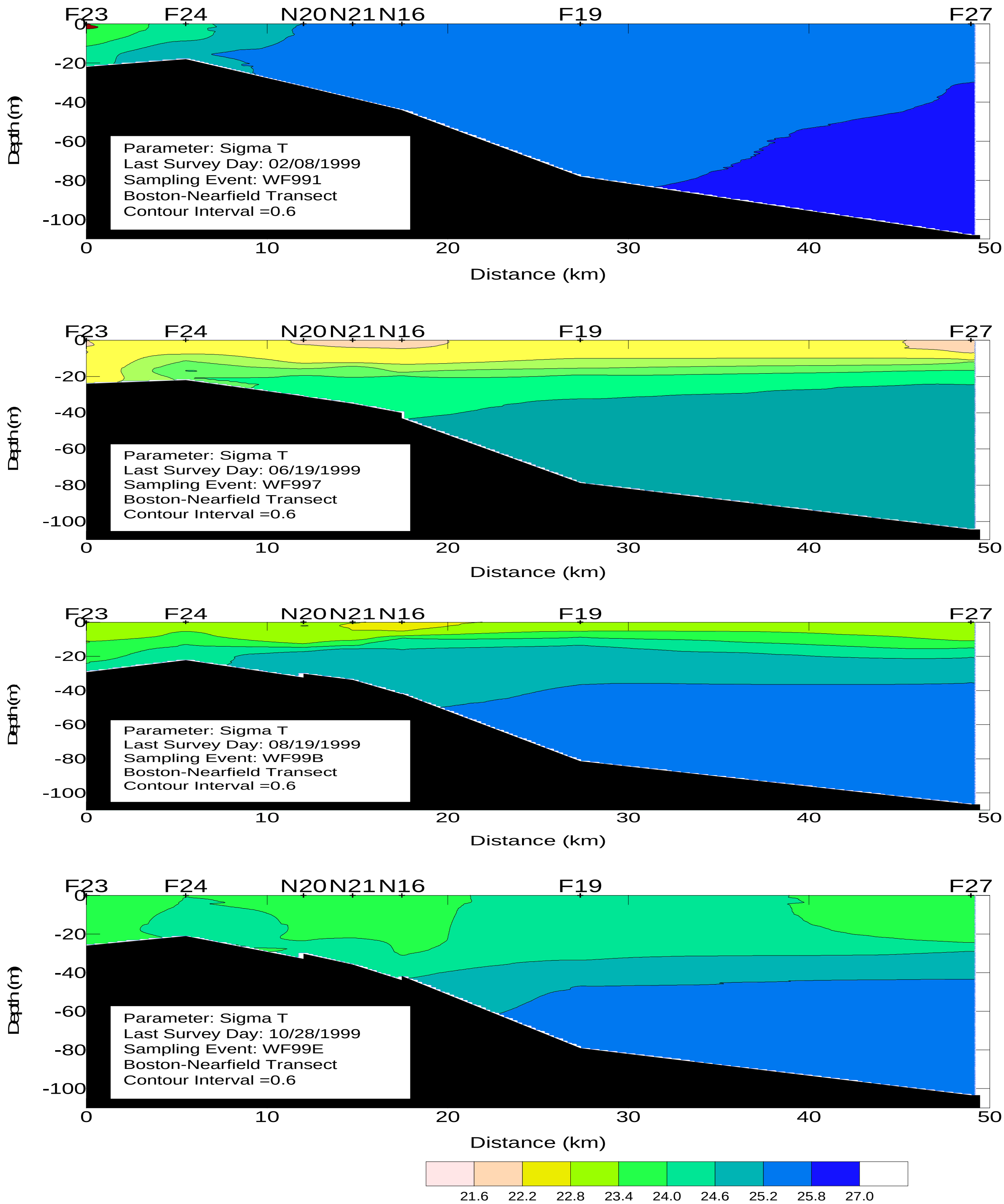


Figure 3-12. Density along the Boston-Nearfield transect from Boston Harbor to the Gulf of Maine in February, June, August and October 1999.

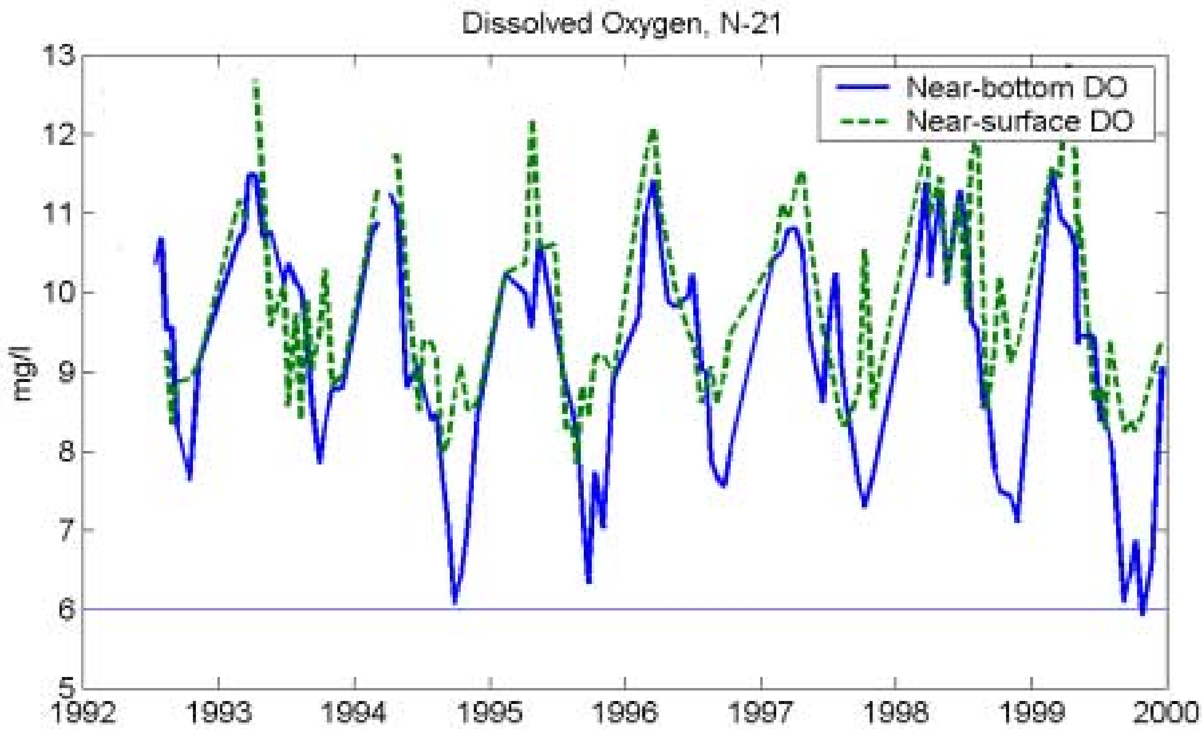


Figure 3-13. Near-surface and near-bottom dissolved oxygen at station N21 between 1992 and 2000. Dissolved oxygen levels were the lowest ever recorded during the monitoring period at station N21 in October 1999.

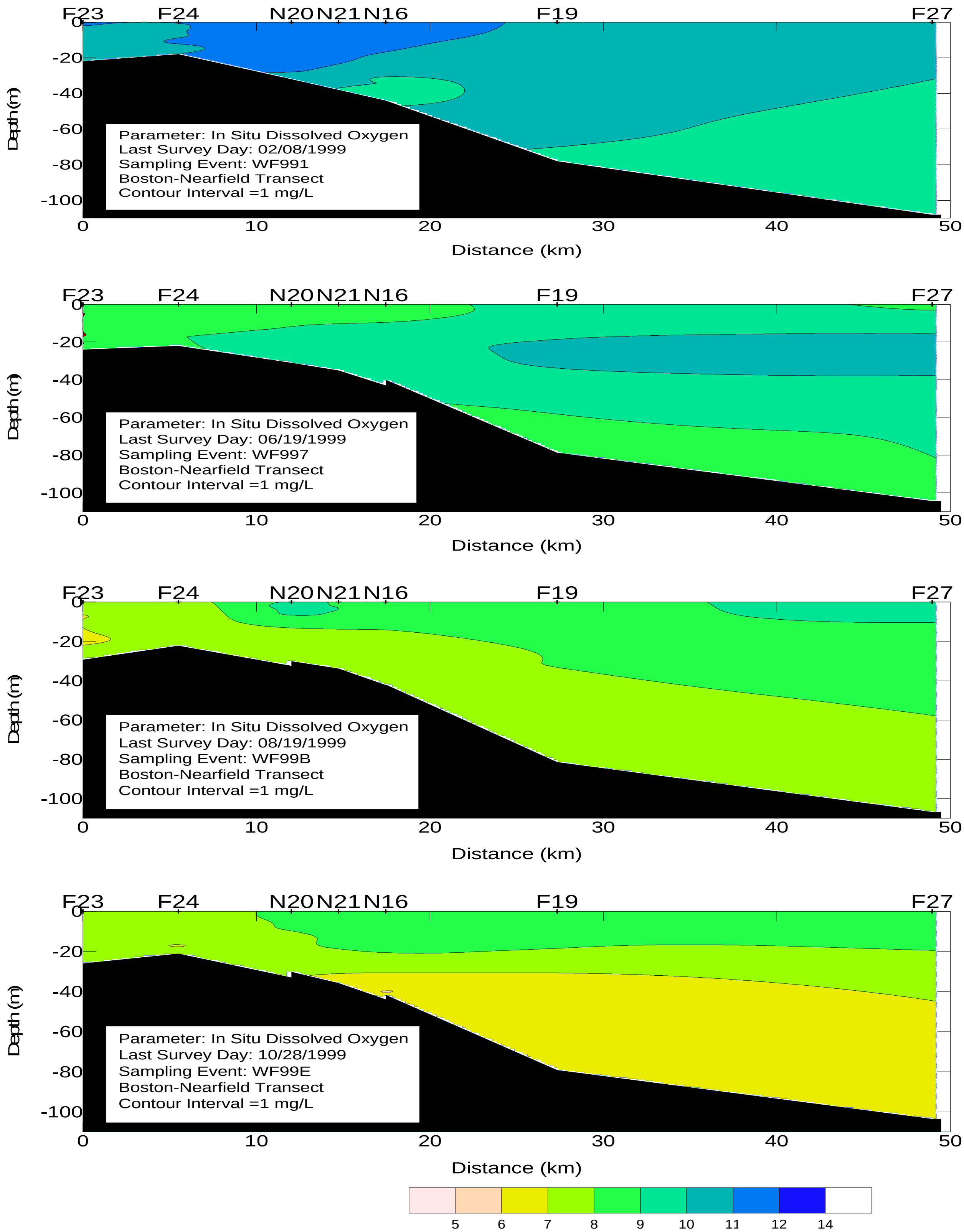


Figure 3-14. Dissolved oxygen along the Boston-Nearfield transect from Boston Harbor to the Gulf of Maine in February, June, August and October 1999.

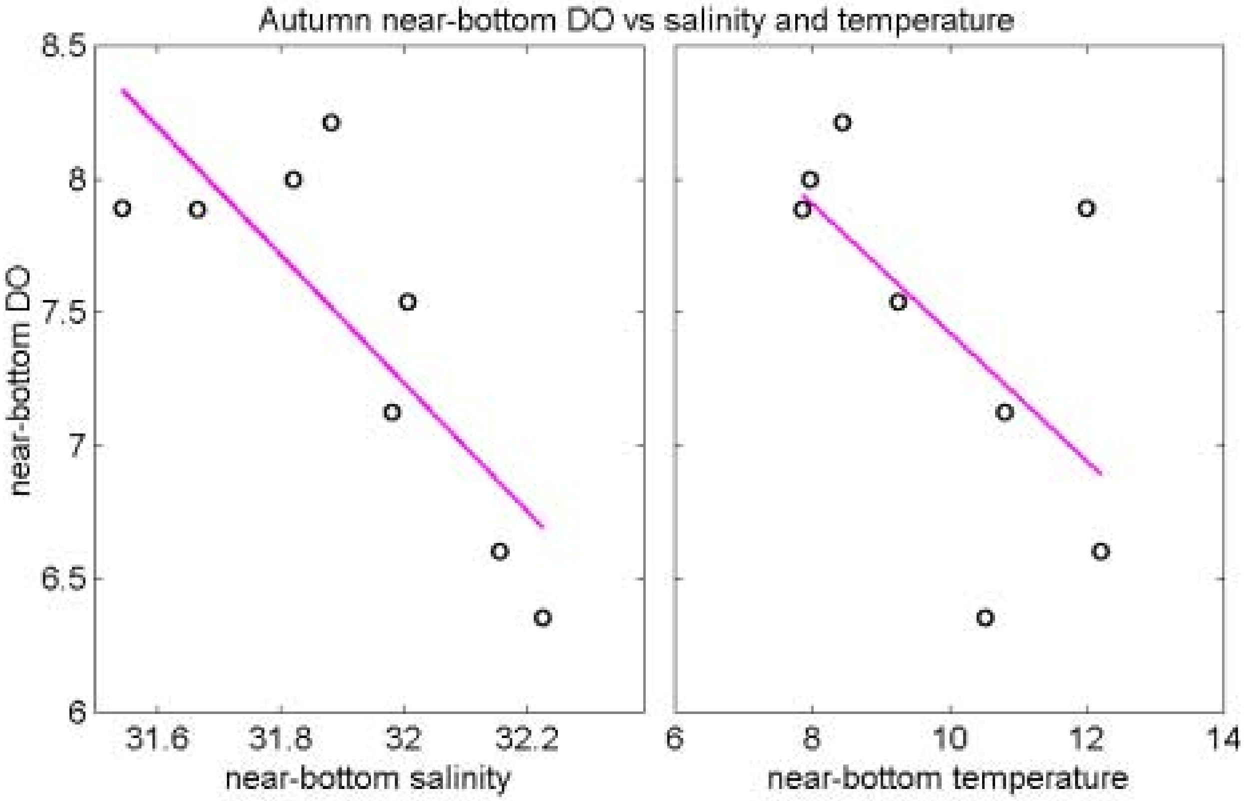


Figure 3-15. Variations of near-bottom salinity and temperature to dissolved oxygen during the autumn (September and October), based on averages of stations N13–N21 for each baseline monitoring year 1992-1999. The correlation coefficient between salinity and dissolved oxygen is r=0.81. The correlation coefficient between temperature and dissolved oxygen is r=0.61. Both are significant at the 95% level.

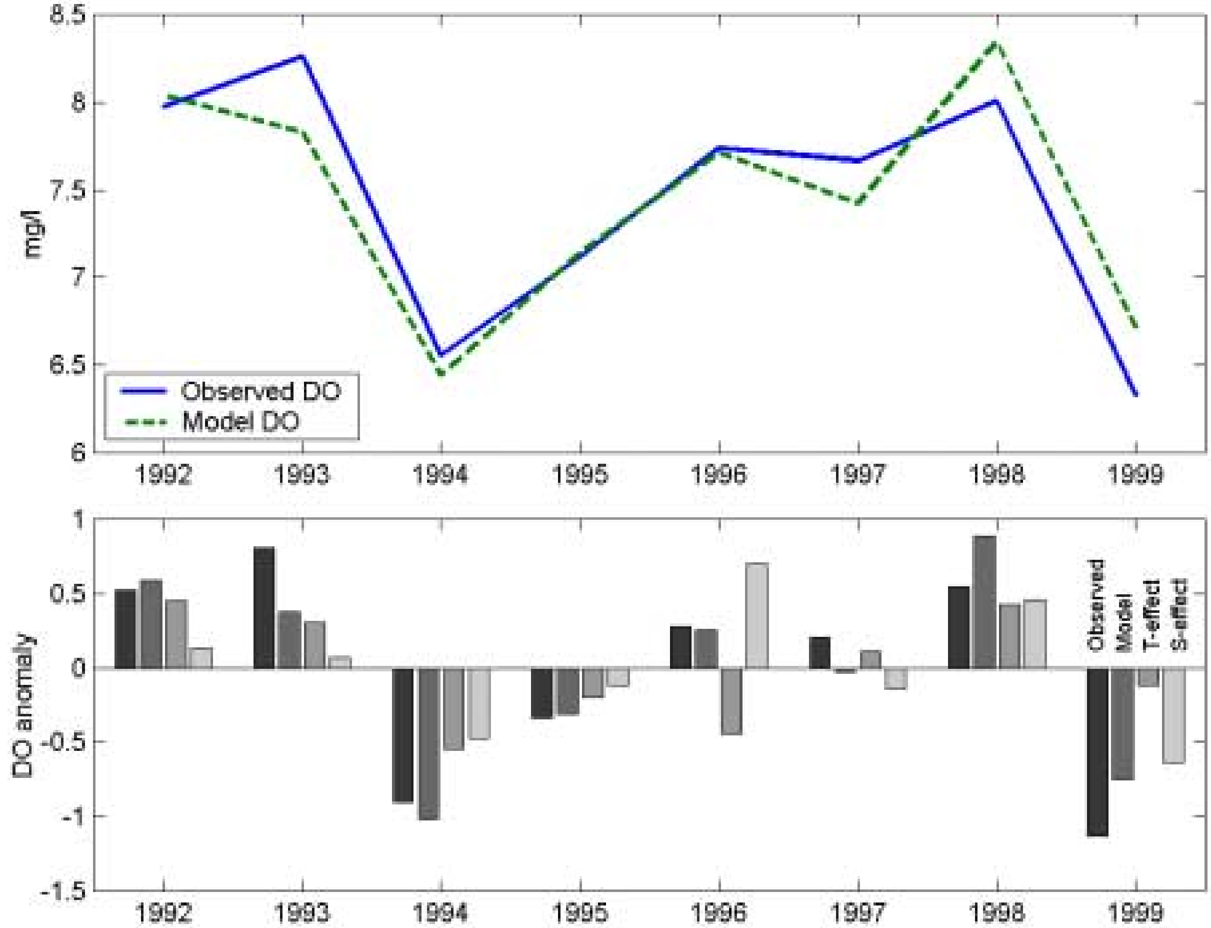


Figure 3-16. Average bottom dissolved oxygen during September-October, compared with linear regression model based on temperature and salinity variation (see text for details). The bar plot in lower panel shows the individual contributions due to temperature and salinity for each of the years.

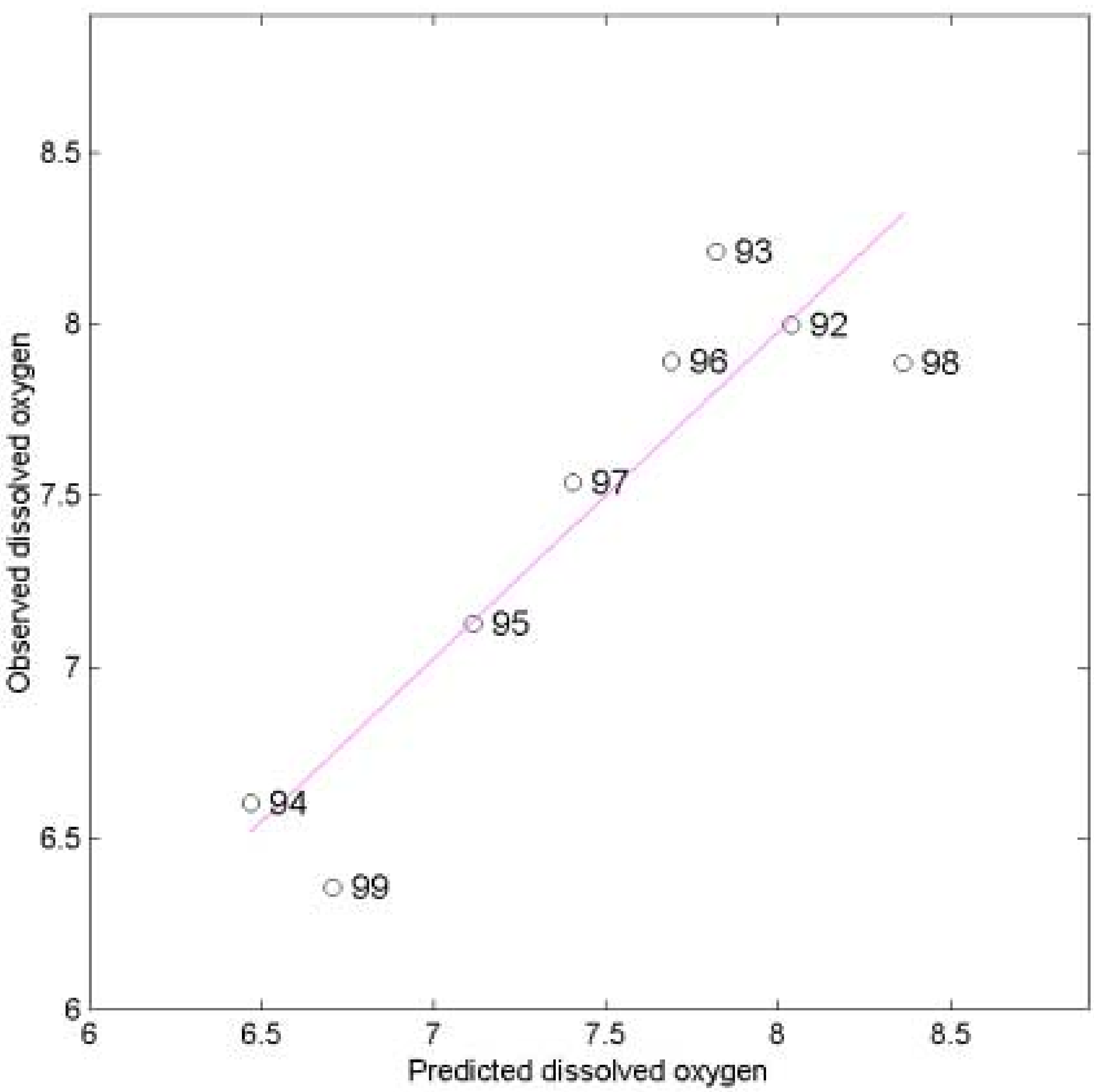


Figure 3-17. Observed compared to model predicted dissolved oxygen concentrations (mgL^{-1}) in nearfield bottom waters during September-October. The correlation coefficient between observed and predicted concentrations is r=0.92 (significant at P=0.05).

4.0 WATER QUALITY

Data presented in this section are organized by type of data. Temporal trends in the data are presented on narrow (nearfield) and broad (regional) spatial scales and compared on an interannual basis over the entire baseline monitoring period – 1992 to 1999. The physical data on temperature, salinity and density presented in the previous section provide the stage upon which discussions of the main water quality parameters are developed. Sections 4.1, 4.2 and 4.3 present an overview of the distribution of nutrients, chlorophyll *a* and dissolved oxygen respectively. A summary of the major results of these water quality measurements is provided in Section 4.4.

4.1 Nutrients

This section provides an overview of the trends and distribution of nutrients in Massachusetts and Cape Cod Bays in 1999 with particular focus on dissolved inorganic nutrients in the nearfield. The higher frequency sampling in the nearfield allows for a more detailed examination of the temporal trends of nutrients in Massachusetts Bay. The data are presented as individual values at representative stations, as mean survey values across the area and as annual means. The farfield data are grouped by geographic region (see Figure 2-2) as in previous annual reports to examine regional variability in nutrient distribution.

A detailed presentation of the data was provided in the two semi-annual reports for 1999 (Libby *et al*., 1999a and 2000). The discussion presented in this section focuses on the major themes that were observed in the dissolved inorganic nutrient data in 1999. This includes the nutrient dynamics associated with the seasonal phytoplankton blooms and the continuation of high ammonium concentrations in Boston Harbor, near-harbor coastal waters and the western nearfield.

In general, nutrient concentrations were relatively high in early February when the water column was well mixed and biological uptake of nutrients was limited. The winter/spring bloom led to a reduction in nutrient concentrations in the surface and mid-depth waters from February to April. With the onset of stratification, nutrient concentrations in the surface layer were depleted throughout the nearfield by late April/early May. Seasonal stratification led to the persistent nutrient depleted conditions in the surface and mid-depth waters and ultimately to an increase in nutrient concentrations in bottom waters due to increased rates of respiration (see Section 5.2) and remineralization of organic matter. In the fall, nutrient concentrations increased with the breakdown of stratification and return to a well-mixed water column.

4.1.1 Nearfield Trends

Nutrient trends in the nearfield are summarized by plotting dissolved inorganic nutrient concentrations versus time (Figures 4-1 and 4-2). These figures present the average and range of the surface, mid-depth and bottom values for each nearfield survey. The field protocol called for the “mid-depth” sample to be adjusted vertically to capture any subsurface chlorophyll maximum, if present.

During the first three surveys (February and March), nitrate (NO_3), silicate (SiO_4) and phosphate (PO_4) concentrations were relatively high and uniform over the water column (Figures 4-1 and 4-2). NO_3 and SiO_4 concentrations decreased between early and late February (Figure 4-1) coincident with increasing productivity and phytoplankton abundance. By March, NO_3 and SiO_4 concentrations had increased, while productivity, chlorophyll concentrations and phytoplankton counts in the nearfield had decreased. By April, however, NO_3 concentrations had become depleted and perhaps nutrient limiting in the nearfield surface and mid-depth waters while remaining high at depth ($\geq$6 µM;

Figure 4-1a). The sharp decrease in NO_3 was coincident with a decrease in PO_4 concentrations (Figure 4-2a). Nearfield surface waters remained depleted in NO_3 and PO_4 through October.

The March to April draw down in NO_3 and PO_4 was concomitant with the onset of stratification and spring bloom maxima in production, chlorophyll concentrations and phytoplankton counts in the nearfield. SiO_4 concentrations did not follow this trend and concentrations actually increased from late February to early May (Figure 4-1b). The increase in SiO_4 concentrations was coincident with an increase in bottom water ammonium (NH_4) concentrations (Figure 4-2b) and is indicative of remineralization of organic material from the winter/spring bloom (centric diatom, *Chaetoceros* spp.). From early to mid-May, there was a sharp decrease in surface SiO_4 concentration from 8 μM to 1 μM. This rapid change in SiO_4 concentrations was coincident with an increase in phytoplankton abundance that resulted from a dramatic increase in centric diatoms during the week between the two surveys (see Section 6.1).

Summer conditions of depleted nutrient concentrations existed in the surface waters until October. Bottom water concentrations reached a minimum in June and generally increased through early September due to biological degradation and remineralization processes. In mid-August, nutrient concentrations had, for the most part, increased both at the surface and at depth, perhaps the result of coastal upwelling. By late September, biological utilization had reduced NO_3 concentrations to low levels (<1 μM) in the surface and mid-depth waters. A subsurface maximum in chlorophyll concentrations (>20 $\mu g\ L^{-1}$) was present during the late September and October surveys (see Figure 4-22). The combination of biological utilization at depth and increased vertical mixing led to decreases in nutrient concentrations in the mid-depth and bottom waters over this period. By late October, nutrient concentrations in the surface and mid-depth waters had increased in the nearfield and continued to increase through December. A gradient in concentration between the surface and bottom waters, however, continued to be present until the December survey.

One of the most noteworthy observations for 1999 was the continued presence of elevated concentrations of ammonium in the western nearfield and coastal stations that correlated with high concentrations observed in Boston Harbor. This had also been observed during the fall/winter period of 1998. The source of the ammonium was determined to be an increase in the discharge of ammonium from the Deer Island facility (Libby *et al*., 1999b; Taylor, submitted). This increase results from a combination of increased treated sewage flow from the Deer Island Outfall as all sewage from the MWRA system is now treated at the Deer Island facility as well as the treatment process. Secondary treatment, which is now fully on line during low flow, treats the sewage more completely and breaks down organic wastes. One of the consequences or by-products of the secondary treatment process is higher ammonium concentrations in the effluent (Hunt *et al*., 2000).

As demonstrated in this set of nearfield average figures, a wide range in nutrient concentrations was frequently observed at each sampling depth (Figures 4-1 and 4-2). Generally, the range in nutrient values across the nearfield was small during the winter/spring conditions (February and March), increased during the onset of stratified summer conditions (April and May), was small and relatively consistent over the stratified summer (June to August), and then increased in the fall (September to November) before well-mixed conditions returned in December. This range is primarily the result of variations in station depth (increasing to the east) and station location (proximity to Boston Harbor). To examine the variability across the nearfield, surface and bottom water nutrient data from representative stations were examined (Figures 4-3 and 4-4). The stations are situated at the four corners (N01, N04, N07, and N10) and center of the nearfield (N21; see Figure 2-2).

The trends in surface and bottom water NO_3 presented in Figure 4-3 are generally representative of the trends observed for SiO_4 and PO_4 for changes in concentrations from west to east across the nearfield. During the winter/spring bloom in February and March, NO_3 concentrations were more depleted at the inshore stations suggesting an inshore to offshore progression in the bloom. Surface water concentrations were depleted across the nearfield from April to October and bottom water concentrations were higher at the deeper offshore stations over this period. The most prominent exception being at station N10, where there was little variation between surface and bottom water concentrations for each of the nutrients measured (including NH_4) and concentrations tended to increase from mid-August through December (Figure 4-3). Ammonium concentrations were generally low during the first half of 1999 and the main source of variability was due to input of NH_4 from Boston Harbor. The harbor nutrient signal was observed at station N10 for each of the nutrients, but it was most clearly seen in the high NH_4 concentrations that were measured in the spring and fall (Figure 4-4). In the fall, the export of NH_4 and PO_4 rich waters from Boston harbor led to high surface water concentrations at inshore stations N01 and N10 and a wide range of values across the nearfield (Figure 4-4).

4.1.2 Farfield Comparisons

The annual nutrient cycle in Massachusetts and Cape Cod Bays was examined using contour maps and nutrient versus depth plots. To distinguish regional concentration differences and processes, the data have been grouped by geographic region: Boston Harbor, Boundary, Cape Cod Bay, Coastal, Nearfield and Offshore (Figure 2-2). A small subset of the farfield data are presented here to focus the discussion on the major regional trends that were observed in 1999 (a comprehensive data presentation was provided in Libby *et al*. 1999b & 2000).

As has been the case during each of the baseline years, the highest nutrient concentrations in 1999 were consistently measured at the Boston Harbor and harbor influenced coastal and nearfield stations (Figures 4-5 and 4-6). Nutrient concentrations were generally high in surface waters during the first winter survey in early February (WF991) as shown for dissolved inorganic nitrogen (DIN) in Figure 4-7. As had been seen during the previous winter (1998), ammonium concentrations continued to be high at Boston Harbor stations and nearby coastal waters (Figure 4-6b), which resulted in a strong gradient of decreasing DIN from the harbor (>20 μM) to the nearfield (<7 μM; Figure 4-7). By late February, mean nutrient concentrations had decreased throughout the region and generally continued to decline into April with the continuation of the winter/spring bloom. As observed in the nearfield, however, SiO_4 concentrations increased from February to April in the coastal, offshore and boundary stations in Massachusetts Bay (Figure 4-5b). In April (WF994), unusual patterns in surface nutrient concentrations were observed due to the month long duration of the survey. Interestingly, the pattern when evaluated based on date of sample collection reveals that April was not only a dynamic month weather wise (hence the long survey), but it also was a period of increasing biological production and utilization of nutrients. Nutrient concentrations at the boundary and northern offshore area stations (sampled April 1st and 6th) were relatively high and comparable to the values observed in late February while nutrient concentrations had decreased to relatively low levels in the nearfield and southern offshore area stations (sampled April 11th and May 5th). This is clearly illustrated in Figure 4-8 showing surface water NO_3 concentrations.

Over the summer, dissolved inorganic nutrients were generally depleted in the surface waters at all stations in Massachusetts and Cape Cod Bays except those in or near Boston Harbor, which continued to be a source of nutrients. Trends in mean NO_3 concentrations were similar across Massachusetts Bay with low values over in June and then increasing concentrations in August and on into October (Figure 4-5a). In Cape Cod Bay, NO_3 concentrations remained low ($\leq$1 μM) from June through October. Mean SiO_4 and PO_4 concentrations increased across the bays from June to October. Mean NH_4 concentrations remained relatively low in Cape Cod Bay and at offshore, boundary and nearfield stations in Massachusetts Bay, while substantial increases in NH_4 concentrations were observed at Boston Harbor and coastal stations from April to October (Figure 4-6b). By October, surface water nutrient concentrations had increased at the harbor and inshore stations while remaining relatively depleted in the nearfield and further offshore. The harbor signal continued to be observed in surface water DIN distribution with concentrations of >20 μM measured both within and just outside the harbor (Figure 4-9). The strong gradient from these harbor and coastal stations into the nearfield was primarily driven by very high NH_4 concentrations in the harbor (10-20 μM; Figure 4-10) and biological utilization of nearly all DIN in the nearfield surface waters.

In November, high NH_4 concentrations continued to be present in the western nearfield with an inshore to offshore decrease in concentration away from the harbor (Figure 4-11). This pattern continued to be evident during the December nearfield survey. No harbor data were collected in November or December of 1999 for HOM3. A comparison between HOM3 data and MWRA data from their Boston Harbor Water Quality (BHWQ) monitoring program is presented below in Section 4.1.4. In contrast to the early winter of 1998, the elevated NH_4 concentrations in 1999 did not translate into unusually high chlorophyll concentrations, although concentrations of ~5 $\mu g\ L^{-1}$ were sustained in the nearfield surface waters through late November. The input of NH_4 into coastal and nearfield waters in late summer and early fall, however, may have contributed to the elevated chlorophyll, production and phytoplankton abundances that were observed in August and September 1999 (see Sections 4.2, 5.2 and 6.1, respectively).

4.1.3 Interannual Comparisons

The year to year variability in nutrient concentrations is dependent upon a variety of physical and biological factors. This section focuses on characterizing the year to year variability and evaluating the major events or deviations from the ‘normal’ trends that were observed in 1999, primarily the continued observation of high ammonium concentrations in Boston Harbor, nearby coastal waters and the western nearfield in 1999. Data are presented as survey means and annual means for each area (as defined in Figure 2-2).

The occurrence of a bloom in phytoplankton and chlorophyll of varying intensity often characterizes the winter/spring period in Massachusetts and Cape Cod Bays. The presence of elevated nutrient concentrations, increasing light availability and water temperatures, and the onset of seasonal stratification establish conditions that are conducive for a bloom to occur in the bays. The intensity of the winter/spring draw down of nutrients is related to the strength of the bloom – the more intense the bloom the lower the concentrations of nutrients in the surface waters. During the summer-stratified period, nutrients are generally depleted in the surface waters and tend to increase at depth as organic material is degraded and nutrients remineralized. During years when upwelling conditions are favorable, nutrient concentrations may increase in July and August in Western Massachusetts Bay at western nearfield and coastal stations. The fall is often a period of increasing nutrient concentrations as the water column returns to well-mixed winter conditions and production decreases. This fall trend may be punctuated by decreases in nutrient concentrations during strong fall blooms (i.e. *Asterionellopsis glacialis* bloom in the fall of 1993).

This general pattern for nutrient concentrations is depicted for NO_3 in Figure 4-12 for the nearfield area. The interannual variability is much less than the seasonal concentration range in that results from spring draw down and fall increases each year. There are, however, interannual differences in the timing and extent of the nutrient dynamics. For NO_3, the 1999 data fall within the range of seasonal trends observed during previous baseline years. The winter/spring draw down of NO_3 was not as intense as during 1992 or 1996, when substantial blooms led to a sharp decline in NO_3 concentrations in both surface and bottom waters from February to March. The 1999 draw down was not delayed as in 1998, when a winter/spring bloom was not observed and nutrient concentrations remained elevated in the surface waters until May. NO_3 concentrations were depleted in the nearfield surface waters for an extended period in 1999 in comparison to other years and this may have been due to the combination of calm weather conditions and an atypical late summer bloom of the diatom *Leptocylindrus danicus* (see Section 6.1).

A comparison of survey mean nutrient concentrations for each of the six areas across the bays is presented in Figures 4-13 to 4-16. As with the nearfield data, the year to year trends are similar for each of the areas though there are differences between areas. Mean NO_3 minima were higher than during previous years for each of the areas except Cape Cod Bay (Figure 4-13). In Cape Cod Bay, NO_3 concentrations generally decrease more quickly in the spring, remain low over the summer and stay low into the fall. The early spring decrease is related to the earlier occurrence of the spring bloom in Cape Cod Bay waters relative to the other areas. The persistence of low nutrient conditions may also be related to the lack of nutrient at depth in these shallow waters.

Area mean SiO_4 concentrations exhibited a similar trend to NO_3, with generally higher annual minima in 1999 in each of the areas except Cape Cod Bay where they were lower than most previous years (Figure 4-14). Cape Cod Bay SiO_4 concentrations were comparable to the low levels in 1996 when a substantial diatom bloom was observed.

Plots of area mean PO_4 and NH_4 show that annual concentration minima and maxima where generally higher in 1999 than during previous baseline monitoring years (Figure 4-15 and 4-16). Mean PO_4 concentrations in Boston Harbor were again high (>1.5 μM) during the fall of 1999 as they had been in 1998. NH_4 concentrations in the harbor were the highest observed over the 1992 – 1999 period and continued a trend that was first observed in Boston Harbor in 1998. This trend of increasing NH_4 also appears to be occurring at the other five areas in Cape Cod and Massachusetts Bay (Figure 4-16).

A review of annual mean nutrient concentrations in each of the areas shows a corresponding trend of increasing annual means for each of the nutrients in all six areas except for SiO_4 at the boundary stations (Figure 4-17 and 4-18). The trends in increasing NO_3 and SiO_4 were not significantly different from zero except for NO_3 at offshore stations (where $r = 0.78$; note: $r \geq 0.71$ indicates significant difference from zero at $P = 0.05$ level for $df = 6$). Significant increases in annual mean PO_4 concentrations (correlation coefficients of 0.74 to 0.88) were observed for each area except Boston Harbor ($r = 0.65$). Based on the linear regression of annual mean PO_4, there was an increase in annual mean PO_4 of 0.24 μM PO_4 at these five areas from 1992 to 1999. The trend in increasing annual mean NH_4 concentrations was significant in Cape Cod Bay ($r = 0.74$), coastal Massachusetts Bay ($r = 0.73$) and Boston Harbor ($r = 0.87$, significant at the $P = 0.01$ level). Regression results for the Boston Harbor stations indicate there was a 5 μM increase in NH_4 over the baseline period. The factors affecting regional nutrient concentrations are not known but may be related to Gulf of Maine influences and long-term variations. The dramatic increase in NH_4 concentrations, however, is primarily due to local changes – the increased discharge of NH_4 from the Deer Island Facility. The increased discharge resulted from an increase in the volume of sewage treated at Deer Island (transfer of sewage from Nut Island in 1998) and the switch to secondary treatment. A comparison of Boston Harbor Water Quality Monitoring (BHWQM) and HOM3 data is presented next to provide additional information on the nutrient trends in Boston Harbor.

As first observed in 1998, concentrations of NH_4 at Boston Harbor stations were higher in 1999 than in 1994 to 1997. Figure 4-19 presents a time series of surface NH_4 concentrations from BHWQM and HOM stations in the inner Boston Harbor (stations 24 and F30) and north Boston Harbor (stations 106, 142 and F23). The data from the two monitoring programs is generally in agreement and shows NH_4 concentrations in the fall/winters of 1998 and 1999 that are 5-10 μM higher than the measurements collected from 1994-1997. The data from both the HOM and BHWQM programs over the last five years for stations in inner and north Boston Harbor show the seasonal changes in NH_4 (Figure 4-19) and the general biological cycle as measured by chlorophyll concentration (Figure 4-20). The nutrient concentrations decrease from the winter to the summer and then increase from the end of the summer through the fall. This is due to a normal biological progression in the harbor of increasing chlorophyll concentration, phytoplankton abundance, productivity and nutrient utilization from winter to summer and then a decrease in primary productivity and nutrient utilization in the late summer or fall when the system "shuts down".

At these five Boston Harbor stations, the annual mean NH_4 concentrations showed a significant increase in NH_4 over the baseline period (r = 0.86, significant at P =0.01). Figure 4-21a shows that the increase was due to higher annual mean NH_4 at these harbor stations in 1998 and 1999. The increase in annual mean concentration from 1998 to 1999 was likely due to the fact that the transfer of sewage flow from Nut Island to Deer Island, which began in April 1998, was not completed until July 1998. Thus, the 1998 annual mean was only affected by an increase in discharges from Deer Island over the second half of the year. The increase in NH_4 concentrations was concomitant with, and may have led to, an increase in annual mean chlorophyll at the Boston Harbor stations (r = 0.53, significant at P = 0.01; Figure 4-21b). The trends in chlorophyll concentration are not as clear as those observed for NH_4, but there may be a link between the observed changes in nutrient concentrations in the harbor and the relatively consistent trend of increasing chlorophyll from 1996 to 1999. The changes in nutrient dynamics, specifically the increased discharge and ambient concentration of NH_4, and coincident changes in Boston Harbor water quality may be examined in more detail in the 1999 Nutrient Issues Review. Particular attention should be focused on potential impacts of elevated NH_4 concentrations in the effluent discharged at the offshore outfall.

4.2 Chlorophyll

This section presents an overview of the trends and distribution of chlorophyll in Massachusetts and Cape Cod Bays in 1999 and an interannual comparison with the 1992-1998 baseline monitoring data set. The reported data represent chlorophyll as measured by calibrated *in situ* fluorescence at discrete sampling depths. The *in situ* fluorescence measurements were calibrated with analytical chlorophyll *a* measurements made at a subset of stations on each survey (Albro *et al.*, 1998). Unless specified as chlorophyll *a*, the term chlorophyll in this report refers to the post-survey calibrated *in situ* fluorescence values.

The chlorophyll data presented in this report are from the surface, mid-depth, and bottom sampling depths. The mid-depth sample was collected at the subsurface chlorophyll maximum, if present. The data are presented as mean survey values across areas and as individual values at representative stations. The farfield data are grouped by geographic region (see Figure 2-2) as in previous reports to examine regional variability in nutrient distribution. A detailed presentation of the data was provided in the two semi-annual reports for 1999 (Libby *et al*. 1999a and 2000). The discussion presented in this section focuses on the major themes that were observed in the chlorophyll data in 1999. These include the winter/spring bloom, elevated summer concentrations and the fall bloom. The 1999 chlorophyll concentrations were higher than during any previous baseline year on both a seasonal and annual basis.

4.2.1 Nearfield Trends

During the winter/spring of 1999 (February through April), chlorophyll concentrations were generally high throughout the nearfield (mean = 4.91 μgL^{-1}) as a result of the winter spring bloom that was observed. Chlorophyll concentrations decreased somewhat over the summer, but remained relatively high in comparison to previous baseline years (mean = 2.18 μgL^{-1}). Very high chlorophyll concentrations were observed in the nearfield during the fall season (mean = 6.72 μgL^{-1}). These high concentrations were the result of an early fall increase in chlorophyll concentrations in September and a fall bloom in the nearfield in October. The overall annual mean for all stations and all depths sampled during the nearfield surveys was 4.41 μgL^{-1} in 1999. This is the highest annual average by almost a factor of two compared to previous baseline monitoring years. A wide range in chlorophyll values was observed during each nearfield survey (maximum range of >50 μgL^{-1} in early September surface waters). The high chlorophyll concentrations and the wide range of values observed are discussed in more detail below.

Trends in the nearfield chlorophyll concentrations are summarized in Figure 4-22. This figure presents the average and range of the surface, mid-depth, and bottom values for each nearfield survey. Note that when a subsurface chlorophyll maximum was present, the mid-depth sample represents the water quality characteristics associated with the feature. For most of 1999, the survey mean for the mid-depth chlorophyll concentrations was consistently higher than the surface and bottom mean values indicating that the chlorophyll maximum was subsurface for most of the year.

Due to the extremely high chlorophyll concentrations observed in September of 1999, the axis in Figure 4-22 covers a very wide range of values from 0 to 60 μgL^{-1}. Although chlorophyll concentrations may appear to be relatively low from February through August, the actual concentrations are quite high in comparison to previous baseline monitoring years (see Section 4.2.3 for discussion). The high chlorophyll concentrations in the nearfield during the winter/spring period of 1999 were a continuation of the elevated concentrations observed in late 1998 (Libby *et al*., 1999b).

During the winter/spring bloom, chlorophyll concentrations tended to increase from early February to April. Concentrations at mid-depth, the subsurface chlorophyll maximum, ranged from 5 to 8 μgL^{-1} in February and March and increased to ~12 μgL^{-1} in April. Surface chlorophyll concentrations in April were high at station N10 (>13 μgL^{-1}) and decreased to <5 μgL^{-1} across the rest of the nearfield (Figure 4-23). This was coincident with a very strong inshore to offshore decrease in nutrient concentrations. With the onset of stratification, the winter-spring bloom had depleted nutrients (especially NO_3) in the nearfield surface waters. The availability of nutrients at depth led to the subsurface chlorophyll maximum that was located just above the pycnocline. Phytoplankton abundances in the nearfield chlorophyll maximum samples were almost double that of the surface samples (stations N04, N18 and N16). As would be expected, the elevated chlorophyll concentrations and phytoplankton abundance were concomitant with high production rates during the April survey.

By early May, chlorophyll concentrations had decreased to <1 μgL^{-1} for the surface, mid-depth and bottom water means. This was coincident with an equally severe decrease in phytoplankton abundance from 2-3 million cells L^{-1} to ~0.5 million cells L^{-1} from April to early May. Mean surface and bottom water concentrations remained low over the summer. A subsurface chlorophyll maxima was consistently present in the nearfield at an average concentration of ~5 μgL^{-1} from mid-May to early August (Figure 4-22). The surface chlorophyll concentrations at the harbor influenced station N10 were generally higher and more variable over the summer than the rest of the nearfield (1-10 μgL^{-1}).

In early August, the mean chlorophyll concentrations in the surface and mid-depth waters were about 2 and 5 $\mu g\ L^{-1}$, respectively. By late August, the surface and mid-depth concentrations had doubled to 5 and 10 $\mu g\ L^{-1}$. Productivity reached a maximum at station N18 in late August (see Section 5.1) and may have signaled the beginning of a late summer bloom in the nearfield as chlorophyll concentrations continued to increase into September (Figure 4-22). Mean chlorophyll concentrations reached annual maxima for the surface (19 $\mu g\ L^{-1}$) and mid-depth (24 $\mu g\ L^{-1}$) waters in early September. A very wide range of chlorophyll concentrations was observed for both surface and mid-depth samples during this survey. This resulted from a southwest to northeast difference in the depth of the chlorophyll maximum. A surface chlorophyll maximum was observed in the southwestern corner of the nearfield and a subsurface chlorophyll maximum was observed over the remainder of the nearfield (Figure 4-24). The increase in chlorophyll from late August to early September was not coincident with an increase in phytoplankton or production. In fact, total phytoplankton abundance and production decreased at stations N04 and N18 over this time period.

The distribution of chlorophyll in the nearfield in early September suggests that there were two separate phytoplankton assemblages. Production and phytoplankton samples are only collected at stations N04 and N18 both of which exhibited strong subsurface chlorophyll maxima so there are no data available to assess the phytoplankton community in the high surface chlorophyll layer observed at the inshore nearfield stations. Phytoplankton abundance in the subsurface chlorophyll maxima was relatively low (~1 million cells L^{-1}) and the high chlorophyll concentrations may have been due to a physiological response to lower light levels rather than elevated biomass or an increase in abundance of the >20-μm screened phytoplankton (primarily *Ceratium* species).

High chlorophyll concentrations (>20 μg L^{-1}) continued to be observed at mid-depth across the nearfield in late September. Surface concentrations, however, had decreased to <10 μg L^{-1} (Figure 4-22). Elevated bottom water chlorophyll concentrations were observed during this survey and may have been due to the senescence of the late summer bloom observed during the two previous surveys. During the October combined survey, the mean chlorophyll concentration at the subsurface chlorophyll maximum had decreased to ~7 μg L^{-1} and surface concentrations had decreased to ~4 μg L^{-1}. Both total and >20-μm screened phytoplankton had decreased since September, while production rates had increased from the summer/fall low observed in late September. The trend of increasing production continued into late October when peak fall bloom productivity rates of ~1750 $mgCm^{-2}d^{-1}$ were observed at stations N04 and N18 (see Section 5.1). The increased production was not strongly expressed in the chlorophyll or phytoplankton data. Surface water chlorophyll concentrations increased to ~7 μg L^{-1}, which was also the concentration observed in the mid-depth waters. By late November, chlorophyll concentrations had decreased to ≤5 μg L^{-1} over the entire water column. No fluorescence data were available for the December survey due to instrument malfunction, but extracted chlorophyll concentrations were low and had a range of 0.06 to 3.08 μg L^{-1} for the nearfield.

4.2.2 Farfield Comparisons

The annual mean fluorescence during the farfield surveys was 3.65 μgL^{-1}, which was lower than the annual mean for the nearfield surveys (4.41μgL^{-1}) but substantially higher than previous baseline years. For the regional areas, the 1999 mean fluorescence values were 4.40 μgL^{-1} in Boston Harbor and Cape Cod Bay, 3.06 μgL^{-1} at the boundary stations, 4.55 μgL^{-1} at the coastal stations, and 2.76 μgL^{-1} at the offshore stations. Time series plots of chlorophyll concentrations for each of the farfield areas are presented in Figure 4-25. Typical seasonal patterns in chlorophyll were observed in 1999 for the bays and Boston Harbor. In the bays, maximum area mean chlorophyll values (> 4 μgL^{-1}) were observed during the winter/spring and fall blooms. Area mean chlorophyll concentrations were lower, but remained relatively high (2-4 μgL^{-1}), over the summer. Boston Harbor concentrations increased from a low mean value (<1.0 μgL^{-1}) in early February to a maximum in June (~9 μgL^{-1}).

4.2.3 Interannual Comparisons

The major themes observed in the chlorophyll data in 1999 included the winter/spring bloom, elevated summer concentrations and the fall bloom. All of which contributed to unprecedented chlorophyll concentrations throughout Cape Cod and Massachusetts Bays. This section focuses on evaluating the major events or deviations from the 'normal' trends that were mentioned in the previous sections in comparison to the annual seasonal cycles for chlorophyll during previous baseline monitoring years (1992-1999).

The annual cycle of chlorophyll in the nearfield is presented in Figures 4-26 and 4-27 for each of the baseline monitoring years. The data are presented as survey means with error bars (standard deviations) representing the magnitude of the spatial variability in data (horizontal and vertical) during each survey. In Figures 4-26 and 4-27, the annual cycle has been divided into three 'seasons': spring (January to April), summer (May to August), and fall (September to December). Seasonal means for the chlorophyll data are provided for each of the baseline monitoring years in Table 4-1. These time periods represent common seasonal patterns in physical and biological processes that have been observed in the nearfield area.

The mean chlorophyll concentration for the nearfield for winter/spring (February through April) of 1999 was 4.91 μgL^{-1}, which is greater than any previous winter/spring mean obtained for the nearfield during the baseline monitoring period. Based on chlorophyll concentrations, large spring blooms only occurred during three of the previous seven years of baseline monitoring: 1992, 1994 and 1996. Seasonal mean chlorophyll concentrations were approximately 2 μgL^{-1} or more during each of these years (Table 4-1). The winter/spring mean chlorophyll value in 1999 was more than double that during these previous spring bloom years.

Note that even though winter/spring nearfield chlorophyll concentrations were unprecedented for the baseline monitoring program, phytoplankton abundance was not substantially different than previous years and actually rather low in comparison to previous winter/spring blooms (see Section 6.1). The reason for this may have been because the abundant taxa during the winter/spring bloom were chain forming diatoms (*Chaetoceros* spp.). Although the total abundances were not substantially higher than previous years, the larger cell size and higher chlorophyll per cell ratio for *Chaetoceros* spp. may have led to this apparent disconnect between chlorophyll concentration and total phytoplankton abundance. Davis and Gallager (2000) noticed a similar disconnect between chlorophyll concentrations and *Chaetoceros* abundance, but attributed the high chlorophyll concentrations to the presence of smaller phytoplankton that were not measured using the Video Plankton Recorder. For the HOM stations and surveys, this does not appear to be the case as total phytoplankton counts (which include smaller phytoplankton species) were not substantially elevated in comparison to previous years and were dominated by *Chaetoceros* spp. It does appear, however, that *Chaetoceros* spp. cells, which occurs in gelatinous masses or colonies, may have been underestimated by whole-water sampling techniques, as concurrent zooplankton net tow samples were full of coagulated green material that was attributed to the *Chaetoceros* bloom. The high abundance of *Chaetoceros socialis* and *Chaetoceros* chains was also noted by researchers using a video plankton recorder to quantify plankton in the bays in late February 1999 (Davis and Gallager, 2000). They noted that colonies of *C. socia*lis were abundant, but extremely patchy in Massachusetts and Cape Cod Bays. This may have also contributed to the relatively wide range in chlorophyll concentrations observed during the February to April surveys. However, as noted in Section 4.2.1, the majority of the variability during each survey was due to inshore to offshore gradients and vertical gradients in chlorophyll concentration.

Table 4-1. Seasonal chlorophyll concentrations in the nearfield ($\mu g\ L^{-1}$). Data from all surveys, stations and depths (A-E).

	Winter/Spring			Summer			Fall		
Year	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**
1992	1.93	1.52	364	1.83	1.61	595	2.45	1.77	339
1993	0.89	0.73	417	1.80	1.68	728	4.05	4.18	525
1994	1.89	1.33	525	1.53	1.13	608	2.46	1.81	525
1995	1.04	1.56	456	0.73	1.14	645	2.60	3.42	511
1996	2.44	2.24	480	0.81	0.88	532	1.41	1.95	424
1997	1.29	1.35	471	1.08	2.10	581	0.67	0.61	404
1998	0.84	0.88	348	1.92	2.75	664	2.43	3.13	442
1999	4.91	3.75	378	2.18	3.23	679	6.72	8.36	479

The 1999 nearfield mean chlorophyll concentrations decreased from April to May and remained relatively constant (2-3 μgL^{-1}) until mid-August when it increased to ~4 μgL^{-1} (Figure 4-27). Although lower than the winter/spring or fall seasonal means, the summer seasonal mean chlorophyll concentration in the nearfield (2.18 μgL^{-1}) was also the highest observed during the 1992-1999 period and continued the trend of elevated summer concentrations first observed in 1998. Variability in chlorophyll concentrations during each survey was lower during the summer than the other seasons, but was relatively high in comparison to previous baseline summers (Figures 4-26 and 4-27). This variability resulted from a strong inshore to offshore decrease in surface chlorophyll and a vertical gradient at the deeper offshore stations (subsurface chlorophyll max).

The bloom in late October 1999 was not as substantial as some previous fall blooms (i.e. 1993 and 1995). However, due to an anomalous late summer bloom, the fall mean chlorophyll concentration in 1999 was the highest of the baseline period (6.72 μgL^{-1}) exceeding even the 1993 fall mean (4.05 μgL^{-1}) that resulted from the major bloom of *Asterionellopsis glacialis*. The late summer phytoplankton bloom was observed in the nearfield and throughout most of Massachusetts Bay in August and September. Levels of phytoplankton abundance, primary production and chlorophyll did not parallel each other as clearly as observed during the winter/spring bloom. Nearfield phytoplankton abundance peaked in early August, productivity in mid-August and chlorophyll concentrations, though increasing in August, did not reach maximum levels until September.

In 1999, spatial variability was highest during the September surveys when mean chlorophyll concentrations were at a maximum. The wide range in values was due to the seemingly distinct chlorophyll layers observed during the early September survey. Southwestern nearfield stations had surface chlorophyll maxima that were >50 μgL^{-1} while in the northeast surface chlorophyll concentrations were <5 μgL^{-1} (see Figure 4-24). At the northwestern and offshore nearfield stations, chlorophyll concentrations of >30 μgL^{-1} were observed in a subsurface chlorophyll maximum. Bottom water concentrations were low (<2 μgL^{-1}) across the nearfield during this survey. The inshore/offshore gradients and vertical gradients in chlorophyll concentrations in September 1999 are typical for fall surveys. During each of the baseline monitoring years, the variability of chlorophyll data has been highest during the fall season. This is due to the spatial dynamics and intensity of the fall blooms (or as in 1999 the late summer bloom), which vary significantly over the nearfield monitoring area.

The 1999 winter/spring mean chlorophyll concentration (4.91μgL^{-1}) was also almost double the 1992-1998 threshold value for winter/spring season of 2.51 μgL^{-1} (Ellis *et al*., 2000). The 1999 fall mean chlorophyll concentration (6.72 μgL^{-1}) also exceeded the proposed seasonal chlorophyll threshold value (4.03 μgL^{-1}). The 1999 summer mean concentration (2.18 μgL^{-1}) was only slightly lower than the summer threshold value of 2.22 μgL^{-1}. The seasonal thresholds were calculated as 95th percentile of the baseline mean for seasonal mean chlorophyll concentrations for 1992 to 1998 (Ellis *et al*., 2000). The annual mean chlorophyll concentration for the nearfield in 1999 exceeded the proposed warning level threshold of 3.45 μgL^{-1} that was set at two times the annual mean for 1992 to 1998. If the Massachusetts Bay outfall had gone on line prior to 1999 as planned, these extremely high chlorophyll values may have been attributed to the outfall. Instead, the 1999 data will be used to reevaluate the range of variability in nearfield chlorophyll concentrations and to recalculate the chlorophyll threshold values. Although clearly not related to the future outfall, the elevated nearfield chlorophyll concentrations that were first observed in the fall of 1998 and continued through 1999 may be associated with the increases in NH_4 concentrations in, and exported from, Boston Harbor (see Section 4.1.3). The harbor and nearfield interactions related to increased discharge and ambient concentrations of NH_4 and the connection with increased chlorophyll concentrations in the harbor and nearfield should be examined in detail in the 1999 Nutrient Issues Review.

The annual average chlorophyll concentrations for each of the six areas are presented in Table 4-2. These values were calculated using all of the data collected during each of the surveys including all stations and each sampling depth. In 1999, as seen in the nearfield, the annual mean chlorophyll concentrations were the highest observed over the baseline period from 1992 to 1999.

To examine the interannual variability on a regional and temporal basis, chlorophyll data from each geographical area are presented in Figure 4-28. The trends in chlorophyll concentrations in the harbor have been the same year to year with an increase through the summer and generally low concentrations in the spring and fall. The Boston Harbor survey mean chlorophyll concentration was ~ 9 μgL^{-1} in June 1999, which was the highest observed in the harbor from 1992-1999. The temporal cycle of chlorophyll at the coastal stations is often similar to the harbor, but this was not the case in 1999. The coastal area has exhibited a mixture of harbor and offshore trends over the baseline period. In 1992, 1995, 1997 and 1998, the coastal chlorophyll cycle mimicked that seen in the harbor. During the other years, a bay trend of elevated spring and/or fall concentrations was observed (Figure 4-28a).

In the nearfield, chlorophyll concentrations in 1999 were among the highest observed from 1992-1999. The survey mean chlorophyll concentration during the September bloom in 1999 (~12 μgL^{-1}) was higher than any previous value for the nearfield and second only to the survey mean value for the coastal stations during the October 1993 bloom. The offshore and boundary stations tended to display annual cycles that were similar to the nearfield (Figure 4-28b). In Cape Cod Bay, the winter/spring bloom was usually the dominant annual chlorophyll event though a major winter/spring bloom was not observed during every baseline monitoring year. In 1993 and 1999, the fall bloom had the highest mean chlorophyll concentrations in Cape Cod Bay.

For all six areas, the data in Figure 4-28 suggest that there was an increase in chlorophyll concentrations from 1997 to 1999. This is more apparent in Figure 4-29 that presents the annual mean chlorophyll concentrations for each of the areas (data also in Table 4-2). Unlike the nutrient annual mean trends, there is no significant trend in annual mean chlorophyll over the baseline period from 1992 to 1999. There is, however, a very striking shift to increasing chlorophyll after 1997. The factors controlling this increase in annual mean chlorophyll concentrations are likely related to the previously described regional and local factors affecting nutrient concentrations. One potential effect of the increase in chlorophyll (as an indicator of biomass) from 1997 to 1999 is that there may have been an increase in the flux of organic material to bottom waters, which contributed to the low DO concentrations in 1998 and 1999 (see Section 4.3).

Table 4-2. Comparison of annual mean chlorophyll concentrations in Massachusetts and Cape Cod Bays. Data from all surveys, stations and depths (A-E).

	Annual Mean (μgL^{-1})					
Year	**Nearfield**	**Boston Harbor**	**Boundary**	**Cape Cod Bay**	**Coastal**	**Offshore**
1992	2.02	3.83	1.64	3.24	2.91	2.05
1993	2.27	3.37	1.44	3.42	3.76	2.09
1994	1.93	2.31	2.09	3.58	2.57	1.87
1995	1.37	2.09	0.82	1.89	1.54	0.76
1996	1.45	2.71	1.32	2.85	2.09	1.40
1997	1.02	1.41	0.85	1.34	1.06	0.78
1998	2.04	3.03	2.66	2.65	3.12	1.69
1999	4.41	4.40	3.06	4.40	4.55	2.74

4.3 Dissolved Oxygen

This section provides an overview of the trends and distribution of dissolved oxygen (DO) in the bottom waters of Massachusetts and Cape Cod Bays in 1999 and an interannual comparison with the 1992-1998 baseline monitoring data set. The data that are reported represent *in situ* sensor data collected during sampling events at the five sampling depths (A-E). The *in situ* measurements were calibrated against DO concentration determined by a standard Winkler titration method at a subset of stations on each survey (Albro *et al*., 1998). The DO data are presented as mean survey values across areas and as individual values at representative stations. The farfield data are grouped by geographic region (see Figure 2-2) as in previous reports to examine regional variability in nutrient distribution. DO data collected from stations in Stellwagen Basin (F12, F17, F19, and F22) have been grouped to evaluate DO trends in these deep waters. A detailed presentation of the data was provided in the two semi-annual reports for 1999 (Libby *et al*. 1999a and 2000). Spatial and temporal trends in the concentration of dissolved oxygen (DO) are evaluated for the nearfield area (Section 4.3.1) and for the entire region (Section 4.3.2).

In 1999, the minimum bottom water DO concentration was 5.15 mgL^{-1} in the nearfield at station N11 in early September. Regionally, a DO concentration minimum of 5.58 mgL^{-1} was observed at offshore station F15 (south of the nearfield) in October. The DO minimum in the nearfield occurred relatively early in the fall and along the shallow, inshore side of the nearfield. The annual minimum usually occurs later in the fall and at the deeper offshore nearfield stations. The early DO minimum may have resulted from a combination of relatively low bottom water DO concentrations earlier in the summer and the large amount of organic material produced in the western nearfield during the late summer bloom.

The lowest 1999 nearfield survey mean bottom water DO (5.93 mgL^{-1}) also occurred in early September. The 1999 minimum was the lowest observed during the baseline monitoring program (1992-1999) and was lower than the proposed warning threshold of 6.0 mgL^{-1}. Due to the early occurrence of such low DO concentrations, there was added concern about the levels that would be found in October when minima usually are observed in the nearfield area. Mixing events in September (Hurricane Floyd – September 17th – 19th) prevented DO levels from continuing to decline into late September and October.

4.3.1 Nearfield Trends

In 1999, the winter/spring bloom led to increased respiration (see Section 5.2) and relatively low bottom water DO concentrations during the setup of stratified conditions in early summer. Stratification persisted into late October in the nearfield and survey mean DO concentrations decreased from February to October in the nearfield bottom waters. The low initial bottom water DO concentrations observed at ‘setup’ in June (nearfield mean = 9.1 mgL^{-1}) contributed to extremely low survey mean values observed in early September and late October 1999.

Dissolved oxygen concentrations for surface, mid-depth and bottom waters at the nearfield stations are plotted for each of the nearfield surveys in Figure 4-30. This figure presents the average and range of values for each of the depths. From February to April, the average DO concentrations for the nearfield area were high and ranged from 10.5-12 mgL^{-1}. A maximum average DO concentration of >13 mgL^{-1} was observed in the surface waters in April and was coincident with elevated chlorophyll concentrations and high primary production. Following the April survey, DO concentrations decreased over the entire water column reaching average concentrations in May of 9.5 – 11 mgL^{-1}. The lower DO concentrations observed in May were coincident with annual maxima in respiration rates. Elevated respiration rates likely continued through May and into June, as mean DO concentration decreased by 2 mgL^{-1} in the surface waters by the mid-June survey. Mean surface DO concentration was lower than the mean bottom water concentration in June and was likely due to warmer water temperatures and higher respiration rates in the surface waters during this survey. Production at the subsurface chlorophyll maximum resulted in higher DO concentrations at mid-depth than at the surface during June and July.

Following the June survey, the gradient in DO concentration between the surface and bottom waters increased from 0.5 mgL^{-1} in July to 2.5 mgL^{-1} in early September (Figure 4-30). Surface water DO concentrations decreased from a summer maxima of >9 mgL^{-1} in early August to minima of ~8.3 mgL^{-1} in September and October. Decreasing temperatures resulted in increased surface DO concentrations (9 mgL^{-1}) in November and December. Nearfield mean bottom water DO concentrations reached a minimum value of 5.93 mgL^{-1} in early September. This mean value was driven by concentrations of 5-5.5 mgL^{-1} along the western nearfield. The bottom water DO minimum usually occurs later in the fall and at the deeper offshore nearfield stations. The low DO concentrations may have occurred at these inshore stations due to a combination of relatively low bottom water DO earlier in the summer and the large amount of organic material produced during the late summer bloom.

By late September, mean bottom water DO concentration had increased to 6.5 mgL^{-1} in the nearfield. The increase was likely due to increased mixing caused by storm events in September (Hurricane Floyd). DO concentrations continued to increase into October when the mean nearfield bottom water concentration approached 7 mgL^{-1}. By late October, however, bottom water DO concentrations had again decreased to ~6 mgL^{-1} due to an increase in bottom water respiration rates. Bottom water DO concentrations continued to be low in the nearfield into late November. The water column was well mixed by December and DO concentrations were relatively uniform over all depths.

4.3.2 Farfield Comparisons

The DO of bottom waters was compared between areas over the course of the six combined surveys. A time series of the average bottom water DO concentration for each area is presented in Figure 4-31a. In 1999, average bottom water DO concentrations in the farfield ranged from 6 to 12 mgL^{-1}. As observed in the nearfield area, DO concentrations were high (10-12 mgL^{-1}) in the farfield bottom waters from February through April. Lower concentrations were consistently observed at the deeper boundary and offshore areas during this period. Between the April and June surveys, there was a sharp decline in bottom water DO throughout the Bays. In Boston Harbor and Cape Cod Bay, bottom water DO concentrations declined by more than 3 mgL^{-1}. Declines of 1.5-2 mgL^{-1} were found in the other areas. The trend of declining bottom water DO concentrations following the establishment of stratification and the cessation of the winter-spring bloom is typical for the bays. Area mean DO concentration reached minimum values (~7.2 mgL^{-1}) in the coastal and Cape Cod Bay areas by the August survey and remained relatively unchanged by October. At offshore and boundary stations, mean DO concentration was comparable to the coastal and Cape Cod Bay values in August, but continued to decrease reaching minima in October (approximately 6.8 mgL^{-1} at the boundary stations and 6.2 mgL^{-1} at the offshore stations). In Boston Harbor, mean bottom water DO concentrations of 7.5 mgL^{-1} were observed during both August and October.

The DO pattern in Stellwagen Basin (stations F12, F17, F19, and F22) was similar to that observed at the boundary, offshore and nearfield areas of Massachusetts Bay (Figure 4-31b). There was, however, a larger gradient between surface and bottom water DO concentrations in February and April at the deeper Stellwagen Basin stations than for the nearfield. The range in values observed in the nearfield during these surveys may be indicative of a similar gradient of ~2 mgL^{-1} existing at the deeper nearfield stations (Figure 4-30). Mean bottom water concentrations declined from 10 mgL^{-1} in April to ~6.2 mgL^{-1} in November at the Stellwagen Basin stations.

4.3.3 Interannual Comparisons

The DO cycle in the nearfield for each of the baseline monitoring years is presented in Figure 4-32. In 1999, as during most years (except 1998), the DO cycle follows a repetitive pattern of higher concentrations in late winter/early spring, decreasing concentrations through the summer to the fall and then increasing concentrations following the overturn of the water column in the fall.

The 1999 winter/spring DO concentrations fell in the middle of the range for February through April seen during previous years. Mean bottom water DO concentrations declined from an annual maximum of 11.4 mgL^{-1} in February to an annual minimum of 5.9 mgL^{-1} in early September. Only during 1994 have nearfield bottom waters decreased 5.5 mgL^{-1} over the annual cycle (Figure 4-32). The decline in bottom water DO was driven by the input of organic material from the winter/spring bloom and the late summer bloom. The unprecedented chlorophyll concentrations imply that there was a substantial amount of organic material produced in the nearfield in 1999. The flux of this organic material into the bottom waters resulted in the exceptionally low DO concentrations during the fall of 1999.

In 1999, the minimum bottom water DO concentration was 5.15 mgL^{-1}, which was measured at station N11 during the early September nearfield survey. The 1999 minimum value was comparable to the 1994 minimum (5.19 mgL^{-1}), but not as low as the December 1998 minimum concentration of 4.54 mgL^{-1}. In December 1998, a deep halocline was still present at the deeper eastern nearfield stations where this DO concentration was measured. The strength and duration of stratification are important factors in the decline of bottom water dissolved oxygen concentrations. Although mixing events in September prevented DO levels from continuing to decline into late September and October, the 1999 survey mean DO minimum was the lowest observed during the baseline monitoring program (1992-1999). The mean bottom water DO concentration for the nearfield in early September (5.93 mgL^{-1}) was lower than the proposed warning threshold of 6.0 mgL^{-1} and approached that level (6.02 mgL^{-1}) again in late October.

The annual cycle observed in Stellwagen basin is usually similar to that seen for the nearfield area: high concentrations in late winter/early spring, a decrease in concentrations through the summer and into the fall, and an increase in concentrations increase after October (Figure 4-33). The 1999 data followed this trend, but no measurements were made in Stellwagen Basin after October to verify the return to winter conditions. The survey mean minimum concentration of 6.26 mgL^{-1} and the minimum concentration of 5.96 mgL^{-1} were the lowest values for Stellwagen Basin over the 1992-1999 baseline period.

The rate of DO decline in the nearfield from June to October has been relatively uniform over the baseline period from a low of –0.019 $mgL^{-1}d^{-1}$ in 1997 to a high of –0.031 $mgL^{-1}d^{-1}$ in 1992 (Figure 4-34). The rate of DO decline in 1999 was in the middle of this range (-0.025 $mgL^{-1}d^{-1}$), but the rate of decline was lower due to an increase in mean DO from early September to October. The rate of decline was substantially higher (–0.036 $mgL^{-1}d^{-1}$) from June to early September 1999. The 1999 rate of DO decline in Stellwagen Basin (–0.021 $mgL^{-1}d^{-1}$) was comparable to the nearfield rate and was in the middle of the range observed during the baseline monitoring period (Figure 4-35). The rates ranged from a low of –0.012 $mgL^{-1}d^{-1}$ in 1997 to a high of –0.030 $mgL^{-1}d^{-1}$ in 1998.

During the baseline monitoring period, the rate of DO decline was consistently lower in Stellwagen Basin in comparison to the nearfield area (average of –0.020 $mgL^{-1}d^{-1}$ vs. –0.025 $mgL^{-1}d^{-1}$) and the annual DO minimum was consistently higher (Figure 4-36). In 1999, the relationship held true to form as the lowest mean DO concentration for the baseline period was observed for both areas. The consistency of this relationship indicates that the bottom water DO characteristics in the two areas are controlled by the same mechanisms.

The low initial bottom water DO concentrations observed at ‘setup’ in June (9.1 mgL^{-1}) and the additional flux of organic material to bottom waters following the late summer bloom contributed to the rapid decline and extremely low survey mean values observed in early September 1999. Another factor that gave rise to the low 1999 bottom water DO concentrations was the lack of any re-aeration events from February to early September. During previous baseline years, an increase in bottom water DO concentrations occurred in July or August due to a re-aeration event. The steady declines in 1994 and 1999 were not punctuated by any of these events.

In Section 3.5, the relationship between high salinity and low DO concentrations was discussed and linked to a relationship between Merrimack River flow and nearfield bottom water salinity. In years with higher river flow (January to September average), nearfield bottom waters had a lower salinity in the fall (September and October) and higher DO concentrations. In 1994 and 1999, Merrimack River flow was relatively low, bottom water salinity was high and the lowest bottom water DO concentrations were observed. The mechanism that relates the trends in these parameters is only speculative at this time, but may be related to the residence time of water in the coastal zone or diffusion/mixing of DO (and lower salinity water) into nearfield bottom waters during substantial storm events. The residence time mechanism may influence bottom water DO concentrations by increasing (longer residence time) or decreasing (shorter) the depletion of DO due to local respiration of organic material. Storm events could directly affect bottom water DO by increased vertical mixing or indirectly by increasing Merrimack River flow and intensifying the freshet plume. Another indirect affect may be due to changes in primary production and phytoplankton abundances caused by these physical mechanisms. Once again, the connections between these physical mechanisms and biological processes is speculative at this point and will require further data analysis and modeling to clarify the underlying relationships.

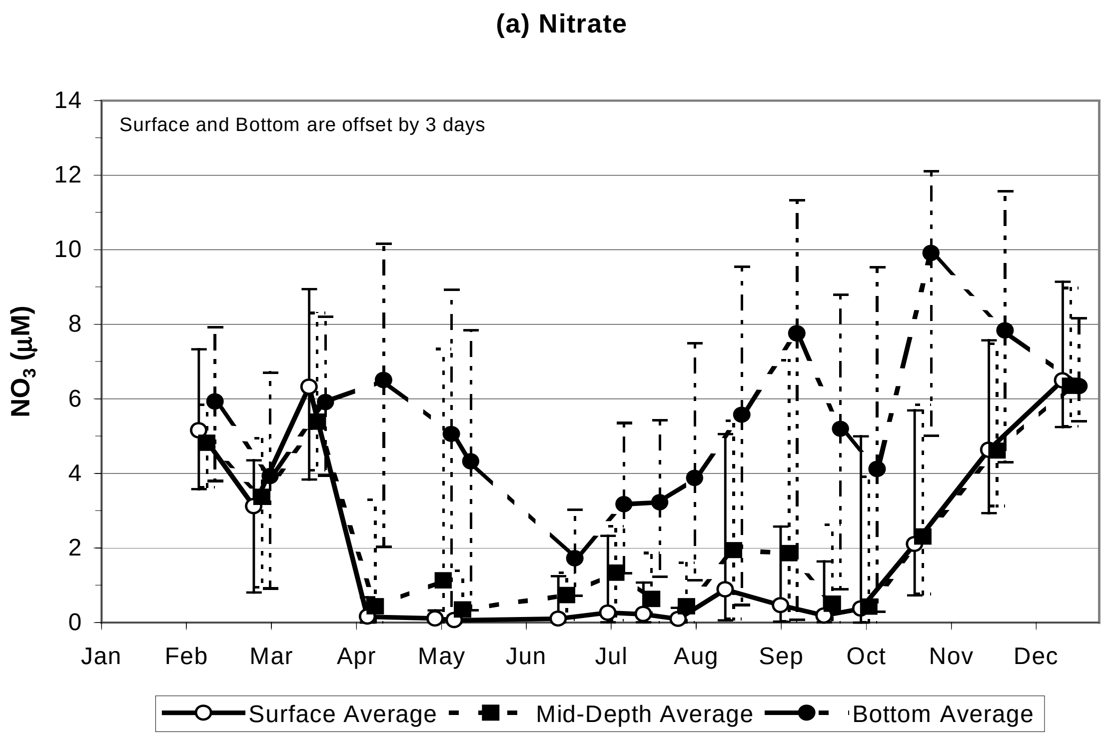
4.4 Summary of 1999 Water Quality Events

In general, the 1999 trends in nutrient, chlorophyll and dissolved oxygen concentrations were typical for the nearfield area in comparison to previous baseline monitoring years. The 1999 maximum or minimum values for many of these parameters, however, were the highest or lowest for the 1992 to 1999 period. A review of annual mean nutrient concentrations showed a trend of increasing nutrients across Cape Cod and Massachusetts Bay from 1992 to 1999. In Boston Harbor, for instance, there has been a 5 μM increase in NH_4 over the baseline period (primarily due to increased discharge of NH_4 from the Deer Island Facility). The increase in NH_4 concentrations was coincident with an increase in annual mean chlorophyll at the Boston Harbor stations.

Nearfield chlorophyll concentrations exceeded proposed winter/spring (4.76 μgL^{-1}) and annual (3.45 μgL^{-1}) threshold values. Annual mean chlorophyll concentrations in each of the six areas of the bays (see Figure 2-2) achieved baseline maxima in 1999. No significant trend in annual mean chlorophyll over the baseline period was found, but there was a very strong tendency of increasing chlorophyll from 1997 to 1999. The factors controlling this increase in annual mean chlorophyll concentrations are likely related to the regional and local factors affecting nutrient concentrations. One potential effect of the increase in chlorophyll (as an indicator of biomass) from 1997 to 1999 is that there may have been an increase in the flux of organic material to bottom waters, which contributed to the low DO concentrations in 1998 and 1999.

The 1999 nearfield survey mean bottom water DO minimum (5.93 mgL^{-1}) was the lowest observed during for the baseline monitoring program and it was lower than the proposed warning threshold of 6.0 mgL^{-1}. A baseline minimum was also measured in Stellwagen Basin with a survey mean DO minimum concentration of 6.26 mgL^{-1}. The low initial bottom water DO concentrations observed at 'setup' in June (9.1 mgL^{-1}), the additional flux of organic material to bottom waters following the late summer bloom and the lack of re-aeration events contributed to the rapid decline and extremely low survey mean values observed in 1999. Physical mechanisms related to the residence time of water in the coastal zone or diffusion/mixing of DO (and lower salinity water) into nearfield bottom waters during substantial storm events may also play an important direct or indirect role in controlling bottom water DO concentrations in Massachusetts Bay.

If the outfall had gone on line prior to 1999, the high chlorophyll values and low DO concentrations may have been attributed to the outfall. On the other hand, the low values may never have occurred as the discharge would have been offshore and may not have affected chlorophyll and DO in the nearfield as significantly as the harbor discharge. The 1999 data will be used to reevaluate the range of variability in nearfield chlorophyll and DO concentrations. Chlorophyll threshold values will be recalculated based on all baseline data and new DO threshold values could be adopted if necessary and scientifically acceptable (e.g. EPA value of 4.8 mgL^{-1} proposed for mid-Atlantic waters from Cape Cod to Cape Hatteras, EPA 1999).



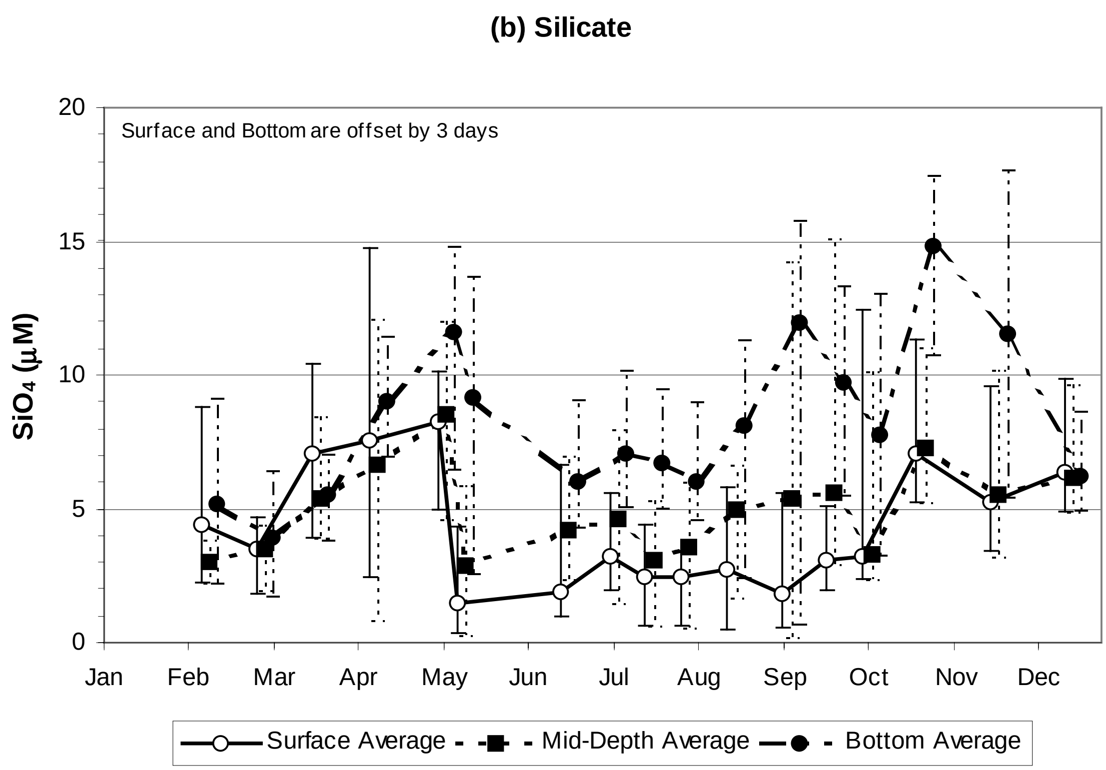
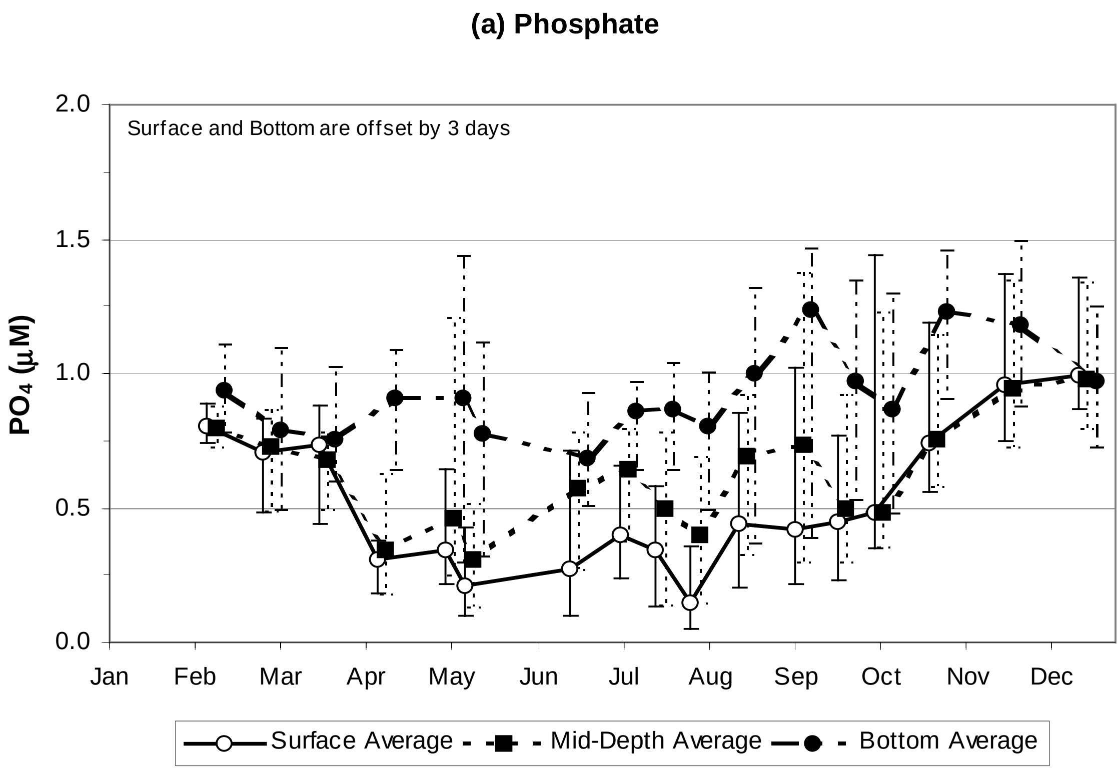


Figure 4-1. 1999 nearfield nutrient cycles for (a) NO_3 and (b) SiO_4. Survey average and range for surface, mid-depth and bottom samples collected during each nearfield survey. Surface and bottom data offset for clarity.



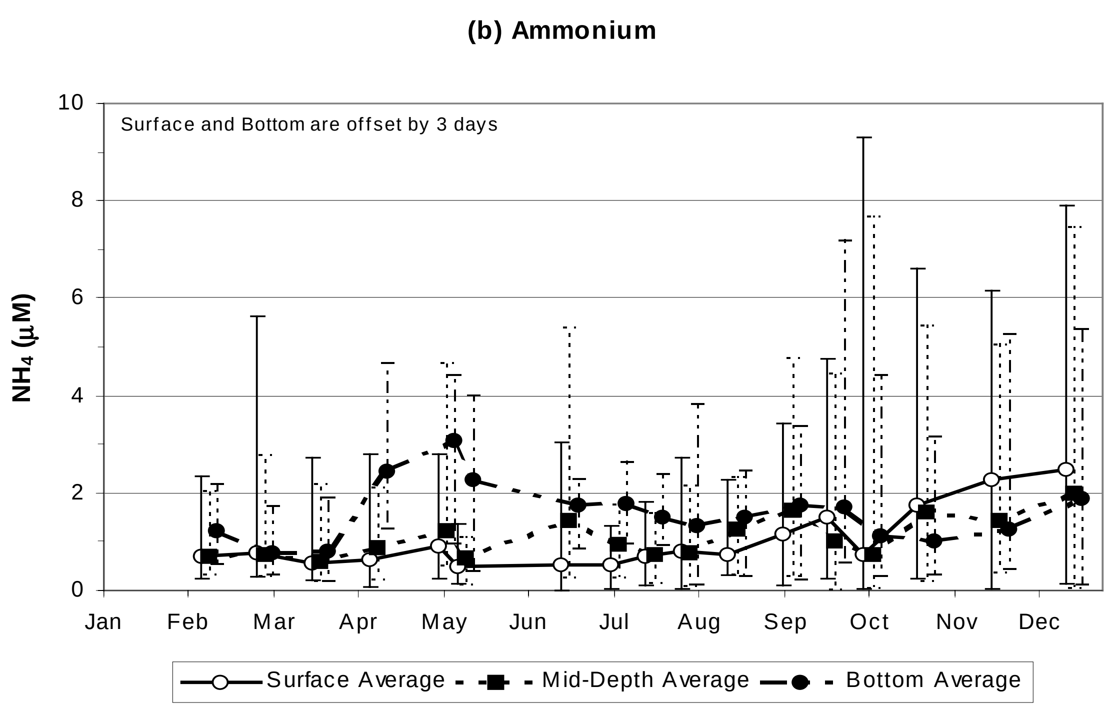


Figure 4-2. 1999 nearfield nutrient cycles for (a) PO_4 and (b) NH_4. Survey average and range for surface, mid-depth and bottom samples collected during each nearfield survey. Surface and bottom data offset for clarity.

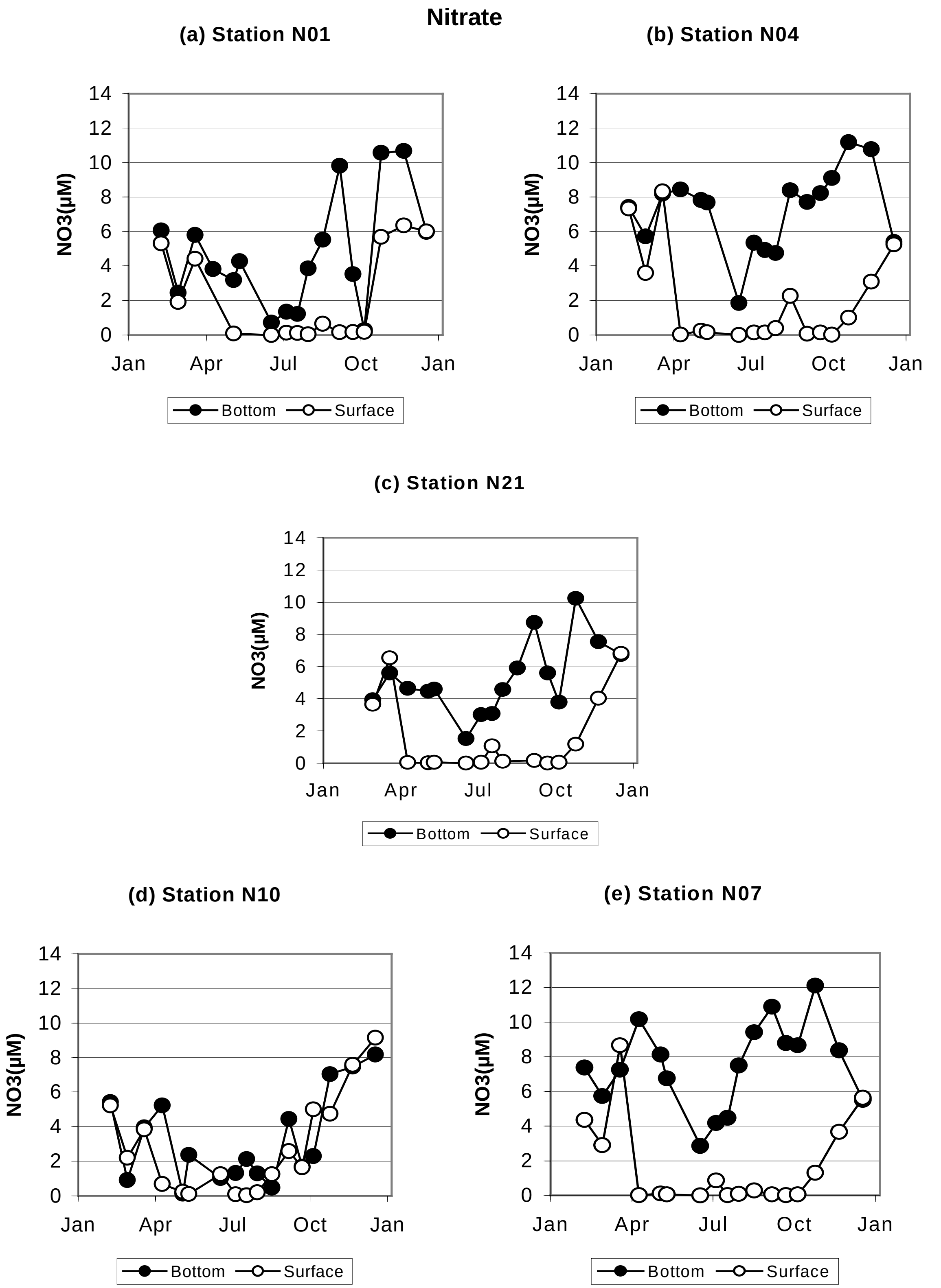


Figure 4-3. Time-series of surface and bottom water NO_3 concentrations for five representative nearfield stations.

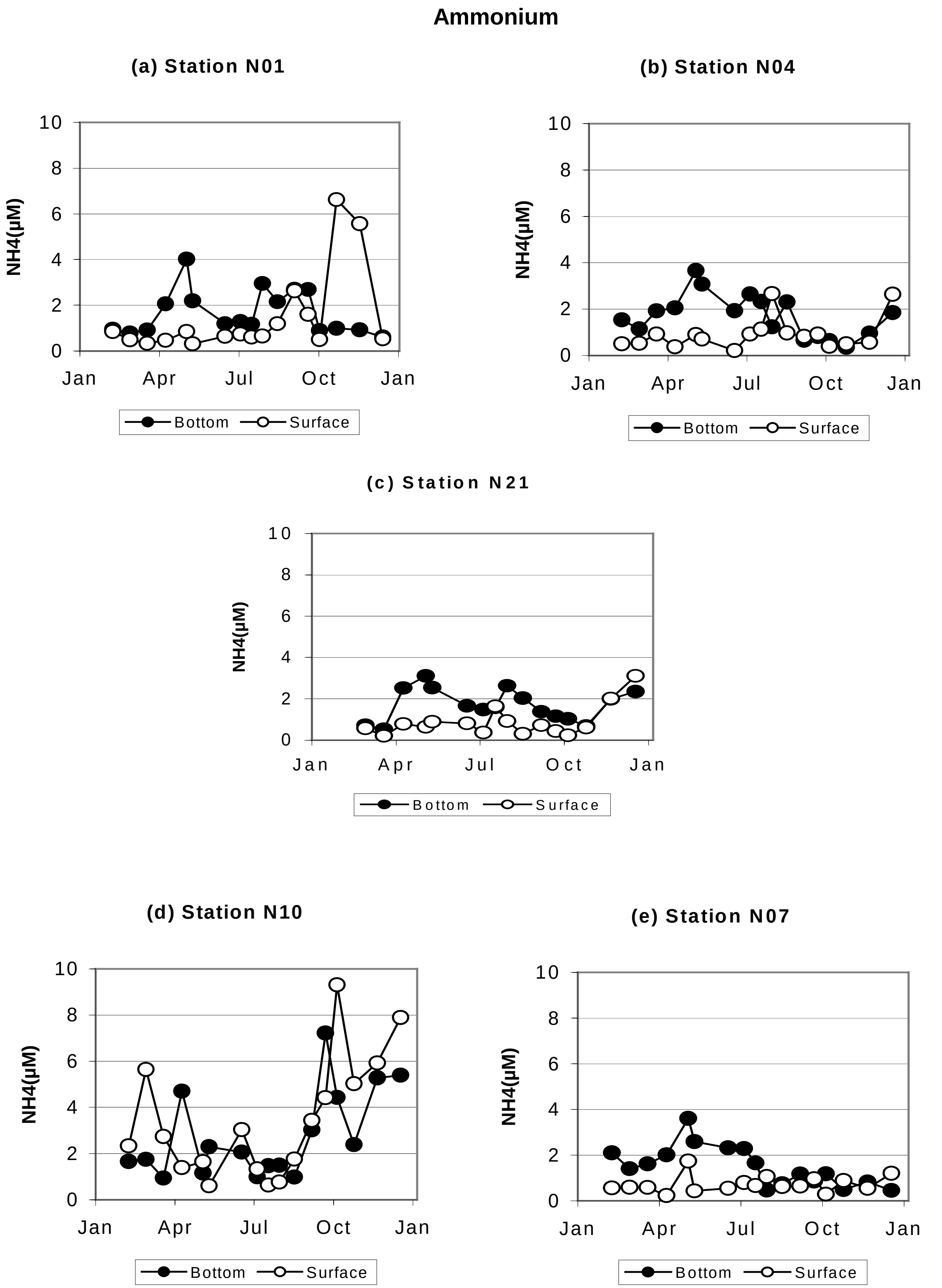


Figure 4-4. Time series of surface and bottom water NH_4 concentrations for five representative nearfield stations.

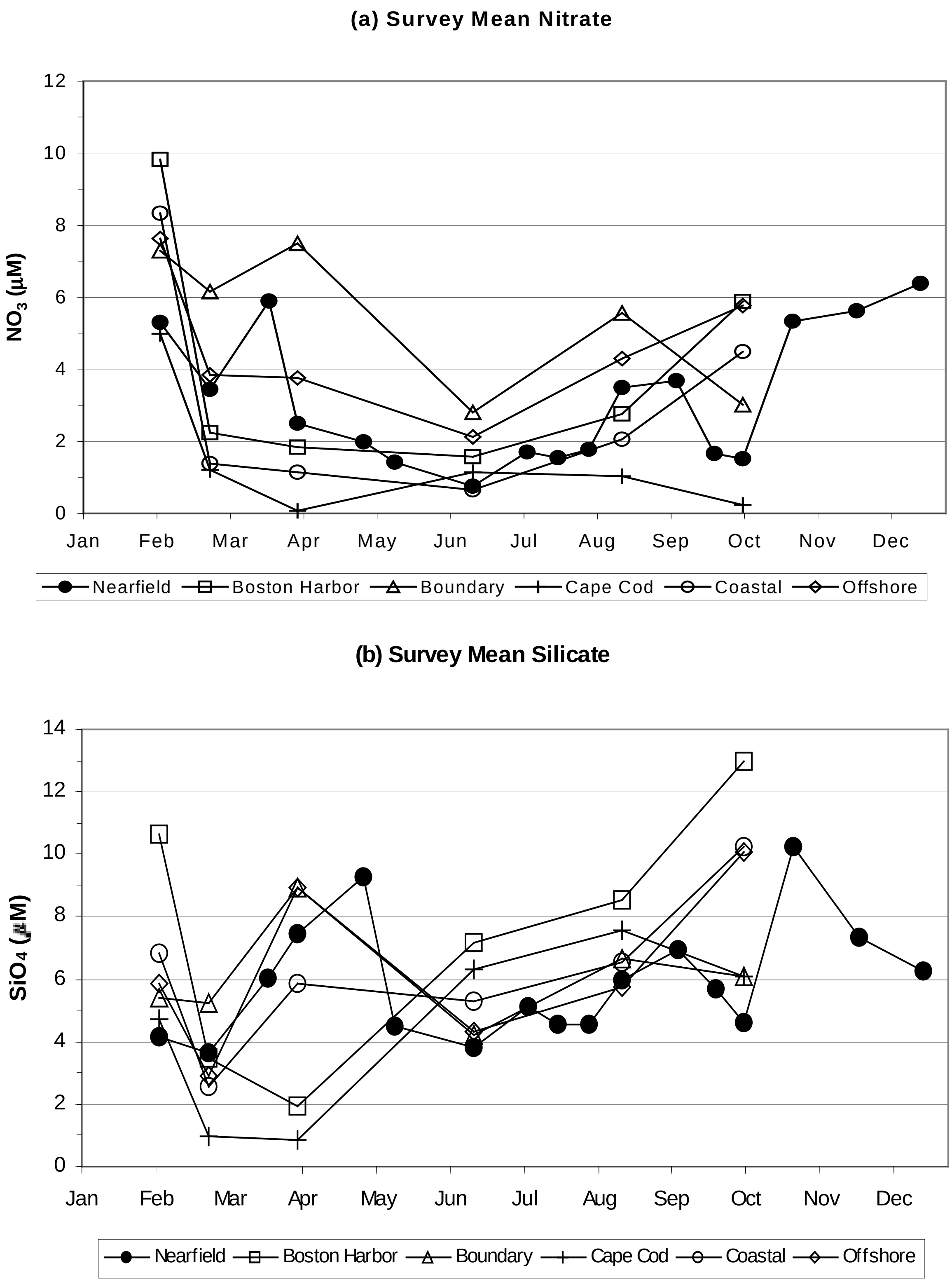


Figure 4-5. Time-series of survey mean (a) NO_3 and (b) SiO_4 concentration in Massachusetts and Cape Cod Bays. Data collected from all depths and all stations in the six areas.

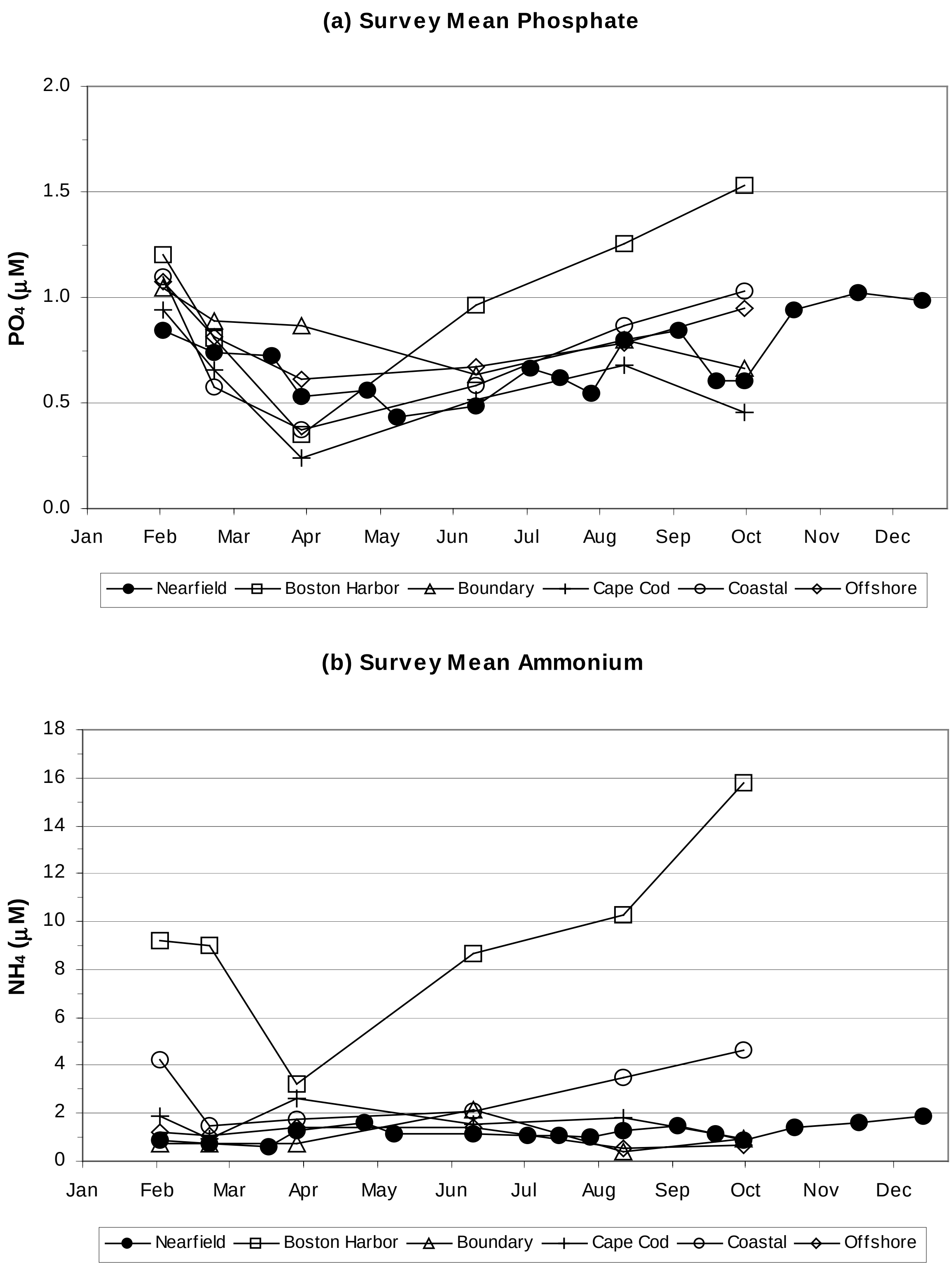


Figure 4-6. Time-series of survey mean (a) PO_4 and (b) NH_4 concentration in Massachusetts and Cape Cod Bays. Data collected from all depths and all stations in the six areas.

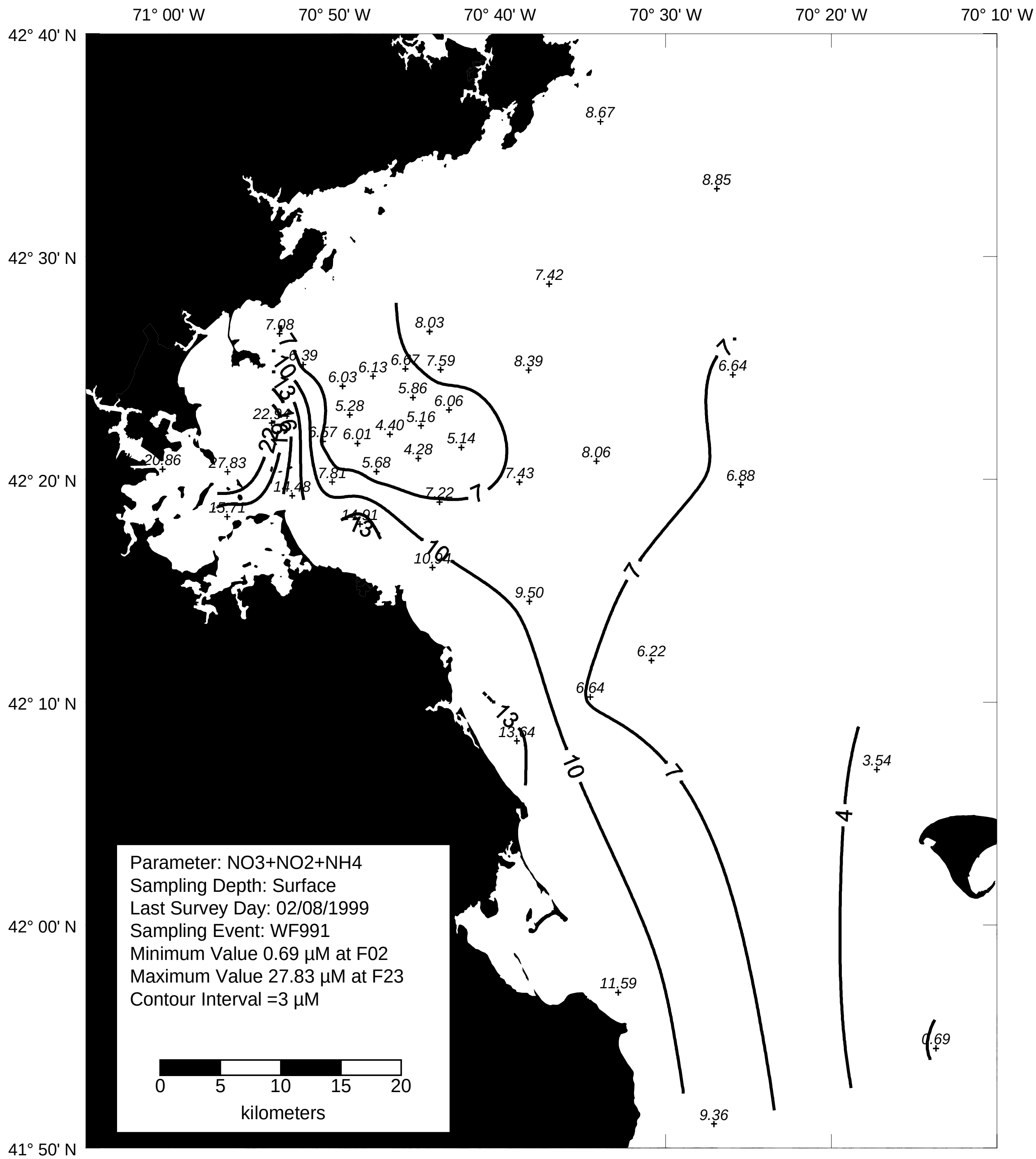


Figure 4-7. Surface contour of DIN for farfield survey WF991 (February 1999).

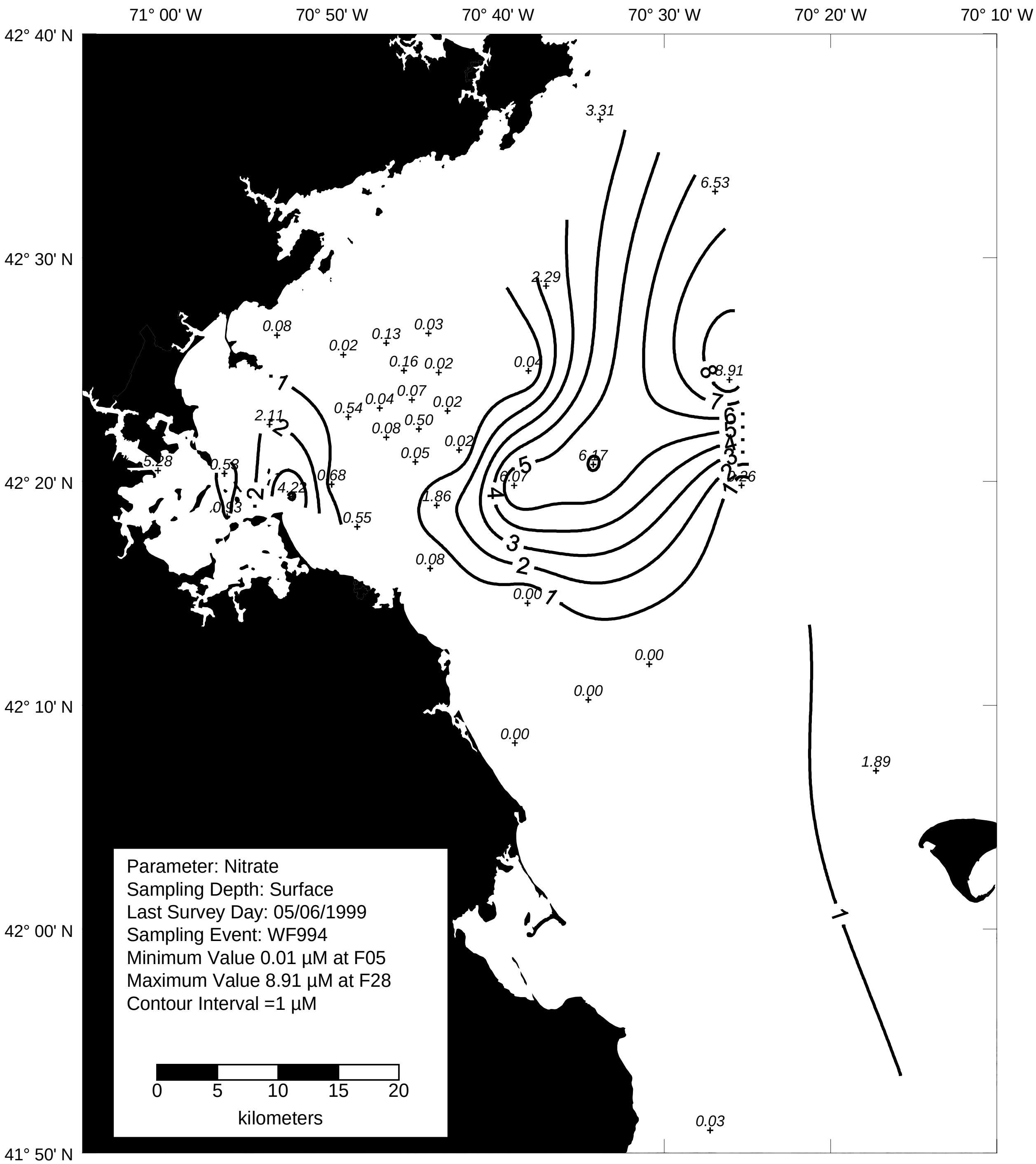


Figure 4-8. Surface contour of NO_3 for farfield survey WF994 (April 1999).

Note: All data from the Cape Cod Bay, boundary, nearfield and harbor areas were collected between April 1st and April 11th (see Figure 2-2). Southern coastal and offshore stations (N16F, F05, F06, F07, F10, F13, F14 and F19) were sampled on April 26th and May 6th.

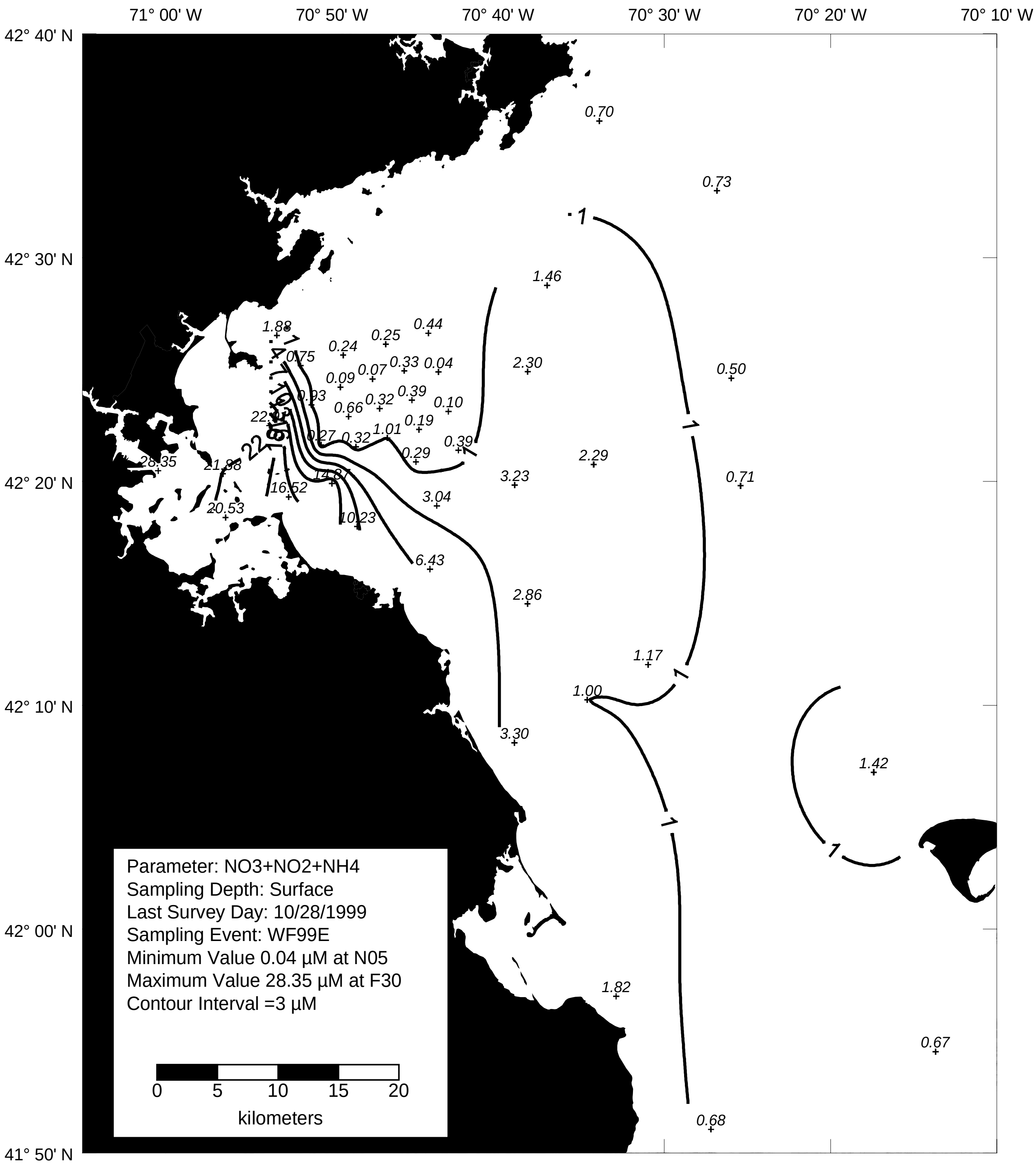


Figure 4-9. Surface contour plot of DIN for farfield survey WF99E (October 1999).

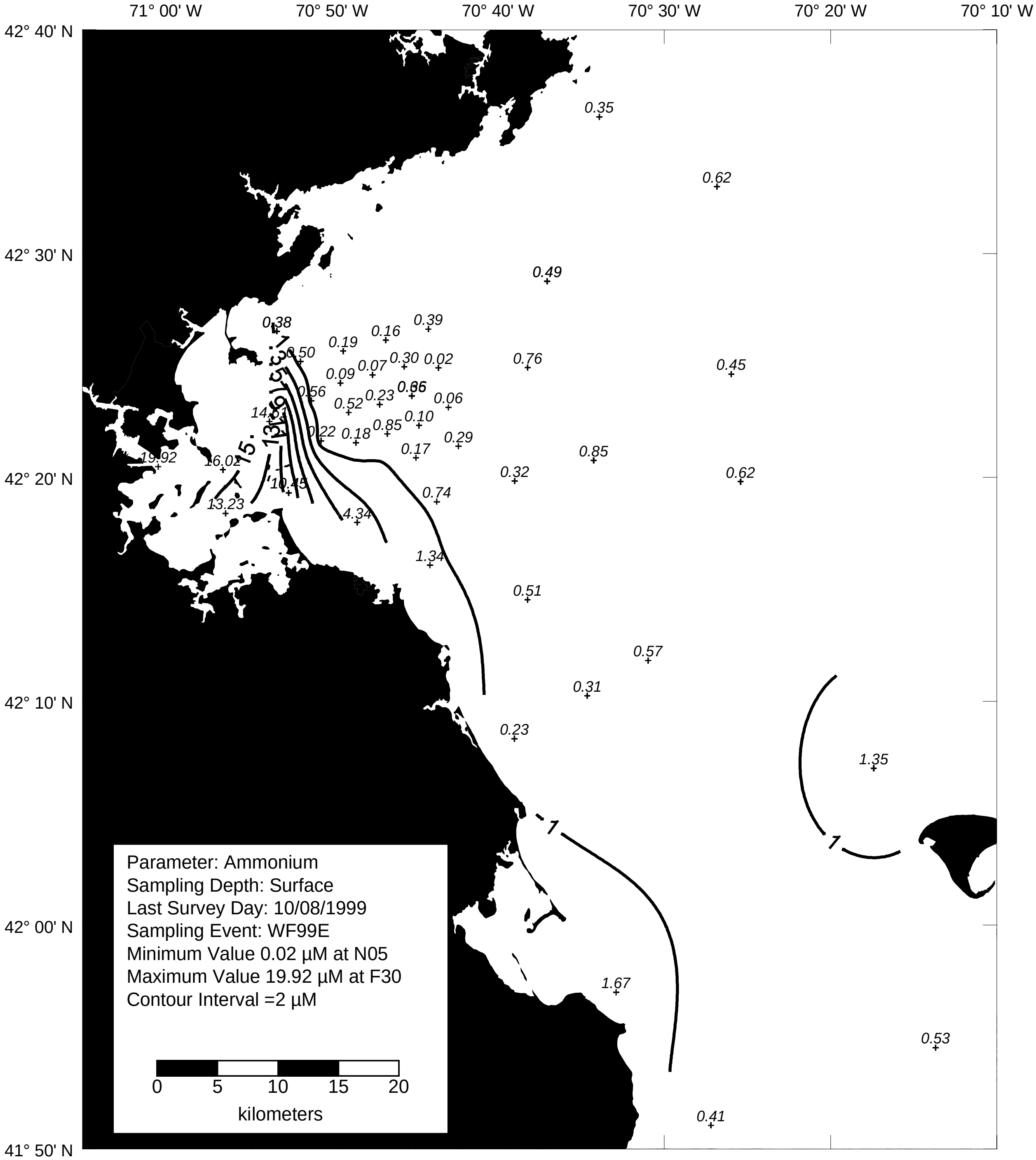


Figure 4-10. Surface contour of NH_4 for farfield survey WF99E (October 1999).

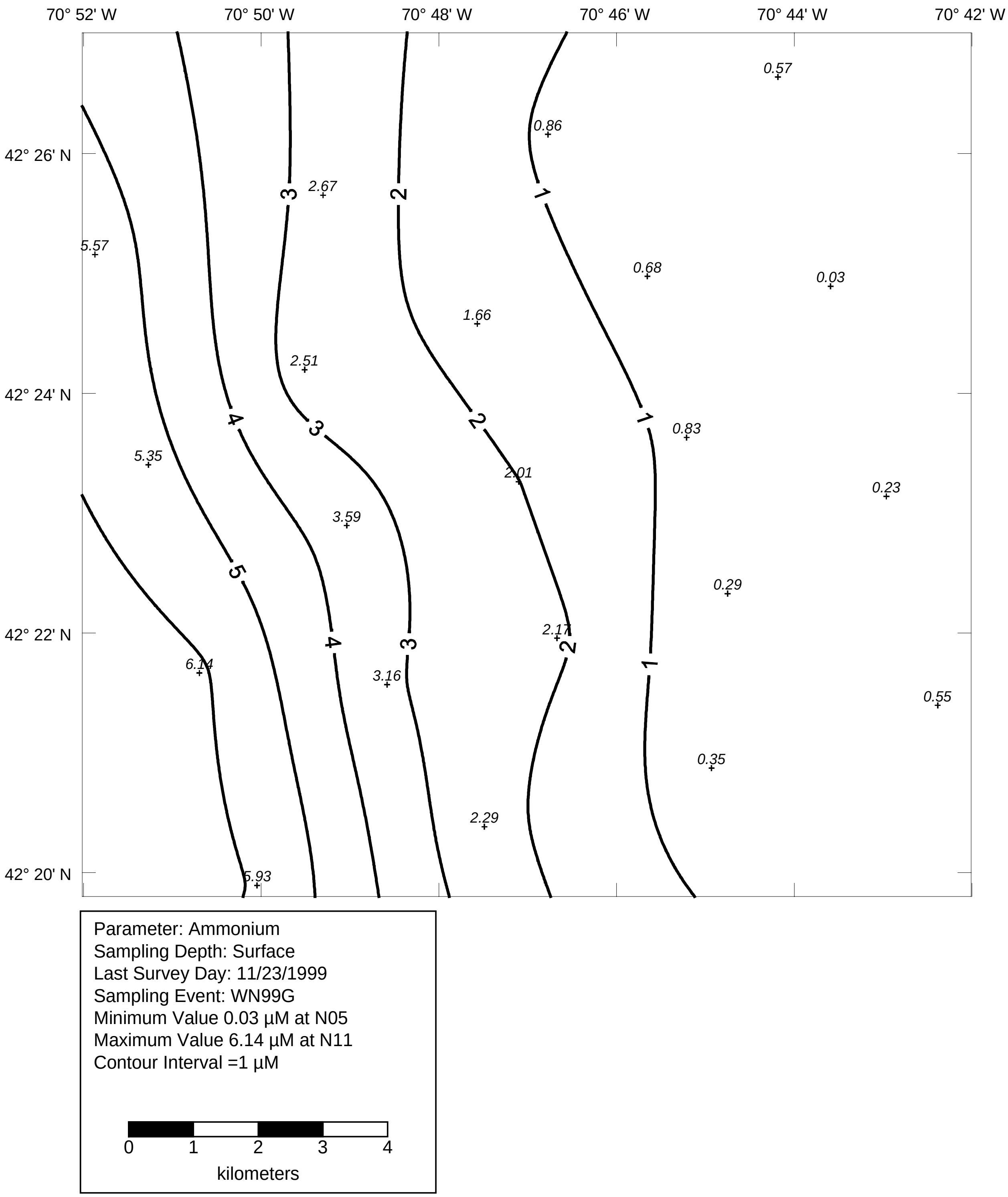


Figure 4-11. Surface contour of NH_4 for nearfield survey WN99G (November 1999).

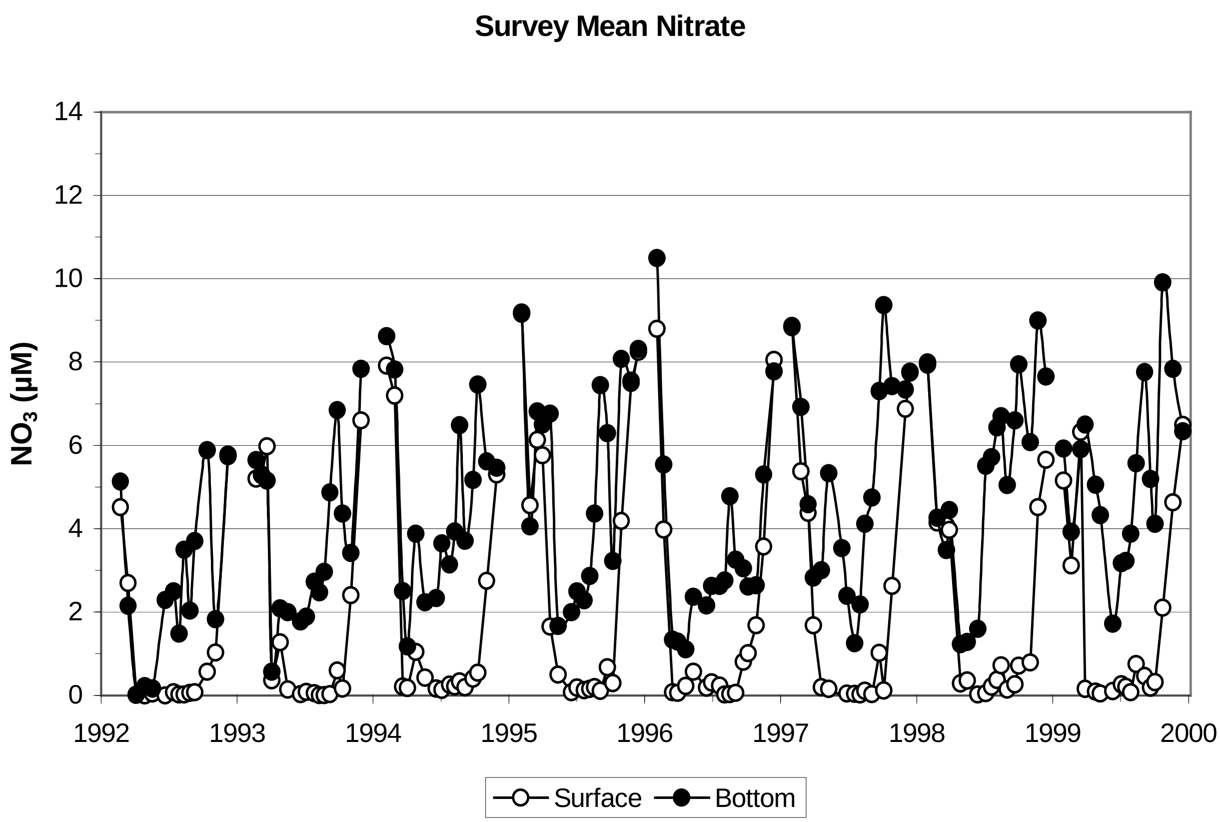
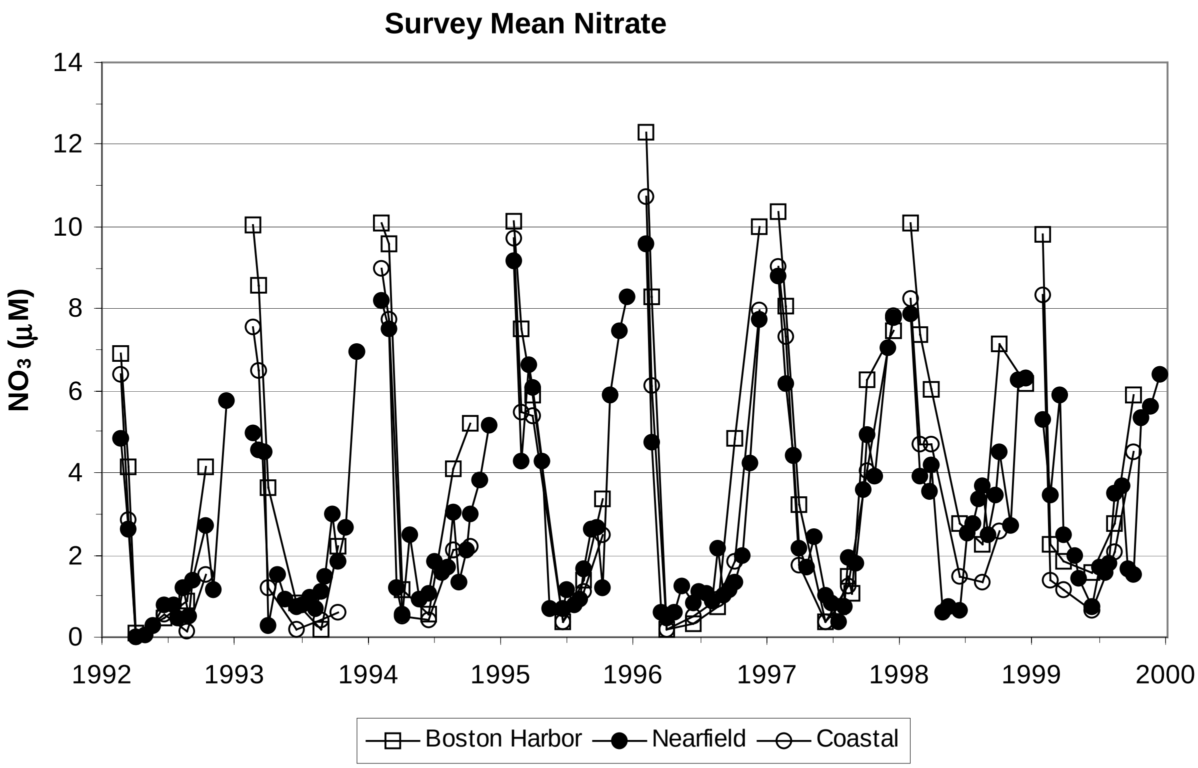


Figure 4-12. Interannual NO_3 cycle in the nearfield. Survey surface and bottom depth means at all nearfield stations.



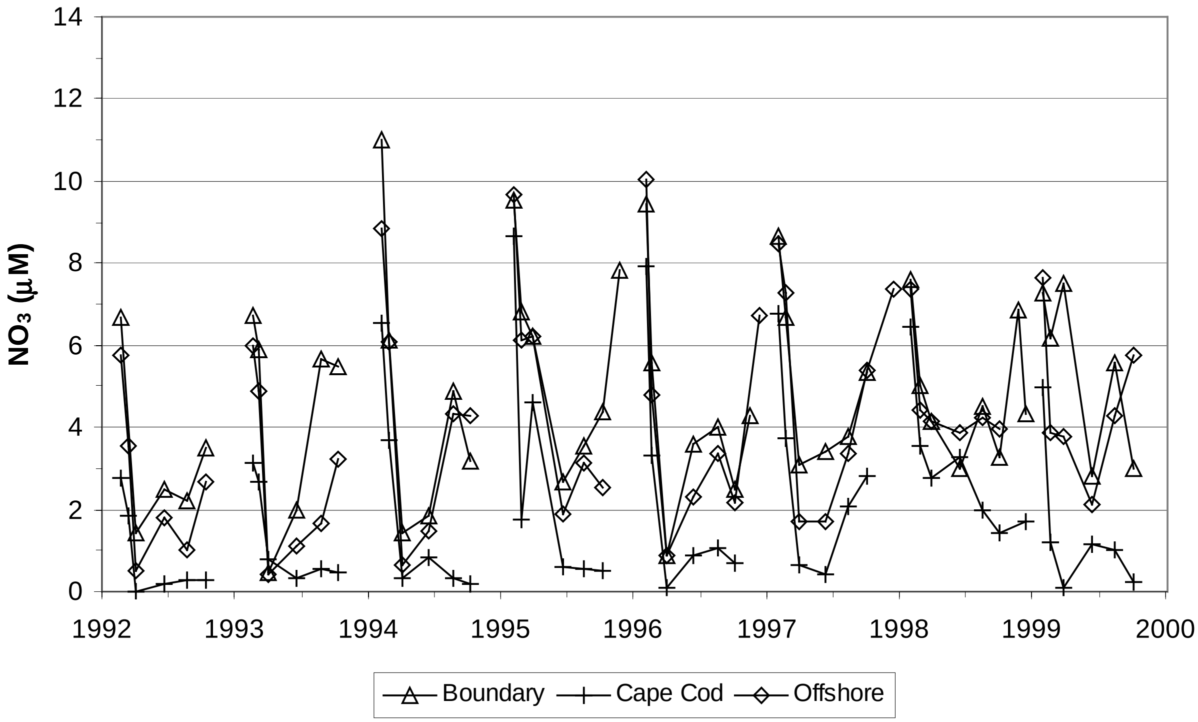
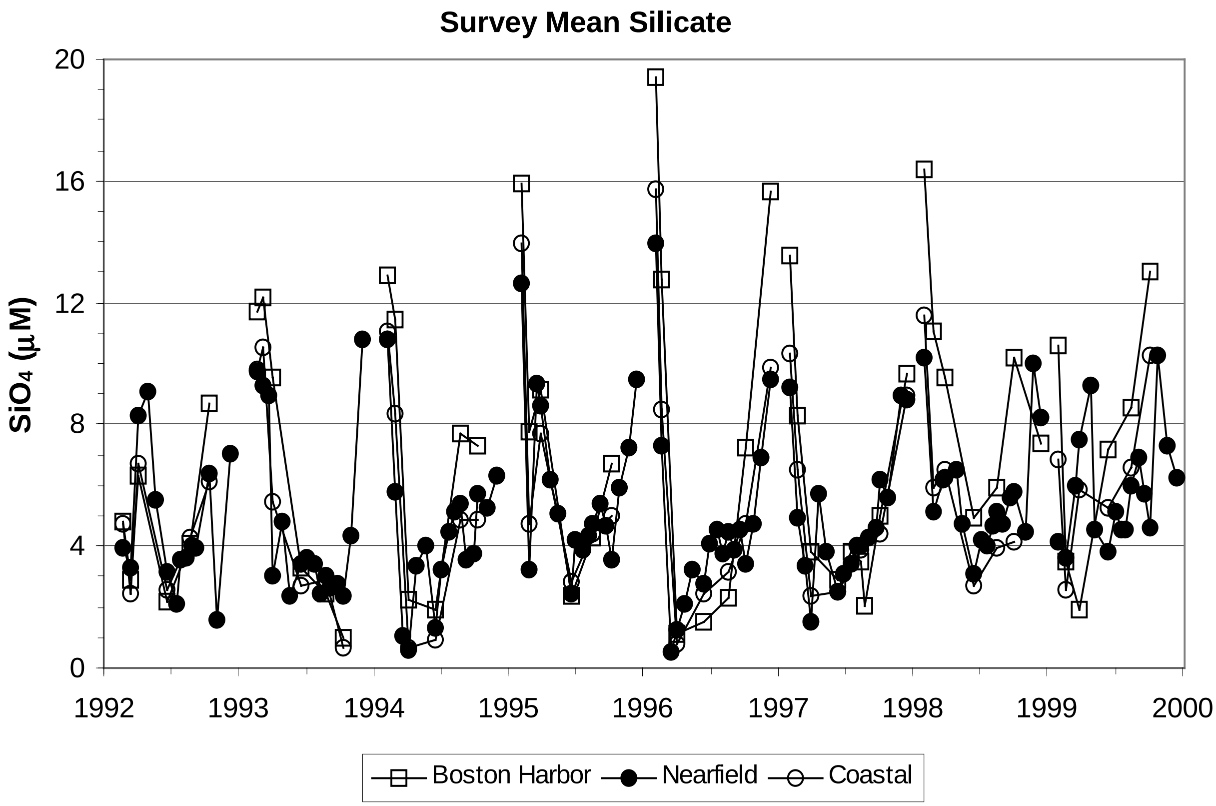


Figure 4-13. Interannual NO_3 cycle in Massachusetts and Cape Cod Bays. Mean of data collected from all depths and all stations in the six areas.



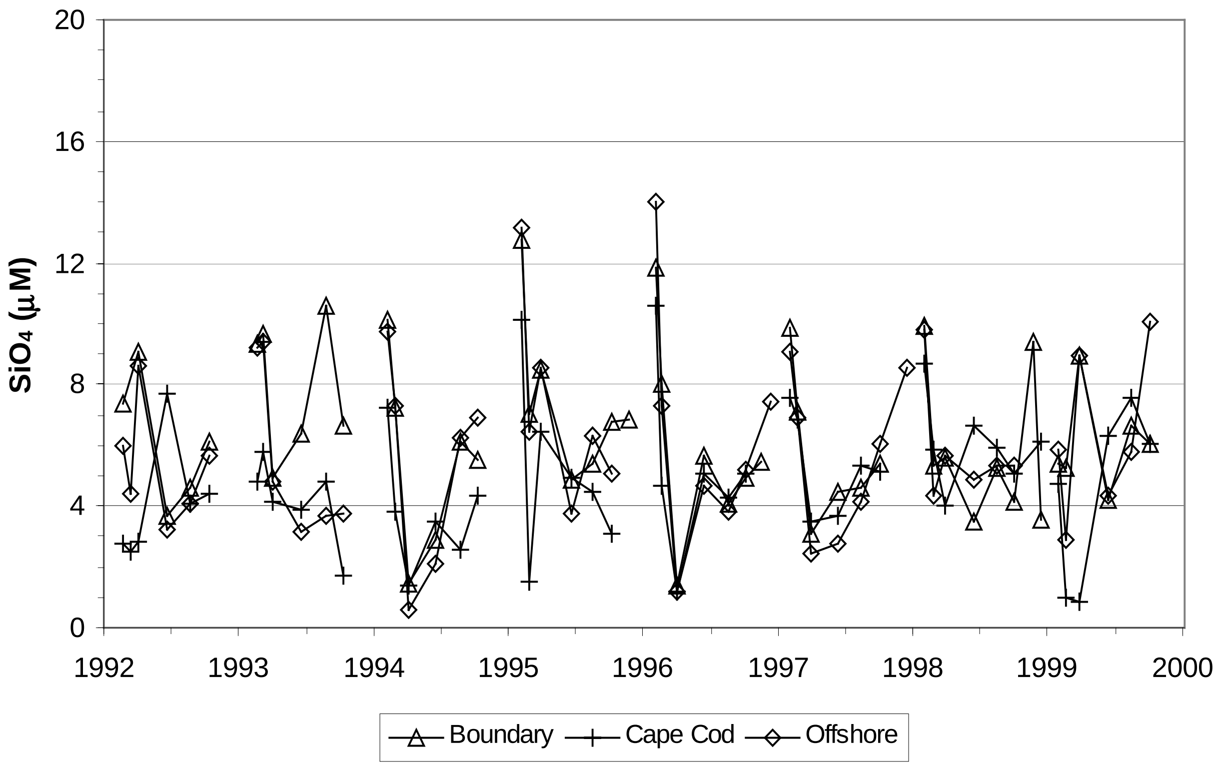


Figure 4-14. Interannual SiO_4 cycle in Massachusetts and Cape Cod Bays. Mean of data collected from all depths and all stations in the six areas.

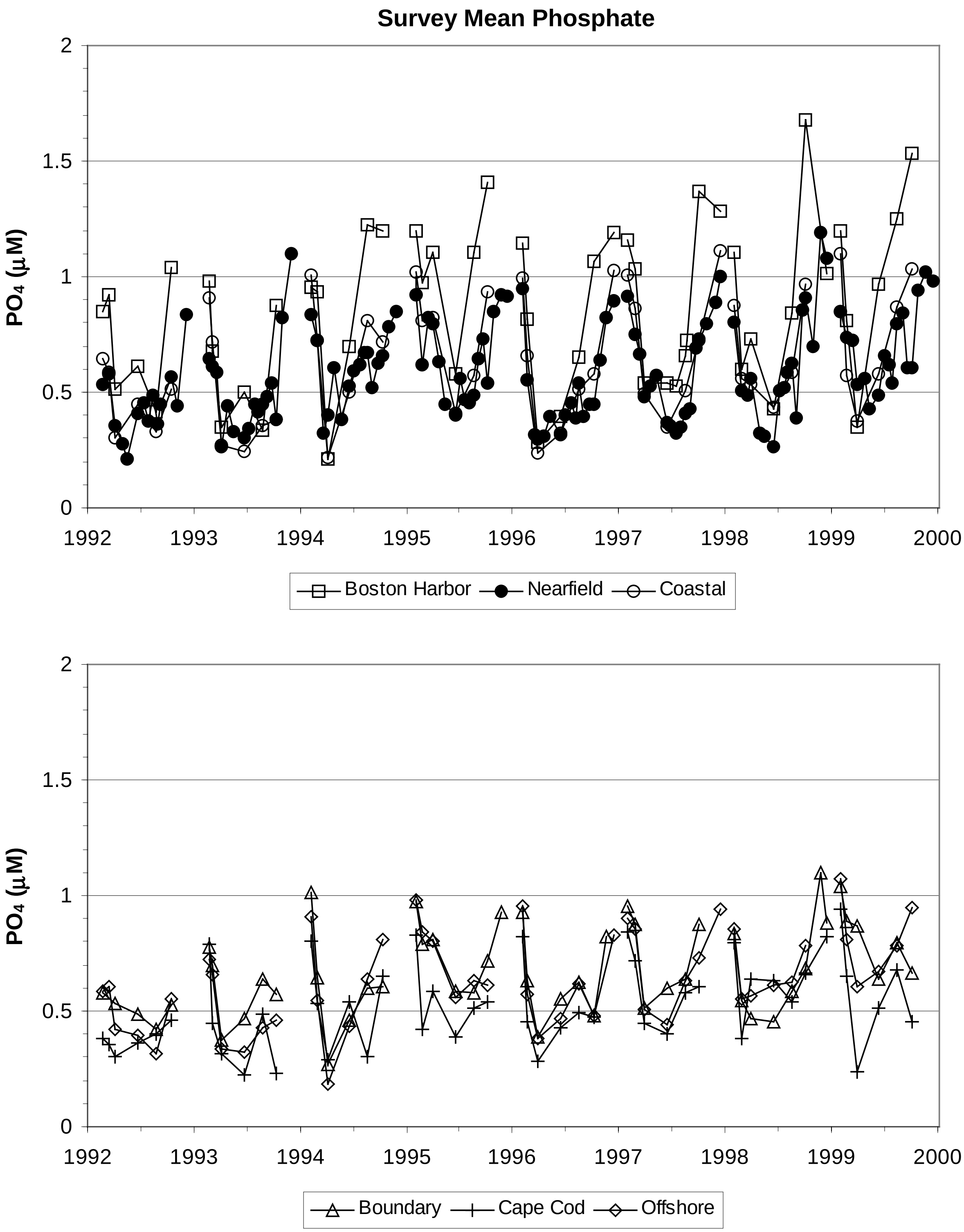
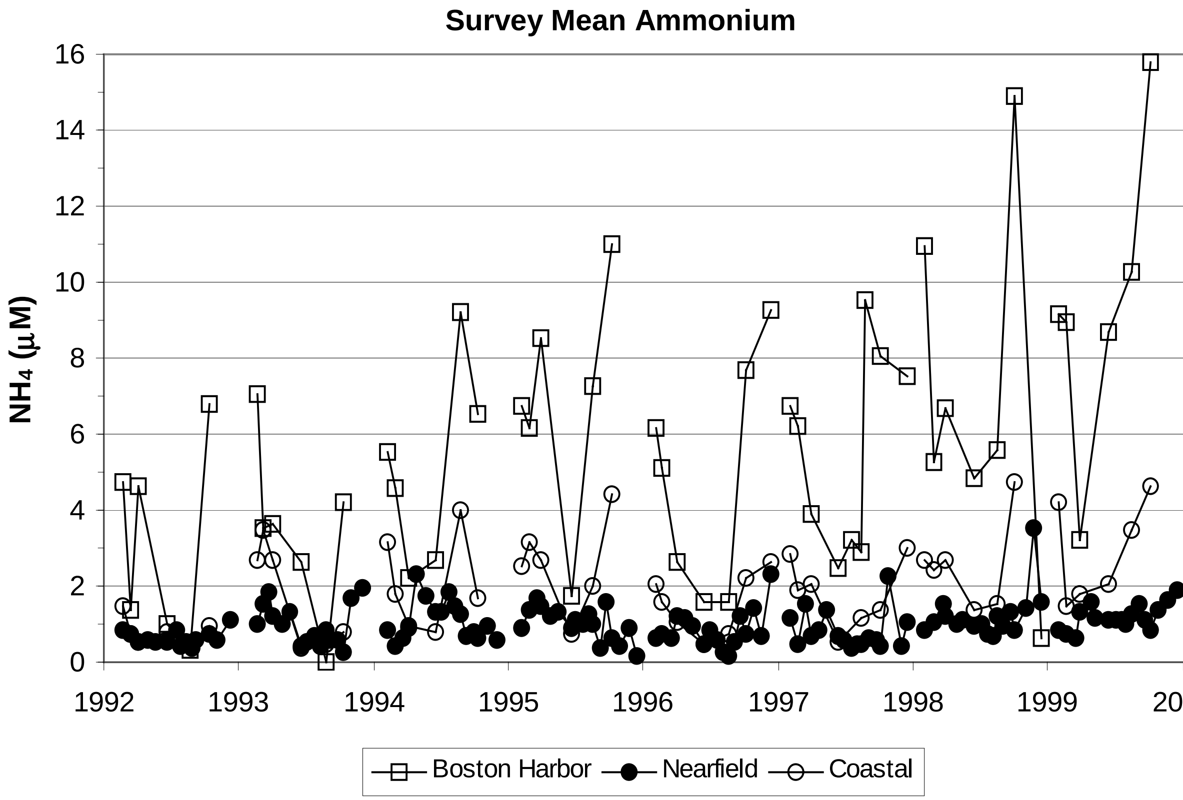


Figure 4-15. Interannual PO_4 cycle in Massachusetts and Cape Cod Bays. Mean of data collected from all depths and all stations in the six areas.



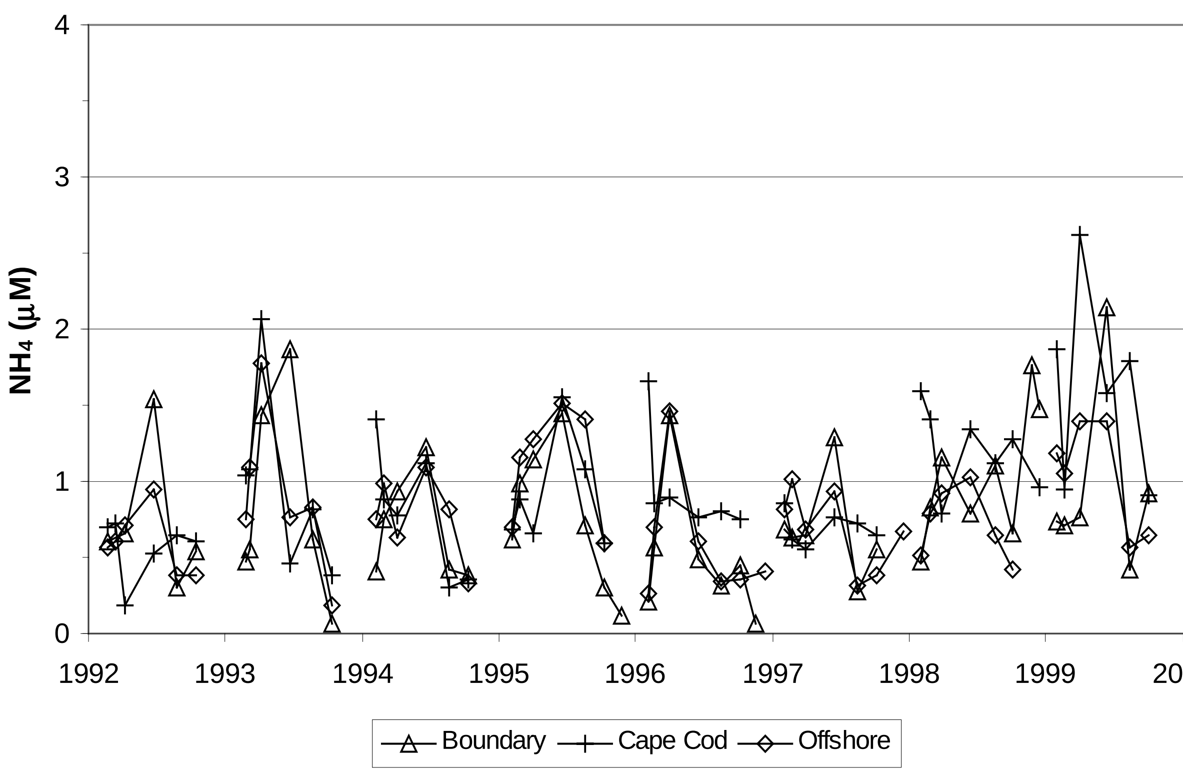
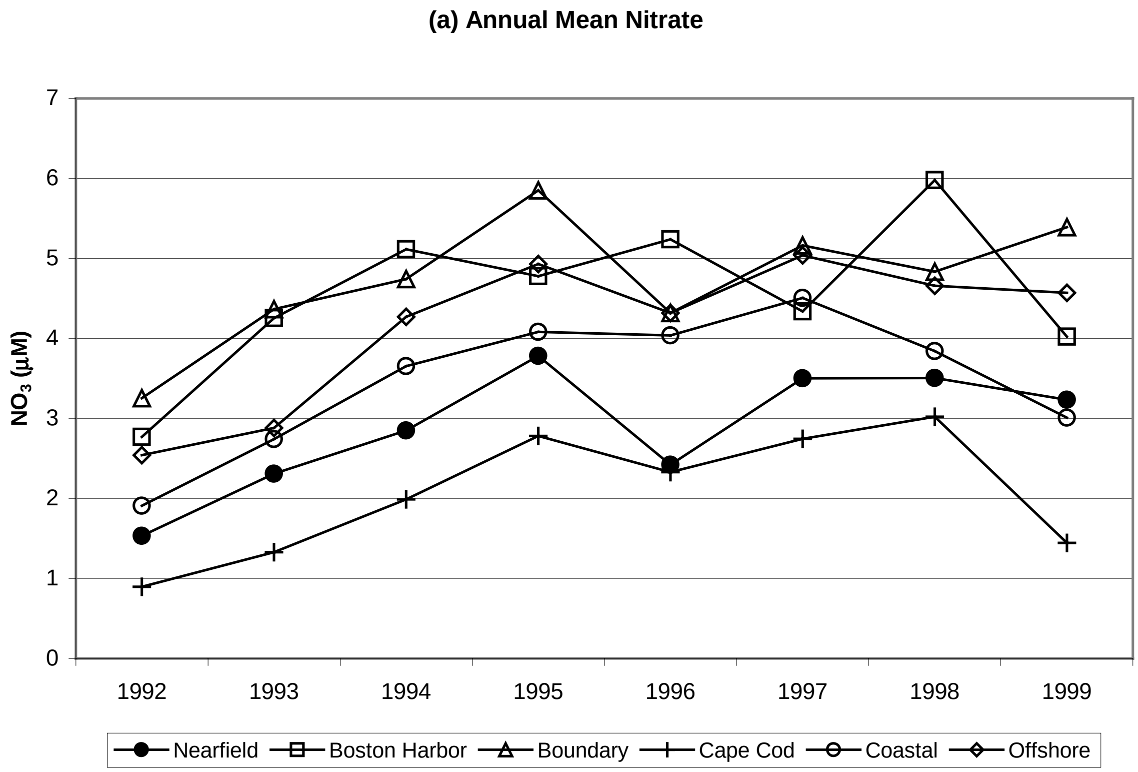


Figure 4-16. Interannual NH_4 cycle in Massachusetts and Cape Cod Bays. Mean of data collected from all depths and all stations in the six areas. Note different scales.



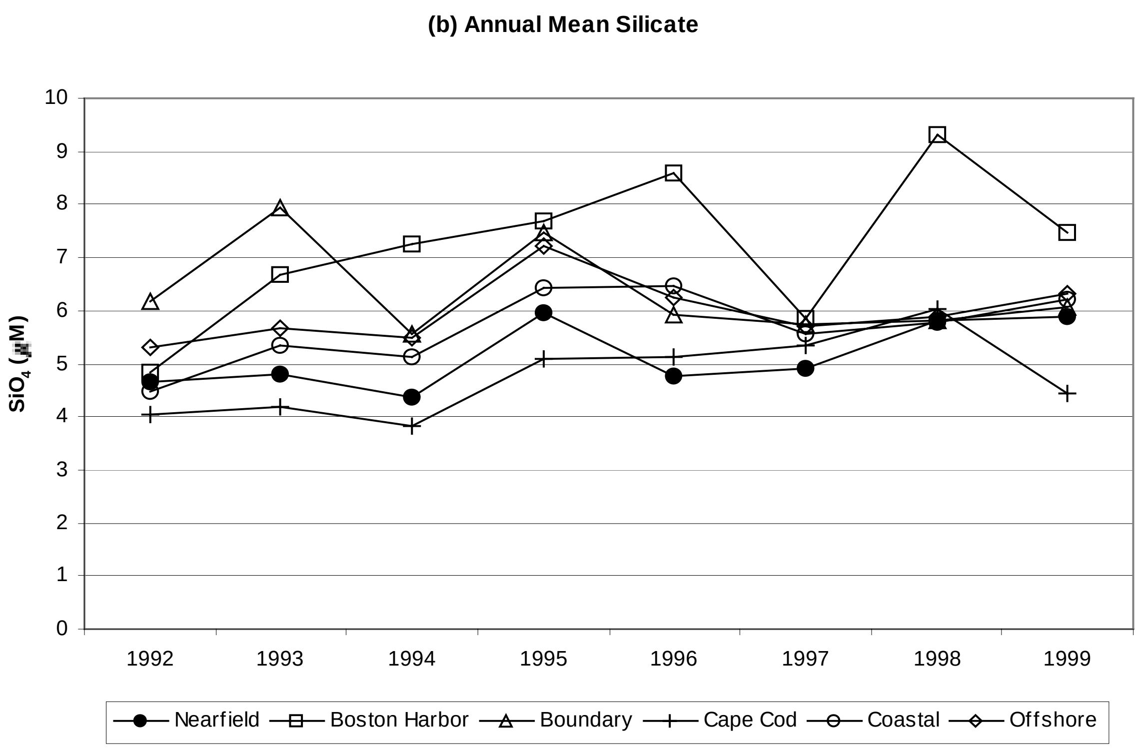


Figure 4-17. Annual mean (a) NO_3 and (b) SiO_4 in Massachusetts and Cape Cod Bays. Mean of data collected from all depths, all stations and all surveys in the six areas.

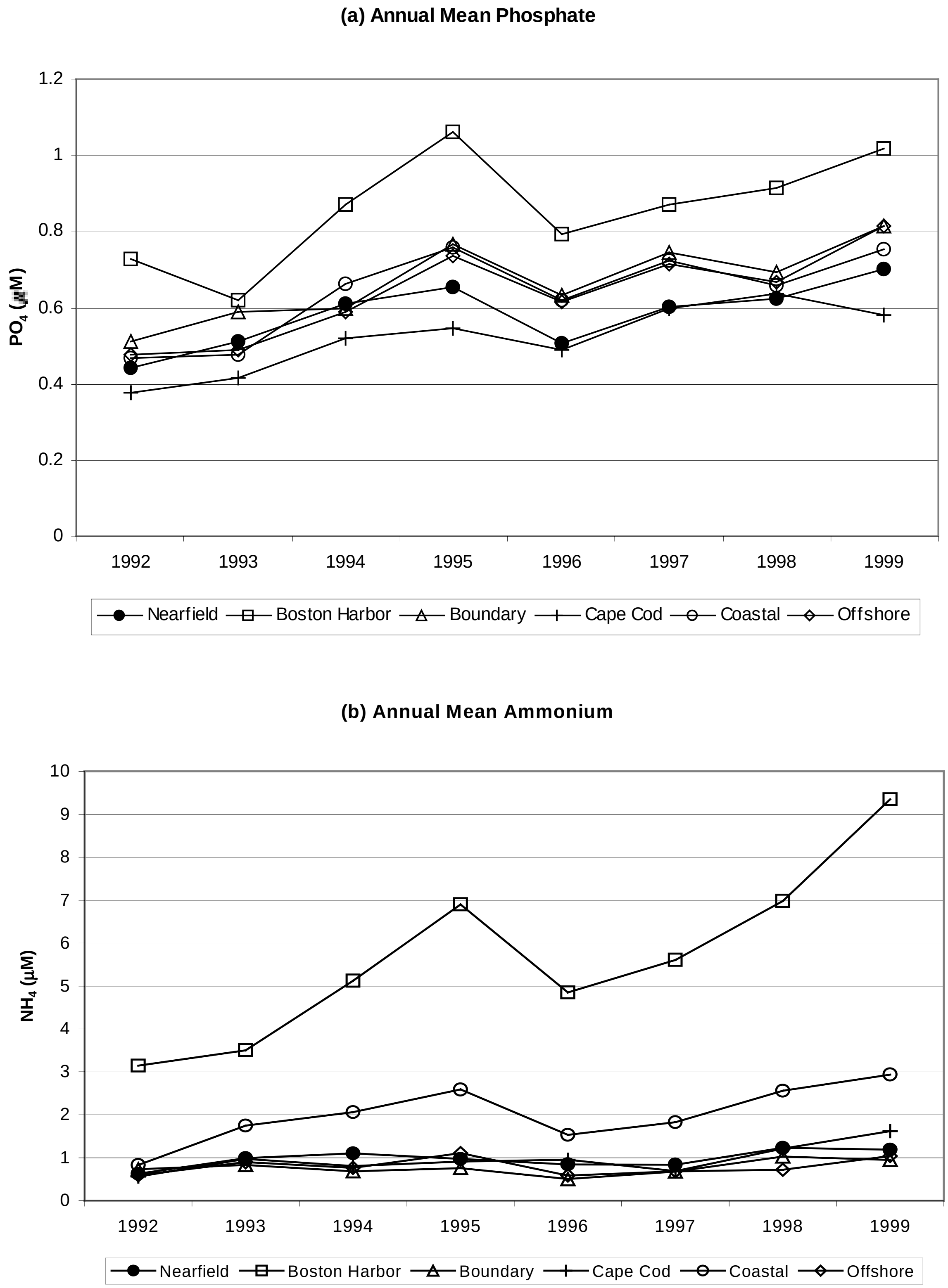
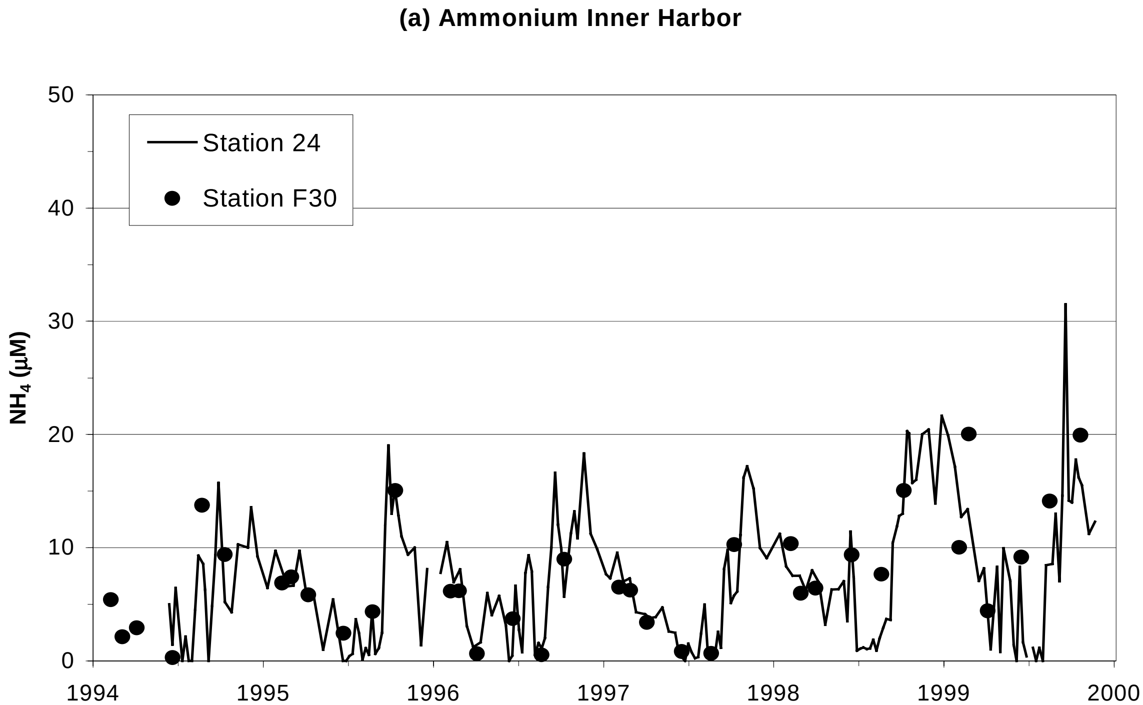


Figure 4-18. Annual mean (a) PO_4 and (b) NH_4 in Massachusetts and Cape Cod Bays. Mean of data collected from all depths, all stations and all surveys in the six areas.



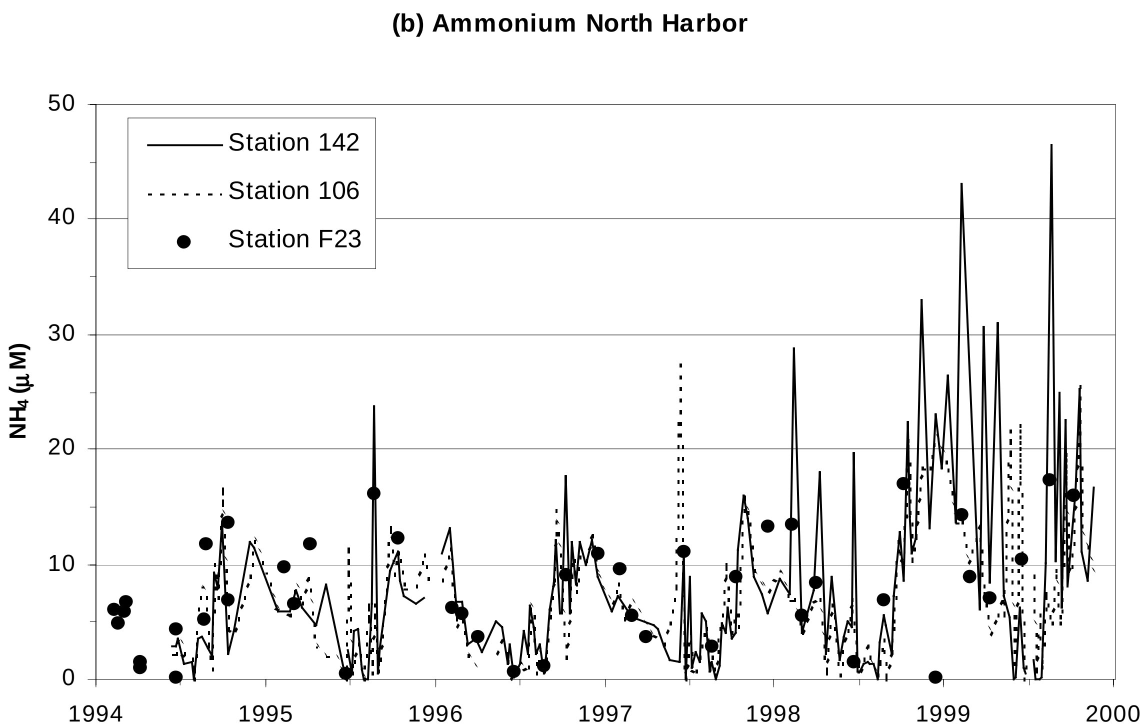
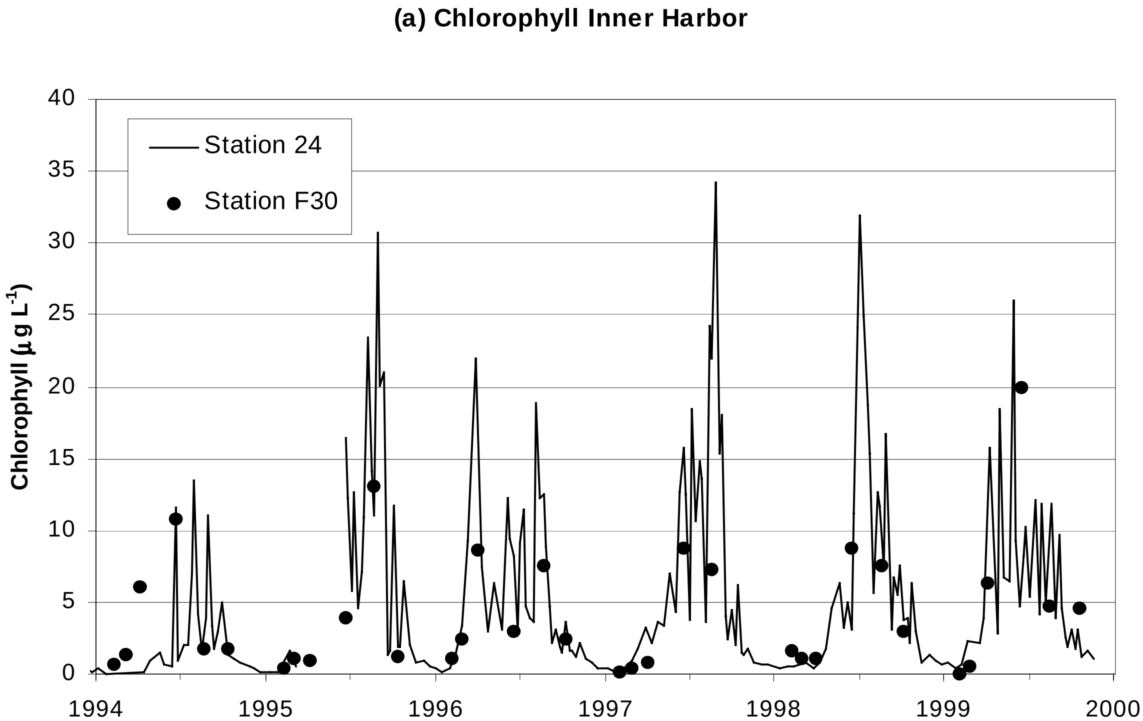


Figure 4-19. Time-series of surface water NH_4 Concentrations in (a) Inner Boston Harbor at stations 24 (BHWQM) and F30 and (b) North Boston Harbor at stations 106 and 142 (BHWQM) and F23.



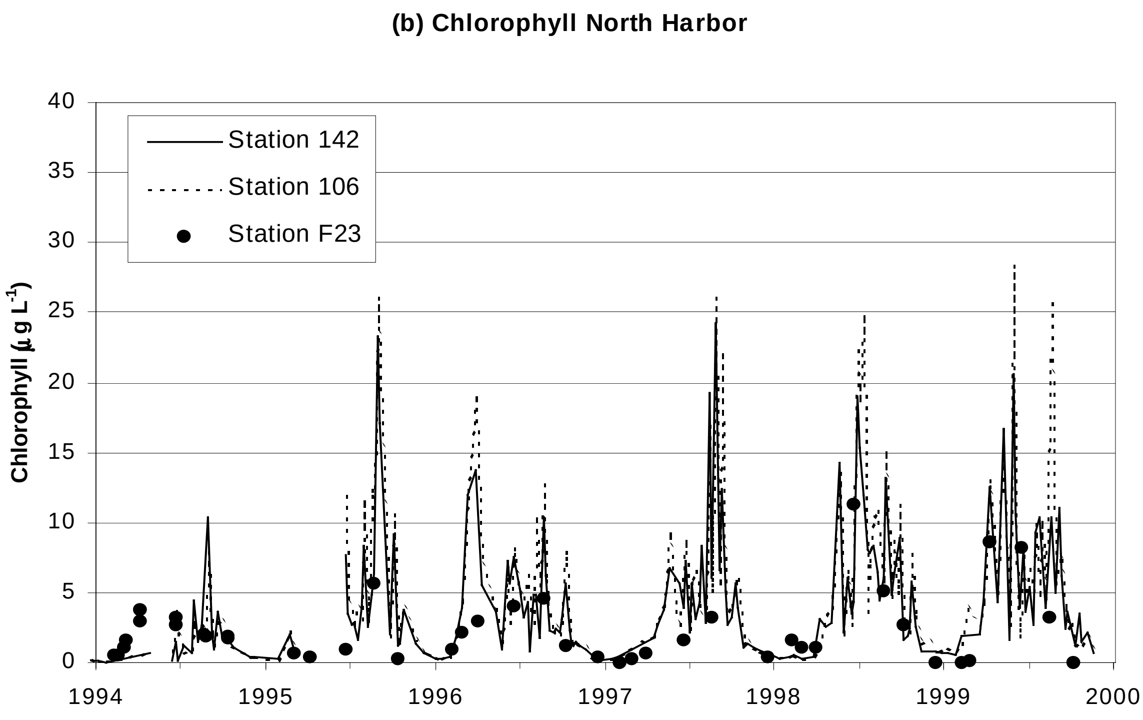
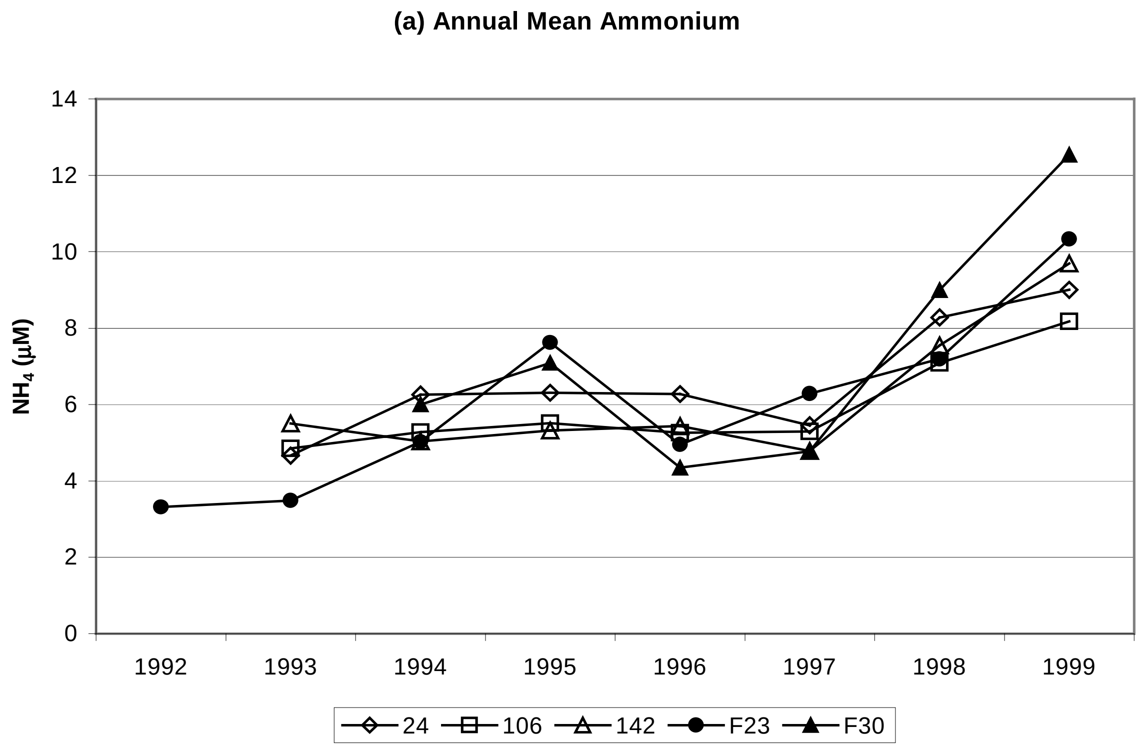


Figure 4-20. Time-series of surface water chlorophyll concentrations in (a) Inner Boston Harbor at stations 24 (BHWQM) and F30 and (b) North Boston Harbor at stations 106 and 142 (BHWQM) and F23.



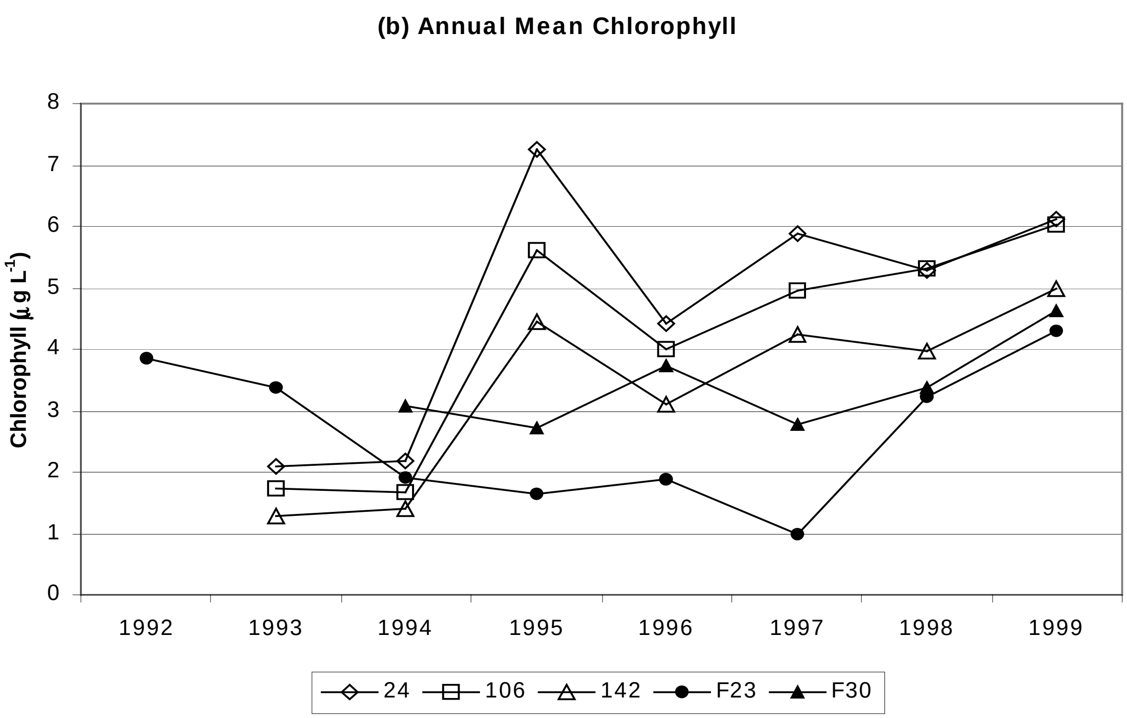


Figure 4-21. Annual mean (a) NH_4 and (b) chlorophyll concentrations in Boston Harbor at stations 24, 106 and 142 (BHWQM) and F23 and F30. Mean of data collected from surface and bottom depths for each year.

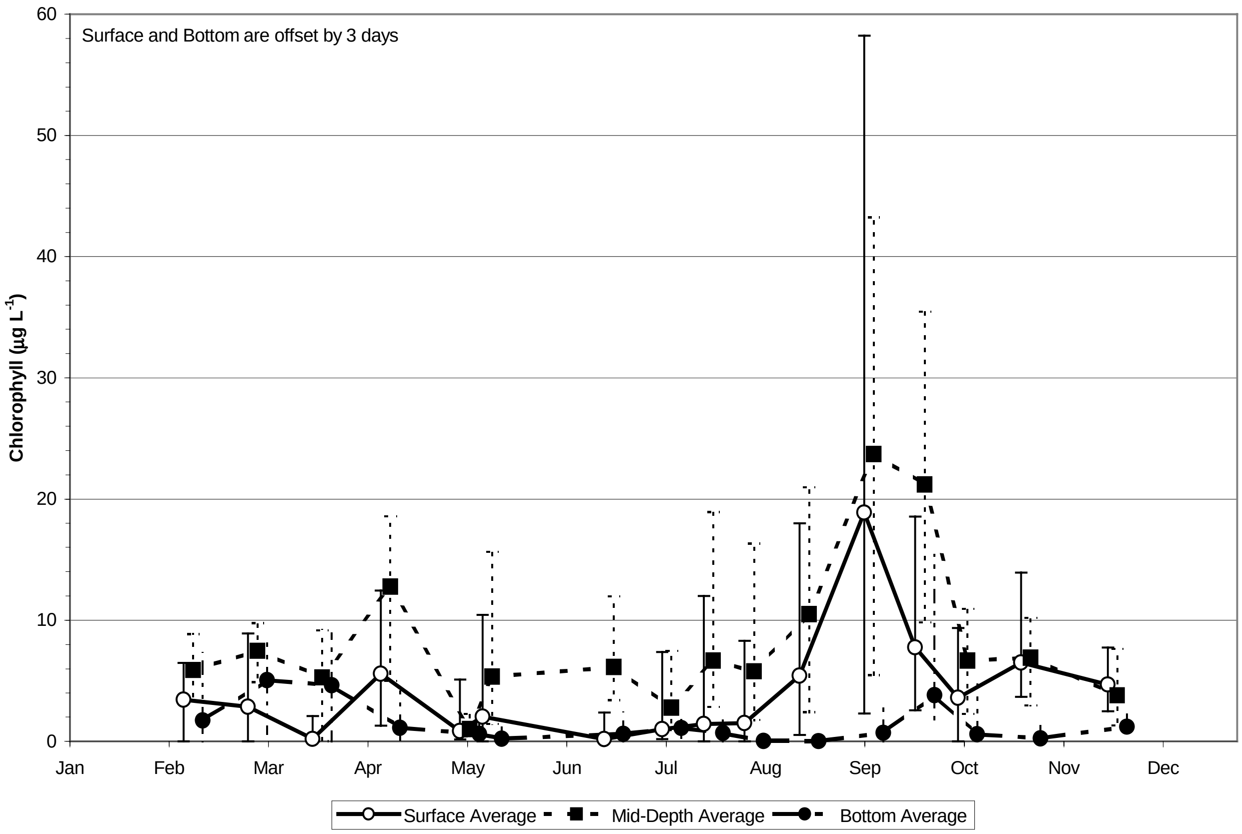


Figure 4-22. 1999 nearfield chlorophyll cycle. Survey average and range for surface, mid-depth and bottom samples collected during each nearfield survey.

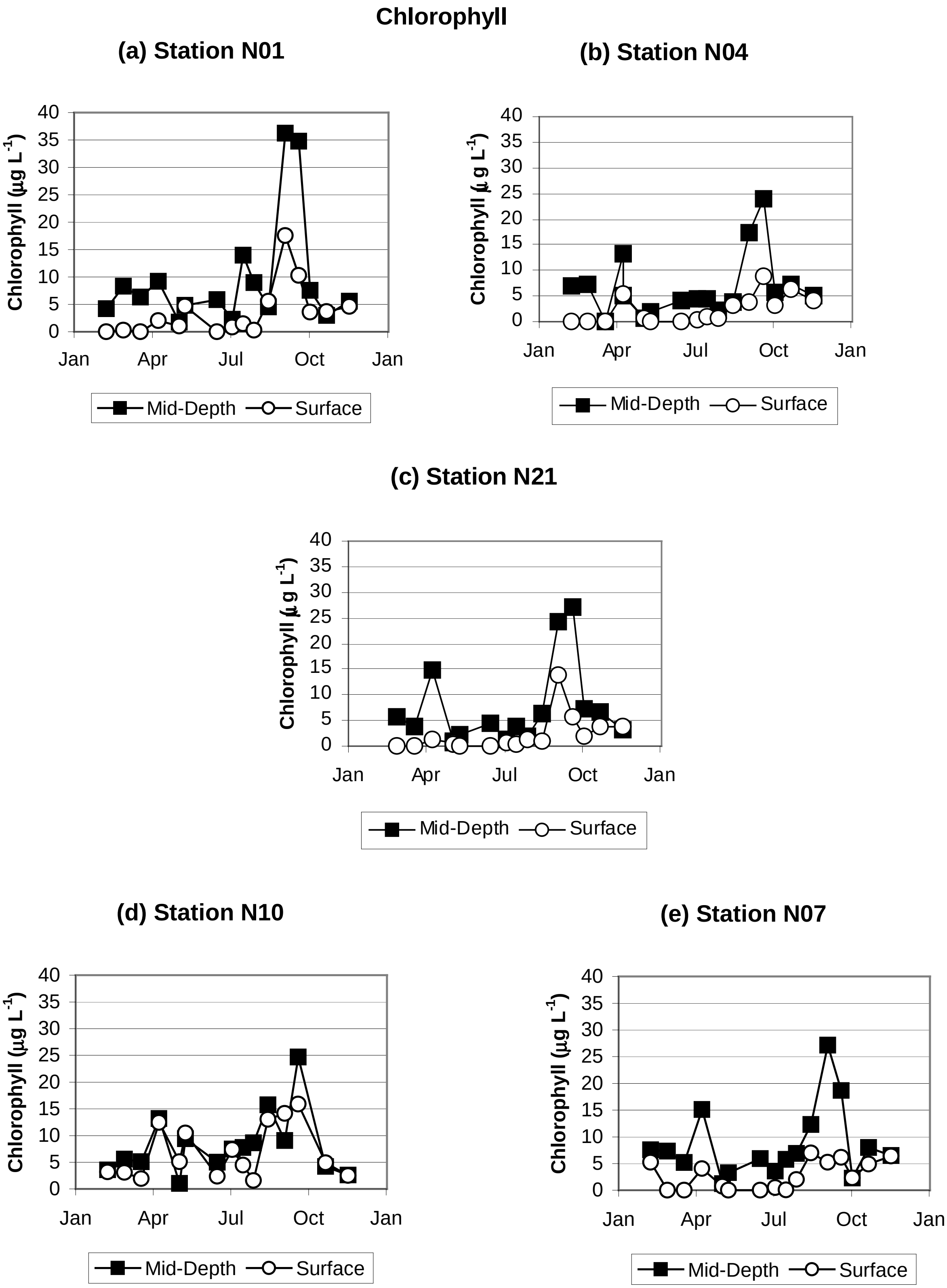


Figure 4-23. Time-series of surface and mid-depth chlorophyll concentrations for five representative nearfield stations.

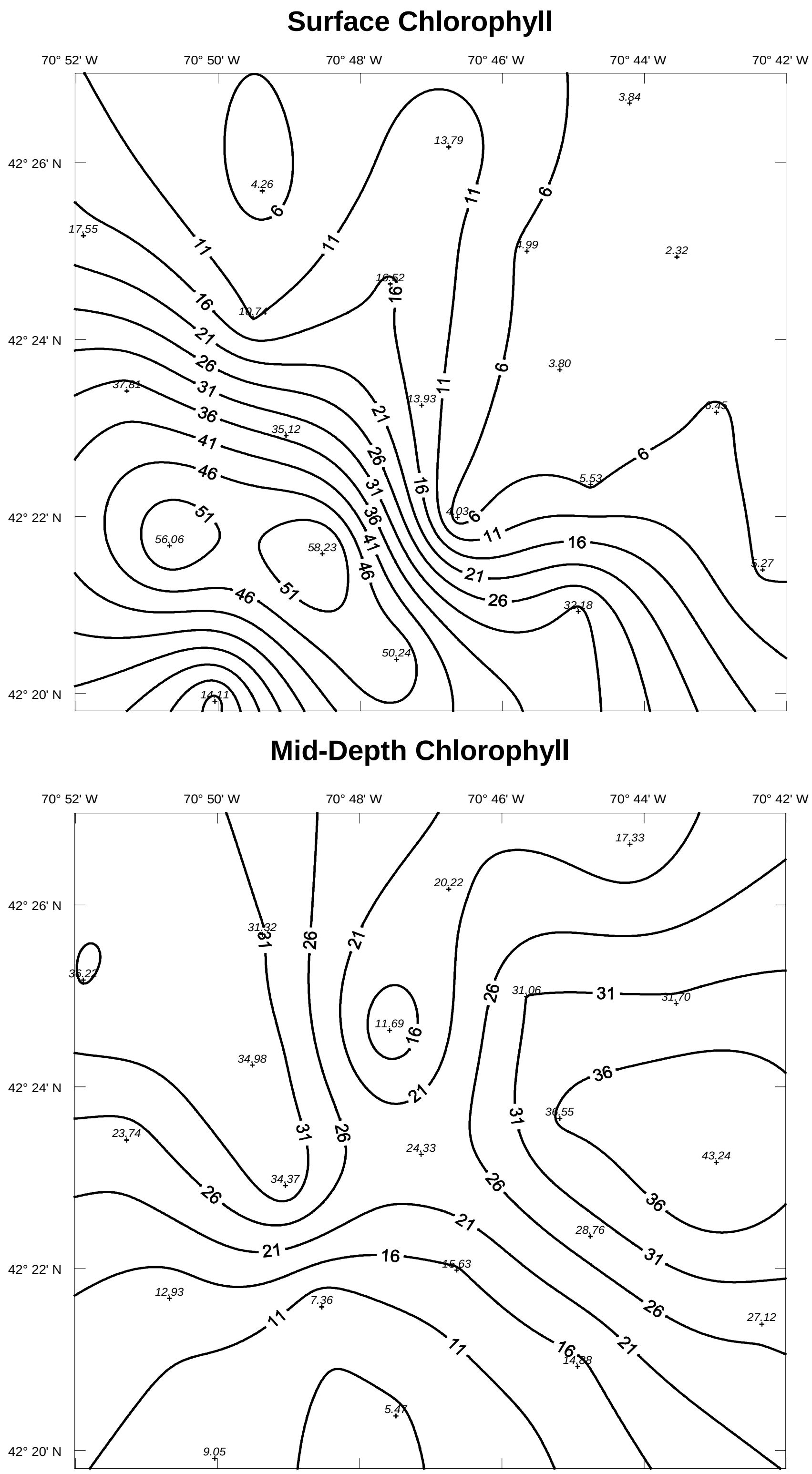


Figure 4-24. Contour of (a) surface and (b) mid-depth chlorophyll for nearfield survey WN99C (early September 1999). Contour intervals of 5 $\mu g\ L^{-1}$.

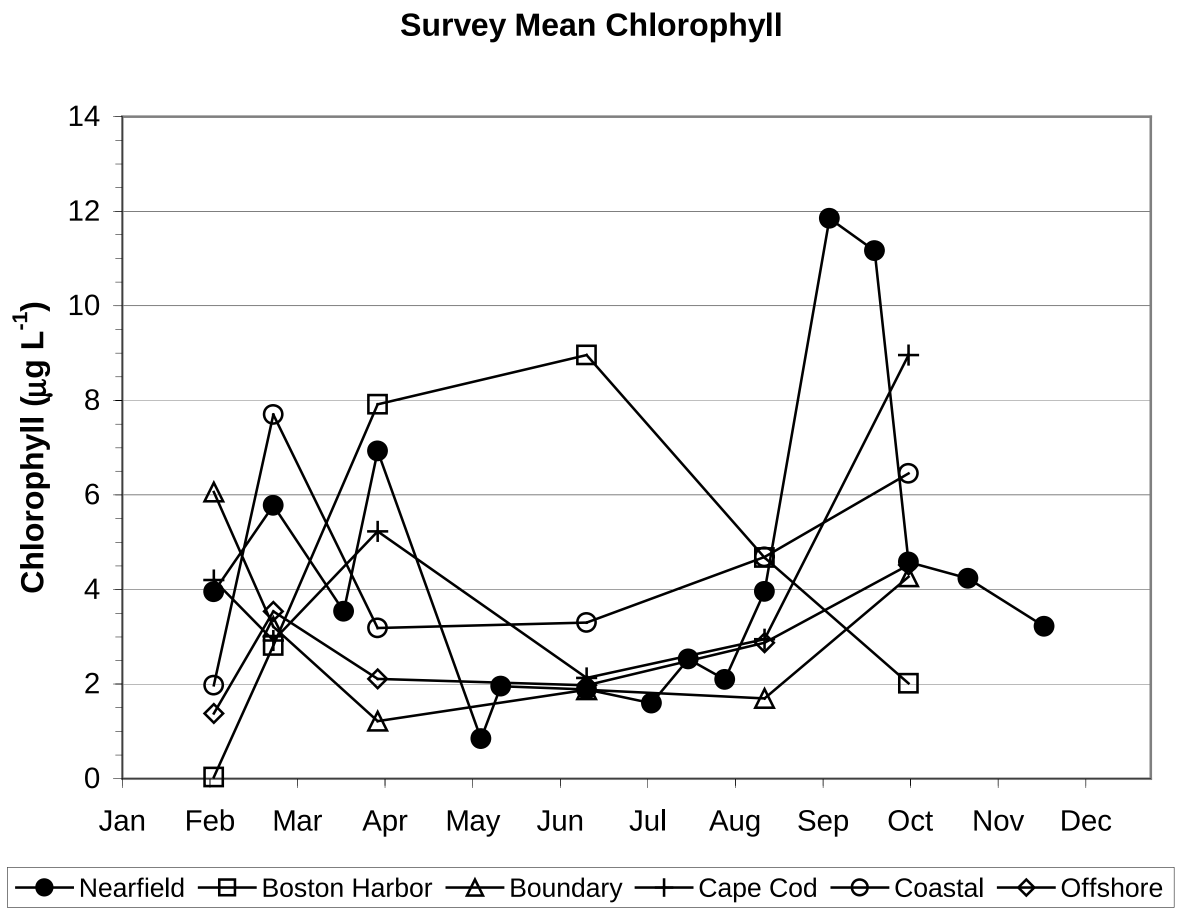


Figure 4-25. Time-series of mean chlorophyll concentrations in Massachusetts and Cape Cod Bays. Data collected from all depths and all stations in the five farfield areas.

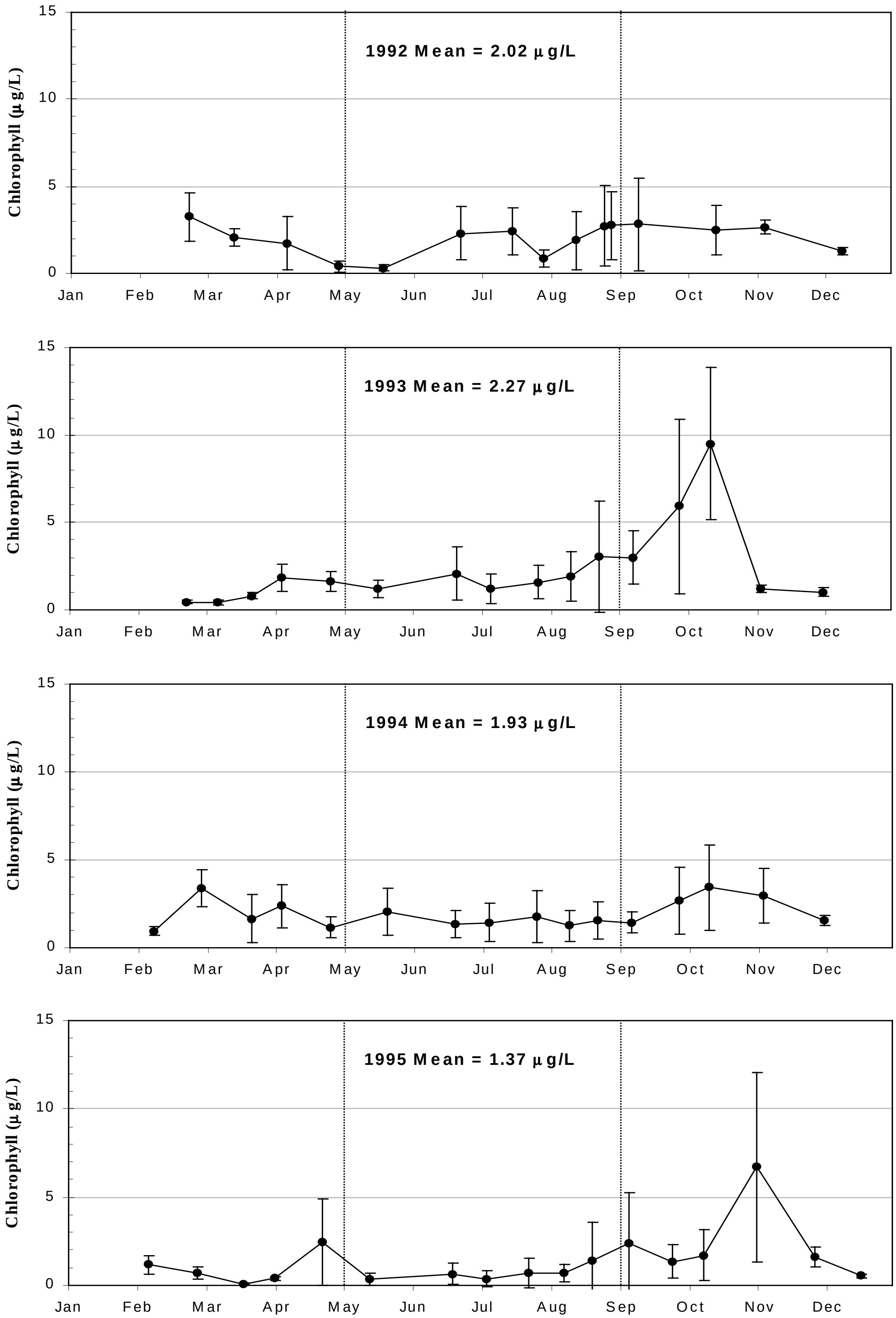


Figure 4-26. Interannual nearfield chlorophyll cycle for 1992 to 1995. Mean of data from all depths at all nearfield stations. Error bars represent ± one standard deviation.

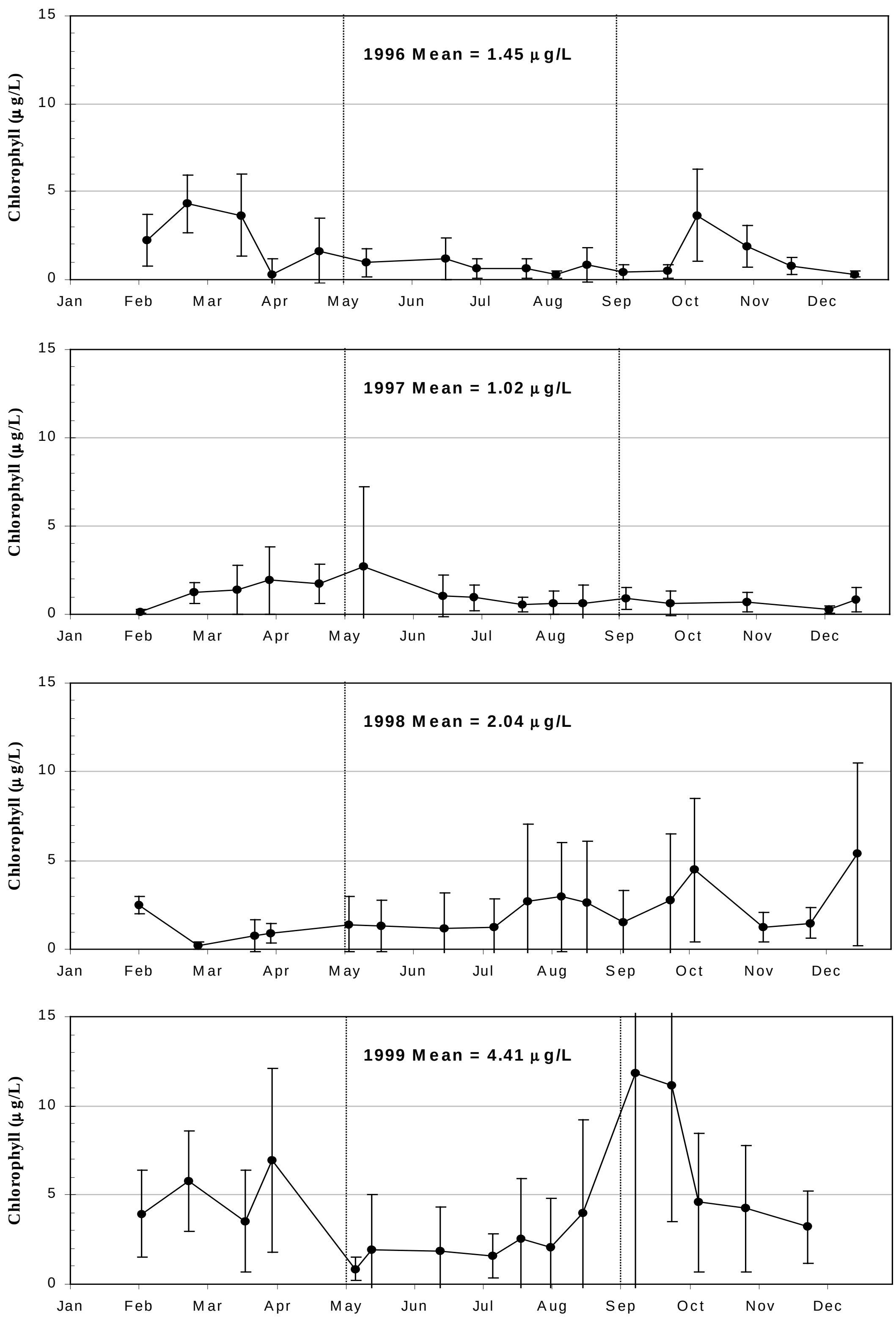
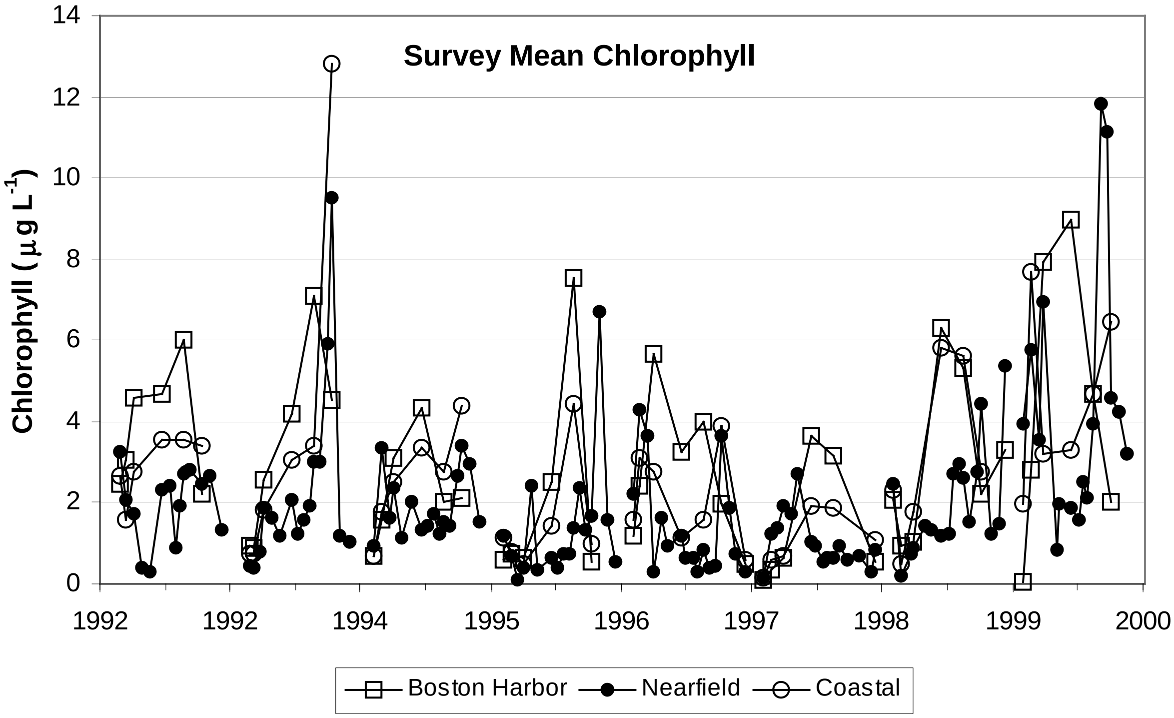


Figure 4-27. Interannual nearfield chlorophyll cycle for 1996 to 1999. Mean of data from all depths at all nearfield stations. Error bars represent ± one standard deviation. Early and late September 1999 maxima were 58.2 and 35.5 μgL^{-1}, respectively - data not shown.



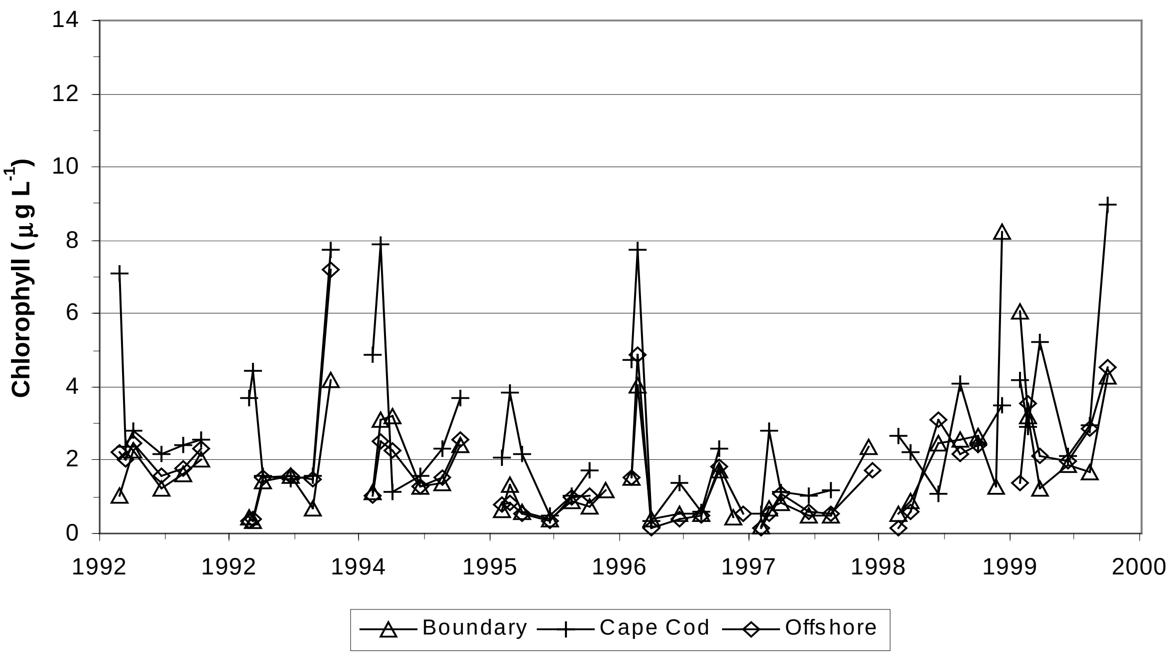


Figure 4-28. Interannual chlorophyll cycle in Massachusetts and Cape Cod Bays. Mean of data collected from all depths and all stations in the six areas.

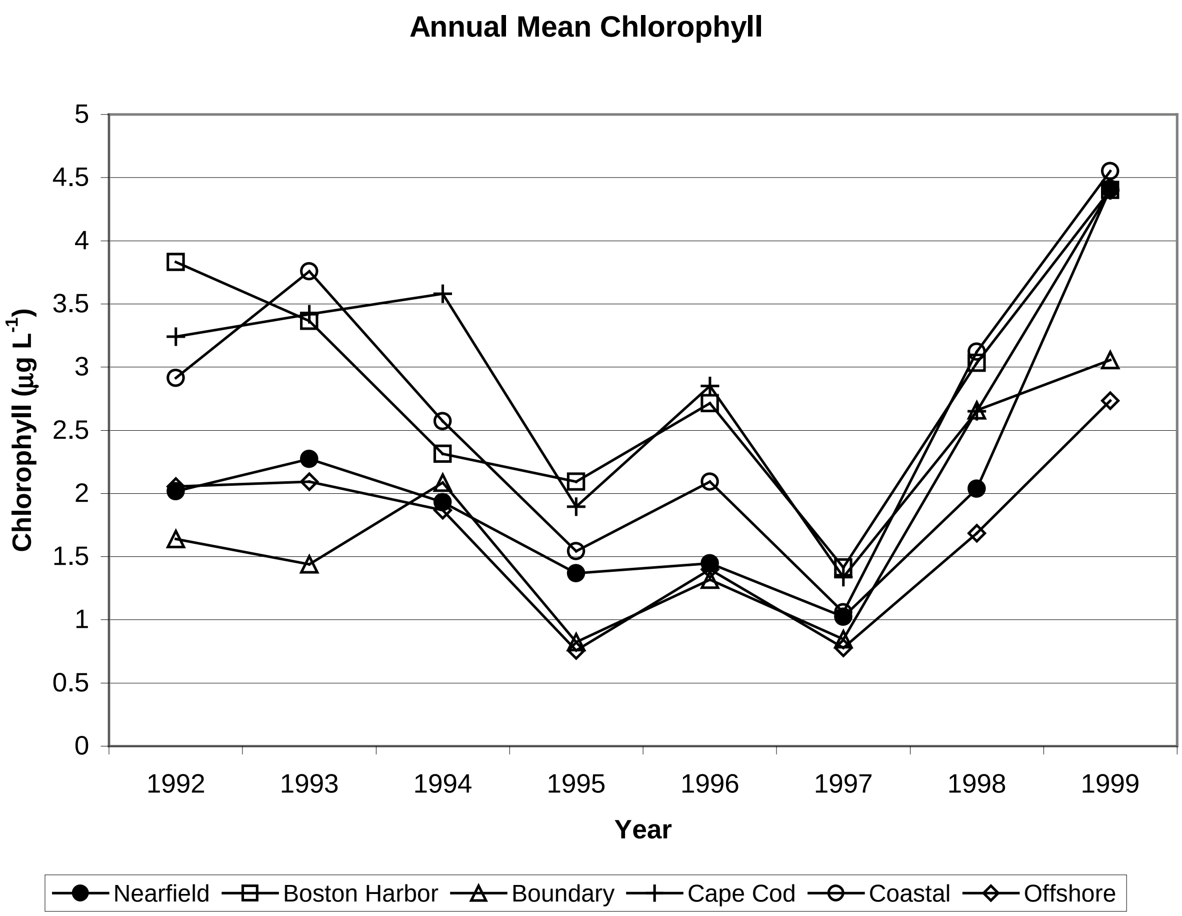


Figure 4-29. Annual mean chlorophyll in Massachusetts and Cape Cod Bays. Mean of data collected from all depths, all stations and all surveys in the six areas.

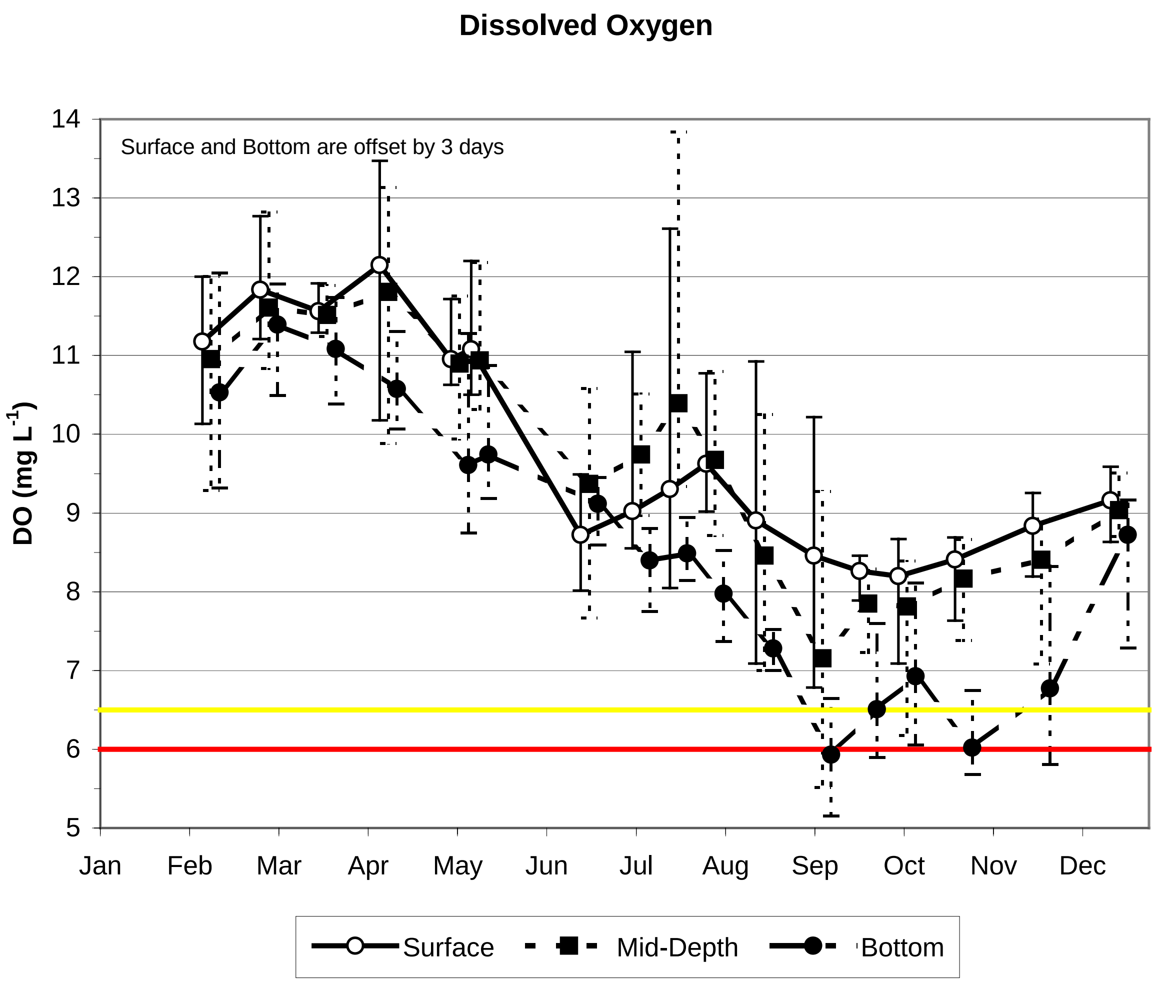


Figure 4-30. 1999 nearfield DO cycle. Survey average and range for surface, mid-depth and bottom samples collected during each nearfield survey. Proposed caution (6.5 mgL^{-1}) and warning (6 mgL^{-1}) thresholds are marked for comparison. Surface and bottom data offset for clarity.

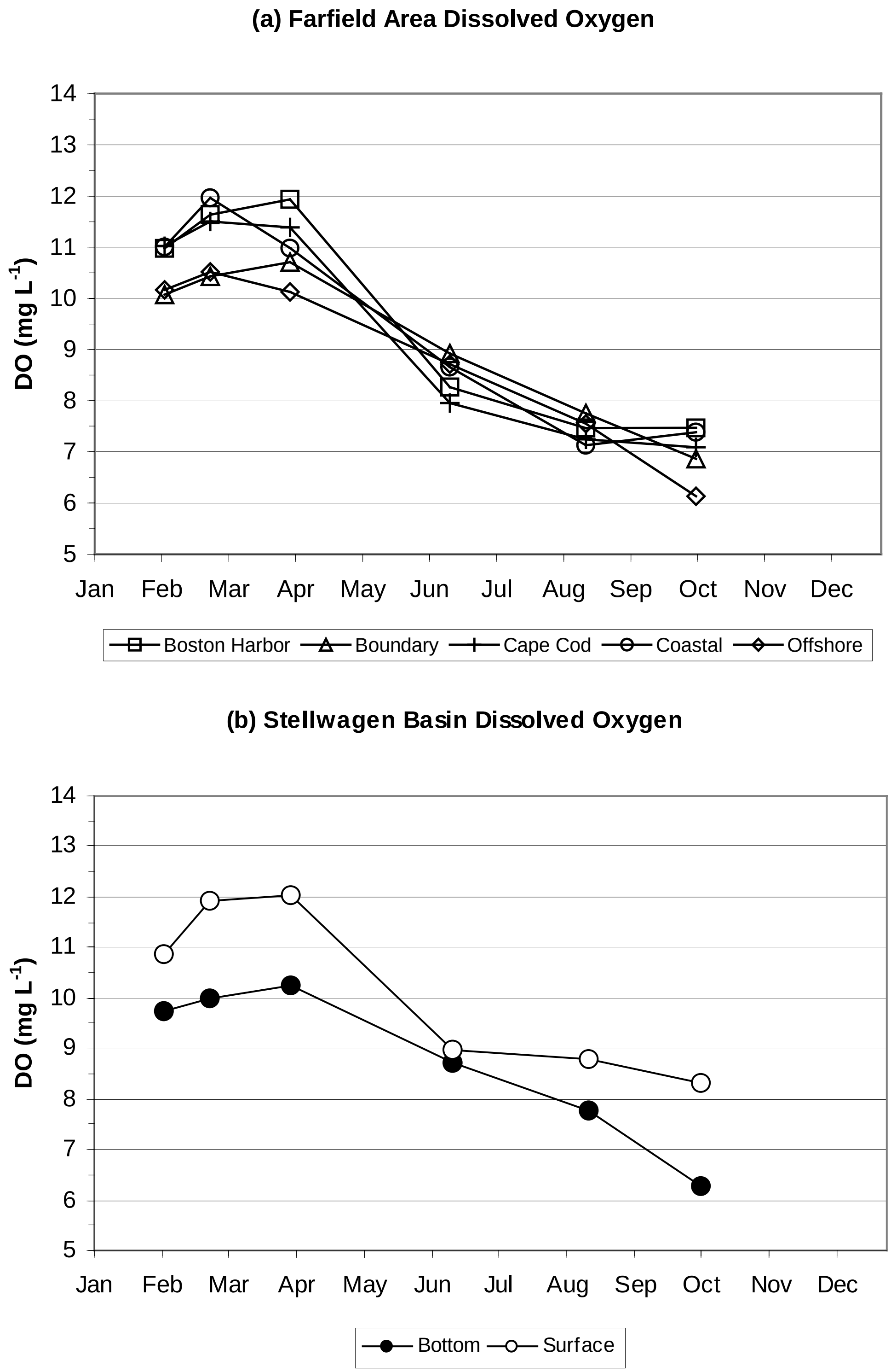


Figure 4-31. (a) Time-series of average bottom dissolved oxygen concentration in Massachusetts and Cape Cod Bays. Data collected from all depths and all stations in the five farfield areas. (b) Time-series of average surface and bottom dissolved oxygen concentration in Stellwagen Basin for 1999 (stations F12, F17, F19 and F22).

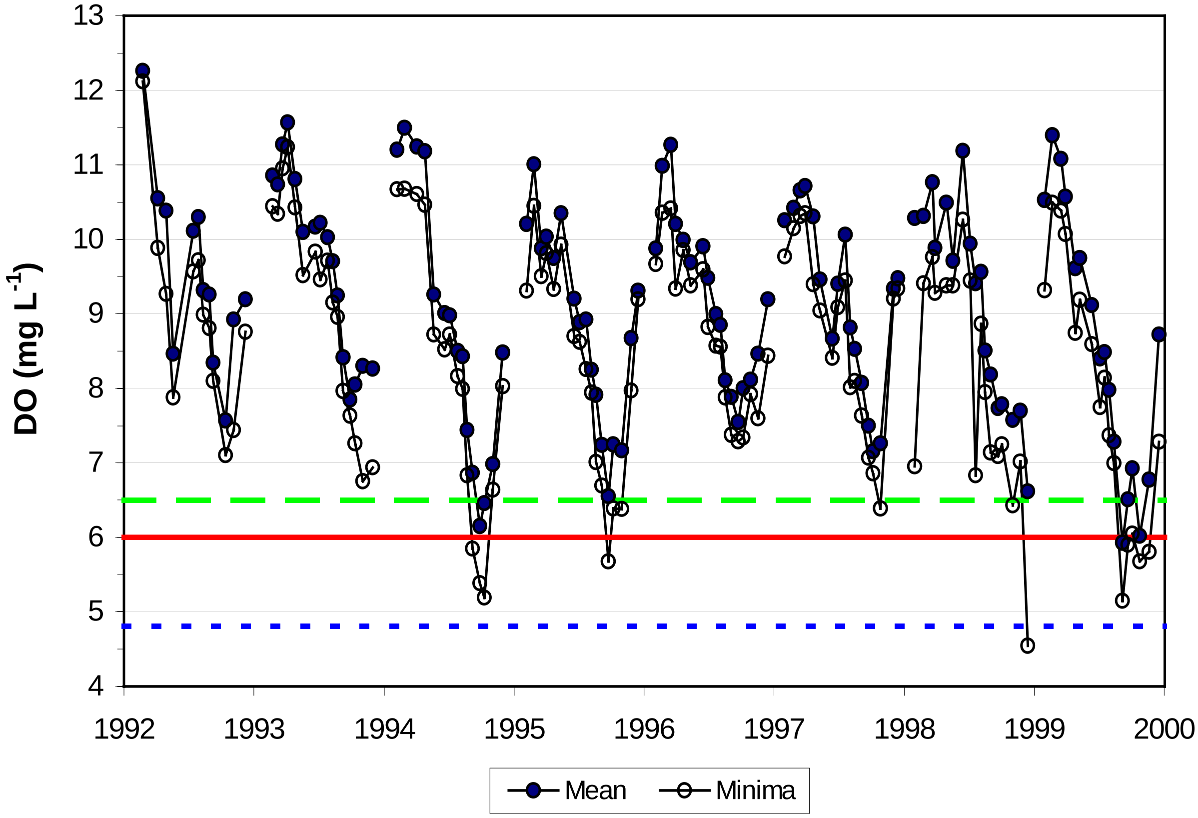


Figure 4-32. Interannual dissolved oxygen cycle in the nearfield. Mean and minimum bottom data from each survey at all nearfield stations. EPA criteria for mid-Atlantic waters (4.8 mgL^{-1}) and proposed caution (6.5 mgL^{-1}) and warning (6 mgL^{-1}) thresholds are marked for comparison.

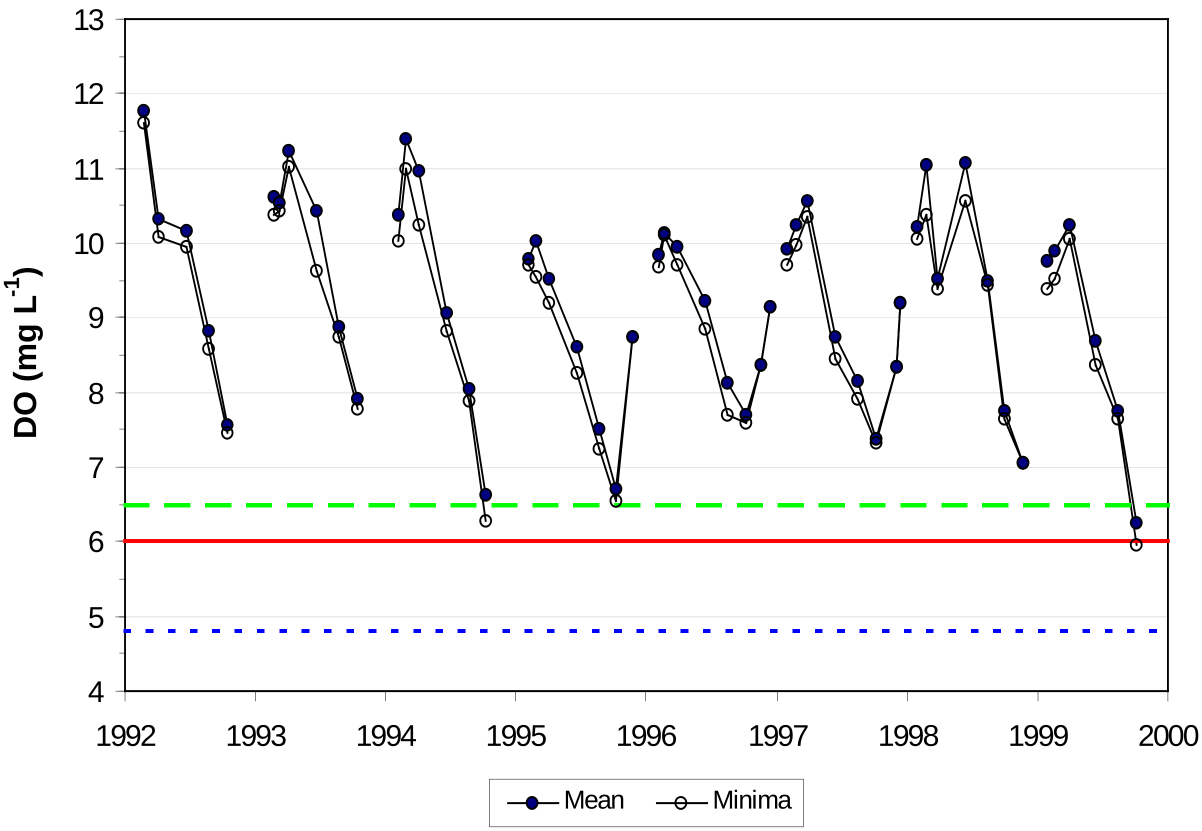
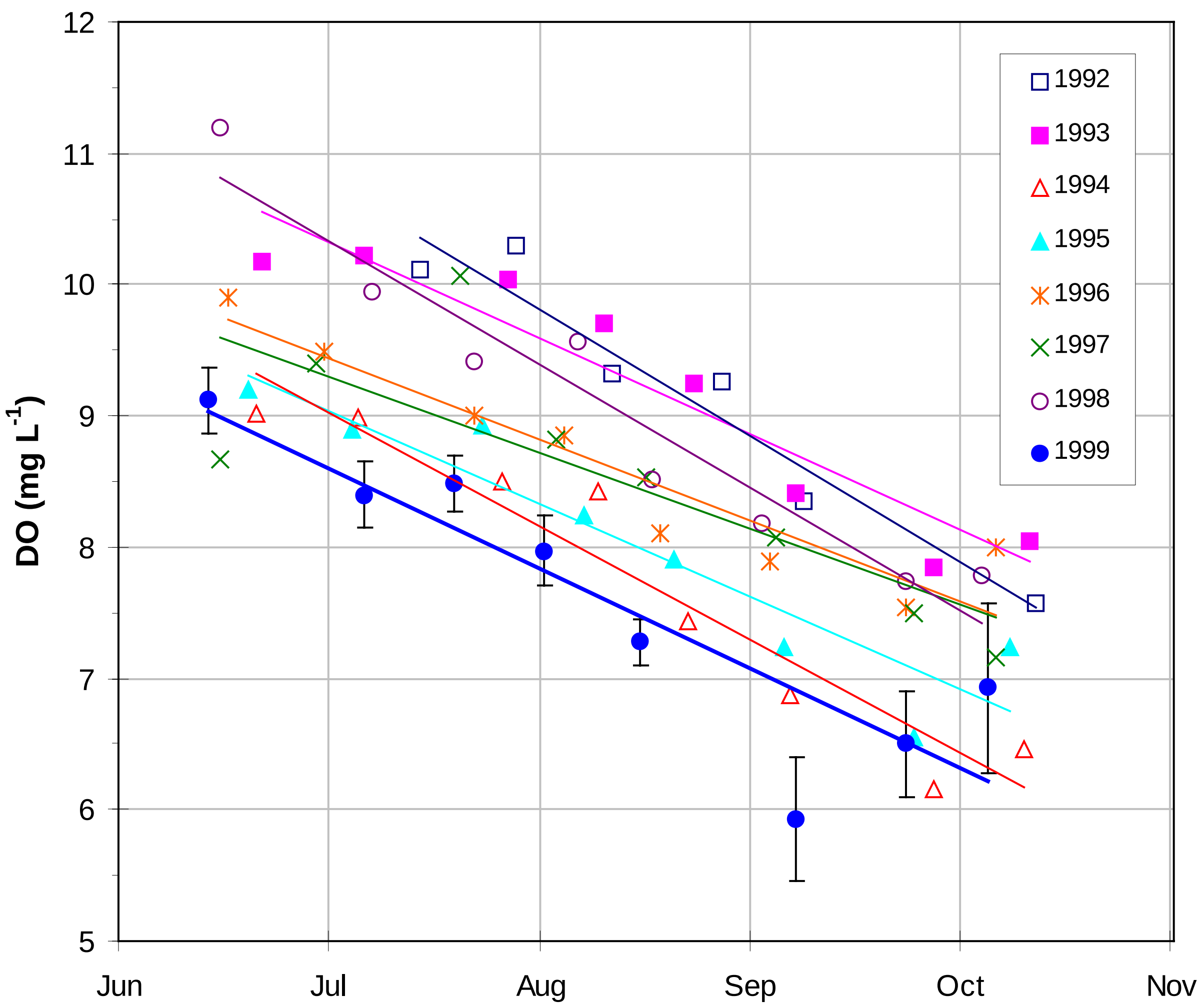
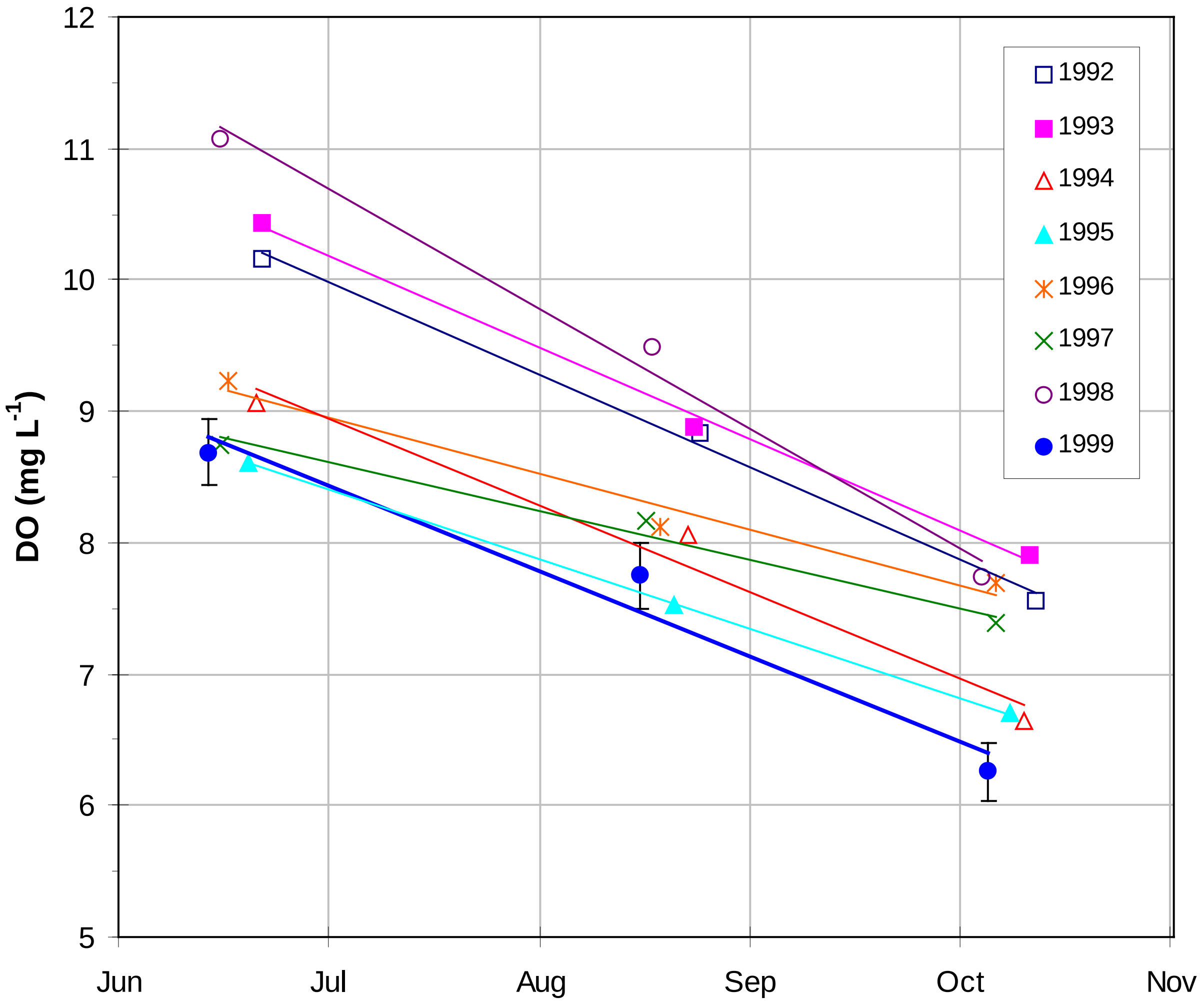


Figure 4-33. Interannual dissolved oxygen cycle in Stellwagen Basin. Mean and minimum bottom data from each survey at stations F12, F17, F19 and F22. EPA criteria for mid-Atlantic waters (4.8 mgL^{-1}) and proposed caution (6.5 mgL^{-1}) and warning (6 mgL^{-1}) thresholds are marked for comparison.



Year	Slope (mg/L/day)	Intercept* (mg/L)	R^2
1992	-0.031	11.7	0.931
1993	-0.024	11.1	0.901
1994	-0.028	9.9	0.923
1995	-0.023	9.7	0.880
1996	-0.020	10.0	0.889
1997	-0.019	9.9	0.638
1998	-0.030	11.3	0.932
1999	-0.025	9.4	0.803
* Predicted DO on June 1st based on:			
DO = Slope * Date + Intercept			

Figure 4-34. Interannual comparison of DO decline in nearfield bottom waters. Mean of all nearfield stations. Error bars represent ± one standard deviation.



Year	Slope (mg/L/day)	Intercept* (mg/L)	R^2
1992	-0.023	10.7	0.996
1993	-0.023	10.9	0.997
1994	-0.021	9.6	0.972
1995	-0.017	8.9	1.000
1996	-0.014	9.4	0.969
1997	-0.012	9.0	0.982
1998	-0.030	11.6	0.988
1999	-0.021	9.1	0.964
* Predicted DO on June 1st based on:			
DO = Slope * Date + Intercept			

Figure 4-35. Interannual comparison of DO decline in Stellwagen Basin bottom waters. Mean for stations F12, F17, F19 and F22. Error bars represent ± one standard deviation.

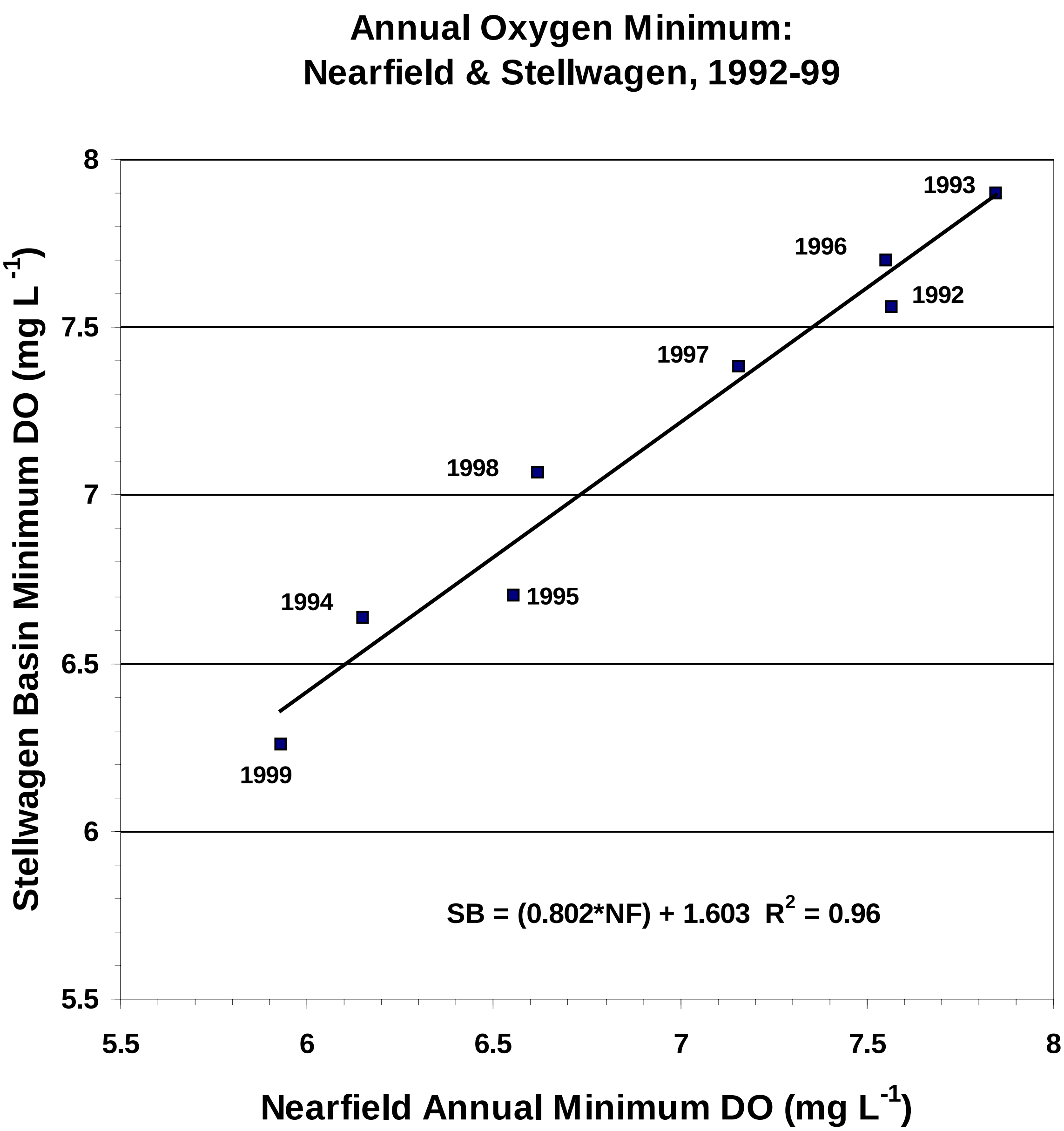


Figure 4-36. Annual DO minimum in nearfield and Stellwagen Basin – 1992-1999.

5.0 PRODUCTIVITY AND RESPIRATION

5.1 *Productivity*

Production measurements were made at two nearfield stations (N04 and N18) and one farfield station (F23) near the entrance of Boston Harbor. Station N04, an outer nearfield station has been monitored for phytoplankton production since 1992 and it is an important historical reference site. Station N18, located 1.5 km south of the outfall site has been monitored since 1997 when it was included in the survey because it is in a region potentially influenced by effluent when the outfall comes online. Both N04 and N18 were visited 17 times over the 1999 season for measuring production. Phytoplankton production at the Boston Harbor outer edge station, F23, was measured 6 times over the annual cycle in 1999. F23 has traditionally been sampled less frequently than the high-density nearfield productivity stations. Samples were collected at five depths throughout the euphotic zone and incubated in temperature controlled incubators. After collection of the productivity samples, they were returned to the Marine Ecosystems Research Laboratory (MERL) in Rhode Island. ^{14}C production was determined using standard procedures (e.g., Strickland and Parsons 1972). Chlorophyll concentrations presented and used for calculations in this section are extracted chlorophyll values. Details on the methods used for measuring and calculating production are provided in Albro *et al*. 1998 and Libby *et al*. 1999b. Production data for 1999 have been presented in detail in the semi annual report appendices (Libby *et al*. 1999a and 2000).

5.1.1 Nearfield Production

In 1999, the nearfield stations (N04 and N18) and the Boston Harbor station (F23) continued to exhibit different patterns in the seasonal cycle of primary productivity (Figure 5-1). Areal production in 1999 at the nearfield sites (N04 and N18) was characterized by both spring and fall blooms. Although absent in 1998, such blooms generally occur at these stations. The bloom periods exhibited an average 2-4-fold increase in productivity compared to non-bloom periods (summer and late fall). Areal production at the nearfield stations was relatively high (> 700 mg C m^{-2} d^{-1}) during the initial survey in early February. Values increased at both sites to major production peaks by late February, decreased somewhat during the third survey (March) then increased again to a second peak in early April. At both stations, the timing and extent of the spring blooms in production were similar. The peak bloom at station N04 occurred in late February with a production rate of 2147 mg C m^{-2} d^{-1}. Station N18 did not reach its maximum value at this time, but was characterized by an obvious peak in production (> 1500 mg C m^{-2} d^{-1}; Figure 5-1). The situation was reversed for the second spring production peak in early April. Areal production reached ~1650 mg C m^{-2} d^{-1} at station N04, while the spring peak in production for N18 of 2176 mg C m^{-2} d^{-1} was reached at this time. The spring bloom in 1999 was a typical winter-spring bloom numerically dominated by diatoms and microflagellates. *Chaetoceros* spp. were dominant at the nearfield stations N04 and N18 during both production peaks and were also dominant throughout Massachusetts and Cape Cod Bays suggesting a baywide bloom. The magnitude of the spring bloom in 1999 was similar to that observed in 1997 (2100 – 2600 mg C m^{-2} d^{-1}) for N18 and N04. The end of the winter-spring bloom period coincided with the onset of stratification and the depletion of nitrogen in the surface waters.

During the stratified summer period (see Section 3.4), areal productivity gradually increased from ~250-700 mg C m^{-2} d^{-1} in April to ~ 1400 – 2000 mg C m^{-2} d^{-1} in early August. Areal production at the nearfield stations (N04 and N18) was similar throughout most of this sampling period. Areal production was at its peak summer value (~1400 mg C m^{-2} d^{-1}) for station N04 in early August. Production at station N18 was somewhat higher at this time with a value of ~2000 mg C m^{-2} d^{-1}. The major difference in the annual productivity cycle between these stations occurred during the subsequent survey in mid-August. At station N04 areal productivity declined to less than 1000 mg C m^{-2} d^{-1}, while at station N18 productivity increased to the highest value recorded during 1999 (~3500 mg C m^{-2} d^{-1}). Productivity at station N18 (and also N16 where productivity was measured pre-1997) is generally greater than that observed at station N04. However, the elevated production in August of 1999 is somewhat unusual since it is greater than the productivity recorded at station F23, at the outer edge of Boston Harbor. This continues a trend first noted in 1997. In 1995 and 1996, the highest areal productivity values were recorded at station F23. Beginning in 1997, the highest areal productivity measurements over the annual cycle were recorded in the central nearfield region (station N18) rather than in Boston Harbor. The elevated productivity at station N18 coincided with elevated nitrate values and may have been related to coastal upwelling. The phytoplankton at station N18 were dominated by the diatom *Leptocylindricus danicus* during this period of elevated productivity, while station N04 was characterized primarily by microflagellates, the typical summer dominants.

Areal production at stations N04 and N18 was remarkably similar for the remainder of the 1999 monitoring period. A well-established fall bloom was observed at both stations (Figure 5-1). The bloom was initiated in late September, reached its peak (~1750 mg C m^{-2} d^{-1}) in late October and declined by the November survey. The bloom lasted about 8 weeks and was the same magnitude as the fall blooms observed in 1998 and 1997. The bloom peak was characterized by a 2-4-fold increase in diatom abundance relative to the preceding survey and coincided with the increase in nutrients associated with the breakdown of seasonal stratification. Productivity during the fall bloom was about 2-3 times greater than during the summer when stratification limited the supply of nutrients to the euphotic zone (see Section 4.1.1). Production decreased during the late November survey then reached its lowest annual level in December at station N04 and its second lowest value of the year at station N18. The fall productivity pattern observed in 1999 was similar to that observed in prior years, although peak values were somewhat depressed.

The vertical distribution of primary productivity (mg C m^{-3} d^{-1}) over the annual cycle at stations N04 and N18 indicated that the majority of production was occurring in the upper 10 m of the water column at both stations (Figures 5-2 and 5-3). The peaks in areal productivity reported during late February and early April at station N04 were concentrated in the surface water (Figure 5-2). At station N18, the initial productivity peak was also confined to surface waters (<5 m) but the secondary bloom in early April was distributed throughout the water column (Figure 5-3). At the two nearfield stations, surface production tended to decrease following the spring peak values but increased again in July. For both stations N04 and N18, the highest winter-spring production values observed (>200 mg C m^{-3} d^{-1}) occurred at the surface in late February. Peak production values tended to be correlated with the occurrence of the highest chlorophyll *a* measurements.

A subsurface (10-20 m) productivity maximum was measured at station N18 in June. A subsurface production maximum was also observed at station N04 during the June survey, however, the peak depth of occurrence was observed at ~ 12 m (Figures 5-2 and 5-3). Subsurface productivity maxima tended to occur at both station N04 and N18 during June and July 1999.

The volumetric data reveal that the increased areal productivity (>120 mg C m^{-3} d^{-1}) reported during late summer (2 August 1999) at station N04 was concentrated in the upper 5 m of the water column (Figure 5-2). Areal productivity at station N18 was also elevated during early August, with high values observed in the surface and mid-surface waters at depths less than 5 m (Figure 5-3). At station N18, the annual productivity peak occurred in mid-August and was distributed throughout the upper 10 m of the water column with values from the surface to mid-depth samples ranging from ~280-390 mg C m^{-3} d^{-1} (Figure 5-3). At the two-nearfield stations, surface productions tended to decrease following the late summer peak values, but increased again in late October. For station N04, the highest production values observed (~220 mg C m^{-3} d^{-1}) occurred at the surface in late February and early April 1999. For station N18, the highest production value observed (~390 mg C m^{-3} d^{-1})

was recorded at mid-depth (6.75 m) in August 1999. Peak production values tended to be correlated with the occurrence of the highest chlorophyll *a* measurements.

The subsurface (5-6.75 m) productivity maximum measured at station N18 in mid-August was a major component of the elevated areal productivity recorded. Station N04 did not exhibit a subsurface elevation in productivity, thus accounting for the wide difference in areal production between the nearfield sites during the mid-August survey. This situation was reversed during the fall bloom period. A subsurface production maximum was observed at station N04 during the late October survey, but not at station N18. The productivity pattern at specified depths observed in 1999 was similar to that observed in prior years. At station N04, productivity >20 mg m^{-3} d^{-1} was rarely observed at depths >20 m. At station N18, productivity as high as 60 mg C m^{-3} d^{-1} was recorded at a depth of 20 m with values from 10-30 mg C m^{-3} d^{-1} were frequently observed at those depths.

The annual pattern of average chlorophyll (Figure 5-4) for the nearfield stations N04 and N18 followed the pattern observed for areal production. The winter-spring diatom bloom resulted in elevated phytoplankton biomass during the bloom period and subsurface chlorophyll accumulation in approximately two weeks (Figures 5-4, 5-5 and 5-6). The dominant annual feature for chlorophyll in 1999 was the fall bloom, with 2-4 fold increases in biomass relative to earlier in the year (Figure 5-4). Average chlorophyll values for station N04 and N18 (Figure 5-4) and the vertical distribution of chlorophyll (Figures 5-5 and 5-6) indicated that chlorophyll concentrations were elevated in the spring and fall periods and that subsurface chlorophyll maxima were typical during most periods of elevated phytoplankton biomass. Particularly well-developed sub-surface chlorophyll maxima were associated with the fall phytoplankton bloom. At station N18, elevated chlorophyll values were observed at all depths (surface through bottom samples, maximum depth ~25 m) during the fall bloom. At station N04, the high chlorophyll values also occurred to a depth of 25 m, but because of the greater water column depth at this eastern nearfield station high chlorophyll concentrations were confined to the upper half of the water column.

5.1.2 Harbor Production

At the Boston Harbor productivity/respiration station (F23), areal production was measured six times from February through October 1999 (Figure 5-1). Production ranged from a low of ~200 mg C m^{-2} d^{-1} in early February to a peak value of ~3000 mg C m^{-2} d^{-1} in April 1999. Production was still elevated in June at ~2850 mg C m^{-2} d^{-1}. By August, production declined to 50% of the peak spring-summer values. In October, production was lower than August and did not display the peak annual levels that were observed at the two nearfield sites (Figure 5-1). The production data are in agreement with the chlorophyll data (Figure 5-4), which indicated that the annual peak in both chlorophyll and production occurred during spring at the Harbor station.

The vertical distribution of primary productivity (mg C m^{-3} d^{-1}) over the annual cycle at station F23 indicated that the majority of production was occurring in the upper 5 m of the water column (Figure 5-7). This shallow harbor station is in a poorly stratified region. Production rates and average chlorophyll values were in exceptionally close agreement at this station. Despite the low temporal resolution, samples were collected during both the winter-spring and the fall bloom periods at stations N04 and N18. In contrast to the nearfield, the harbor did not exhibit a predominant spring or fall bloom, although the peak observed productivity occurred at the same time as the spring bloom in the nearfield region.

Average chlorophyll for station F23 (Figure 5-4) and the vertical distribution of chlorophyll (Figures 5-8) indicated that chlorophyll concentrations were elevated in the spring (April and June 1999). Subsurface chlorophyll maxima occurred during the periods of elevated phytoplankton biomass. The contour plots of production versus biomass suggest that the subsurface chlorophyll maxima contributed to areal production in the upper 5 m of the water column. In general, at station

F23, chlorophyll values increased gradually until the peak spring values then decreased again throughout the fall. Production in the harbor was considerably elevated compared to 1998 and continued to show a distinctly different annual cycle when compared to the stratified nearfield sites.

5.1.3 Chlorophyll-Specific Production

Chlorophyll-specific areal production (Figure 5-9, shown in comparison with areal production for all stations) exhibited both spring and summer peaks at stations N04 and N18. Chlorophyll-specific production is an approximate measure for the efficiency of production. The distribution of chlorophyll-specific production indicates that the efficiency of production was high relative to the amount of biomass present at the nearfield stations, particularly prior to the fall period. At both stations N04 and N18 the peak chlorophyll-specific production occurred after the cessation of the winter-spring production peak. By contrast, efficiency of production was low at the Harbor site relative to biomass availability throughout the annual cycle. At the nearfield sites, the late-spring peaks observed in chlorophyll-specific areal production followed a period of elevated areal production (the winter-spring bloom) and increased phytoplankton biomass (Figure 5-4). By contrast, the late summer peaks preceded a period of increased areal production and elevated chlorophyll *a* at station N18 and coincided with the peak summer production at N04.

Chlorophyll-specific areal production was very similar at both nearfield sites (station N04 and N18) over time (Figure 5-9). Chlorophyll-specific areal production was relatively low at the start of the sampling period then gradually increased at both stations until the seasonal maxima were reached during the mid-May survey. Seasonal maxima were ~1100 mg C mg Chl a^{-1} d^{-1}. Following these peak values chlorophyll-specific areal production decreased to less than 450 mg C mg Chl a^{-1} d^{-1} in June 1999 then gradually climbed again reaching late summer peaks in late July – early August (700 - 1000 mg C mg Chl a^{-1} d^{-1}). Chlorophyll-specific areal production then gradually decreased at both stations until the seasonal minima were reached during the late September survey (< 50 mg C mg Chl a^{-1} d^{-1}). Values then gradually climbed to between 100-300 mg C mg Chl a^{-1} d^{-1} for the remainder of the sampling period. Chlorophyll-specific areal production was relatively low and constant at station F23 ranging from ~150-375 mg C mg Chl a^{-1} d^{-1} over the annual cycle.

The spatial and temporal distribution of chlorophyll-specific production on a volumetric basis were summarized by contour plots over the sampling period (Figures 5-10 to 5-12). Chlorophyll-specific production can be used as an indicator of the optimal conditions necessary for photosynthesis. Chlorophyll-specific daily production was concentrated in the upper 10 m of the water column at station N04 during the sampling cycle (Figure 5-10). Peak values were observed in the upper 5-m during the spring bloom periods and during early August. During the spring and early summer moderate production per unit chlorophyll was observed at depths of 10-20 m but absent during the late summer and fall at station N04. Chlorophyll-specific production was relatively low at all depths greater than 20 m.

Chlorophyll-specific production at station N18 was also concentrated in the upper portions of the water column (Figures 5-11). Peak chlorophyll-specific production occurred in the upper 5-7 m of the water column similar to observations recorded at station N04. Elevated chlorophyll-specific productions occurred during May and late July at station N18. The observed pattern at station N18 suggests that the efficiency of photosynthesis continued to be relatively high and variable throughout the spring and early summer then declined again during the late summer period of low nutrients and stratification. Efficiency increased again in the fall. When the efficiency of photosynthesis is high but not reflected in higher phytoplankton biomass (measured as total chlorophyll *a*) it suggests that other processes (such as predation by zooplankton) were important in controlling the patterns observed.

At station F23, chlorophyll-specific production was concentrated in the upper 10 m throughout the annual cycle (Figure 5-12). Chlorophyll-specific production was elevated during the summer period of peak phytoplankton production at this station. There was some evidence of increased phytoplankton efficiency during the spring and fall bloom periods as well at this station.

5.1.4 Potential Production

Potential production for a cloudless day was calculated for each day production was measured and at all five depths. Figure 5-13 provides examples of the daily photosynthetically active irradiance on both the sampling day and a cloudless day close in time to the day of sampling for the first six surveys. Daily light was highly variable because of clouds as expected. Light ranged from being relatively low (cloudy) as on 7 February and 29 April to close to that expected on a cloudless day as on 27 February and 20 March. When the daily light field for a cloudless day was substituted for the observed cloudy-day light field it was possible to determine the potential (or maximum) production for each sample period. Figure 5-14 shows the potential daily production (mg C m^{-3} d^{-1}) for each station and depth over the annual cycle. The seasonal pattern closely followed that observed for daily production suggesting that no major production peaks were missed because of dense cloud cover. For station N04 the spring and fall blooms remained the dominant features of the annual cycle. For station N18, the late summer production peak dominated the seasonal cycle but the spring and fall bloom periods were also very well represented. Similarly for station F23, the gradual increase to a seasonal spring production peak followed by a decline was observed.

The potential and measured areal productions (mg C m^{-2} d^{-1}) are compared over the seasonal cycle for each station in Figure 5-15. Although potential production was approximately 50% greater than measured production on some dates (29 April) the over all pattern was very similar. By chance, cloudy days tended to occur during periods of very low productivity with the exception of the late April survey. Potential annual production (g C m^{-2} y^{-1}) at each station was about 30 - 135 g C m^{-2} y^{-1} greater than measured production (see inset on Figure 5-15 with higher values being the annual potential productivity).

5.1.5 P-I Curve Parameters

The response of phytoplankton to changes in their physical environment is frequently characterized by indices of photoadaptation of the phytoplankton populations. Two such indices are α [mg C m^{-3} hr^{-1} (μE m^{-2} s^{-1})$^{-1}$] or α^B [mg C (mg Chl *a*)$^{-1}$ hr^{-1} (μE m^{-2} s^{-1})$^{-1}$] and P_{max} (mg C m^{-3} hr^{-1}) or P^B_{max} (mg C mg Chl a^{-1} hr^{-1}), the parameters derived from the photosynthesis versus irradiance curves. The utility of α^B and P^B_{max} for comparing phytoplankton populations was demonstrated by Harrison and Platt (1980) who showed that the parameters were sensitive to a wide range of environmental variables. Cote and Platt (1984) also demonstrated that the effects of transient physical phenomena, such as storms and periods of upwelling are reflected in changes in photosynthetic parameters. Changes in these indices may thus define response to a dynamically changing physical environment.

Examination of α [mg C m^{-3} hr^{-1} (μE m^{-2} s^{-1})$^{-1}$] and α^B mg C (mg Chl *a*)$^{-1}$ hr^{-1} (μE m^{-2} s^{-1})$^{-1}$ over the season (Figures 5-16 and 5-17) revealed some interesting differences. The time series data for nearfield stations N04 and N18 (Figure 5-16) clearly demonstrated the tendency for α to vary with primary productivity over the seasonal cycle. There was a marked 3-4-fold increase in α at the time of the spring and fall blooms at both stations. Additionally, station N18 shows a marked increase during the August period of elevated production. During the fall bloom period, as well as at other times of the year, there was a tendency for α to decrease with depth. A similar tendency has been noted in previous years (Libby *et al*. 1999b). At station F23, α showed similar variability over the annual cycle, with a 2-4 fold increase in April during the period of peak productivity. Interestingly, α was not elevated at F23 during the June period of similarly high productivity.

By contrast, α^B (Figure 5-17) was characterized by sporadic periods of elevated values at the nearfield sites. The previously observed tendency for decreasing values of α with depth was not as consistent when α was normalized to biomass. At station F23, α^B was relatively constant over the seasonal sampling period.

Similar contrasts exist when the seasonal values for P_{max} (mg C m^{-3} hr^{-1}) and P^B_{max} (mg C mg Chl *a*$^{-1}$ hr^{-1}) are compared (Figures 5-18 and 5-19). P_{max} essentially followed the seasonal patterns observed for both production at depth (mg C m^{-3} d^{-1}) and areal production (mg C m^{-2} d^{-1}) (Figure 5-1). At the nearfield sites, P_{max} exhibited seasonal peaks during the spring and fall bloom periods, as well as a marked increase at station N18 during the August production maximum. The seasonal pattern was also very similar to that observed for α (Figure 5-16). Additionally P_{max} also displayed a tendency to vary with depth. At station F23, the observed time series for P_{max} was very similar to the seasonal pattern observed for areal productivity at that site (Figure 5-1).

P^B_{max} was considerably less variable over the seasonal cycle than either P_{max} or α^B at the nearfield stations (Figure 5-19). At station N18, P^B_{max} was relatively constant from mid-June through December. Minor peaks occurred during the spring and were typically observed at single depths only. At station N04, peaks were somewhat more frequent and often included multiple rather than single depths. At station F23, the biomass-normalized values for P_{max} varied considerably with depth and over the annual cycle. The seasonal changes in magnitude of the P-I curve parameters were very different at the nearfield stations compared with station F23. At the nearfield sites, the spring increase in photosynthetic indices is most likely tied to improved light availability as the season progresses. Increases at other times of the year were related to improved nutrient availability either as a result coastal upwelling (station N18, August) or the breakdown of stratification in the fall (station N04 and N18).

Because of the close similarity in the station-specific seasonal patterns between α and P_{max}, we regressed the estimated parameters of the P-I curves against each other to examine the strength of the suggested relationship (Figure 5-20). A significant ($P<0.0001$) and positive relationship exists between the parameters even when they are normalized to biomass (Figure 5-20). When we examined the data from 1995-98, we noted similar positive relationships ($P<0.0001$) (Figure 5-21). The slope of the relationship between α and P_{max} is lower in 1995-98 compared with 1999, but there is no significant difference in the slope of the equations for α^B versus P^B_{max} over time ($P>0.05$, ANCOVA). A number of studies have similarly demonstrated a correlation between α^B and P^B_{max} (Harding *et al*. 1982, 1983, Cote and Platt 1984, Forbes *et al*. 1986). Such a correlation is considered important if P^B_{max} is to be used as an index of phytoplankton response to environmental variables since it implies a similar variation in photosynthetic rate at any specified irradiance (Forbes *et al*. 1986).

The frequency distributions for the biomass normalized P-I curve parameters are shown in Figures 5-22 and 5-23 for each station and for all station combined. Examination of the frequency distributions for α^B at the 3 stations did not reveal discernable differences between the sample sites (Figure 5-22). When all data were pooled, a positively skewed distribution was observed for α^B with a mean value of 0.031 mg C (mg Chl *a*)$^{-1}$ hr^{-1} and nearly all of the values were below the theoretical maximum of 0.11 mg C (mg Chl *a*)$^{-1}$ hr^{-1} (Cleveland *et al*. 1989, Lohrenz *et al*. 1994). Only 5 of 200 samples (2.5%) exceeded an α^B value of 0.12; values greater than the theoretical maximum have also been reported by others (Lohrenz *et al*. 1994, Cibik *et al*. 1996). The values determined for 1999 are very close to the mean value (0.048) reported by Cibik *et al*. (1996) for the 1995 dataset but lower than the mean (0.06) reported by Kelly and Doering (1995) for 1994. However, when the frequency distribution for 1999 is compared to the combined data for 1995-98 there is a slight shift to the left in the distribution pattern (Figure 5-24). The frequency distribution for α^B in 1999 is much closer to the long term distribution pattern than that observed in 1998, a year with no spring bloom.

The frequency distributions for P^B_{max} (mg C mg Chl a^{-1} hr^{-1}) at stations N04, N18 and F23 were also not distinguishable from each other (Figure 5-23). Pooled data revealed a positive skewness (n=200), but no evidence of a bimodal distribution as was suggested in 1995 (Cibik *et al*. 1996). No values were greater than the theoretical maximum of 25 (Lohrenz *et al*. 1994). The mean value (2.79 mg C mg Chl a^{-1} hr^{-1}) is lower than mean values reported in 1995 (Cibik *et al*. 1996) and 1994 (Kelly and Doering (1995). However, the distribution pattern in 1999 is very similar to the pooled data for 1995-98 (Figure 5-24).

To summarize our analysis of the P-I curves parameters we noted:

- seasonal patterns were similar between stations N04 and N18 but different from F23
- parameter values tended to decrease with increased depth in the water column
- chlorophyll-specific parameters increased during the spring and the fall bloom periods
- the noted increases in photosynthetic indices were most likely tied to elevated light levels during the spring and improved nutrient availability in the summer (coastal upwelling) and fall (breakdown of stratification)
- photosynthetic parameters (normalized and not normalized to biomass) were significantly ($P<0.05$) and positively correlated in 1999, as well as in 1995-98
- frequency distributions were similar between 1999 and the pooled data from 1995 through 1998.

5.1.6 Comparison with Prior Years

Unlike production in 1998, areal production at all three-survey stations in 1999 followed the typical pattern observed for productivity in most years (Figures 5-25 and 5-26). In general, nearfield stations are characterized by the occurrence of a winter/spring phytoplankton bloom, variable production during the summer and a fall bloom (Figures 5-25 and 5-26). With the exception of the unusual elevated productivity at station N18 in August 1999, productivity at the nearfield sites followed the generally observed pattern. A gradual pattern of increasing areal production from winter through summer is more typical of the harbor station F23 (Figure 5-25). When the seasonal patterns at station F23 are compared from 1995 through 1998, the peak production values were observed to decline over time (Figure 5-25). In 1999, production values at F23 increased to values observed in prior years. During 1995-1998, peak areal productions at station F23 ranged from 1000 to 8000 mg C m^{-2} d^{-1}. The peak areal production observed at station F23 in 1999 was ~3000 mg C m^{-2} d^{-1} – a value 3-times greater than the peak values observed in1998. The apparent decrease in productivity at this station from 1995 to 1998 was shown to be coincidental and not an established trend with time.

The spring phytoplankton blooms observed at the nearfield stations from 1995-1998 typically reached values ranging from ~225 – 3000 mg C m^{-2} d^{-1}. The magnitude of the spring bloom in 1999 was close to the magnitude observed in 1997 (2100 –2600 mg C m^{-2} d^{-1}), but much greater than the unusually low spring productivity observed in 1998. The fall phytoplankton blooms observed at nearfield stations (N04, N16 and N18) in 1995-1998 generally reached values of 1600 to 4000 mg C m^{-2} d^{-1}, with blooms typically lasting 1-2 months (Figures 5-25 and 5-26). The fall phytoplankton bloom during 1999 fell at the lower end of this range with peak values of ~1800 mg C m^{-2} d^{-1} at station N04 and ~1700 mg C m^{-2} d^{-1} at station N18. The late August bloom at station N18 was not observed in prior years.

In general, chlorophyll-specific production was low in 1999 compared with 1995-97, but close to the values observed in 1998 (see for example stations F23 and N04, Figure 5-27). The annual productivity estimates in 1999 at all three stations were much higher than those observed in 1998 (a year with no spring phytoplankton bloom), but intermediate to values observed from 1992 through 1997 (Figure 5-28).

Cibik *et al*. (1998b) observed a tendency for the winter-spring phytoplankton bloom to begin offshore and follow a gradient from offshore to nearshore waters. The results from 1999 further support this observation. The bloom was initially (27 February) most intense at the offshore station (N04) followed by a later (7 April) peak in intensity at stations N18 and F23. A gradient in light penetration is thought to be the underlying factor (Cibik *et al*. 1998b).

5.1.7 Modeling of Phytoplankton Production

As in prior years, we empirically examined the relationship between measured photic zone productivity (mg C m^{-2} d^{-1}) and a composite function (BZ_pI_0) derived by Cole and Cloern (1987) where B is phytoplankton biomass (mg Chl *a* m^{-3}), Z_p, the photic depth (m) and I_0 surface irradiance (E m^{-2} d^{-1}). Significant linear relationships ($P<0.05$) were found for all stations in 1999 (Figure 5-29). The relationships for the nearfield sites were much improved when outliers (2 at N04 and 3 at N18, values shown as open circles in the figure) were removed. Examination of the data revealed that the outliers represented time periods when deep subsurface chlorophyll maxima were present. These deep subsurface chlorophyll maxima resulted in elevated photic zone chlorophyll concentrations that did not contribute to organic carbon production as efficiently as predicted by the model. In Table 5-1 we compare the slope of the equations developed in 1999 with those uncovered in previous years. Based on these values it is apparent that the slope of the equation is variable both between stations and among years. The model may allow increased temporal and spatial coverage of productivity within the system under study if the source of the observed variability in the slope is uncovered.

Table 5-1. Slope of Equation $P = mBZ_pI_0 + b$ from 1994 through 1999.

	Station		
Year	**F23**	**N04**	**N16-18**
1994	0.56	0.56	0.56
1995	1.87	0.39	0.64
1996	0.88	0.23	0.56
1998	0.22	0.28	0.31
1999	0.44	0.38	0.23

Because of the variability in the above fitted relations, we also regressed both areal productivity (mg C m^{-2} d^{-1}) and the parameters of the P-I curves (P_{max} and α) against phytoplankton biomass (mg Chl *a* m^{-3}). An alternative approach for modeling production might be to predict the parameters of the P-I curves from measured variables and then use the predicted values to calculate production on a daily basis. The results from the linear regression of areal production versus mean chlorophyll *a* are seen in Figure 5-30. For station F23 the r^2 values for production as a function of biomass are greater than for the composite factor, but both relationships are significant with $P<0.05$. For the nearfield sites the results were variable and again required the removal of the outliers representing the periods when subsurface chlorophyll maxima were present but not contributing efficiently to productivity. For station N04 the relationship explained less of the variability in productivity while for N18 the results were equivalent. In both cases the relationships were significant ($P<0.05$). Biomass alone is capable of explaining 31-84% of the variation in production at the three stations.

The relationships between the P-I curve parameters and phytoplankton biomass were highly significant ($P<0.05$) as well (Figures 5-31 and 5-32). Between 42-68% of the variation in the parameters was accounted for by chlorophyll *a*. The best fit was obtained at station F23. At the nearfield sites the fit was again improved by removal of the outliers (values shown as open circles in the figure) which occurred during the period of subsurface chlorophyll maxima. The prediction of P-I curve parameters as a function of biomass may prove to be an alternative approach for modeling production.

5.1.8 Production Summary

The major features established by the analysis of production measurements during 1999 were as follows:

- annual productivity at stations N04, N18 and F23 was intermediate between values observed in prior years
- during 1999 the seasonal productivity pattern was generally typical of that observed in prior surveys, with distinct spring and fall blooms at the nearfield sites and a gradual increase in productivity followed by a gradual decline at station F23
- bloom periods exhibited an average 2-4 fold increase in productivity compared to non-bloom periods (summer and late fall)
- an unusual late summer bloom occurred at station N18 with an important subsurface component
- the observed apparent decline in productivity at station F23 from 1995-98 was reversed with 1999 values intermediate between 1996 and 1997
- productivity was significantly correlated with the composite parameter BZ_pI_0 (but the relation was variable across years and influenced by the presence of subsurface chlorophyll maxima).

5.2 Respiration

Respiration measurements are made at the same nearfield (N04, N18) and farfield (F23) stations as productivity and at an additional station in Stellwagen Basin (F19). All four stations are sampled during each of the 6 combined farfield/nearfield surveys and stations N04 and N18 are also sampled during the other 11 nearfield surveys. Due to electrical problems with the incubators, there are no respiration data for the early February survey (WF991). The data for the April survey (WF994) have been qualified in the database as suspect because incubator temperatures increased to ~10°C for 24 to 48 hours. The *in situ* temperatures for the WF994 respiration samples were 5.0 ± 2.0 °C. The increase in incubator temperature to 10 °C for a short time period probably had a negligible effect on the respiration rates for these samples and the data have been included in this report.

Respiration samples are collected from three depths (surface, mid-depth, and bottom) and incubated in the dark at *in situ* temperatures for 8±1 days. Respiration rates are calculated based on the difference in initial and final dissolved oxygen concentrations (each measured in triplicate; see Albro *et al*. 1998 for details). Both respiration (in units of μM O_2 hr^{-1}) and carbon-specific respiration (μMO_2 μMC^{-1} hr^{-1}) rates are presented in the following sections. Carbon-specific respiration was calculated by normalizing respiration rates to the coincident particulate organic carbon (POC) concentrations. Carbon-specific respiration rates provide a relative indication of the biological availability (labile) of the particulate organic material for microbial degradation.

5.2.1 Water Column Respiration

During the surveys conducted in February (WF992) and March (WN993), respiration rates were generally low in the nearfield area (<0.10 μMO_2 hr^{-1}) and comparable over depth (Figure 5-33). By April (WF994), respiration rates had increased 2 to 4-fold in the nearfield (0.1 to 0.4 μMO_2 hr^{-1}). Similar increases were observed at Harbor station F23 and less significant increases at offshore station F19 (Figure 5-34). Respiration rates reached a maximum for 1999 in the nearfield in early May (WN995) with rates at station N18 ranging from 0.5 to 0.8 μMO_2 hr^{-1} with the highest rate observed in the mid-depth waters (Figure 5-33a). Respiration rates were lower at station N04, but continued to increase from the levels observed during the April survey (Figure 5-33b). The increase in respiration rates in April was coincident with the peak production values observed for the winter-spring bloom. By early May, the senescent bloom may have fueled the high respiration rates that were observed as the readily available labile organic material was degraded. Respiration rates during this time period were generally higher in the surface and mid-depth waters where the temperatures were warmer and higher rates of primary production were observed.

By mid-May (WN996), respiration rates remained relatively high, but had decreased to 0.2 to 0.35 μMO_2 hr^{-1} in the nearfield. At station N18, they continued to decrease into June reaching rates of ≤0.10 μMO_2 hr^{-1} over the entire water column. At station N04, respiration rates in the mid-depth and bottom waters decreased to levels comparable to those observed at station N18. The respiration rate in surface water at station N04, however, increased to ~0.65 μMO_2 hr^{-1}, which was coincident with an increase in surface water respiration at offshore station F19 (Figure 5-34b). In the Harbor, respiration rates had decreased from the maximum levels observed in April, but were generally higher than those observed at the three other stations (except station N04 surface water; Figure 5-34a).

Nearfield respiration rates remained relatively low (<0.20 μMO_2 hr^{-1}) during the July surveys with the highest values being observed in the surface waters at station N18. By early August (WN99A), respiration rates had increased to ~0.25 μMO_2hr^{-1} in the surface and mid-depth waters at N18 and surface waters at N04. Nearfield respiration rates reached a summer maximum during the late August survey (WF99B) with rates reaching 0.3 μMO_2hr^{-1} in the surface and mid-depth waters at station N18 (Figure 5-33a). This was coincident with elevated chlorophyll concentrations and very high production at this station. Respiration rates at station N04 had decreased to 0.16 μMO_2hr^{-1} at the surface and increased to 0.1 μMO_2hr^{-1} in mid-depth waters. Bottom water respiration rates remained low (<0.05 μMO_2hr^{-1}) at station N04 for the remainder of 1999. At harbor station F23, respiration rates continued to decline from the maximum values observed in April and ranged from 0.1-0.2 μMO_2hr^{-1} (Figure 5-34a). Respiration rates at the Stellwagen Basin station F19 exhibited a similar pattern with surface respiration decreasing from June to August, while mid-depth and bottom water respiration rates remained <0.1 μMO_2hr^{-1} (Figure 5-34b).

By early September (WN99C), respiration rates in the surface and mid-depth waters of both nearfield stations had decreased to 0.09 to 0.13 μMO_2hr^{-1}. In late September (WN98D), respiration rates had increased slightly over the entire water column at each of the stations reaching values of ~0.2 μMO_2/hr in the surface and mid-depth waters at station N04 and ~0.15 at those depths at N18. The increase was coincident with an increase in chlorophyll levels in late September. During the October surveys (WF99E and WN99F), an increase in production was observed at stations N04 and N18, but chlorophyll concentrations were lower than those observed in August and September. Respiration rates remained comparable to those observed in September and ranged from 0.10-0.17 μMO_2hr^{-1} at the surface and mid depths. Bottom water rates remained low at station N04 (<0.03 μMO_2hr^{-1}), but increased by late October to 0.13 μMO_2hr^{-1} at station N18. Respiration rates decreased with the decreasing water temperatures through November (WN99G) and December (WN99H). By late November, respiration rates were <0.1 μMO_2hr^{-1} at each of the depths at stations N04 and N18.

5.2.2 Carbon-Specific Respiration

Carbon-specific respiration accounts for the effect variations in the size of the particulate organic carbon (POC) pool have on respiration. Differences in carbon-specific respiration result from variations in the quality of the available particulate organic material or from environmental conditions such as temperature. Particulate organic material that is more easily degraded (more labile) will result in higher carbon-specific respiration. In general, newly produced organic material is the most labile. Water temperature is the main physical characteristic that controls the rate of microbial oxidation of organic material – the lower the temperature the lower the rate of oxidation. When stratified conditions exist, the productive, warmer surface and/or mid-depth waters usually exhibit higher carbon-specific respiration rates and bottom waters have lower carbon-specific respiration rates due to both lower water temperature and lower substrate quality due to the degradation of particulate organic material during sinking. POC was not measured at station F19, therefore the discussion in this section focuses on the nearfield (N04 & N18) and Harbor (F23) stations. It is recommended that POC measurements be added to the suite of parameters measured at F19. The relatively small increase in effort and cost would provide a more complete representation of respiration in the offshore waters.

There was a general increase in POC concentrations from February to April. POC then decreased and remained relatively low through July. Levels increased again in August and reached annual maxima in the nearfield in September (Figure 5-35). This is consistent with the pattern observed in chlorophyll. POC concentrations at the harbor station increased during the month of February, remained relatively high through April, and then decreased over the August and October 1999 farfield surveys. POC concentrations were higher at the harbor station than in the nearfield from February to June, but were much lower than the nearfield POC concentrations in August and October (Figure 5-35).

Carbon-specific respiration rates reached a maximum over the water column at station N18 in early May (0.035-0.045 $\mu MO_2\,\mu MC^{-1}\,hr^{-1}$; Figure 5-36). POC concentrations had decreased to ~20 µMC at the nearfield stations by early May coincident with significant decreases in chlorophyll concentration and production rates due to the senescence of the winter-spring bloom. The increase in carbon-specific respiration rates at station N18 may have been due to the presence of a more labile pool of POC, but is more likely due to elevated concentrations of dissolved organic carbon (DOC), which reached a seasonal peak of >400 µMC in early May (Figure 5-37).

Except for the mid-May peak in carbon-specific respiration at station N18 and peaks observed in the surface water at station N04 in May and June, carbon-specific respiration remained relatively low (<0.01 $\mu MO_2\,\mu MC^{-1}\,hr^{-1}$) at the three stations in 1999 (Figure 5-36). Although nearfield water column respiration rates increased in the late summer and fall (Figure 5-33), coincident increases in POC concentrations resulted in little change in carbon-specific respiration rates. Given the high chlorophyll concentrations and production rates at station N18 in late August and the increase in POC concentrations by early September that resulted, it could be expected that carbon-specific respiration would increase with the increased availability of newly produced, labile organic carbon. The lack of an increase in carbon-specific respiration at N18 may be indicative of the timing of the bloom and surveys. In late August, respiration and production reached maximum levels for the summer and fall at station N18 and relatively high POC and chlorophyll concentrations were measured. The late August survey may have been conducted at the beginning of this late summer diatom bloom (supported by increases in POC and chlorophyll from late August to early September). An increase in respiration rates had been observed from earlier in the month, but respiration had not caught up with production at the time of sampling. By early September, production values had greatly decreased at N18 and although POC concentrations were very high, the carbon-specific respiration rates were relatively uniform. This suggests that less labile carbon was present and that the early September survey was conducted near or after the conclusion of this late summer diatom bloom. There was also a large decrease in DOC concentrations at station N18 from the August surveys to the early September survey (Figure 5-37).

5.2.3 1992-1999 Interannual Comparison

A comparison of bottom water respiration rates for the entire baseline period shows that the magnitude of the rates observed in the nearfield were substantially higher in the spring of 1999 than at any other time from 1992 to 1998 (Figure 5-38a). As mentioned previously, the high respiration rate observed in April at station N18 was coincident with the peak production values observed for the winter-spring bloom and by May, the failure of the bloom may have fueled high respiration rates as labile organic material was degraded. The abnormally high respiration rates observed in the nearfield in 1999 may have contributed to the unprecedented low DO concentrations that were observed during the fall of 1999. As noted in Section 4.3, the June bottom water DO concentrations, which have been used as a measure of DO at the start of strongly stratified summer conditions, in 1999 were among the lowest observed for the baseline period. Respiration rates during the remainder of 1999 were comparable to those observed during previous years.

The magnitude of bottom water respiration rates at Boston Harbor station F23 were comparable to previous years, but the occurrence of the annual maximum in April deviated from the more typical pattern of a summer peak in bottom water respiration (Figure 5-38b). The April maximum in bottom water respiration was coincident with peak POC concentrations at station F23 (see Figure 5-35c). Bottom water respiration rates at offshore station F19 have remained relatively low and consistent from 1995 to 1999.

5.2.4 Respiration Summary

Trends in the respiration data followed those observed with other biological and biomass parameters. In the winter/spring, the seasonal bloom and high production rates led to relatively high biomass (POC and chlorophyll). The availability of labile particulate and dissolved material following the bloom resulted in high respiration rates in the nearfield. The substantial increase in chlorophyll and phytoplankton abundance in late summer was matched by increasing POC concentrations and respiration rates.

The major features established by the analysis of respiration measurements during 1999 were as follows:

- The increase in respiration rates in April was coincident with the peak production values observed for the winter-spring bloom and the cessation of the bloom by early May fueled the high respiration rates as the readily available labile organic material was degraded.
- By early May, significant decreases in POC and chlorophyll concentrations and production rates had occurred due to the senescence of the winter-spring bloom. Carbon-specific respiration rates, however, increased considerably and achieved maxima of 0.035-0.045 $\mu MO_2\ \mu MC^{-1}\ hr^{-1}$, likely in response to elevated DOC concentrations.

- Nearfield respiration rates reached a secondary maximum during the late August survey at station N18 coincident with elevated chlorophyll concentrations and very high production.
- At station N18, POC concentrations increased sharply from late August to early September reaching annual maximum of 175 μM in mid-depth waters. The high POC concentrations were consistent with the trends observed in chlorophyll and the large increase from late August to early September may have resulted from the high production that was observed in late August.
- Carbon-specific respiration rates were low, however, from late August through September. The lack of a relationship between carbon-specific respiration and the high production rates observed in mid-August suggests that the WF99B (mid-August) and WN99C (early September) surveys may have been conducted before and after the height of the late summer diatom bloom.
- Bottom water respiration rates in the nearfield were substantially higher in the spring of 1999 compared to previous baseline monitoring results. These abnormally high respiration rates may have been a contributing factor to the unprecedented low DO concentrations that were observed during the fall of 1999.

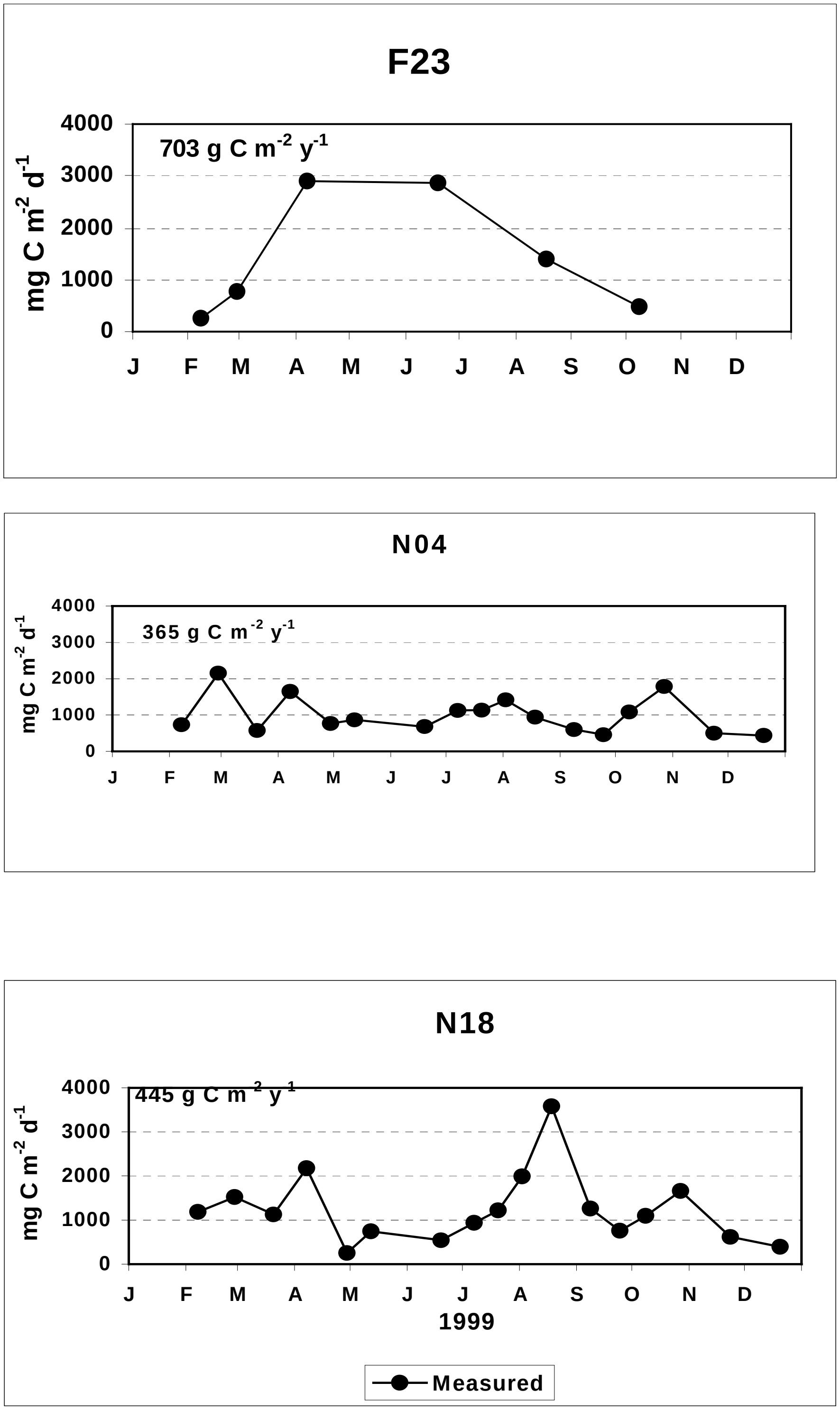


Figure 5-1. Areal production ($mgCm^{-2}d^{-1}$) for stations F23, N04, and N18 over the 1999 annual cycle. Annual production ($gCm^{-2}y^{-1}$) is indicated in the inset of each panel.

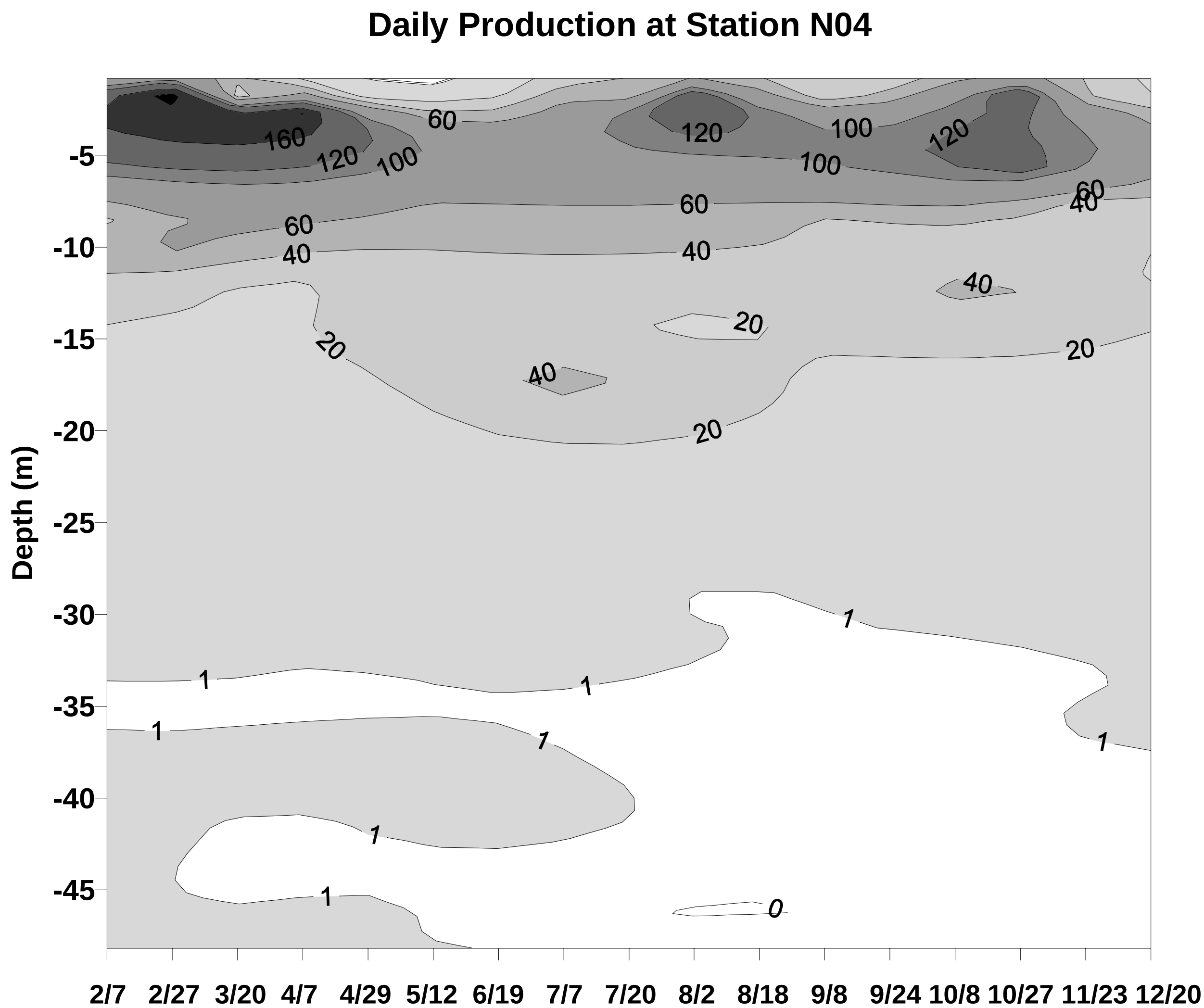


Figure 5-2. Time series of contoured daily production (mgC$m^{-3}d^{-1}$) over depth (m) at station N04.

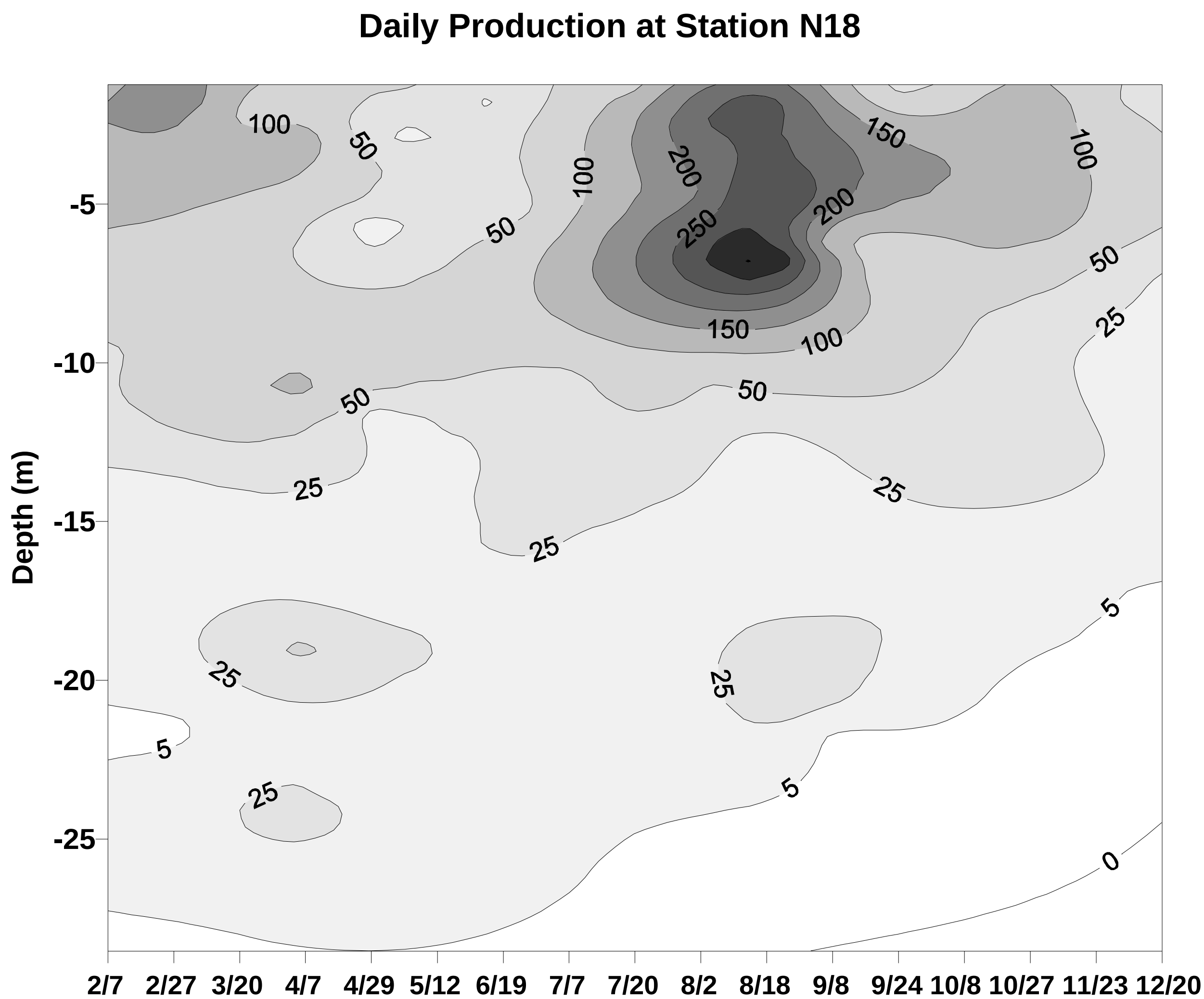


Figure 5-3. Time series of contoured daily production ($mgCm^{-3}d^{-1}$) over depth (m) at station N18.

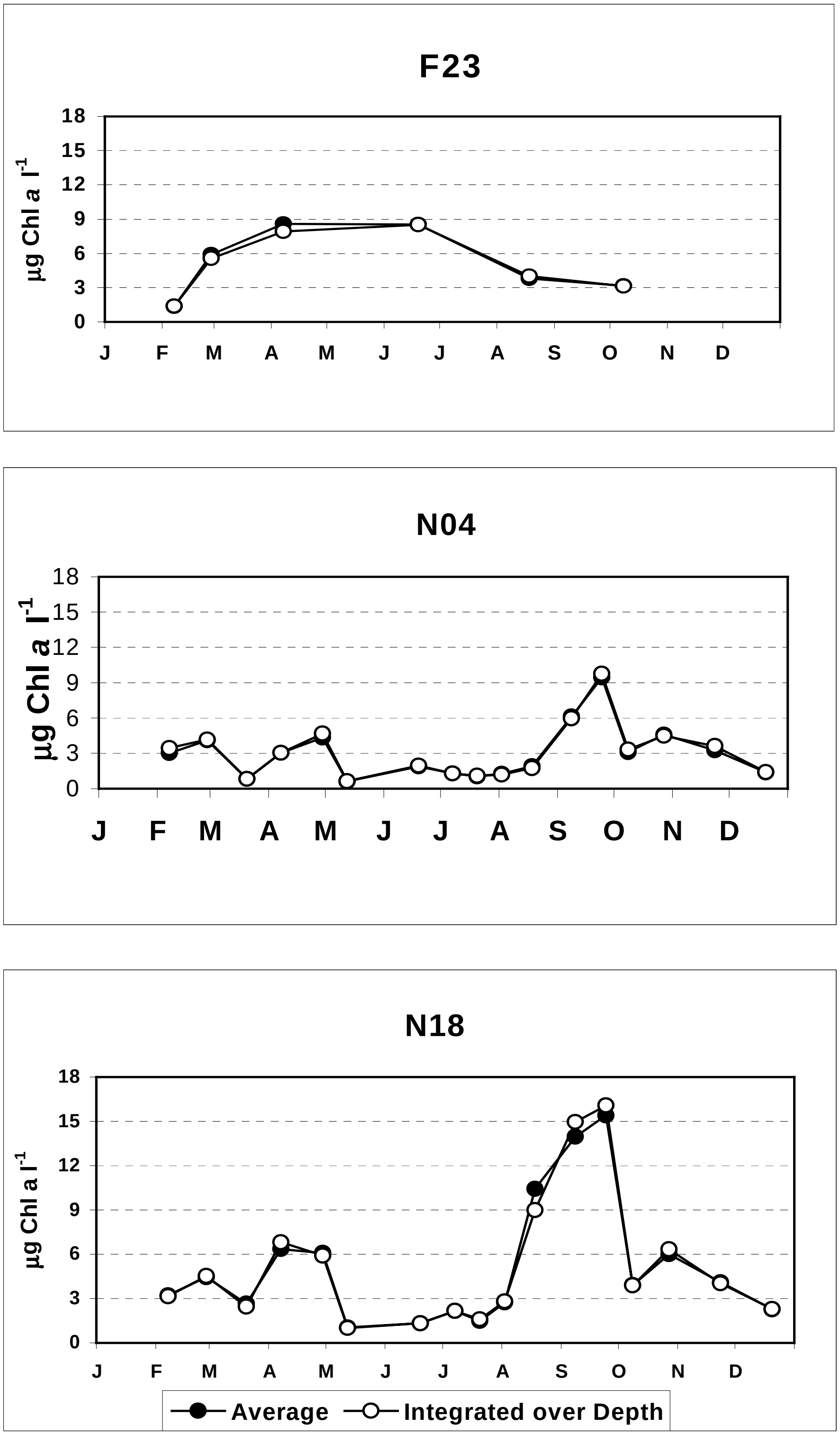


Figure 5-4. Chlorophyll *a* distribution for the 1999 season represented as averaged over depth and integrated over depth at stations F23, N04, and N18.

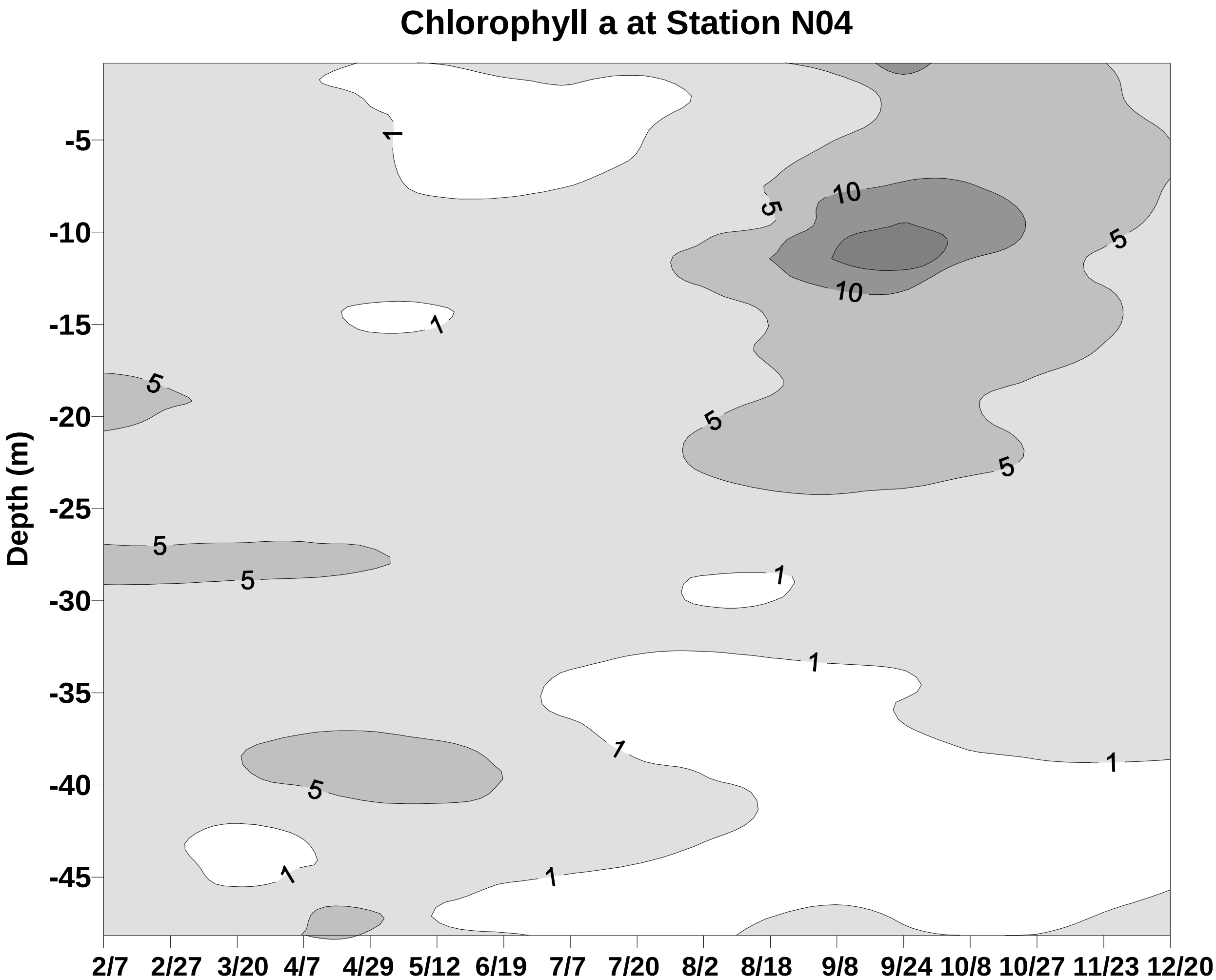


Figure 5-5. Time series of contoured chlorophyll *a* (µg l^{-1}) over depth (m) at station N04.

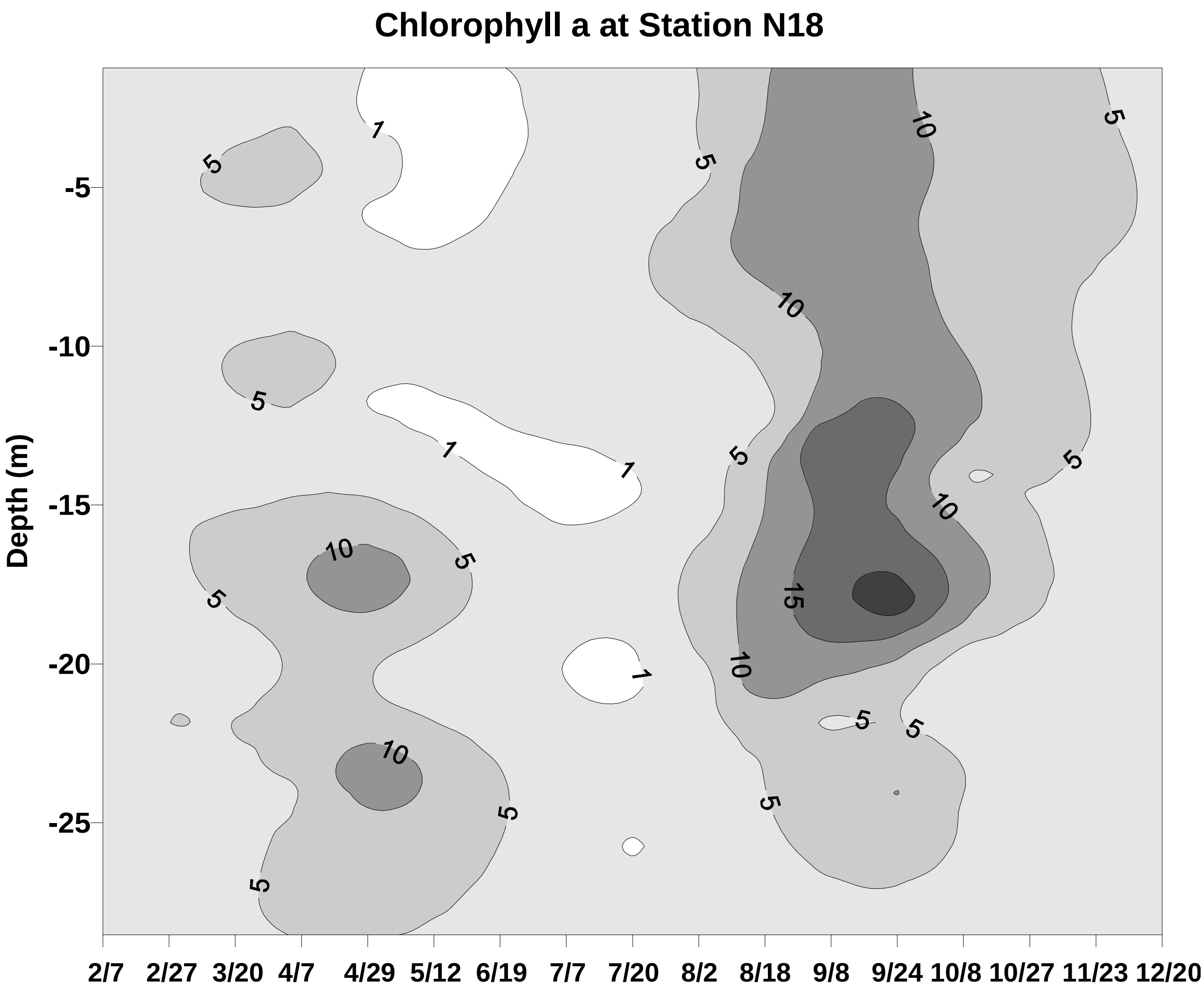


Figure 5-6. Time series of contoured chlorophyll *a* (μg l^{-1}) over depth (m) at station N18.

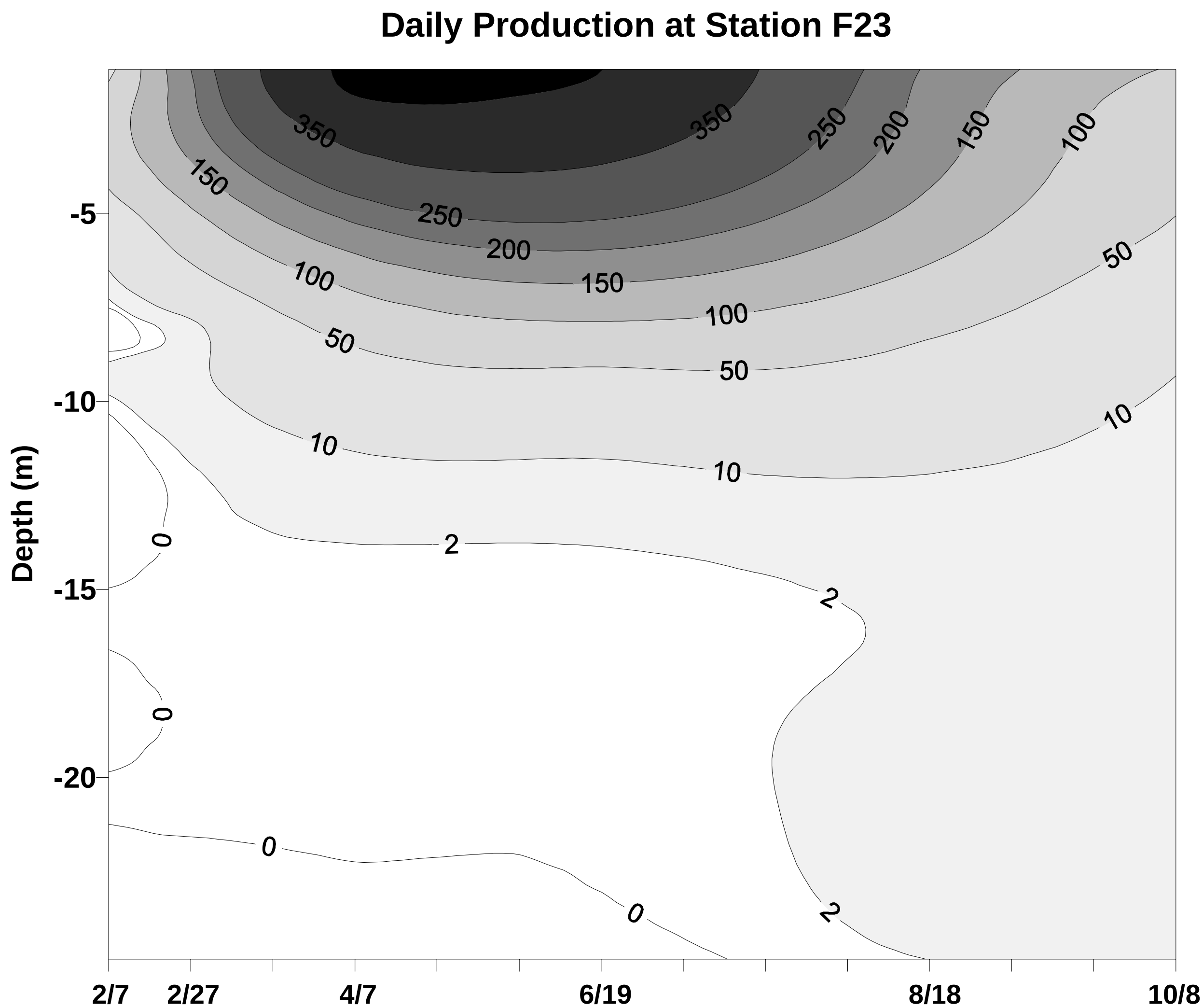


Figure 5-7. Time series of contoured daily production ($mgCm^{-3}d^{-1}$) over depth (m) at station F23.

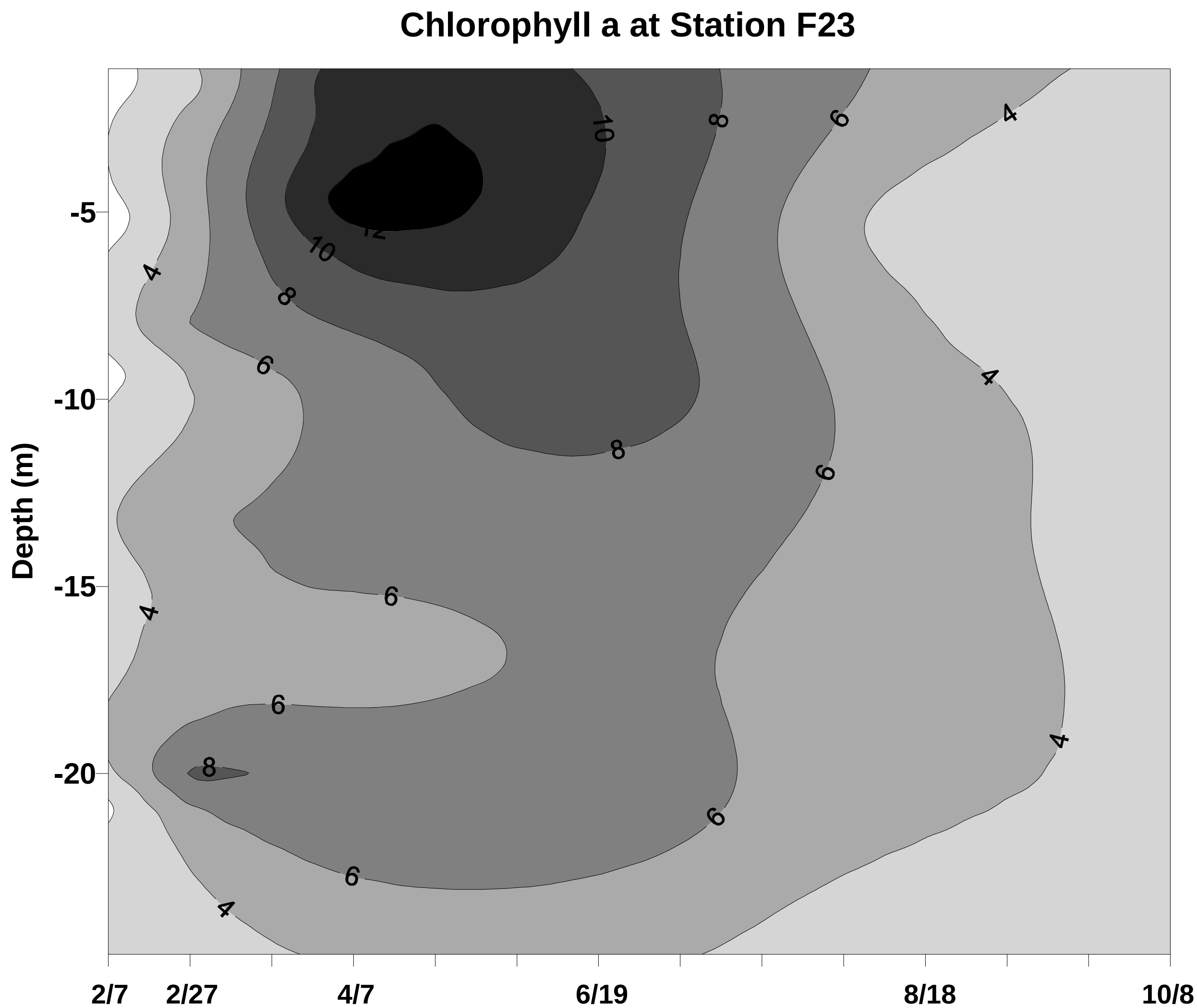


Figure 5-8. Time series of contoured chlorophyll *a* ($\mu g\ l^{-1}$) over depth (m) at station F23.

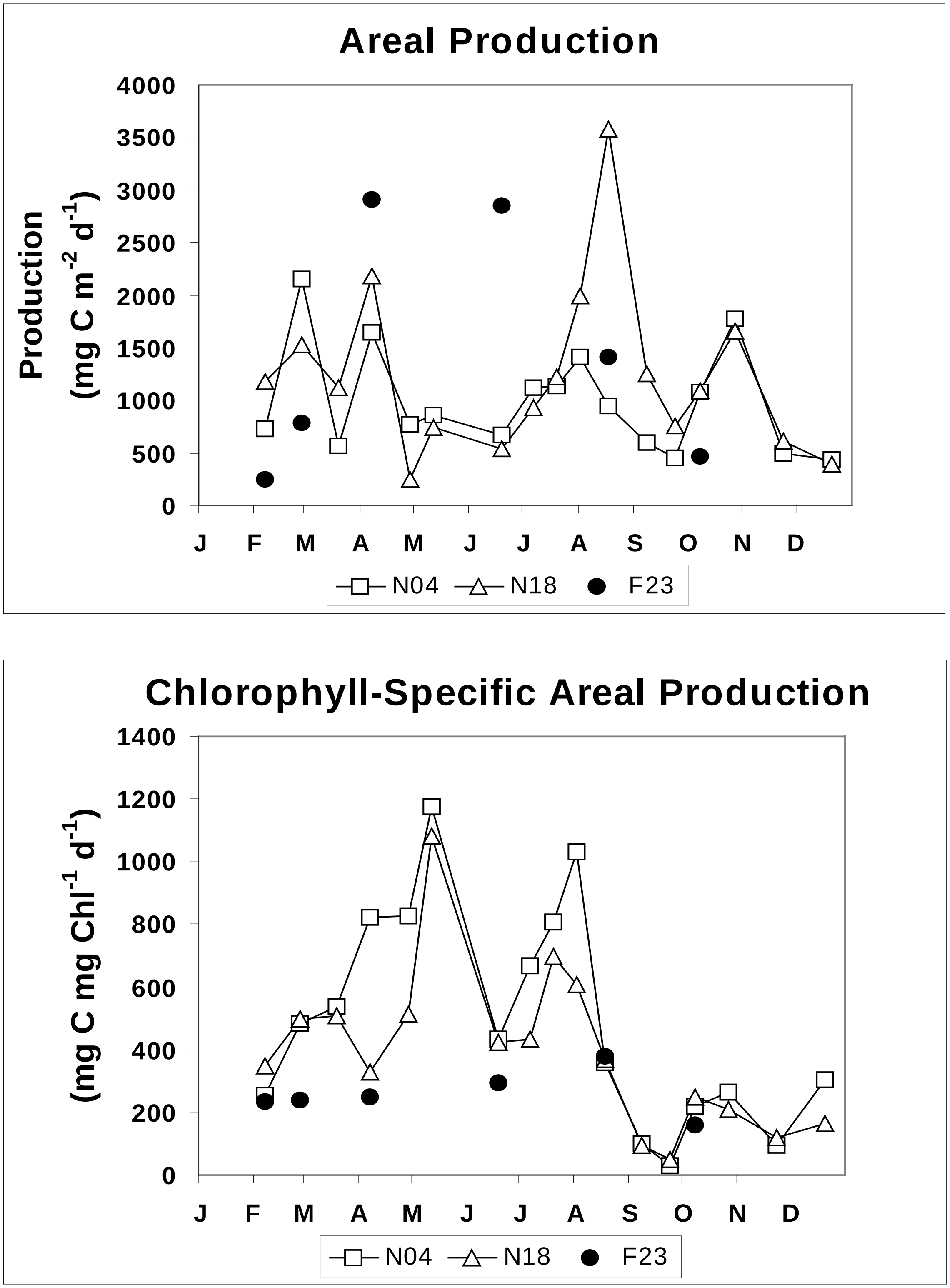


Figure 5-9. Time series of areal production ($mgCm^{-2}d^{-1}$) and chlorophyll-specific areal production ($mgCmgChla^{-1}d^{-1}$) for stations N04, N18 and F23 over the annual cycle.

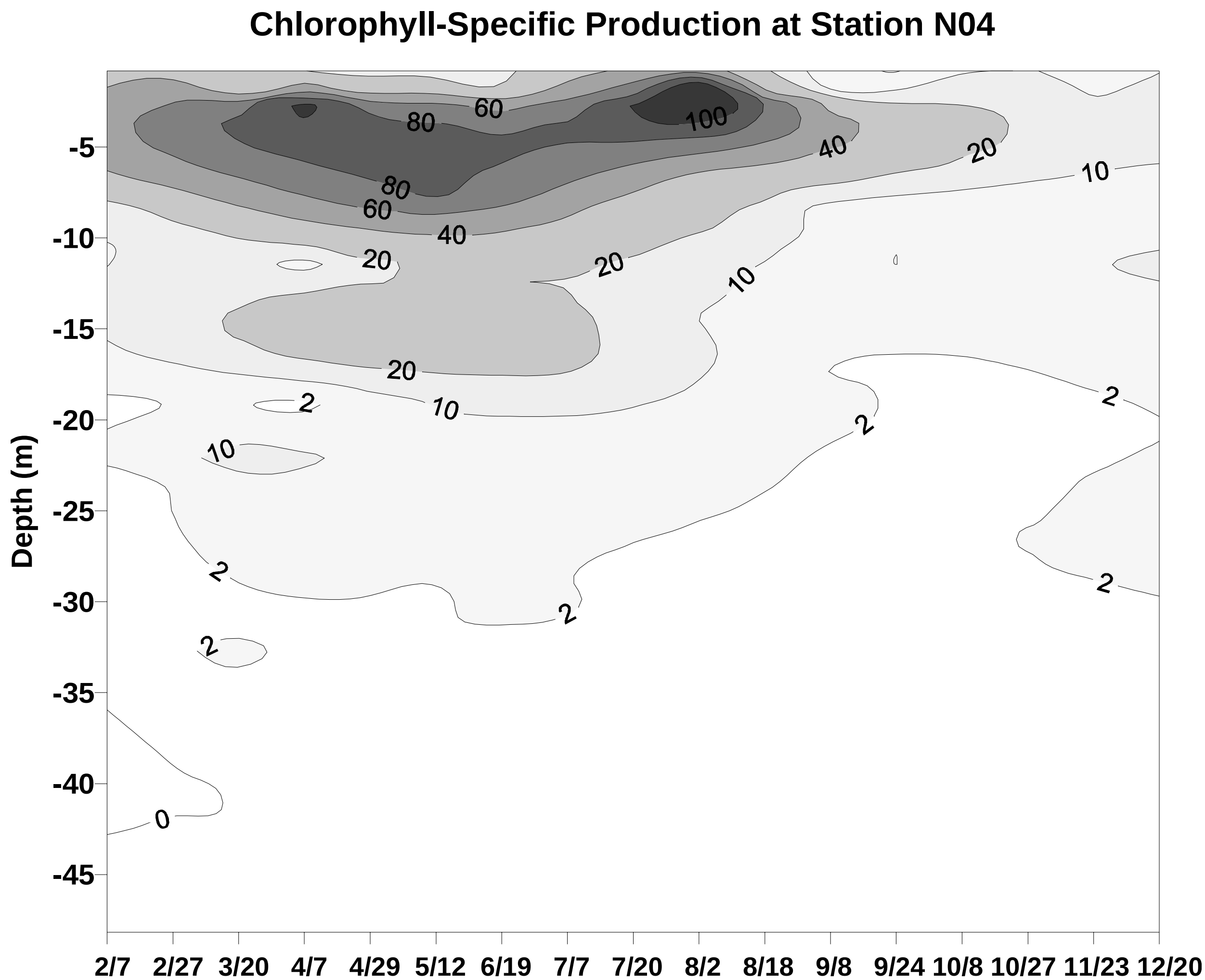


Figure 5-10. Time series of contoured chlorophyll-specific production ($mgCmgChla^{-1}d^{-1}$) over depth (m) at station N04.

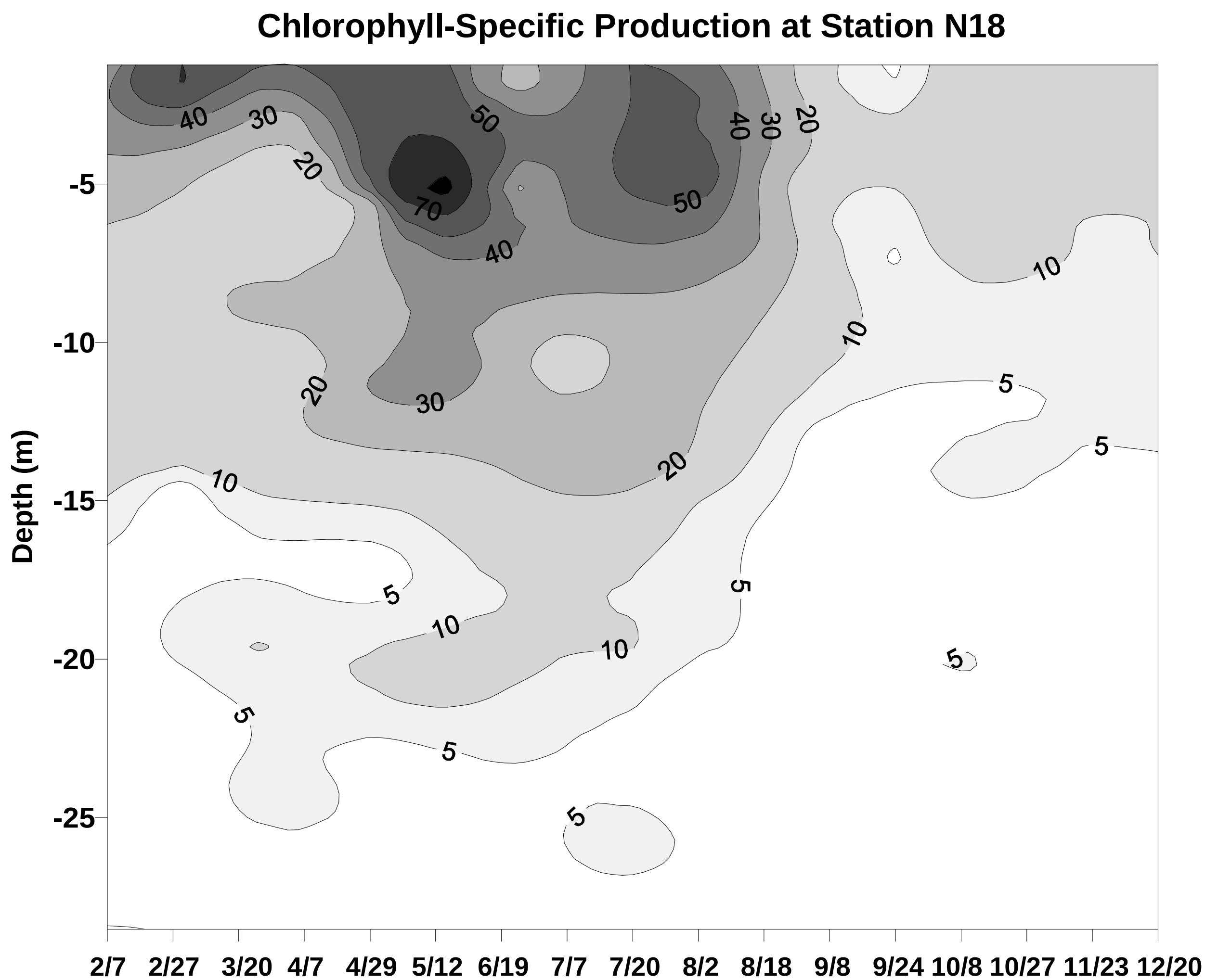


Figure 5-11. Time series of contoured chlorophyll-specific production ($mgCmgChla^{-1}d^{-1}$) over depth (m) at station N18.

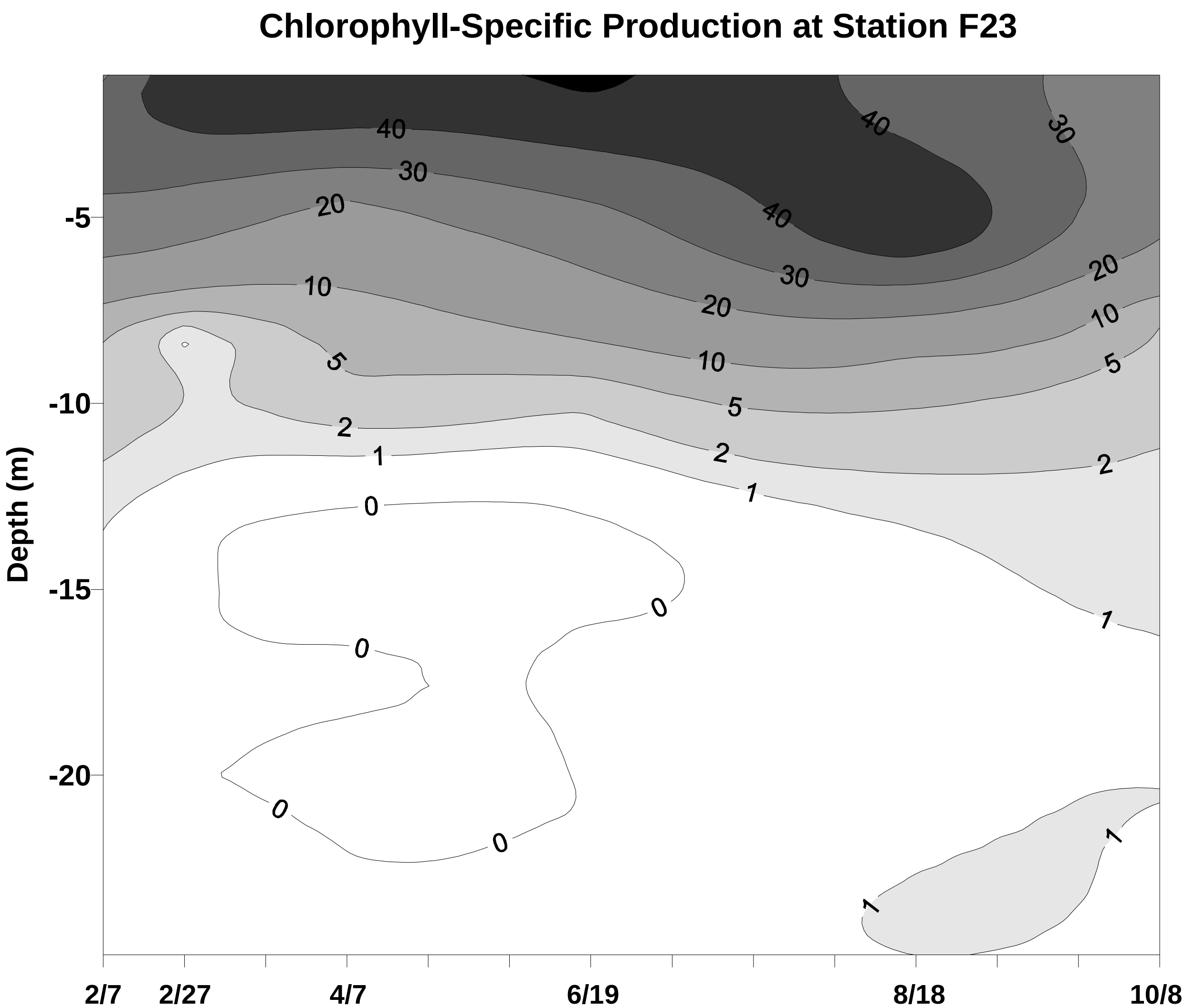


Figure 5-12. Time series of contoured chlorophyll-specific production ($mgCmgChla^{-1}d^{-1}$) over depth (m) at station F23.

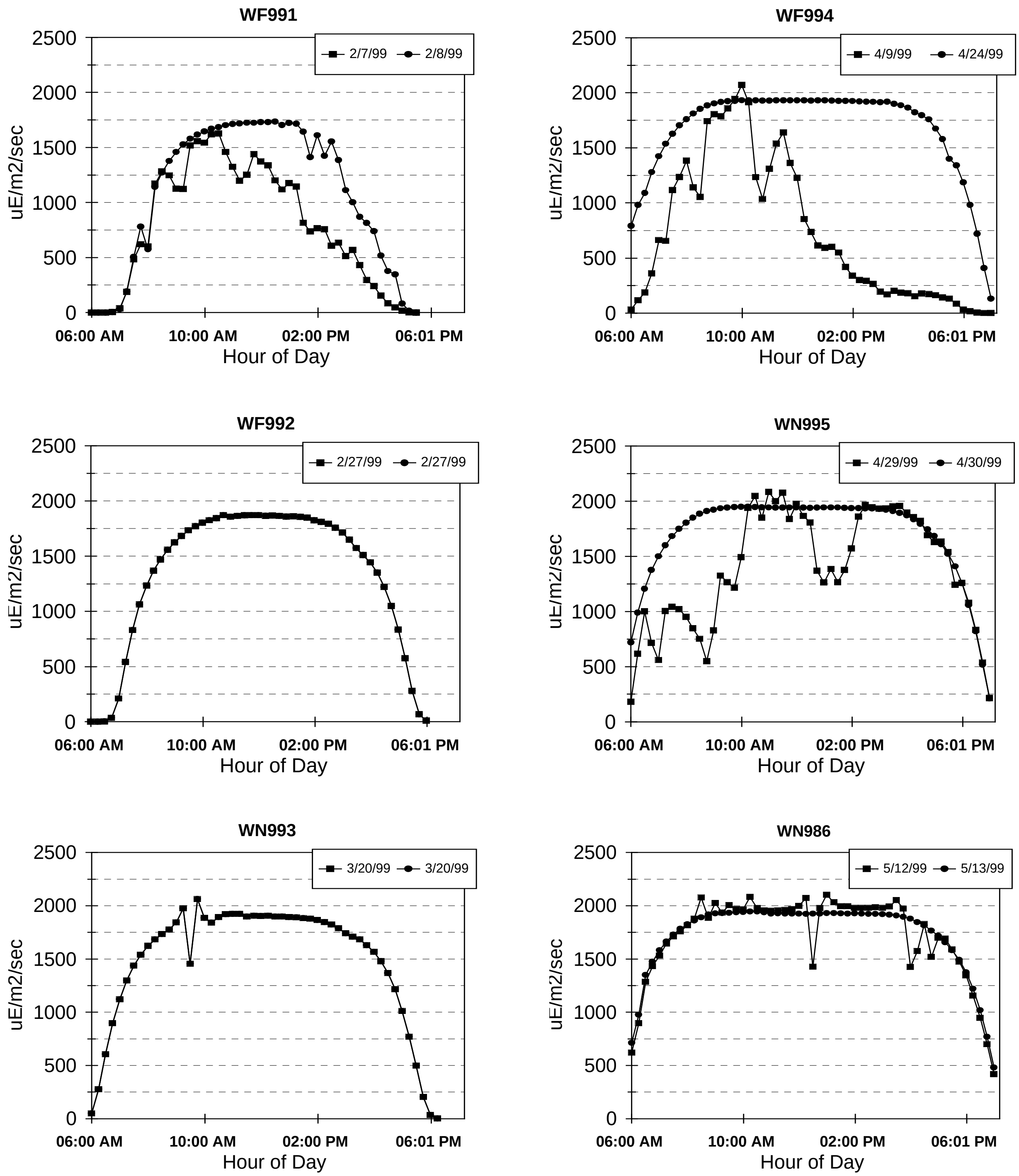


Figure 5-13. Photoperiod light field over the course of the day during the first six surveys demonstrating the differences between observed light on the day of the survey and theoretical maximum light from a cloudless day close in time to the survey date (used to calculate potential production).

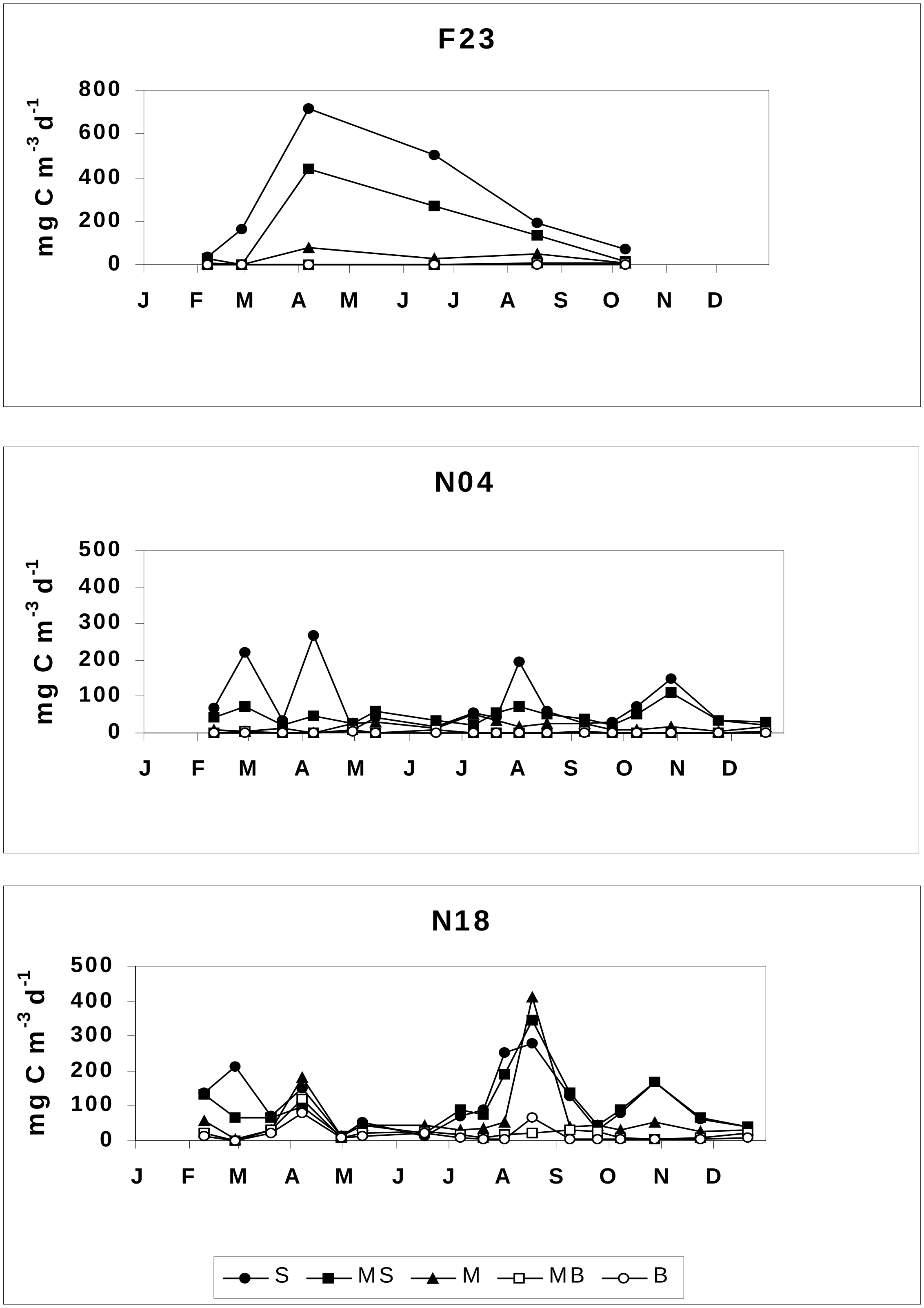


Figure 5-14. Potential production (mgCm^{-3}d^{-1}) calculated using incident light from a cloudless day over the annual cycle for each station and depth at stations F23, N04, and N18.

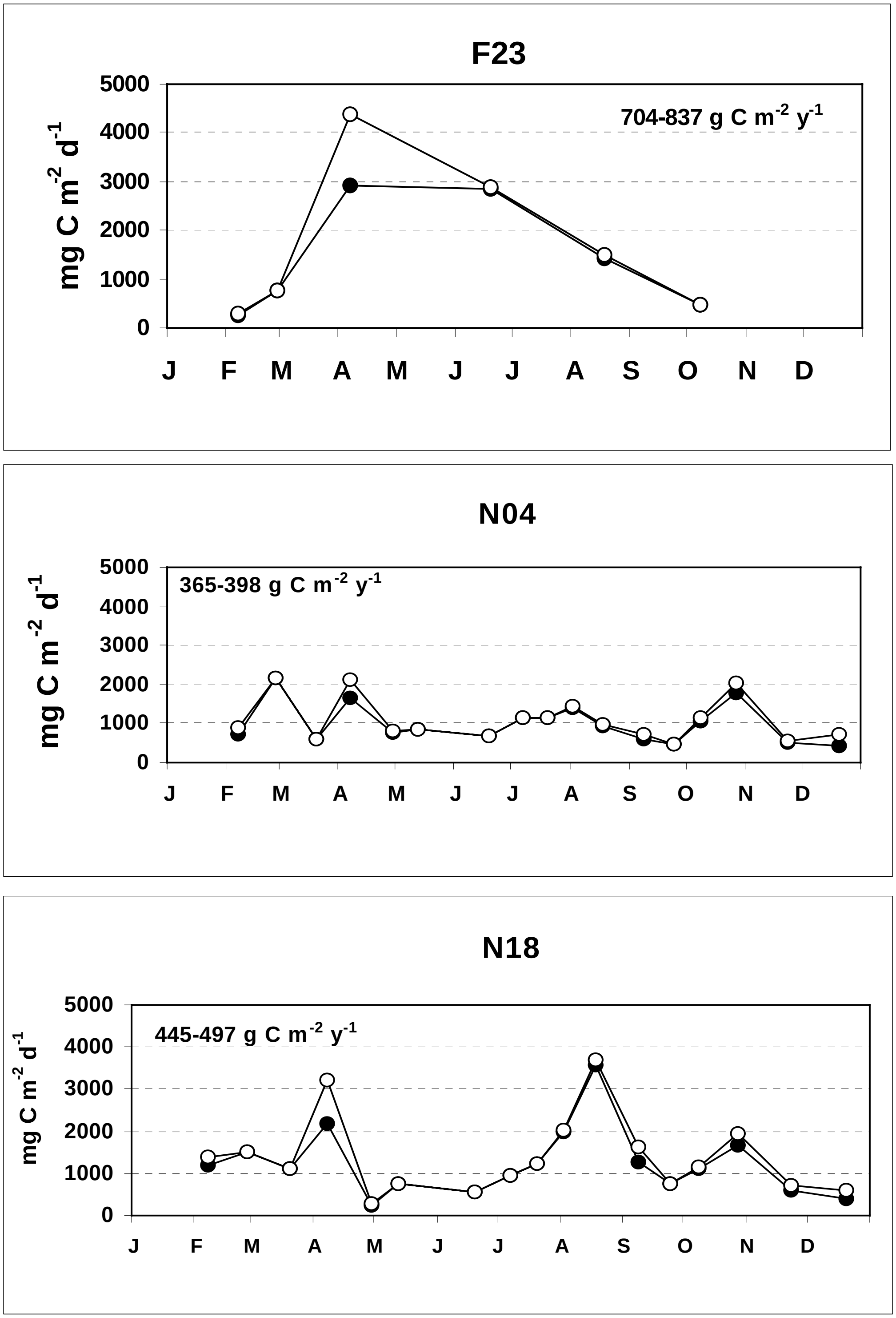


Figure 5-15. Measured and potential areal production ($mgCm^{-2}d^{-1}$) for the 1999 season at stations F23, N04, and N18. Annual and potential annual production ($gCm^{-2}y^{-1}$) are shown in the panel insets, with the higher value being the potential annual production at each station.

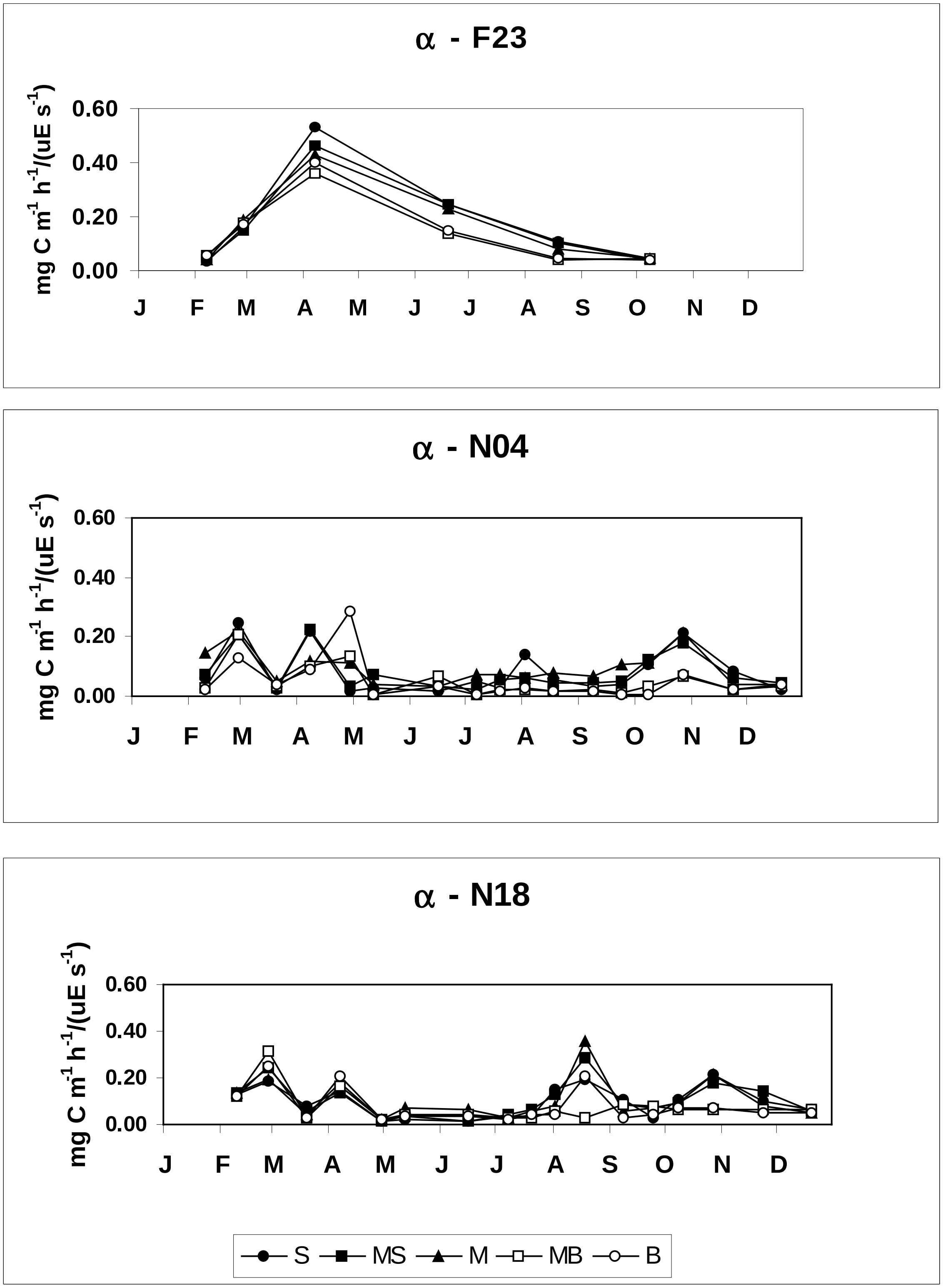


Figure 5-16. Alpha, α, [mgCm^{-3}hr^{-1}(μE m^{-2} s^{-1})] in 1999 at stations F23, N04, and N18 at 5 depths.

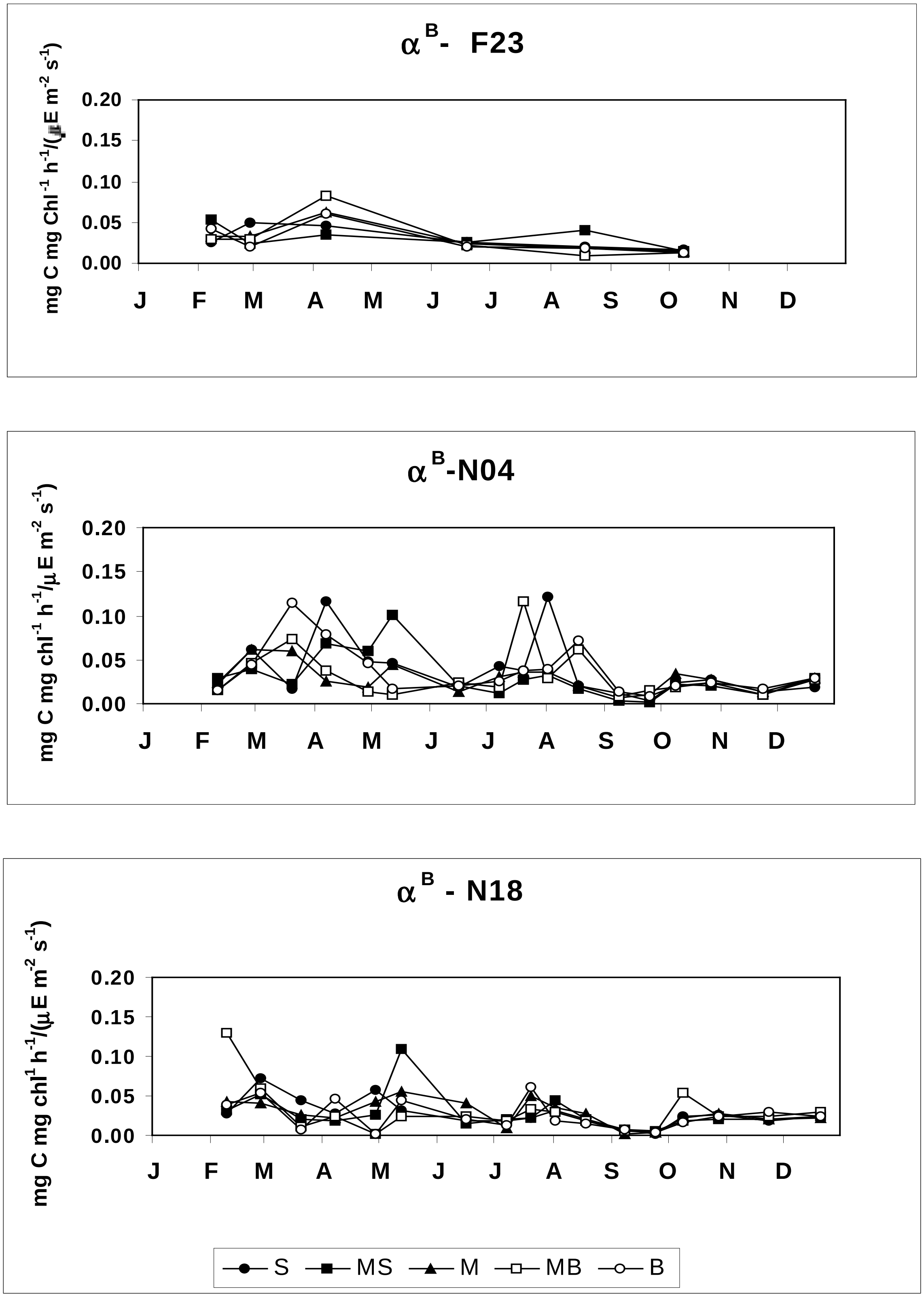


Figure 5-17. Chlorophyll-specific alpha, α^B, mgC(mgchla)$^{-1}$ hr^{-1} in 1999 at stations F23, N04, and N18 at 5 depths.

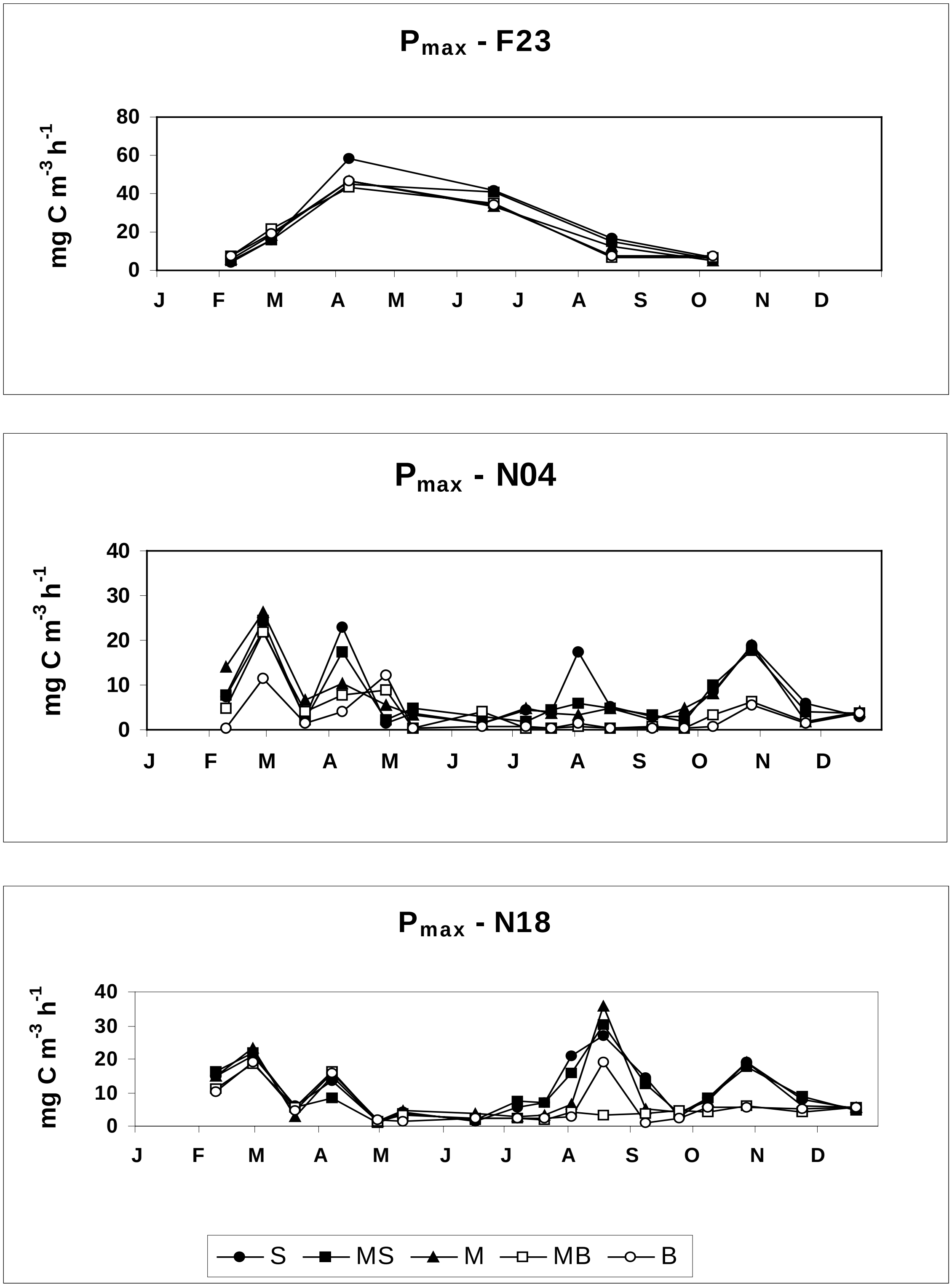


Figure 5-18. P_{max} **($mgCm^{-3}hr^{-1}$) in 1999 at stations F23, N04, and N18 at 5 depths.**

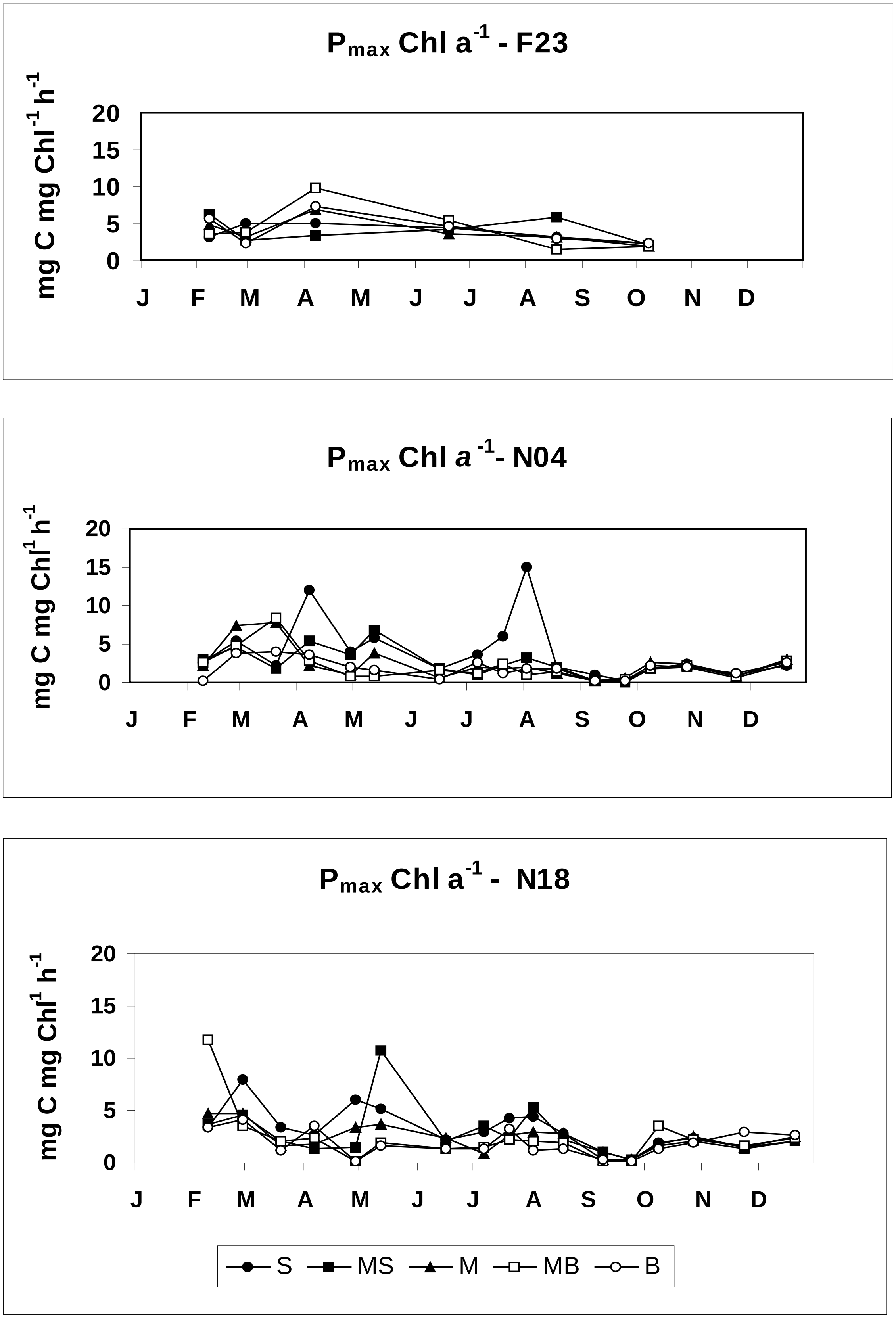


Figure 5-19. P^{B}_{max} (mgCmgChla^{-1}hr^{-1}) in 1999 at stations F23, N04, and N18 at 5 depths.

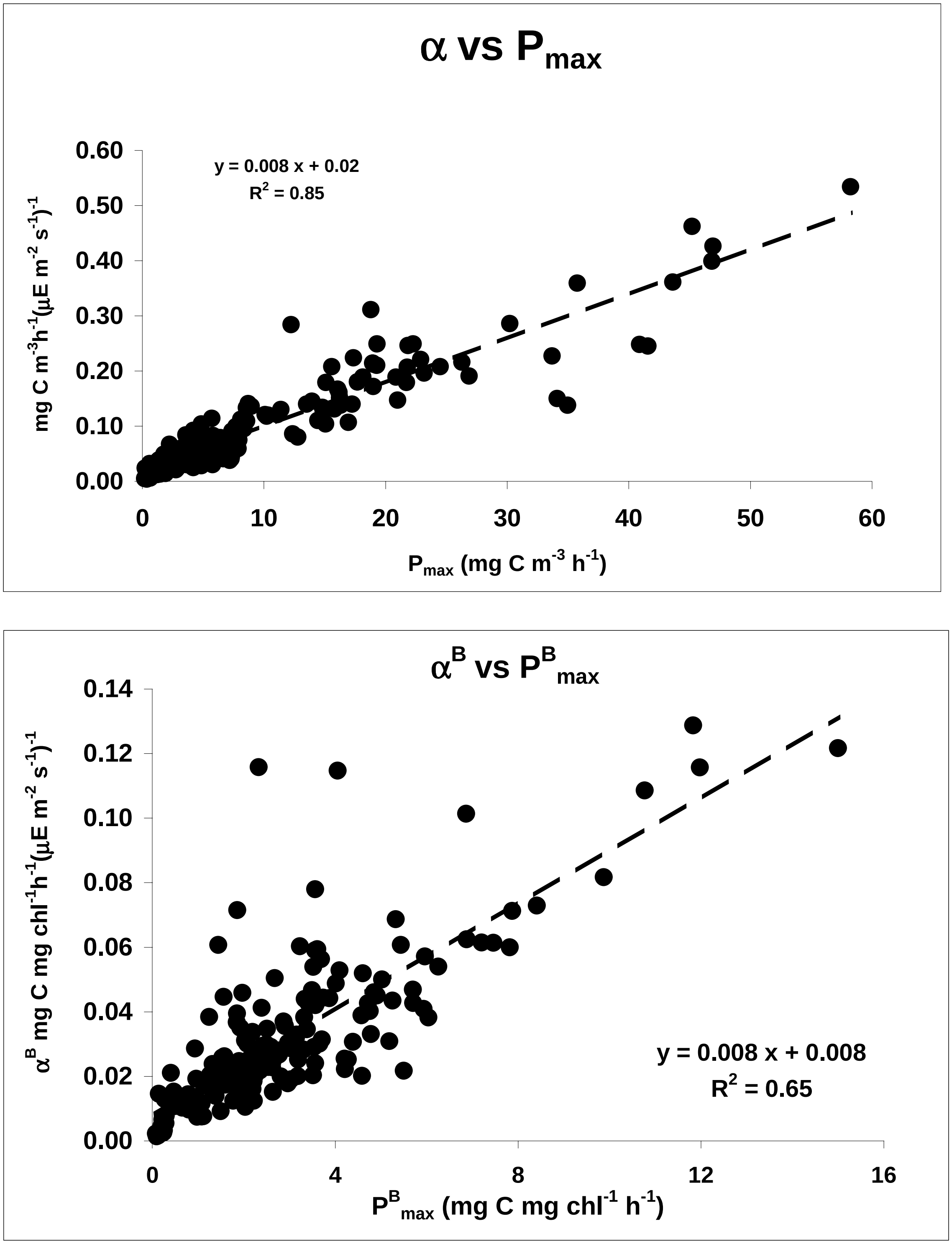


Figure 5-20. Relationship between the fitted values of the parameters of the P-I curves not normalized (α and P_{max}) and normalized (α^B and P^B_{max}) to phytoplankton biomass using the seasonal data for 1999.

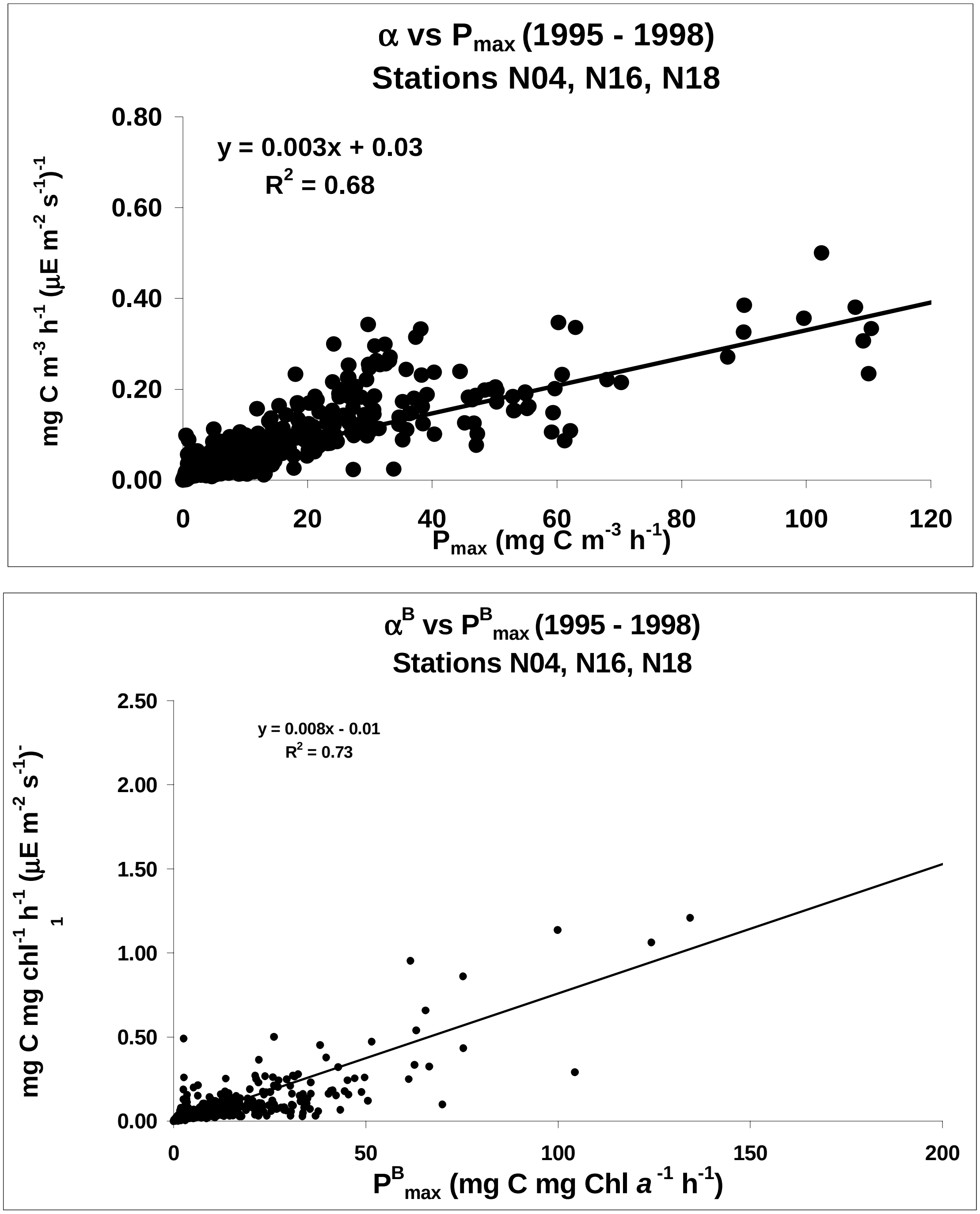


Figure 5-21. Relationship between the fitted values of the parameters of the P-I curves not normalized (α and P_{max}) and normalized (α^B and P^B_{max}) to phytoplankton biomass using the seasonal data for 1995-98.

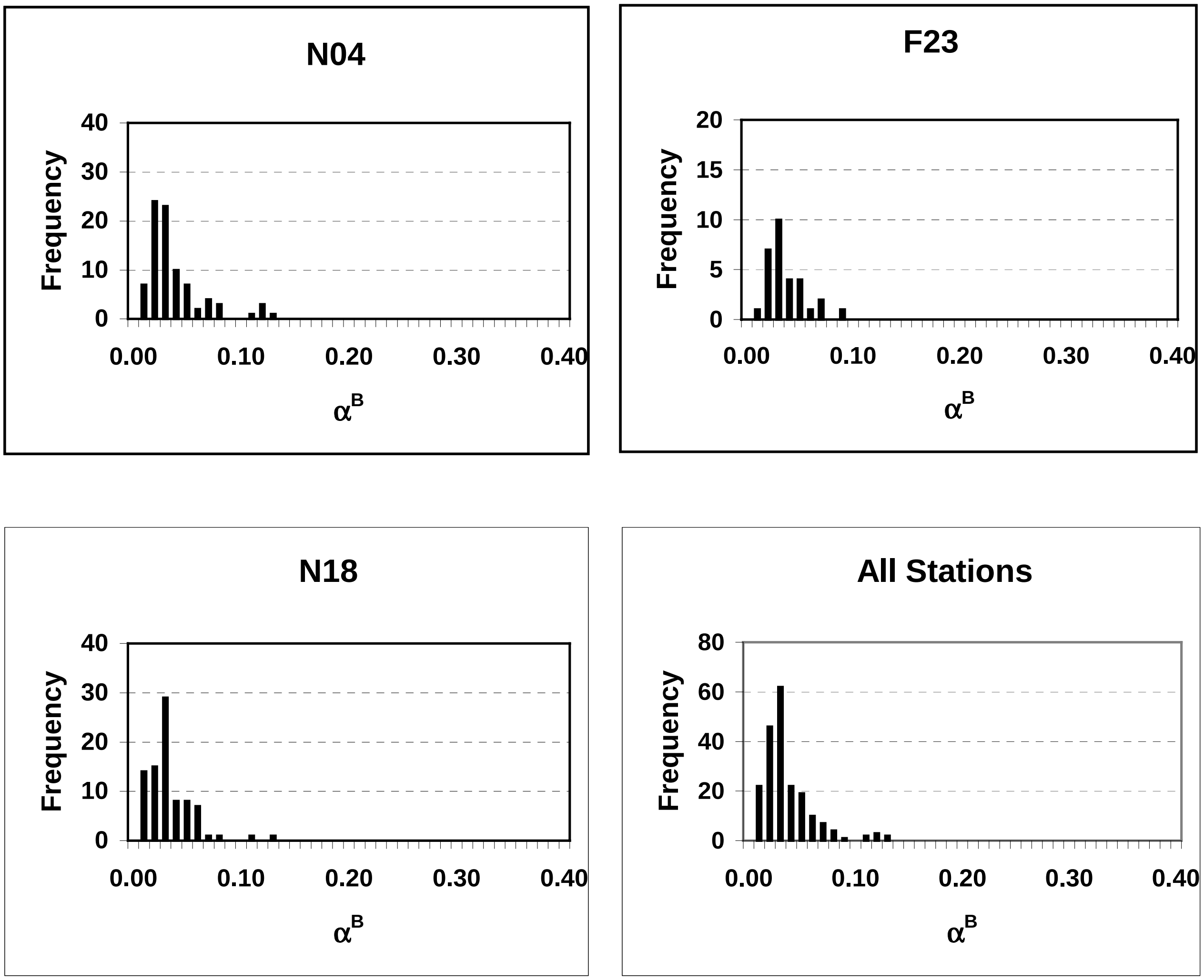


Figure 5-22. Frequency distributions for chlorophyll-specific alpha for stations F23, N04, N18 and the pooled data during 1999.

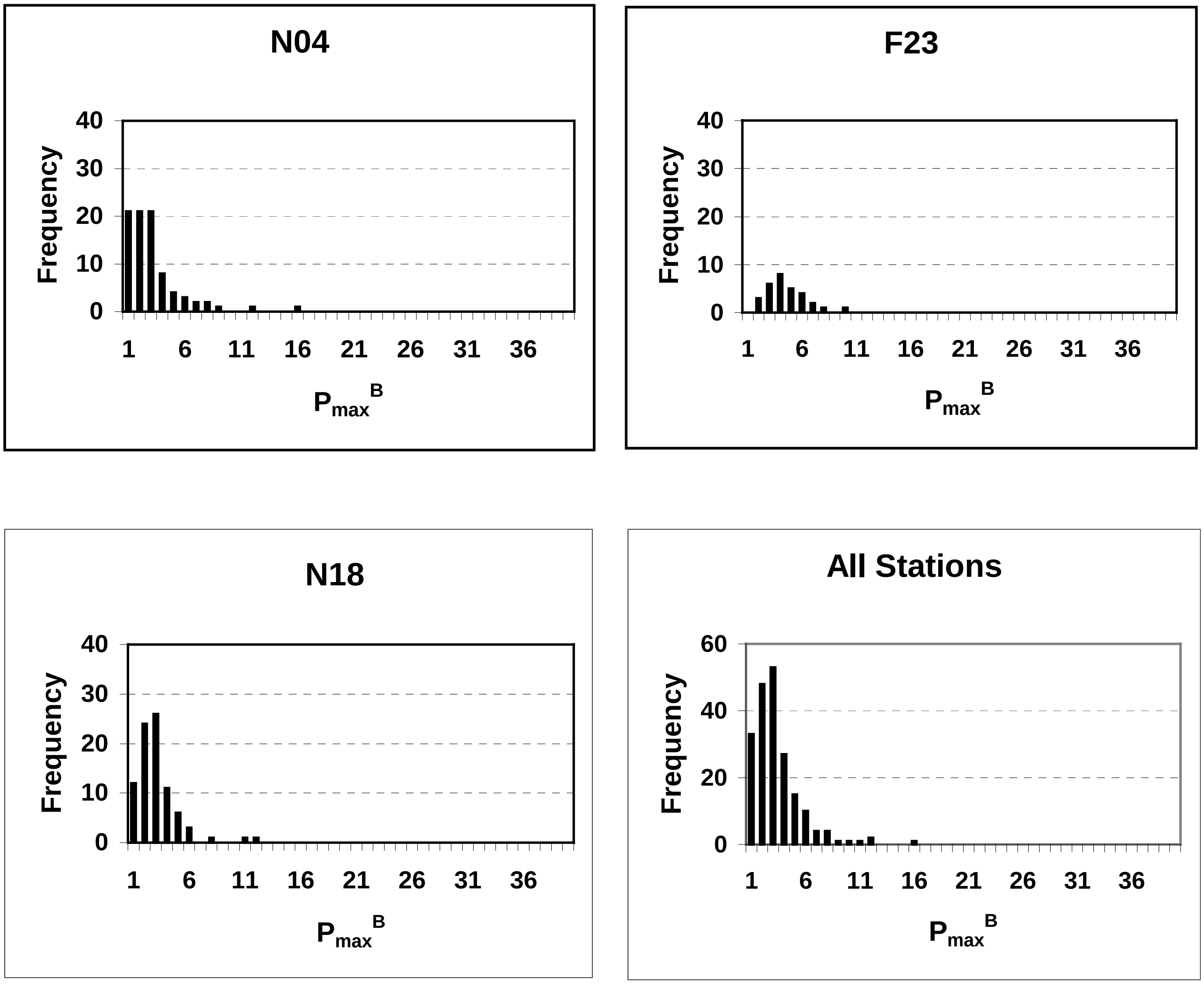
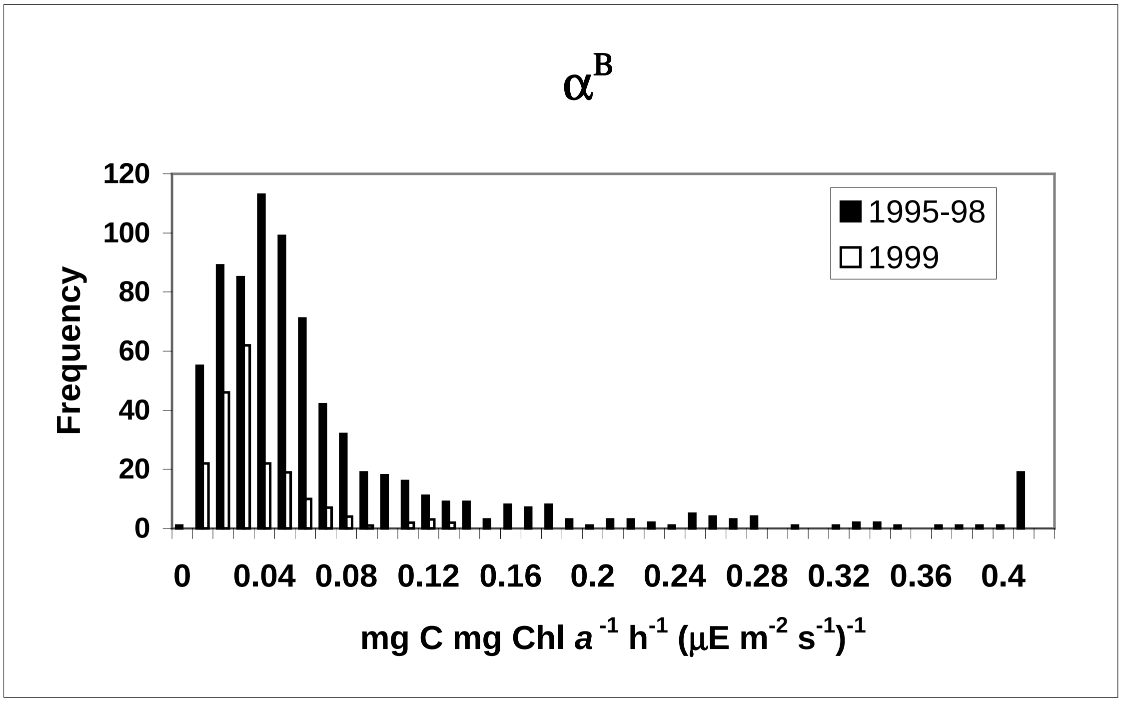


Figure 5-23. Frequency distributions for chlorophyll-specific P^B_{max} for stations F23, N04, N18 and the pooled data during 1999.



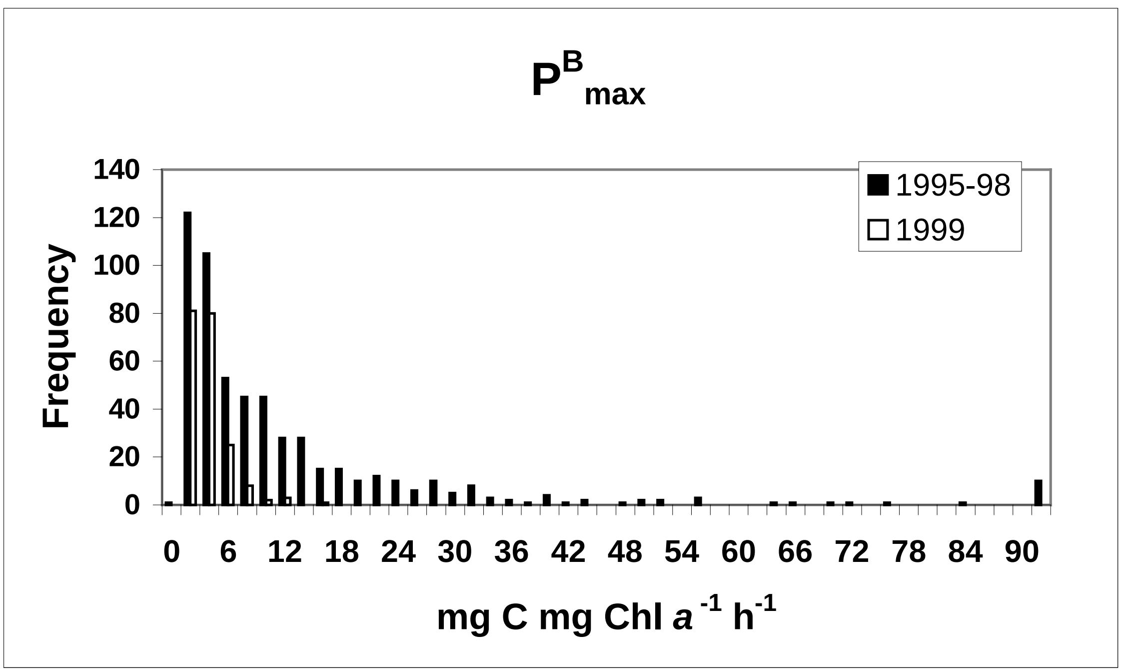
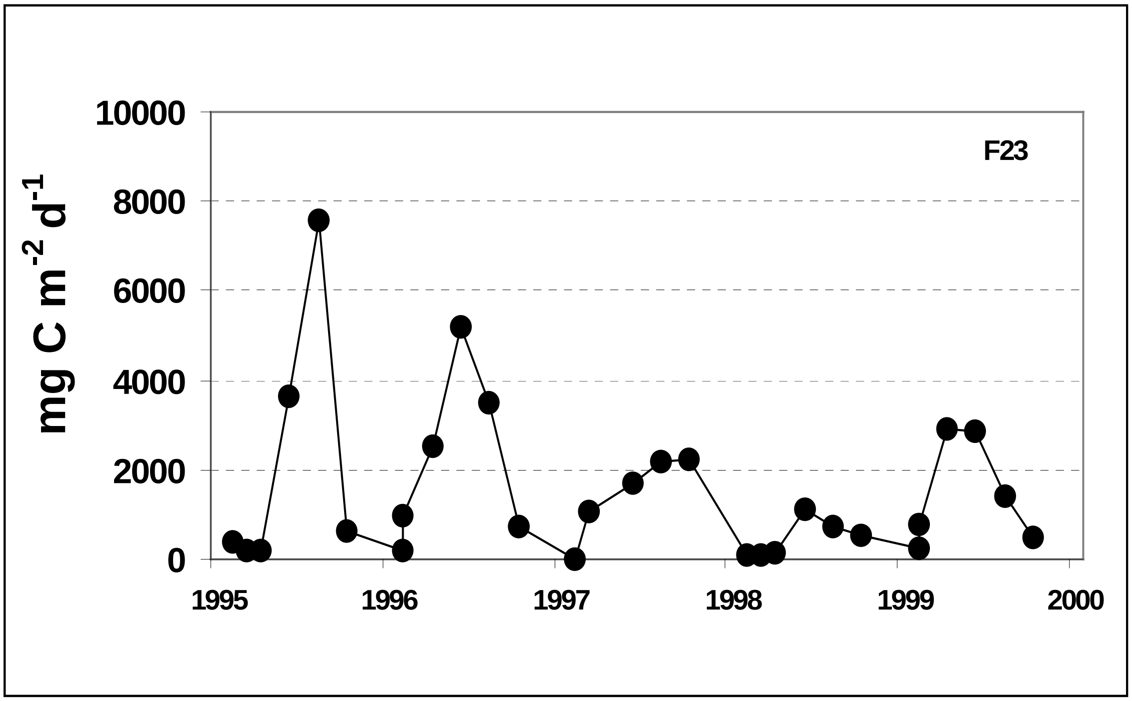


Figure 5-24. Frequency distributions for chlorophyll-specific alpha and P^B_{max} for stations F23, N04, N16 and N18 comparing the 1999 data with earlier years (1995-1998).



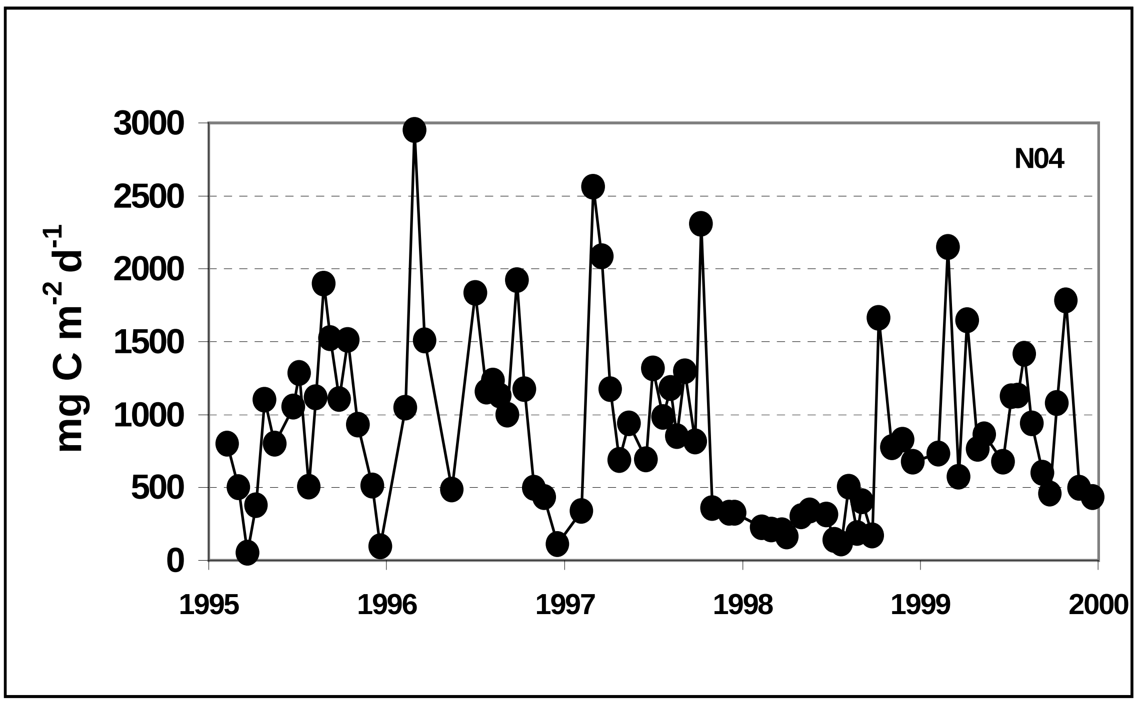


Figure 5-25. Measured phytoplankton production (mg C m^{-2} d^{-1}) from 1995-1999 for stations F23 and N04. Data for 1999, present study; data for 1998 from Libby *et al*. 1999b; data for 1995-97 from Cibik *et al*. 1996-98.

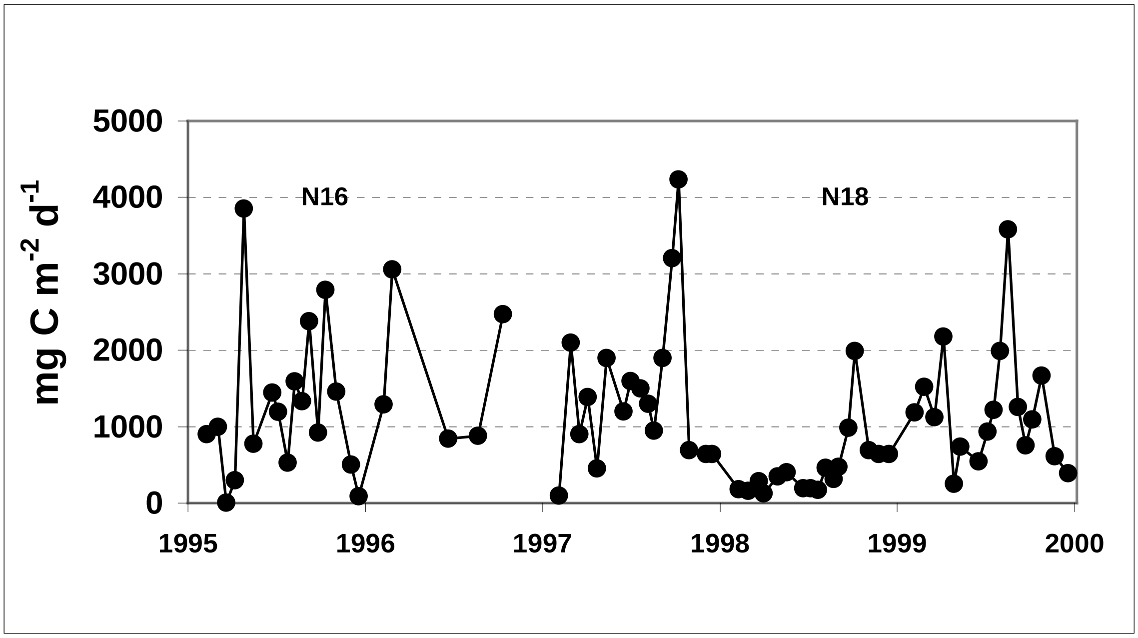
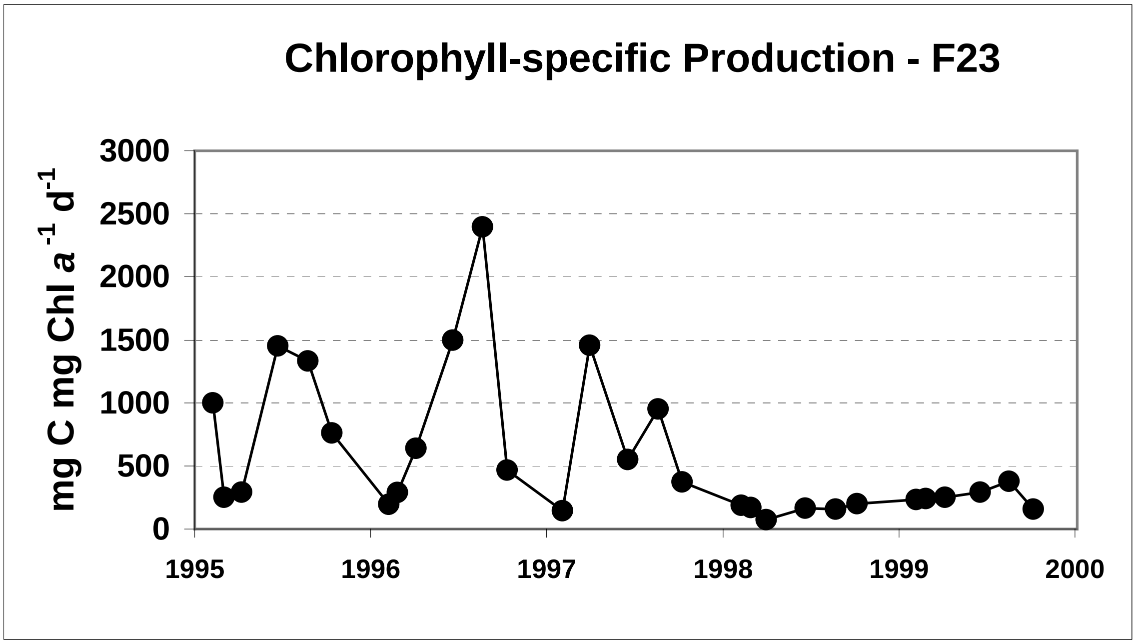


Figure 5-26. Measured phytoplankton production (mg C m^{-2} d^{-1}) from 1995-1999 for stations N16 and N18. Data for 1999, present study; data for 1998 from Libby *et al*. 1999b; data for 1995-97 from Cibik *et al*. 1996-98.



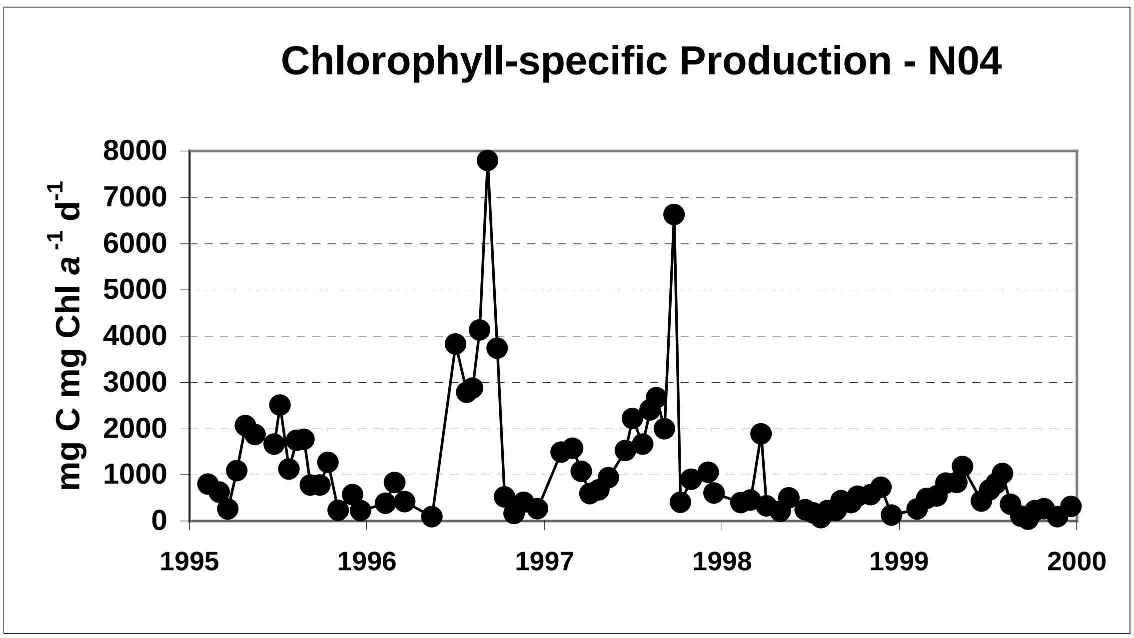


Figure 5-27. Measured chlorophyll-specific phytoplankton production (mg C mg Chl a^{-1} d^{-1}) from 1995-1999 for stations F23 and N04. Data for 1999, present study; data for 1998 from Libby *et al*. 1999b; data for 1995-97 from Cibik *et al*. 1996-98.

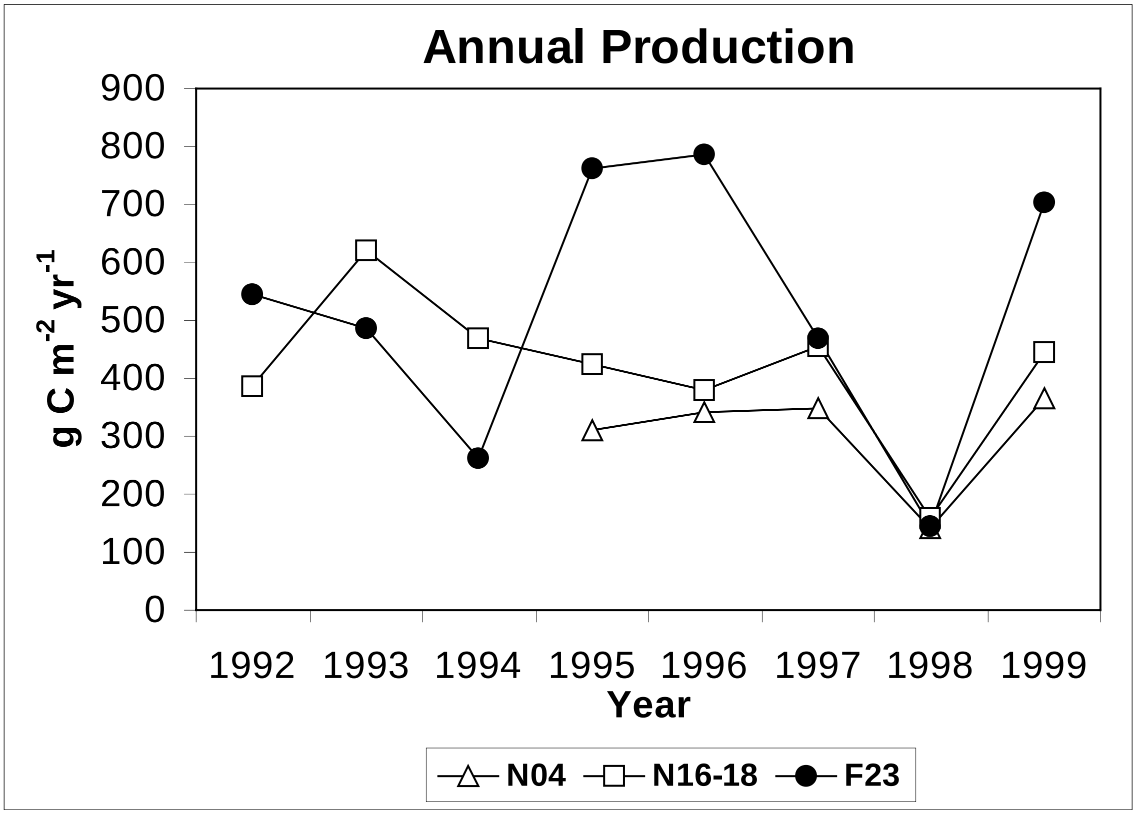


Figure 5-28. Annual production (g C m^{-2} yr^{-1}) for stations F23, N04, and N16/N18 from 1992-1999. Data for 1999, present study; data for 1998 from Libby *et al*. 1999b; data for 1995-97 from Cibik *et al*. 1996-98; data for 1992-94 from Kelly and Doering 1995.

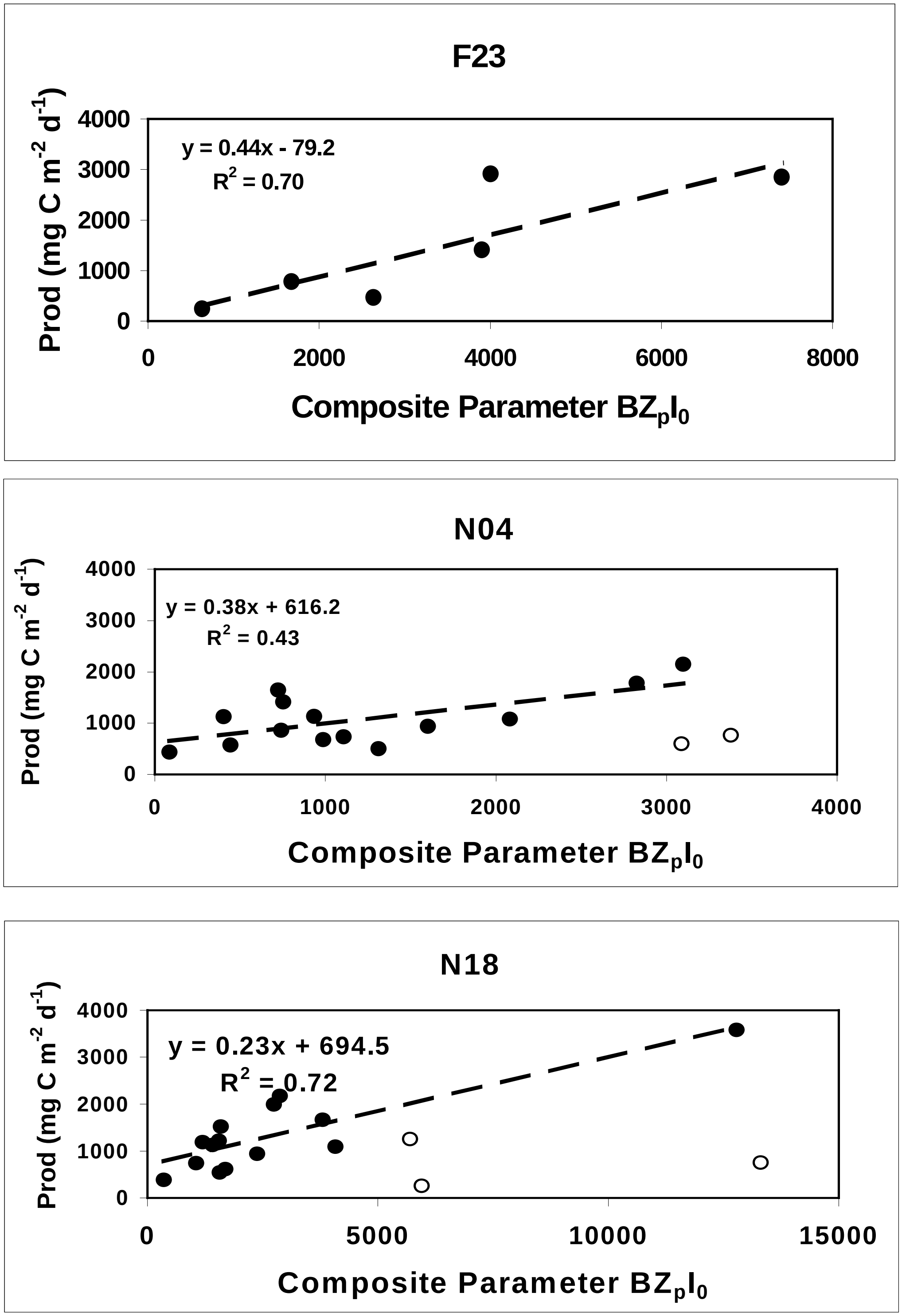


Figure 5-29. Relationships between areal production (mg C m^{-2} d^{-1}) and the composite function BZ_pI_0 (see text) for stations F23, N04 and N18 in 1999.

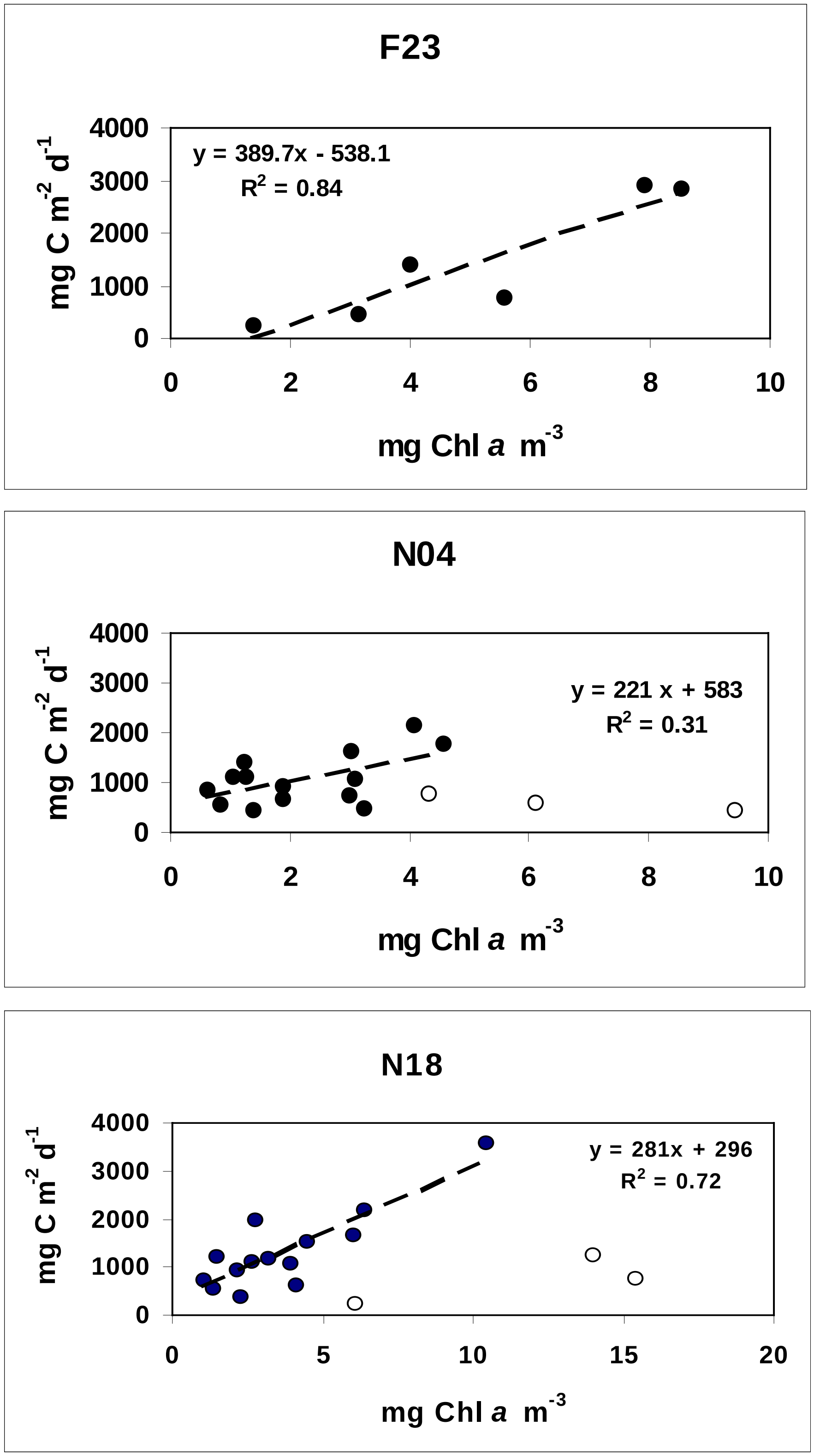


Figure 5-30. Relationships between areal production (mg C m^{-2} d^{-1}) and phytoplankton biomass (mg Chl a m^{-3}) for stations F23, N04 and N18 in 1999.

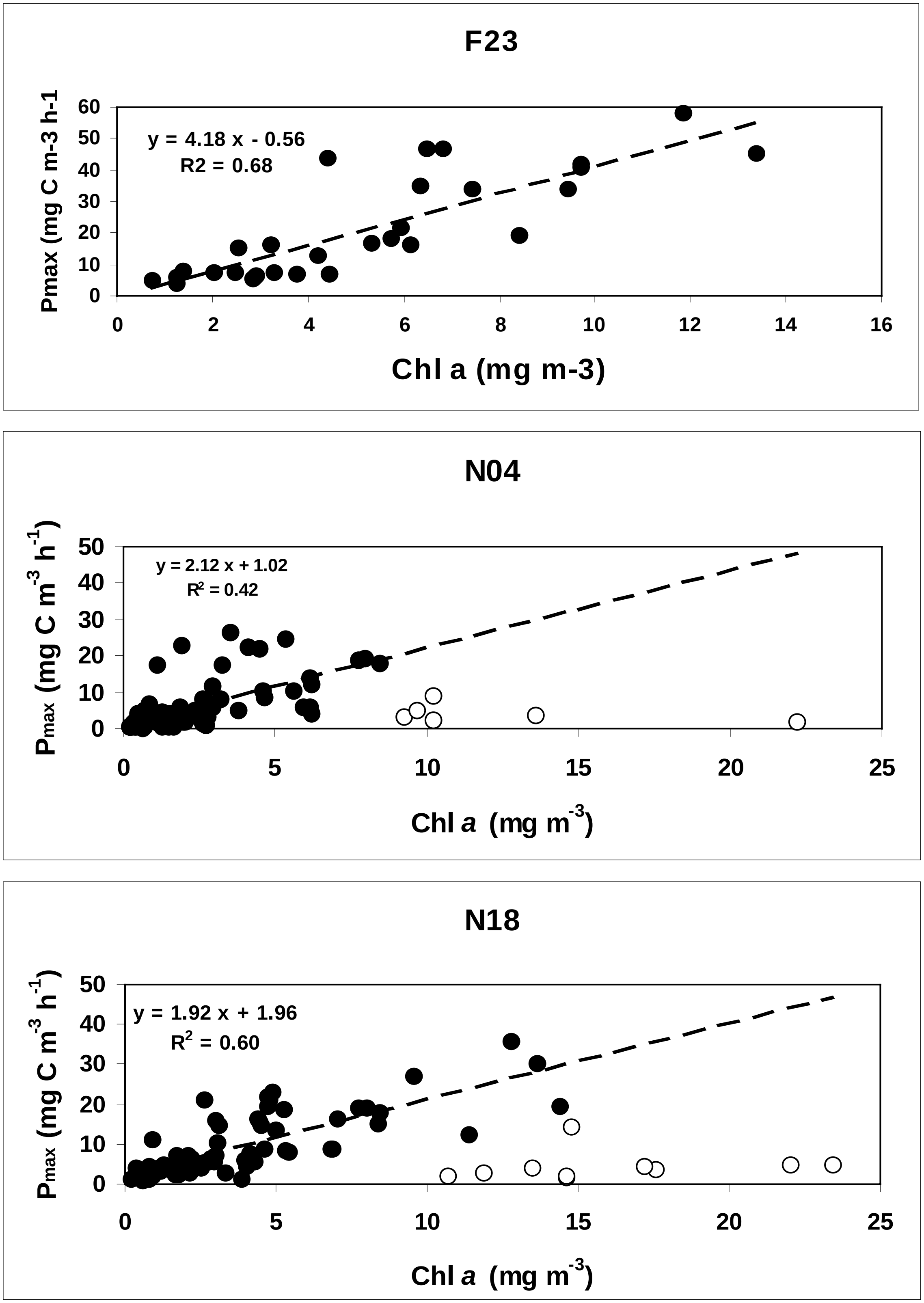


Figure 5-31. Relationship between the fitted values of P_{max} and phytoplankton biomass (mg Chl a m^{-3}) using the seasonal data for 1999.

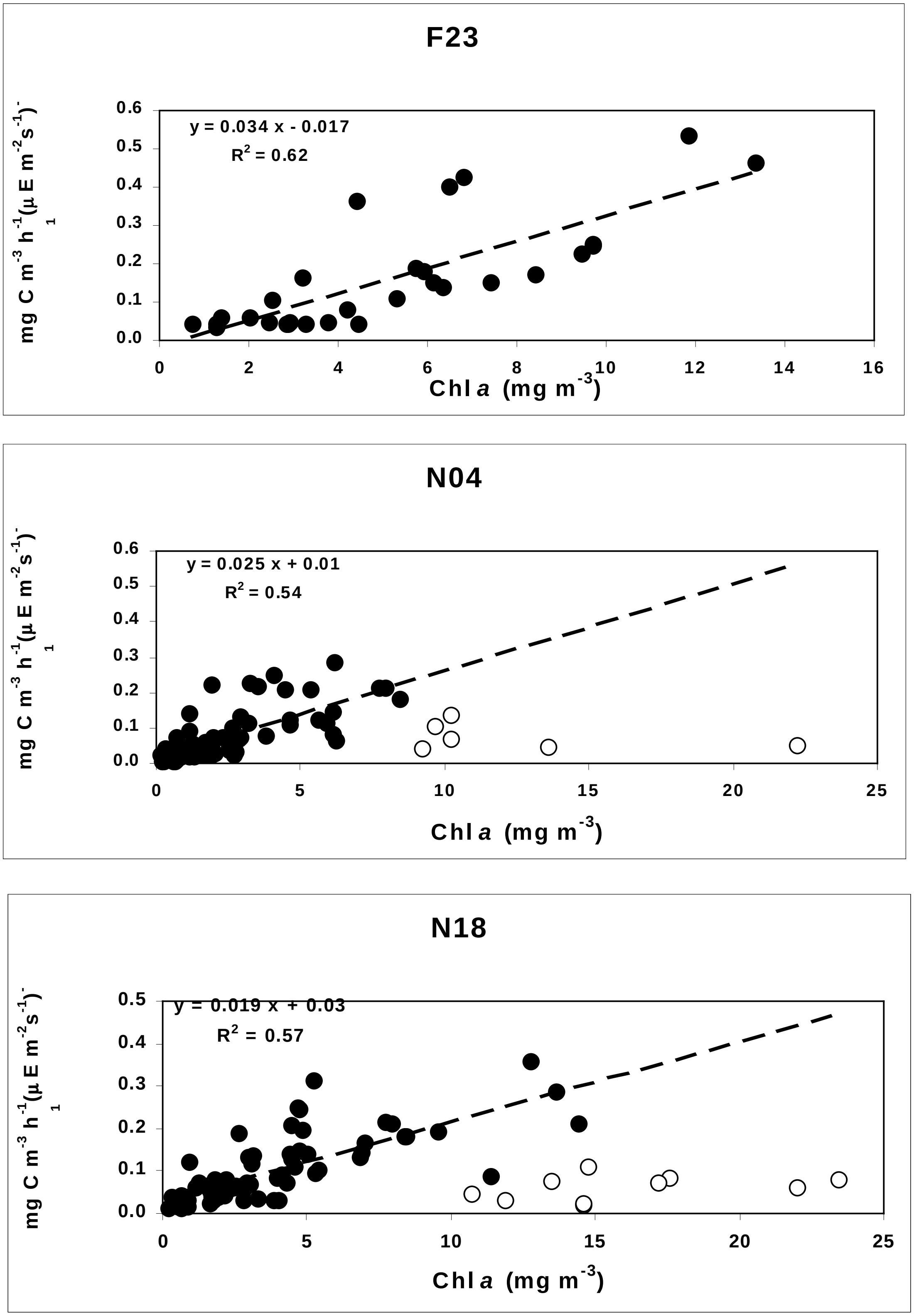
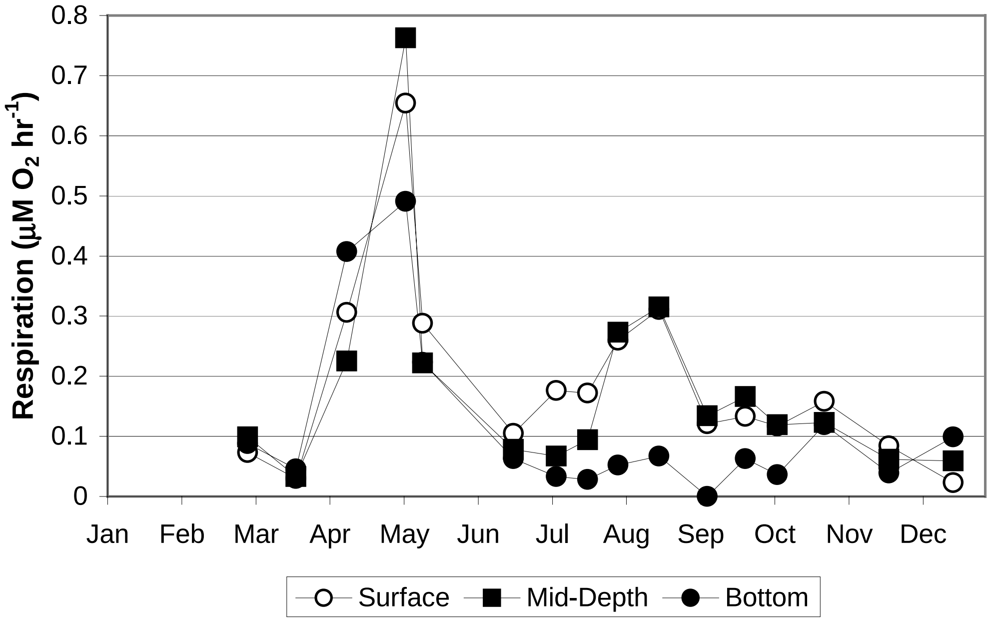


Figure 5-32. Relationship between the fitted values of α and phytoplankton biomass (mg Chl a m^{-3}) using the seasonal data for 1999.

(a) Station N18



(b) Station N04

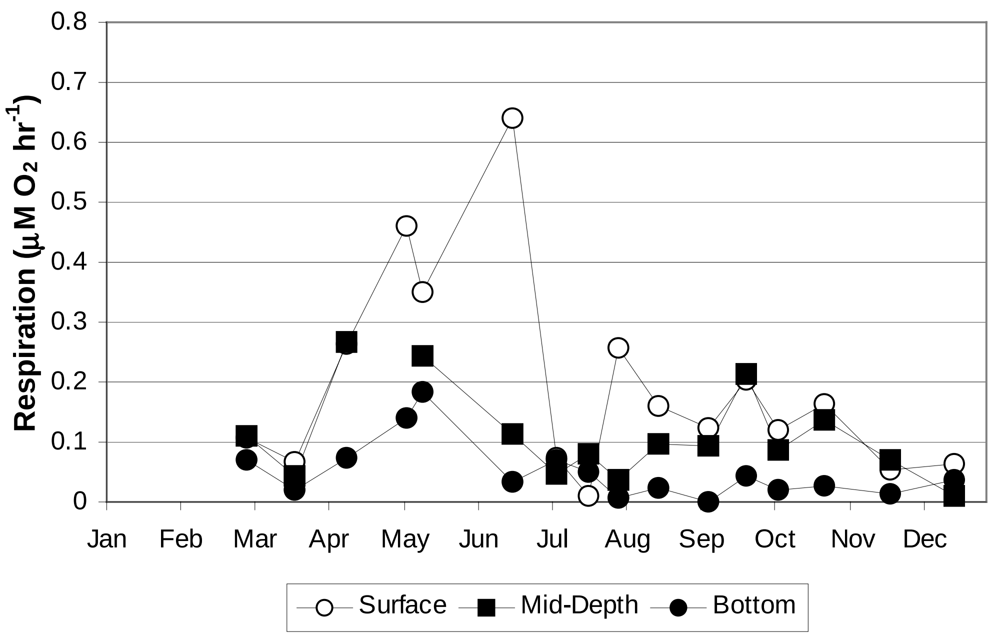
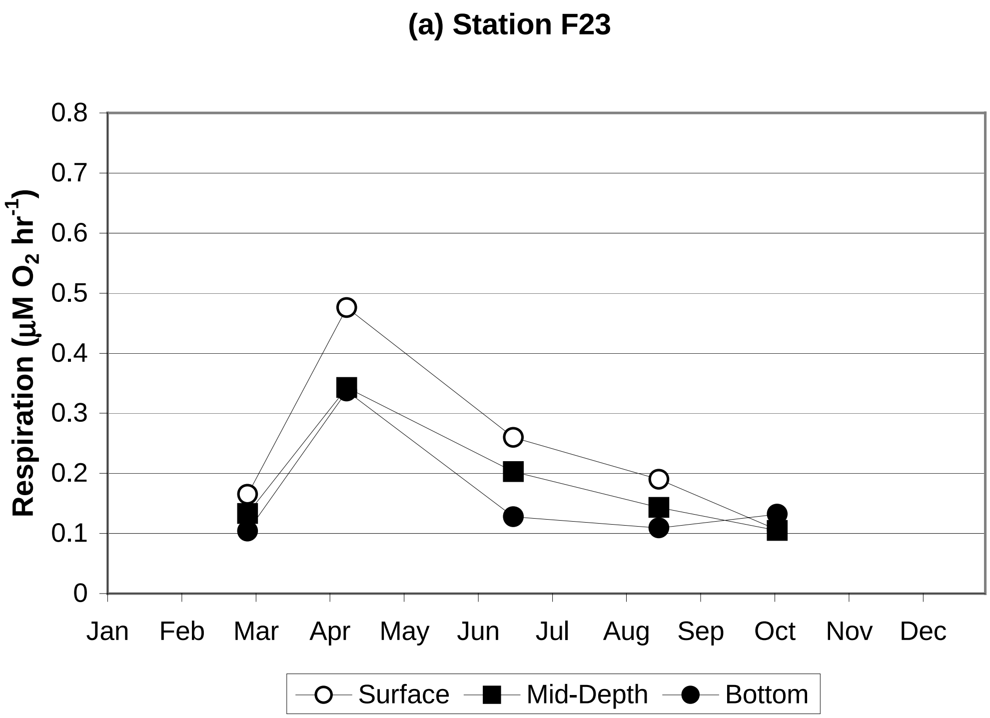


Figure 5-33. Time-series of respiration (μM O_2 hr^{-1}) at stations N18 and N04.



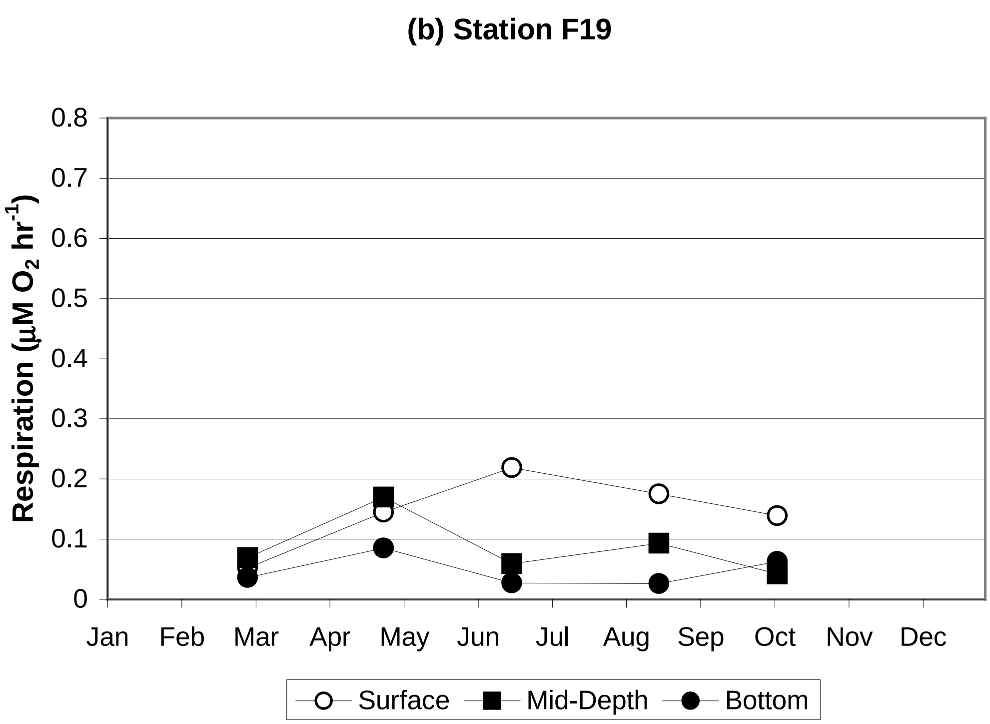


Figure 5-34. Time-series of respiration (μM O_2 hr^{-1}) at stations F23 and F19.

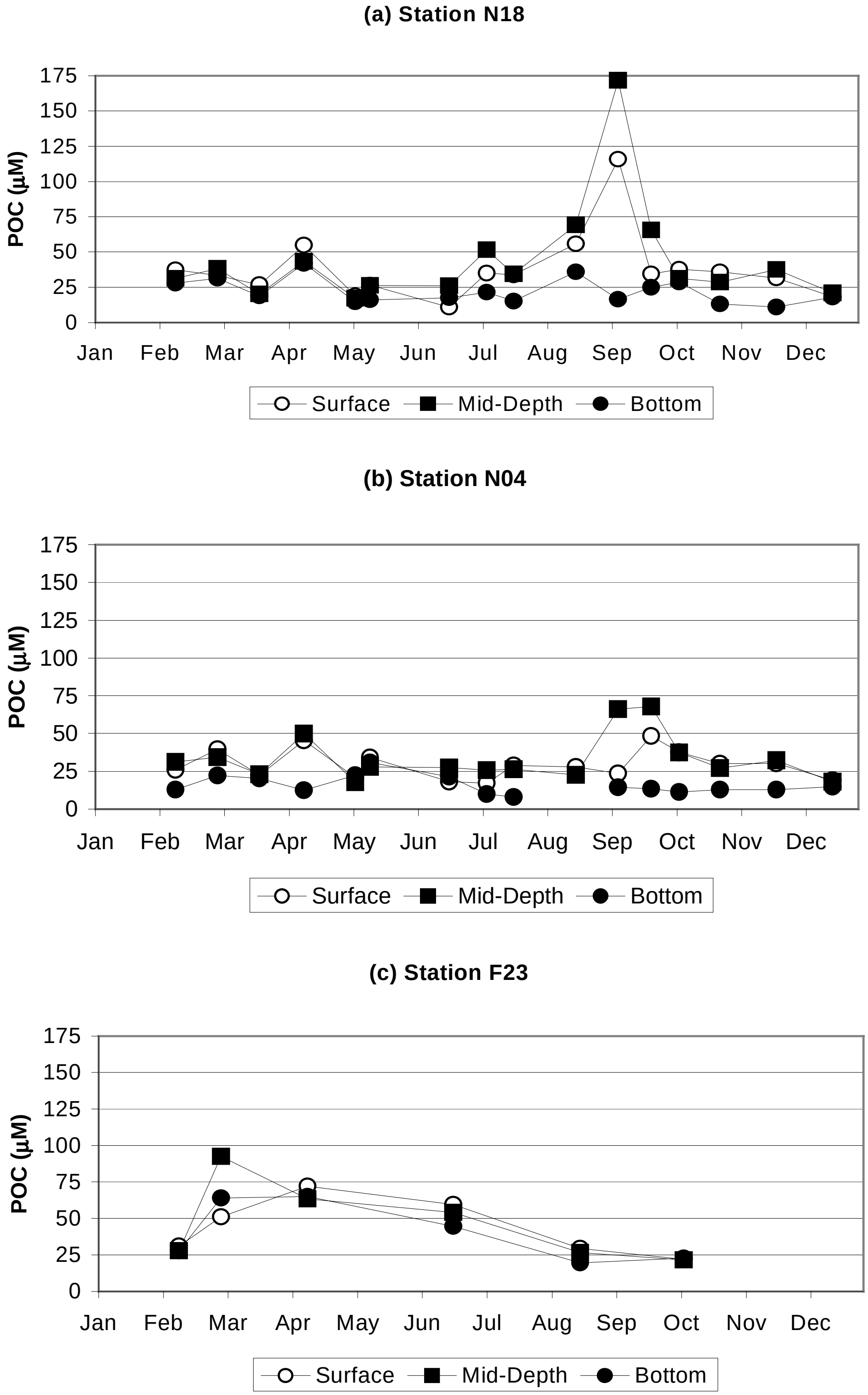


Figure 5-35. Time-series of POC (µM) at stations N18, N04 and F23.

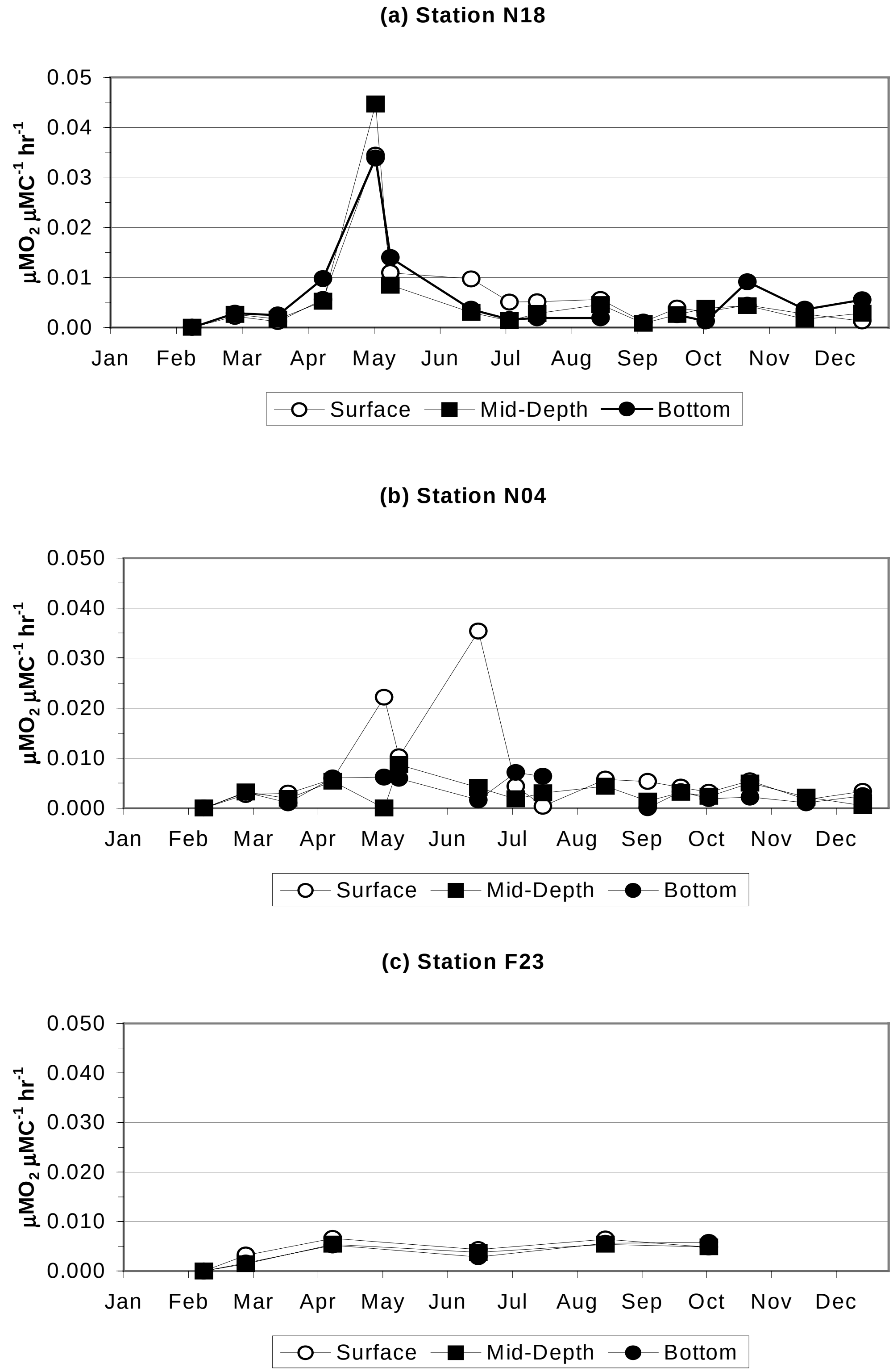


Figure 5-36. Time-series of carbon-specific respiration (μM O_2 μM C^{-1} hr^{-1}) at stations N18, N04 and F23.

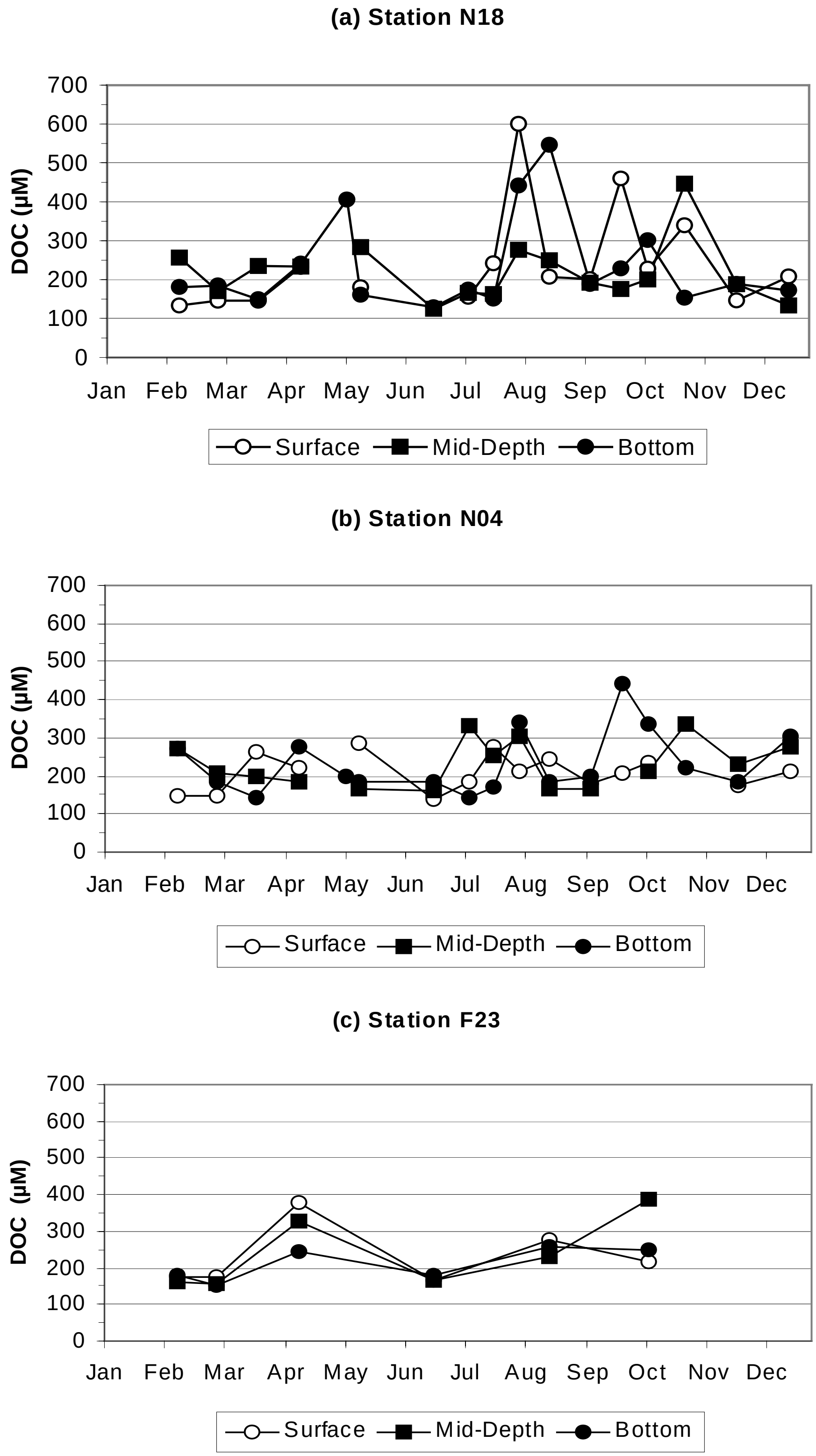
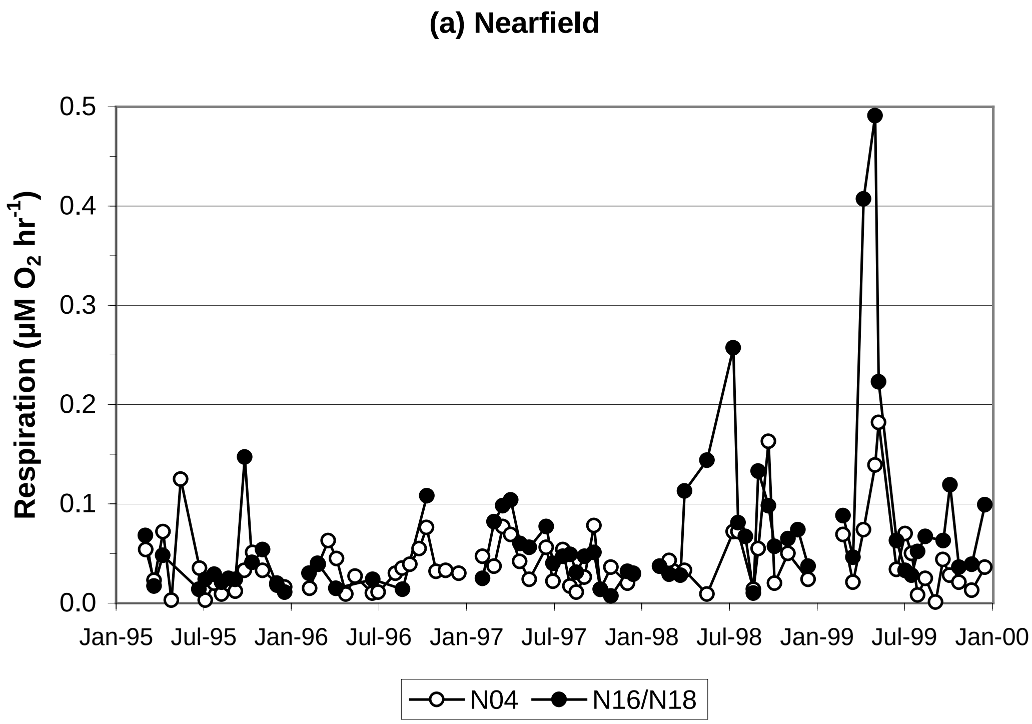


Figure 5-37. Time-series of DOC (µM) at stations N18, N04 and F23.



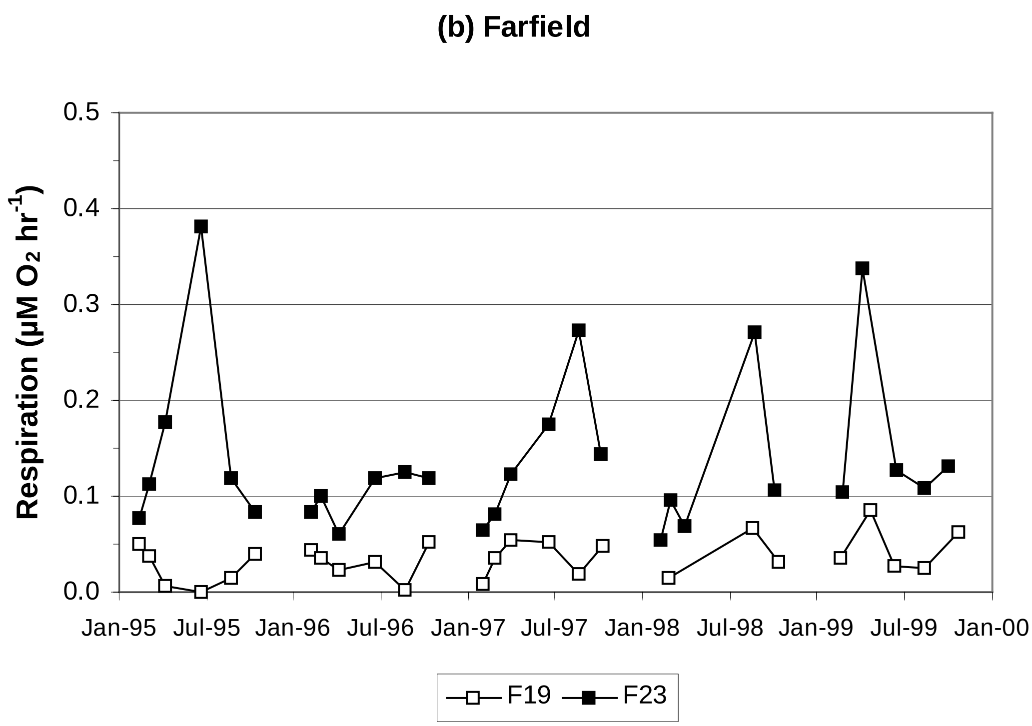


Figure 5-38. Time-series of bottom water respiration (μM O_2 hr^{-1}) at stations N04, N16/N18, F23, and F19 for 1995-1999.

6.0 PLANKTON

Plankton samples were collected on each of the water column surveys conducted during 1999. Phytoplankton and zooplankton samples were collected at two stations (N04 and N18) during each nearfield survey and at 11 farfield plus the two nearfield stations (total = 13) during the farfield surveys. During the first three farfield surveys of 1999 (WF991, WF992, and WF994), zooplankton samples were collected at two additional stations in Cape Cod Bay (F32 and F33). Phytoplankton samples included both whole-water and 20 μm-mesh screened samples from the surface and subsurface chlorophyll maximum depths. Zooplankton samples were collected by vertical/oblique tows with 102 μm-mesh nets. Methods of sample collection and analyses are detailed in Albro *et al*. (1998).

In this section, the seasonal trends in plankton abundance and regional characteristics of the plankton assemblages are evaluated. Total abundance and relative abundance of major taxonomic groups are presented for each phytoplankton (Section 6.1) and zooplankton (Section 6.2) community. Tables providing data on cell densities and relative abundance for all dominant plankton species (>5% abundance) were included in the 1999 semi-annual reports (Libby *et al*. 1999a and 2000). A brief overview of highlights of patterns in the plankton in 1999 is presented below. Details are considered in Sections 6.1 and 6.2. A discussion of several points that emerge from the 1999 results in relation to baseline plankton patterns in Massachusetts Bay is provided in Section 6.3.

Whole-Water Phytoplankton – In 1999 there was a moderate winter/spring phytoplankton bloom. Whole-water phytoplankton abundance increased from February through early May. Abundance declined somewhat from mid May through July, followed by secondary increases in August. Abundance subsequently declined in the fall and early winter, although there was a minor increase at some stations in October. Phytoplankton assemblages were dominated by a mixed assemblage of microflagellates and diatoms, including the potentially toxic diatom *Pseudo-nitzschia pungen*s in February and again in the fall. There were no confirmed blooms of nuisance algae in 1999, although the winter and fall *Pseudo-nitzschia* records for *P. "pungens*" could have included some of the domoic-acid-producing species *P. multiseries*. The total abundances of *Pseudo-nitzschia "pungens*" did not exceed 82 x 10^3 cells L^{-1}, which is well below the Canadian marker of 5 x 10^5 cells L^{-1} for increased vigilance for domoic acid in shellfish.

Screened Water Phytoplankton (> 20 μm) – Abundances of dinoflagellates recorded from screened samples were low from February through early May. Dinoflagellate abundance increased through the summer, reached high levels at most stations through October and November, and did not decline until December in the nearfield. Assemblages were dominated by the dinoflagellates *Ceratium fusus, C. longipes* and *C. tripos,* which continued a sustained presence from the previous year.

Zooplankton – Total zooplankton abundance generally increased from February through May with levels < 200 x 10^3 animals m^{-3}. Maximum abundance was in June and July with levels of > 500 x 10^3 animals m^{-3}. These are the highest zooplankton abundance levels recorded for the entire 1992-1999 baseline. Zooplankton abundance declined from mid August through December with all values < 100 x 10^3 and most values < 50 x 10^3 animals m^{-3}. The zooplankton were dominated, as typical for this coastal system, by copepod nauplii, adults and copepodites of the small copepods *Oithona similis* and *Pseudocalanus* spp., with seasonal subdominant contributions from meroplankters such as planktonic polychaete larvae, gastropod and bivalve veligers, and a mixture of other normally-occurring taxa. High abundance levels in Boston Harbor during summer were largely due to meroplankton pulses, in particular polychaete larvae, whereas high abundances in the nearfield were due to abundant adults and copepodites of the small copepods *Oithona similis* and *Pseudocalanus* spp.. Copepods of the genus *Acartia*, which are normally abundant primarily in the reduced-salinity waters of Boston Harbor were in unusually low abundance in the first half of 1999, possibly influenced by a major drought during this period.

6.1 Phytoplankton

6.1.1 Seasonal Trends in Total Phytoplankton Abundance

Total phytoplankton abundance in the nearfield exhibited normal seasonal trends indicative of spring and fall blooms and an unusually high abundance in late summer (Figure 6-1 and Table 6-1). The spring bloom was observed as an increase in phytoplankton abundance from early February (0.65×10^6 cells L^{-1}) to late February (1.48×10^6 cells L^{-1}). There was a slight decrease in phytoplankton abundance in March, but higher abundances were again observed in April (2.02×10^6 cells L^{-1}). A similar trend was observed for the farfield data with total phytoplankton abundance increasing from 0.65×10^6 cells L^{-1} in early February to ~1.5×10^6 cells L^{-1} in late February and April (Figure 6-2 and Table 6-1).

Nearfield phytoplankton abundance declined in early May to $<0.5 \times 10^6$ cells L^{-1} and then increased in mid-May to 1.29×10^6 cells L^{-1}. Total phytoplankton abundance was low throughout Massachusetts and Cape Cod Bays in June (means $<1.0 \times 10^6$ cells L^{-1}) and remained low in the nearfield through June and July (0.56 and 0.39×10^6 cells L^{-1}, respectively). The annual maximum phytoplankton abundance for the nearfield was observed in early August (2.81×10^6 cells L^{-1}). This summer increase in abundance was primarily due to a large increase in microflagellates and was coincident with an increase in chlorophyll concentrations and production. Total phytoplankton abundance remained elevated in the nearfield through August (1.65×10^6 cells L^{-1}) and farfield abundance reached an annual maximum during the mid-August survey (1.77×10^6 cells L^{-1}). Though total abundance had decreased in the nearfield from early to mid-August, there was a species shift with diatoms becoming dominant in the both the nearfield and the rest of Massachusetts Bay. Nearfield phytoplankton abundance generally declined from September through December ($\leq 1.0 \times 10^6$ cells L^{-1}) except for a small increase that was observed in late October (1.40×10^6 cells L^{-1}) that coincided with the fall bloom observed as increased chlorophyll concentrations and production.

Total abundances of dinoflagellates, silicoflagellates and protozoans in 20 µm-mesh-screened water samples were considerably lower than those recorded for total phytoplankton in whole-water samples, due to the screening technique which selects for larger, albeit rarer cells. Screened phytoplankton abundance essentially increased from February through November in both the nearfield and farfield (Figures 6-3 and 6-4; Table 6-2). This increase in screened phytoplankton abundance largely reflected a sustained bloom of the dinoflagellates *Ceratium longipes, C. tripos,* and *C. fusus* and was a continuation of a sustained presence that was observed during the previous year. Nearfield and farfield screened phytoplankton abundance was low from February to early May ($<1 \times 10^3$ cells L^{-1}) and increased in late May remaining relatively high over the summer to early September (2-5 $\times 10^3$ cells L^{-1}). The sustained bloom of *Ceratium* spp. reached high abundances in the fall (8-17 $\times 10^3$ cells L^{-1}) with a nearfield maximum of 17×10^3 cells L^{-1} and a farfield maximum of 8.5×10^3 cells L^{-1} in October.

Table 6-1. Nearfield and farfield averages and ranges of abundance (10^6 cells L^{-1}) of whole-water phytoplankton

Survey	Dates (1999)	Nearfield Mean	Nearfield Range	Farfield Mean	Farfield Range
WF991	2/2 – 2/8	0.65	0.57 - 0.72	0.65	0.37 - 1.18
WF992	2/23 – 2/28	1.48	1.16 - 1.69	1.39	0.57 - 2.53
WN993	3/20	1.17	1.04 - 1.33	NA	NA
WF994	4/1 to 5/6	2.02	0.83 - 3.03	1.57	0.42 - 3.42
WN995	5/5	0.46	0.33 - 0.63	NA	NA
WN996	5/12	1.29	1.06 - 1.50	NA	NA
WF997	6/14 – 6/19	0.38	0.18 - 0.78	0.94	0.28 - 1.63
WN998	7/7	0.56	0.35 - 0.95	NA	NA
WN999	7/20	0.39	0.18 - 0.81	NA	NA
WN99A	8/2	2.81	0.78-4.63	NA	NA
WF99B	8/16-19	1.65	1.15-2.51	1.77	0.69-3.25
WN99C	9/8	1.09	1.02-1.24	NA	NA
WN99D	9/24	1.00	0.90-1.22	NA	NA
WF99E	10/6,8,22,28	0.85	0.43-1.22	1.03	0.47-1.58
WN99F	10/27	1.40	1.19-1.73	NA	NA
WN99G	11/23	0.67	0.55-0.89	NA	NA
WN99H	12/20	0.53	0.30-0.92	NA	NA

NA- Data not available because the farfield stations were not sampled during this survey.

6.1.2 Nearfield Phytoplankton Community Structure

Whole-Water Phytoplankton – Phytoplankton assemblages were numerically dominated over much of the year by microflagellates (Figure 6-5a). During the spring bloom, a mixed assemblage of chain-forming centric diatoms primarily consisting of *Chaetoceros socialis* and *C. debilis* was numerically dominant with microflagellates not becoming dominant until April. Microflagellates continued to be dominant for the remainder of 1999. Subdominant contributions were made by the pennate diatom *Pseudo-nitzschia pungens* in February, the centric diatom *Skeletonema costatum,* the dinoflagellate *Prorocentrum minimum* and cryptomonads (< 10 µm) in May, and centric diatoms of the genus *Thalassiosira* and *S. costatum* during the summer. In mid-August, there was a dramatic increase in the centric diatom *Leptocylindrus danicus* that was coincident with increased chlorophyll concentrations and the annual production maximum at station N18. Subdominants in the fall included cryptomonads, *Pseudo-nitzschia* spp., and various centric diatoms. Centric diatoms (<10 µm) and *Thalassiosira* spp. increased in abundance during the fall bloom observed in late October. In 1999, the nearfield assemblages were generally similar to those observed at the boundary, nearfield, Boston Harbor, Cape Cod Bay, and coastal stations.

Table 6-2. Nearfield and farfield average and ranges of abundance (cells L^{-1}) for >20 µm-screened dinoflagellates

Survey	Dates (1999)	Nearfield Mean	Nearfield Range	Farfield Mean	Farfield Range
WF991	2/2 – 2/8	651	378 - 770	381	112 – 996
WF992	2/23 – 2/28	496	351 - 547	387	102 – 973
WN993	3/20	641	523 - 705	NA	NA
WF994	4/1 to 5/6	341	84 - 605	398	93 – 1034
WN995	5/5	631	584 - 728	NA	NA
WN996	5/12	2387	1833 - 2950	NA	NA
WF997	6/14 – 6/19	2171	828 - 3517	2798	275 – 18735
WN998	7/7	2134	1541 - 2709	NA	NA
WN999	7/20	1874	740 - 3570	NA	NA
WN99A	8/2	2015	1265-2871	NA	NA
WF99B	8/16-19	4246	1037-8385	5475	262-29115
WN99C	9/8	4642	609-11110	NA	NA
WN99D	9/24	12070	6606-19260	NA	NA
WF99E	10/6,8,22,28	9887	5878-15902	8587	373-24060
WN99F	10/27	8794	6968-11166	NA	NA
WN99G	11/23	17007	9018-23704	NA	NA
WN99H	12/20	6128	4422-7354	NA	NA

NA- Data not available because the farfield stations were not sampled during this survey.

Screened-Water Phytoplankton – The dinoflagellates recorded for screened samples were overwhelmingly dominated throughout the year by *Ceratium fusus, C. longipes* and *C. tripos*. These dinoflagellates were major contributors to the sustained increase in screened phytoplankton in the nearfield from August through November (Figure 6-3). Other dinoflagellates such as *Dinophysis norvegica, Prorocentrum minimum* and *Gyrodinium sprirale* and the silicoflagellate *Distephanus speculum* were subdominant during the first half of the year as were the dinoflagellate *Prorocentrum micans* and the silicoflagellates *Dictyocha fibula* and *D. speculum* during the second.

6.1.3 Farfield Phytoplankton Assemblages

Whole-Water Phytoplankton - From late winter through early spring, most farfield station assemblages were dominated at both depths by mixed assemblages of unidentified microflagellates and centric diatoms. Dominant taxa were generally the same as those listed above for the nearfield area. In early February, the pennate diatom *Pseudo-nitzschia pungens* was observed at stations across the bays (Figures 6-5b, 6-6 and 6-7). The winter/spring bloom of *Chaetoceros* spp. observed in the nearfield from February to April was also a baywide event. The April combined nearfield/farfield survey was conducted over the course of more than one month. The majority of the stations were sampled during the first two weeks of April, but stations N16, F06, and F13 were sampled in late April and early May. Relatively high phytoplankton abundance and a mixed assemblage of microflagellate/centric diatoms were observed at all stations except for the three stations sampled in late April/early May and the boundary station F27, which had been sampled in early April

(Figure 6-8). The delay in sampling allowed observation of changes in the phytoplankton community that may be associated with the spring freshet (see Section 3.3).

The sustained winter-spring bloom evidenced by primary productivity and chlorophyll was also apparent from large accumulations of green material in zooplankton net tows. Although this bloom was not as dramatic in terms of whole water cell abundance, this discrepancy is perhaps resolved by the fact that much of the green material in zooplankton nets was coagulated *Chaetoceros* spp. cells, many of which were undoubtedly *C. solialis* which was abundant during this period. *C. socialis* occurs in gelatinous masses, and a concurrent survey in February, 1999 using the Video Plankton Recorder (Davis and Gallager, 1999) revealed that colonies of *C. social*is were abundant, but extremely patchy in Massachusetts and Cape Cod Bays. Thus, it is possible that the whole-water phytoplankton samples underestimated abundance of this species, whereas zooplankton nets and/or VPR technology integrated patchiness over larger spatial areas.

As observed in the nearfield, there was a late summer bloom of the centric diatom *Leptocylindrus danicus* throughout Massachusetts Bay that was coincident with increased chlorophyll concentrations. In Boston Harbor, *L. danicus* was dominant at station F31 in the south harbor, but at inner harbor station F30 and north harbor station F23 *L. danicus* was not even a subdominant. In addition to microflagellates, cryptomonads and *Thalassiosira* spp. were present in high abundance at stations F23 and F30. The summer increase in centric diatoms was not observed in Cape Cod Bay where there was little change in abundance or phytoplankton assemblages over the summer and fall of 1999 (Figure 6-5b).

As discussed above, a fall bloom was observed in the nearfield in late October. Farfield data suggest that this bloom was not limited to the nearfield area. The October farfield survey (WF99E) was conducted over the course of about three weeks. Most phytoplankton stations were sampled in early October, but nearfield station N16, offshore station F06 and coastal station F13 were all sampled in late October. The phytoplankton assemblage at these three stations included a higher number of centric diatoms (Figure 6-9) similar to that observed in the nearfield in late October. These data suggest that the increase in unidentified centric diatoms (<10 μm) and *Thalassiosira* from early to late October occurred over western Massachusetts Bay and may have been a more widespread event.

Screened Phytoplankton – Predominant taxa in screened samples from farfield stations were generally similar to those recorded for the nearfield, detailed above. The major feature of screened assemblages was the prolonged multispecies bloom of *Ceratium* (*C. fusus*, *C. tripos*, *C. longipes*). This bloom was particularly apparent throughout most of the farfield from June through October (Figure 6-4).

6.1.4 Nuisance Algae

There were no confirmed blooms of harmful or nuisance phytoplankton species in Massachusetts and Cape Cod Bays during 1999. Some species that have caused harmful blooms in different seasons in previous years, such as *Phaeocystis pouchetii* (early spring) were unrecorded in 1999. Non-toxic species whose blooms have caused anoxic events elsewhere, such as *Distephanus speculum* and *Ceratium tripos*/*longipes* were routinely present, but not at abundances approaching those previously associated with anoxia.

The toxic dinoflagellate *Alexandrium tamarense* was unrecorded, although a few cells of the genus *Alexandrium* spp. that could not be positively identified as *A. tamarense* were recorded in April, May and July, resulting in calculated abundances of 1.4 – 9.1 cells L^{-1}. In most cases, these records were for single cells in the aliquots examined. There was no paralytic shellfish poisoning (PSP) toxicity recorded in shellfish at the Massachusetts Bay stations monitored by the Massachusetts Division of Marine Fisheries in 1999 (personal communication, Bruce Keafer, Woods Hole Oceanographic Institution).

Potentially toxic species of the diatom genus *Pseudo-nitzschia* were present, in some cases, in moderately high numbers. *Pseudo-nitzschia pungens* (which could include the toxic *P. multiseries*) were found in 24 samples in February (WF991 and WF992) at levels of <200 x 10^3 cells L^{-1}, and in 2 nearfield samples in early September (WN99C) at levels of 92-134 x 10^3 cells L^{-1}.

It was unclear as to which of potentially several species of this genus were present. While the non-toxic species *P. delicatissima* was identified with confidence, species reported as *P. pungens* could be either non-toxic *P. pungens*, or possibly domoic-acid-producing *P. multiseries*, since it is impossible to distinguish the two without performing scanning electron microscopy (SEM) counts on intercostal poroids on the underside of bleach- or acid-washed thecae. We have recently confirmed using SEM that some of the *Pseudo-nitzschia* present in Boston Harbor in August, 1998 were *P. multiseries*.

6.1.5 1992-1999 Phytoplankton Interannual Comparisons

For the baseline period (1992-99), mean total phytoplankton abundance in selected areas of the system (nearfield, harbor, Cape Cod Bay and coastal areas, see Figure 2-2) were generally < 2 x 10^6 cells L^{-1} (Figure 6-10). Higher abundances were recorded during some years, particularly 1995 and 1997, and during the *Asterionellopsis glacialis* bloom in October 1993. In general, the magnitude and trends in 1999 phytoplankton abundance were similar to those observed during other years lacking a substantial spring or fall bloom – 1994, 1996, and 1998. There was, however, a moderate winter-spring phytoplankton bloom in 1999, evidenced more in terms of primary productivity and chlorophyll than in terms of phytoplankton cell abundance. Winter-spring phytoplankton counts were higher than in 1998 when no clear spring bloom was observed in phytoplankton abundance or productivity (Libby *et al*. 1999b). A review of the 1992 to 1999 phytoplankton and chlorophyll data (see Section 4.2.3) suggests that the spring bloom may not be as common in Massachusetts Bay as previously thought. Large spring blooms as defined by chlorophyll data in past years (1992 and 1997) were due to blooms of *Phaeocystis*, which does not bloom every year, and was not recorded in 1999. Further, in some previous years, the spring bloom appeared to be limited to Cape Cod Bay, and was not manifest in the nearfield area. Fall blooms are often localized events with elevated production rates and chlorophyll concentrations associated with a diatom dominated mixed phytoplankton assemblage.

The whole-water phytoplankton assemblages in 1999 were generally similar to those found during other baseline monitoring years. A description of the common paradigm of "normal" seasonal succession is presented based upon the 1992-1999 baseline monitoring data. In whole-water phytoplankton samples, microflagellates are usual numerical-dominants throughout the year, and their abundance generally tracks water temperature, being most abundant in summer and least abundant in winter (Figure 6-11). Microflagellate area means over the course of the 1992-1999 baseline are remarkably repeatable (except for 1995) with summer peaks generally in the range of 1 – 2 x 10^6 cells L^{-1} in most years. In addition to microflagellates, the following taxa are dominant in Massachusetts and Cape Cod Bays during the periods identified below:

<u>Winter (primarily February</u>) – diatoms abundant, including *Chaetoceros debilis, C. socialis, Thalassiosira nordenskioldii,*and *T. rotula;*

<u>Spring (March, April, May)</u> – usually (except during *Phaeocystis* years) including assorted species of *Thalassiosira, Chaetoceros*, as well as the dinoflagellate *Heterocapsa rotundatum,* and (especially nearshore) cryptomonads;

<u>Summer (June, July, August</u>) – microflagellates are at peak abundance, with cryptomonads, *Skeletonema costatum* (especially nearshore), *Leptocylindrus danicus, Rhizosolenia delicatula, Ceratulina pelagica*, and various small-sized species of *Chaetoceros*;

Fall (September through December) – diatoms are abundant, including *Asterionellopsis glacialis, Rhizosolenia delicatula, Skeletonema costatum, Leptocylindrus minimus, L. danicus,* as well as cryptomonads, and assorted gymnodinoid dinoflagellates.

Superimposed over the background dominance of microflagellates and common diatoms, in some years there are outbursts of a single species such as *Asterionellopsis glacialis* in fall of 1993, or *Phaeocystis pouchetii* in spring of 1992 and 1997, or congeners such as the frequent summer-fall blooms of *Ceratium longipes/tripos*. Although such periodic blooms may be intermittent, they can be dramatic. Why such species bloom in some years but not others is unclear.

Over the baseline, screened-water dinoflagellate assemblages are normally dominated by the same non-toxic taxa that were abundant in 1999. These include *Ceratium longipes, C. tripos,* other *Ceratium* species, and various species of *Dinophysis, Protoperidinium,* and athecate dinoflagellates. The toxic species *Alexandrium tamarense*, though usually recorded in trace amounts in late spring and early summer, has not been abundant since MWRA sampling began in 1992. The frequency of sampling for the HOM program, however, may not adequately capture the occurrence of *A. tamarense*. In 1993 for example, shellfish PSP toxicity caused by *A. tamarense* was high in the bays and extended to a section of Cape Cod Bay (Sandwich, MA) that had never before recorded toxicity, while only a slight increase in *A. tamarense* abundance was observed by the HOM program for that year. Also, targeted sampling for *A. tamarense* during the spring-early summer red tide season by Don Anderson's group from Woods Hole Oceanographic Institution has often revealed higher abundances of this species in Massachusetts Bay than in MWRA sampling during the same months. *Alexandrium tamarense* is thought to initiate spring blooms from cyst beds in the Casco Bay region of Maine and become transported southward in a reduced-salinity plume from the Kennebec River (Anderson, 1997). Occasionally these bloom reach Massachusetts Bay, when northeast winds cause downwelling conditions, pressing the Maine coastal current along the shoreline.

6.2 Zooplankton

6.2.1 Seasonal Trends in Total Zooplankton Abundance

Total zooplankton abundance in the nearfield increased 4-fold from February (29 x 10^3 animals m^{-3}) to June (158 x 10^3 animals m^{-3}; Figure 6-12 and Table 6-3). Zooplankton abundance decreased slightly in July (~100 x 10^3 animals m^{-3}) before reaching maximum abundance for the year of >200 x 10^3 animals m^{-3} in early August. Nearfield zooplankton abundance declined from mid August through December with all values < 100 x 10^3 animals m^{-3} and most values < 50 x 10^3 animals m^{-3}. A similar seasonal pattern was observed in zooplankton abundance at the farfield stations – increasing abundance from February, maximum abundance during the summer (~200 x 10^3 animals m^{-3} in June), and decreasing abundance in the fall (Figure 6-13 and Table 6-3). In June, zooplankton abundance ranged from <100 to > 500 x 10^3 animals m^{-3} across the bays. The maximum abundance value during June was 518.5 x 10^3 animals m^{-3} at station F30 in Boston Harbor, this is the highest zooplankton abundance value recorded for the entire 1992-1999 baseline. The zooplankton assemblage at station F30 was dominated by planktonic polychaete larvae, which constituted 87% of total zooplankton collected (404.4 x 10^3 animals m^{-3}). The abundance of *Acartia* spp. was unusually low in Boston Harbor in 1999, possibly due to a persistent drought. The zooplankton were dominated, as typical for this coastal system, by copepod nauplii, adults and copepodites of the small copepods *Oithona similis* and *Pseudocalanus* spp., with seasonal subdominant contributions from meroplankters such as polychaete larvae, gastropod and bivalve veligers, and a mixture of other normally-occurring taxa Harbor.

Table 6-3. Nearfield and farfield average and ranges of abundance (10^3 animals m^{-3}) for zooplankton

Survey	Dates (1999)	Nearfield Mean	Nearfield Range	Farfield Mean	Farfield Range
WF991	2/2 – 2/8	29.2	19.1 - 36.8	16.9	4.7 - 32.3
WF992	2/23 – 2/28	41.6	0.2 - 72.3	28.4	12.4 - 67.7
WN993	3/20	31.5	30.4 - 32.5	NA	NA
WF994	4/1 to 5/6	44.0	5.8 - 112.8	38.1	4.1 - 196.0
WN995	5/5	73.9	73.7 - 74.1	NA	NA
WN996	5/12	120.0	116.6 - 123.4	NA	NA
WF997	6/14 – 6/19	157.6	120.5 - 201.2	183.6	75.1 - 518.5
WN998	7/7	105.4	46.0 - 164.8	NA	NA
WN999	7/20	95.7	78.8 - 112.6	NA	NA
WN99A	8/2	209.5	185.8-233.1	NA	NA
WF99B	8/16-19	55.9	41.4-79.5	50.4	15.2-83.2
WN99C	9/8	49.5	32.8-66.3	NA	NA
WN99D	9/24	20.0	19.5-20.4	NA	NA
WF99E	10/6,8,22,28	20.8	16.0-26.5	18.6	2.3-38.9
WN99F	10/27	29.8	29.8-29.9	NA	NA
WN99G	11/23	36.5	30.7-42.4	NA	NA
WN99H	12/20	25.5	23.5-27.4	NA	NA

NA- Data not available because the farfield stations were not sampled during this survey.

6.2.2 Nearfield Zooplankton Community Structure

From February (WF991) through May (WN996) the nearfield zooplankton assemblages were dominated by copepod nauplii, females and copepodites of *Oithona similis*, and gastropod veligers. By June (WF997), in addition to copepod nauplii and *O. similis*, there was increasing dominance by bivalve veligers and *Pseudocalanus* spp. copepodites. The importance of bivalve veligers decreased in July relative to June, whereas dominance by copepod nauplii and *O. similis* and *Pseudocalanus* spp. copepodites continued. In August and September, the dominance by copepod nauplii and *O. similis* and *Pseudocalanus* spp. copepodites was shared at various times by bivalve veligers, the tunicate *Oikopleura dioica*, and adults and copepodites of *Microsetella norvegica*, *Paracalanus parvus* and *Centropages* spp. Although not numerically dominant, gelatinous zooplankton (salps or the ctenophore, *Pleurobrachia pileus)* were very abundant in mid to late summer. In August, they were observed by the field team in the surface waters throughout Massachusetts and Cape Cod Bays and sightings of the gelatinous spheres were reported from Maine to Nantucket. Copepod nauplii and *O. similis* and *Centropages* spp. copepodites were dominant from October through the end of the year.

6.2.3 Zooplankton Assemblages

At farfield stations during February – May, copepod nauplii and *Oithona similis* females and copepodites were dominants. Gastropod veligers or the tunicate *Oikopleura dioica* were subdominant at various stations during this period. By June, the dominance by copepod nauplii and *Oithona similis* was shared or supplanted at various stations by meropolankters such as bivalve and gastropod veligers and, particularly in Boston Harbor, by planktonic polychaete larvae. The usually high abundance of *Acartia* spp. in Boston Harbor was not observed during 1999. Since this copepod inhabits primarily low-salinity harbor waters, its low abundance in Boston Harbor possibly reflects the prolonged drought in the mid-Atlantic and New England regions from winter through mid-summer of 1999. Although salinity data at HOM stations did not show a significant increase in 1999, Farfield it is expected that the effect on *Acartia* nauplii may be more pronounced in the upper reaches of the harbor that are influenced directly by freshwater inputs from the Charles and Mystic Rivers. During the second half of the year, farfield zooplankton assemblages were dominated at most stations by typical taxa such as copepod nauplii and *Oithona similis*, *Pseudocalanus* spp., *and Centropages* spp. adults and copepodites, with sporadic subdominant contributions by meroplanktonic polychaete larvae, gastropod, and bivalve veligers.

6.2.4 1992-1999 Zooplankton Annual Comparisons

Total zooplankton abundance means for 1999 were generally higher in most areas in comparison to other baseline years, except for 1992 (Figure 6-14). Comparisons of area means for total zooplankton abundance with patterns for *Oithona similis* abundance over the same period reveal general similarity of patterns albeit on different scales (Figure 6-15), highlighting the importance of this copepod species to overall patterns of abundance. Nearfield abundance of *O. similis* was unusually high in the nearfield, but low in Boston Harbor as usual. Abundance of *Pseudocalanus* spp. copepodites was unprecedented in 1999 in comparison to other baseline years with abundance values exceeding 65 x 10^3 animals m^{-3} in August 1999 (Figure 6-16). However, much of the high zooplankton abundance in 1999 was due to summer pulses of meroplankton (Figure 6-17), particularly polychaete larvae in Boston Harbor, which exceeded previous meroplankton abundance, in some cases by an order-of-magnitude. Such meroplankton (planktonic larvae of benthic invertebrates), often dominate the numbers in many zooplankton samples, but their periods of abundance are ephemeral, and likely more related to reproductive cycles of their macrobenthic parents, than to processes in the plankton.

6.3 Discussion of Plankton Results

There are several points that emerge from the 1999 results and from previous attempts to summarize plankton patterns in Massachusetts Bay that prompt further discussion.

There was a winter/spring phytoplankton bloom in both the nearfield and much of the farfield from early February to early April, evidenced by general increases in chlorophyll, primary production and phytoplankton cell abundance during this period. During the bloom, phytoplankton assemblages were comprised primarily of microflagellates and a mixed assemblage of diatoms, mainly of the genus *Chaetoceros*.

There was also a secondary late summer phytoplankton bloom in the nearfield and throughout most of Massachusetts Bay in August and September. Levels of chlorophyll, primary productivity and phytoplankton cell abundance did not parallel each other as clearly as observed during the winter/spring bloom, and this bloom was comprised primarily of microflagellates and the diatom *Leptocylindrus danicus*. It is possible that the elevated ammonium levels during the summer may have contributed to this bloom, since microflagellates frequently dominate the phytoplankton under conditions where ammonium is a primary component of the total dissolved inorganic nitrogen. In addition, the sustained increase in *Ceratium* spp. in the screened water fraction, particularly from August through October (see Figure 6-3), likely contributed disproportionately to the high chlorophyll levels. *Ceratium* spp. cells are large and have been observed with epifluorescence microscopy to be packed with red-fluorescing chlorophyll (Turner, personal observations). Further, shading of deeper layers by abundant *Ceratium* spp. cells may have contributed to the reduction in primary productivity from mid-August through September, at a time when chlorophyll was still high. The late summer bloom was not as pronounced in Cape Cod Bay as in Massachusetts Bay.

There was also a fall bloom in the nearfield and western Massachusetts Bay in October, evidenced by increases in chlorophyll, primary productivity, and cell abundance. The phytoplankton increase during this period was primarily in terms of diatoms of the genus *Thalassiosira*.

Zooplankton abundance exhibited the typical pattern of increases through the winter and spring, high levels in the summer, followed by declines in the fall. The typical dominants such as copepod nauplii, *Oithona similis* adults and copepodites, and *Pseudocalanus* spp. copepodites comprised much of most assemblages. In Boston Harbor, meroplankton pulses overwhelmed abundance at some stations and resulted in the highest total zooplankton abundances for the entire 1992-1999 baseline.

Area means revealed that 1999 was uncharacteristic of other baseline years in terms of the low abundance of copepods of the genus *Acartia* in Boston Harbor (Figure 6-18). This was particularly the case for *Acartia tonsa*, the warm-season congener, but also evident for the generally less-abundant cold-season congener *A. hudsonica*. The 1999 declines in warm-season *Acartia* abundance were particularly apparent at Stations F30 and F23, which have previously evidenced much higher abundances of *Acartia* than at Station F31. Abundances of *Acartia* spp. in Boston Harbor also appear to be undergoing substantial declines in 1998 and 1999, compared to peak years of 1995-1997.

The restriction of *Acartia tonsa* to estuarine/harbor habitats was investigated by Tester and Turner (1991) who found that with copepods from Beaufort, North Carolina, the salinity tolerance of *Acartia tonsa* naupliar stages was a major factor restricting this species to estuarine waters. Naupliar survival was optimal (> 70%) at salinities of 20-25 ppt, and temperatures near 20^{o}C. Naupliar survival declined rapidly at salinities greater than 25 ppt, and it is known that for *Acartia tonsa*, resting eggs begin to be produced at temperatures near 10^{o}C (Zillioux and Gonzalez, 1972). Tester and Turner confirmed that eggs held at 10^{o}C hatched poorly and none of the nauplii survived. Thus, it appears that parameters relating to naupliar survival restrict *Acartia tonsa* to waters of low salinities and warm temperatures, such as Boston Harbor, in the summer and fall. In essence, the physiological tolerances of the younger instars determines the biogeographic distribution of the species, as with many other animals. The conclusion that *Acartia tonsa* is restricted to warm low-salinity embayments was recently supported by studies of salinity tolerance in the harbor of Marseilles (Cervetto *et al*. 1999).

We might speculate that the extremely low 1999 abundance of *Acartia* spp. in their primary habitat of Boston Harbor could be related to the drought during the first half of the year. However, this was not glaringly apparent from comparisons of salinity and *Acartia* abundance in Boston Harbor (Figure 6-19). We suspect that this is because the lag time from development of *Acartia* nauplii into identifiable copepodites and adults (at least a week at typical summer temperatures) is such that correlations between simultaneously collected *Acartia* and salinity data become blurred. Similarly, although the June 1998 major runoff event is clearly apparent in salinity data from Boston Harbor, this freshet did not instantly result in elevated abundances of *Acartia* spp. Another reason for the apparent disconnect between *Acartia* abundance and salinity at the three Boston Harbor stations may be that these stations are not located in the upper reaches of the harbor where lower salinity is usually observed. The areas near inputs from the Charles and Mystic rivers would be more likely to show the effect of the drought and potentially it could be in these inner harbor areas that *Acartia* nauplii survival is directly affected by meteorological conditions. The salinity trends in the upper reaches of the harbor for 1999 versus previous baseline years should be examined in more detail once data are available from the MWRA Boston Harbor Monitoring Program (data presently in QC/QA review).

A final factor that could have played a role in *Acartia* abundance in 1999 was the elevated NH_4 concentrations observed in the harbor. On one hand, the high concentrations could have had a toxic effect and decreased nauplii survival. The effect of high ammonia (NH_3) concentrations on the survival of *Acartia tonsa* nauplii were examined by Sullivan and Ritacco (1985) in experimental ecosystems. The NH_3, and coincident NH_4, concentrations where Sullivan and Ritacco observed a substantial decrease in nauplii survival, however, were much higher (NH_4 >100 μM for any decrease in survival) than the NH_4 concentrations observed in Boston Harbor. On the other hand, it was once thought that increases in *Acartia* abundance would be indicative of increased nutrient concentration and that *Acartia* abundance should be used as a warning threshold for the new outfall. The "*Acartia* hypothesis" was dismissed in Libby *et al.* (1999b), which noted the importance of higher temperatures and lower salinity to nauplii survival in Boston Harbor rather than higher concentrations of food (more eutrophic conditions). In 1999, the decrease in *Acartia* in Boston Harbor occurred despite the increase in NH_4 concentrations and unprecedented chlorophyll concentrations. The lack of a relationship between the nutrient and chlorophyll increases in 1999 and *Acartia* abundance support the elimination of the proposed *Acartia* warning threshold for the nearfield.

During February 1999, there was an additional survey in Massachusetts and Cape Cod Bays using the Video Plankton Recorder (VPR) (Davis & Gallager, 2000). Comparisons of zooplankton data from the VPR survey with HOM net samples, for appropriate larger copepods such as *Pseudocalanus* spp. adults, which would be recorded with both techniques, revealed that abundances agreed in absolute magnitude with each other. Correlation length scales for VPR data were obtained by plotting normalized covariance functions versus lagged distance. This indicated a strong positive correlation at scales less than 10 km, but this correlation became nearly zero at 20-50 km, and negative at the bay-wide scales of > 50 km. This indicated that locations separated by > 20 km, such as HOM stations F01 and F02 in Cape Cod Bay, were independent of each other, but that stations closer than 20 km should be correlated to some degree to one another. This correlation should be considered in statistical tests for post-discharge effects.

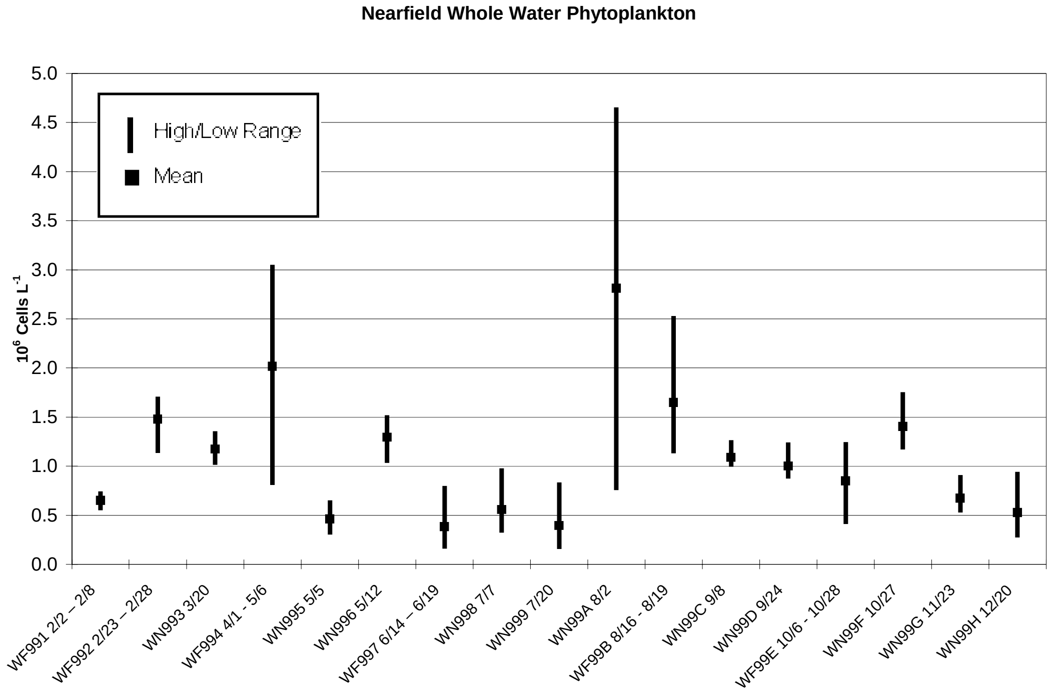


Figure 6-1. Total phytoplankton abundance for nearfield whole-water samples. Mean and range for all nearfield stations and depths sampled.

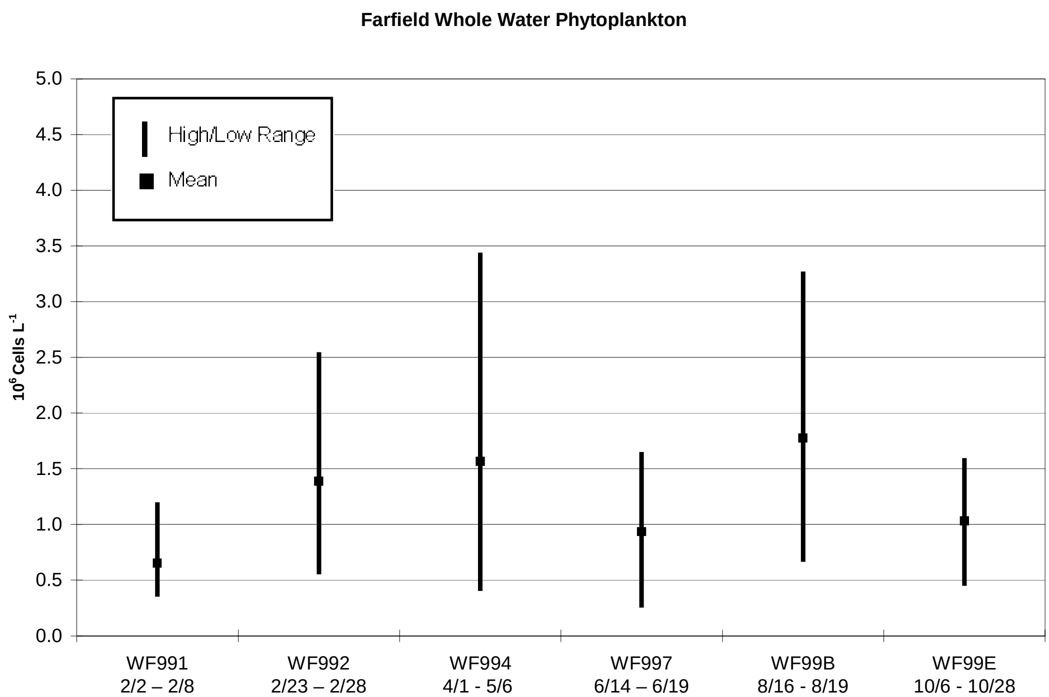


Figure 6-2. Total phytoplankton abundance for farfield whole-water samples. Mean and range for all farfield stations and depths sampled.

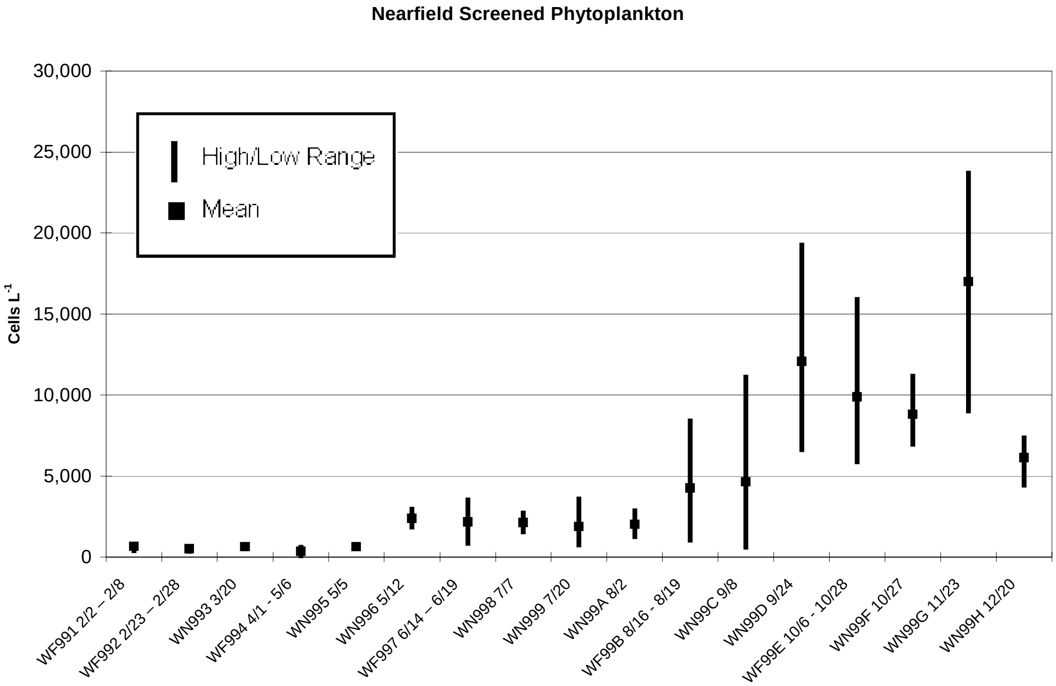


Figure 6-3. Total phytoplankton abundance for nearfield 20-μm screened samples. Mean and range for all nearfield stations and depths sampled.

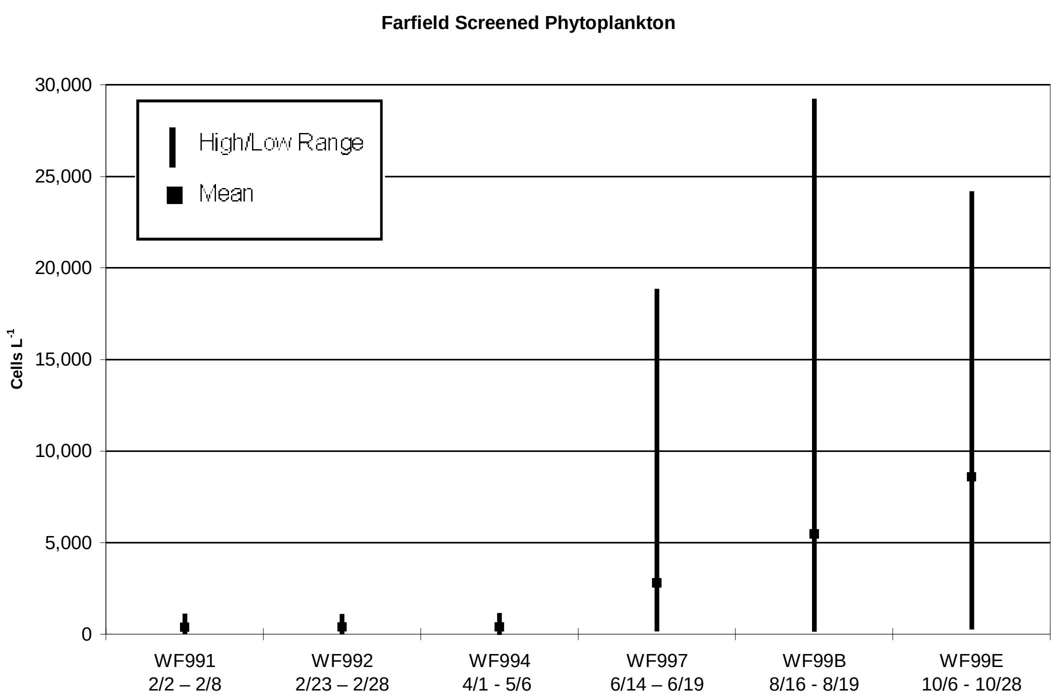
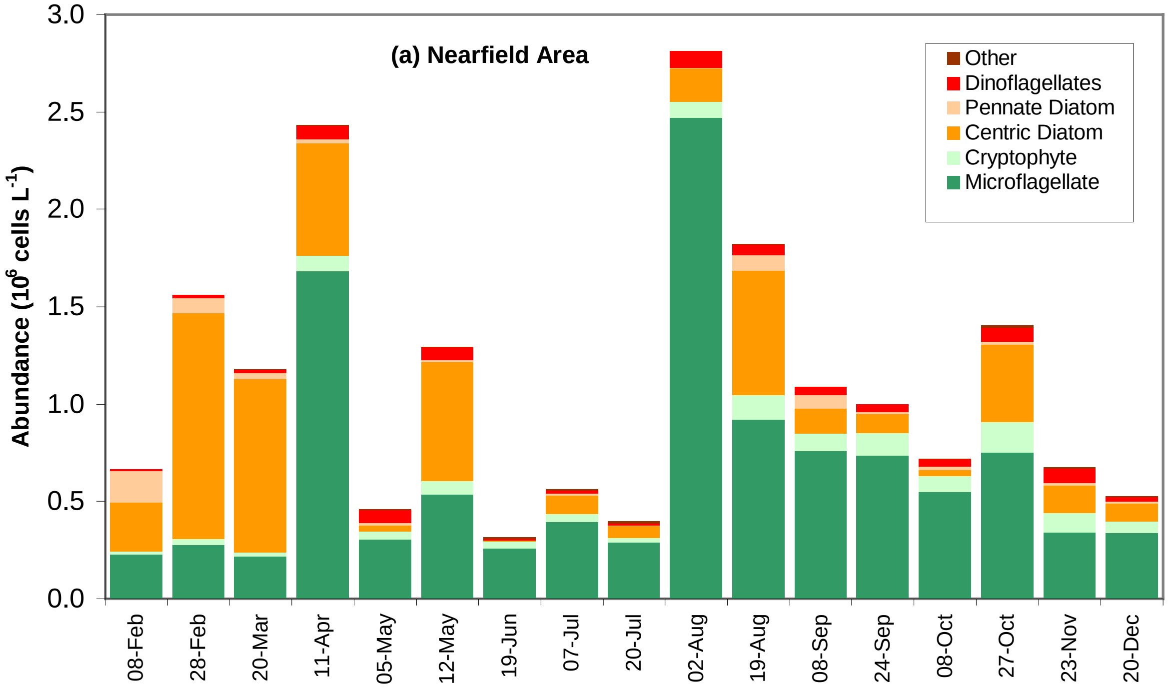


Figure 6-4. Total phytoplankton abundance for farfield 20-μm screened samples. Mean and range for all farfield stations and depths sampled.



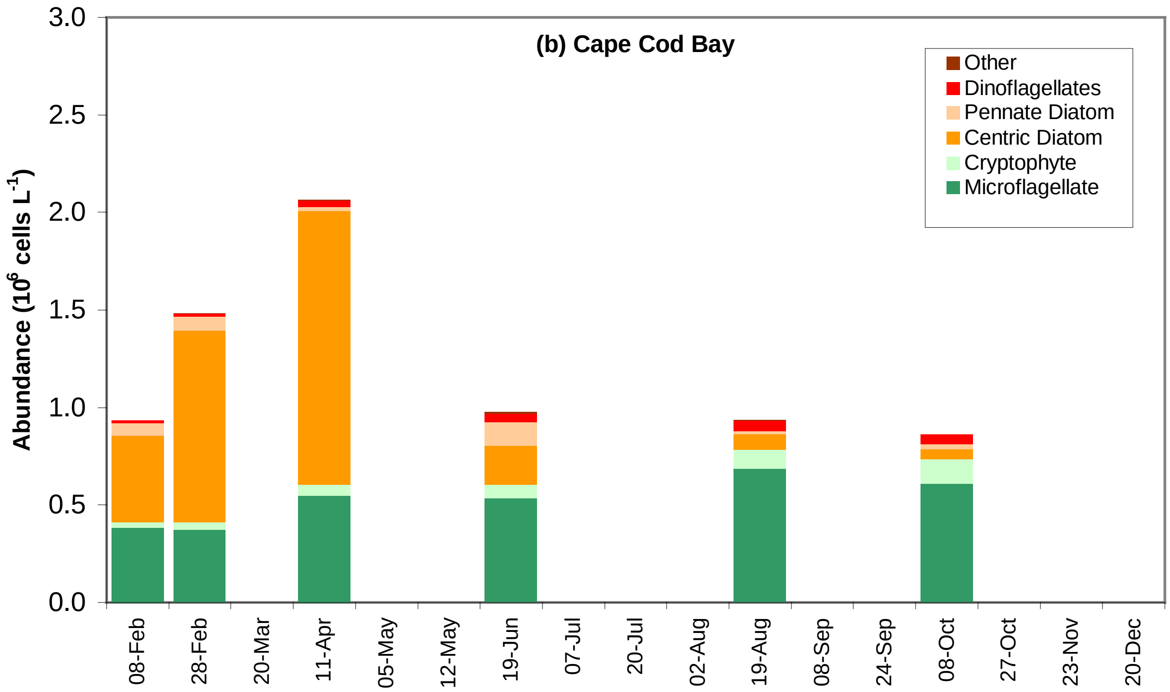
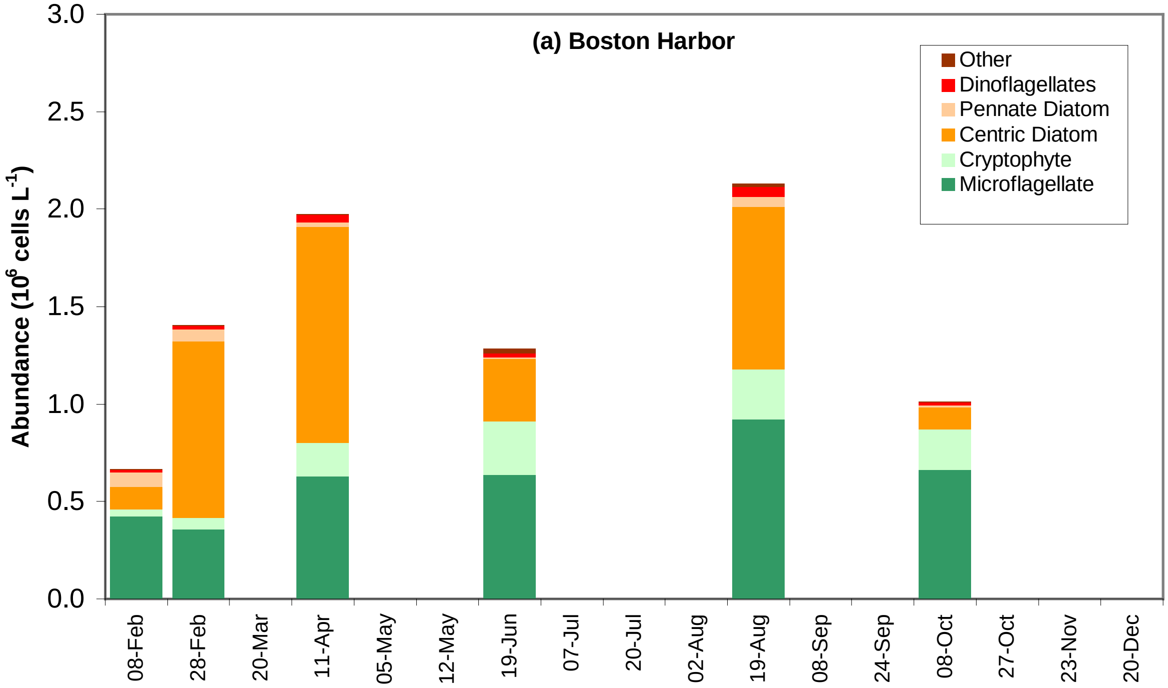


Figure 6-5. Average phytoplankton abundance by major taxonomic group, (a) nearfield area and (b) Cape Cod Bay. Data are average of surface and mid-depth samples from N04 and N18 and F01 and F02, respectively.



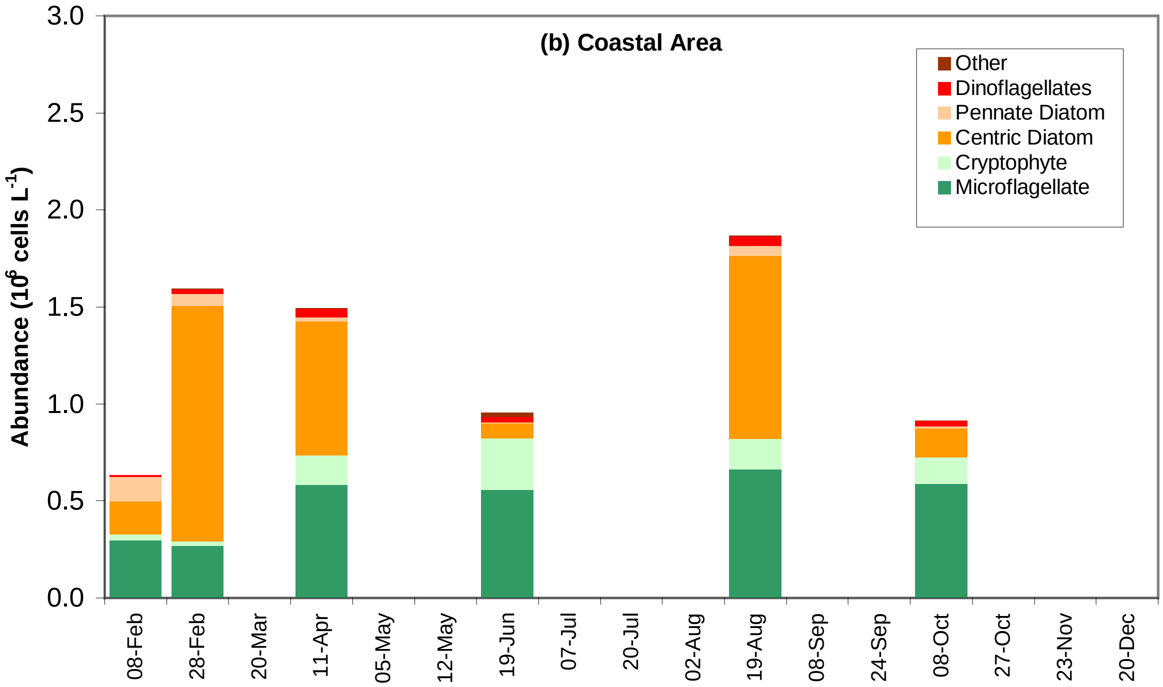
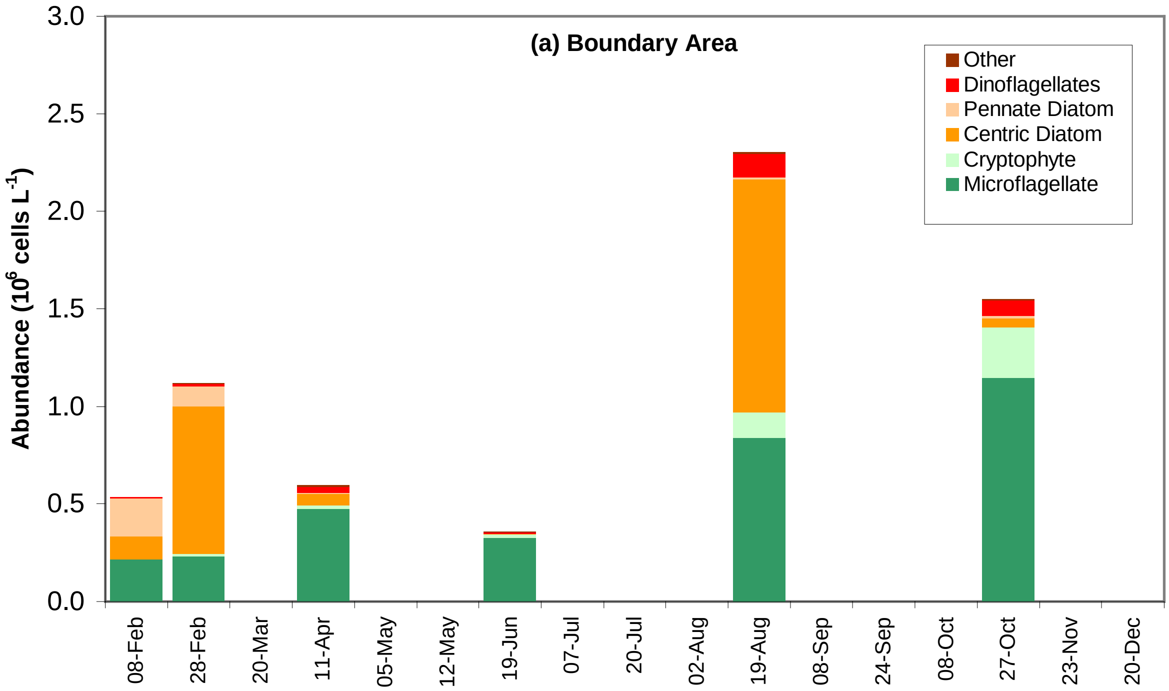


Figure 6-6. Average phytoplankton abundance by major taxonomic group, (a) Boston Harbor and (b) Coastal Area. Data are average of surface and mid-depth samples from F23, F30 and F31 and F13, F24 and F25, respectively.



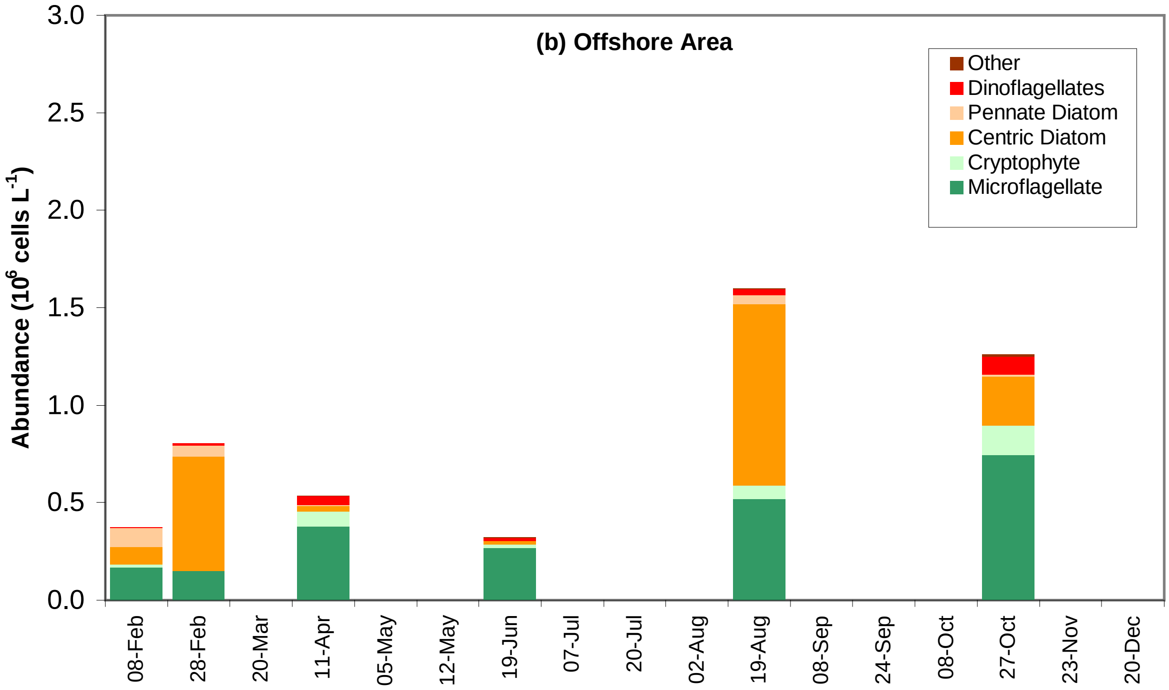
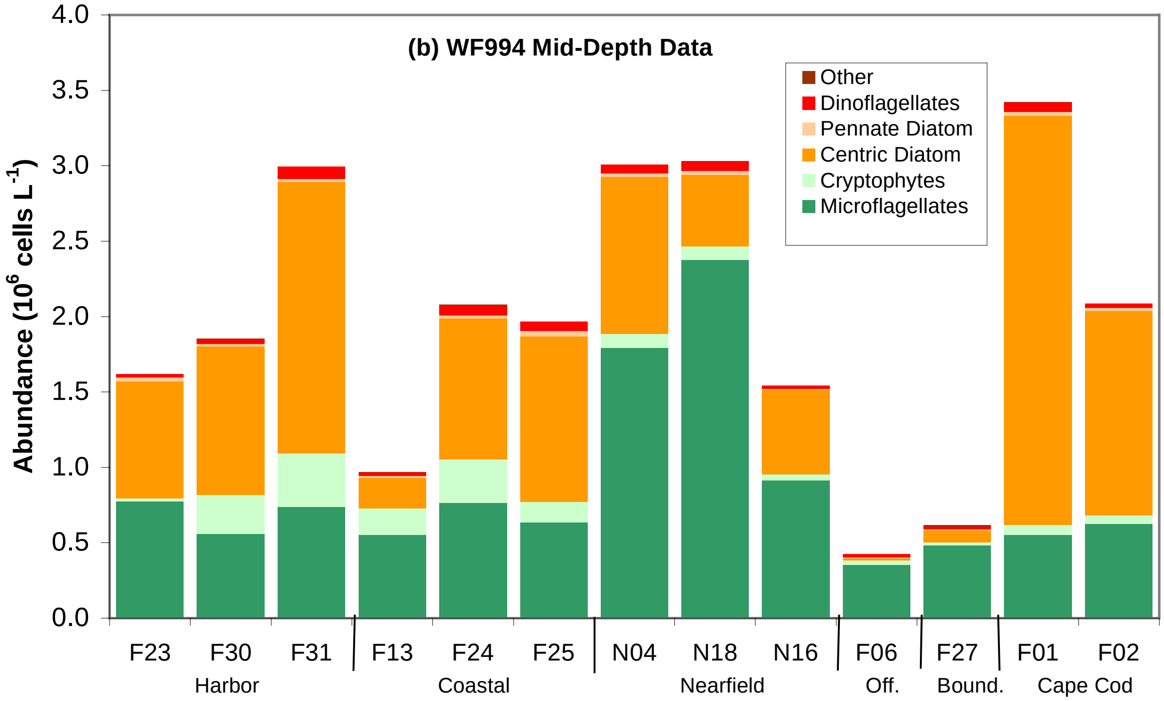


Figure 6-7. Average phytoplankton abundance by major taxonomic group, (a) boundary and (b) offshore area. data are average of surface and mid-depth samples from F27 and F06, respectively.



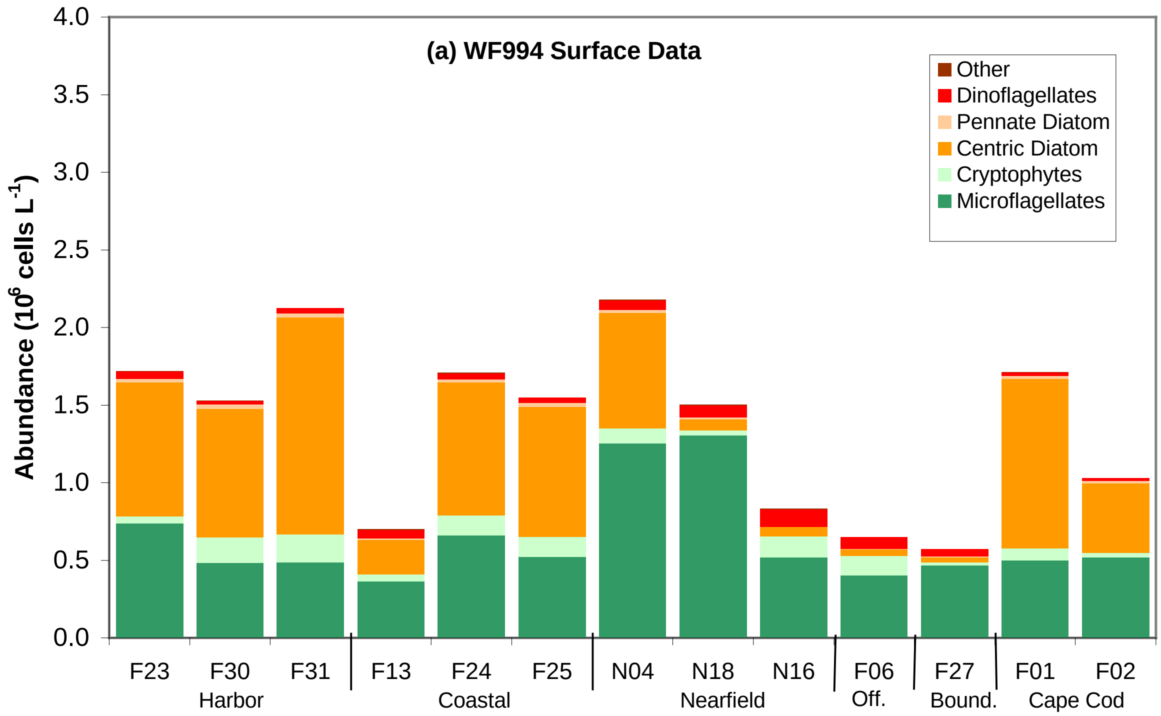


Figure 6-8. Phytoplankton abundance by major taxonomic group – WF994 survey results April 1 - May 6, 1999.

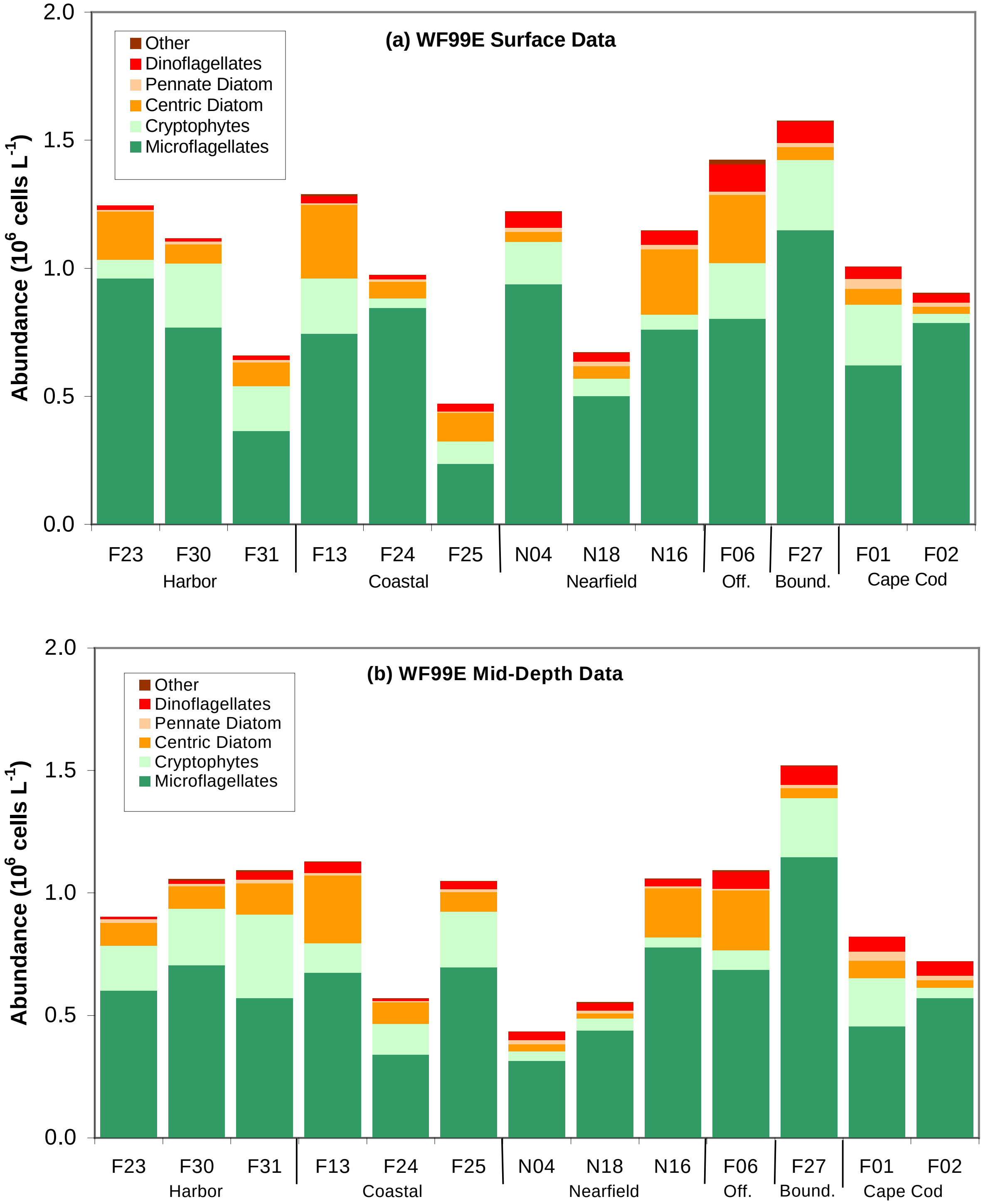


Figure 6-9. Phytoplankton abundance by major taxonomic group – WF99E survey results October 6-28, 1999.

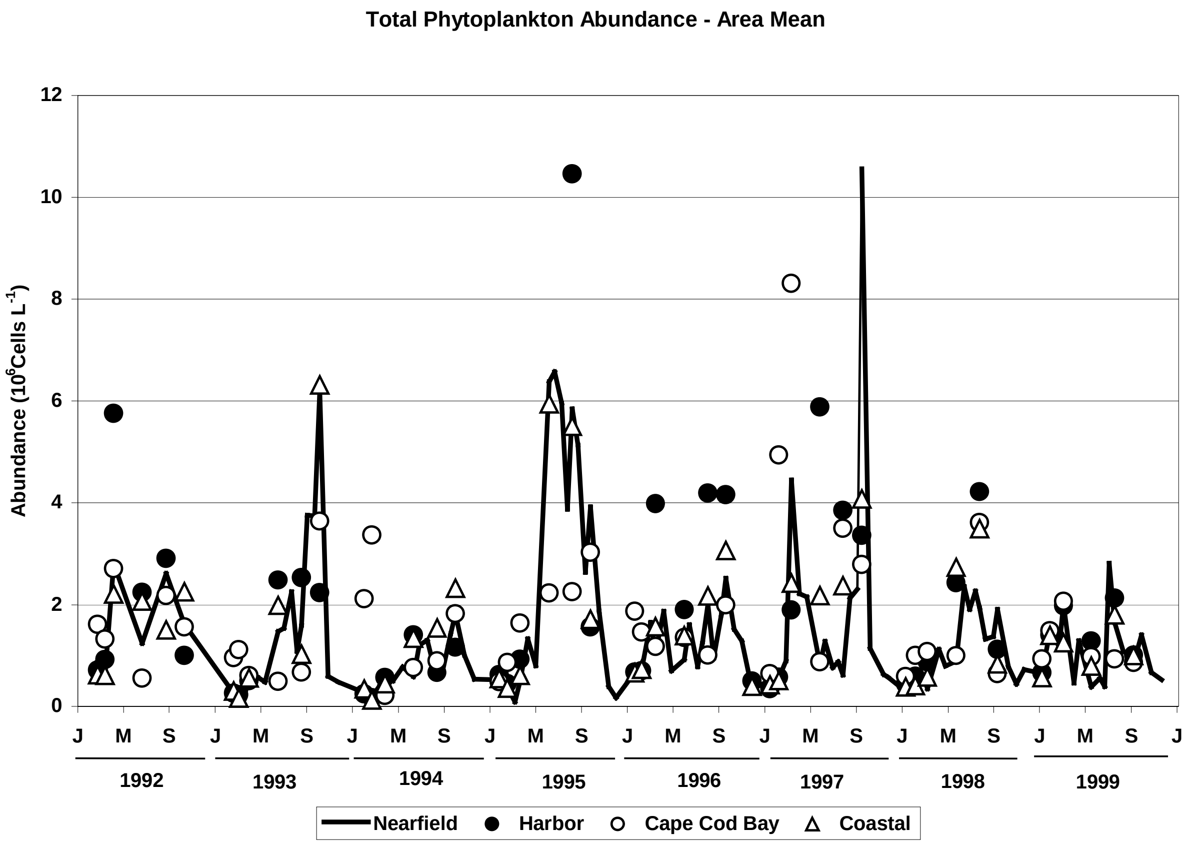


Figure 6-10. Total phytoplankton abundance for whole-water samples at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations and depths sampled by survey (see Figures 6-5 and 6-6 for station groupings).

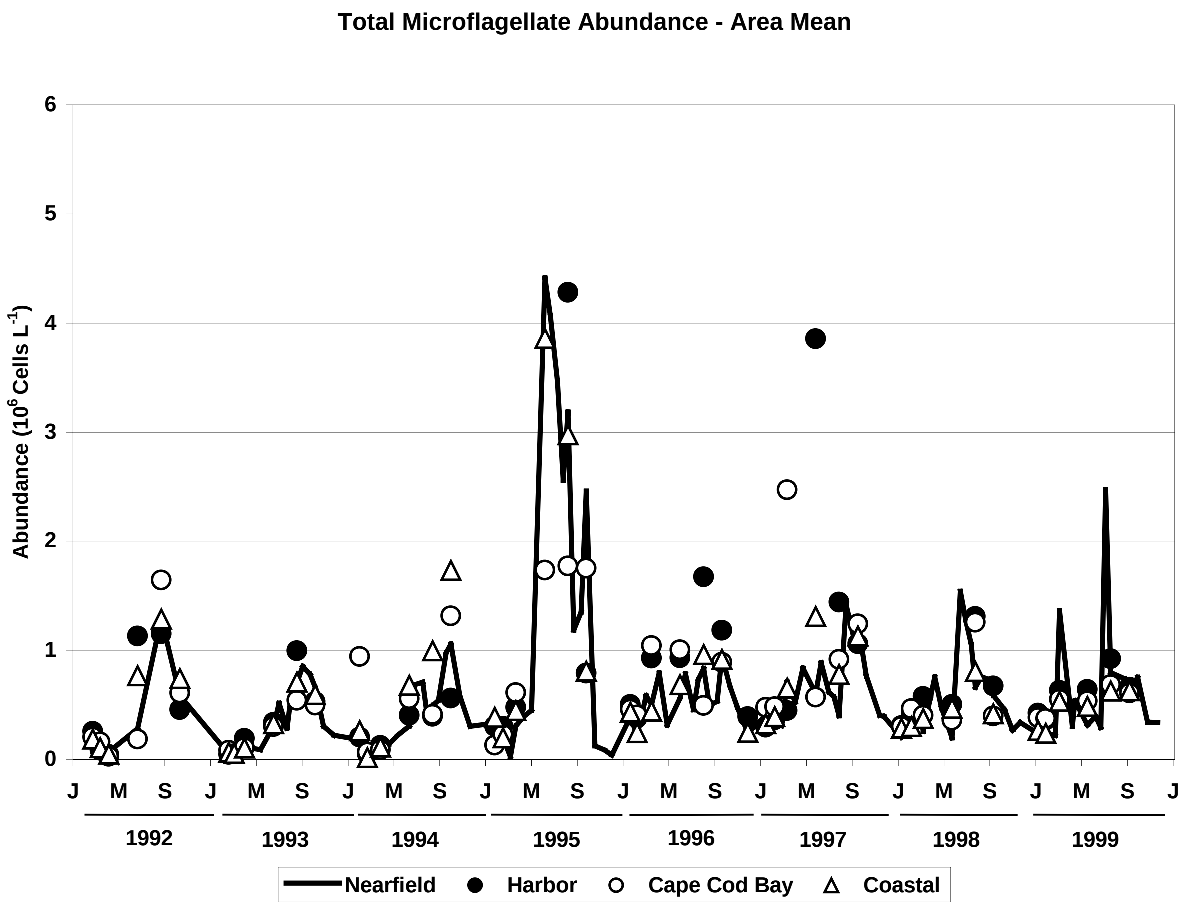


Figure 6-11. Total microflagellate abundance for whole-water samples at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations and depths sampled by survey (see Figures 6-5 and 6-6 for station groupings).

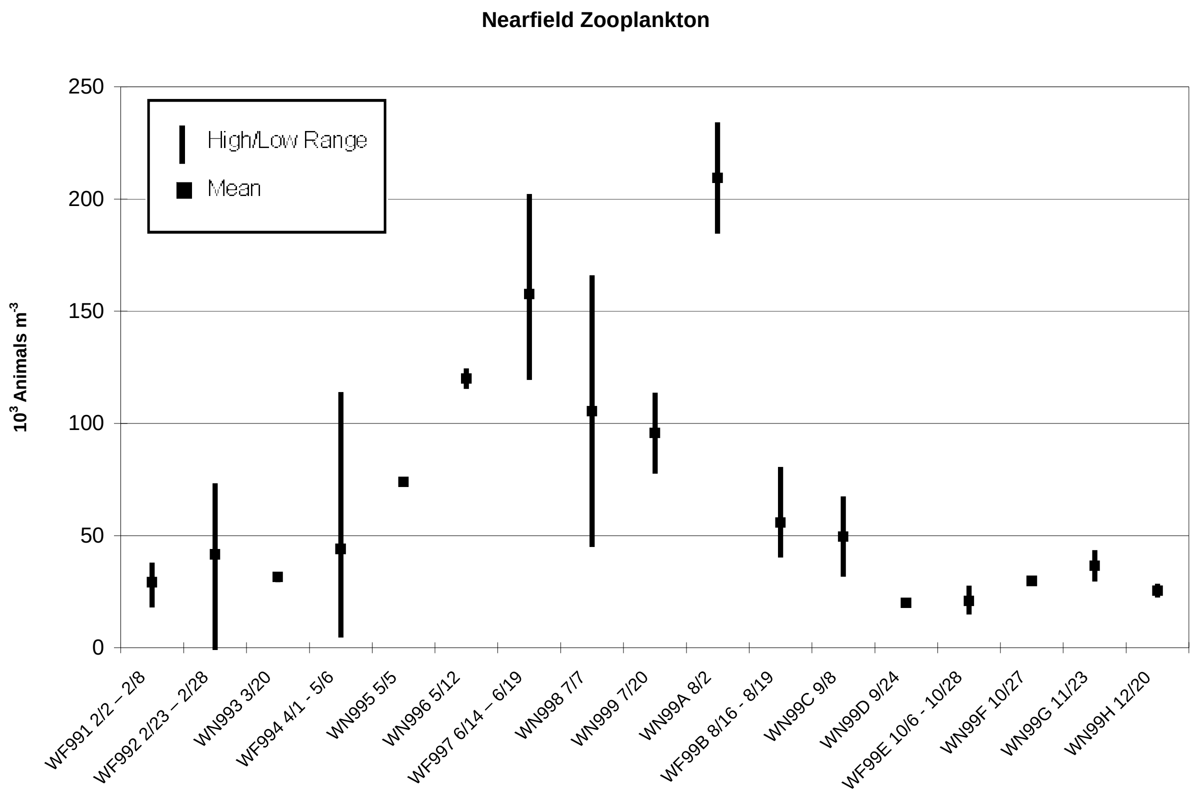


Figure 6-12. Total zooplankton abundance for nearfield. Mean and range for all nearfield stations and depths sampled.

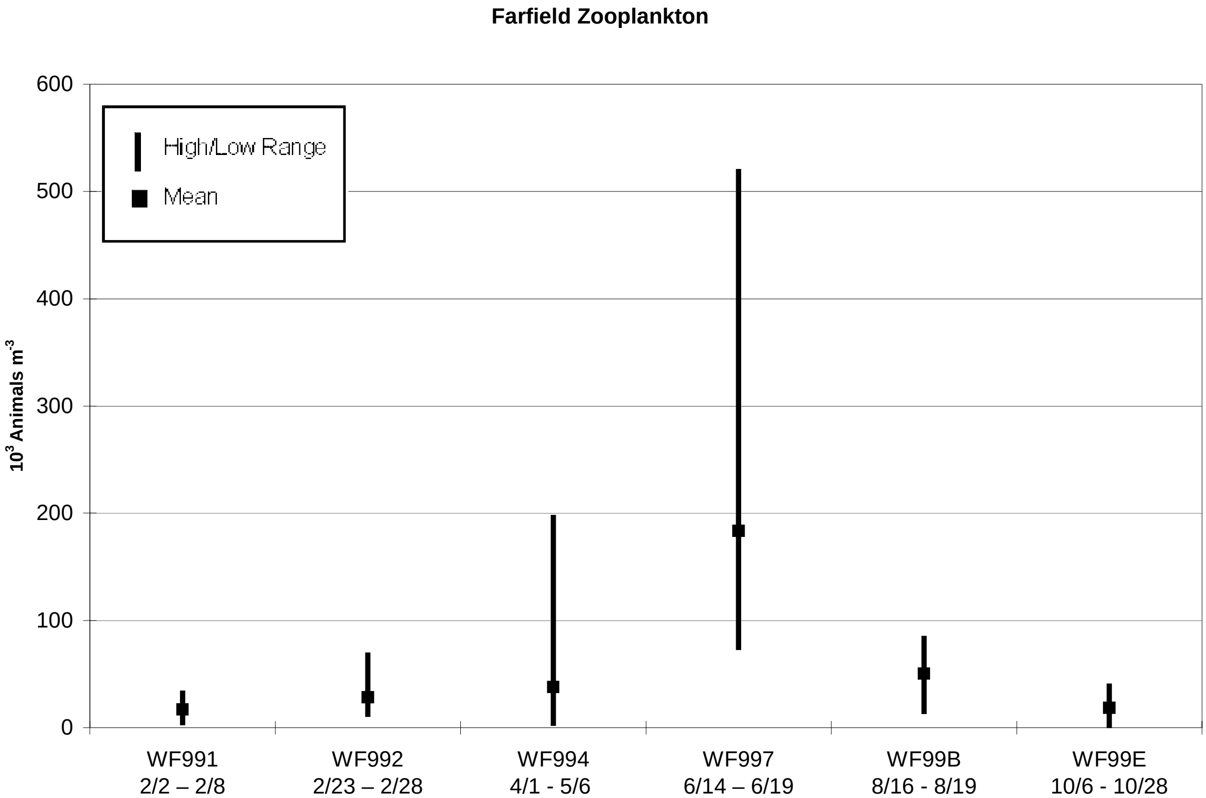


Figure 6-13. Total zooplankton abundance for farfield. Mean and range for all farfield stations and depths sampled.

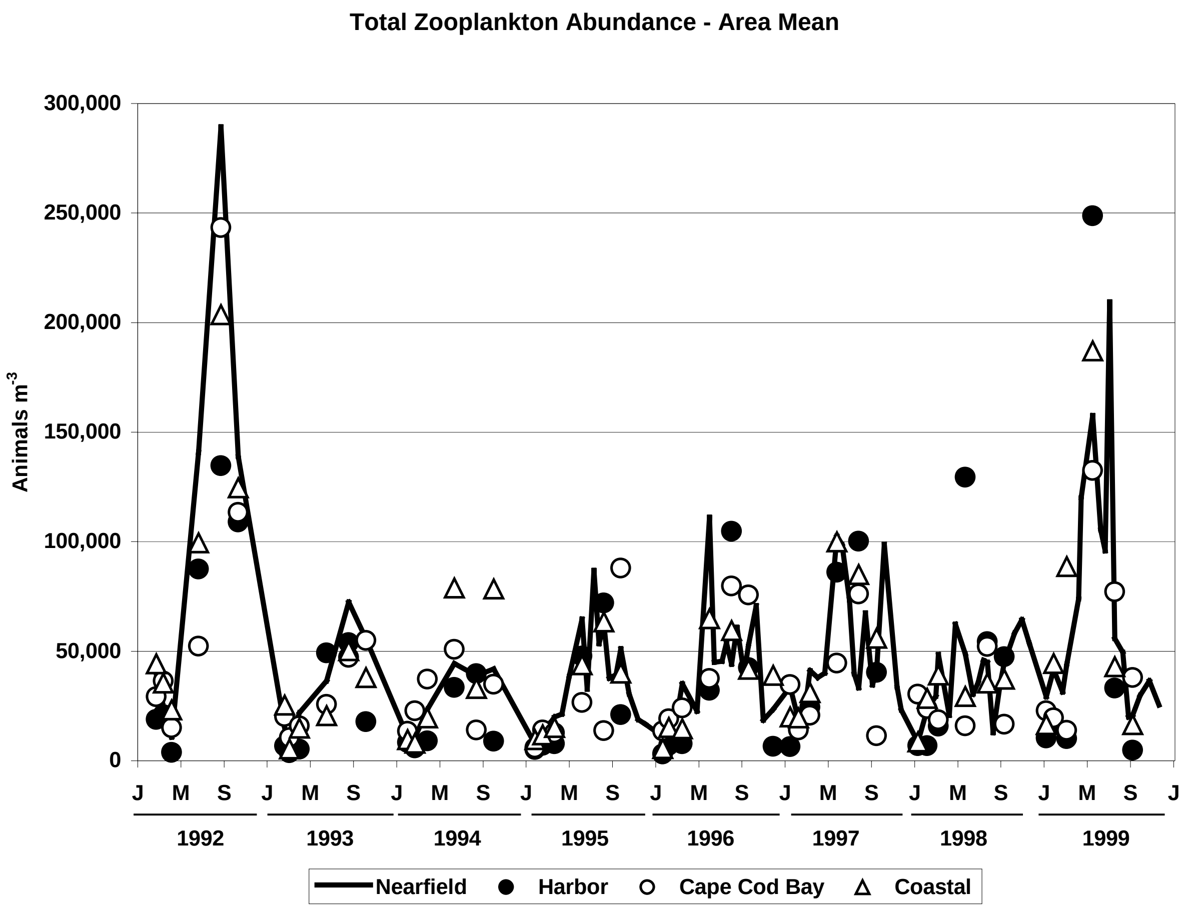


Figure 6-14. Total zooplankton abundance at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations sampled by survey (see Figure 2-2 for area stations).

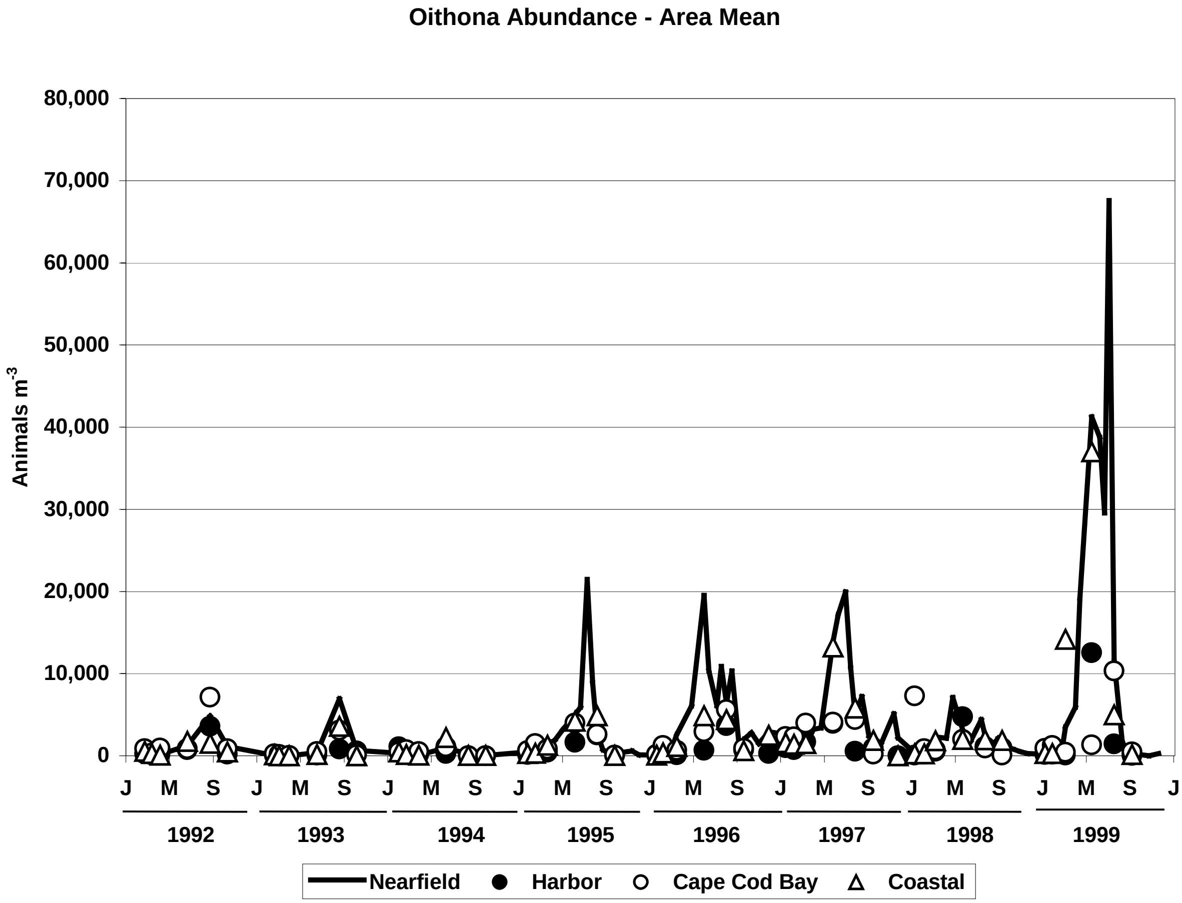


Figure 6-15. ***Oithona similis*** **adult and copepodite abundance at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations sampled by survey (see Figures 6-5 and 6-6 for station groupings).**

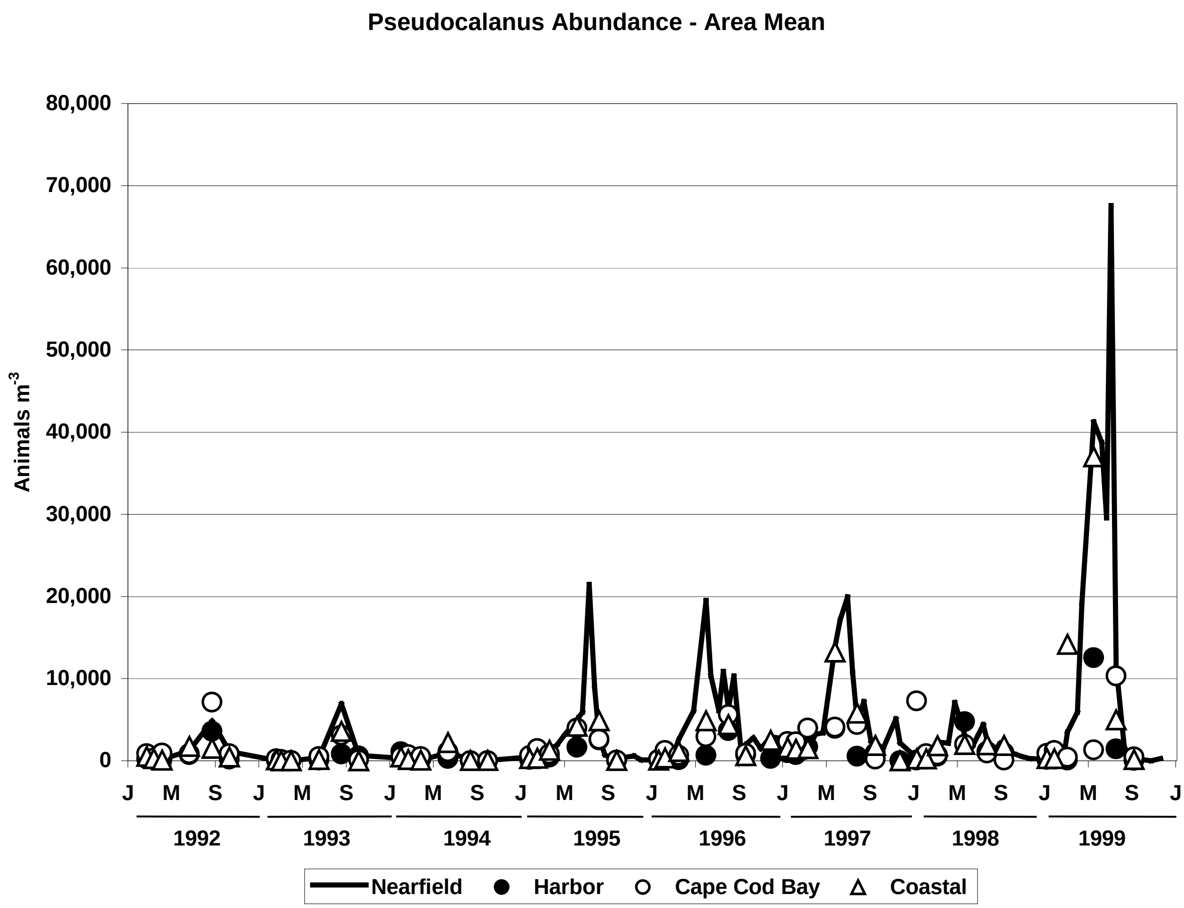


Figure 6-16. ***Pseudocalanus*** **adult and copepodite abundance at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations sampled by survey (see Figures 6-5 and 6-6 for station groupings).**

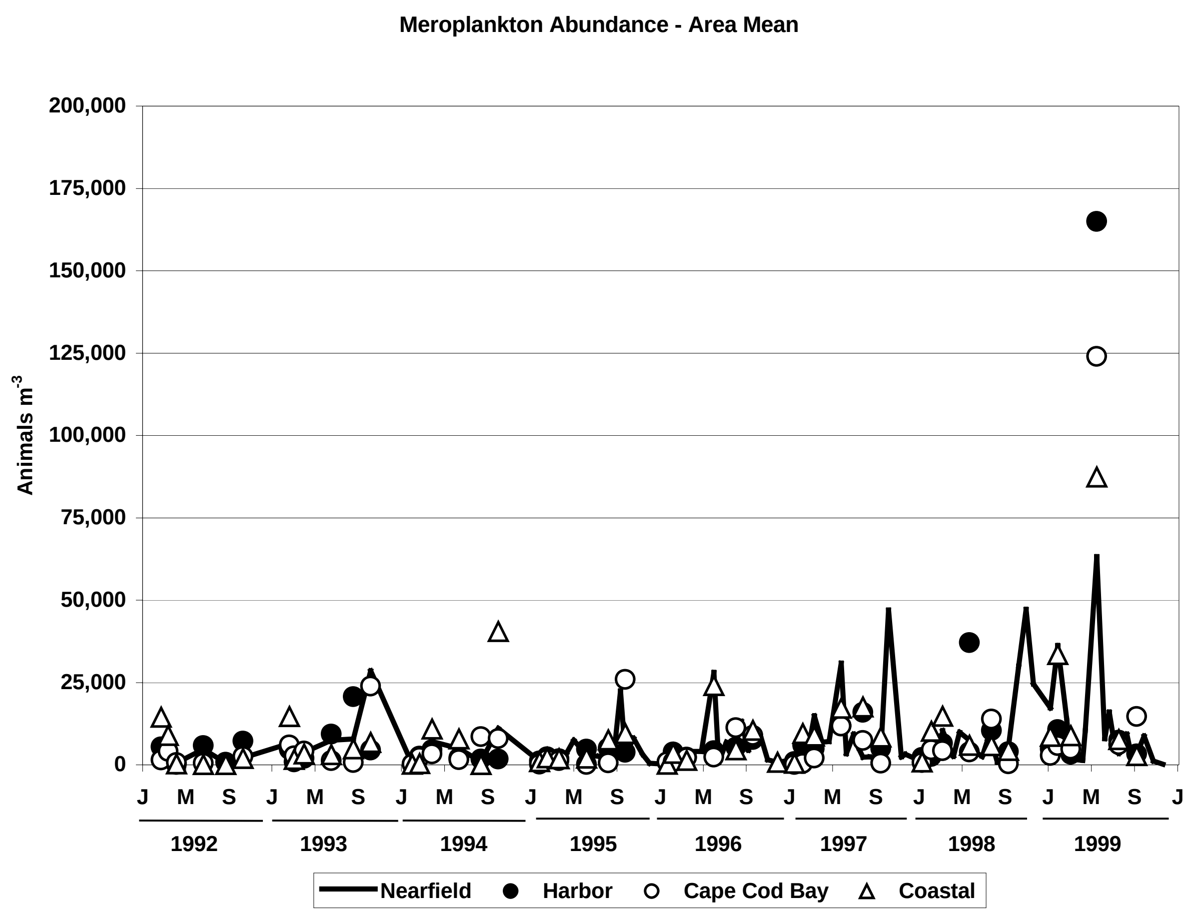


Figure 6-17. Meroplankton abundance at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations sampled by survey (see Figures 6-5 and 6-6 for station groupings).

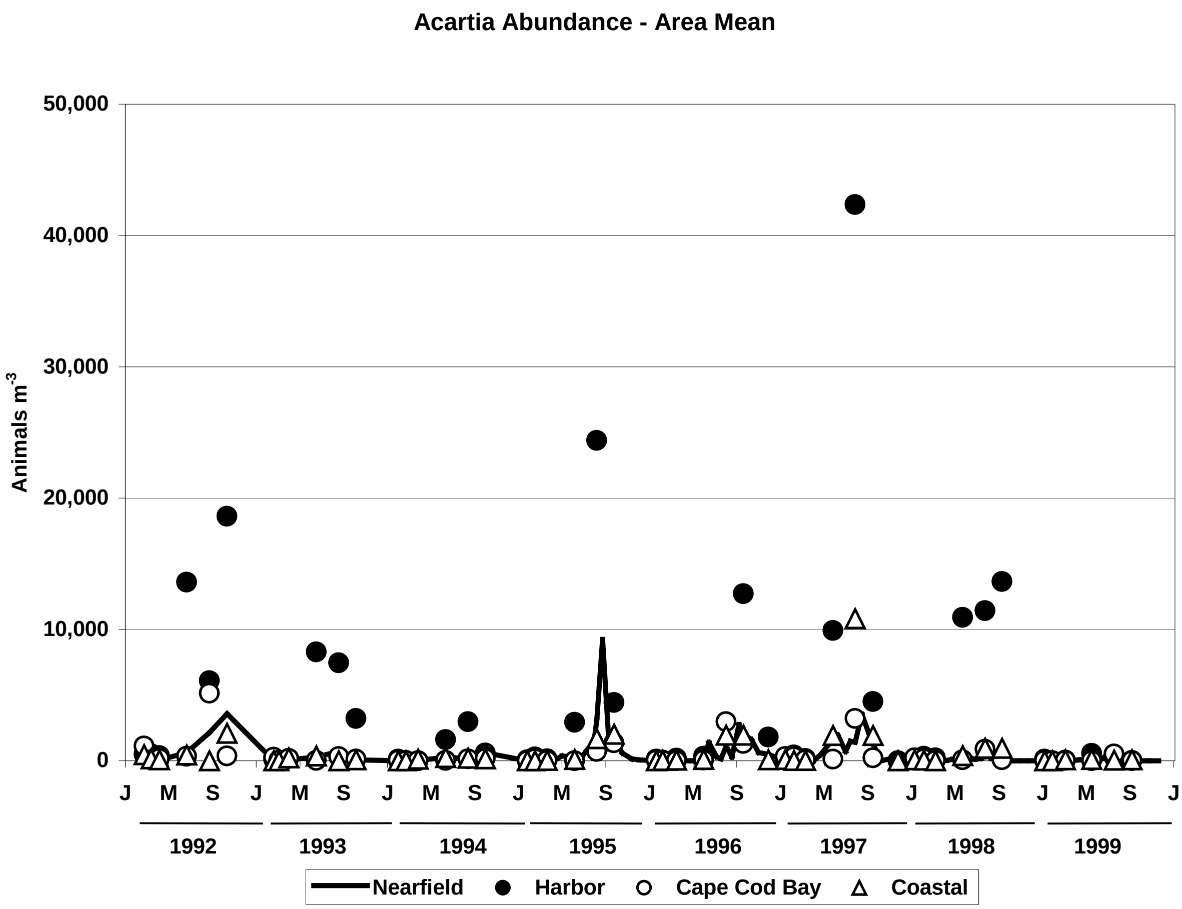


Figure 6-18. ***Acartia*** **spp. adults and copepodites abundance at selected areas for the entire baseline period, 1992-1999. Mean value for all area stations sampled by survey (see Figures 6-5 and 6-6 for station groupings).**

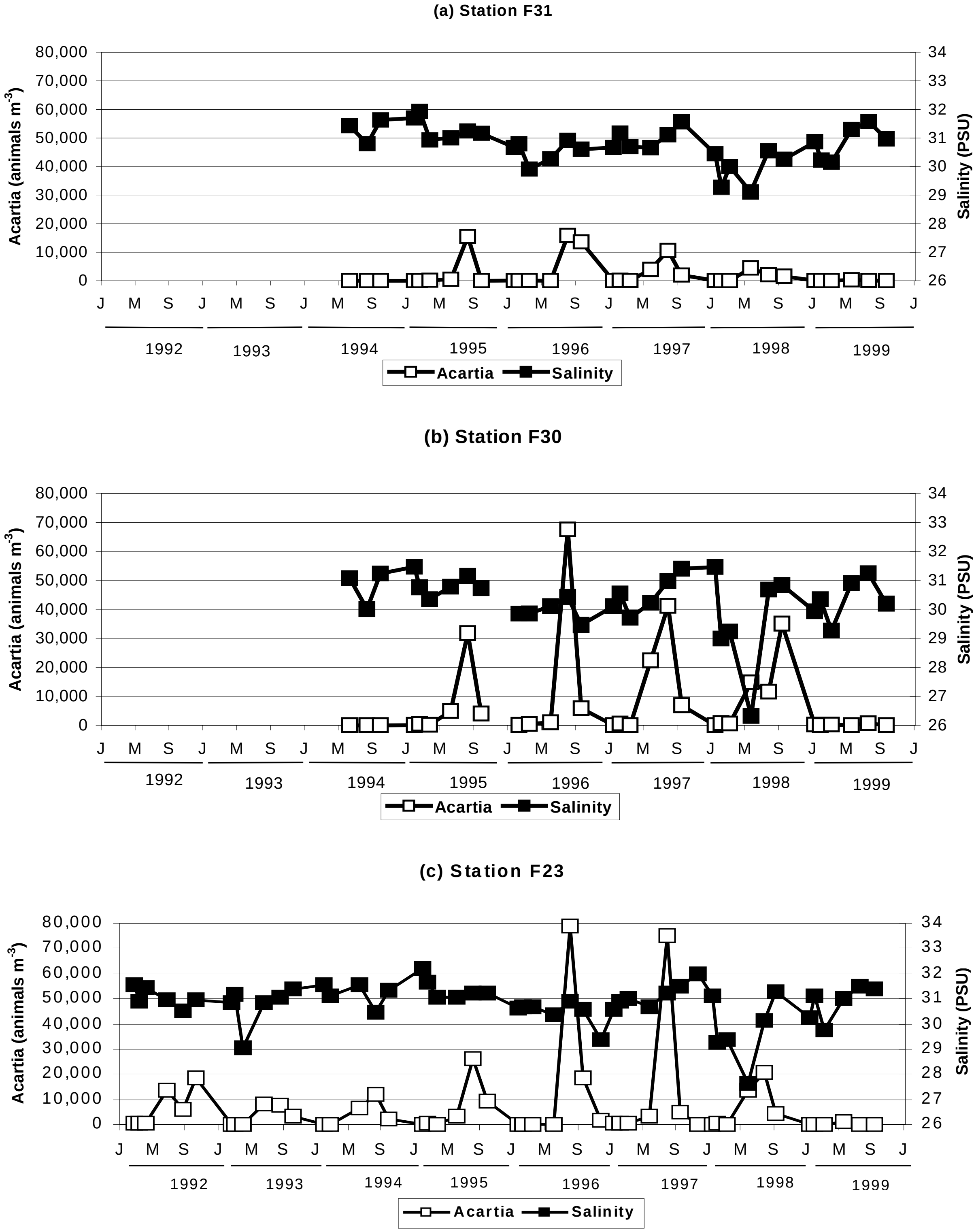


Figure 6-19. ***Acartia*** **spp. adults and copepodites abundance at Boston Harbor stations (a) F31, (b) F30 and (c) F23 for the entire baseline period, 1992-1999. Mean salinity for all depths sampled.**

7.0 SUMMARY OVERVIEW OF 1999

This section provides an overview of the trends in water quality and the major water column events that occurred in 1999. Over the course of the baseline monitoring program from 1992 to 1999 a general trend of events in Cape Cod and Massachusetts Bays has been recognized though the timing and interannual manifestation of these events varies. In the spring, the water column transitions from well mixed to stratified conditions with the onset of seasonal stratification and a phytoplankton bloom frequently occurs during this period due to increasing light availability, increasing temperatures and elevated nutrient concentrations. The summer is a period of strong stratification, depleted nutrients and a relatively stable mixed-assemblage phytoplankton community. In the fall, stratification deteriorates returning to well-mixed conditions, nutrients increase due to mixing and advection from the harbor and a fall phytoplankton bloom regularly develops

In 1999, there was a winter/spring phytoplankton bloom in both the nearfield and much of the farfield from early February to April, evidenced by general increases in chlorophyll, primary production and phytoplankton cell abundance during this period. During the bloom, phytoplankton assemblages were comprised primarily of microflagellates and a mixed assemblage of diatoms, mainly of the genus *Chaetoceros*. It is interesting that although the winter/spring nearfield chlorophyll concentrations were unprecedented for the baseline monitoring program phytoplankton abundance was not substantially different than previous years and actually rather low in comparison to previous winter/spring blooms. The reason for this may have been because the abundant taxa during the winter/spring bloom were larger, chain-forming diatoms (*Chaetoceros* spp.). Although the total abundances were not substantially higher than previous years, the cell size and higher chlorophyll per cell ratio for *Chaetoceros* spp. may have led to this apparent disconnect between chlorophyll concentration and total phytoplankton abundance. Davis and Gallager (2000) noticed a similar disconnect between chlorophyll concentrations and *Chaetoceros* abundance, but attributed the high chlorophyll concentrations to the presence of smaller phytoplankton that were not measured using the Video Plankton Recorder (VPR). At the HOM stations, this was not the case as total phytoplankton counts (which include smaller phytoplankton species) were not substantially elevated in comparison to previous years and were dominated by *Chaetoceros* spp.

The VPR study noted numerous colonies and gelatinous masses of *Chaetoceros* and estimated that video enumeration of the cells may have been off by a factor of 10 or more. Zooplankton net tows during the HOM surveys were covered with gelatinous green material and may indicate that *Chaetoceros* abundance was underestimated by the whole-water sampling technique. Along the same line of reasoning, the very high chlorophyll concentrations that were measured in situ fluorescence and by extraction techniques may also have been underestimates of actual chlorophyll concentrations in the bays. As a result of the winter/spring *Chaetoceros* bloom, bottom water respiration rates in the nearfield were substantially higher in the spring of 1999 compared to previous baseline monitoring results. These abnormally high respiration rates contributed to the unprecedented low DO concentrations that were observed during the fall of 1999.

An atypical late summer phytoplankton bloom was observed in the nearfield and throughout most of Massachusetts Bay in August and September. Levels of chlorophyll, primary productivity and phytoplankton cell abundance did not parallel each other as clearly as observed during the winter/spring bloom. Nearfield phytoplankton abundance peaked in early August, productivity in mid-August and chlorophyll concentrations, though increasing in August, did not reach maximum levels until September. The August phytoplankton bloom was comprised primarily of microflagellates and the diatom *Leptocylindrus danicus*. It is possible that the elevated NH_4 concentrations during the summer may have contributed to this bloom, since microflagellates frequently dominate the phytoplankton under conditions where ammonium is a primary component of the total dissolved inorganic nitrogen. Although total phytoplankton counts had decreased in the nearfield by mid-August, the abundance of *L. danicus* had increased and may have resulted in the increase in production and chlorophyll. The increase in *Ceratium* spp. in the >20-µm screened water fraction from August through October likely contributed disproportionately to the increase in chlorophyll in September. Further, shading of deeper layers by abundant *Ceratium* spp. cells may have contributed to the reduction in primary productivity from mid-August through September, at a time when chlorophyll was still high. The late summer bloom was not as pronounced in Cape Cod Bay as in Massachusetts Bay. There was also a fall bloom in the nearfield and western Massachusetts Bay in October, evidenced by increases in chlorophyll, primary productivity and cell abundance. The phytoplankton increase during this period was primarily in terms of diatoms of the genus *Thalassiosira*.

Zooplankton abundance exhibited the typical pattern of increases through the winter and spring, high levels in the summer, followed by declines in the fall. The typical dominants, *Oithona similis* and *Pseudocalanus* spp., comprised most assemblages. In Boston Harbor, meroplankton pulses overwhelmed abundance at some stations and resulted in the highest total zooplankton abundances for the entire 1992-1999 baseline. Area means revealed that 1999 was also uncharacteristic of other baseline years in terms of the low abundance of copepods of the genus *Acartia tonsa* in Boston Harbor. The decrease in abundances of *Acartia* in Boston Harbor appears to be a continuing trend with substantial declines in 1998 and 1999, compared to peak years of 1995-1997. The extremely low 1999 abundance of *Acartia* spp. in their primary habitat of Boston Harbor could be related to the drought during the first half 1999 because of species intolerance for salinity >25 ppt. However, this was not glaringly apparent from comparisons of salinity and *Acartia* abundance in Boston Harbor. We suspect that this is because the lag time from development of *Acartia* nauplii into identifiable copepodites and adults is such that correlations between simultaneously collected *Acartia* and salinity data become blurred. The spatial coverage of HOM stations in Boston Harbor may not include areas (i.e. mouth of Charles or Mystic Rivers) where the effect of the drought on salinity (and developing nauplii) was occurring.

It is also of note that it was once thought that increases in *Acartia* abundance would be indicative of increased nutrient concentration and food availability. It was proposed that *Acartia* abundance should be used as a warning threshold for the new outfall. The "*Acartia* hypothesis" was dismissed based on the importance of higher temperatures and lower salinity to nauplii survival in Boston Harbor rather than higher concentrations of food (Libby *et al*., 1999b). In 1999, the decrease in *Acartia* in Boston Harbor occurred despite the increase in NH_4 concentrations and unprecedented chlorophyll concentrations. The lack of a relationship between the nutrient and chlorophyll increases in 1999 and *Acartia* abundance support the elimination of the proposed *Acartia* warning threshold for the nearfield.

The major water column result of 1999 was that the minimum or maximum value for many of the physical, chemical and biological parameters were the lowest or highest observed for the entire baseline monitoring program. These extreme minima and maxima and the interaction between physical, chemical and biological processes are discussed below.

The most outstanding meteorological characteristics of 1999 were the dry conditions during the summer and fall drought. The drought conditions contributed to high salinity in nearfield bottom waters. The lack of significant storm events directly affects bottom water salinity by weakening vertical mixing or indirectly by decreasing Merrimack River flow and diminishing the freshet plume. A relationship between Merrimack River flow, bottom water salinity and bottom water dissolved oxygen at the outfall site was revealed in regression analyses of the parameters. In 1999, the anomalously high salinity resulting from low flow was correlated to the low bottom water dissolved oxygen conditions. This connection may be associated with the variability of residence time of water in the Western Maine Coastal Current.

The annual mean nutrient concentrations showed a significant trend of increasing nutrients across Cape Cod and Massachusetts Bay from 1992 to 1999. In Boston Harbor, for instance, there has been a 5 μM increase in NH_4 over the baseline period (primarily due to increased discharge of NH_4 from the Deer Island Facility in 1998 and 1999). The increase in NH_4 concentrations was coincident with an increase in annual mean chlorophyll at the Boston Harbor stations.

In 1999, nearfield chlorophyll concentrations exceeded winter/spring (2.51 μgL^{-1}), fall (4.03 μgL^{-1}) and annual (3.45 μgL^{-1}) warning threshold values (based on 1992-1998 data). Annual mean chlorophyll concentrations in each of the six areas of the bays achieved baseline maxima in 1999. No significant trend in annual mean chlorophyll over the baseline period was established, but there was a very strong suggestion of increasing chlorophyll from 1997 to 1999. The factors controlling this increase in annual mean chlorophyll concentrations are likely related to the regional and local factors affecting nutrient concentrations. One effect of the increase in chlorophyll (as an indicator of biomass) from 1997 to 1999 was an increase in the flux of organic material to bottom waters and low DO concentrations in 1998 and 1999.

The 1999 nearfield survey mean bottom water DO minimum (5.93 mgL^{-1}) was the lowest observed during for the baseline monitoring program and it was lower than the proposed warning threshold of 6.0 mgL^{-1}. A baseline minimum was also measured in Stellwagen Basin with a survey mean DO minimum concentration of 6.26 mgL^{-1}. The low initial bottom water DO concentrations observed at 'setup' in June, the additional flux of organic material to bottom waters following the late summer bloom and the lack of re-aeration events contributed to the rapid decline and extremely low survey mean values observed in 1999. Physical mechanisms related to the residence time of water in the coastal zone or diffusion/mixing of DO (and lower salinity water) into nearfield bottom waters during substantial storm events may also play an important direct or indirect role in controlling bottom water DO concentrations in Massachusetts Bay.

If the outfall had gone on line prior to 1999, the high chlorophyll values, low DO concentrations and even the increase in nutrient concentrations may have been attributed to the outfall. The 1999 data and the trends that have been discussed in this report for increasing nutrient and chlorophyll concentrations are indicative of the high degree of natural variability in the Cape Cod Bay and Massachusetts Bay systems. The factors affecting regional chlorophyll and nutrient concentrations are not fully understood but may be related to Gulf of Maine influences and long-term variations. The dramatic increase in NH_4 concentrations in Boston Harbor and nearby coastal waters, however, is primarily due to local changes – the increased discharge of NH_4 from the Deer Island Facility. The capability to differentiate between regional environmental variability or long-term trends and the effect of local impacts is one of the anticipated goals of the baseline monitoring program. To this end, the 1999 data will be used to reevaluate the range of variability in nearfield chlorophyll and DO concentrations and new thresholds will be implemented as necessary prior to bringing the new outfall online.

A number of topics have been highlighted in this report that should be addressed in a more detailed analysis. These topics are presented here as recommendations for the 1999 Nutrient Review.

- Closer examination of salinity, Merrimack River flow and bottom water DO concentrations relationship. Is there additional data that may allow the mechanisms behind this relationship to be better understood? What are the impacts on the future outfall?
- Link between increased discharge and ambient concentration of NH_4 in Boston Harbor and coincident changes in water quality in the harbor and nearby coastal and nearfield waters (i.e. concomitant increases in NH_4 and chlorophyll concentrations, changes in phytoplankton community, etc.)

- Focus on potential impact of increased NH_4 concentrations in effluent discharge from the future outfall – not dealt with specifically by BEM. High NH_4 concentrations in effluent versus very low background concentrations at the outfall and possible effects on production and phytoplankton community structure at the summer subsurface chlorophyll maximum.
- Detailed examination of decrease in *Acartia* abundance in Boston Harbor utilizing Boston Harbor Water Quality or other data sets that may be available (i.e. New England Aquarium) to understand the salinity trends in the upper reaches of the harbor in 1999 versus previous years.

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