1998 annual water column monitoring report

Massachusetts Water Resources Authority

Environmental Quality Department
Report ENQUAD 1999-16

Citation:

Libby, PS, Albro CS, Hunt, CD, Geyer, WR, Keller, AA, Oviatt, CA, Turner J. 2000. **1998 Annual Water Column Monitoring Report**. Boston: Massachusetts Water Resources Authority. Report ENQUAD 99-16. 173 p.

1998 ANNUAL
WATER COLUMN MONITORING REPORT

Submitted to

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June 21, 2000

Report No. 99-16

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 1998 water column monitoring results, assesses spatial and temporal trends in the data, and compares these results and trends for 1998 with previous baseline monitoring years (1992-1997).

In 1998, the Massachusetts and Cape Cod Bays region was influenced, as was much of the country, by weather patterns associated with the El Niño event in the Equatorial Pacific. The winter of 1998 was relatively warm and the winter and spring seasons were disrupted by numerous storms and record rainfall events (particularly in June). These conditions resulted in warm water temperatures and high flow conditions in the early spring, which contributed a relatively early onset of stratification. Due to the high flow conditions in late winter/early spring and June, surface salinity was lower in Western Massachusetts Bay during 1998 than any previous baseline-monitoring year. The unusually low surface salinity gave rise to strong stratification during the summer of 1998.

No spring bloom was observed in 1998 even though elevated nutrient concentrations persisted in the surface waters until May. Nutrient and production data indicate that bloom conditions existed and that the phytoplankton community may have started to bloom (nutrient draw down between February and March and high productivity), but an increase in biomass was not achieved. Potential factors influencing the occurrence of a spring phytoplankton bloom include nutrient limitation, light availability, photic depth, temperature and predation. Regardless of the factors that resulted in the lack of a 1998 spring bloom, the baseline monitoring data suggest that spring blooms may not be as typical of Massachusetts Bay as was once thought. Large spring blooms as defined by chlorophyll data in past years (1992 and 1997) have been partly due to blooms of *Phaeocystis*, which does not bloom every year and was not recorded in 1998. Further, in some previous years, the spring bloom appeared limited to Cape Cod Bay and was not largely representative of most of the nearfield area. Thus, the presence or absence of a major spring phytoplankton bloom appears to be part of the large envelope-of-variability for the MWRA sampling area.

Instead of being dominated by a major winter/spring or fall bloom, phytoplankton abundance steadily increased from low levels in February to maximum levels during the summer and fall followed by declines in November and December. The phytoplankton assemblages were numerically dominated by microflagellates and cryptomonads, with subdominant contributions by various chain-forming diatoms. Perhaps the singular phytoplankton event of the year was the yearlong bloom of *Ceratium longipes/C. tripos*, which began unusually early in February, exhibited sustained increases through July, and continued through the late summer and fall, into December. This bloom of *Ceratium*, though of significant abundance, was 1-2 orders of magnitude less abundant than past blooms of these species that have caused large-scale anoxia in the New York Bight in 1976.

In 1998, the zooplankton were dominated, as typical in this coastal system, by copepod nauplii, adults and copepodites of the small copepods *Oithona similis* and *Pseudocalanus* spp., with seasonal subdominant contributions from gastropod and bivalve veligers, and a mixture of other normally-occurring taxa. Zooplankton abundance generally increased from February through April, and reached the highest numbers in mid-May in the nearfield. By June, zooplankton abundance was unusually high at all stations and generally remained at high levels from August through December.

Annual productivity at stations N04, N18 and F23 was lower than in prior years. Typically, the spring phytoplankton bloom accounts for greater than 30% of the annual production at the monitoring sites. In 1998, the fall bloom dominated the seasonal productivity pattern. As with the winter/spring bloom, the fall bloom is not a consistent annual characteristic in the bays. The intensity of the fall bloom and the phytoplankton species that bloom has varied from year to year during the baseline-monitoring period. In 1998, the fall bloom was not a single species bloom, but rather a general increase in the numbers of a variety of chain-forming diatoms. The bloom was more clearly observed in increased chlorophyll concentrations and peak production rates that were measured in the nearfield than in phytoplankton abundance.

The overturn of the water column and the return to winter conditions was delayed in 1998 compared to previous baseline monitoring years. The water column was stratified until November throughout much of the nearfield and a deep halocline was still present in December at the deeper eastern nearfield stations. The strength and duration of stratification are important factors in the decline of bottom water dissolved oxygen concentrations. Due to the persistence of stratified conditions in 1998, bottom water DO concentrations decreased over the entire June to December time period in the nearfield area. The delay in mixing led to the annual minimum in bottom water DO concentration in December. Relatively high bottom water DO concentrations observed at the setup of stratified conditions in June kept the minima from reaching extremely low levels that had been observed during previous years.

In November and December 1998, anomalously high concentrations of ammonium and phosphate were observed in the western nearfield that correlated with high concentrations observed by the MWRA in Boston Harbor. The source of the anomalously high nutrient concentrations has not been determined. The high concentrations may have been due to the transfer of south system sewage flow from Nut Island to the Deer Island facility, increased secondary treatment at the Deer Island facility, or other unknown factors. Although the transfer of south system sewage flow from Nut Island to Deer Island increased the volume of effluent discharged into the north harbor by a third, the volume of MWRA effluent discharged into the harbor as a whole was unchanged. The increased flow in the north harbor did not immediately result in increased ambient nutrient concentrations. Boston Harbor's summer biological community may have been able to adapt and utilize the increased nutrient input initially, but once the system shut down in September/October elevated nutrient concentrations were measured both in the harbor and nearby coastal waters.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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 1998. This was the seventh consecutive year of MWRA baseline monitoring.

The 1998 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 1999b). The purpose of this report is to present a compilation of the 1998 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 1998 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 1998 water column data.

2.0 1998 WATER COLUMN MONITORING PROGRAM

This section provides a summary of the 1998 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 1998 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 1998 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. 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 1998 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 17 surveys that were conducted in 1998 (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. Additional samples were collected at farfield stations in the fall and winter of 1998. This included a late November sampling at station F12 to monitor dissolved oxygen concentrations in the deep bottom waters of Stellwagen Basin. In December, the survey was designed to determine the nutrient concentrations upon the return to winter conditions at stations in Boston Harbor, Massachusetts Bay, and Cape Cod Bay.

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

Table 2-1. Water quality surveys for 1998 (WF981-WN98H)

Survey #	Type of Survey	Survey Dates
WF981	Farfield/Nearfield	February 3 – 10
WF982	Farfield/Nearfield	February 27 – March 2
WN983	Nearfield	March 24
WF984	Farfield/Nearfield	March 31 – April 3
WN985	Nearfield	May 1
WN986	Nearfield	May 19
WF987	Farfield/Nearfield	June 17 –22
WN988	Nearfield	July 8 – 13
WN989	Nearfield	July 23
WN98A	Nearfield	August 5
WF98B	Farfield/Nearfield	August 18 – 25
WN98C	Nearfield	September 3
WN98D	Nearfield	September 24
WF98E	Farfield/Nearfield	October 5 – 17
WN98F	Nearfield	November 4
WN98G	Nearfield	November 25
WN98H	Nearfield	December 16

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 2-2. 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

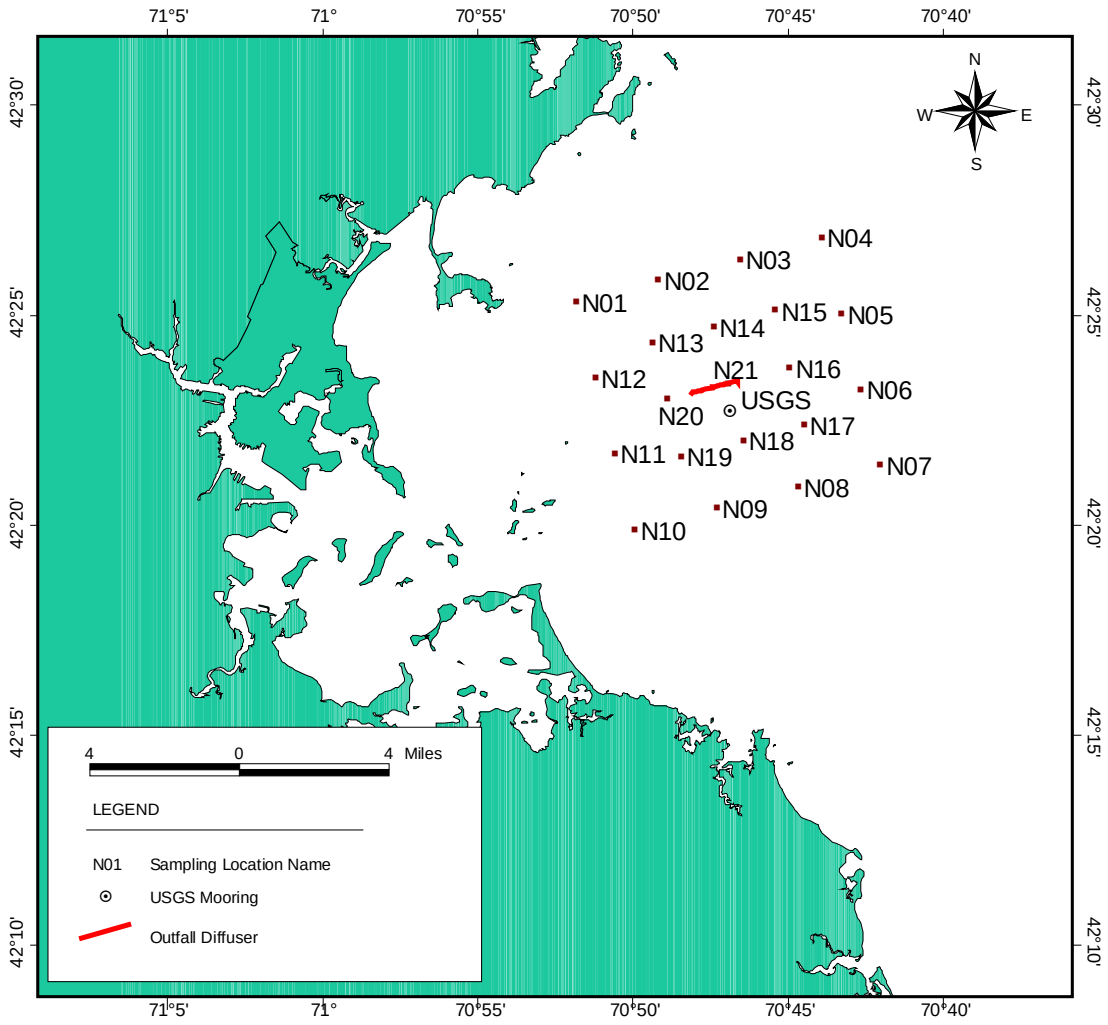


Figure 2-1. Locations of nearfield stations, MWRA offshore outfall, and USGS mooring.

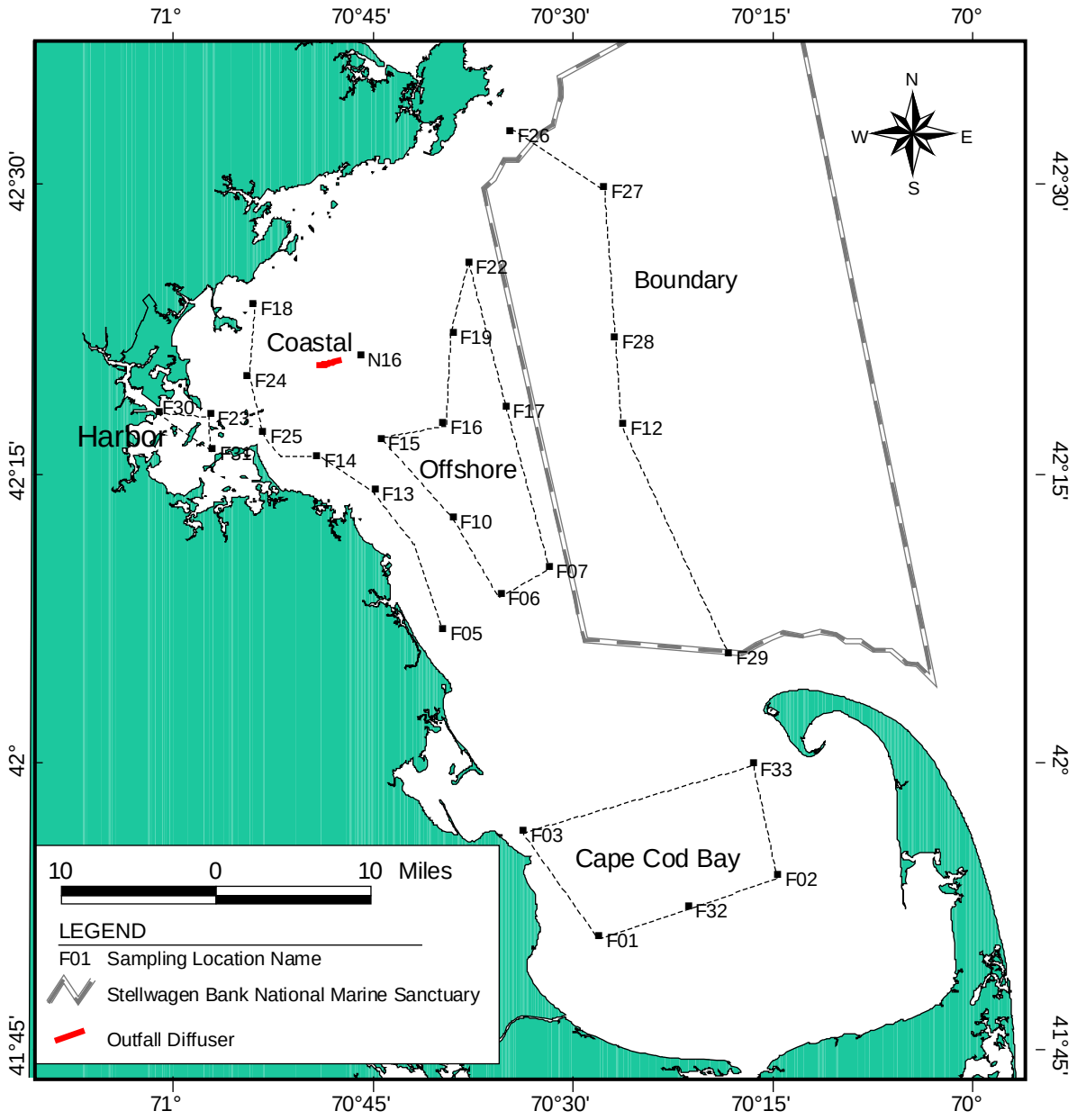


Figure 2-2. Locations of farfield stations and geographical classifications.

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. In 1998, the Massachusetts and Cape Cod Bays region was influenced, as was much of the country, by weather patterns associated with the El Niño event in the Equatorial Pacific. The winter of 1998 was relatively warm and the winter and spring seasons were disrupted by numerous storms and record rainfall events.

The freshwater inflows come locally from the Charles River, the MWRA outfalls, and direct precipitation, with comparable magnitudes from each (approximately 10 m^3s^{-1} long-term average). Direct precipitation is calculated for a 300-km^2 area in western Massachusetts Bay that includes Boston Harbor, Broad Sound and the nearfield area. The Merrimack River is a much larger source of freshwater (250 m^3s^{-1} long-term average), but its plume only intermittently enters Massachusetts Bay, and the surface salinity near the outfall site is more highly correlated with the Charles River (r=0.9) than the Merrimack (r=0.6; Figure 3-1). All of the local inputs are highly correlated with each other (Figure 3-2), so the Charles River flow provides a good indicator of the forcing function for salinity variation in western Massachusetts Bay.

The freshwater inflow was well above average during the first half of 1998 (Table 3-1, Figures 3-3 and 3-4), and the annual mean flow of the Charles was the highest of the decade. The high flows in May and June were particularly anomalous, as shown in the annual discharge curve (Figure 3-4). This large, late freshwater input produced the lowest salinities ever observed in western Massachusetts Bay (as will be shown below). The remainder of the year was slightly drier than average.

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 1998. In Massachusetts Bay, downwelling conditions predominate in winter/spring and fall and upwelling conditions occur on a relatively regular basis during the summer months due to prevailing winds that blow from the south and southwest. The southerly winds lead to Ekman divergence in surface flow away from the coast and an upwelling of bottom waters. The winds in early 1998 were strongly downwelling favorable, which should also produce strong throughflow between the Gulf of Maine and Massachusetts Bay. This downwelling tendency continued through June, due to the relatively stormy conditions in the spring. The summer period had relatively strong upwelling conditions, and the last several months had weak downwelling winds. Wind speeds for 1998 were typical of the decadal average (Table 3-3).

The only notable feature of the annual heat flux cycle for 1998 was an anomalously warm winter (Table 3-4). The wintertime mean air temperature determines the water temperature at the onset of stratification, which may affect the stratification and bottom water temperature for much of the year. As will be seen, the warm winter produced warmer than average bottom water temperatures for the first half of 1998.

Table 3-1. River discharge summary for the Charles and Merrimack Rivers, 1990-1998. 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	*	8
1998	21	21	8	7	14
Mean	14	12	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	*	257
1998	401	451	122	116	273
Mean	303	349	97	246	249

*Data not available for October – December 1997.

Table 3-2. North-South component of wind stress, 1990-1998. 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
Mean	-2.3	0.1	0.6	-1.7

Table 3-3. Wind speed, 1990-1998. Seasonally averaged speed in m/s 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
Mean	7.3	5.4	4.8	7.0

Table 3-4. Winter air temperature, 1993-1998. 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
Mean	0.7

3.2 Temperature

3.2.1 Nearfield Description

The temperature variation in the nearfield in 1998 (Figure 3-5) 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. During July and August, both surface and bottom waters cooled slightly, due presumably to the upwelling-favorable conditions during this period. The fall cooling was slightly more rapid than the climatological average.

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 and 1997 (cf. Table 3-4). However, the maximum surface water temperature was lower in 1998 than any other year. The maximum bottom water temperature was also the lowest observed during the 7-year monitoring period. The low water temperatures may be explained in part by upwelling-favorable winds during the summer months, which tend to cause cool water to be transported landward from the deeper waters of Massachusetts Bay, cooling both surface and deep waters. Note that 1992, 1993 and 1998 all had relatively cool bottom waters (<10°C) just prior to destratification; these were also years with the highest upwelling

index during the summer months (Table 3-2). The cold bottom water temperatures are thus probably the result of enhanced advection from the deeper waters of Massachusetts Bay.

3.2.3 Regional Comparisons

The surface waters tend to follow a similar annual cycle throughout Massachusetts and Cape Cod Bays (Figure 3-6). During the summer of 1998, the nearfield temperatures were slightly higher than all of the stations except for Cape Cod Bay (although these differences may be attributed to short-term variations on different sampling days.) The most pronounced regional differences were observed at the coastal stations (Figure 3-7). During the summer, the coastal stations were considerably cooler than nearfield station N21. Most notable was station F05, the nearshore station at Scituate, which was more than 5° colder than N21. The lower temperatures at the coast are likely due to upwelling. The more pronounced anomalies in 1998 than in other strong upwelling years (*e.g.*, 1993) are probably the result of particular conditions during sampling days.

Bottom temperatures vary considerably on a regional basis, due in large part to the depth variations of the different stations. The deep waters of Stellwagen Basin do not get as cold in the winter nor as warm in the summer as the nearfield stations. Station F02 in Cape Cod Bay often gets colder in the winter than N21, although it did not during the winter of 1998. The temperatures in the deep water at F18 (near the North Shore) were higher during the summer of 1998 than N21; this contrasts most summers when their temperatures were comparable.

3.3 Salinity

3.3.1 Nearfield Description

The surface and bottom salinity were lower in Western Massachusetts Bay during 1998 than any of the observations during the monitoring program (Figure 3-8). In fact, the surface salinities were lower during June than any of the lightship observations described by Bumpus (1974; covering the period 1956–1970). The salinity was normal in the fall of 1997, but by the first measurements in February 1998 it was already significantly lower than the climatological average. Both surface and bottom salinity dropped sharply during March, and surface salinity continued to drop to a minimum of 28 psu in the middle of June. The bottom water reached its minimum at the end of April, and slowly rose through the rest of the year. The unusually low surface salinities during May, June, and July are certainly due to the high flow conditions during those months (Table 3-1, Figure 3-4). The near-bottom waters are not as sensitive to the freshwater input, although the bottom salinity was still the lowest of the monitoring program during the months of March–July. The salinity increased sharply at the end of July and more gradually during the rest of the year, but it still remained lower than its climatological average.

3.3.2 Interannual Comparisons

1998 had significantly lower salinities than any of the other years of the monitoring program. The only year that came close was 1993. The local run-off explains most of the variation, although it appears that there is some influence of winds as well. The salinity drop in 1994 had about half the amplitude as that in 1993, with almost the same amount of discharge through the freshet period. However, there was more upwelling in 1994 than 1993, which appears to diminish the freshwater signal. This occurs because the freshwater is displaced offshore during upwelling and replaced by higher salinity water. Also, upwelling prevents the entry of the Merrimack plume into Massachusetts Bay. The extreme salinity anomaly during 1998 is mainly explained by the large freshwater input,

but the downwelling conditions through June (Table 3-2) reinforced the low-salinity conditions. The rapid increase in salinity in July is due in part to the return to upwelling conditions.

3.3.3 Regional Comparison

The surface salinity showed substantial spatial variability during 1998 (Figures 3-9 and 3-10), indicating strong spatial gradients in western Massachusetts Bay. The freshest water was found to the north at F18, and the water became progressively saltier to the east and south. The bottom water showed mainly a gradient from higher salinities offshore to lower salinities onshore. An interesting feature of the deep salinity is that the offshore waters (station F27) showed a similar variation as the nearfield, including the large decrease during the spring of 1998. The high correlation of the variations in deep, offshore salinity with the nearshore salinity suggests that much of the variability reflects changes in the offshore source waters, rather than mixing with fresher surface waters. The difference in salinity between the offshore and onshore water is probably not due to mixing, rather it reflects the difference in depths of the stations. Comparison of the salinity at comparable depths between F27 and N21 shows that the differences are small between these two stations. Thus, the low bottom salinities that occurred during the summer of 1998 were the result of low salinities at depths of 20–40 m in the Gulf of Maine. These low salinities were the result of the high regional inflow, *e.g.*, the Merrimack and the other rivers to the northeast.

3.4 Stratification

3.4.1 Nearfield Description

The stratification was unusually strong during the summer of 1998 (Figure 3-11), due mainly to the large freshwater input. For the MWRA water column reports, vertical stratification is defined by the presence of a pycnocline with a density gradient of greater than 1.0 between the surface and bottom waters. During the first survey in early March, there was a small vertical salinity gradient, but stratification was not observed until the early May survey. The stratification rose sharply until mid-June, due both to temperature and salinity effects (compare solid and dashed lines in Figure 3-11, upper panel). Temperature stratification was determined using the mean of the surface and bottom salinity and calculating density based on the mean salinity and the observed surface and bottom water temperatures. The stratification weakened from its extreme value during July and August as the freshwater signal diminished. For the remainder of the year the stratification was slightly elevated from the climatological average. There was still thermal stratification on the last survey at the end of November.

3.4.2 Interannual Comparisons

During most years the stratification is dominated by thermal effects, except for a brief period in the spring when the freshwater-induced stratification predominates. The 1998 observations were unusual in that the freshwater-induced stratification remains at high levels well into June, when the thermal stratification is maximal. Another unusual characteristic of 1998 was the early stratification; apparently the large freshwater inflows in February were adequate to stratify the water column. The warm winter and high run-off during the winter were apparently responsible for these anomalous conditions.

3.4.3 Regional Comparisons

The regional variations in stratification mainly reflect the regional variations in salinity during summer of 1998 (Figure 3-12). The stratification was strongest where the surface salinities were lowest. The only other notable feature of the regional variations in stratification is that the Gulf of Maine waters (station F27) sometimes remain stratified for the winter due to salinity.

3.5 Summary

The notable characteristics of the forcing conditions for 1998 included the following:

- Warm winter;
- Very wet spring (particularly June);
- Persistent southerly (upwelling) winds in summer.

The observed oceanographic conditions follow from these forcing conditions:

- Warm bottom water in the early spring;
- Very low salinity, surface and bottom, and high stratification;
- Less warming of bottom water than normal.

The regional comparison of deep salinity variation suggests that the water properties of the deep water in the nearfield are mainly controlled by processes outside Massachusetts Bay, rather than local mixing during the stratified months.

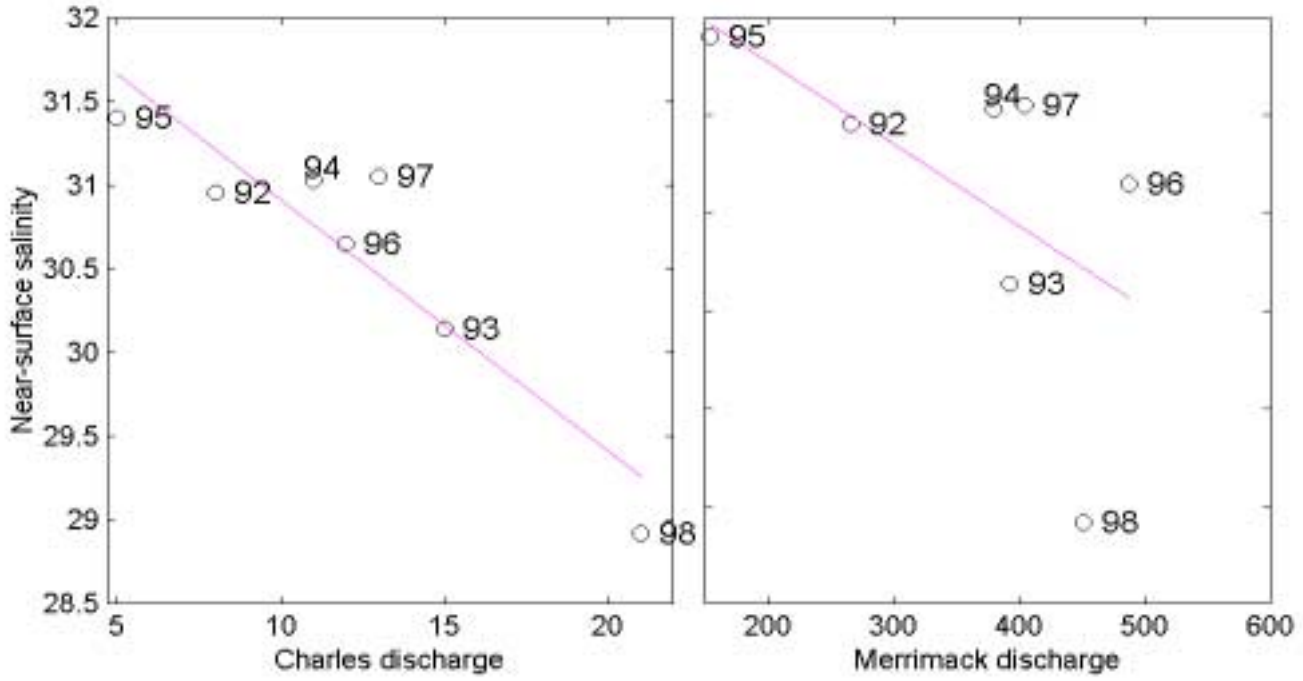


Figure 3-1. Relationship between spring average (April–June) nearfield, surface salinity ("A" depth data from stations N13–N21) and spring average (April–June) discharge of the Charles and Merrimack Rivers (r=-0.91 and r=-0.58, respectively). River discharge data from the USGS gauging stations on the Charles River in Waltham and the Merrimack River in Lowell.

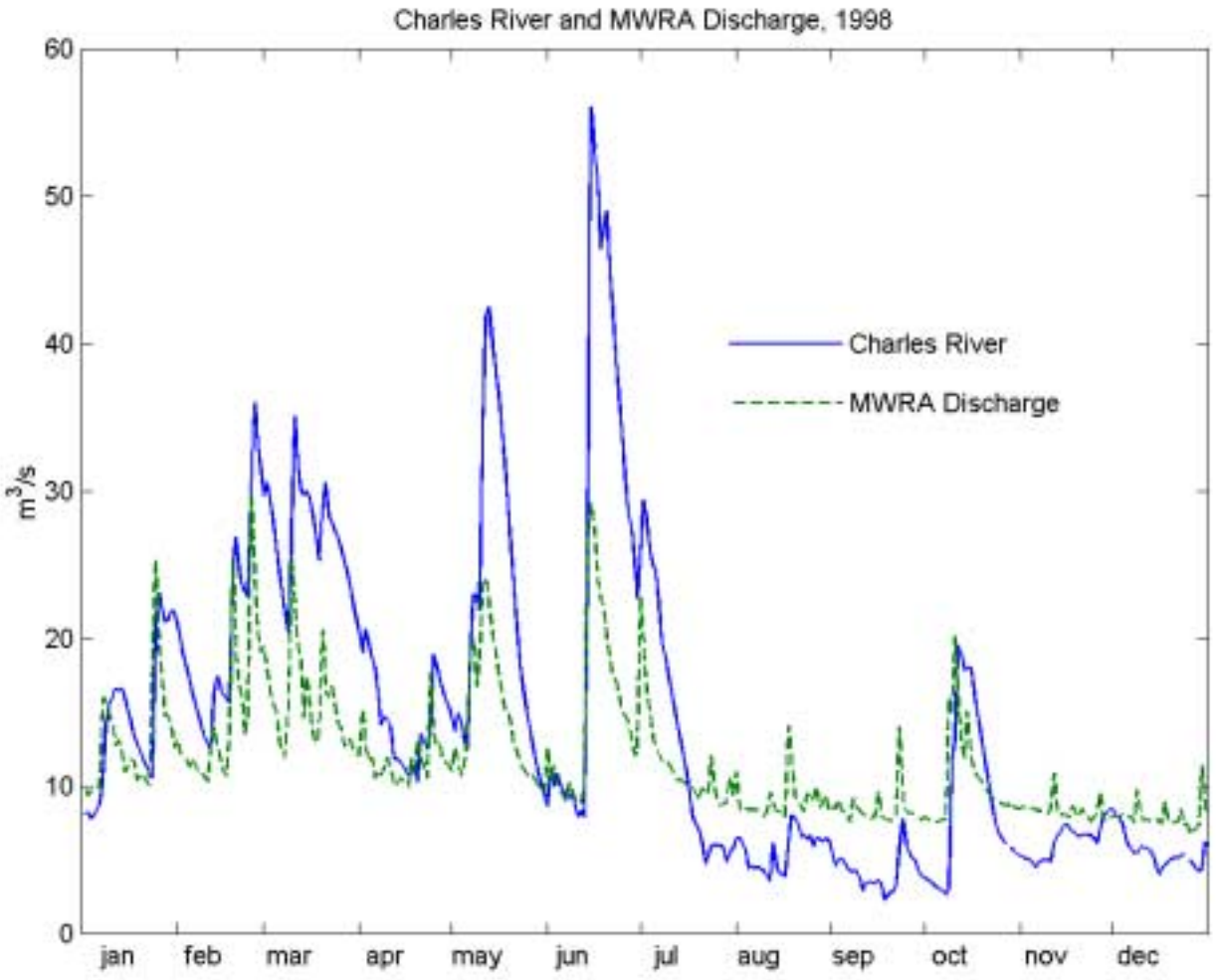


Figure 3-2. Comparison of Charles River (at USGS gauging sstation in Waltham, MA) and MWRA daily average discharge (combined flows from Nut and Deer Islands) for 1998.

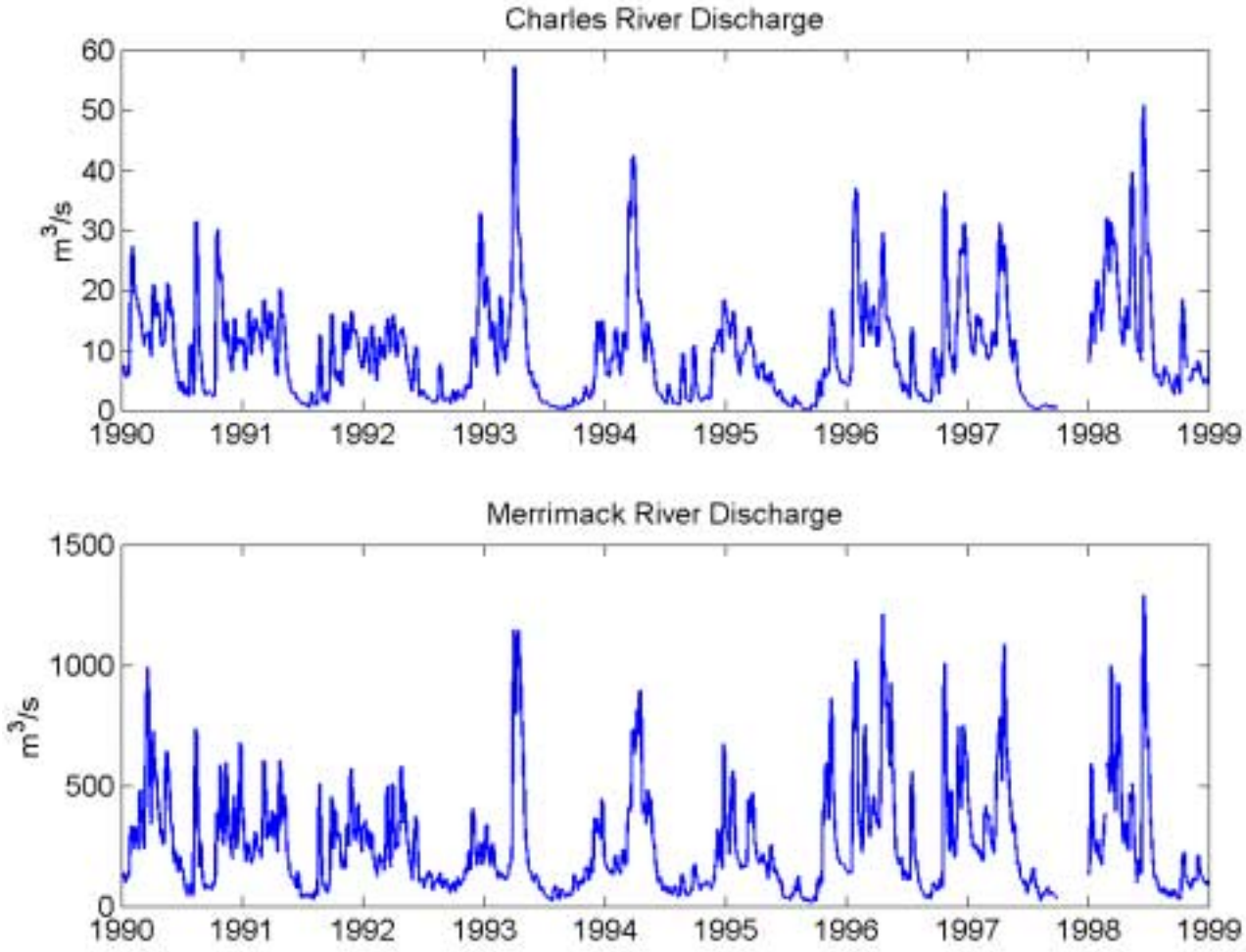


Figure 3-3. Charles River (at Waltham) and Merrimack River (at Lowell) discharge, 1990–1998 (5 day running mean).

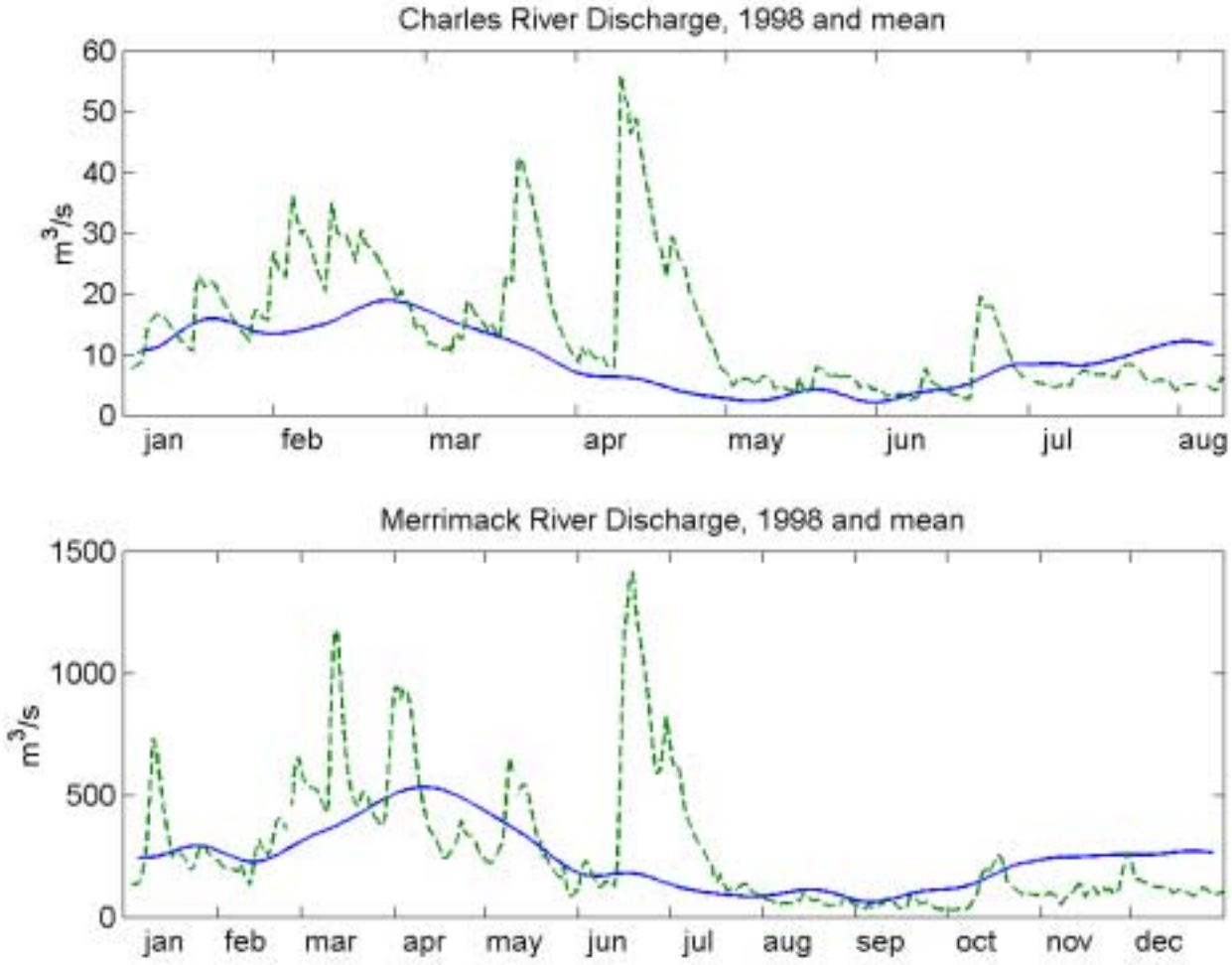


Figure 3-4. Comparison of daily Charles and Merrimack River discharge for 1998 to 10-year average annual cycle (smoothed by a 30-day running mean).

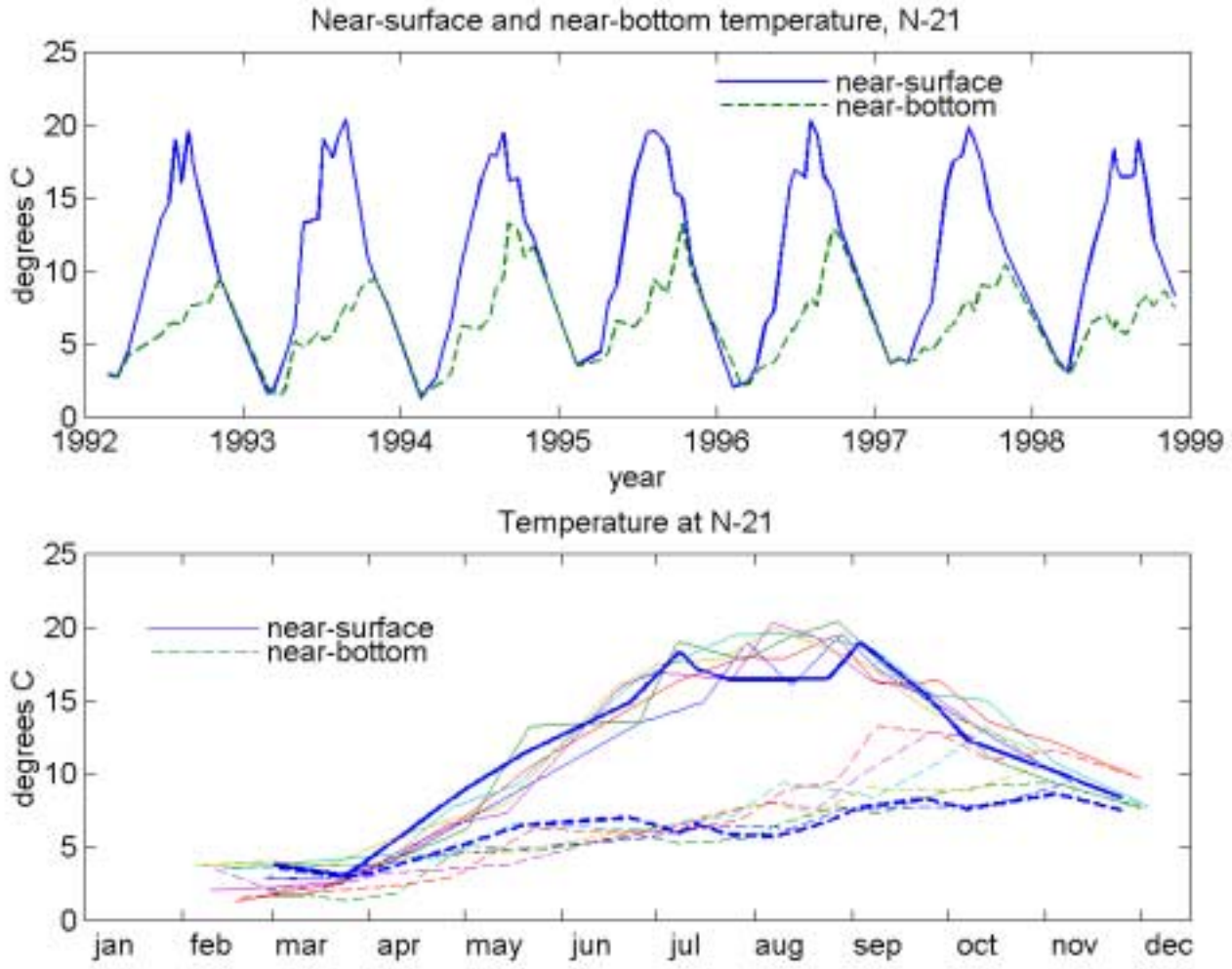


Figure 3-5. Near-surface and near-bottom temperature at nearfield station N21, 1992–1998. The lower panel shows the annual cycle for each year, with 1998 shown in bold lines.

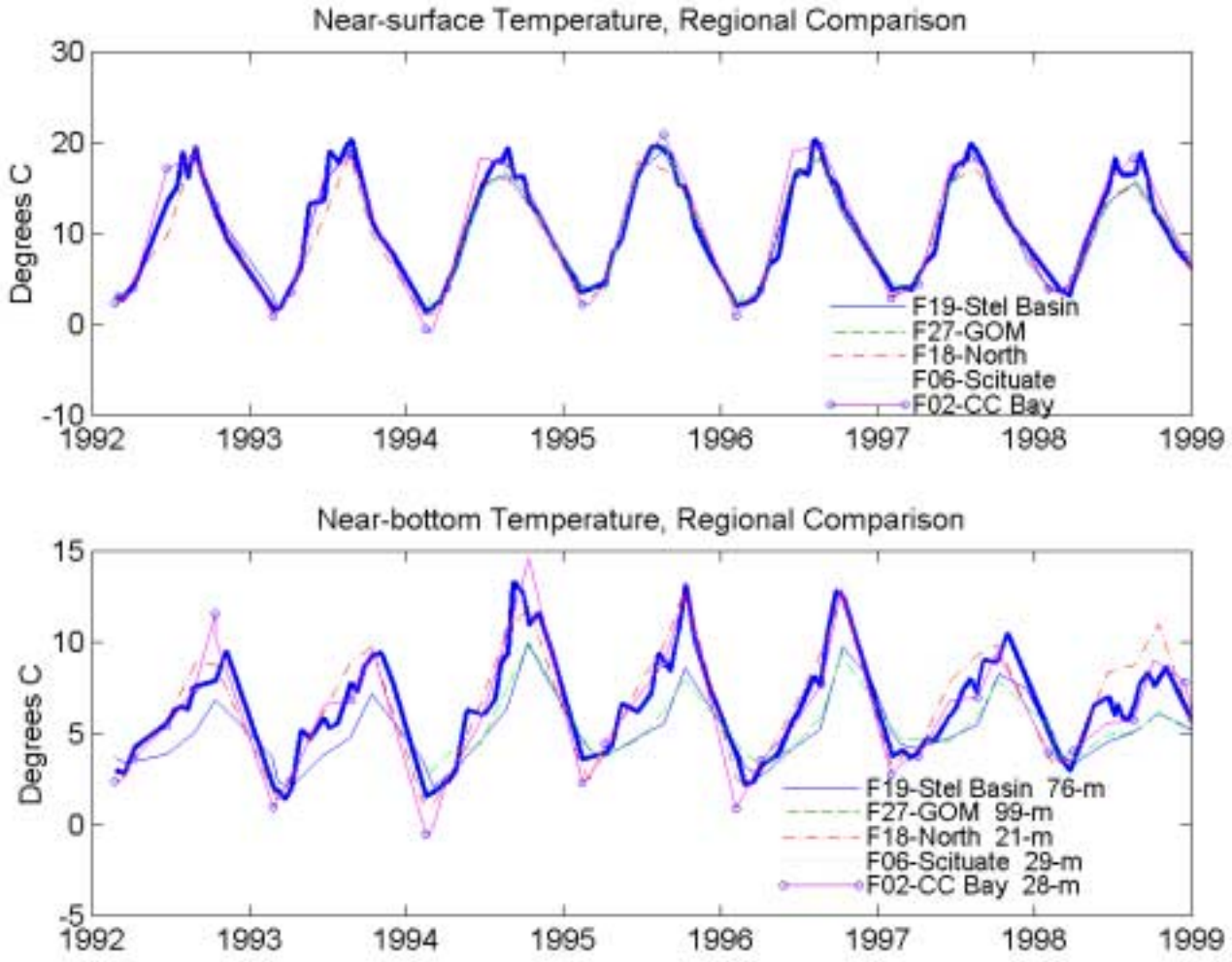


Figure 3-6. Comparison of near-surface and near-bottom temperature at N21 (bold lines) to selected farfield stations.

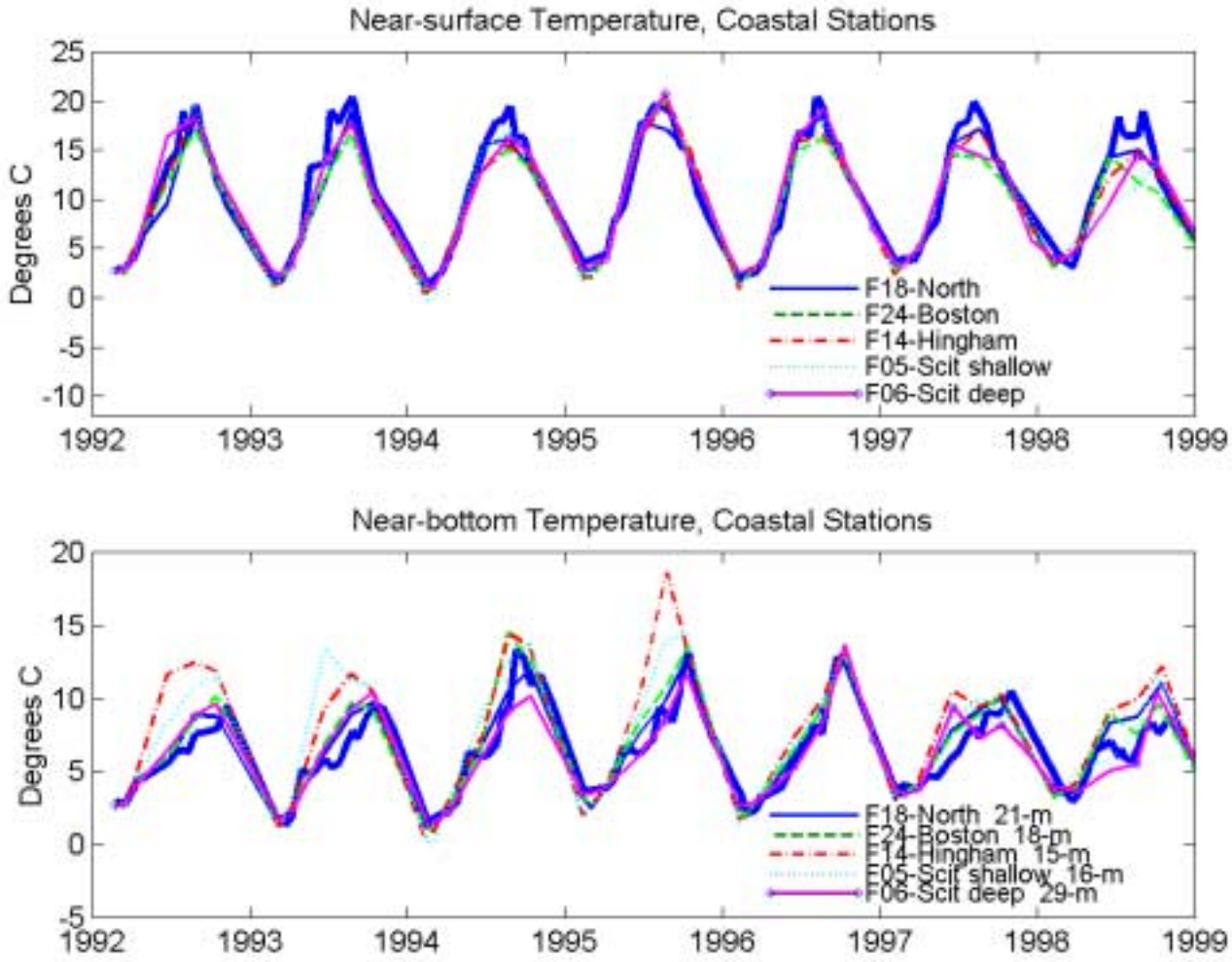


Figure 3-7. Comparison of near-surface and near-bottom temperature at N21 (bold lines) to selected coastal stations.

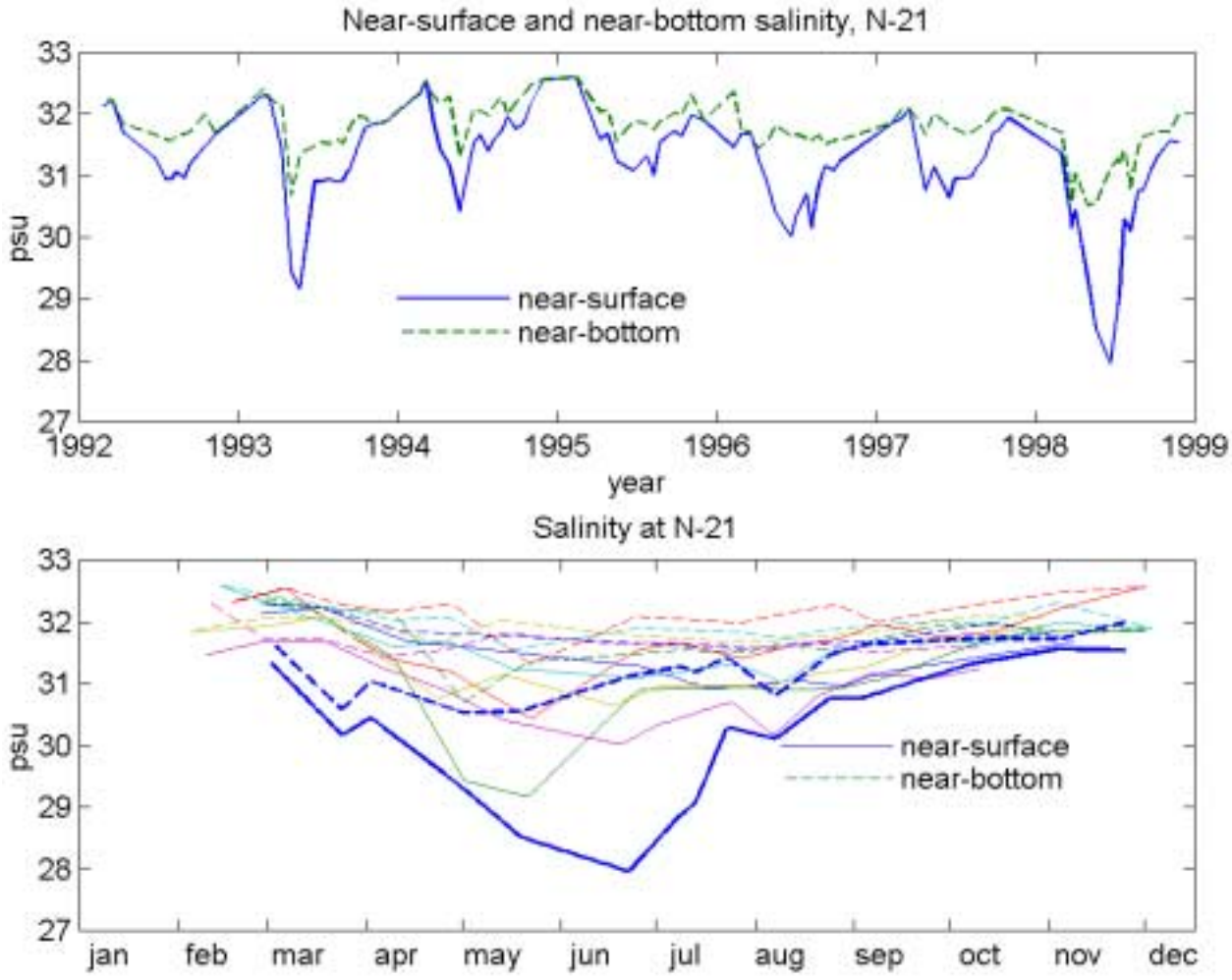


Figure 3-8. Near-surface and near-bottom salinity at nearfield station N21, 1992–1998. The lower panel shows the annual cycle for each year, with 1998 shown in bold lines.

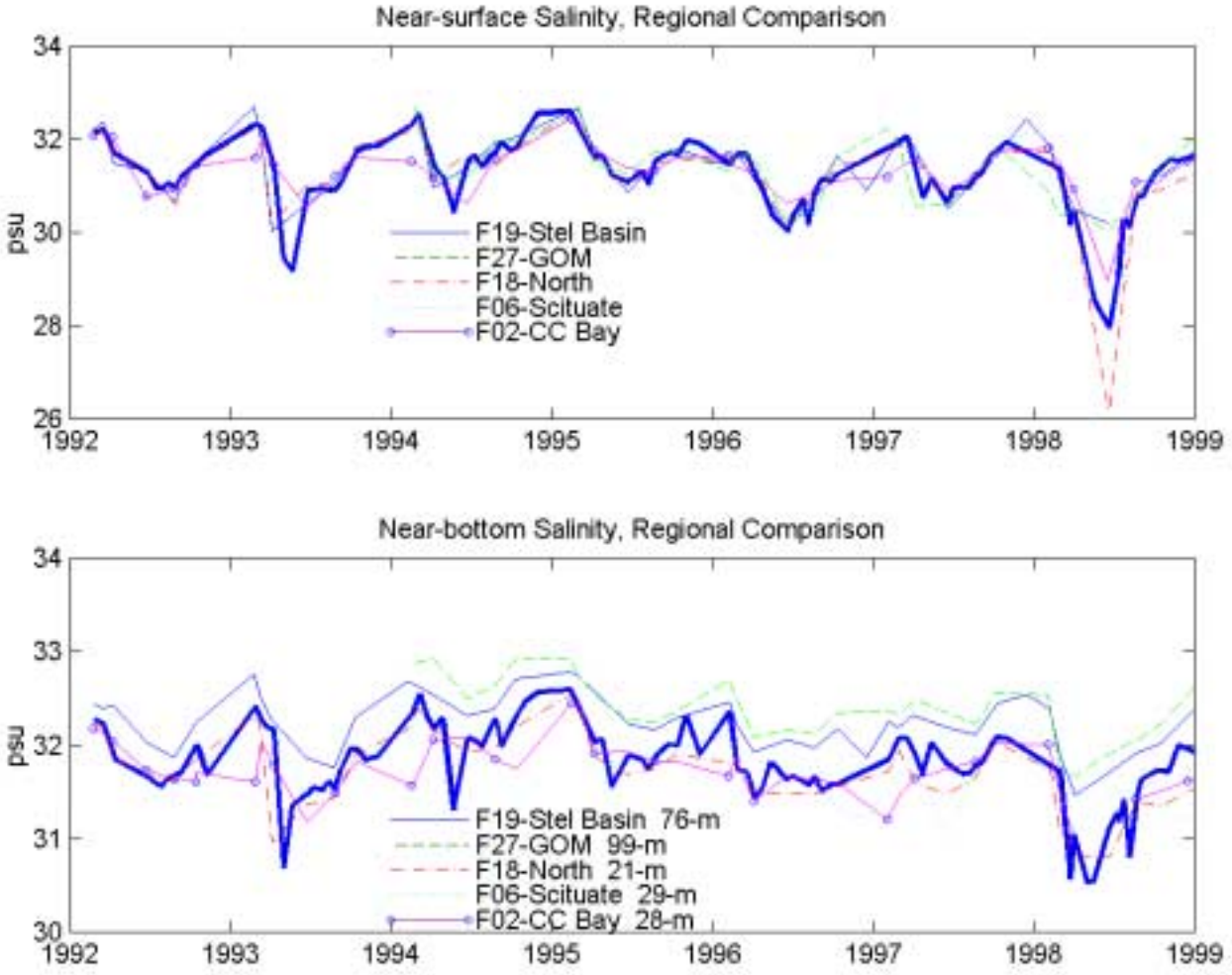


Figure 3-9. Comparison of near-surface and near-bottom salinity at N21 (bold lines) to selected farfield stations.

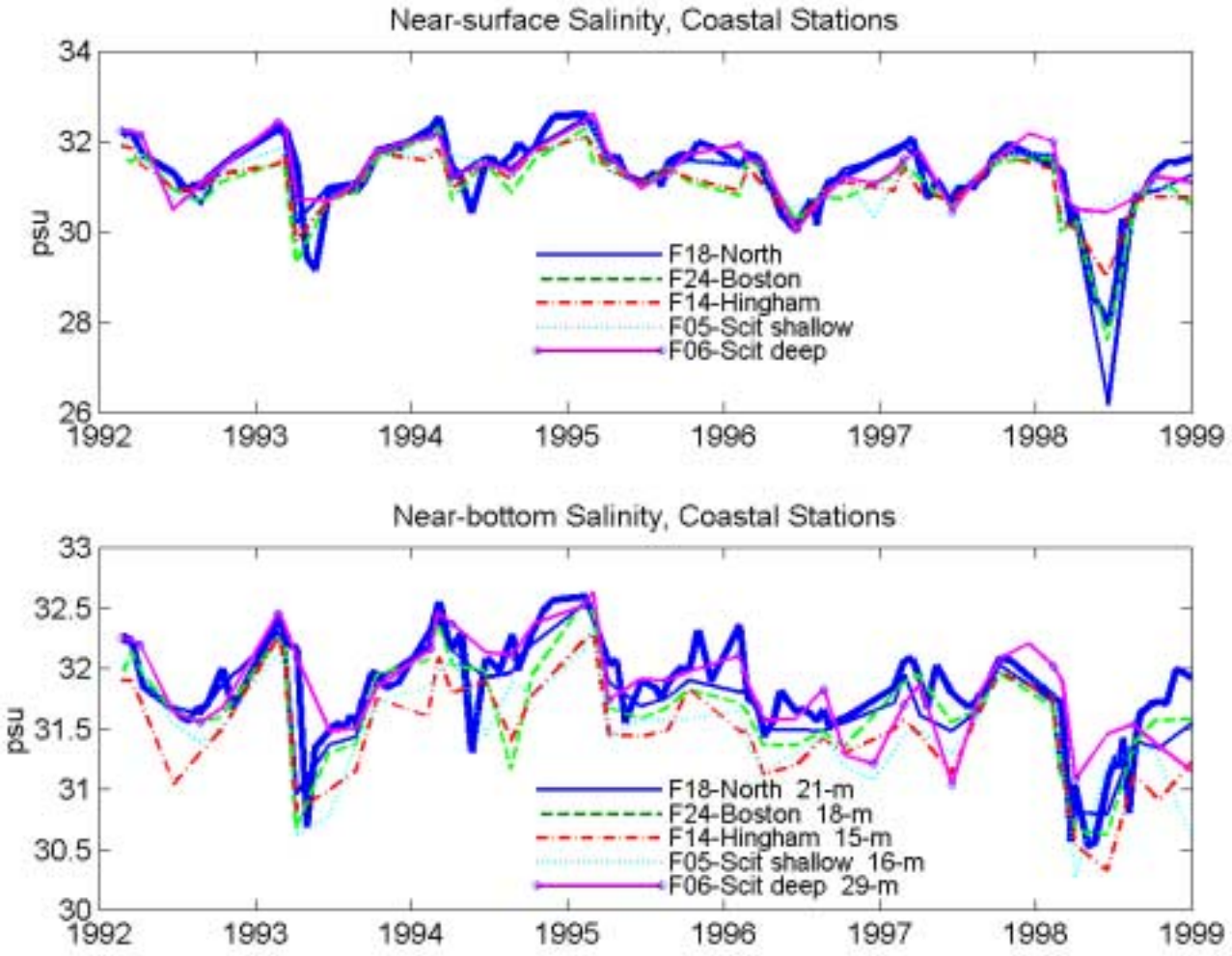


Figure 3-10. Comparison of near-surface and near-bottom salinity at N21 (bold lines) to selected coastal stations.

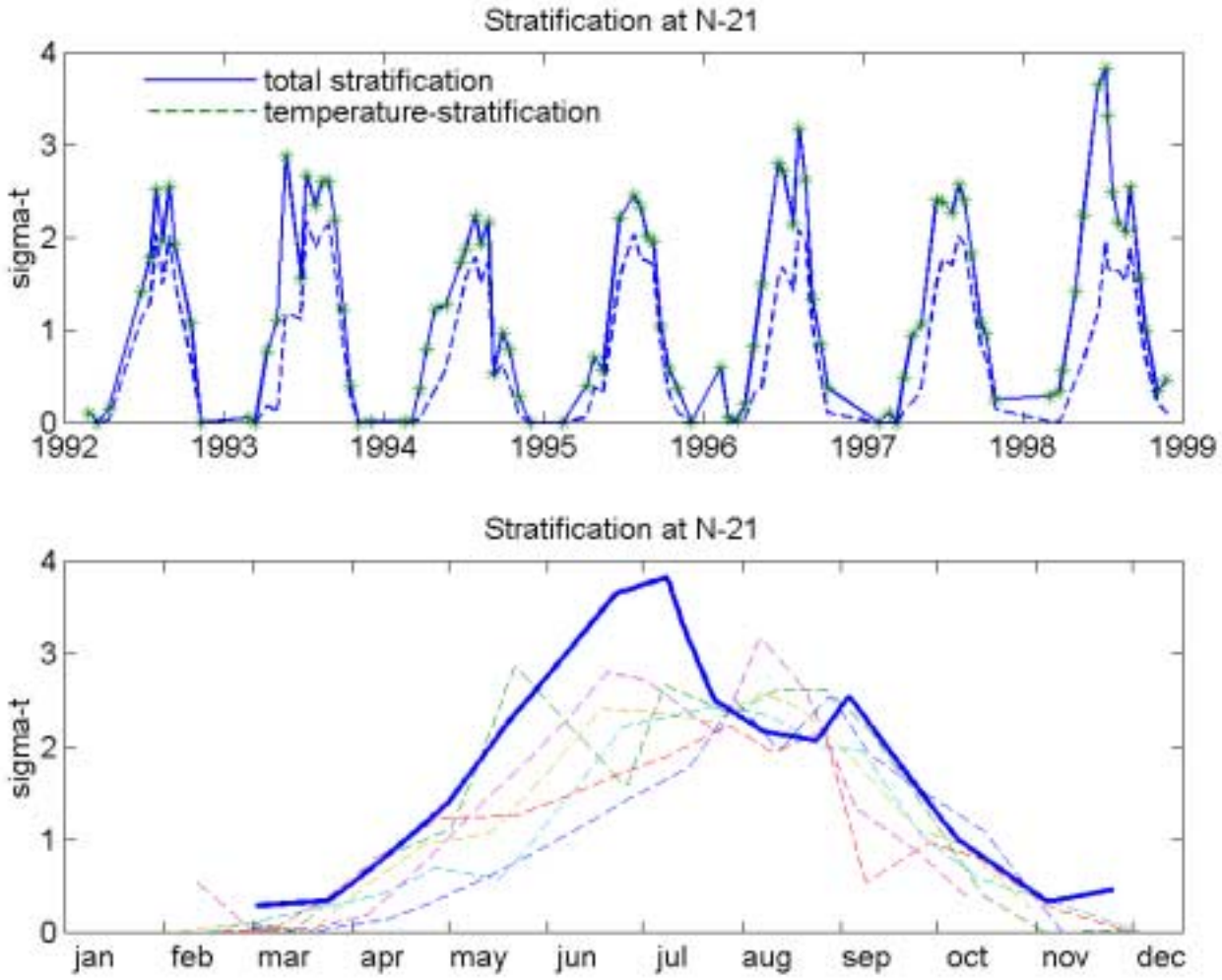


Figure 3-11. Stratification (density difference between near-bottom and near surface) at nearfield station N21, 1992–1998. The dashed line in the upper panel shows the stratification due only to temperature variation, and the solid line includes both salinity and temperature effects. The bottom panel shows the annual cycle for 1998 in a bold trace, and the other years with dashed lines.

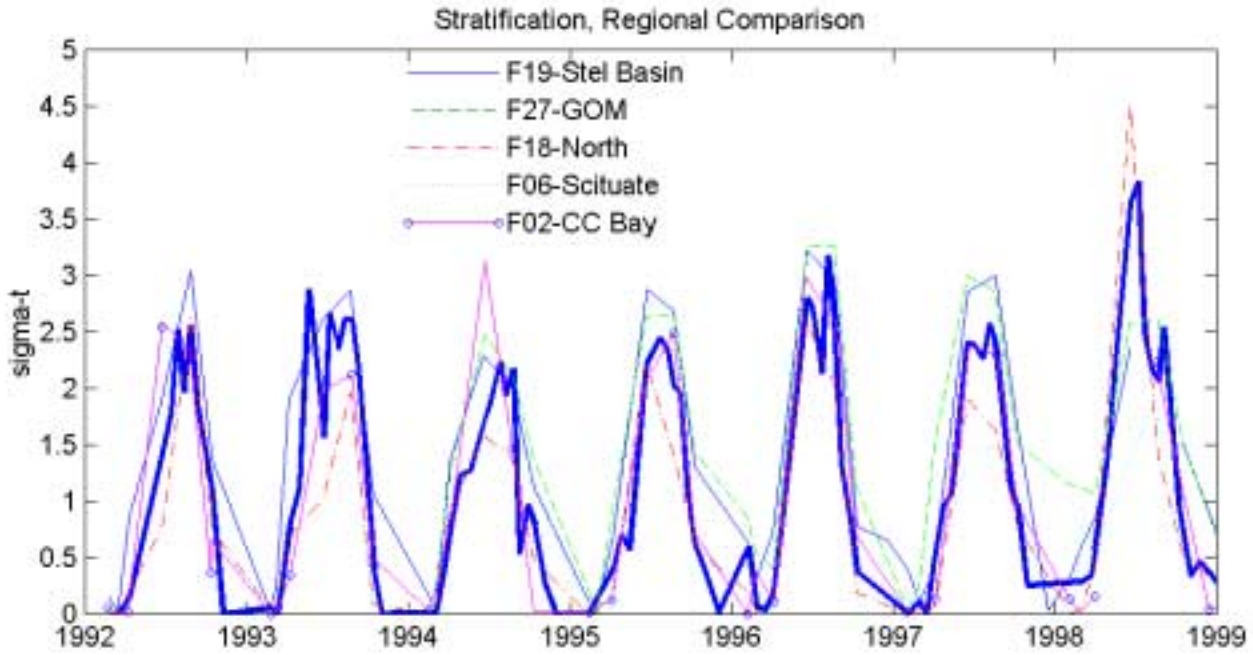


Figure 3-12. Comparison of stratification at N21 (bold lines) to selected farfield stations.

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 baseline monitoring period. 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 presented in this section. 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 1998 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 nearfield data are presented both as mean survey values across the area 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 1998 (Libby *et al.*, 1999a and 1999b). The discussion presented in this section focuses on the major themes that were observed in the dissolved inorganic nutrient data in 1998. These include the lack of a strong spring draw down of nutrients, the input of nutrients to the surface waters during summer upwelling events and the atypical winter nutrient concentrations in Boston Harbor and the western nearfield.

4.1.1 Nearfield Trends

Nutrient trends in the nearfield were summarized by plotting dissolved inorganic nutrient concentrations versus time (Figures 4-1and 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 depth of the "mid-depth" sample to be adjusted vertically to capture any subsurface chlorophyll maximum, if present.

There was a strong decrease in NO_3, SiO_4 and PO_4 concentrations between the first two surveys (WF981 and WF982) at each of the sampling depths, but it was not accompanied by an increase in chlorophyll (see Section 4.2). From late February to early April, nutrient concentrations remained relatively constant over the water column in the nearfield (Figures 4-1 and 4-2). The draw down in nutrient concentrations that was observed in February 1998 is normally associated with the occurrence of a winter/spring bloom and suggests that a bloom may have been initiated in February of 1998. The presence of replete nutrient concentrations through early April, however, indicates that the bloom did not fully develop.

A combination of physical and biological factors may have contributed to the extended period of replete nutrients in the spring. In 1998, the water column became slightly stratified relatively early and winter water temperatures were warm (see Section 3). These physical factors should have been conducive to a phytoplankton bloom and a draw down in nutrients in Massachusetts Bay. Freshwater flow in February was cited as a contributing factor to early stratification, but the storm events associated with the high flow also led to episodic mixing and to increased terrestrial runoff of nutrients into the bays (see Figure 3-4). Additionally, winds from January to March were strongly downwelling favorable (see Section 3.1 and Table 3-2). Although weak stratification was observed relatively early in 1998, inputs of nutrients from runoff and episodic mixing events were a feature for

most of the spring. As will be discussed in Section 5, areal productivity was relatively low throughout the region during the winter and spring, although chlorophyll-specific areal production was elevated in February and March. The data suggest that the phytoplankton community that was present was productive and that factors other than nutrient limitation were curtailing bloom development. Moreover, the abundance of phytoplankton remained < 10^6 cells L^{-1} until May, thus biological nutrient uptake was relatively low. This combination of physical factors and biological inactivity resulted in elevated nutrient concentrations in the surface waters throughout most of the region from February to April.

By the May nearfield survey (WN985), NO_3 concentrations had been depleted throughout the water column across most of the nearfield (Figure 4-1a). This was coincident with an increase in phytoplankton abundance from April to May – primarily microflagellates and cryptomonads. Phosphate concentrations also decreased from April to May, but did not reach depleted levels in the surface waters until mid-June (Figure 4-2a). Surface water SiO_4 concentrations remained elevated until July (WN988) because of the dominance of microflagellates and cryptomonads rather than diatoms from February through May 1998 and the average SiO_4 concentrations in the mid-depth and bottom waters remained >2 µM throughout the year (Figure 4-1b).

Nutrients were generally depleted in the surface waters during the summer while concentrations in the mid-depth and bottom waters increased in July and August from the lower concentrations observed in May and June. A combination of factors contributed to this difference in nutrient distribution over the water column. Whole water and screened (>20-µm) phytoplankton communities achieved maximum populations in August and utilized the nutrients in the surface layer. At the same time, upwelling events supplied nutrients to the nearfield waters that both supported the phytoplankton assemblage and contributed to increasing concentrations of nutrients in the mid-depth and bottom waters. The third factor that may have contributed to higher nutrient concentrations at depth was the seasonal increase in remineralization of nutrients.

In 1998, the change from a stratified to a well-mixed water column in the fall was delayed until late November. As a result of the persistent stratification and a fall diatom bloom, the average nitrate and silicate concentrations remained low in the nearfield surface waters through early November. By the end of November (WN98G), the water column had become relatively well mixed and elevated NO_3 and SiO_4 concentrations were observed throughout the nearfield (Figure 4-1). In contrast, PO_4 concentrations began to increase in surface waters by late September and continued to increase during the fall bloom and into December (Figure 4-2a). This increase in PO_4 may have been due to an increased export of nutrients from Boston Harbor and the inability of phytoplankton to utilize the available PO_4 because of nitrogen limitation in the nearfield. Examination of nutrient-nutrient plots (Figure 4-3) showed that nearfield surface waters were generally depleted in DIN relative to PO_4 and that nitrogen limiting conditions existed from late September to October.

Average ammonium concentrations were generally low (~1µM) in the nearfield from February to November (Figure 4-2b). A significant increase in NH_4 concentrations in late November was correlated with elevated PO_4 concentrations. The high NH_4 and PO_4 concentrations were coincident with abnormally high levels of these nutrients in Boston Harbor. Ammonium concentrations in December had returned to a typical range for winter conditions, but the availability of NH_4 and PO_4 in late November may have contributed to the anomalously high chlorophyll concentrations that were observed in the nearfield in December (see Section 4.2).

As demonstrated in this set of nearfield average figures, a wide range in nutrient concentrations was frequently observed at each sampling depth. Generally, the range in NO_3 and PO_4 values across the nearfield was smaller during the winter/spring conditions, increased during the stratified summer/fall conditions, while a wide range in SiO_4 and NH_4 values was observed throughout 1998. 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 are presented in Figures 4-4, 4-5, 4-6, and 4-7. The stations are situated at the four corners of the nearfield (N01, N04, N07, and N10) and the center of the nearfield (N21).

From February to May, NO_3 and PO_4 concentrations decreased in surface and bottom waters at each of the representative nearfield stations (Figures 4-4 and 4-5). By May, NO_3 concentrations had been depleted in the surface and bottom waters at the shallower, inshore stations (N01, N10 and N21) and in the surface waters at the deeper, offshore stations (N04 and N07). Phosphate concentrations continued to decrease in the surface waters until reaching depleted levels in June. The variability in the data (Figures 4-1 and 4-3) during this time period was primarily due to an inshore to offshore gradient of decreasing nutrient concentrations.

Silicate concentrations showed a general decline in surface and bottom waters from February to July. Due to the rainfall events that occurred in February and June, there was more temporal and spatial variability in SiO_4 concentrations over this time period (Figure 4-6). Ammonium concentrations were generally low during the first half of 1998 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 (Figure 4-7).

The water column was strongly stratified across the nearfield from July to October. During this time, the surface waters remained relatively depleted in nutrients while nutrient concentrations steadily increased in the bottom waters. The variability in surface water nutrient concentrations was due to the harbor influence that increased concentrations at the inshore nearfield stations (*i.e.* station N10). In the bottom waters, the wide range in nutrient concentrations was due to an inshore to offshore increase in station depth and a corresponding increase in bottom water NO_3, SiO_4, and PO_4 concentrations. In November, the export of NH_4 and PO_4 rich waters from Boston Harbor led to high average concentrations and a wide range of values across the nearfield (Figure 4-7).

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 1998 (a comprehensive data presentation was provided in Libby *et al.* 1999a and b).

As the series of contour plots illustrates (Figures 4-8 to 4-11), the highest nutrient concentrations were consistently measured at the harbor and harbor-influenced coastal and nearfield stations. Dissolved inorganic nutrients were generally at a maximum in surface waters during the first winter survey (WF981). The distribution of dissolved inorganic nitrogen (DIN; Figure 4-8) was similar to that of the other nutrients with the highest concentrations being measured in Boston Harbor and elevated concentrations throughout the bays. By late February, surface water ammonium and phosphate concentrations had decreased (except at the harbor and harbor-influenced coastal stations) while relatively high concentrations of nitrate and silicate were still present in surface waters throughout the region. Similar nutrient conditions were observed for the surface waters in April: elevated concentrations at harbor and harbor influenced stations, low ammonium and phosphate concentrations throughout the region and elevated concentrations of nitrate and silicate continued to be present in the nearfield and offshore.

By June, however, nutrients were present in low concentrations throughout the region except at the harbor-influenced stations (as represented by DIN in Figure 4-9). Silicate levels were high in the

nearfield and along the coast from Boston to Gloucester due to heavy rains and the resulting runoff (Figure 4-10). In August (WF98B), dissolved inorganic nutrients were generally depleted in the surface waters at the offshore stations in Massachusetts and Cape Cod Bays. The highest concentrations were observed at the harbor stations and elevated concentrations were seen at the coastal and western nearfield stations due to harbor discharge and periods of coastal upwelling. By October (WF98E), surface water nutrient concentrations had increased at the harbor and inshore stations while remaining relatively depleted offshore (Figure 4-11). During the November and December surveys, high ammonium and phosphate concentrations were observed at the harbor stations and along the western nearfield area.

The vertical distribution of nutrients reveals a similar trend of lower nutrient concentrations in the surface waters offshore and away from Boston Harbor. The nutrient vs. depth plots also demonstrate the seasonal variations in the vertical distribution of nutrients across the region. During the first combined nearfield/farfield survey in early February (WF981), the well-mixed water column was replete with nutrients. There was an inshore/offshore gradient of decreasing nutrient concentration for each of the nutrients. This pattern can be clearly seen in the DIN vs. depth plot showing very high concentrations at the Boston Harbor stations and elevated levels at the nearby coastal and nearfield stations (Figure 4-12a). The high DIN concentrations were driven by high NH_4 in the harbor (Figure 4-12b). A few lower DIN values were measured in Cape Cod Bay that may have indicated the initial nutrient draw down usually associated with the winter/spring bloom.

By late February (WF982), nutrient concentrations had decreased, but were still replete throughout the bays. DIN concentrations, for example, were approximately 4 μM lower in the surface layer than they had been during the first survey and were still present in moderate to high concentrations in each of the geographic regions (Figure 4-13a). At a number of coastal, Cape Cod Bay and nearfield stations, DIN concentrations in the surface layer were <2 μM suggesting that, even though there had not been a significant winter-spring bloom, the phytoplankton biomass had drawn down nutrient concentrations in February. There was little change in the nutrient concentrations and distribution between late February and April (Figure 4-13b). A clear inshore/offshore decrease in surface water nutrient concentrations was present and all nutrients were replete throughout the bays. The subset of low DIN concentrations that had been observed in February, however, was no longer present, which supports the phytoplankton and productivity data indicating that no winter/spring bloom occurred in 1998. Due to the lack of nutrient utilization in the surface waters, there was little change in the vertical distribution of nutrients during the first 3 combined farfield/nearfield surveys.

By June (WF987), nutrient levels in the surface waters at the non-harbor-influenced stations were generally depleted (Figure 4-14a). Ammonium concentrations still exhibited a strong harbor/coastal signal with a dominant inshore/offshore horizontal gradient of decreasing concentrations. Phosphate and nitrate were depleted in the surface waters, as was silicate except along the coast and in the nearfield area where the heavy June rains and associated runoff contributed to elevated concentrations. Due to the utilization of nutrients in the surface waters, there was a strong vertical gradient of increasing concentration with depth. At the deeper boundary and offshore stations, DIN concentrations had increased from the April measurements.

During the August combined farfield/nearfield survey (WF98B), nutrient concentrations were generally low in the surface waters and increased with depth. The typical inshore/offshore gradient of decreasing concentration was observed for each of the dissolved inorganic nutrients. As shown for DIN in Figure 4-14b, low concentrations were observed in the surface layer and concentrations increased near the pycnocline (~20 m). The elevated nutrient concentrations at the pycnocline were coincident with the subsurface chlorophyll maximum that was observed at the offshore stations during this survey. As discussed in Section 3, the August survey was conducted during a period of intermittent upwelling conditions. Due to biological utilization of NO_3, this is not clearly illustrated in Figure 4-14b, but DIN concentrations had increased from the levels observed in June while at the

same time nutrient utilization had increased due to an increase in phytoplankton abundance and productivity. DIN concentrations below the pycnocline had increased since June due to a combination of biological and physical factors. Seasonal stratification had separated the surface and bottom waters and, while nutrient utilization had increased in the surface layer, decomposition/remineralization of organic materials increased in the bottom layer. The increase was especially evident at the deeper nearfield, offshore, and boundary stations. The upwelling events entrained these nutrient rich bottom waters to the inshore nearfield and coastal stations.

In October (WF98E), nutrient concentrations were low and generally depleted in the surface waters at the Cape Cod, nearfield, offshore and boundary stations and increased with depth (Figure 4-15a). The harbor signal was very strong especially for NH_4, which was high at the Boston Harbor and nearby coastal stations (Figure 4-15b). Phosphate concentrations were generally higher in October than August and exhibited a strong inshore/offshore gradient of decreasing concentrations across all depths. Silicate and nitrate concentrations in the bottom waters had increased slightly since the August survey. The degradation of summer phytoplankton assemblages and remineralization of the nutrients at depth continued to contribute to the increase in bottom water nutrient concentrations.

The NH_4 and PO_4 concentrations observed in the harbor, coastal and western nearfield waters during the October survey (WF98E) were anomalously high. During the November survey (WN98G), high NH_4 and PO_4 concentrations were again observed in the nearfield with an inshore to offshore decrease in concentration away from the harbor. Nutrient data collected by MWRA for the Boston Harbor monitoring program were also anomalous with NH_4 concentrations 5-10 μM higher than any measurement from 1993-1997 (pers. com., D. Taylor). The reason for these high concentrations has not been determined, but it is expected that activities within Boston Harbor led to these atypical conditions. The anomalous NH_4 and PO_4 concentrations are discussed in more detail in Section 4.1.3.

4.1.3 Interannual Comparisons – 1998 Events

The year to year variability in nutrient concentrations is dependent upon a variety of physical and biological factors. This section focuses on evaluating the major events that were mentioned in the previous sections. In 1998, there were three interesting observations that require further discussion: the lack of a strong spring draw down of nutrients, the input of nutrients to the surface waters during summer upwelling events, and the atypical winter nutrient concentrations in Boston Harbor and the western nearfield.

The winter/spring period in Massachusetts and Cape Cod Bays is often characterized by the occurrence of a bloom in phytoplankton and chlorophyll. 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. In the winter/spring period in 1998, no bloom was observed and elevated nutrient concentrations persisted in the surface waters until May. Nutrient and production data indicate that bloom conditions existed and that the phytoplankton community had started to bloom (nutrient draw down between the first two surveys in February and high productivity), but an increase in biomass was not achieved and a winter/spring bloom did not occur in Massachusetts Bay. Other factors may play a role in the realization of a winter/spring bloom – zooplankton grazing, resident phytoplankton assemblage, and many other physical, chemical, and/or biological factors that have not been resolved. The absence of a major winter/spring bloom in 1998 is discussed in more detail in Sections 5 and 6. The lack of a bloom, however, did result in persistently high nutrient concentrations in the surface waters from February to May.

Physical oceanographic data indicated that significant upwelling events occurred in July and August of 1998. The coincident nutrient data observed at coastal stations along the south shore and in the western nearfield suggested that these events input cool, nutrient rich bottom water into the coastal

surface waters. To illustrate the effect of upwelling in the nearfield, time series contour plots of temperature at the two eastern corners of the nearfield (stations N01 and N10) are presented in Figure 4-16. The figure clearly depicts the intrusion of cooler water over the entire water column in July and August. The figure depicts decreases in temperatures of 2 to 5 °C during the period of upwelling. Coincident nutrient data in time series contour plots of NO_3, PO_4, and SiO_4 at station N01 (Figure 4-17) show the effect of the upwelling events on nutrient concentrations in the nearfield. During the upwelling period, NO_3 and SiO_4 concentrations were 2 to 4 μM higher and PO_4 concentrations were approximately 0.5 μM higher at station N01. The upwelled nutrients supported an abundant phytoplankton community (highest total abundance for 1998). If not for the increased utilization of nutrients by the phytoplankton, the upwelled nutrient signal in the surface layer may have been even stronger. The upwelling signal was not as clear in the nutrient data from station N10 due to the strong influence of harbor export at this station.

During the fall of 1998, anomalously high concentrations of ammonium and phosphate were observed in Boston Harbor, coastal waters (stations F24 and F25) and the western nearfield. In October (WF98E), surface water NH_4 concentrations were >15 μM in the harbor and >10 μM at stations F24 and F25 (Figure 4-18). There was a sharp gradient of decreasing concentration between these coastal stations and the nearfield. This sharp gradient resulted from the utilization of the NH_4 (and other nutrients) by a fall bloom that was occurring in the western nearfield area. During the November surveys (WN98F and WN98G), high NH_4 and PO_4 concentrations were again observed in the nearfield with an inshore to offshore decrease in concentration away from the harbor (Figure 4-19). By December (WN98H), nutrient concentrations had decreased. This may have been due to increased nutrient utilization (an atypical increase in chlorophyll and phytoplankton abundance) rather than a decrease in the export from the harbor.

In the fall and winter of 1998, nutrient data collected by MWRA for the Boston Harbor monitoring program were also anomalous with NH_4 concentrations 5-10 μM higher than any measurement from 1995-1997. The data from both the Harbor Outfall and Boston Harbor monitoring programs over the last four years for stations in north and south Boston Harbor show the general seasonal NH_4 cycle in the harbor (Figure 4-20). A similar pattern was observed for PO_4 (Figure 4-21). 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 phytoplankton abundance and 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".

The source of the anomalously high nutrient concentrations has not been determined, but is likely due to the transfer of south system sewage flow from Nut Island to the Deer Island facility. The transfer of sewage flow from Nut Island to Deer Island began in April 1998 and was completed July 1998. Once completed, the transfer in flow increased the discharge from Deer Island by approximately one-third. In July and August, the increased discharge volume did not result in increased ambient nutrient concentrations in the harbor (Figures 4-20 and 4-21). The harbor's summer biological community may have been able to adapt and utilize the increased nutrient input (plankton and benthos). However, once system production shut down occurred in September/October, anomalously high NH_4 and PO_4 concentrations were measured in the northern portion of the harbor and nearby coastal waters (Figures 4-20a and 4-21a). In south Boston Harbor, there was no clear change in the seasonal cycle of these nutrients, although the summer period of low concentrations may have extended later into the fall in 1998 in comparison to previous years (Figure 4-20b and 4-21b).

The observation that the NH_4 concentrations were up to 50% higher during the fall/winter of 1998 compared to the previous three years suggests the increase in the Deer Island discharge of ~30% may not be the only factor that contributed to the higher concentrations. In comparison to the north system flow, the south system flow is enriched in NH_4 as it includes the filtrate from the MWRA sludge-

fertilizer plant in Quincy. Another factor could be the increase in secondary treatment at Deer Island as the second battery was brought online in February 1998. Secondary treatment results in an increase in NH_4 concentrations over primary treatment.

Determination of the source and/or cause of the increased nutrient concentrations are beyond the scope of this annual monitoring report, and may be a moot point once the discharge is transferred to the new outfall in September. Regardless of the source, anomalously high NH_4 and PO_4 concentrations were observed in Boston Harbor and nearby coastal and western nearfield waters in the fall of 1998. In October, the strong nutrient gradient that was observed in the western nearfield was coincident with elevated chlorophyll concentrations and high production rates. It is suspected that the increased nutrient export from Boston Harbor may have triggered or contributed to this localized fall bloom in the western nearfield.

4.2 Chlorophyll

This section provides an overview of the trends and distribution of chlorophyll in Massachusetts and Cape Cod Bays in 1998 and an interannual comparison with the 1992-1997 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 surface, mid-depth, and bottom sampling depths. The mid-depth sample coincides with the subsurface chlorophyll maximum if one was present in the water column. 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 1998 (Libby *et al.* 1999a and 1999b). The discussion presented in this section focuses on the major themes that were observed in the chlorophyll data in 1998. These include the lack of a winter/spring bloom, elevated summer concentrations, localized nearfield fall bloom, and the atypical winter chlorophyll concentrations.

4.2.1 Nearfield Trends

During the winter/spring of 1998 (February to May), chlorophyll concentrations were generally low throughout the nearfield (mean = 0.84 μgL^{-1}) and no winter spring bloom was observed. Chlorophyll concentrations increased from May to July and were relatively high for the remainder of the summer (mean = 1.92 μgL^{-1}). The summer increase in chlorophyll was coincident with increasing phytoplankton abundance. High chlorophyll concentrations were observed in the nearfield during the fall season (mean = 2.43 μgL^{-1}). These high concentrations were the result of a localized fall bloom in the nearfield in October and an atypical increase in chlorophyll concentrations in December. The overall annual mean for all stations and all depths sampled during the nearfield surveys was 2.04 μgL^{-1}.

Trends in the nearfield chlorophyll concentrations are summarized in a time-series plot (Figure 4-22). This figure presents the average and range of the surface, mid-depth, and bottom values for each nearfield survey. Following field protocol, the depth of the "mid-depth" sample is adjusted vertically to capture the subsurface chlorophyll maximum, if present. For most of 1998, 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 an instrument malfunction, *in situ* fluorescence data was not collected in early February (WF981). However, extracted chlorophyll *a* concentrations were all less than 1 μgL^{-1}. Chlorophyll concentrations continued to be relatively low (<2 μgL^{-1}) during the months of March and April (WF982, WN983 and WF984) in the nearfield (Figure 4-22). By May 1st (WN985), the water column in the nearfield was beginning to stratify and nutrient concentrations in the surface waters had decreased. Mean chlorophyll concentrations in the upper 20 m (surface and mid depths) of the water column were low (~1 μgL^{-1}) while the concentrations below the pycnocline ranged from 1-6 μgL^{-1}. This chlorophyll distribution can represent either localized production at depth or sinking phytoplankton. Based on the productivity data (see Figure 5-2), it appears that the high subsurface chlorophyll concentrations resulted from localized production that was coincident with elevated nutrient concentrations.

Mean chlorophyll concentrations in the surface and mid-depth waters increased by the middle of May and into June. Chlorophyll concentrations had decreased by early July (WN988), but then increased and remained at moderate levels in the surface and mid-depth waters through the summer. By late July (WN989), chlorophyll concentrations had increased in the surface and mid-depth waters with mean values of 4 and 7 μgL^{-1}, respectively, and a range of concentrations from less than 1 μgL^{-1} to more than 18μgL^{-1} (Figure 4-22). The high mid-depth concentrations were observed at the northern nearfield stations (Figure 4-23). High surface chlorophyll concentrations were observed in the middle of the nearfield (*e.g.*, station N20) while at the offshore station N07, the chlorophyll concentration were relatively low.

In August, the mean chlorophyll concentrations in the surface and mid-depth waters decreased, but remained relatively high and a wide range in values continued to be observed (Figure 4-22). The increase in chlorophyll in July and the continued high concentrations in August were coincident with a summertime increase in total phytoplankton abundance (Figure 4-24). Phytoplankton abundance reached a maximum in the surface and mid-depth waters at stations N04 and N18 in August (WN98A and WF98B). The high chlorophyll concentration and total phytoplankton abundance were coincident with elevated areal production rates for the nearfield during survey WN98A. By early September, mean chlorophyll concentrations were low (< 3 μgL^{-1}) at each of the depths.

A fall bloom was observed in the nearfield during the late September and October surveys. The bloom appears to have been initiated in the shallow western portion of the nearfield and then progressed offshore. This is suggested by the chlorophyll concentrations which had increased from early to late September at inshore stations N01, N10, and N20 while remaining relatively low at the offshore stations N04 and N07 (Figure 4-23). In October (WF98E), the fall bloom extended over the entire nearfield area. High surface chlorophyll concentrations were observed inshore, while subsurface maxima were seen at the offshore stations. During the late September and October surveys, the mean chlorophyll concentrations at the subsurface chlorophyll maximum were 6.5-7.0 μgL^{-1}.

The inshore to offshore progression of the fall bloom in the nearfield area was corroborated by the productivity and phytoplankton data. During the late September survey (WN98D), production at station N18 (vicinity of station N20) was about 1000 $mgCm^{-2}d^{-1}$ while at station N04 it was only 200 $mgCm^{-2}d^{-1}$. Phytoplankton abundance at station N18 was about four times higher than the abundance at station N04 and the phytoplankton assemblage at N18 was dominated by centric diatoms, which were present in very low numbers at N04. In October, annual peaks in production were measured at both station N18 and station N04. Phytoplankton abundance was high (2-3 million cells L^{-1}) in the mid-depth samples at stations N04, N18 and N16. Centric diatoms (1-2 million cells L^{-1}) dominated the phytoplankton assemblage at these stations. It appears that survey WN98D was conducted during the initiation of the fall bloom and survey WF98E was conducted at or near the peak of the bloom.

By early November (WN98F), the fall bloom had ended and chlorophyll concentrations were $<3\ \mu gL^{-1}$ throughout the nearfield area (Figure 4-22). During previous baseline monitoring years, low chlorophyll conditions persisted after the collapse of the fall bloom, but in December of 1998 an unprecedented winter bloom was observed in the nearfield area with surface chlorophyll concentrations ranging from 3 to $13\ \mu gL^{-1}$. The highest concentrations were observed in the surface water of the western nearfield. The increase in chlorophyll was coincident with a 50% to 100% increase in phytoplankton abundance at stations N04 and N18 from late November to December. Most of the increase was due to an increase in the abundance of diatoms including the pennate diatom *Pseudo-nitzschia pungens*, which was dominant at both N04 and N18.

The anomalously high NH_4 and PO_4 concentrations that were observed in this area during November and December may have triggered the increase in nearfield chlorophyll concentrations and phytoplankton abundance. On the other hand, high chlorophyll concentrations were also observed in and near Cape Cod Bay (stations F02, F03 and F29) and satellite imagery indicated that elevated chlorophyll concentrations were present over most of the western Gulf of Maine waters (Figure 4-25). This suggests that the increase in chlorophyll and phytoplankton in the nearfield may have been part of a regional rather than a localized event. Unfortunately, no farfield samples were collected for phytoplankton analyses. The lack of regional phytoplankton data precludes a direct comparison of Cape Cod Bay and nearfield phytoplankton assemblages to confirm that the increase in diatoms (including *Pseudo-nitzschia pungens*) was a regional phytoplankton event. The input of NH_4 and PO_4 from Boston Harbor may have contributed to the high chlorophyll concentrations that were observed in the nearfield, but based on the chlorophyll data and SeaWIFS images it appears that the nearfield bloom was part of a regional rather than a localized chlorophyll bloom.

4.2.2 Farfield Comparisons

The annual mean fluorescence at the farfield stations was $2.49\ \mu gL^{-1}$, which was higher than the annual mean for the nearfield area ($2.04\ \mu gL^{-1}$). By region, the mean fluorescence values were $3.03\ \mu gL^{-1}$ in Boston Harbor, $2.66\ \mu gL^{-1}$ at the boundary stations, $2.65\ \mu gL^{-1}$ in Cape Cod Bay, $3.12\ \mu gL^{-1}$ at the coastal stations, and $1.69\ \mu gL^{-1}$ at the offshore stations.

Time series plots of chlorophyll concentrations at representative farfield stations are presented in Figures 4-26 and 4-27. As with the nearfield data, chlorophyll concentrations were generally low throughout the region during the first three farfield surveys (WF981, WF982, and WF984) and no winter/spring bloom was detected. At station F01 in Cape Cod Bay, elevated concentrations were observed for the mid-depth/subsurface chlorophyll max sample during this time period. Chlorophyll concentrations were low at station F01 in June (WF987), but achieved annual maximum values in August (WF98B). The Boston Harbor and coastal stations (F23 and F13, respectively) tended to have similar chlorophyll distributions with annual maximum chlorophyll concentrations in June and moderately high values through the remainder of the year (Figure 4-26).

The high concentrations were observed at the offshore stations in June and August. At station F22, the highest concentrations were measured during the August survey ($\sim 7.5\ \mu gL^{-1}$). At the boundary station F26, chlorophyll concentrations were generally low with the highest values being measured in October ($\sim 5\ \mu gL^{-1}$). These chlorophyll concentrations were comparable to those measured in each of the geographic regions except the nearfield. At station N18 and the rest of the western nearfield, a localized fall bloom in chlorophyll was observed. The typical trend of decreasing chlorophyll concentrations after the fall bloom was observed at station N18 in November, but in December chlorophyll concentrations at station N18 had increased to $>12 \mu gL^{-1}$ in the surface waters (Figure 4-27). Anomalously high chlorophyll concentrations were found at other stations throughout the bays in December. The highest concentration was observed at station F29 off Provincetown ($15.5\ \mu gL^{-1}$).

In Cape Cod Bay, chlorophyll concentrations ranged from 1.0 to 8.6 μgL^{-1} and at harbor station F23, chlorophyll values of 3.4 to 6.6 μgL^{-1} were observed.

4.2.3 1992–1998 Interannual Comparisons

The major themes observed in the chlorophyll data in 1998 included the lack of a winter/spring bloom, elevated summer concentrations, localized nearfield fall bloom, and the atypical winter chlorophyll concentrations. 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 (1992-1997).

The 1998 annual cycle of chlorophyll in the nearfield is presented in Figure 4-28 along with the data from previous 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 1998, spatial variability was high during the August, October, and December chlorophyll events due to the inshore/offshore gradients in chlorophyll concentrations that were observed during these events.

In Figure 4-28, the annual cycle has been divided into three 'seasons': spring (January to April), summer (May to August), and fall (September to December). These time periods represent common seasonal patterns in physical and biological processes that have been observed in the nearfield area. 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 and nutrient availability. The summer is a period of strong stratification and depleted surface nutrients and a relatively stable mixed-assemblage phytoplankton community is present throughout the bays. 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 1998, winter/spring chlorophyll concentrations were very low and no spring bloom was observed in the nearfield. The winter/spring mean chlorophyll concentration in the nearfield was 0.84 μgL^{-1} in 1998, which is the lowest spring mean recorded from 1992 to 1998. Based on chlorophyll concentrations, large spring blooms only occurred during three of the last seven years: 1992, 1994, and 1996. Seasonal mean chlorophyll concentrations were approximately 2 μgL^{-1} during each of these years (Table 4-1). The baseline monitoring chlorophyll data indicate that the spring bloom may not be as common in Massachusetts Bay as once thought.

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

In 1998, phytoplankton abundance and chlorophyll concentration increased consistently from February to June and remained high during July and August. This seasonal pattern has often been observed in Boston Harbor, but this was the first time that it had been seen in the nearfield during the baseline monitoring program. The summer mean chlorophyll concentration was 1.92 μgL^{-1} in 1998, which was the highest observed during the 1992-1998 period. The high variability associated with the nearfield chlorophyll data was due to a combination of a strong inshore to offshore decrease in surface chlorophyll and a vertical gradient at the deeper offshore stations (subsurface chlorophyll max).

The 1998 fall bloom was not as substantial as some previous blooms (1993 and 1995). However, due to an anomalous December bloom, the fall mean chlorophyll concentration in 1998 (2.43μgL^{-1}) was comparable to all but the major bloom of *Asterionellopsis glacialis* during in1993, which resulted in the highest fall mean of the baseline period (4.05 μgL^{-1}). The 1998 fall bloom consisted of a mixed assemblage of diatoms. During each of the baseline monitoring years, the variability of chlorophyll data has been highest during the fall bloom. This is due to the spatial dynamics and intensity of the blooms, which vary significantly over the nearfield monitoring area.

The anomalous chlorophyll concentrations that were observed in December 1998 had not been seen during any of the previous baseline monitoring years. Nutrient data suggests that the export of nutrient rich waters from Boston Harbor during November and December may have triggered the bloom, but regional data (farfield chlorophyll measurements and SeaWIFs data) indicate that this was a regional event that encompassed much of the western Gulf of Maine. The mean nearfield concentration in December 1998 of 5.36μgL^{-1} was the third highest nearfield survey mean measured during the baseline monitoring period; the highest (9.5 μgL^{-1}) was measured during the 1993 fall bloom.

The annual average chlorophyll concentrations for the farfield are presented in Table 4-2. These values were calculated by taking the average of the survey means for each area data and include all stations and all depths (A-E) sampled. In 1998, the annual means were all relatively high in comparison to previous baseline years and had increased substantially from the low chlorophyll concentrations observed in 1997. The 1998 annual mean for the boundary area was the highest observed over the baseline period. The 1998 average chlorophyll concentration for Massachusetts and Cape Cod Bays (farfield stations; 2.49 μgL^{-1}) was only exceeded by the values for 1992 and 1993.

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

	Annual Mean (μgL^{-1})						
Year	**Nearfield**	**Farfield***	**Boston Harbor**	**Boundary**	**Cape Cod Bay**	**Coastal**	**Offshore**
1992	2.02	2.57	3.83	1.64	3.24	2.91	2.05
1993	2.27	2.79	3.37	1.44	3.42	3.76	2.09
1994	1.93	2.34	2.31	2.09	3.58	2.57	1.87
1995	1.37	1.27	2.09	0.82	1.89	1.54	0.76
1996	1.45	1.68	2.71	1.32	2.85	2.09	1.40
1997	1.02	1.19	1.41	0.85	1.34	1.06	0.78
1998	2.04	2.49	3.03	2.66	2.65	3.12	1.69

*Annual mean for “Farfield” based on average of survey means including all farfield stations.

To examine the interannual variability on a regional and temporal basis, chlorophyll data at selected stations from each geographical area are presented in Figure 4-29. Chlorophyll concentrations in the harbor tended to increase through the summer and were generally low in the spring and fall. The chlorophyll concentration measured in June 1998 (11.25 μgL^{-1}) was the highest observed at harbor station F23 from 1992-1998. The temporal cycle of chlorophyll at coastal station F13 was similar to the harbor in 1998, but this was not always the case during previous years. The coastal station has exhibited a mixture of harbor and offshore trends over the baseline period. In 1995, 1997 and 1998, the coastal chlorophyll cycle mimicked that seen in the harbor, while during the other years a bay trend of elevated spring or fall concentrations or both was observed.

At nearfield station N18, chlorophyll concentrations in 1998 were among the highest observed from 1992-1998. The 1998 fall bloom had slightly lower chlorophyll concentrations than the major bloom in 1993 (11.0 vs. 11.6 μgL^{-1}) and the high chlorophyll concentrations seen at N18 in December 1998 (10.2-13.1μgL^{-1}) were comparable to the high values measured there in November 1995 (10.8-15.9 μgL^{-1}). This suggests that the high December chlorophyll concentrations observed in 1998 may not be uncommon events. The offshore and boundary stations tended to display annual cycles that were similar to the nearfield. In Massachusetts Bay, the fall bloom usually dominated the seasonal cycle. In Cape Cod Bay (station F02), the winter/spring bloom was the dominant annual chlorophyll event though a major bloom was not observed during every baseline monitoring year.

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 1998 and an interannual comparison with the 1992-1997 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 evaluated DO trends in these deep waters. A detailed presentation of the data was provided in the two semi-annual reports for 1998 (Libby *et al.* 1999a and 1999b). 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).

4.3.1 Nearfield DO Trends

In 1998, the lack of a winter/spring bloom and the major storm event in June led to relatively high bottom water DO concentrations during the setup of stratified conditions in early summer. Stratification persisted into November in the nearfield and survey mean DO concentrations decreased from August to December in the nearfield bottom waters. The relatively high initial bottom water DO concentrations observed at 'setup' in June (nearfield mean = 11.2 mgL^{-1}) kept the survey mean values from reaching the extremely low levels that had been observed during previous years.

Dissolved oxygen concentrations and percent saturation values for both the surface and bottom waters at the nearfield stations were averaged and plotted for each of the nearfield surveys (Figure 4-30). From February to early July, the average surface and bottom water DO concentrations for the nearfield area were similar and generally ranged from 10-11 mgL^{-1} (Figure 4-30a). The highest bottom water concentration was observed in June (11.2 mgL^{-1}). During the first four surveys, the surface and bottom waters were near saturation and increased to supersaturated levels by June (Figure 4-30b). Dissolved oxygen remained supersaturated in the surface waters through the summer.

In late July, there was a 3 mgL^{-1} gradient in DO concentrations between the surface and bottom waters and the average surface water DO concentration in July (12.4 mgL^{-1}) was the highest observed in 1998. The large gradients in DO concentration observed in July resulted from a combination of physical and biological factors. By June (WF987), the nearfield water column was strongly stratified separating the biological and chemical processes of the surface and bottom waters. The elevated surface water DO concentration in July was concomitant with generally high chlorophyll concentrations and high phytoplankton abundance while the decrease in bottom water DO concentrations was coincident with the seasonal increase in respiration rates observed in July (see Section 5.2).

The trends in surface DO concentration in the summer and fall followed changes in biological parameters. The highest DO concentrations were observed in early August when chlorophyll concentrations and phytoplankton abundance were also high. After declining in September, surface DO concentrations increased in October coinciding with the fall bloom. Elevated surface DO concentrations were also seen in December when abnormally high chlorophyll concentrations were observed. The surface waters were supersaturated from August to October and remained near saturation in November and December.

Bottom water DO concentrations continued to decrease from the highest survey average in June to the lowest average in December. The initial decrease from 11.2 mgL^{-1} in June to 7.8 mg L^{-1} in late September constituted the majority of the seasonal decline. Bottom water DO concentrations remained relatively constant from late September to late November. By December, bottom water DO had decreased to 7 mg L^{-1}, which was the minimum value for the nearfield during this time period. The persistence of stratified conditions at the eastern nearfield stations resulted in the continual decline in bottom water DO concentrations. Normally, the water column would become well mixed in November and bottom water DO concentration would increase. In 1998, the delay in mixing combined with the winter chlorophyll bloom led to an annual minimum in bottom water DO concentration during the December survey. Although physical and biological conditions in 1998 led to an extended period of DO decline in the nearfield bottom waters, the 1998 nearfield minimum was not the lowest in comparison to previous baseline monitoring years.

4.3.2 Farfield Comparisons

The DO of bottom waters was compared between areas over the course of the six combined surveys and the last two nearfield surveys. A time series of the average bottom water DO concentration for each area is presented in Figure 4-31. In 1998, average bottom water DO concentrations in the farfield ranged from 7 to 12 mgL^{-1}. High DO concentrations (10-12 mgL^{-1}) were measured in the bottom waters during the February/March farfield surveys (Figure 4-31a). By April, the DO concentrations had decreased to 9-11 mgL^{-1}. Consistent with the lack of a winter/spring bloom and the increased productivity observed during the WF987 survey, mean bottom water DO concentrations were higher (11 ± 0.5 mgL^{-1}) throughout most of the farfield region in June. The distribution of bottom water DO concentrations in June is presented in Figure 4-32. Concentrations were high throughout Massachusetts Bay and no clear pattern was observed. The bottom waters were supersaturated with respect to DO in June with average values ranging from 102-120 %saturation (Figure 4-31b).

From June to October, mean bottom water DO concentrations decreased ~3 mgL^{-1} in each of the areas (Figure 4-31a). The lowest concentrations were observed in Cape Cod Bay and the distribution of DO concentrations in Massachusetts Bay indicated that the lower values occurred at the deeper nearfield and offshore stations (Figure 4-33). In the boundary area, DO concentrations continued to decrease into late November (WN98G) when the lowest bottom water DO concentration for that area was observed at station F12 (7 mgL^{-1}). No other farfield stations were sampled during survey

WN98G and it is unclear if DO concentrations continued to decline throughout the region. By December, DO concentrations in the boundary area, Boston Harbor and Cape Cod Bay had increased. The summer/fall decline in bottom water DO concentrations was also observed in the DO % saturation data (Figure 4-31b). By October, DO % saturation had decreased to 79-92% regionally. The decreasing trend continued into November in the boundary area where DO % saturation reached a regional annual minimum value of 72%. Boundary and Cape Cod bottom waters were near 100% saturation by December, but Boston Harbor bottom water had decreased since October to 82% saturation, which was the lowest % saturation observed in the harbor in 1998.

The DO pattern in Stellwagen Basin (stations F12, F17, F19, and F22) was similar to that observed in the nearfield (Figure 4-34). High concentrations were observed in the surface and bottom waters in June and the values declined from June until late November (Figure 4-34a). There were no increases in surface water DO concentration in August or October as had been seen in the nearfield. Bottom water concentrations declined from 11 mgL^{-1} in June to 7 mgL^{-1} in November. The surface waters were saturated or supersaturated with DO throughout the year in Stellwagen Basin. DO % saturation reached a maximum of 106% in the bottom waters in June and declined to an annual low of 72% in November (Figure 4-34b).

4.3.4 1992–1998 Interannual Comparisons

The DO cycle in the nearfield for each of the baseline monitoring years is presented in Figure 4-35. During each of the previous years, the DO cycle followed a repetitive pattern of high 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. In 1998, a different pattern was observed with variable concentrations in the winter/spring, maximum bottom water concentrations in June, maximum surface water concentrations during the summer, and bottom water concentrations decreased from June through the last survey in December.

The 1998 winter/spring DO concentrations were relatively low in comparison to previous years and comparable to the low values observed in 1995 and 1997. This may have been due to the relatively warm water temperatures in the nearfield during the winter/spring of 1998 (see Figure 3-5). Due to the major June storm event and the lack of an input of organic material from a winter/spring bloom, the bottom water DO concentration observed in June 1998 was high (11.2 mgL^{-1}). This was the highest DO concentration that had been observed this late in the year. For the HOM program, June has been used as the time period when stratification has isolated the bottom water and seasonal bottom water conditions are setup. In August, phytoplankton abundance reached an annual maximum in the nearfield surface waters and resulted in very high DO concentrations (>12 mgL^{-1}). These elevated concentrations had only previously been observed during the winter/spring period in 1992, 1993, and 1996 (1992 and 1996 had significant spring blooms). This even more unusual given that water temperatures in August are >10°C warmer than in the winter/spring period.

In 1998, the water column was stratified until November throughout much of the nearfield and a deep halocline was still present in December at the deeper eastern nearfield stations where the lowest DO concentrations for the year were observed. The strength and duration of stratification are important factors in the decline of bottom water dissolved oxygen concentrations. Due to the persistence of stratified conditions in 1998, bottom water DO concentrations decreased over the entire June to December time period in the nearfield area.

The annual cycle observed in Stellwagen basin during the baseline monitoring period has generally been similar to that seen in the nearfield area. The highest concentrations are usually observed in late winter/early spring, concentrations decreased through the summer and into the fall, and then concentrations increased after October (Figure 4-36). In 1998, the high June concentrations and the continued decline in bottom water concentrations into November were atypical for the basin in

comparison to previous years. The mean minimum concentration of 7.1 mgL^{-1} ranked as the third lowest survey mean value in Stellwagen Basin from 1992-1998.

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 4-37). In 1998, the mean DO concentration continued to decline in the nearfield through the end of the year, albeit at a lower rate. The rate of decline from June to December in 1998 was –0.021 $mgL^{-1}d^{-1}$. The 1998 rate of DO decline in Stellwagen Basin was also the highest observed during the baseline monitoring period (Figure 4-38). The rates ranged from a low of –0.012 $mgL^{-1}d^{-1}$ in 1997 to –0.030 $mgL^{-1}d^{-1}$ in 1998. If the November data were included for 1998, the rate of DO decline still would have been the highest at –0.026 $mgL^{-1}d^{-1}$.

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 4-39). In 1998, the difference between the nearfield and Stellwagen Basin was negligible.

The primary physical and biological factors that influence the rate of DO decline and the magnitude of the annual DO minimum in the nearfield and Stellwagen Basin bottom waters are:

- setup DO concentration,
- strength of stratification,
- frequency and magnitude of reaeration events,
- respiration rates and availability of organic material,
- bottom water temperature (as it affects respiration rates), and
- interval of stratification.

In 1998, the setup DO concentration was higher than it had been during previous monitoring years in both the nearfield and Stellwagen Basin (Figures 4-37 and 4-38). The elevated concentrations resulted from the major June storm event that reaerated the bottom waters. The upwelling events in the nearfield in August did not reaerate the bottom waters (actually this may entrain bottom waters from offshore that also have relatively low DO concentrations), but led to increased production in the surface layer and an eventual increase in organic material settling into the nearfield bottom waters. The interval of stratification and DO decline was longer in 1998 in both areas, but the lower water temperature, lower respiration rates, and gradual increase in mixing in November and December resulted in a slower rate of decline after October.

4.4 Summary of 1998 Water Quality Events

The winter/spring period in Massachusetts and Cape Cod Bays is often characterized by the occurrence of a bloom in phytoplankton and chlorophyll. 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. Other factors may play a role in the realization of a winter/spring bloom – zooplankton grazing, resident phytoplankton assemblage, and many other physical, chemical, and/or biological factors that have not been resolved. In the winter/spring period in 1998, no bloom was observed and elevated nutrient concentrations persisted in the surface waters until May. Nutrient and production data indicate that bloom conditions existed and that the phytoplankton community had started to bloom (nutrient draw down between February and March and high productivity), but an increase in biomass was not achieved and a winter/spring bloom did not occur in Massachusetts Bay. In Cape Cod Bay, however, the data suggest that a bloom may have occurred prior to the first survey in February.

Physical and chemical data suggest that significant upwelling events occurred in July and August of 1998 and that these events transported nutrients into the coastal surface waters. Evidence of this was observed at coastal stations along the south shore and in the western nearfield. The upwelling conditions, along with tidal transport from Boston Harbor, supplied nutrients to the nearfield that supported the high phytoplankton concentrations that were observed in August.

As with the winter/spring bloom, the fall bloom is not a consistent annual characteristic in the bays. The intensity of the fall bloom and the phytoplankton species that bloom has varied from year to year during the baseline-monitoring period. In 1998, the fall bloom was not single species bloom, but rather a general increase in the numbers of a variety of chain-forming diatoms. The bloom was more clearly observed in the increased chlorophyll concentrations and productivity data that were collected.

Stratification during the summer of 1998 was relatively strong (see Figure 3-11) and the overturn of the water column and the return to winter conditions was delayed in 1998 compared to previous baseline monitoring years. The water column was stratified until November throughout much of the nearfield and a deep halocline was still present in December at the deeper eastern nearfield stations. The strength and duration of stratification are important factors in the decline of bottom water dissolved oxygen concentrations. Due to the persistence of strongly stratified conditions in 1998, bottom water DO concentrations decreased over the entire June to December time period in the nearfield area. The delay in mixing, combined with a pulse of organic material from the early winter bloom, led to the annual minimum in bottom water DO concentration (7 mg L^{-1}) observed in December. The DO minimum concentration was not extremely low in comparison to data collected during previous baseline monitoring years. Due to major storm events and the lack of an input of organic material from a winter/spring bloom, the bottom water DO concentrations observed in June were very high (11.2 mg L^{-1}), which subsequently lessened the effect of the delay in returning to well-mixed winter conditions.

In November and December 1998, anomalously high concentrations of ammonium and phosphate were observed in the western nearfield that correlated with high concentrations observed by the MWRA in Boston Harbor. The source of these nutrients was not determined, but may have been due to the transfer of south system sewage flows from Nut Island to the Deer Island facility, increased secondary treatment at the Deer Island facility, or other unknown factors. The increased flow in the north harbor did not immediately result in increased ambient nutrient concentrations. Boston Harbor's summer biological community may have been able to adapt and utilize the increased nutrient input initially, but once the system shut down in September/October elevated nutrient concentrations were measured both in the harbor and nearby coastal waters. The anomalously high NH_4 and PO_4 concentrations may have enhanced the regional bloom that was observed in the nearfield in December.

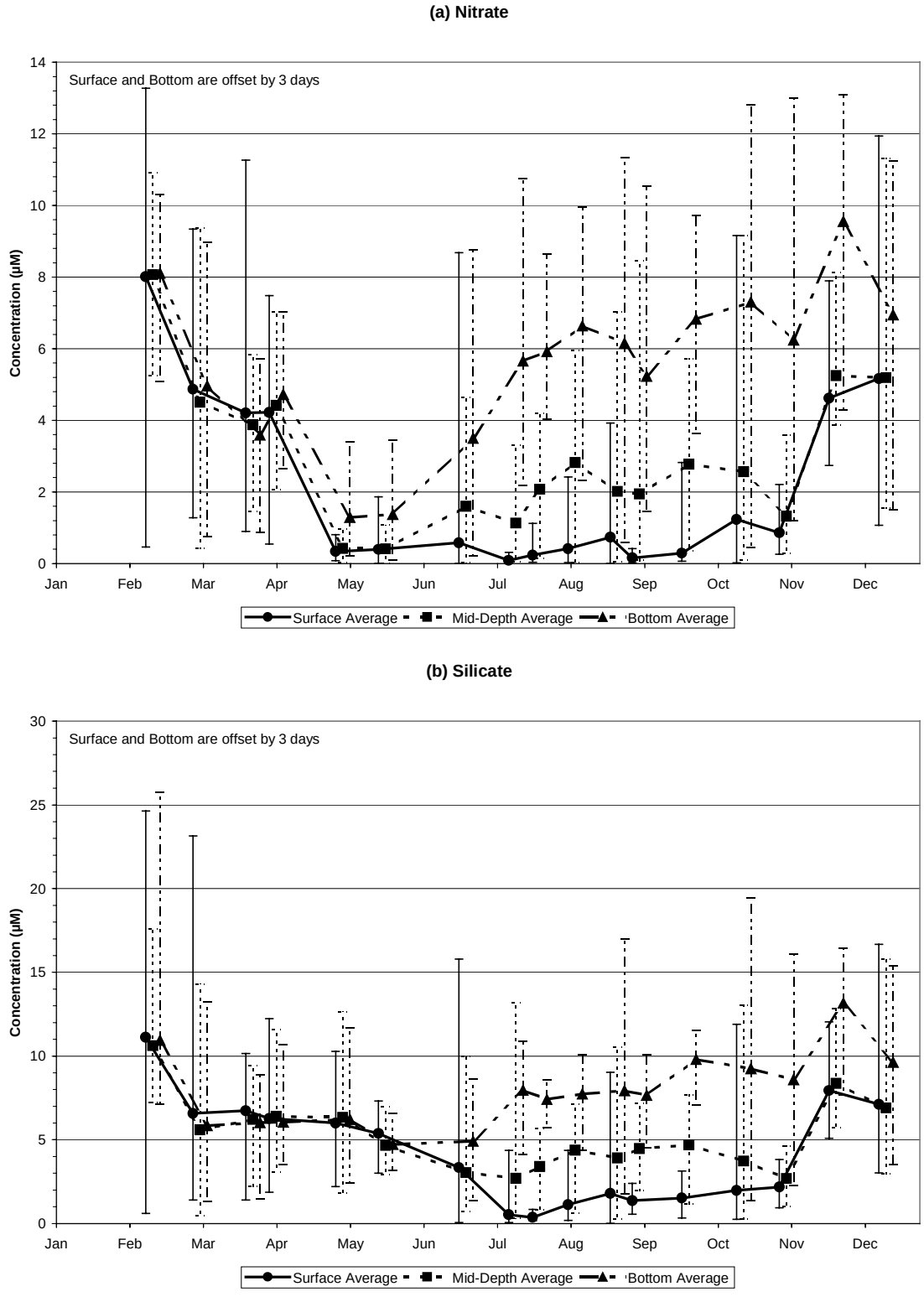


Figure 4-1. 1998 nearfield nutrient cycles for (a) NO_3 and (b) SiO_4. Survey average and range for surface, mid-depth and bottom (A, C and E) samples collected during each nearfield survey. Surface and bottom data offset for clarity.

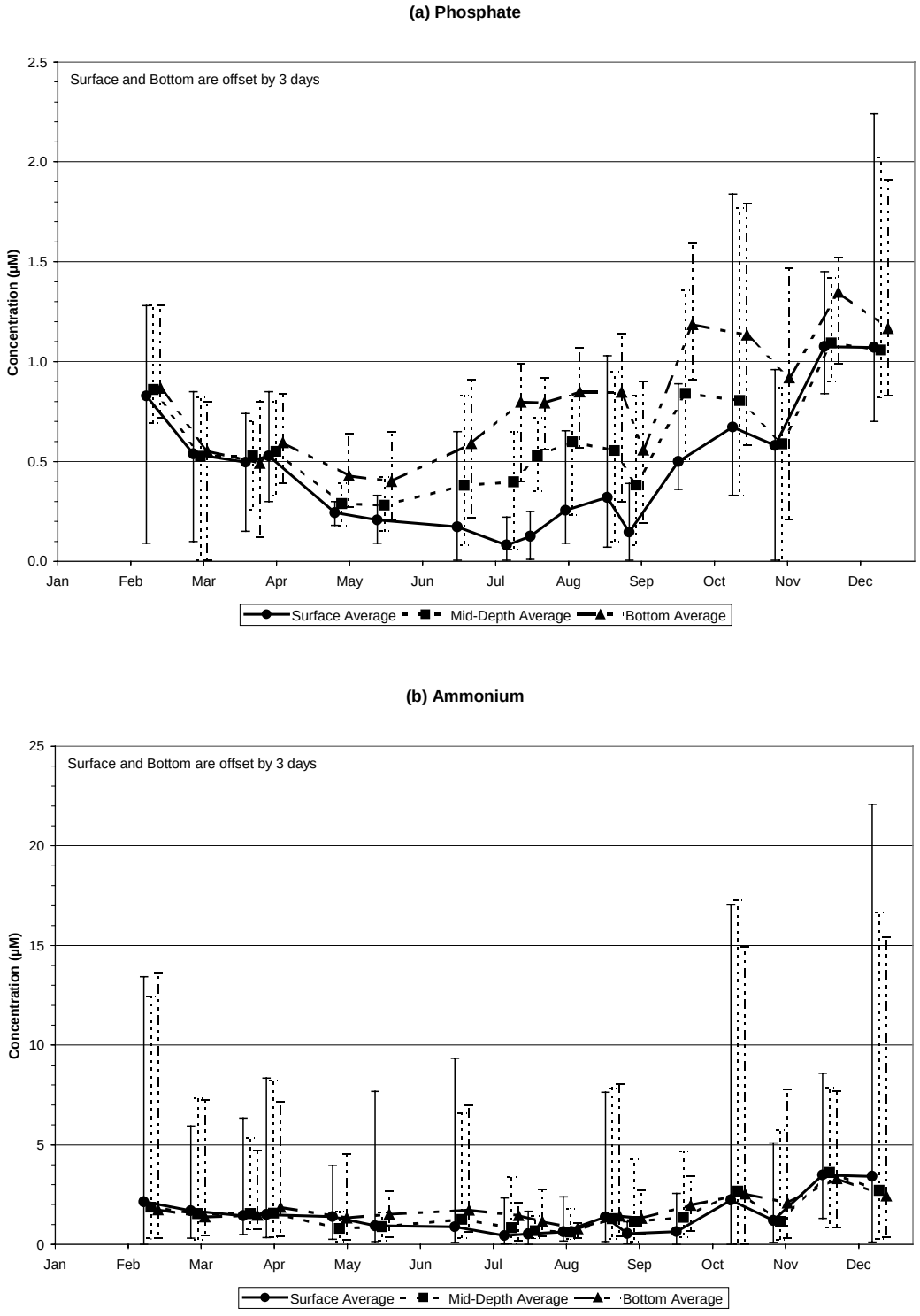


Figure 4-2. 1998 nearfield nutrient cycles for (a) PO_4 and (b) NH_4. Survey average and range for surface, mid-depth and bottom (A, C and E) samples collected during each nearfield survey. Surface and bottom data offset for clarity.

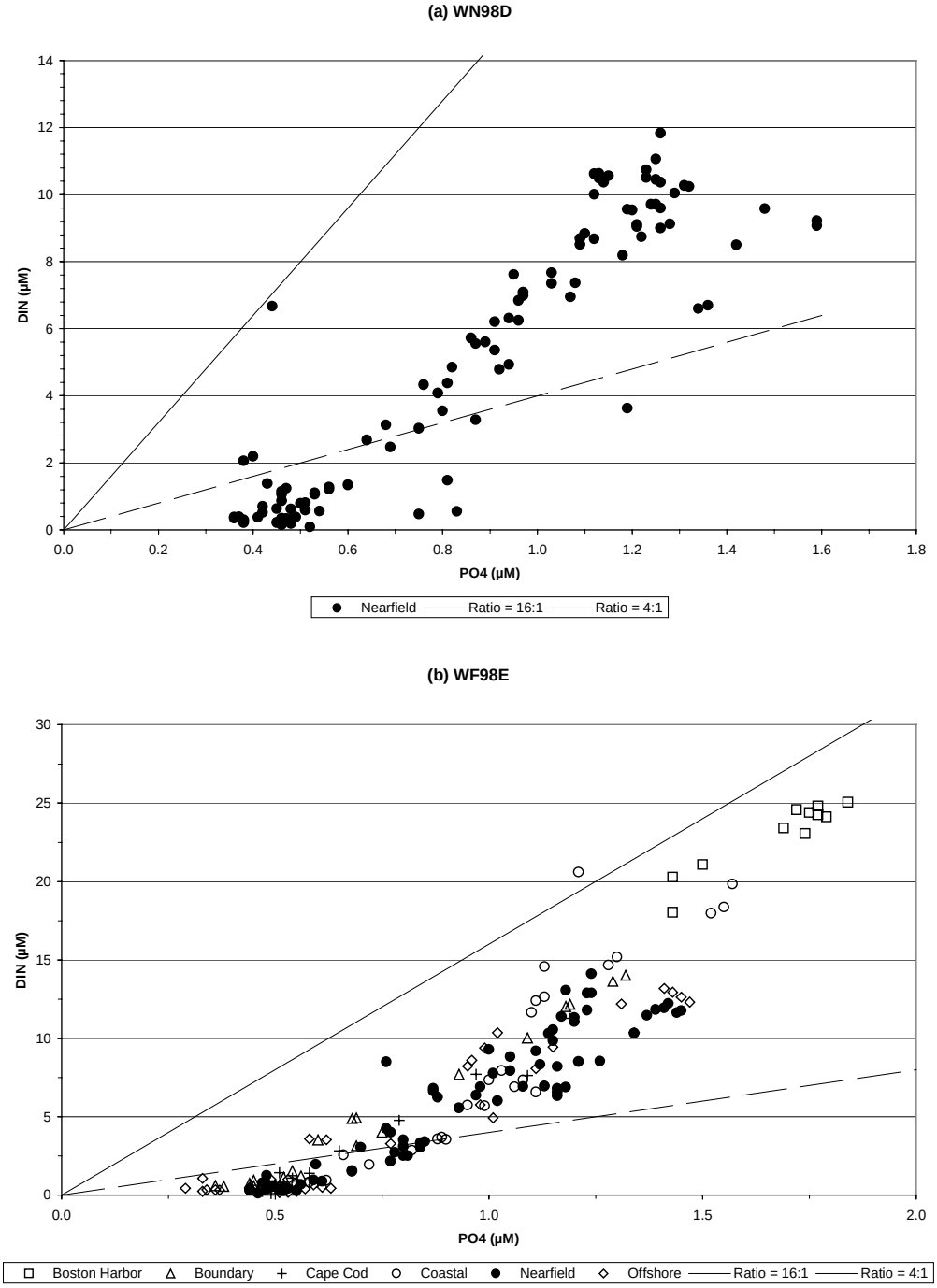


Figure 4-3. DIN vs. phosphate for (a) nearfield survey in late September (WN98D) and (b) farfield survey in October (WF98E).

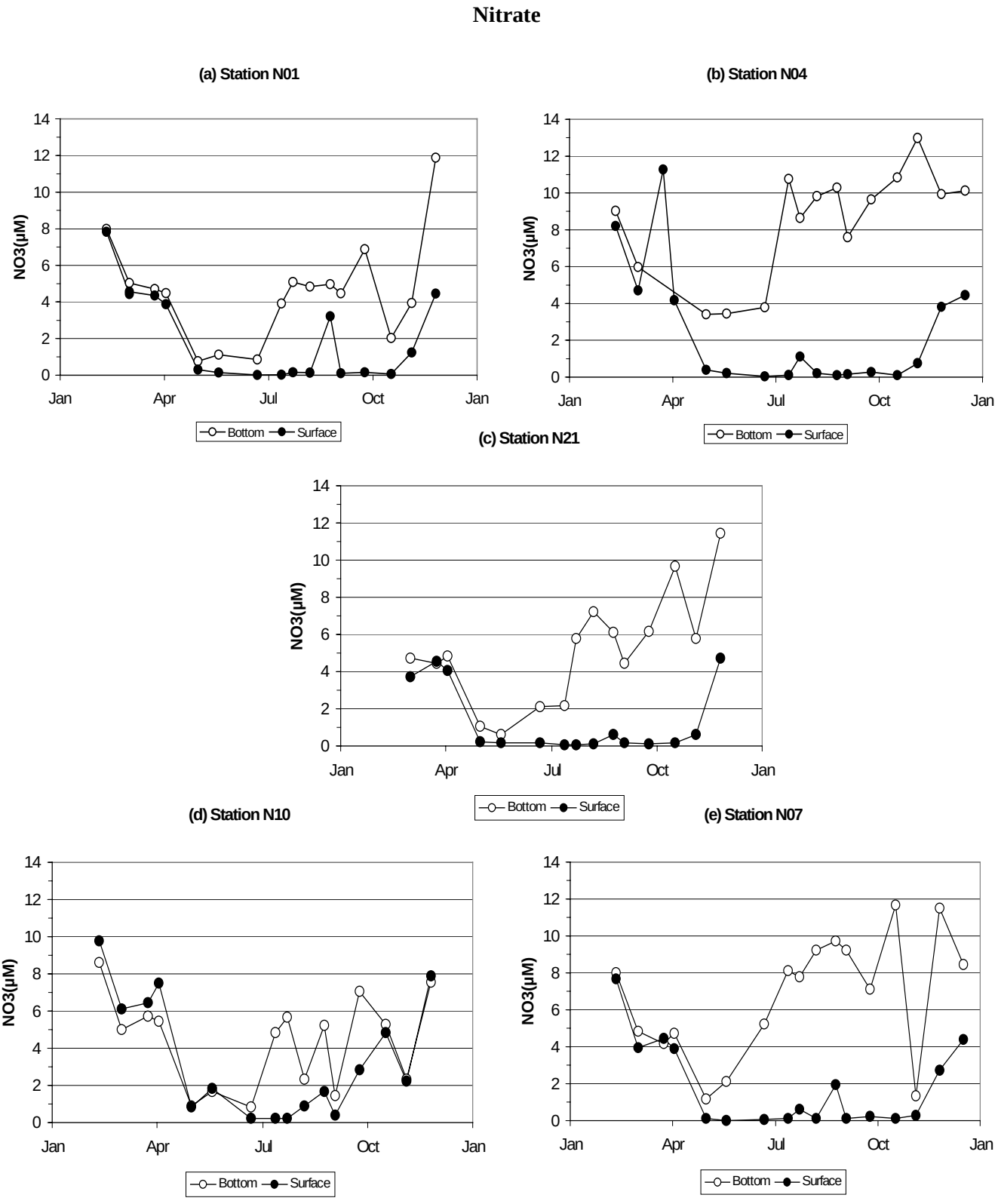


Figure 4-4. Time-series of surface and bottom water NO_3 concentrations for five representative nearfield stations.

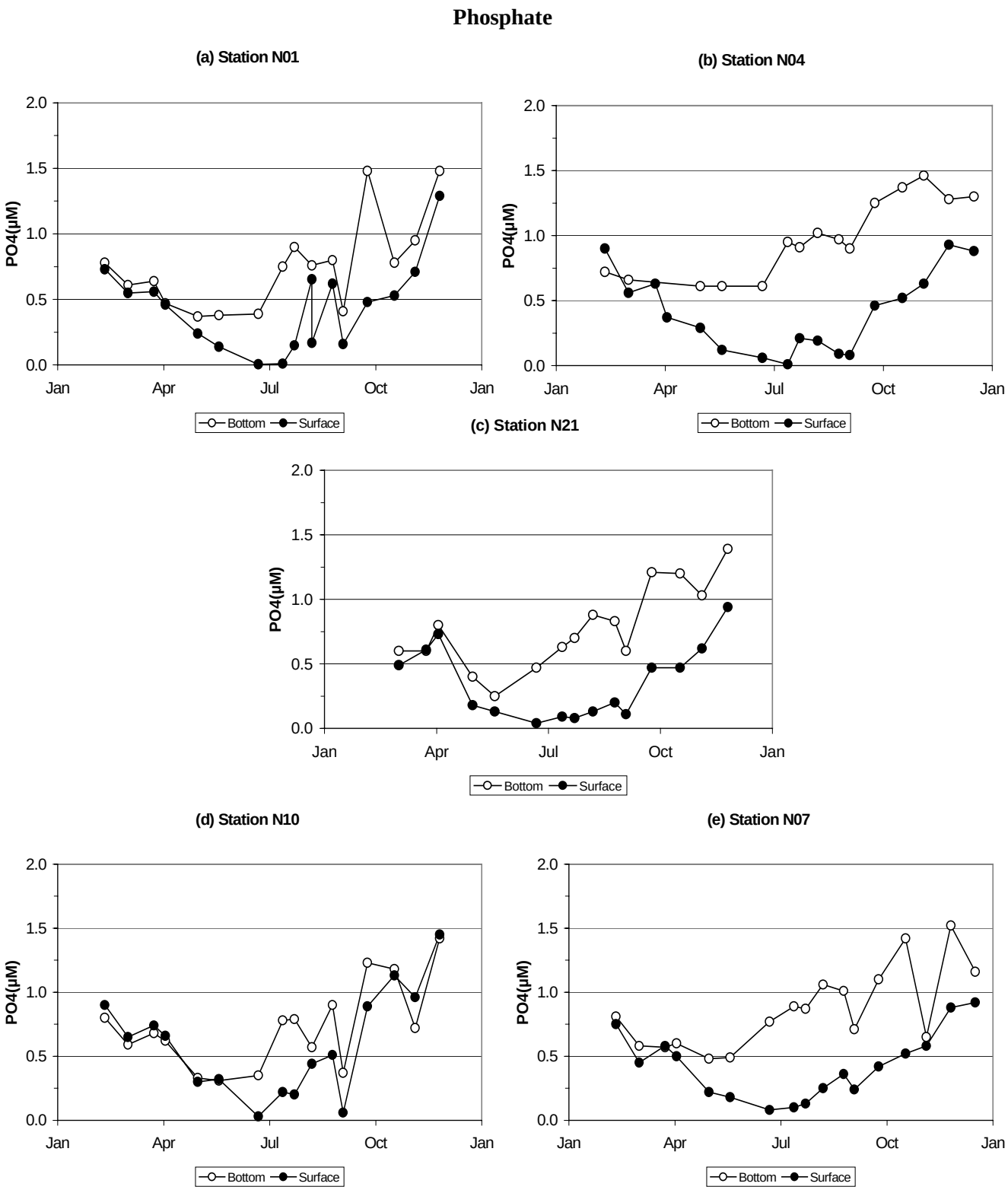


Figure 4-5. Time-series of surface and bottom water PO_4 concentrations for five representative nearfield stations.

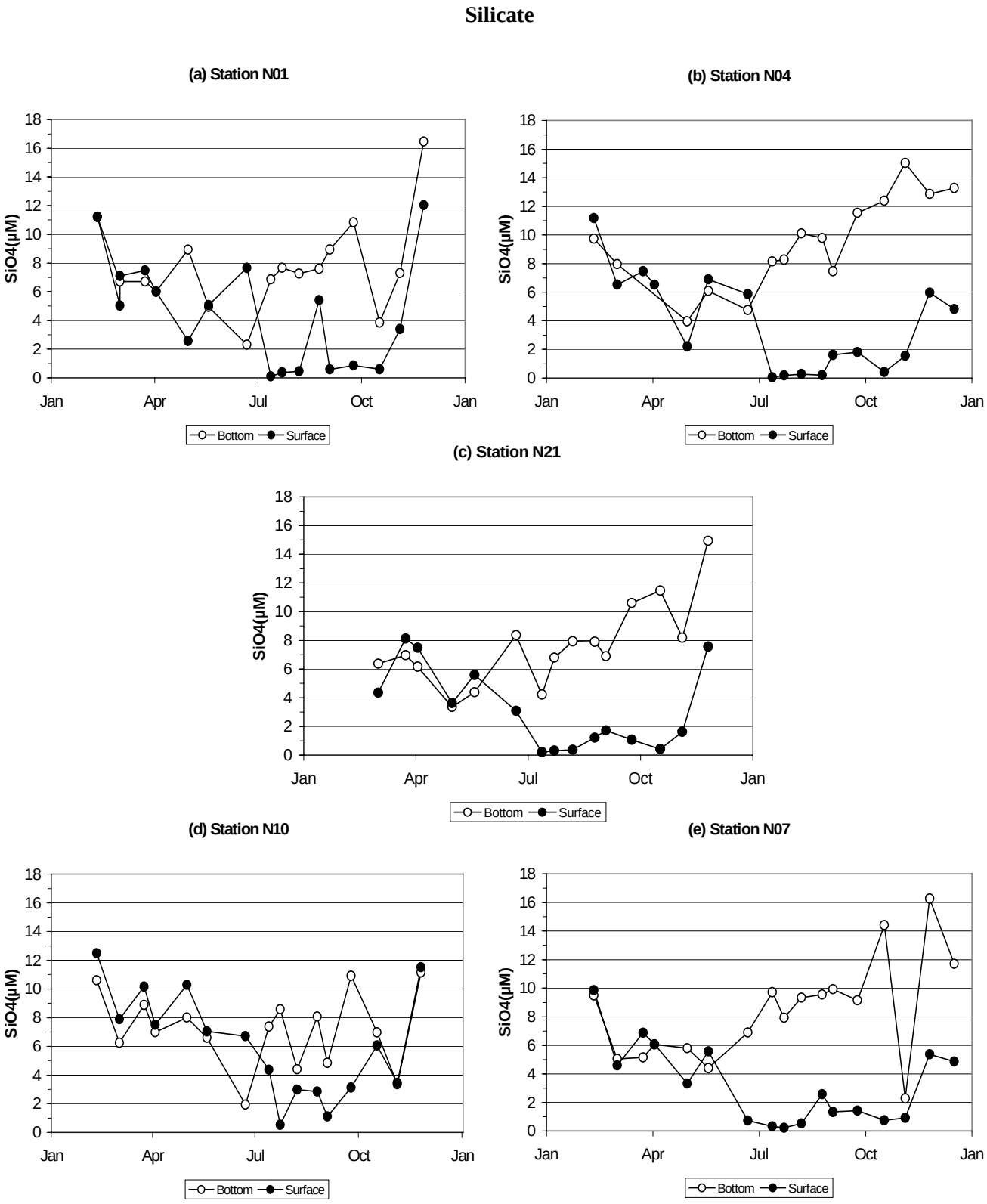


Figure 4-6. Time-series of surface and bottom water SiO_4 concentrations for five representative nearfield stations

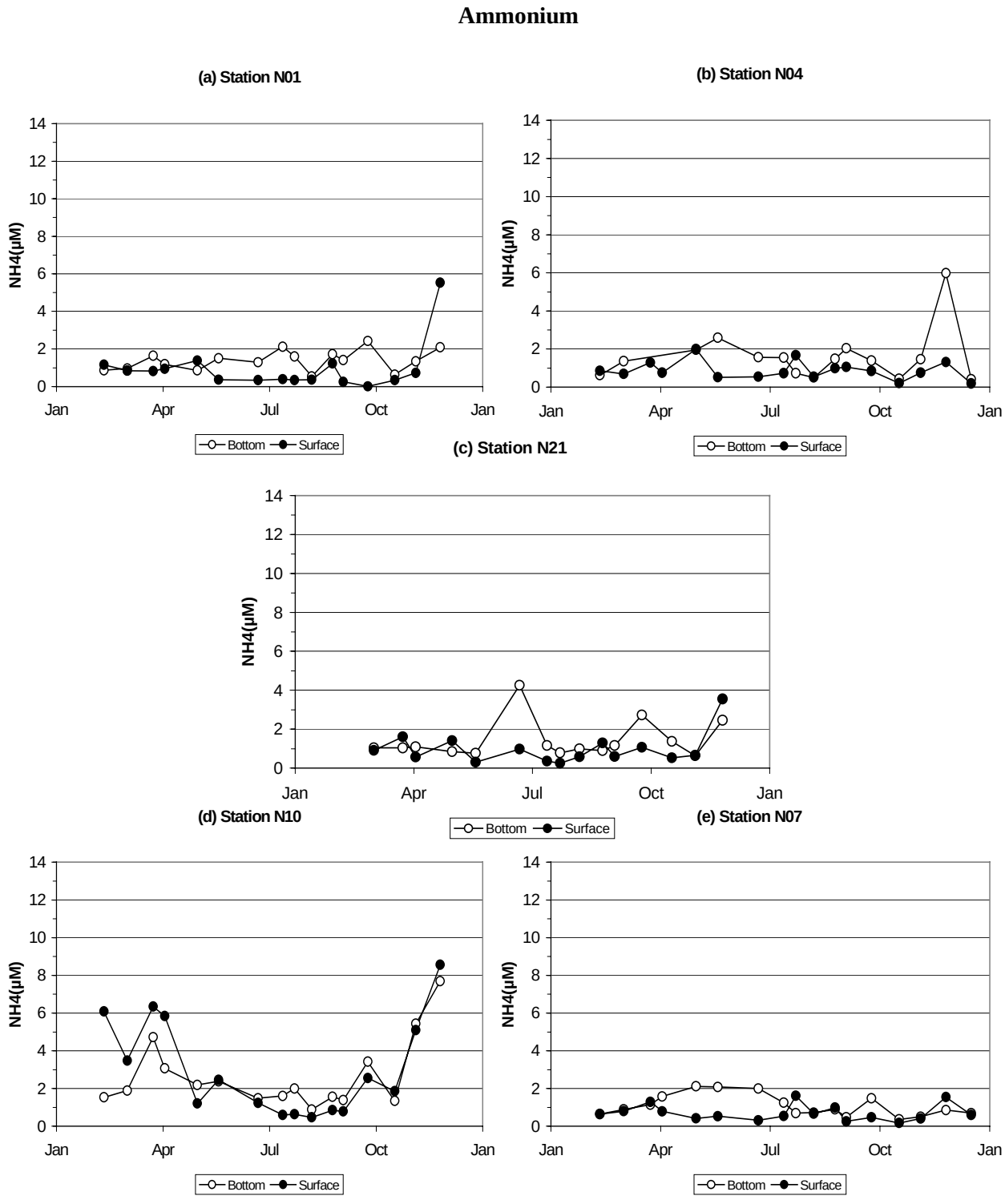


Figure 4-7. Time-series of surface and bottom water NH_4 concentrations for five representative nearfield stations.

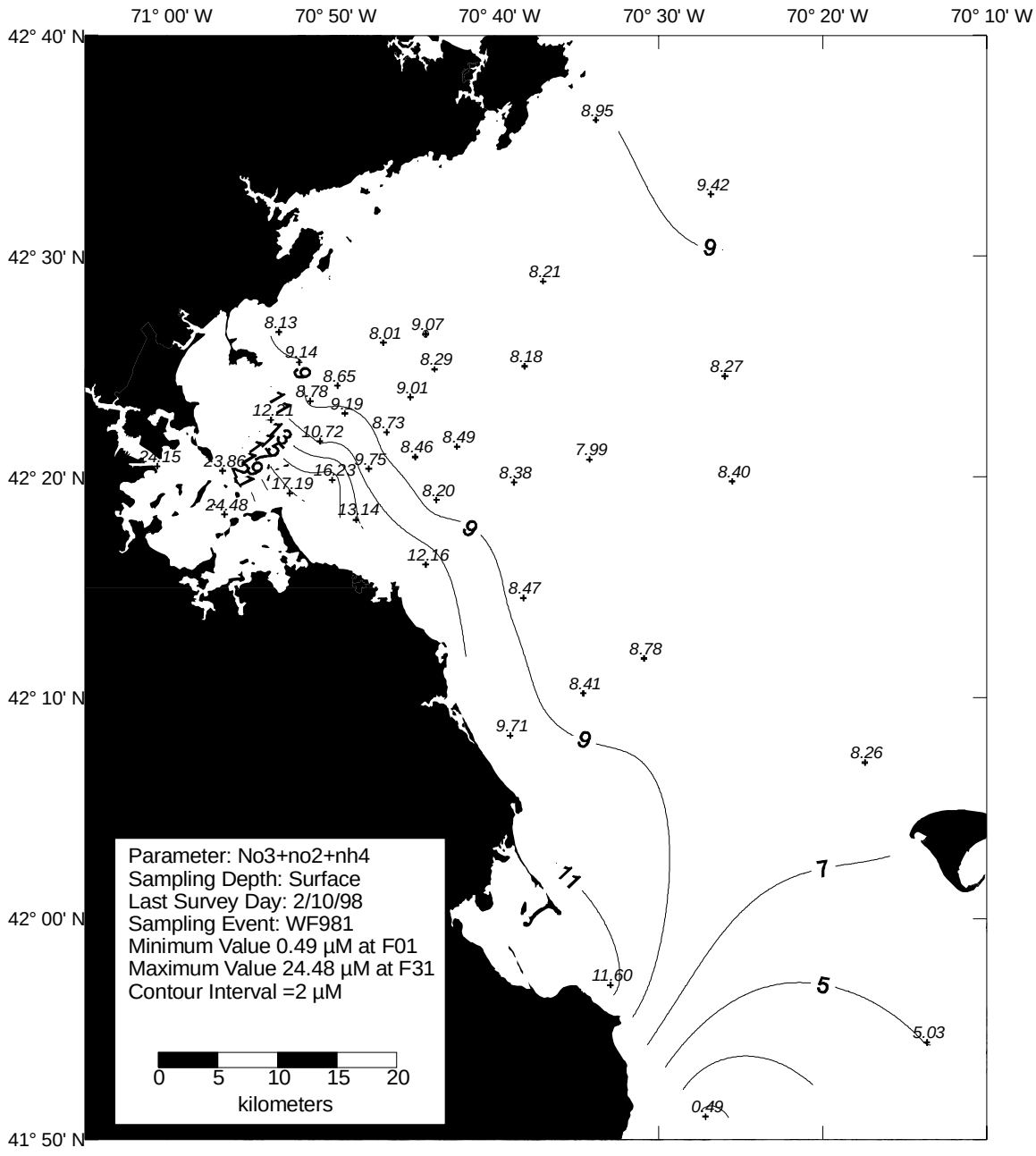


Figure 4-8. Surface contour of DIN for farfield survey WF981 (February 98).

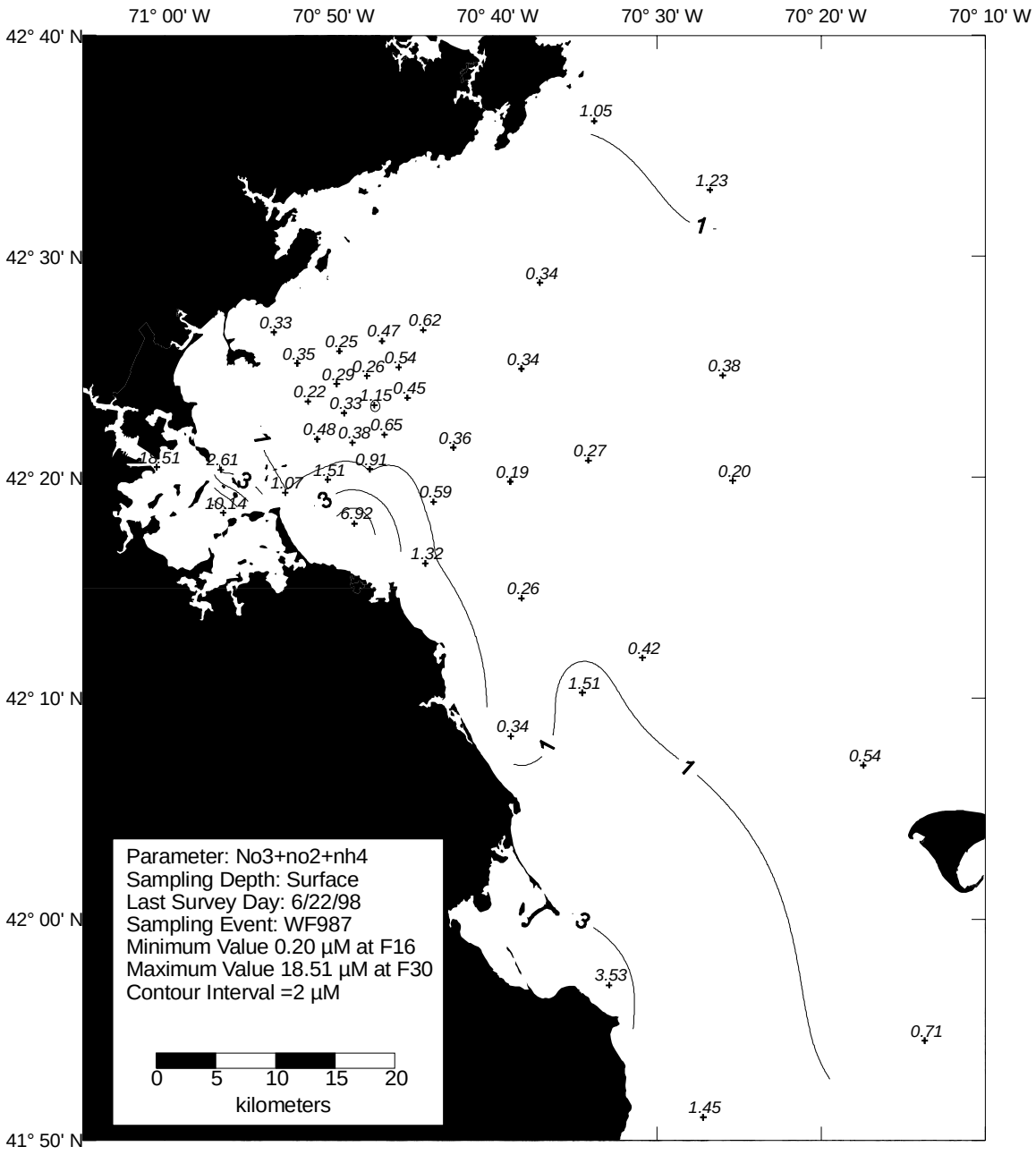


Figure 4-9. Surface contour of DIN for farfield survey WF987 (June 98).

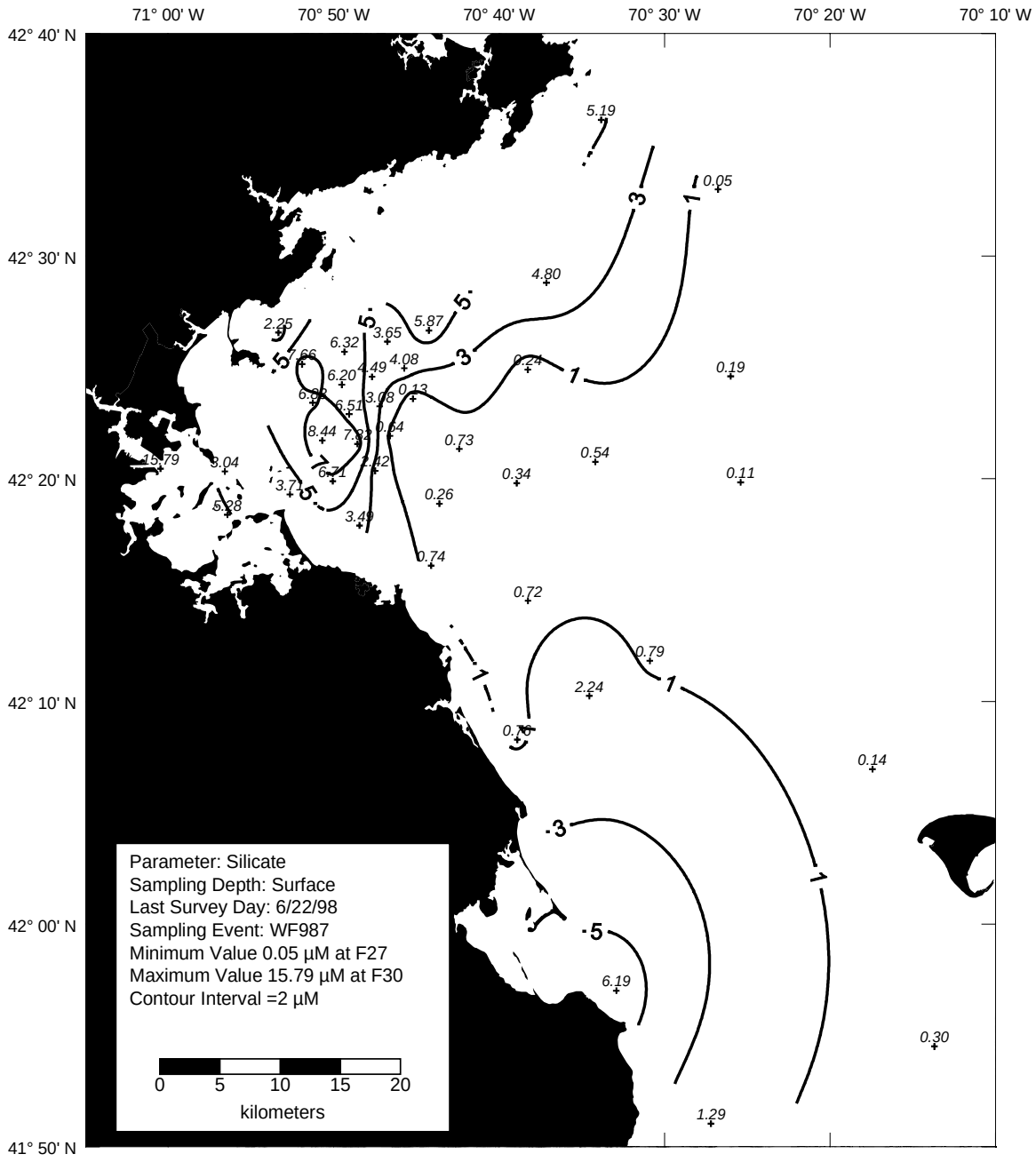


Figure 4-10. Silicate surface contour plot for farfield survey WF987 (June 98).

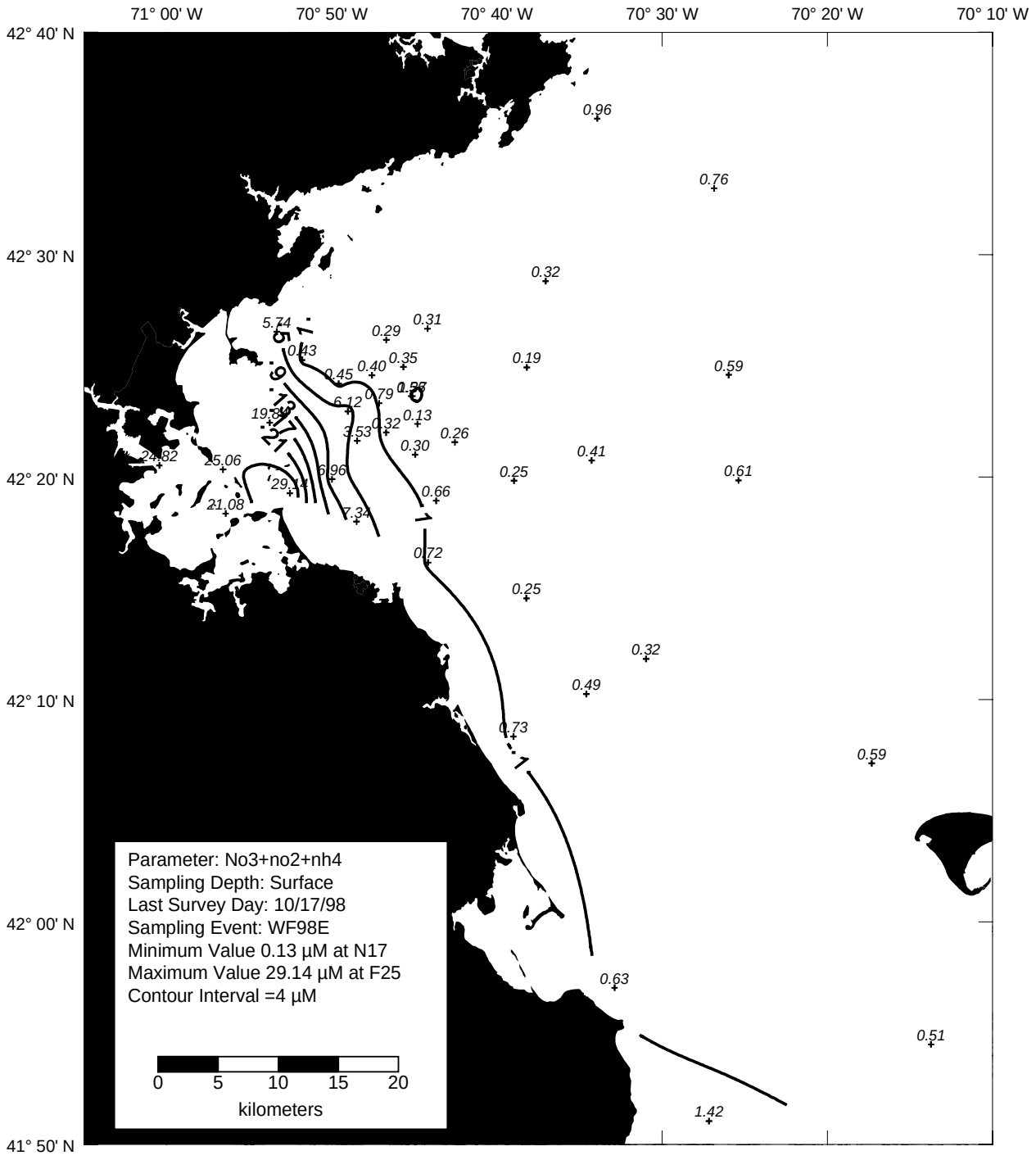


Figure 4-11. Surface contour of DIN for farfield survey WF98E (October 98).

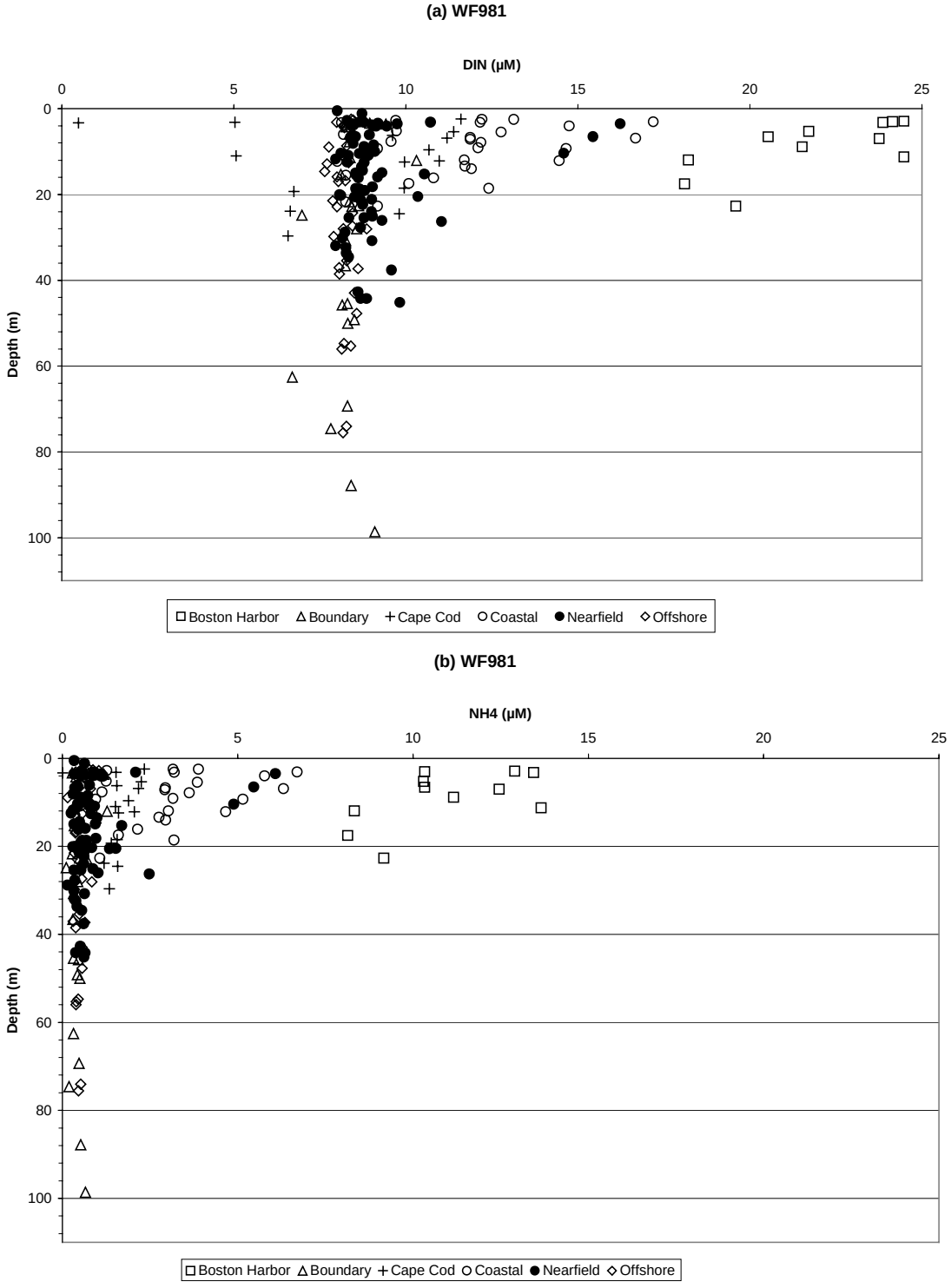


Figure 4-12. Depth vs. (a) DIN and (b) NH_4 for farfield survey WF981 (February 98).

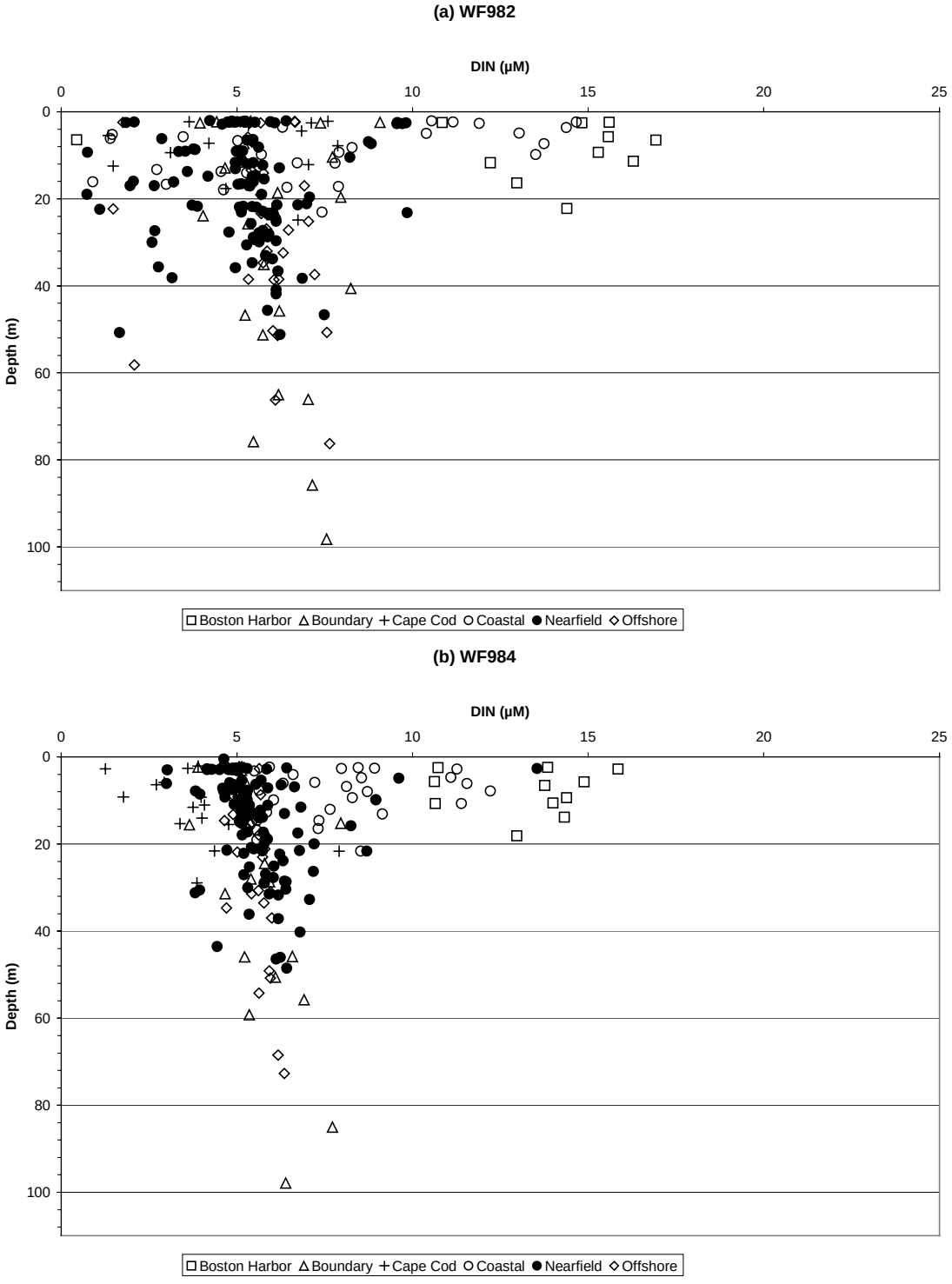


Figure 4-13. Depth vs. DIN for farfield surveys (a) WF982 (Feb 98) and (b) WF984 (April 98).

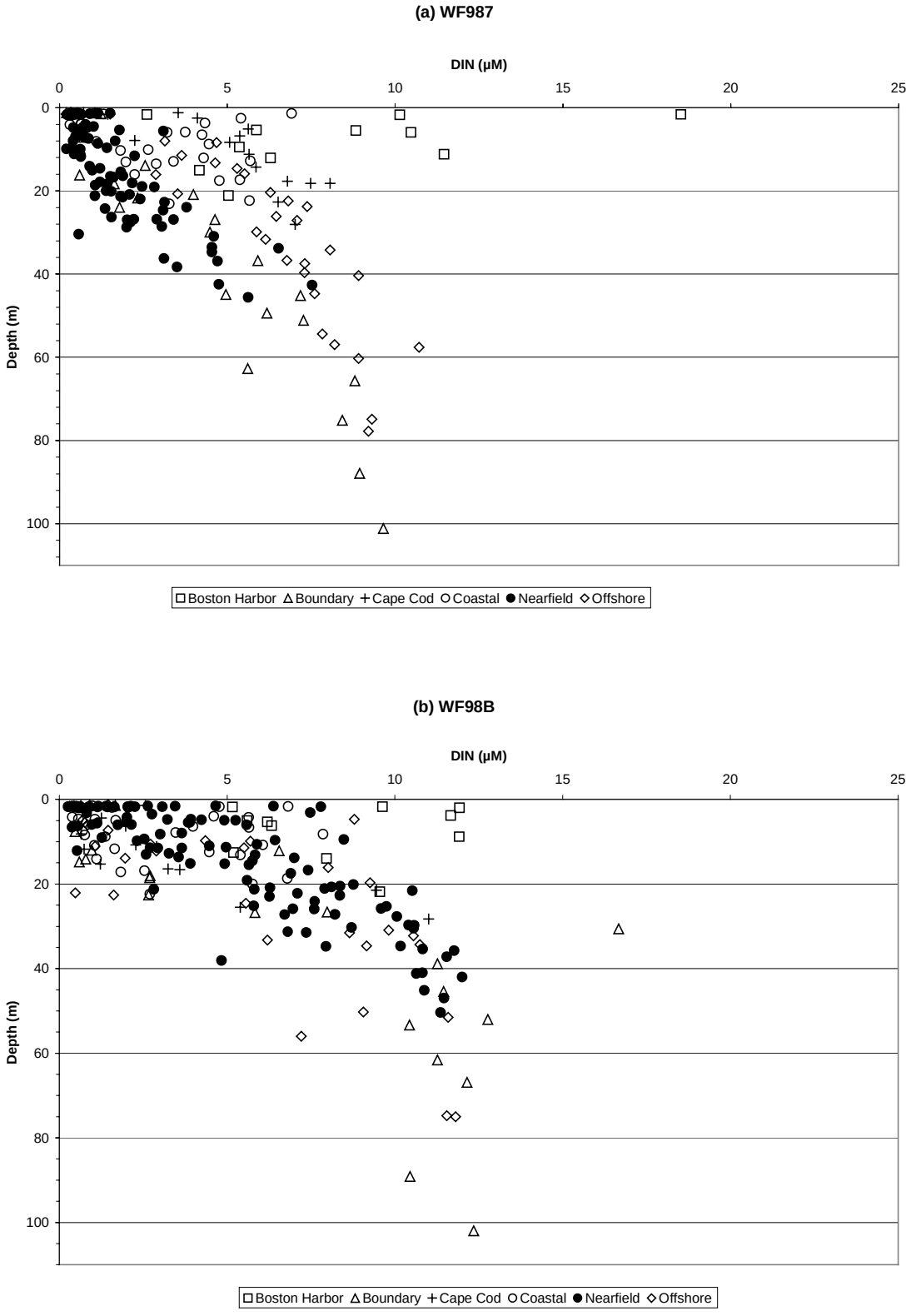


Figure 4-14. Depth vs. DIN for farfield surveys (a) WF987 (June 98) and (b) WF98B (August 98).

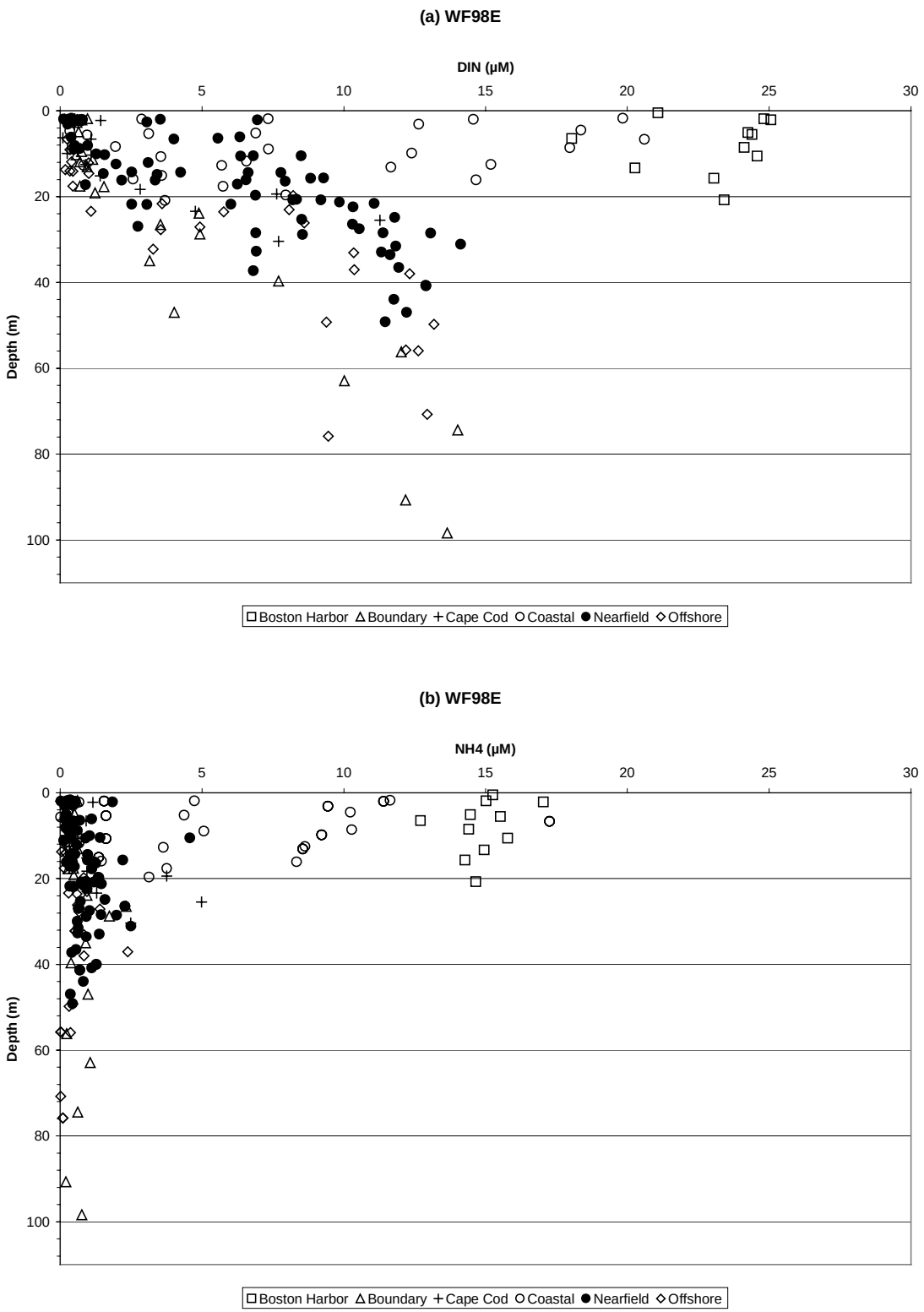


Figure 4-15. Depth vs. (a) DIN and (b) NH_4 for farfield survey WF98E (October 98).

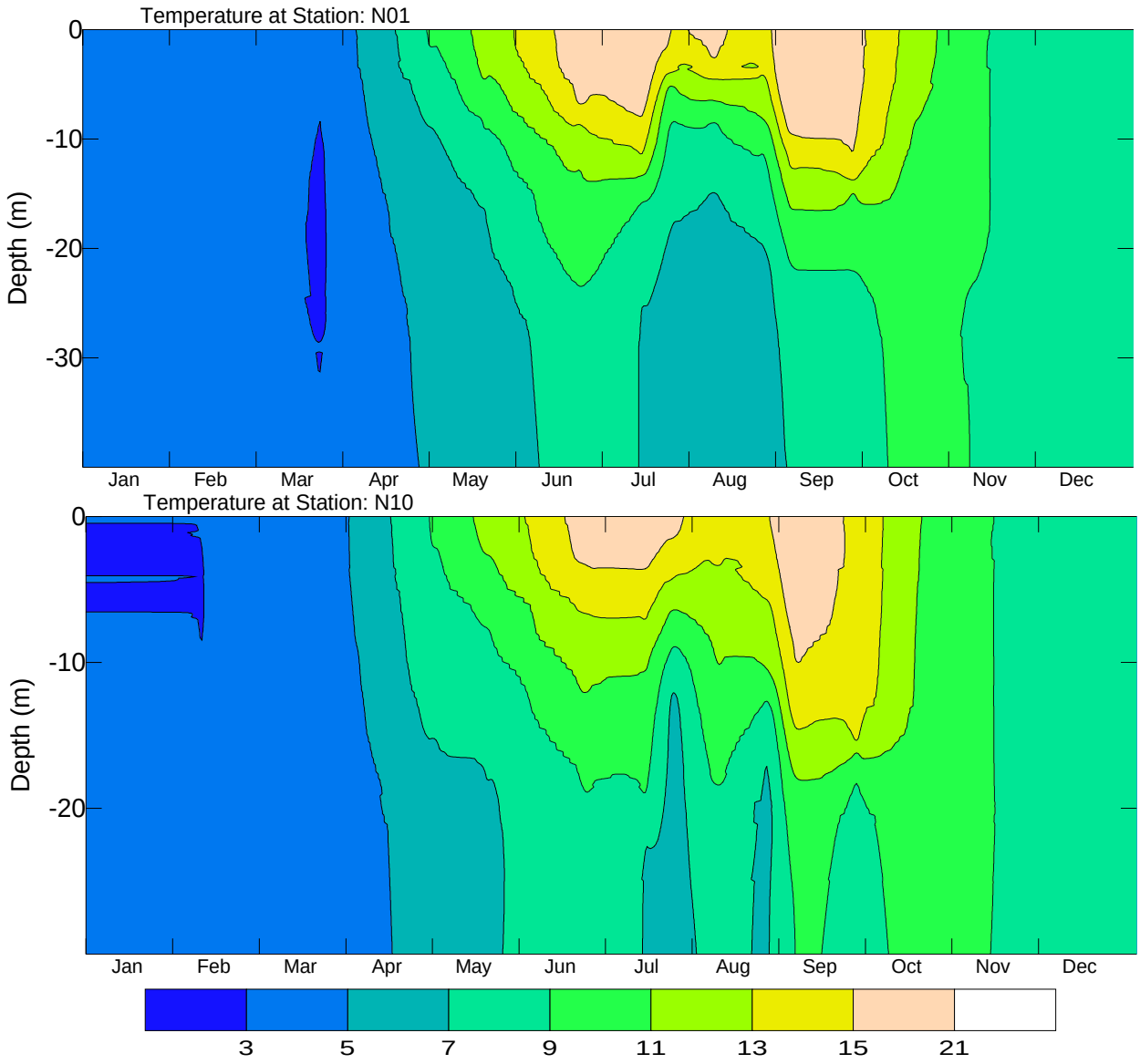


Figure 4-16. Contours of temperature over depth for 1998 at stations N01 and N10.

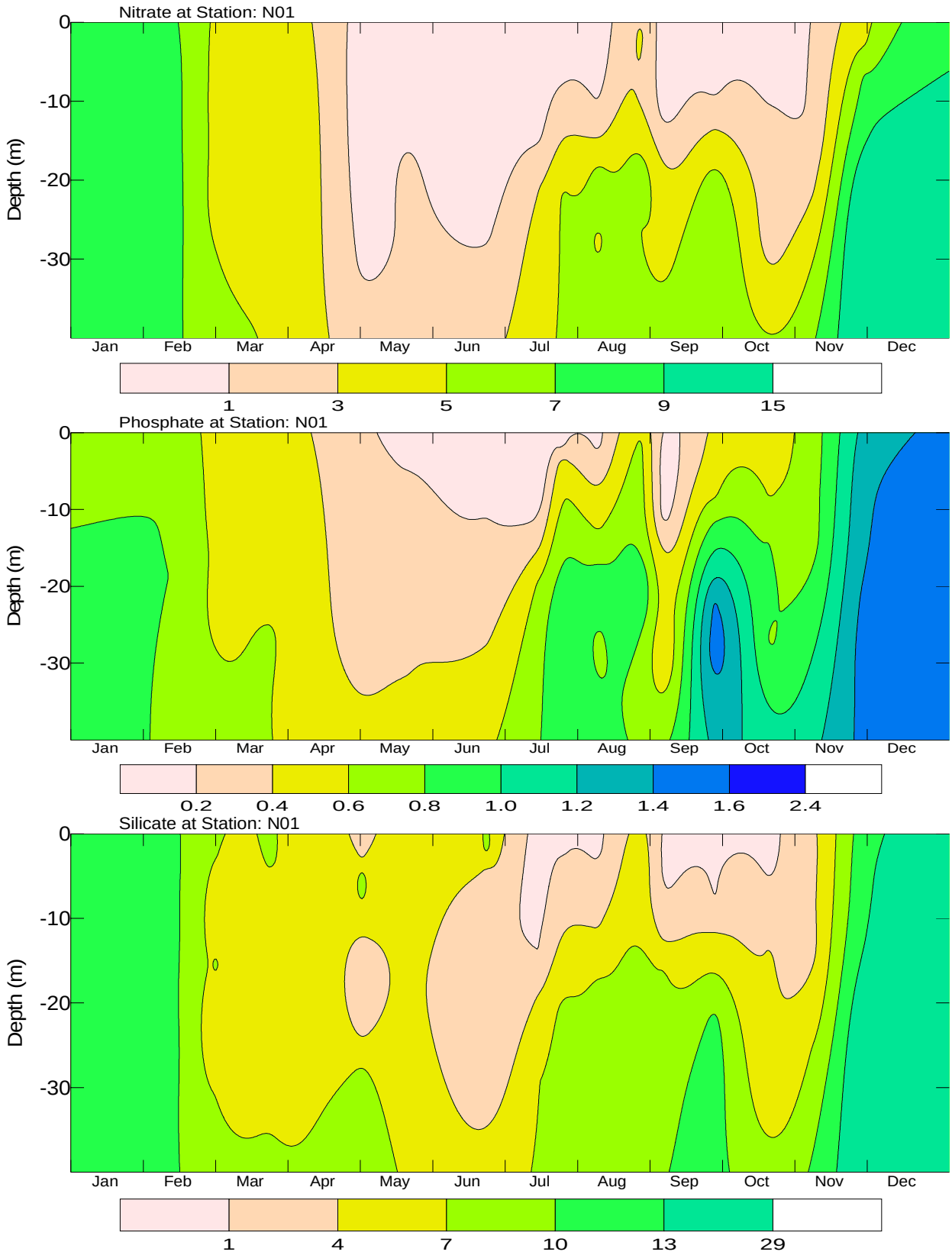


Figure 4-17. Contours of NO_3, PO_4, and SiO_4 over depth for 1998 at station N01.

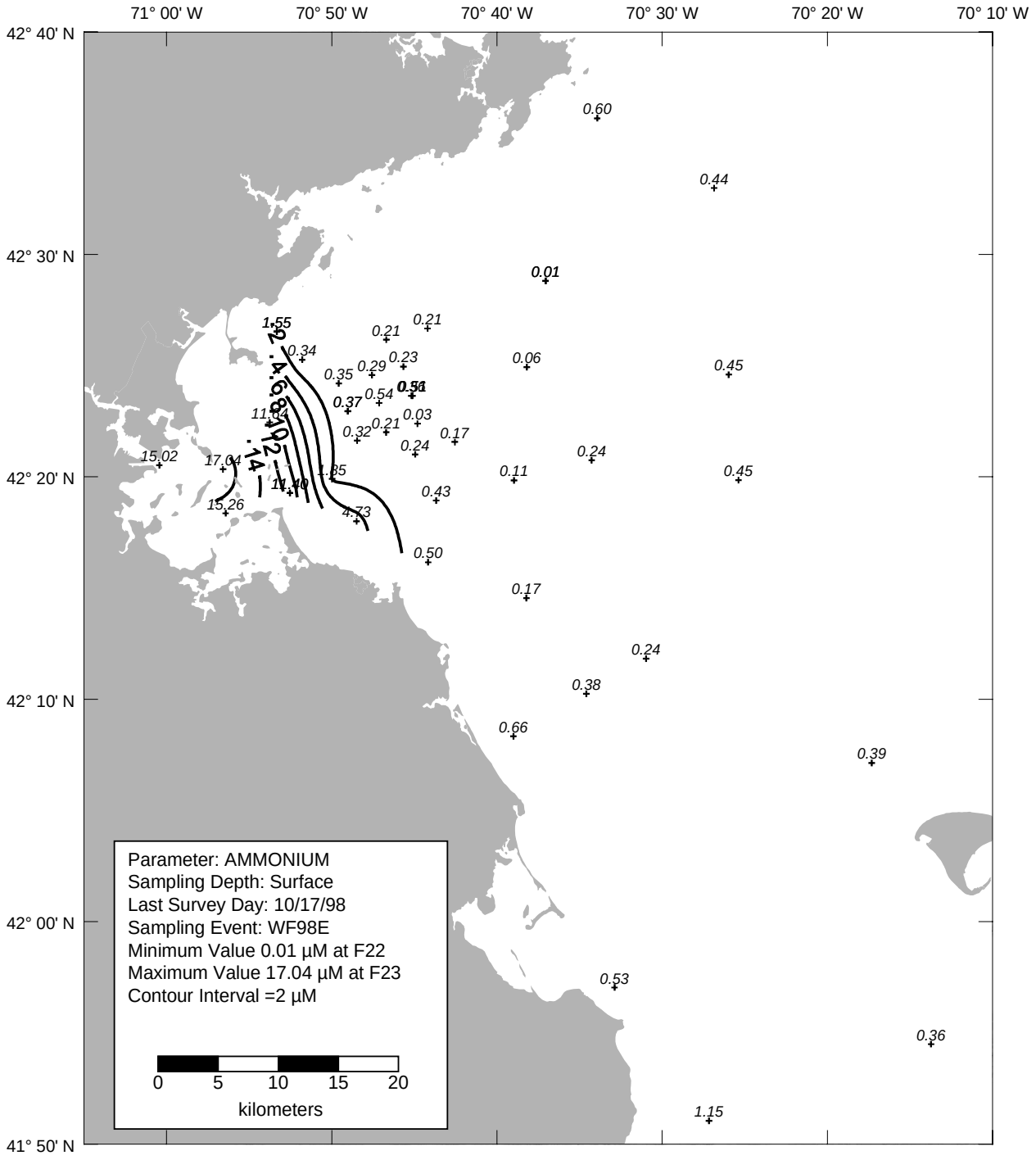
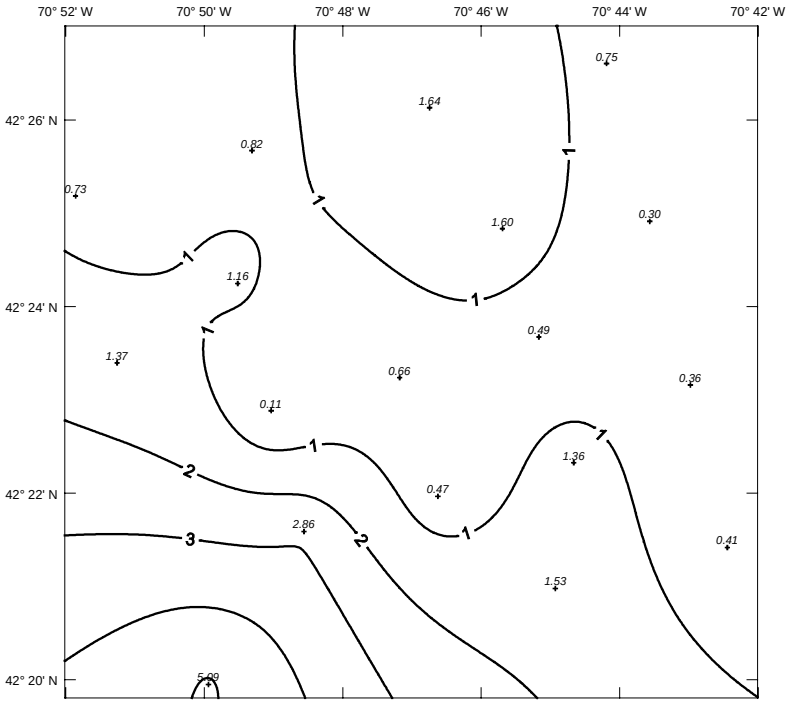


Figure 4-18. Surface contour of NH_4 for farfield survey WF98E (October 98).

(a) WN98F



(b) WN98G

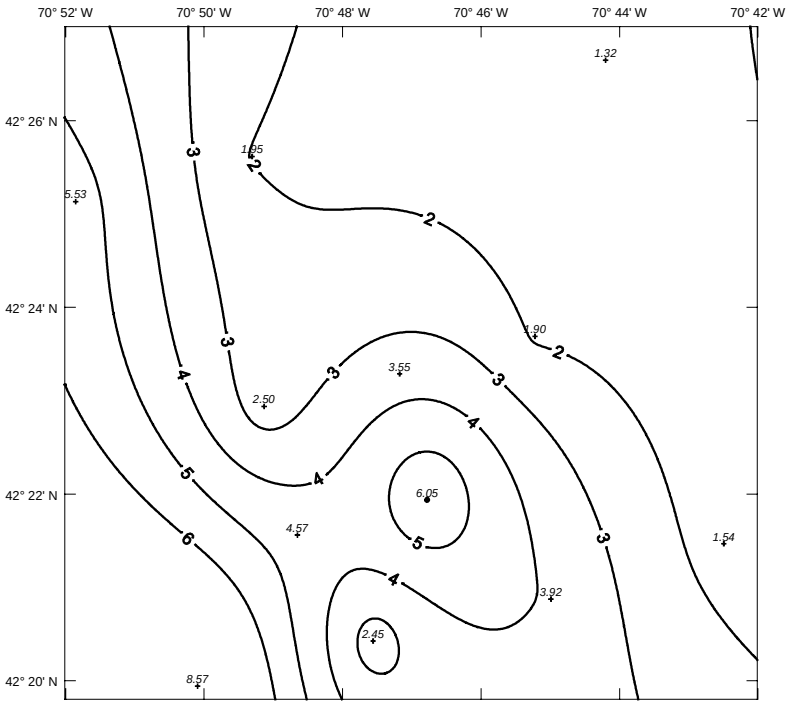


Figure 4-19. Surface contour of NH_4 for nearfield surveys (a) WN98F and (b) WN98G (Nov 98).

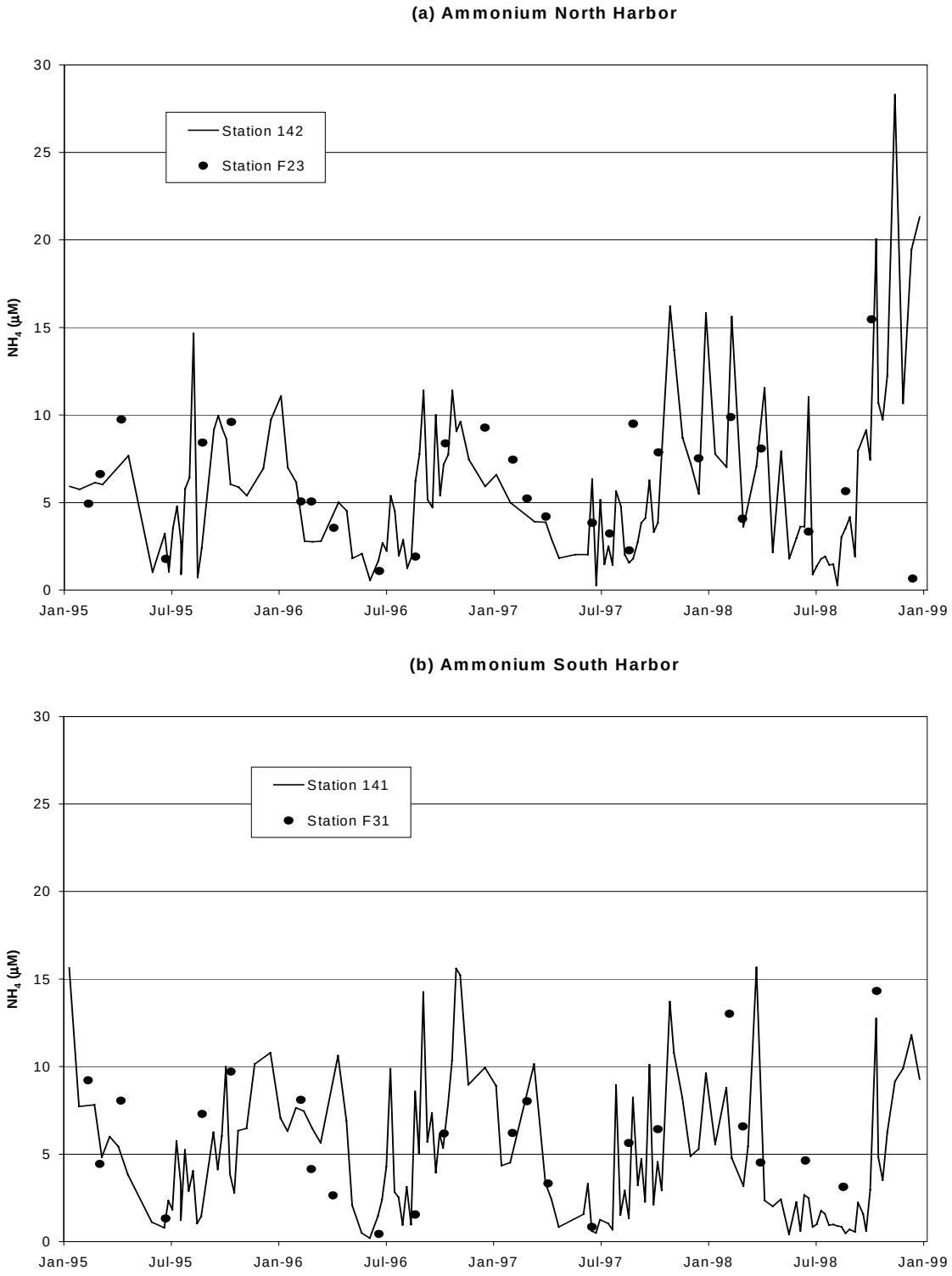


Figure 4-20. Time-series of NH_4 in (a) North Boston Harbor at stations 142 (MWRA) and F23 and (b) South Boston Harbor at stations 141 (MWRA) and F31. Average of all depths sampled.

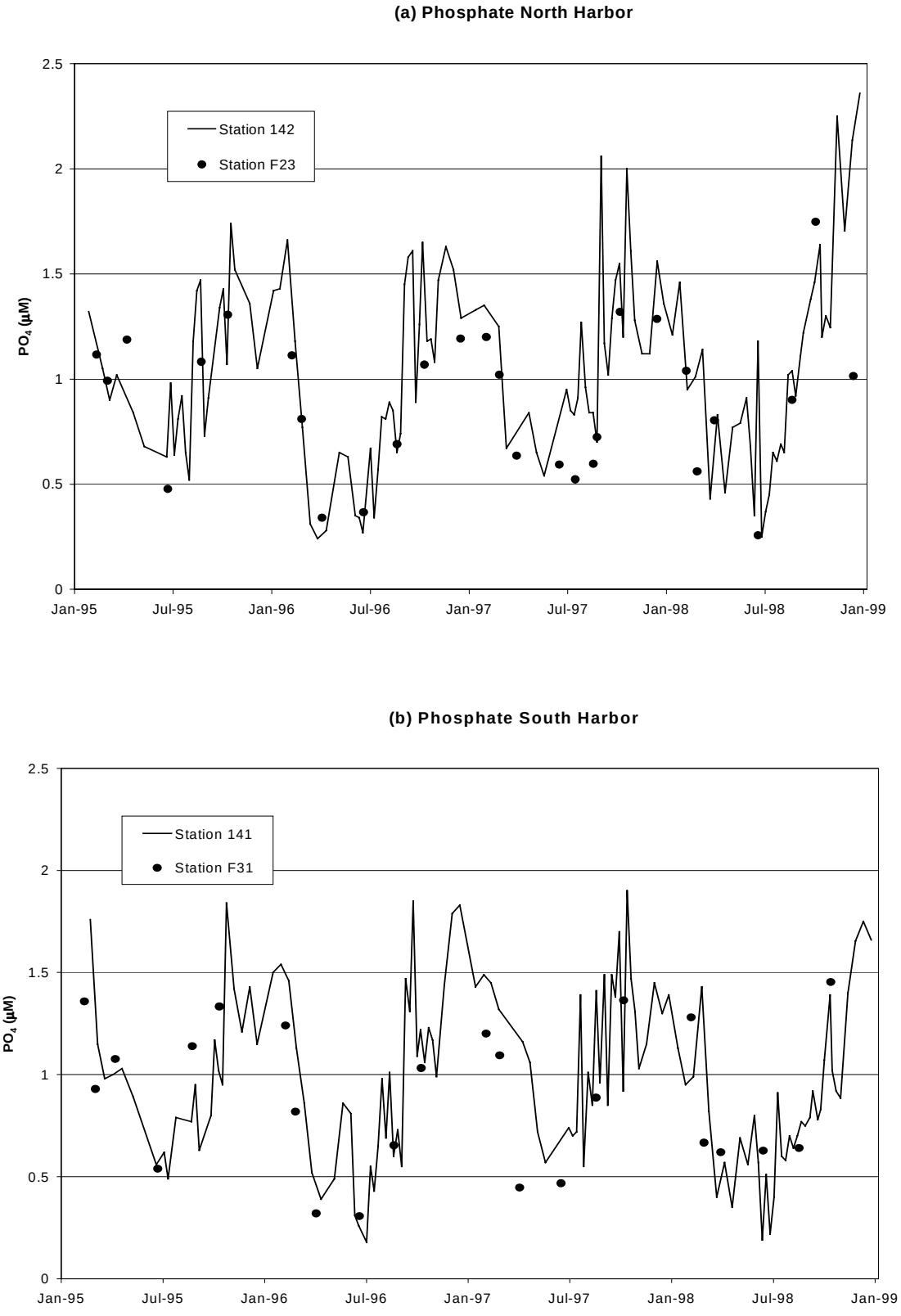


Figure 4-21. Time-series of PO_4 in (a) North Boston Harbor at stations 142 (MWRA) and F23 and (b) South Boston Harbor at stations 141 (MWRA) and F31. Average of all depths sampled.

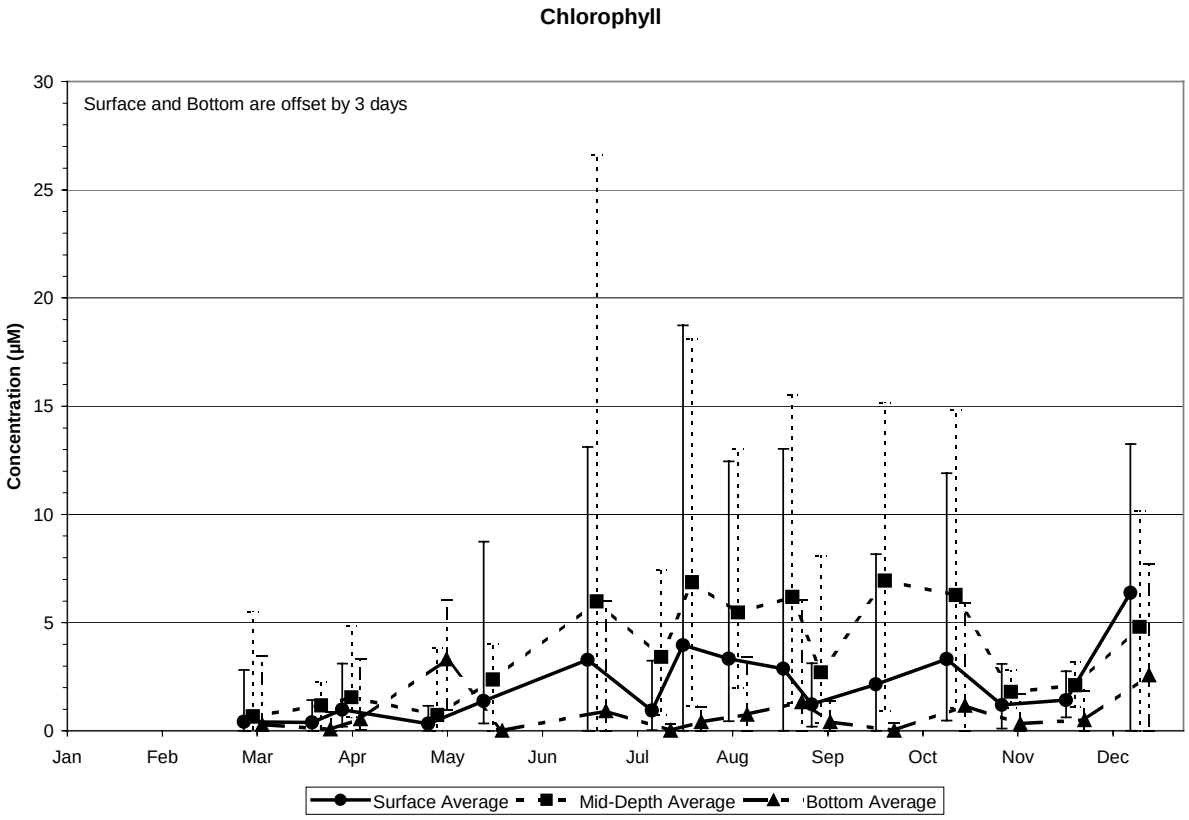


Figure 4-22. 1998 nearfield chlorophyll cycle for the nearfield. Survey average and range for surface, mid-depth and bottom samples collected during each nearfield survey.

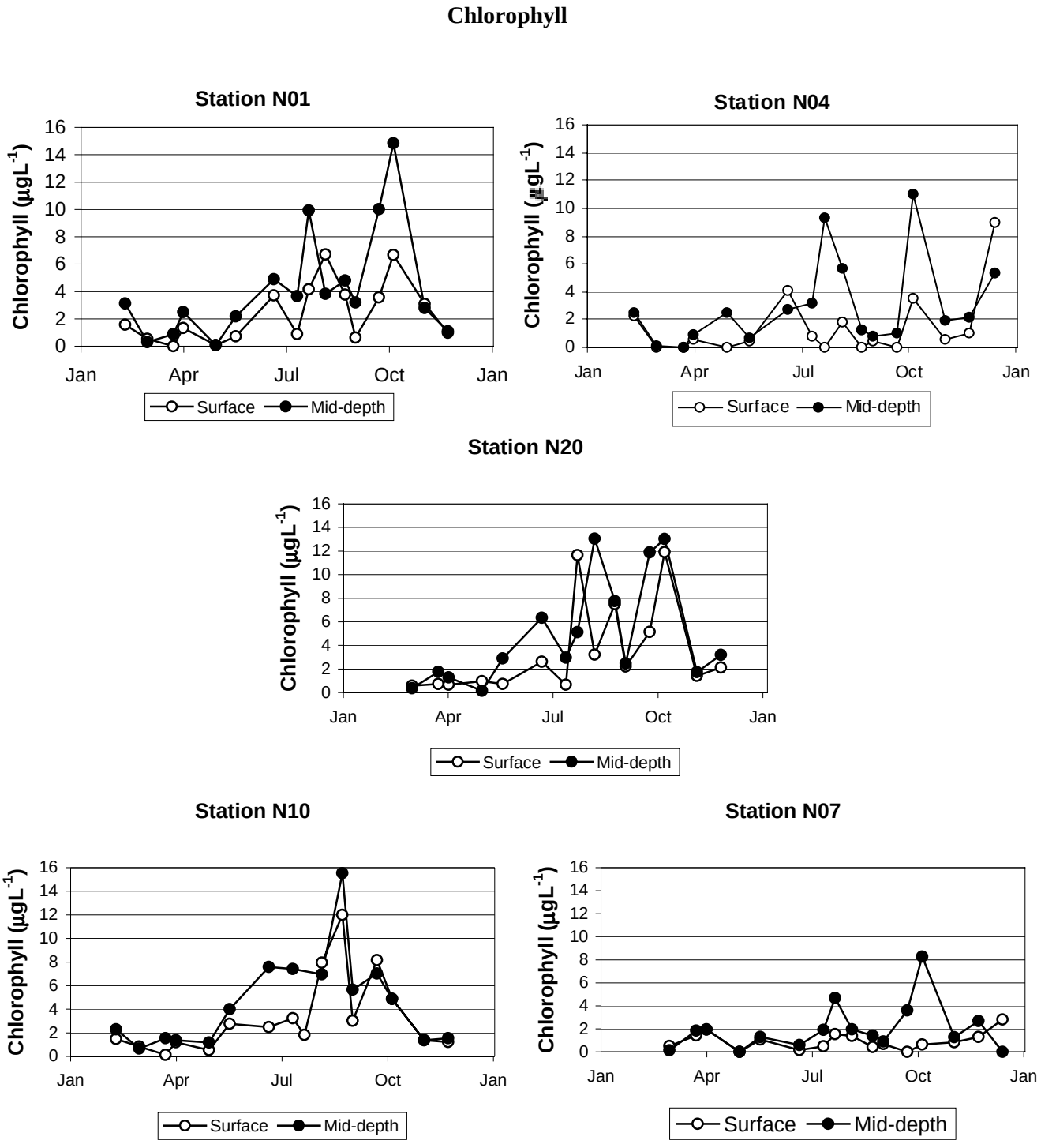


Figure 4-23. Time-series of surface and mid-depth chlorophyll concentrations for five representative nearfield stations.

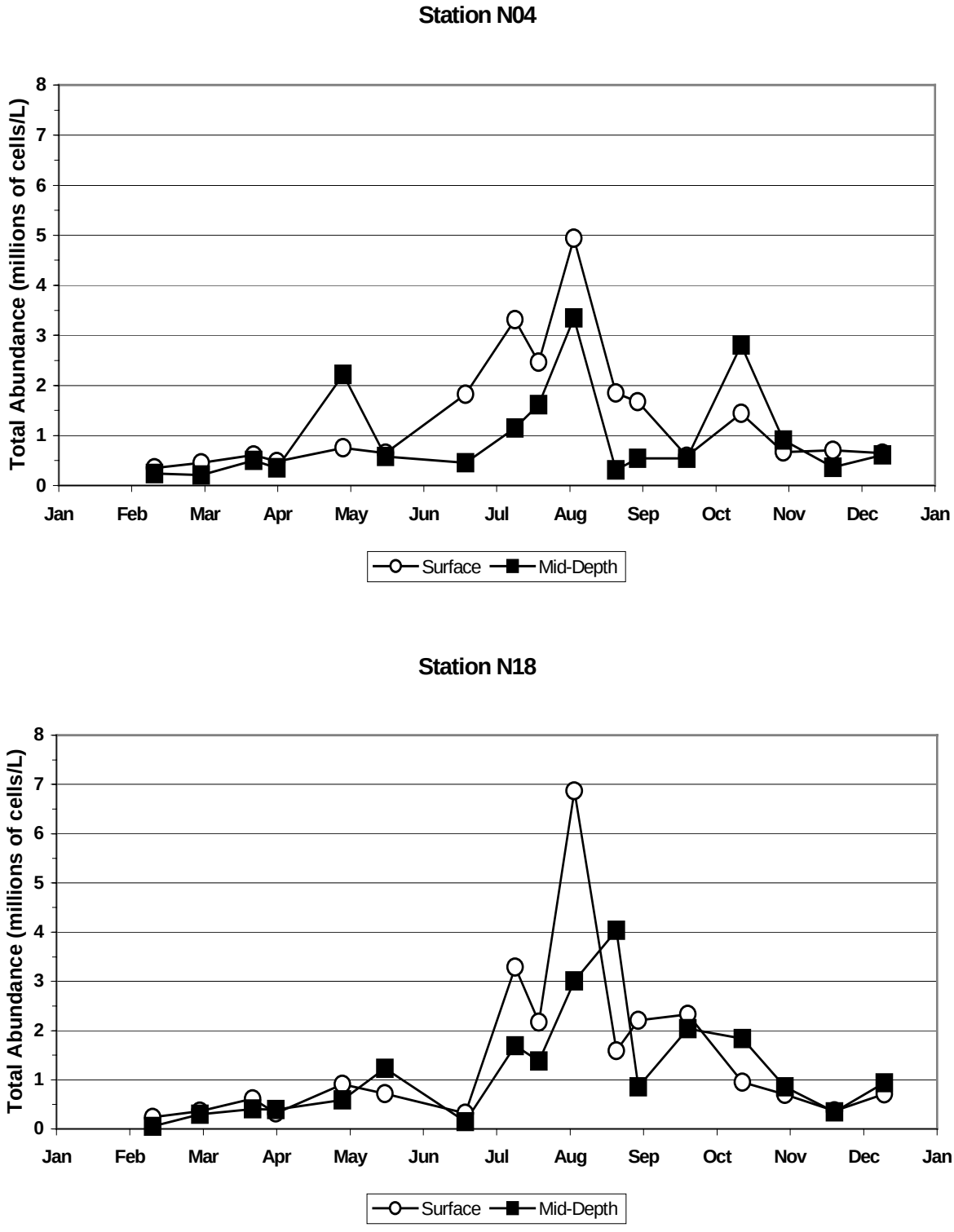


Figure 4-24. Time-series of total phytoplankton abundance at nearfield stations N04 and N18 for surface and mid-depth samples.

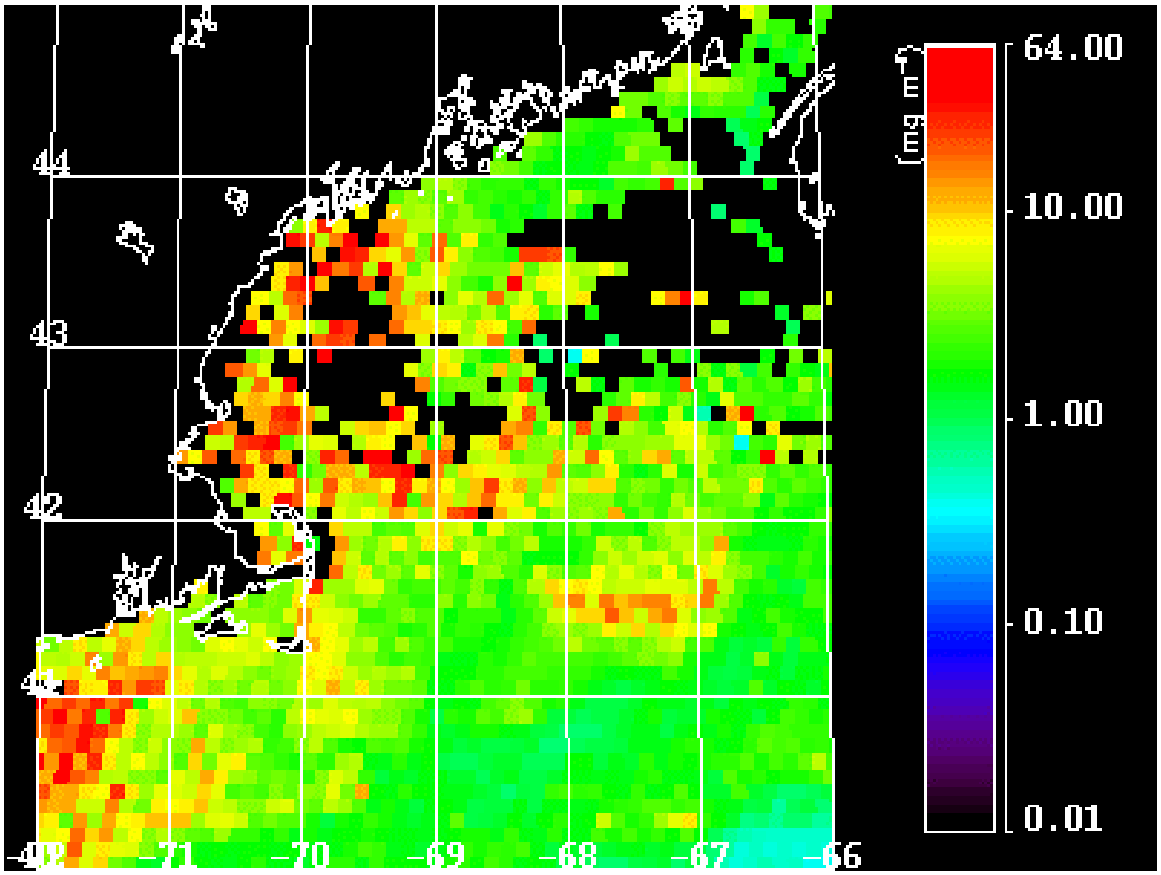


Figure 4-25. Satellite image of average chlorophyll *a* concentrations from December 3, 1998 to December 10, 1998. Data displayed on a log scale and uncorrected (high values are up to 4x higher than observed *in situ* data).

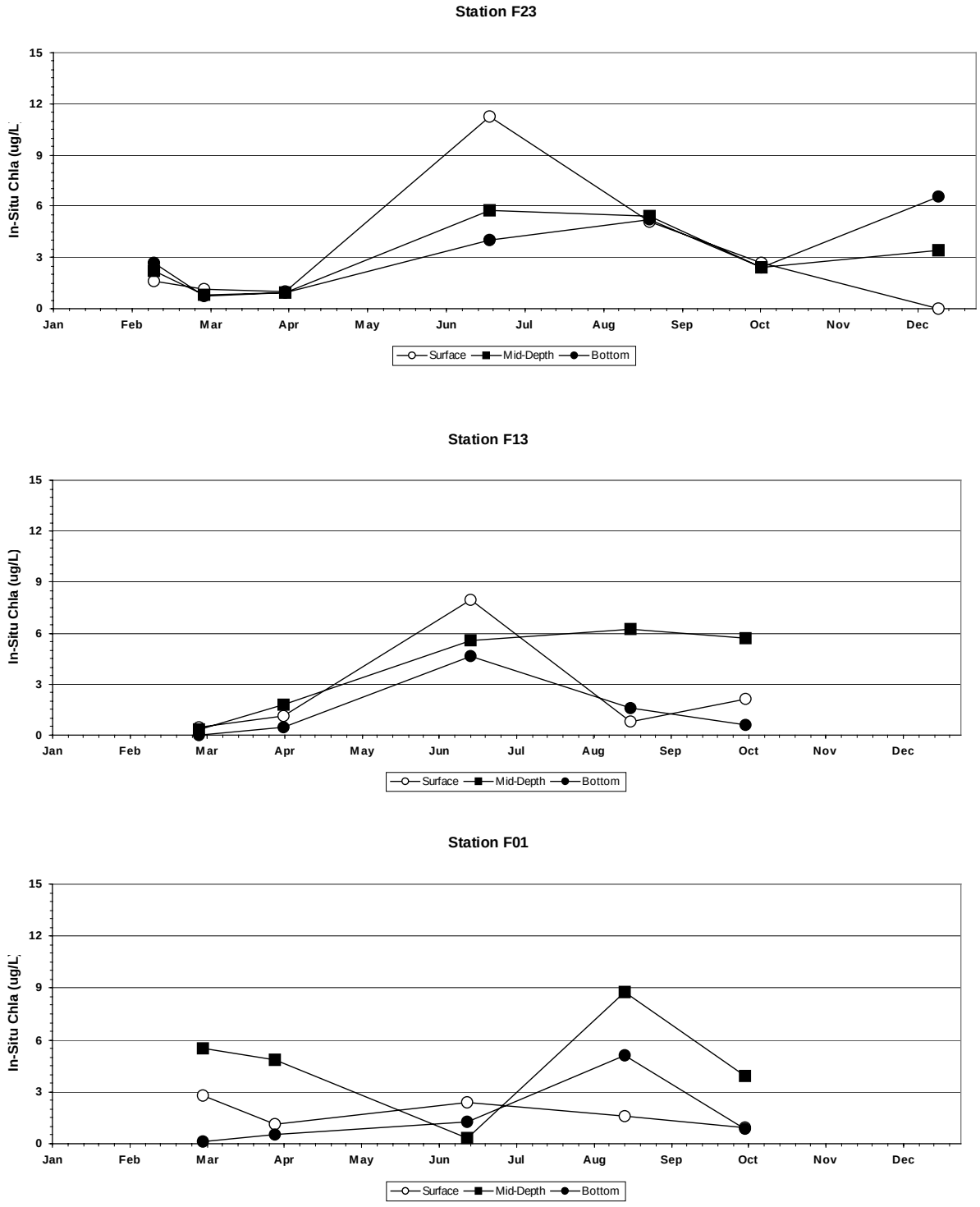


Figure 4-26. Time-series of surface, mid-depth and bottom chlorophyll concentrations at representative farfield stations – F23 (Boston Harbor), F13 (coastal), and F01 (Cape Cod Bay).

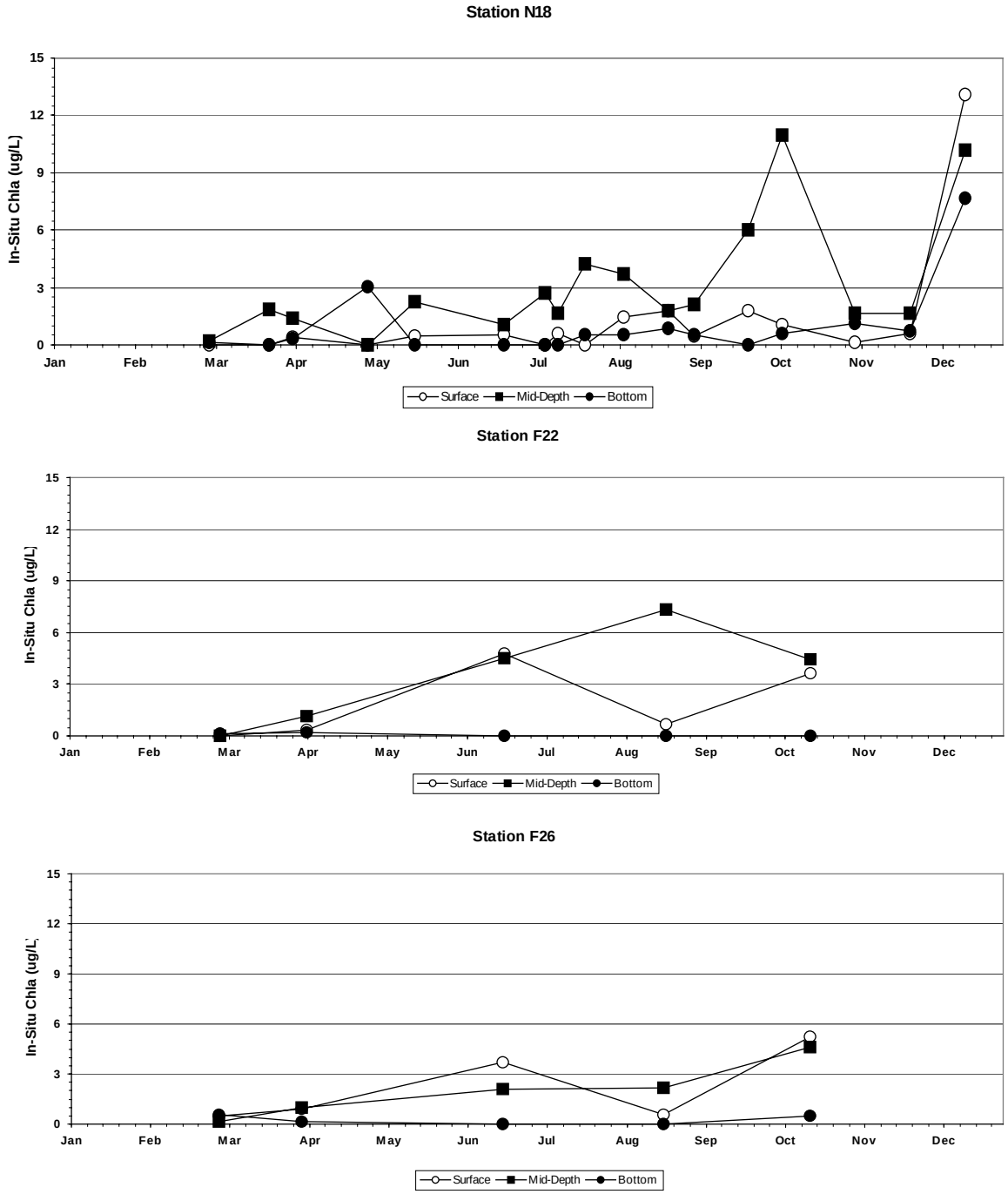


Figure 4-27. Time-series of surface, mid-depth and bottom chlorophyll concentrations at representative nearfield and farfield stations – N18 (nearfield), F26 (boundary), and F22 (offshore).

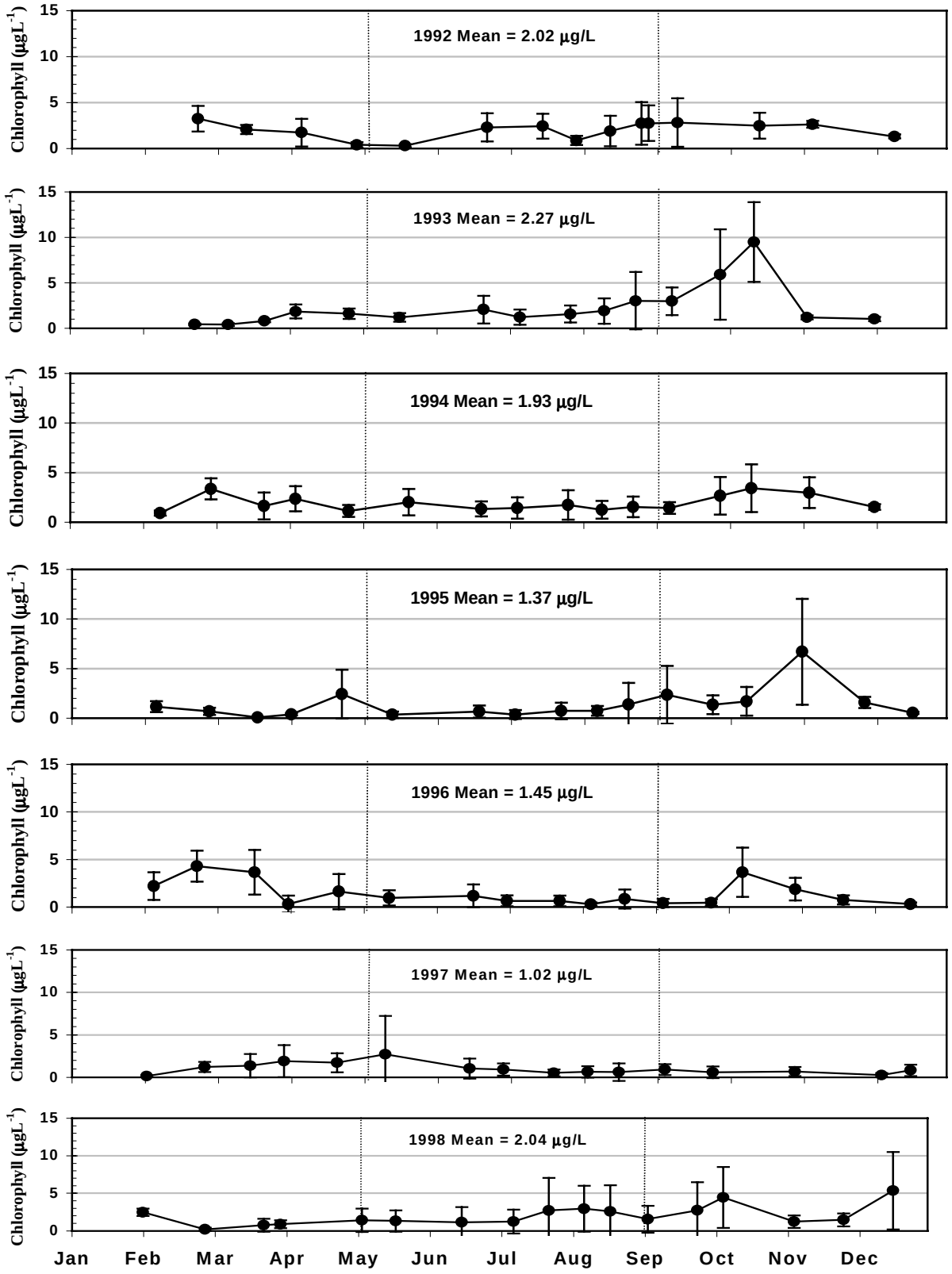


Figure 4-28. Interannual nearfield chlorophyll cycle (as measured by *in situ* fluorescence). Mean of data from all depths at all nearfield stations. Error bars represent ± one standard deviation.

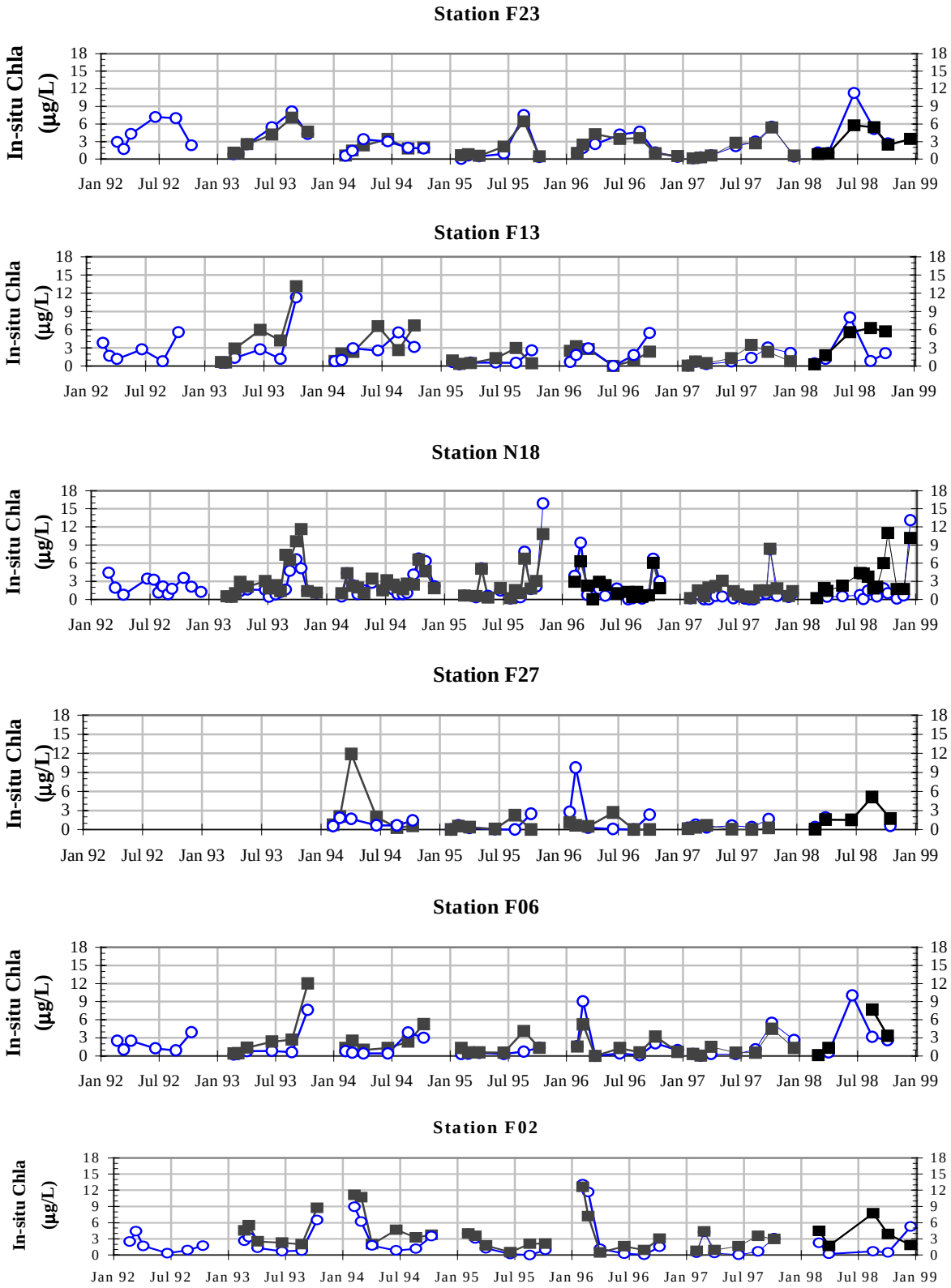


Figure 4-29. Interannual chlorophyll cycle at representative nearfield and farfield stations. Empty circles = surface (A) and filled squares = mid-depth (C).

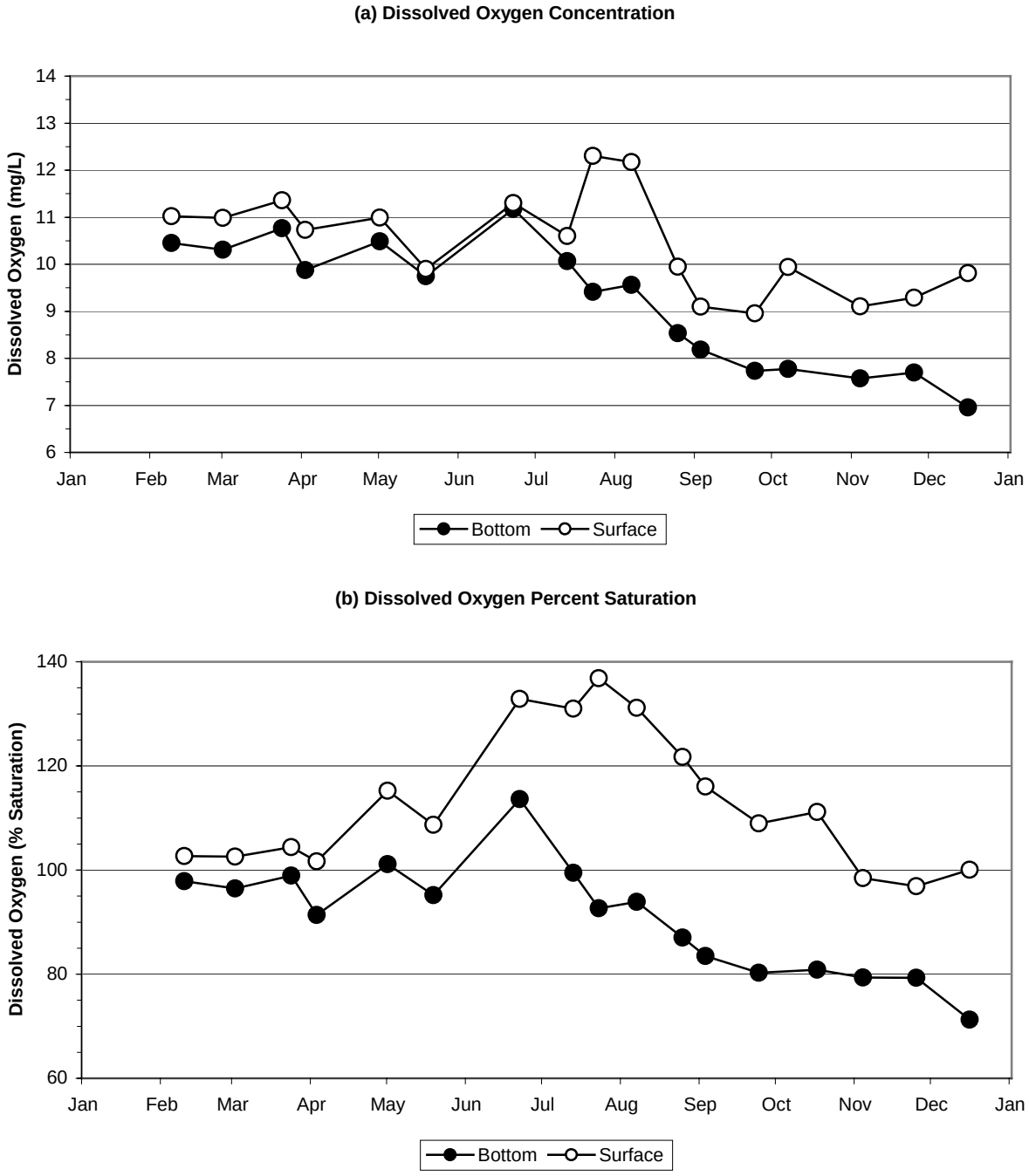


Figure 4-30. Time-series of average surface and bottom dissolved oxygen concentration (a) and percent saturation (b) in the nearfield for 1998.

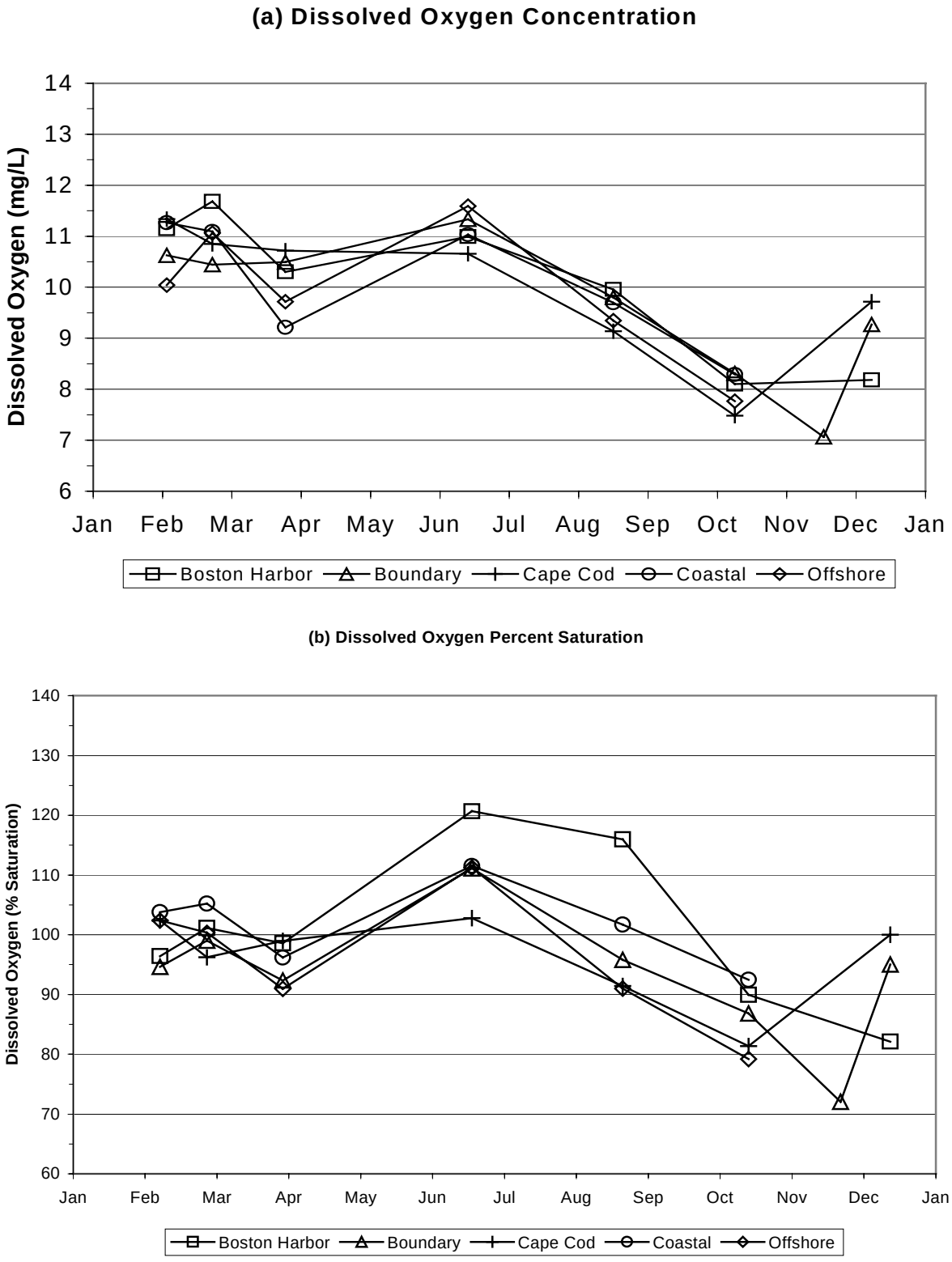


Figure 4-31. Time-series of average bottom dissolved oxygen concentration (a) and percent saturation (b) in the farfield for 1998.

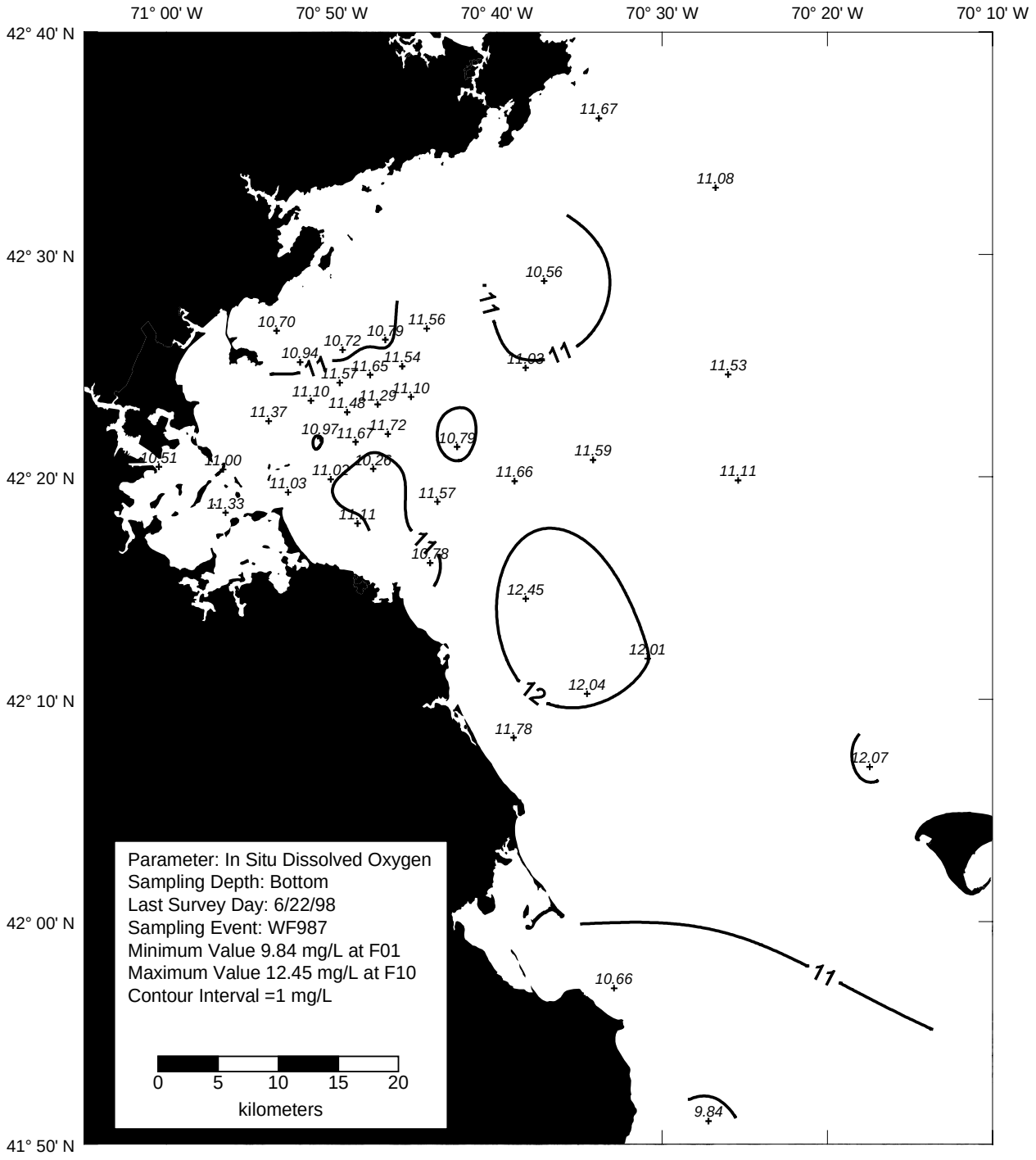


Figure 4-32. Contour of bottom water DO for farfield survey WF987 (Jun 98).

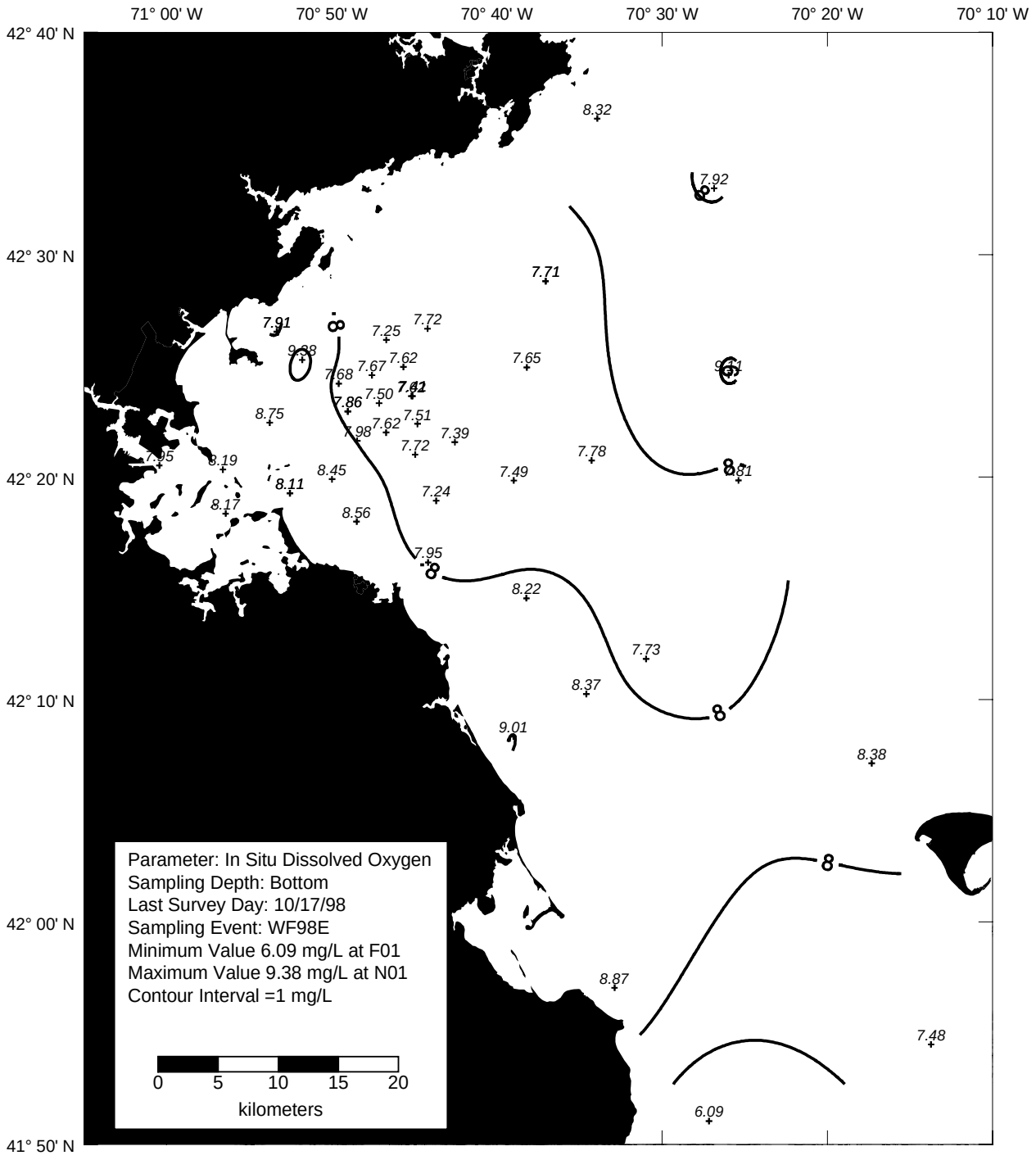


Figure 4-33. Contour of bottom water DO for farfield survey WF98E (Oct 98).

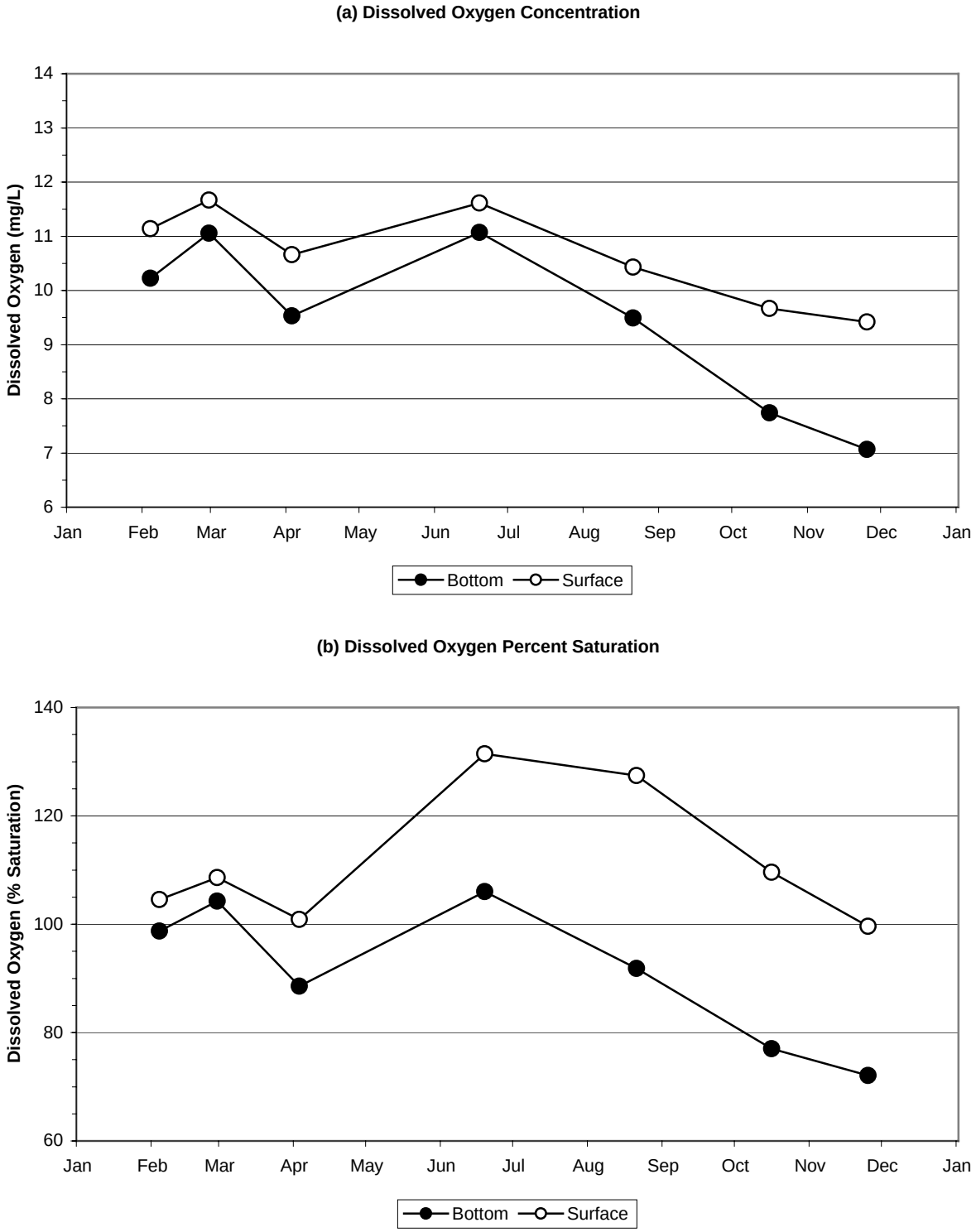


Figure 4-34. Time-series of average surface and bottom dissolved oxygen concentration (a) and percent saturation (b) in Stellwagen Basin for 1998 (stations F12, F17, F19 and F22).

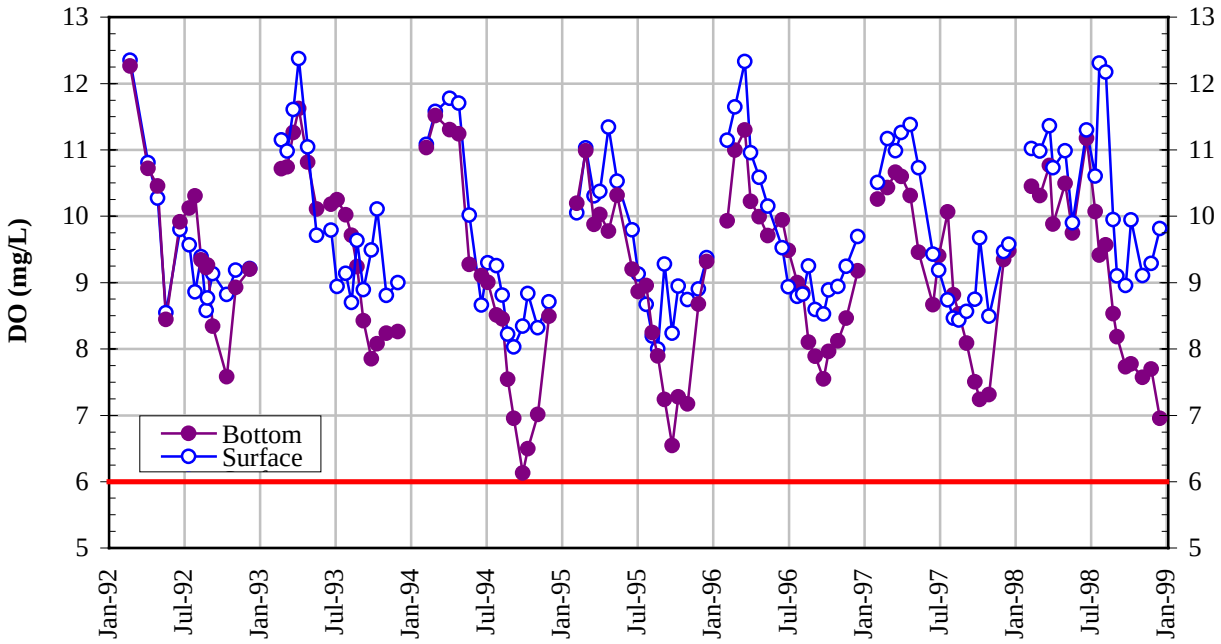


Figure 4-35. Interannual dissolved oxygen cycle in the nearfield. Mean of surface and bottom data from each survey at all nearfield stations.

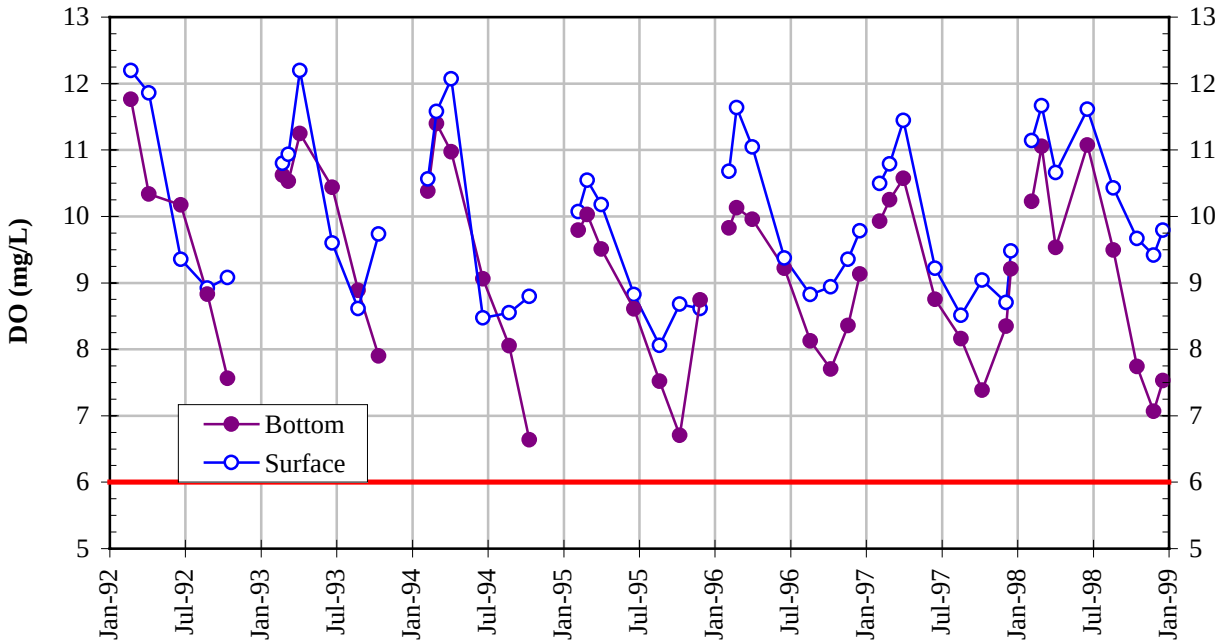
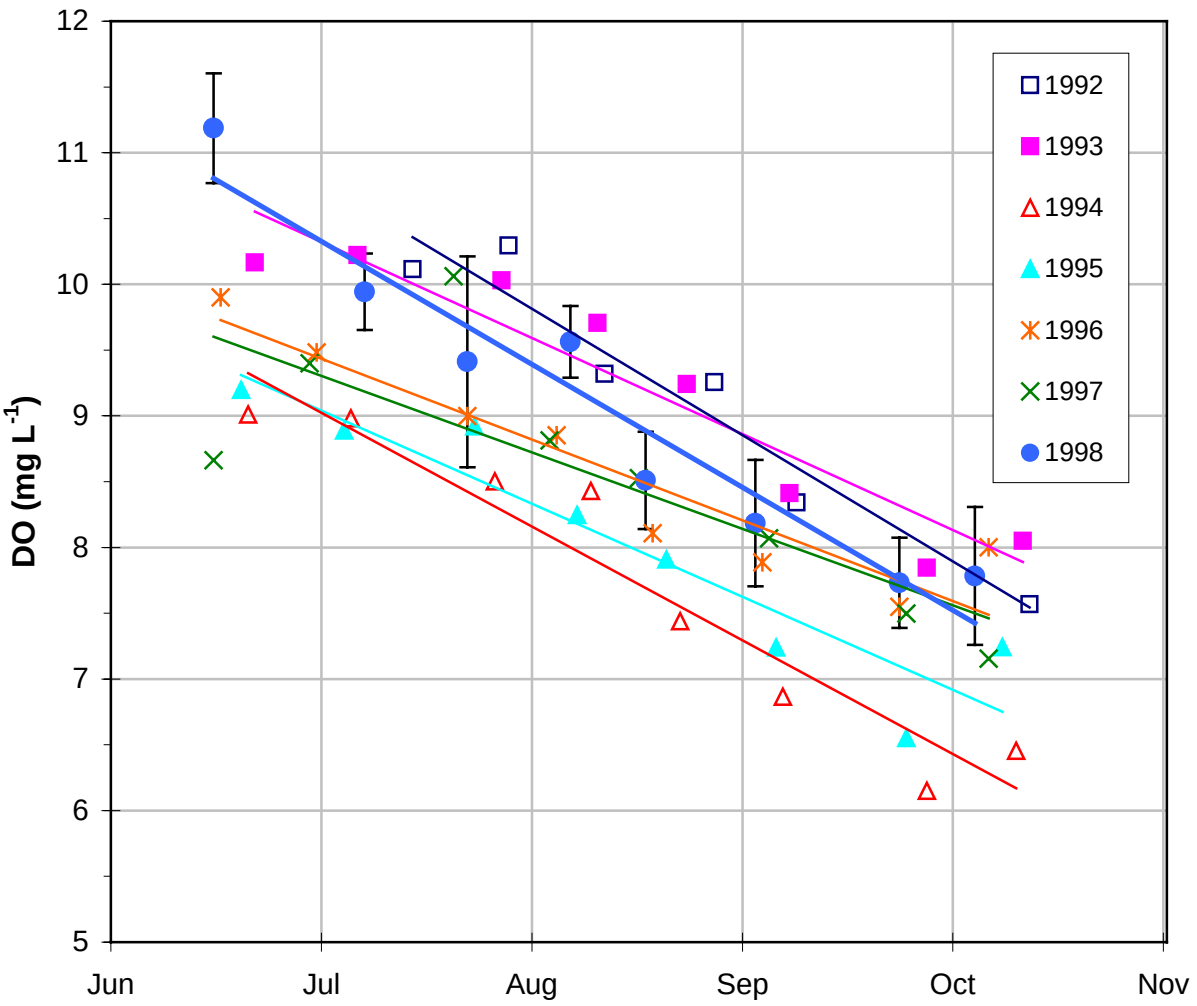
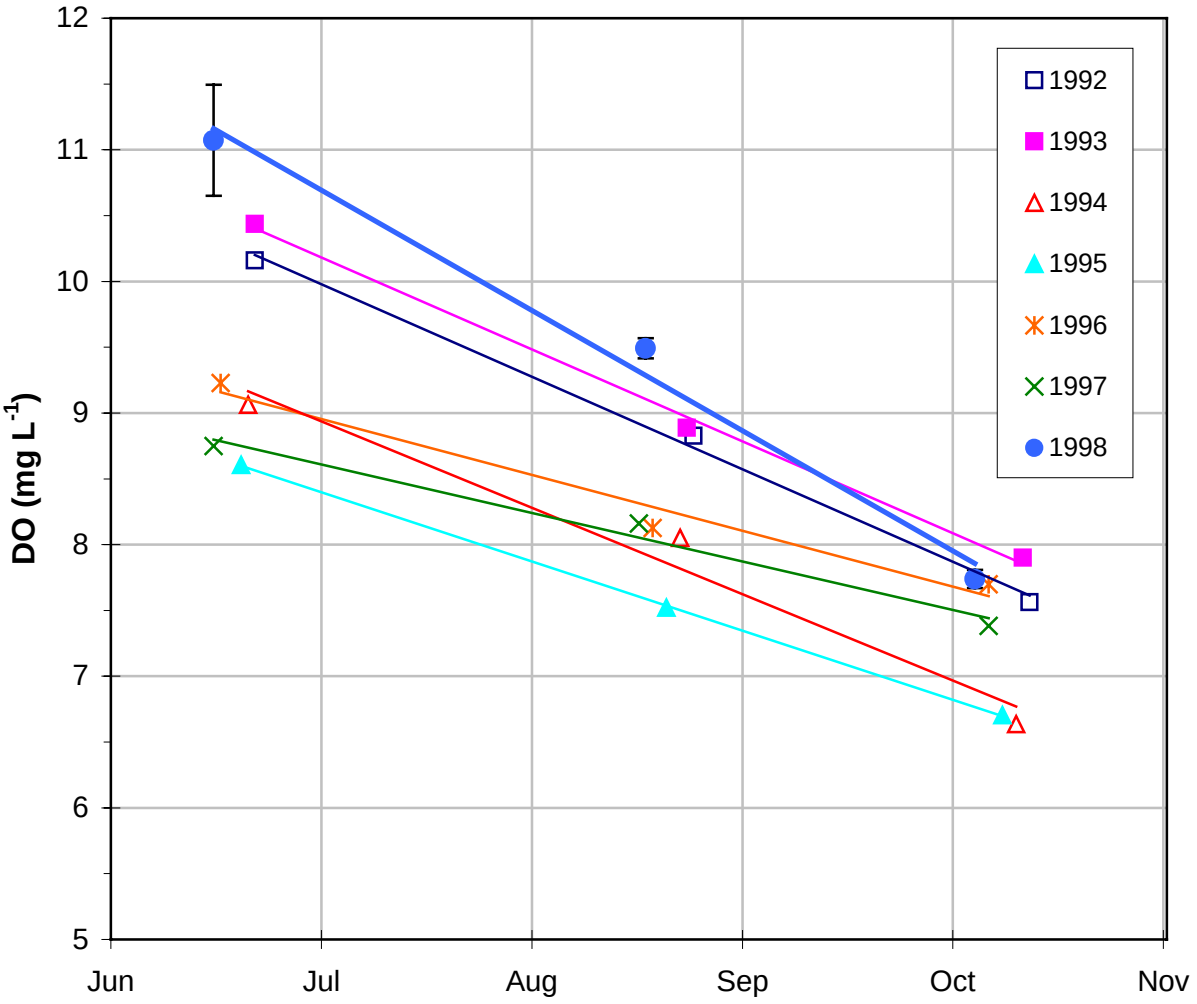


Figure 4-36. Interannual dissolved oxygen cycle in Stellwagen Basin. Mean of surface and bottom data from each survey at stations F12, F17, F19 and F22.



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
* Predicted DO on June 1st based on:			
DO = Slope * Date + Intercept			

Figure 4-37. 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
* Predicted DO on June 1st based on:			
DO = Slope * Date + Intercept			

Figure 4-38. Interannual comparison of DO decline in Stellwagen Basin bottom waters. Mean for stations F12, F17, F19 and F22. Error bars represent ± one standard deviation.

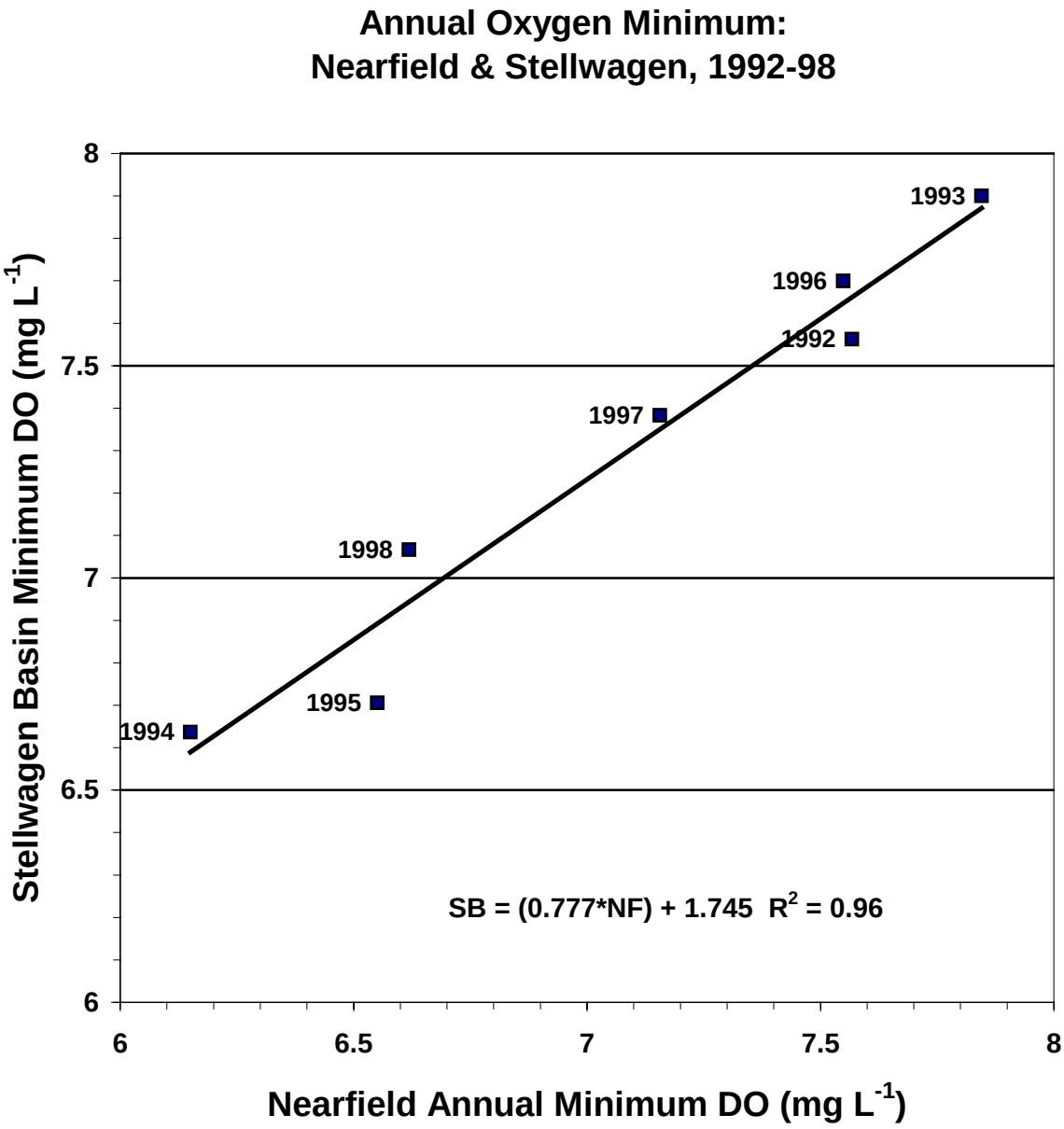


Figure 4-39. Annual DO minimum in nearfield and Stellwagen Basin – 1992-1998.

5.0 PRODUCTIVITY AND RESPIRATION

5.1 Productivity

5.1.1 Approach to Measurement of Primary Production

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 NM 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 new outfall comes online. Both N04 and N18 were visited 17 times over the 1998 season for measuring production. Phytoplankton production at the Boston Harbor outer edge station, F23, was measured 6 times over the annual cycle in 1998. F23 has traditionally been sampled less frequently than the high-density nearfield productivity stations. The measurements for March 1 (WF9802) were lost when the incubators failed. Production values for WF9802 (stations N04, N18 and F23) were estimated using the model parameters from the first cruise (WF9801) and the *in situ* data for temperature, irradiance, and light attenuation from the second. The major assumption of this approach is that model parameters remained constant over the 3-week period between cruises, a relatively good assumption given the similar and very low chlorophyll values for both cruises. With the exception of WF9802, 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; see Taylor 1999, Albro *et al.* 1998 and Libby *et al.* 1999a for details) at various light intensities ranging from approximately 5 –2000 $\mu Em^{-2}sec^{-1}$. The resulting fitted photosynthesis versus irradiance (P-I) curves (*e.g.*, Figure 5-1), measurement of light attenuation with depth (CTD mounted 4π sensor; *e.g.*, Figure 5-2A), and incident irradiance time series data (2π scalar irradiance sensor mounted at Deer Island, MA, see Appendix A of Libby *et al.* 1999a for details) were used to determine hourly production ($mgCm^{-3}h^{-1}$; Figure 5-2B) at 15-minute intervals throughout the 12 hour day for each sampling depth.

Hourly production over the daytime period was characteristically flattened at high light intensities due to effects of light saturation (see incident light at surface depths, Figure 5-2a and the production curves, Figure 5-2b for the surface samples). Daily depth dependent productions ($mgCm^{-3}d^{-1}$; Figure 5-2c) were calculated by trapezoidal integration of hourly production over the photoperiod. Areal production ($mgCm^{-2}d^{-1}$; Figure 5-3) was calculated by trapezoidal integration of measured production over the depth interval of the measurements. Annual production ($gCm^{-2}y^{-1}$) for each station (Figure 5-3 inset) was calculated by trapezoidal integration of daily values over an annual cycle.

Chlorophyll *a* was measured at each of the sampling depths for primary productivity and used to calculate chlorophyll-specific photosynthetic parameters. Figure 5-2d shows a typical continuous chlorophyll *a* profile from a CTD-cast. CTD profiles were collected via fluorometer and used for comparison with measured chlorophyll *a* values. Discrete depth chlorophyll *a* samples were consistently used in the calculation of chlorophyll-specific phytoplankton production. Figure 5-4 shows the measured chlorophyll *a* concentrations for each station over the 1998 annual cycle both as depth-averaged and depth-integrated values.

An advantage of the approach adopted here for measuring primary productivity is that cloud-mediated fluctuations in light intensity are captured by using a 15-minute time interval (see Figure 5-2A) over

the daylight period. In addition the seasonal change in light intensity is automatically incorporated in the computation of production. This approach also permitted calculation of a potential (or maximum) production for each sample day in the event that sampling occurred during overcast conditions. By selecting irradiance data from a sunny day within a week of the monitoring cruise and substituting these values in the calculations, we were able to calculate what the potential production (under maximum light) would be for each sample day.

P-I curves for deriving α [$mgCm^{-3}h^{-1}(\mu E\ m^{-2}s^{-1})^{-1}$], P_{max}($mgCm^{-3}h^{-1}$) and β[$mgCm^{-3}h^{-1}(\mu E\ m^{-2}\ s^{-1})^{-1}$] used in the calculation of primary productivity are shown in Figure 5-1. The higher range of light intensities (0-2000 $\mu Em^{-2}s^{-1}$) used in the incubation of samples in 1998 relative to recent years resulted in the frequent observance of photoinhibition. Of 200 incubations, 105 exhibited inhibition. The model by Webb *et al.* (1974) was used to fit the P-I curves when no inhibition was observed. In cases where photoinhibition was evident the model of Platt *et al.* (1980) was fit (SAS 1985) to obtain the theoretical maximum production, and terms for light-dependent rise in production and degree of photoinhibition.

5.1.2 Nearfield Production

Areal production over the 1998 season (Figure 5-3) exhibited different patterns between the nearfield stations (N04 and N18) and the Boston Harbor station (F23). Areal production at N04, fluctuated between ~100-500 $mgCm^{-2}d^{-1}$ from February 9 (WF981) through September 24 (Figure 5-3). The peak annual production for 1998 (1665-$mgCm^{-2}d^{-1}$) was reached on October 7 (WF98E). Values remained somewhat elevated (~700-800 $mgCm^{-2}d^{-1}$) compared to August and September throughout the remainder of the annual cycle (WN98F-WN98H) at station N04. A similar pattern was observed at station N18, the second nearfield station (Figure 5-3). Areal production varied around 125-450 $mgCm^{-2}d^{-1}$ during February (WF981) through early September (WN98C) then increased to ~1000 $mgCm^{-2}d^{-1}$ on September 24 (WN98D) and reached the annual maximum of 1988 $mgCm^{-2}d^{-1}$ on October 7 (WF98E). Values remained at ~650-700 $mgCm^{-2}d^{-1}$ for the remainder of the year.

A well-established fall bloom was observed at station N18 (Figure 5-3). The bloom was initiated in late August, reached its peak on October 7 and declined by November 4. The bloom lasted about 10 weeks at this station. A less well-developed fall bloom was observed at N04. The bloom at this site was established later (late September), reached a lower peak production level and was a shorter duration. Bloom duration at station N04 appeared to be about 3-4 weeks. Productivity during the fall bloom was about 3-5 times greater than during the summer when stratification limited the supply of nutrients to the euphotic zone. The differences between the peak fall bloom values and the duration of the fall bloom event indicate that fairly short range spatial differences in production rates existed in the region during the fall period. The annual pattern of primary productivity in 1998 was notable because of the conspicuous absence of a spring bloom (discussed later). The fall productivity pattern observed in 1998 was similar to that observed in prior years, although peak values were somewhat depressed.

The vertical distribution of primary productivity ($mgCm^{-3}d^{-1}$) over the annual cycle at stations N04 and N18 indicated that the majority of production was occurring in the upper 20 m of the water column at both stations (Figures 5-5 and 5-6). Fall bloom production occurred predominantly in the upper 5 m of the water column at station N04 (Figure 5-5). At station N18, subsurface production during the fall bloom was greater with peak levels occurring between 5-10 m and elevated production from the surface to 15 m. The subsurface productivity maximum at N18 was large enough to influence areal production (Figure 5-3) and contributed to the higher fall bloom peak observed here compared with station N04.

The annual pattern of average chlorophyll (Figure 5-4) for the outer nearfield (N04, N18) followed the pattern observed for areal production, with the exception of unusually elevated values measured in

December. The high chlorophyll values observed in December were not associated with an increase in phytoplankton productivity. The dominant annual features for chlorophyll in 1998 were the fall bloom, with 2-4 fold increases in biomass relative to earlier in the year and the unusual elevated chlorophyll values observed during the December cruise. Average chlorophyll values for station N04 and N18 (Figure 5-4) and the vertical distribution of chlorophyll (Figures 5-7 and 5-8) indicated that chlorophyll concentrations were elevated in the fall and winter period and that subsurface chlorophyll maxima were typical during most periods of elevated phytoplankton biomass. The unusual elevated chlorophyll values observed in December 1998 were present from the surface to mid-surface depths (~20 m) at station N04 (Figure 5-7). At station N18, elevated chlorophyll values were observed at all depths (surface through bottom samples, maximum depth ~25 m) during the December cruise. The peak chlorophyll values observed during the fall productivity bloom (October) were subsurface chlorophyll maxima at both stations and concentrated at depths of 15-20 m at station N04 and 10-15 m at station N18. The shallower depth of the subsurface chlorophyll maximum at station N18 (Figure 5-8) resulted in a detectable subsurface productivity maximum (Figure 5-6).

5.1.3 Harbor Production

At the Boston Harbor productivity/respiration station (F23), areal production was measured six times from February through October 1998. Production ranged from a low of ~100 $mgCm^{-2}d^{-1}$ in February-March 1998 to a peak value of ~1100 $mgCm^{-2}d^{-1}$ on June 22. Production was still relatively elevated on 24 August (WF98B) at ~750 $mgCm^{-2}d^{-1}$. In October (WF98E) production was lower than August and did not display the peak annual levels that were observed at the two nearfield sites (Figure 5-3). 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 early summer at the harbor station.

The vertical distribution of primary productivity ($mgCm^{-3}d^{-1}$) over the annual cycle at station F23 indicated that the majority of production was occurring in the upper 5-10 m of the water column (Figure 5-9). 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 the fall bloom period at stations N04 and N18 and the results suggest that a fall phytoplankton bloom did not occur at this station.

Average chlorophyll for station F23 (Figure 5-4) and the vertical distribution of chlorophyll (Figure 5-10) indicated that chlorophyll concentrations were elevated in the early summer. Subsurface chlorophyll maxima occurred both during the period of elevated phytoplankton biomass and the subsequent sample period. The contour plots of production versus biomass suggest that the subsurface chlorophyll maxima did not contribute to areal production. In general, at station F23, chlorophyll values increased gradually until the peak summer value then decreased again in October. Production was not measured at F23 during the December survey, but and increase in chlorophyll at harbor station F23 was concomitant with the anomalously high chlorophyll values encountered at stations N04 and N18 (see Figure 4-29).

5.1.4 Chlorophyll-Specific Production

Chlorophyll-specific areal production (Figure 5-11, shown in comparison with areal production for all stations) exhibited both spring and fall peaks at stations N04 and N18. The spring peaks observed in chlorophyll-specific areal production did not result in either elevated areal production or increased phytoplankton biomass. By contrast, the fall peaks were associated with both increased areal production and the fall biomass bloom. Chlorophyll-specific areal production was relatively low and constant at station F23 ranging from ~100-200 $mgCmgChl^{-1}d^{-1}$ over the annual cycle.

Chlorophyll-specific production is an approximate measure for the efficiency of production and frequently reflects nutrient conditions at the sampling sites. Nutrient concentrations were relatively abundant during the winter-spring bloom period suggesting that nutrient limitation was not a factor in the absence of a spring bloom at stations N04 and N18. The observation that phytoplankton biomass failed to accumulate even in the face of elevated chlorophyll-specific areal production (>1500 $mgCmgChl^{-1}d^{-1}$) suggests that an alternative factor was responsible for the bloom failure. The distribution of chlorophyll-specific production further indicates that the efficiency of production was moderately high in relation to the amount of biomass present at the nearfield stations during the fall bloom. At station N18, chlorophyll-specific production was greater than 700 $mgCmgChl\textit{a}^{-1}d^{-1}$ during the early November survey (WN98F). This period of high productivity per unit chlorophyll coincided with the end of the fall bloom. At station N04, the chlorophyll-specific production reached a maximum value of 1059 $mgCmgChl\ \textit{a}^{-1}d^{-1}$ at the same time that production was maximized (Oct 7).

The spatial and temporal distribution of chlorophyll-specific production on a volumetric basis were summarized by contour plots over the sampling period (Figures 5-12 to 5-14). 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 20 m of the water column at station N04 during the sampling cycle (Figure 5-12). Peak values were observed in the upper 5-m during the spring and fall bloom periods. Considerable production per unit chlorophyll was observed at depth during the spring but absent during the fall at station N04. Chlorophyll-specific production was relatively low at all depths during the summer period of stratification at N04.

Chlorophyll-specific production at station N18 was also concentrated in the upper portions of the water column (Figures 5-13). Elevated chlorophyll-specific productions occurred during March and October at station N18. Peak chlorophyll-specific productions occurred during October at station N18 and in early November at station N04. The observed pattern at station N18 suggests that the efficiency of photosynthesis continued to be relatively high and variable throughout the early summer then declined again during the period of summer 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 5-14). 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.

5.1.5 Potential Production

Potential production for a cloudless day was calculated for each day production was measured and at all five depths. Figure 5-15 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 cruises. Daily light was highly variable because of clouds as expected. Light ranged from being relatively low (cloudy) as on cruises WF982 and WF984 to close to that expected on a cloudless day as on cruises WF981 and WN986. 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 5-16 shows the potential daily production ($mgCm^{-3}d^{-1}$) 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 and N18 the fall bloom remained the dominant feature of the annual cycle. Similarly for station F23, the gradual increase to a seasonal summer production peak followed by a decline was observed.

The potential and measured areal productions ($mgCm^{-2}d^{-1}$) are compared over the seasonal cycle for each station in Figure 5-17. Although potential production was approximately 50% greater than measured production on some dates (*e.g.* WF982) the overall pattern was very similar. By chance, cloudy days tended to occur during periods of very low productivity with the exception of the December cruise. Consequently, potential annual productions ($gCm^{-2}y^{-1}$) at each station were about 20 $gCm^{-2}y^{-1}$ greater than measured production (see inset on Figure 5-17 with higher values being the annual potential productivity).

5.1.6 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 [$mgCm^{-3}h^{-1}(\mu Em^{-2}s^{-1})^{-1}$] or α^B [mg C(mgChl*a*)$^{-1}h^{-1}(\mu Em^{-2}s^{-1})^{-1}$] and P_{max} ($mgCm^{-3}h^{-1}$) or P^B_{max} (mgCmgChl$a^{-1}h^{-1}$), 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 and α^B over the season (Figures 5-18 and 5-19) revealed some interesting differences. The more highly resolved time series data for nearfield stations N04 and N18 (Figure 5-18) exhibited nearly constant values for α over much of the season with a marked 3-4-fold increase at the time of the fall bloom. During the bloom period, as well as at other times of the year, there was a marked tendency for α to decrease with depth. A similar tendency has been noted in previous years in Massachusetts Bay (Cibik *et al.* 1996). At station F23, α showed even lower variability over the annual cycle, with a less than 2-fold range over the sample period.

By contrast, α^B (Figure 5-19) was characterized by two periods of elevated values at the nearfield sites. A marked increase in α^B occurred during the period typically characterized by the winter/spring bloom as well as a less well-defined increase during the fall. The previously observed tendency for decreasing values of α with depth was not as consistent when α was normalized to biomass. Again α^B at station F23 was relatively constant over the seasonal sampling period.

Similar contrasts exist when the seasonal values for P_{max}($mgCm^{-3}h^{-1}$) and P^B_{max}(mgC(mgChla^{-1})h^{-1}) are compared (Figures 5-20 and 5-21). P_{max} essentially followed the seasonal patterns observed for both production at depth ($mgCm^{-3}d^{-1}$) and areal production ($mgCm^{-2}d^{-1}$) (Figure 5-3). At the nearfield sites, P_{max} exhibited a single seasonal peak during the fall bloom period. The seasonal pattern was also very similar to that observed for α (Figure 5-18). 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 5-3).

P^B_{max} was considerably more variable over the seasonal cycle than either P_{max} or α^B (Figure 5-21) particularly at station N18. At this station, P^B_{max} exhibited multiple peaks in value, throughout the annual cycle, with major peaks coinciding with the winter-spring bloom period and the fall bloom period. Additional peaks occurred during the spring and summer months as well. At station N04, peaks were also associated with the traditional bloom periods. At station F23, the biomass-normalized values for P_{max} were relatively constant over the annual cycle.

Because of the close similarity in the 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 5-22). A significant and positive relationship exists between the parameters even when they

are normalized to biomass (Figure 5-22). When we examined the data from 1995-97, we noted similar positive relationships (Figure 5-23). Although the slopes of the relationships appear somewhat lower in 1995-97, analysis of covariance revealed no significant differences ($P>0.05$) between the equations. A number of studies have similarly demonstrated a correlation between α^B and P^B_{max} (Harding *et al*. 1982 and 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 5-24 and 5-25 for each station and for all stations combined. Examination of the frequency distributions for α^B at the 3 stations did not reveal discernable differences between the sample sites (Figure 5-24). When all data were pooled, a positively skewed distribution was observed for α^B with a mean value of 0.041 mgC(mgChl*a*)$^{-1}$h^{-1} and nearly all of the values below the theoretical maximum of 0.11 mgC(mgChl*a*)$^{-1}$h^{-1} (Cleveland *et al.* 1989, Lohrenz *et al.* 1994). Only 13 of 200 samples (6.5%) 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 1998 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 1998 is compared to the combined data for 1995-97 there is a noticeable shift to the left in the distribution pattern (Figure 5-26).

The frequency distributions for P^B_{max} (mgCmgChl*a*$^{-1}$h^{-1}) at stations N04, N18 and F23 were also not distinguishable from each other (Figure 5-25). Pooled data revealed a positive skewness (n=200) but no evidence of a bimodal distribution as was suggested in 1995 (Cibik *et al.* 1996). Only one value (P^B_{max} = 26.2 mgCmgChl*a*$^{-1}$h^{-1} at station N04) was greater than the theoretical maximum of 25 (Lohrenz *et al.* 1994). The mean value (2.56 mgCmgChl*a*$^{-1}$h^{-1}) is lower than mean values reported in 1995 (Cibik *et al.* 1996) and 1994 (Kelly and Doering, 1995). Again there is a noticeable shift in the distribution to the left when the 1998 data are compared with the pooled data for 1995-97 (Figure 5-26).

To summarize our analysis of the P-I curves parameters we noted: 1) that the seasonal patterns were similar between stations N04 and N18 but different from F23; 2) that parameter values tended to decrease with decreased depth in the water column; 3) chlorophyll-specific parameters increased during the spring and the fall bloom periods but no spring bloom materialized; 4) the noted increases in photosynthetic efficiency were most likely tied to elevated light levels during the spring and improved nutrient availability in the fall; 5) photosynthetic parameters (normalized and not normalized to biomass) were significantly and positively correlated in 1998, as well as in 1995-97; and 6) frequency distributions were similar between 1998 and 1995 but appeared skewed to the left relative to pooled data from 1995 through 1997.

5.1.7 Comparison with Prior Years – Areal Production

Relative to other years, areal production at all three survey stations was low throughout the late summer and fall periods (Figures 5-27 and 5-28). In general, nearfield stations are characterized by the occurrence of a winter/spring phytoplankton bloom, relatively high production during the summer and a fall bloom (Figures 5-27 and 5-28). A gradual pattern of increasing areal production from winter through summer is more typical of the harbor (station F23) (Figure 5-27). When the seasonal patterns at station F23 are compared from 1995 through 1998, the peak production values are observed to decline over time (Figure 5-27). In 1998, production values at F23 were considerably lower than earlier years. During 1995-1997, peak areal productions at station F23 ranged from 2000

to 8000 mg C m^{-2} d^{-1} in the fall. The peak areal production observed at station F23 in August 1998 was 3-10 times lower than peak values observed in previous years.

The fall phytoplankton blooms observed at nearfield stations (N04, N16 and N18) in 1995-1997 generally reached values of 2000 to 4000 $mgCm^{-2}d^{-1}$, with blooms typically lasting 1-2 months (Figures 5-27 and 5-28). The fall phytoplankton bloom during 1998 was generally a lower magnitude bloom than those observed in prior years at station N04 (peak ~1665 $mgCm^{-3}d^{-1}$). In general, there appears to be a tendency for peak bloom production to be decreasing over time at station N04 (Figure 5-27). Areal production at station N18 has only been measured during 1997 and 1998 (Figure 5-28). The 1998 peak was about half the value observed in 1997 and the duration was somewhat less. Relative to station N16, a nearby site monitored from 1995-1996, the fall bloom at N18 in 1998 was very similar to prior years (Figure 5-28).

In general, chlorophyll-specific production was considerably lower in 1998 compared with 1995-97 (see for example stations F23 and N04, Figure 5-29). However, chlorophyll-specific production during the spring bloom period was equal to that previously observed at stations N04 and N18 and yet, no spring bloom materialized. The complete absence of a winter-spring production peak in 1998 was a significant change from previous years (see discussion below). Typically, the spring phytoplankton bloom accounts for greater than 30% of the annual production at the monitoring sites. The absence of this signature event resulted in annual productivity estimates that were lower than any previously recorded from the study area (Figure 5-30).

5.1.8 Spring Bloom Failure

Potential factors influencing the occurrence of a spring phytoplankton bloom include light availability, limiting nutrients, photic depth, temperature and predation. Analysis of these factors indicated that incident irradiance during the bloom period was not significantly different from other years. In earlier years, spring blooms were initiated at light levels similar to those observed in 1998 suggesting that incident light was not a factor in the 1998-bloom failure. Nutrients were also in abundance during the spring of 1998 since the typical spring draw down of nutrients in the nearfield region did not occur (see Section 4.1). Stratified conditions were not observed until May 1998 and for much of the spring the water column was well mixed supplying nutrients to the surface waters. Additionally, storms in February may have increased terrestrial runoff of nutrients into the bay. Consequently, nutrient concentrations were elevated from February to June.

The photic depth was defined as the 0.5% light level and is shown over the annual cycle at the three productivity sites in Figure 5-31. When the mean photic depths for the spring bloom period (February – April) were compared across years (Table 5-1) the results were mixed. For stations F23 and N18 the photic depth was somewhat shallower than in earlier years. However, the photic depth at N04 was deeper. The differences among years are not significant ($P>0.05$) and the results suggest that variation in photic depth was not responsible for the failure of the 1998 spring bloom. In an examination of data from 1995 to 1999, incident irradiance was not different ($P>0.05$) and light attenuation coefficients were significantly lower ($P=0.009$) in 1998 in comparison to other years (pers. com., A. Keller).

Table 5-1. Mean photic depth (m) during the spring bloom period (Feb–Apr), 1995 to 1998.

	Stations		
Year	**F23**	**N04**	**N16-18**
1995	18.7	42.6	33.6
1996	14.5	22.1	24.0
1997	15.3	26.6	26.8
1998	12.2	40.4	21.0

In general, phytoplankton levels are controlled by a balance between 'bottom-up' control through nutrient limitation and light availability, and 'top-down' processes such as grazing (Ryther and Dunstan 1971, Carpenter *et al.* 1988, Heiskanen *et al.* 1996). The interactions between these controlling factors regulate the biomass levels of the phytoplankton throughout the annual cycle and during bloom periods. Grazing by herbivores is a primary factor that reduces phytoplankton biomass in mesocosm experiments (Prins *et al.* 1995), field observations (Cloern 1982, Hily 1991, Mellina *et al.* 1995), and simulation models (Officer *et al.* 1982). Since temperature regulates grazing rate, variation in winter-spring temperatures may consequently alter the balance of factors leading to bloom development. We hypothesize that increased grazing by the zooplankton could be responsible for the absence of a winter-spring bloom at stations N04 and N18 in 1998. Experimental and correlative data have suggested a correlation between warmer winter temperatures in Narragansett Bay, RI and much reduced or absent winter phytoplankton blooms (Oviatt 1994, Keller *et al.* 1999).

Figure 5-32 shows a series of empirical relationships developed between phytoplankton production, biomass, temperature, and zooplankton abundance during the winter-spring bloom periods at stations N04, N16 and N18 from 1995 through 1998. In the upper figure, we establish that production and biomass were significantly (P=0.004) and positively correlated during the winter-spring bloom period. As was previously demonstrated for Narragansett Bay (Oviatt 1994, Keller *et al.* 1999), there is a significant and inverse relationship between temperature and peak bloom biomass with warmer winter temperatures resulting in less well-developed phytoplankton blooms. There also appears to be a tendency for increased zooplankton abundance during warmer years and an inverse relationship between zooplankton abundance and peak bloom biomass. The warmer winter temperature during 1998 may have played an important role in the absence of a winter-spring phytoplankton bloom.

5.1.9 Modeling of Phytoplankton Production

As in prior years we empirically examined the relationship between measured photic zone productivity ($mgCm^{-2}d^{-1}$) and a composite function (BZ_pI_0) derived by Cole and Cloern (1987) where B is phytoplankton biomass ($mgChl\textit{a}m^{-3}$), Z_p, the photic depth (m) and I_0 surface irradiance ($Em^{-2}d^{-1}$). Significant linear relationships ($P<0.05$) were found for all stations in 1998 (Figure 5-33). In Table 5-2 we compare the slope of the equations developed in 1998 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 5-2. Slope of equation $P = mBZ_pI_0 + b$ from 1994 through 1998.

	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

Because of the high variability in the above fitted relations, we also regressed both areal productivity ($mgCm^{-2}d^{-1}$) and the parameters of the P-I curves (P_{max} and α) against phytoplankton biomass ($mgChlm^{-3}$) alone. 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 5-34. For station N04 and N18 the r^2 values for production as a

function of biomass are greater than for the composite factor. Biomass alone is capable of explaining 63-79% of the variation in production at these two stations. The fit was even stronger at station F23 where 96% of the variation in production was explained as a factor of phytoplankton biomass. This is essentially the same proportion of variation explained by the composite factor at the harbor site. In 1998, a simple linear regression of production versus biomass appeared to be a better predictor of production.

The relationships between the P-I curve parameters and phytoplankton biomass were highly significant as well ($P<0.0001$; Figure 5-35). However, only 53-57% of the variation in the parameters was accounted for by chlorophyll a. The values shown as open circles in the figure were statistical outliers (t-test) and were excluded from the analysis. Although the outliers were all from a single sampling date (October 7, 1998) no causal factors related to their values were uncovered. A mixed phytoplankton assemblage bloom (diatoms and dinoflagellates) was occurring at the time and perhaps the values are related to the phytoplankton species composition. Nevertheless, the prediction of P-I curve parameters as a function of biomass may prove to be an alternative approach for modeling production and will be examined in greater detail in the future.

5.1.10 Production Summary

The major features established by the analysis of production measurements during 1998 were as follows: 1) The annual productivity at stations N04, N18 and F23 was lower than in prior years (primarily due to the absence of a winter-spring bloom); 2) During 1998 the seasonal productivity pattern was dominated by the fall bloom; 3) There was no winter-spring bloom despite increased chlorophyll-specific production during the typical bloom period; 4) Bloom failure was not correlated with nutrient availability or light limitation; 5) Bloom failure may be related to warm winter temperatures and increased grazing by zooplankton (which were more abundant than other years during the winter-spring bloom period); and 6) productivity was significantly correlated with the composite parameter BZ_pI_0 (but the relation was variable across years).

5.2 Respiration

Respiration measurements were 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 were sampled during each of the combined farfield/nearfield surveys and stations N04 and N18 were also sampled during the nearfield surveys. Respiration samples were collected from three depths (surface, mid-depth, and bottom) and were incubated in the dark at *in situ* temperatures for 8±1 days. Respiration was calculated as the difference between initial and final dissolved oxygen concentrations (for additional details see Albro *et al.* 1998). Due to electrical problems with the incubators, there were no respiration data for the June survey (WF987).

Both respiration (in units of μMO_2h^{-1}) and carbon-specific respiration ($\mu MO_2\mu MC^{-1}h^{-1}$) 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 to April, respiration rates were generally low throughout the region ($<0.1\ \mu MO_2hr^{-1}$) and there were no consistent vertical trends in the data (Figure 5-36). In early May (WN985), there was an increase in the respiration rates for the surface and mid-depth samples in the nearfield area. This increase coincided with the onset of seasonal stratification and

increases in productivity, POC concentration and phytoplankton abundance. By mid-May (WN986), respiration rates had decreased to <0.1 μMO_2hr^{-1}over the water column at station N04, but had increased at station N18 to 0.10-0.15 μMO_2hr^{-1} at all three depths sampled. High respiration rates were observed during the two surveys in July. Respiration rates at stations N04 and N18 ranged from 0.07-0.22 μMO_2hr^{-1} and 0.08-0.32 μMO_2hr^{-1}, respectively. The rates generally decreased with depth, which was consistent with the relatively high surface to mid-depth chlorophyll concentrations that were seen during these July surveys.

By early August (WN98A), respiration rates had decreased to 0.05-0.21 μMO_2hr^{-1} at N18 and <0.15 μMO_2hr^{-1} at N04 (Figure 5-36). At station N18, respiration continued to decline through late August (WF98B) with rates of 0.14 μMO_2hr^{-1} in the surface waters and <0.02 μMO_2hr^{-1} at the mid and bottom depths. Respiration rates at station N04 had increased to ~ 0.2 μMO_2hr^{-1} in the surface and mid depth waters by late August, which coincided with an increase in chlorophyll concentrations at this outer nearfield station. The decrease in respiration that was observed in the nearfield in August coincided with the frequent upwelling events and the cooling of the nearshore waters. The upwelling events may have decreased the rates due to the cooler water that was entrained into the nearfield and/or due to the changes in the local circulation patterns that are concomitant with upwelling.

By late September (WN98D), respiration rates in the nearfield had reached levels comparable to July and values were measured that ranged from 0.16-0.23 μMO_2hr^{-1} and 0.1-0.33 μMO_2hr^{-1} at stations N04 and N18 respectively. There was an obvious gradient in rates decreasing from maximum values in surface waters to minimum values in bottom waters. During the October survey WF98E, high chlorophyll concentrations and production rates were observed at mid depth (subsurface chlorophyll maximum) suggesting the presence of a fall bloom. Respiration rates, however, had decreased from September values. At station N04, rates ranged from ~0.17 μMO_2hr^{-1} at the surface and mid depths to 0.02 μMO_2hr^{-1} in the bottom waters and at station N18 respiration rates were 0.15-0.20 μMO_2hr^{-1} at the surface and mid depths and 0.06 μMO_2hr^{-1} in the bottom waters. Though rates had decreased, mid depth respiration values had remained relatively high in comparison and were coincident with the elevated levels of production.

Respiration rates continued to decrease with the decreasing water temperatures through November (WN98F and WN98G) and December (WN98H). By December, respiration rates were <0.05 μMO_2hr^{-1} at each of the depths at stations N04 and N18. The patterns and magnitude of the rates observed in the respiration data for the nearfield stations were similar to previous years for this time period. This is due to the relative consistency of the fall bloom from year to year (Sept-Oct peak in respiration rates) and the decrease in water temperature and increased mixing associated with the fall/winter turnover of the water column (post-bloom decrease in rates).

Given the paucity of data at the farfield stations, it is difficult to clearly characterize the seasonal trends in respiration except that rates were low in the winter/spring and increased with increasing temperature in the summer/fall (Figure 5-37). At station F23, respiration rates were at a maximum at each of the depths (0.15-0.27 μMO_2hr^{-1}) during the August survey (WF98B). Unlike the trends observed at the nearfield stations, respiration was highest in the bottom waters at this shallow harbor station. By the October survey, respiration rates at F23 had decreased to 0.1-0.14 $\mu MO_2\ hr^{-1}$, which coincided with a decrease in chlorophyll concentrations from August to October. Respiration rates at the Stellwagen Basin station F19 were relatively high in August at the surface (0.28 μMO_2hr^{-1}) and ranged from 0.07-0.14 μMO_2hr^{-1} at the bottom and mid depths. Respiration rates had decreased slightly in the surface and bottom waters by the October survey, but had increased to 0.25 μMO_2hr^{-1} at mid depth which coincided with a subsurface chlorophyll maximum at station F19.

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 and 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 July (Figure 5-38), which is consistent with the increase observed in chlorophyll over this time period. POC concentrations were low (10-20 μMC) in the nearfield during the first three surveys and relatively uniform over the well-mixed water column. Over the same time period, POC concentrations were significantly higher at the harbor station F23. In April (WF984), POC concentrations had increased at both nearfield stations to approximately 20-30 μMC. The carbon-specific respiration rates were low (<0.005 $\mu MO_2 \mu MC^{-1} hr^{-1}$) at all three stations from February to April (Figure 5-39).

In May (WN985), POC concentrations had decreased at both nearfield stations. This correlated with the high surface and mid-depth carbon-specific respiration rates measured at station N04. Low carbon-specific respiration rates were still observed at station N18 even though concurrent production measurements were the relatively high for this time period. Ancillary data (low chlorophyll and low phytoplankton abundance) suggest that the sampling at station N18 may have occurred at the initiation of a localized bloom when there was relatively low, yet productive phytoplankton assemblage.

POC concentrations had decreased by mid-May at N18, but increased at N04. This was concomitant with lower carbon-specific respiration at station N04, but higher carbon-respiration for the mid-depth and bottom samples at station N18. This increase in respiration at depth was coincident with higher subsurface production. Though POC concentrations decreased to approximately 10 μMC in the bottom water in June and July, carbon-specific respiration was high in July (no June data). This suggests that the limited amount of particulate organic material reaching the bottom waters had not been substantially degraded or that there was another significant pool of labile organic carbon that is not considered in this comparison. In June, concentrations of dissolved organic carbon (DOC) were very high (>400 μM) in the mid-depth waters at station N04 and N18 and remained high (200-300 μM) in July. The DOC pool of labile carbon may have supported the elevated respiration rates that were observed in July.

There was a general decrease in POC concentrations from early August to early September (station N18) and late September (station N04). POC concentrations then increased reaching maximum values at both stations in October (Figure 5-38). This pattern was consistent with the trends observed in chlorophyll over this time period. POC concentrations were similar in the surface and mid depth waters at station N04 from August to December decreasing from ~30 μM in August to 15-20 μM in September then reaching a maximum of 45-50 μM in October. The bottom water POC concentration at station N04 remained relatively constant (10 μM) from August to October and then

increased to 25 μM in early November (WN98F). This increase was probably due to the settling out of the fall bloom. At station N18, the POC concentrations in the surface and mid depth waters were not comparable until late September when subsurface chlorophyll concentrations had begun to increase and POC concentrations were at a maximum in both the surface (45 μM) and mid depth (42 μM) waters. POC concentrations had decreased slightly at the surface and mid depths by the October survey, but had reached the maximum value in the bottom waters (29 μM). This pattern was similar to that seen at station N04 except it suggests the fall bloom may have senesced and begun sinking out earlier at N18. At station F23, POC concentrations decreased from 40-50μM in August to 15-20μM in December.

At station N04, the decrease in POC concentrations from August to late September was coincident with increasing respiration rates. This resulted in a substantial increase in the carbon-specific respiration rate indicating that even though the total POC was decreasing, the POC that was present was labile or that another pool of labile organic carbon was present. The DOC concentrations at station N04 were higher in September than during previous or subsequent months. The increase in carbon-specific respiration may have resulted from a combination of increased phytoplankton productivity (which increased in September reaching a maximum in October) and increased grazing pressure on the phytoplankton. In October, production and chlorophyll concentrations reach maximum levels and high POC concentrations were measured at both nearfield stations. Carbon-specific respiration rates, however, were low at stations N04 and N18 ranging from 0.002-0.005 $\mu MO_2 \mu MC^{-1} hr^{-1}$ suggesting that the October survey was conducted near the conclusion of the fall bloom. At station N18, carbon-specific respiration rates remained relatively low and constant throughout this time period.

5.2.3 Respiration Summary

Trends in the respiration data followed those observed with other biological and biomass parameters. In the winter/spring, the lack of a seasonal bloom and low production rates led to low biomass (POC and chlorophyll). The combination of low concentrations of organic material and cool temperatures resulted in low respiration rates. The gradual increase in chlorophyll and phytoplankton abundance over the course of the spring and into the summer was matched by increasing POC concentrations and respiration rates. The upwelling events that brought cool, nutrient rich waters to the nearfield area caused a temporary reduction in respiration events in July/August. POC concentrations and respiration rates increased during the fall bloom and then decreased with decreasing production, biomass, and temperatures through the end of the year. Though there were clear differences observed in the 1998 production data compared to 1992-1997, the general pattern and range of respiration rates was similar to previous years of baseline data.

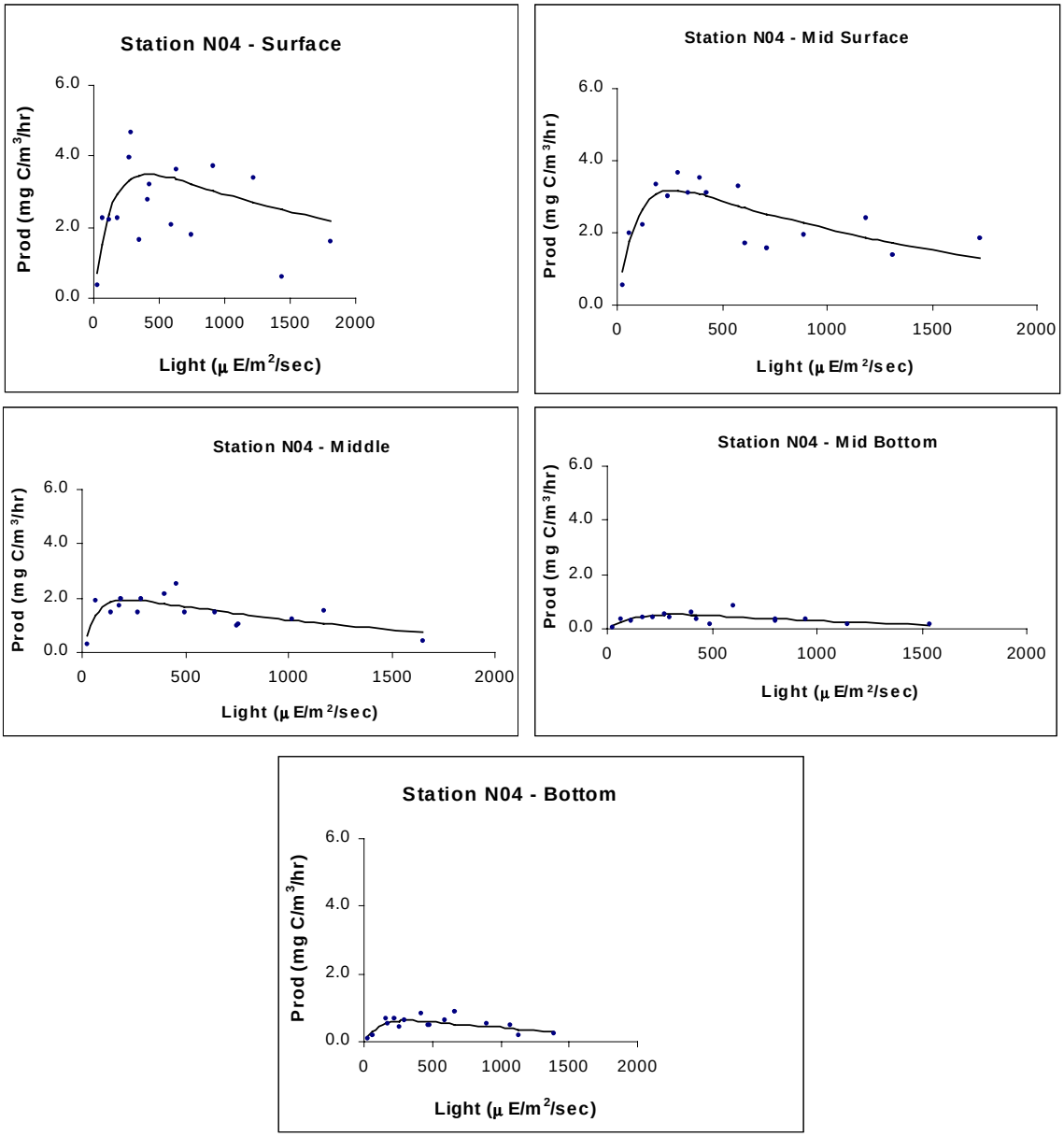


Figure 5-1. An example photosynthesis-irradiance curve from station N04 collected in August 1998.

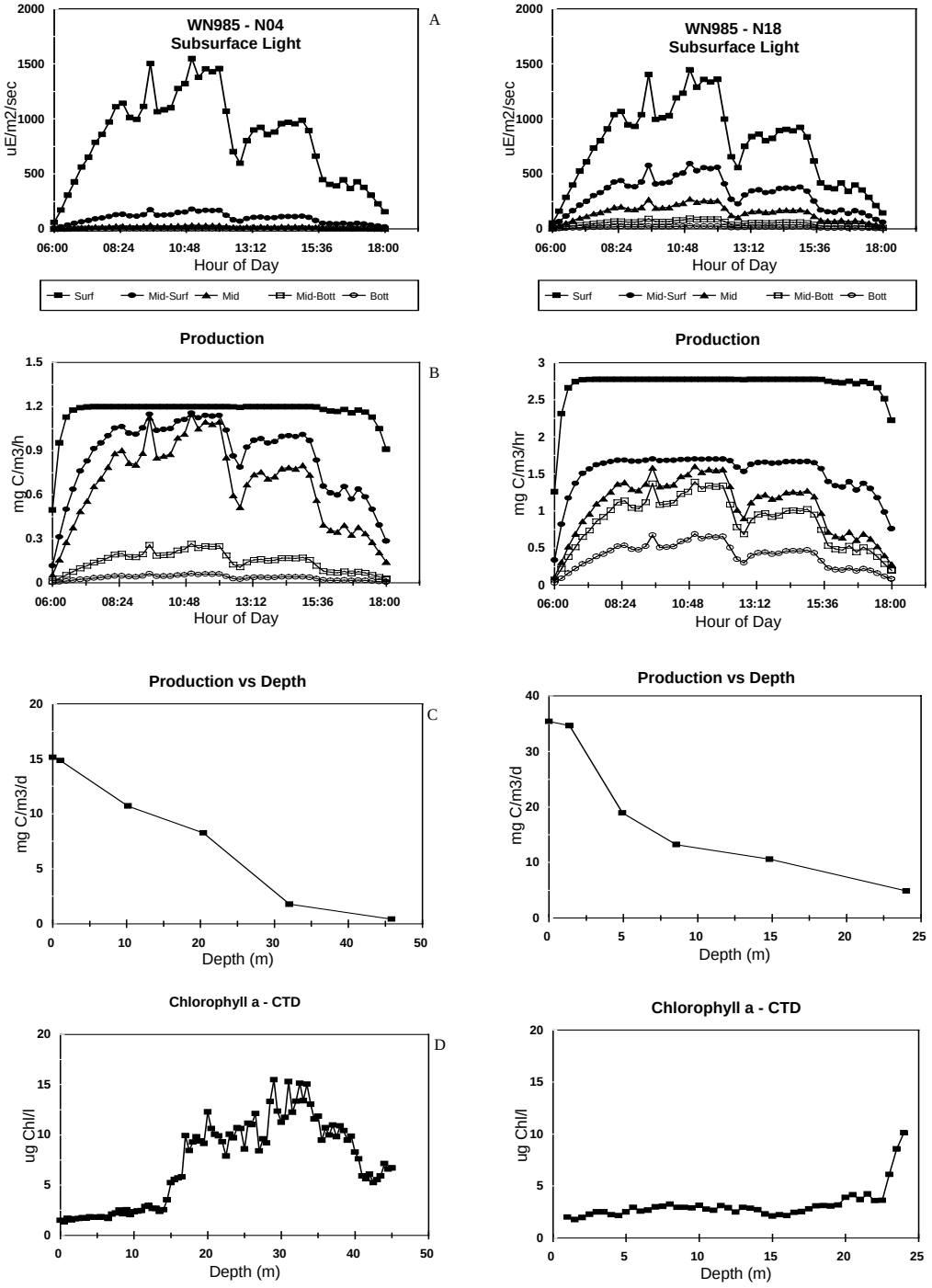


Figure 5-2. Examples of typical 14-C phytoplankton productivity results. A) incident irradiance in 15-min intervals over the course of the day at surface, mid-surface, mid, mid-bottom and bottom depths; B) 14-C production ($mgCm^{-3}h^{-1}$) obtained from P-I curves and *in situ* light intensity at 15 minute intervals throughout the day at surface, mid-surface, mid, mid-bottom and bottom depths; C) daily production ($mgCm^{-3}d^{-1}$) at each sampling depth determined by integrating hourly production over the day; D) chlorophyll *a* (μgl^{-1}) as measured by fluorescence during CTD-casts.

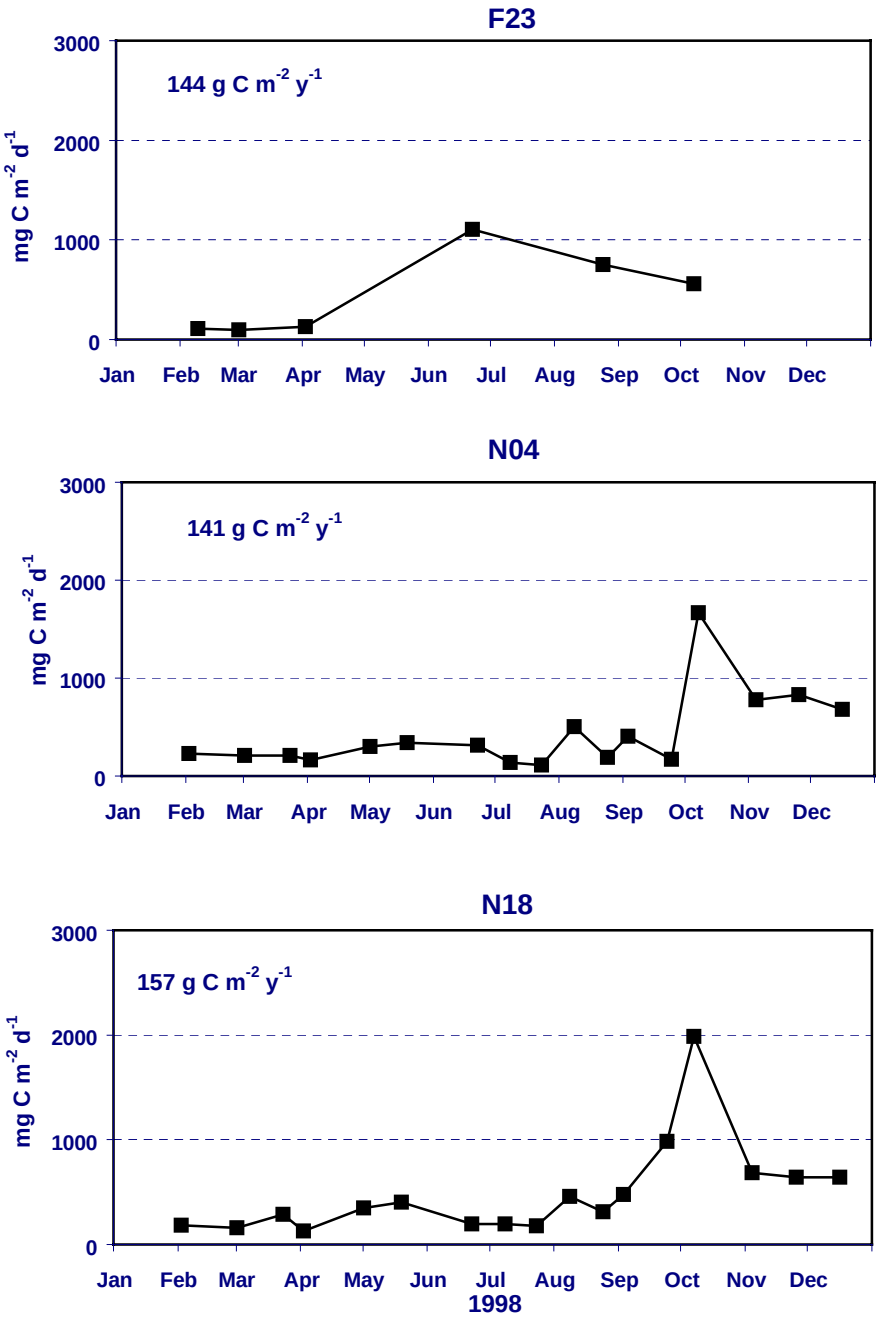


Figure 5-3. Areal production ($mgCm^{-2}d^{-1}$) for the 1998 season. Annual production ($gCm^{-2}y^{-1}$) is indicated in the inset of each panel.

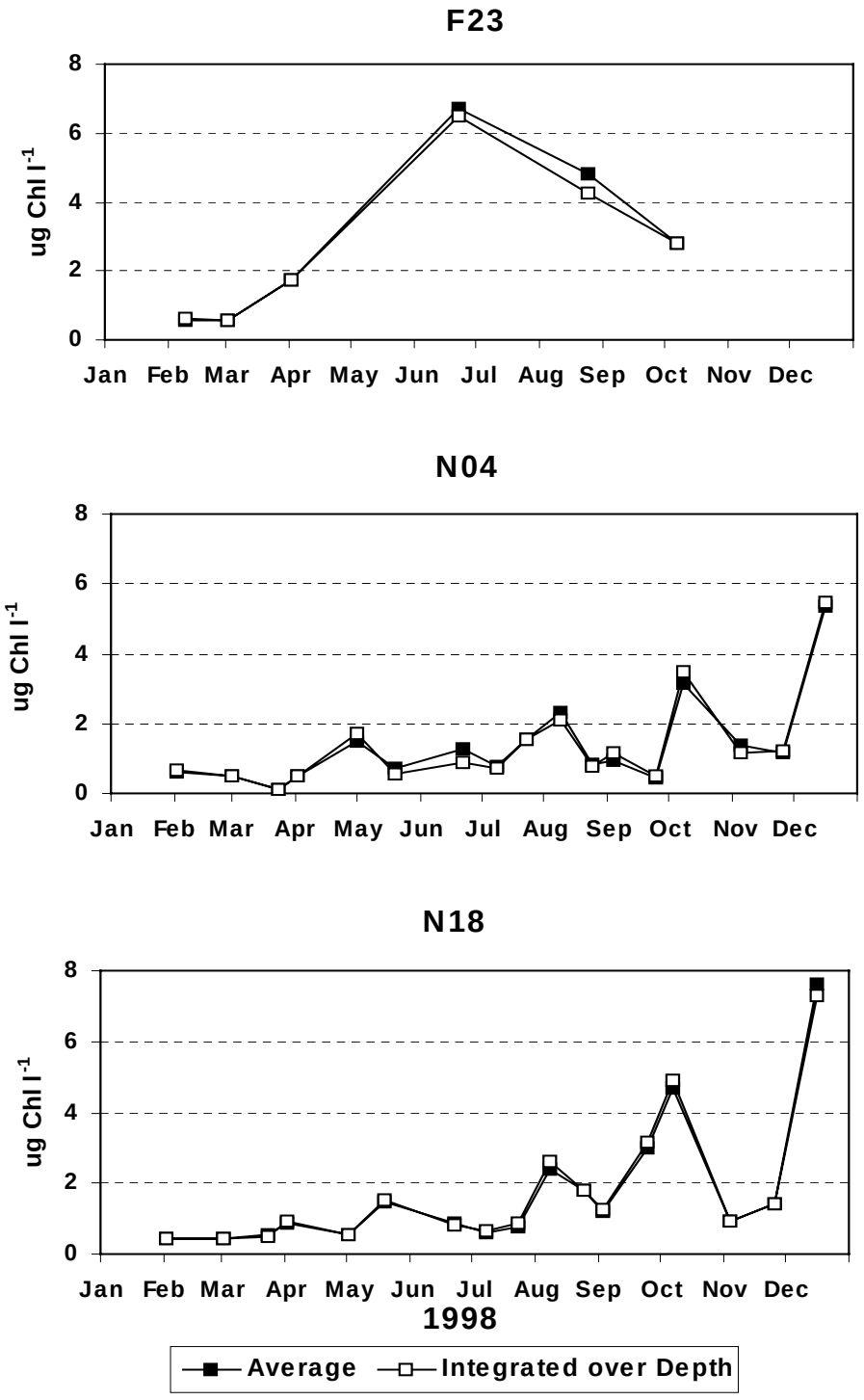


Figure 5-4. Chlorophyll *a* distribution for the 1998 season represented as averaged over depth and integrated over depth.

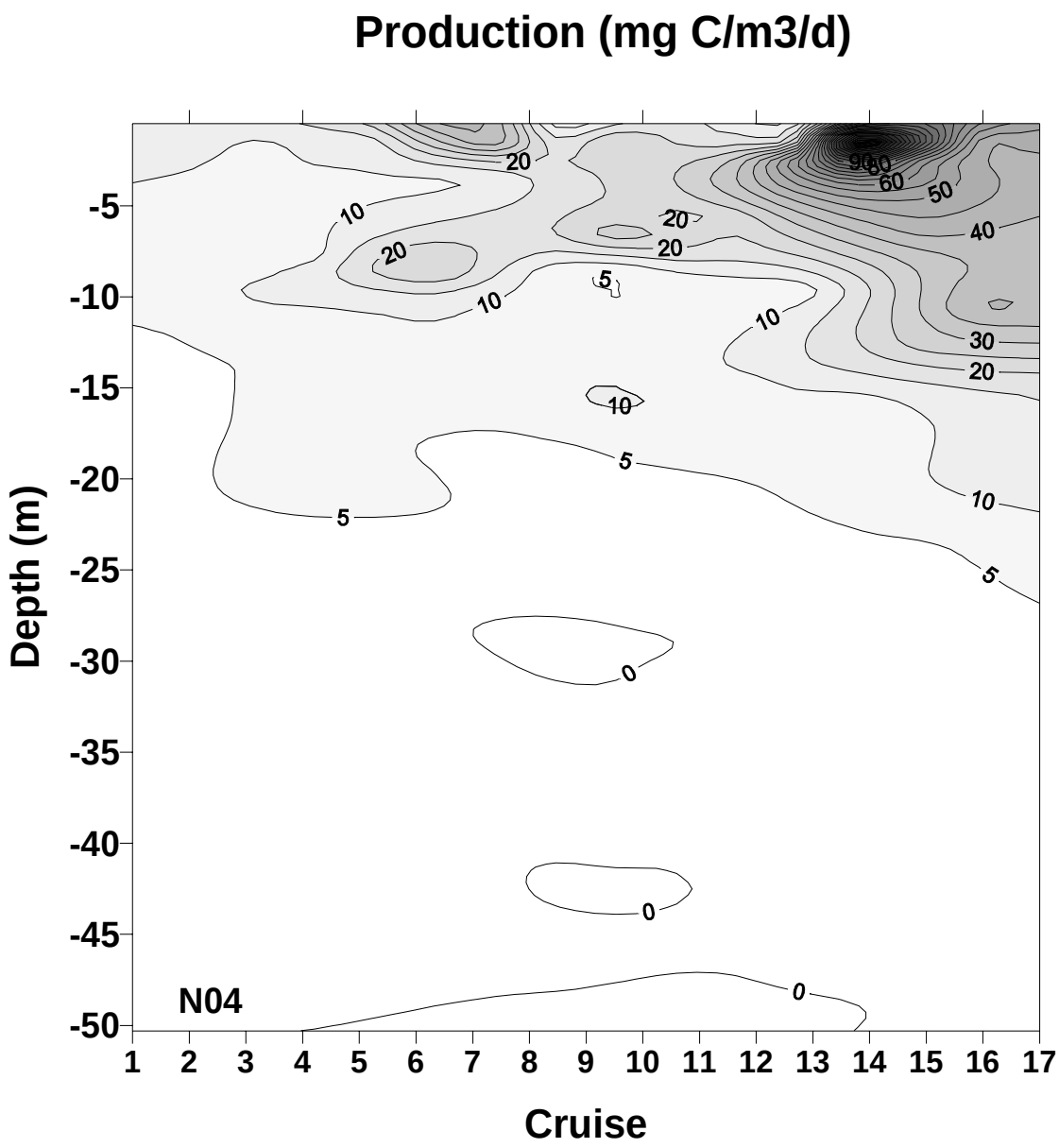


Figure 5-5. Time series of contoured daily production ($mgCm^{-3}d^{-1}$) over depth (m) at station N04.

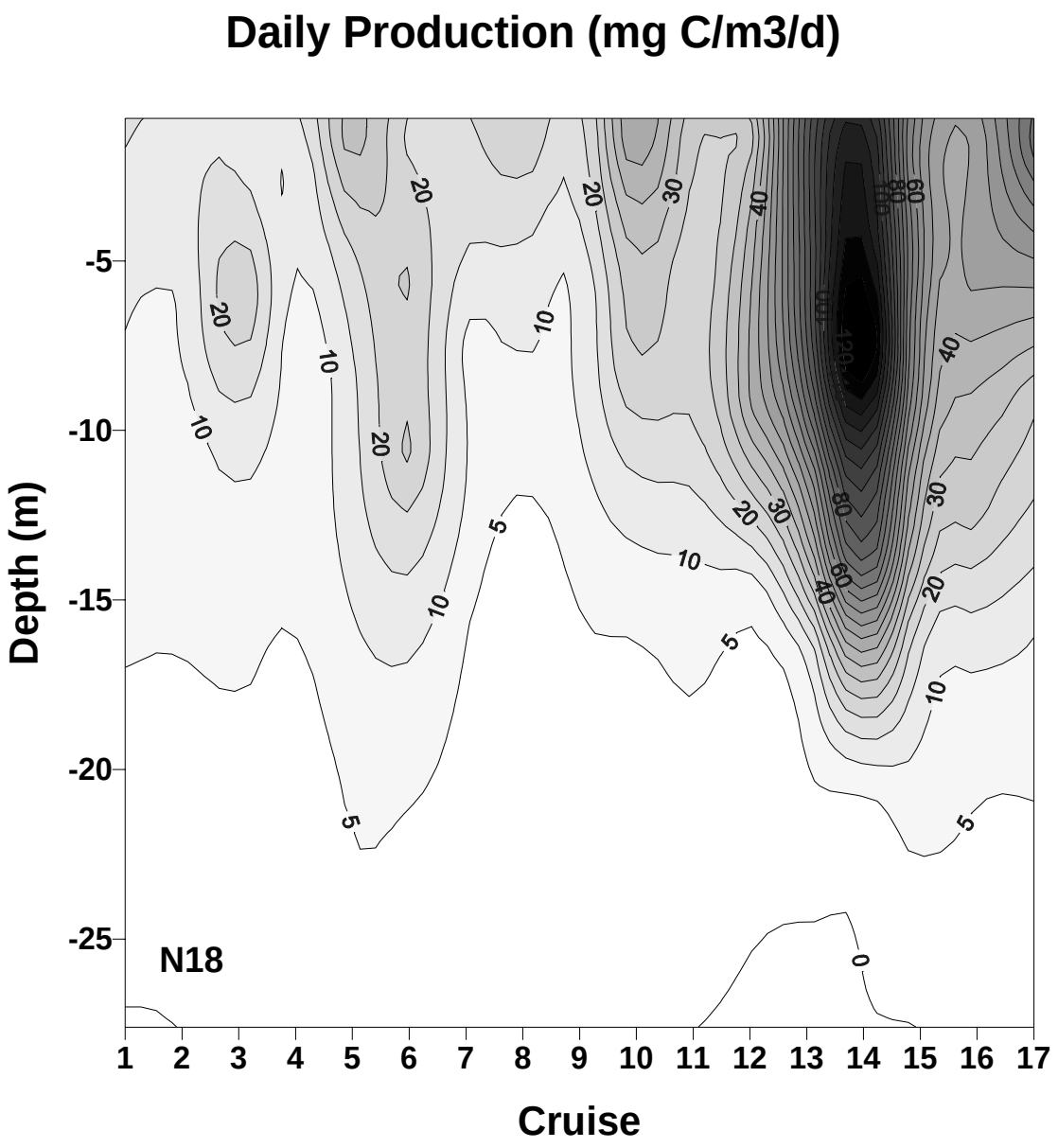


Figure 5-6. Time series of contoured daily production ($mgCm^{-3}d^{-1}$) over depth (m) at station N18.

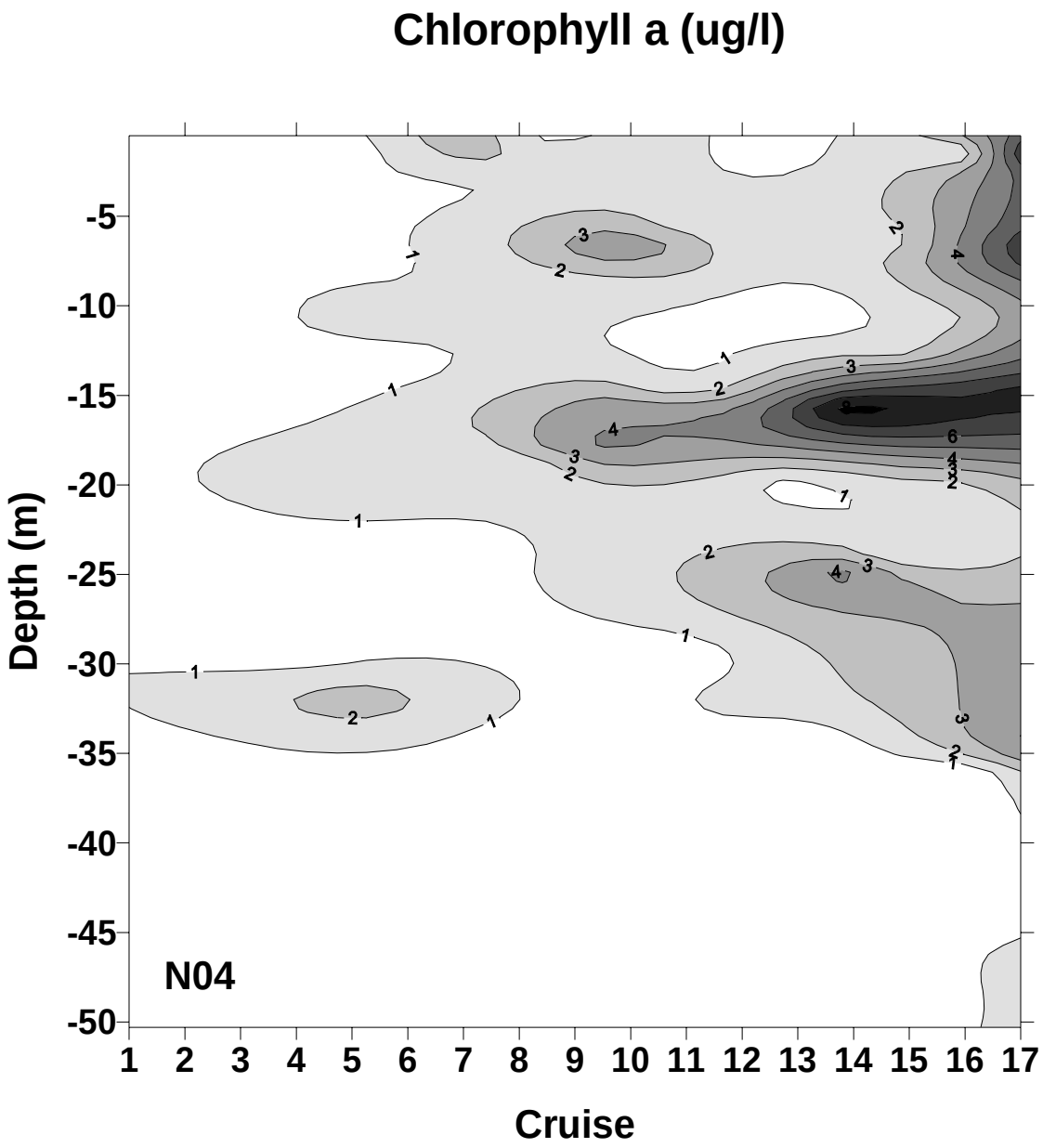


Figure 5-7. Time series of contoured chlorophyll *a* (µg l^{-1}) over depth (m) at station N04.

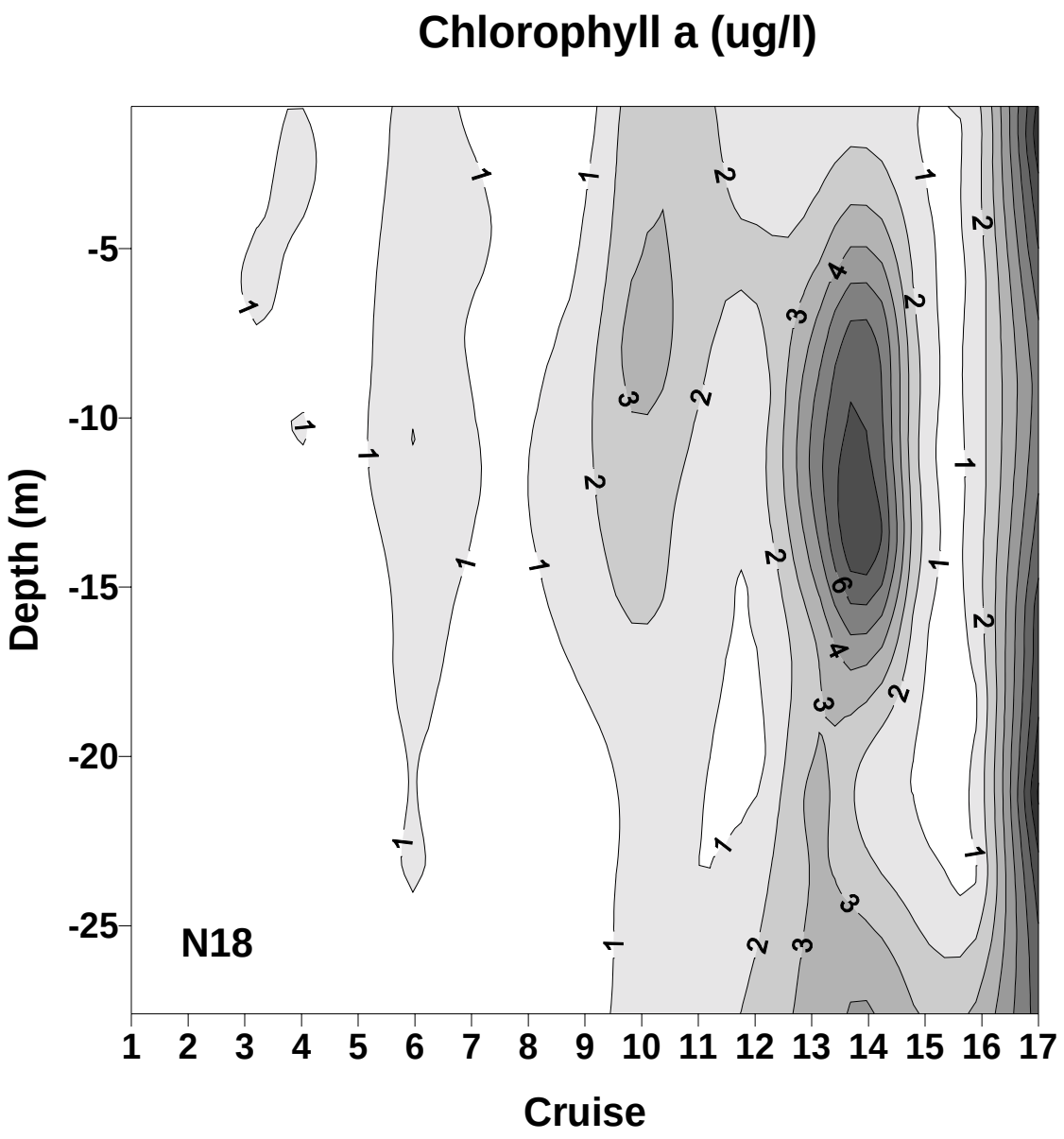


Figure 5-8. Time series of contoured chlorophyll *a* (µg l^{-1}) over depth (m) at station N18.

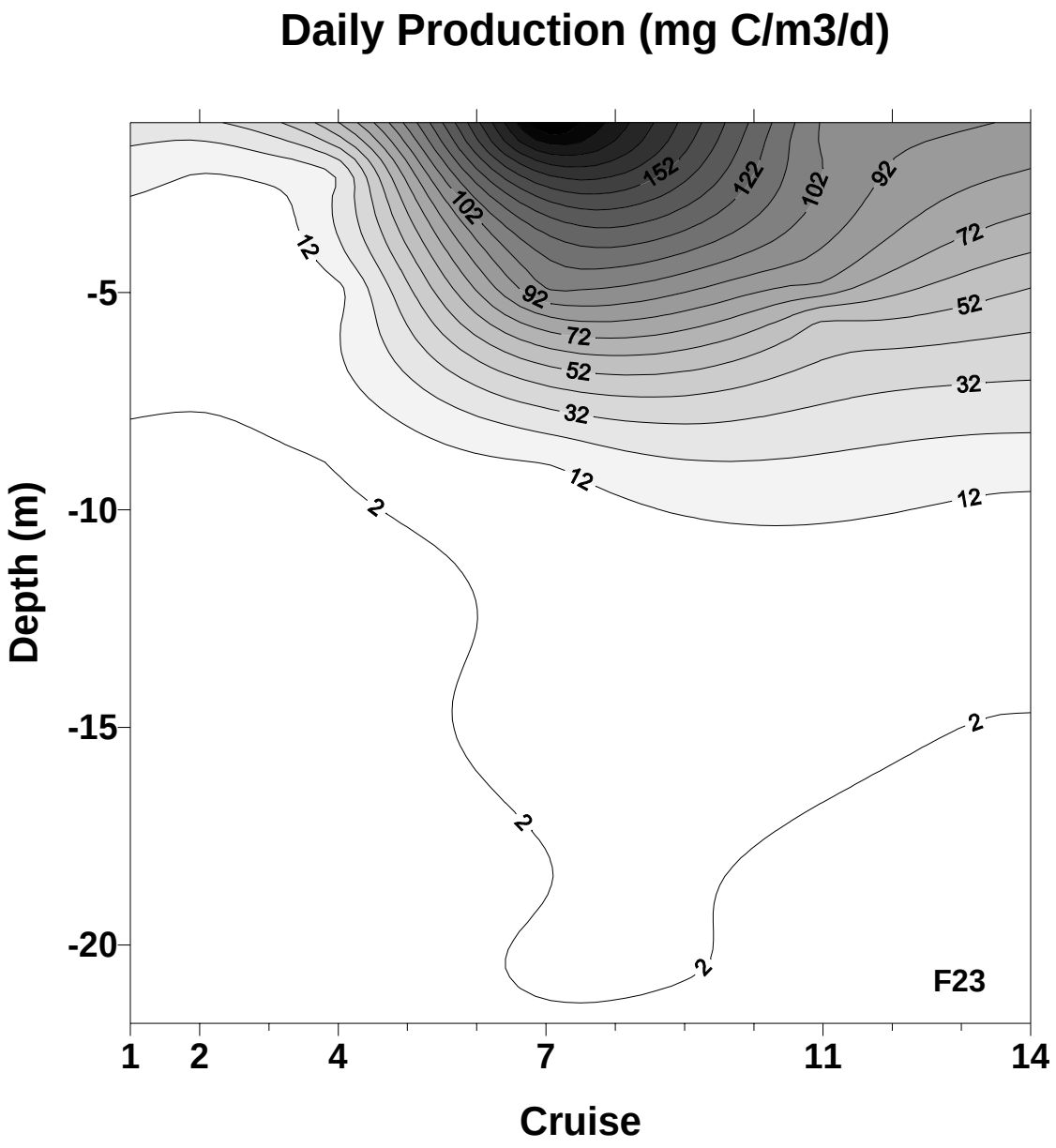


Figure 5-9. Time series of contoured daily production ($mgCm^{-3}d^{-1}$) over depth (m) at station F23.

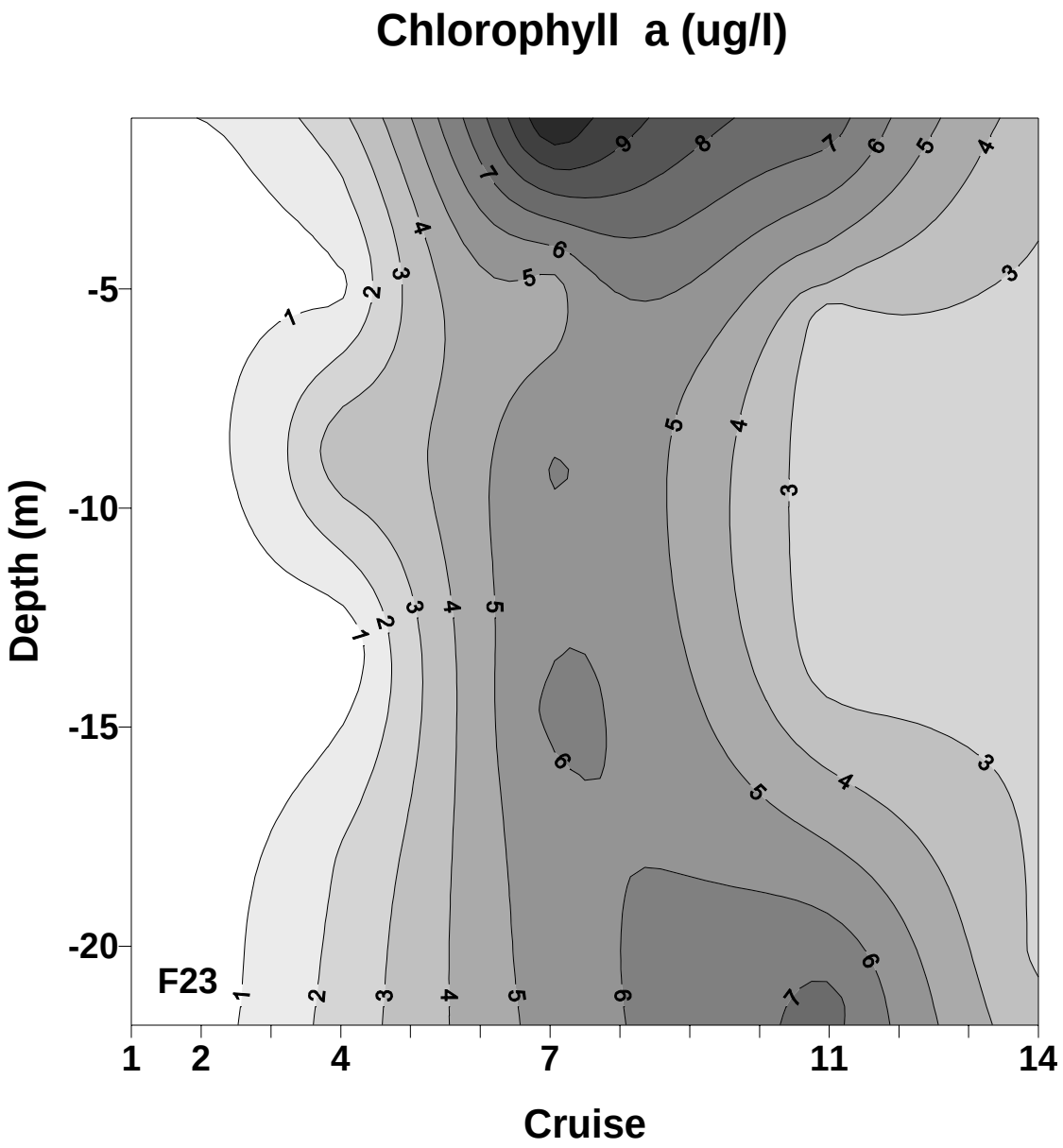


Figure 5-10. Time series of contoured chlorophyll *a* (µg l^{-1}) over depth (m) at station F23.

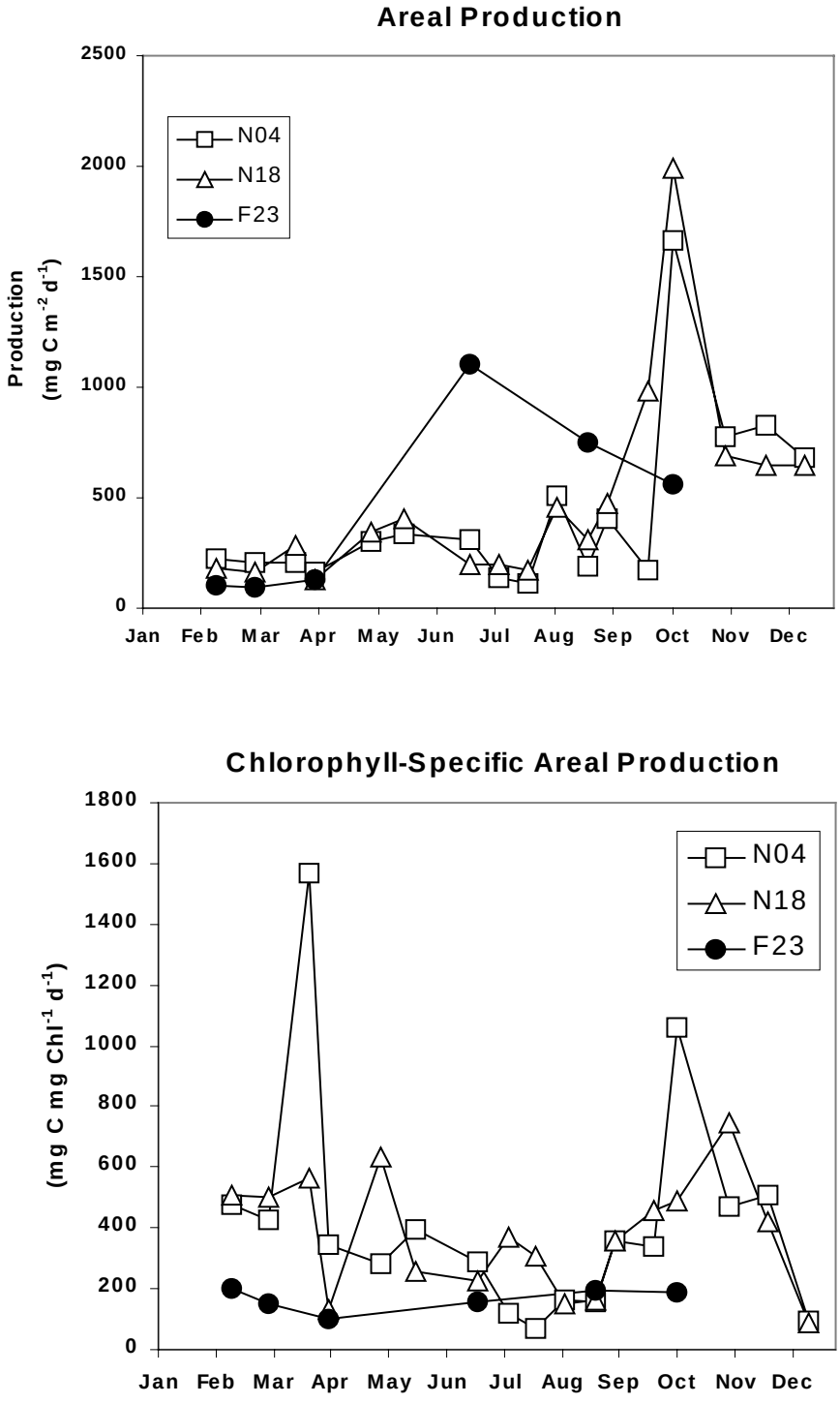


Figure 5-11. Time series of areal production ($mgCm^{-2}d^{-1}$) and chlorophyll-specific areal production ($mgCmgChl\mathit{a}^{-1}d^{-1}$) for stations N04, N18 and F23 over the annual cycle.

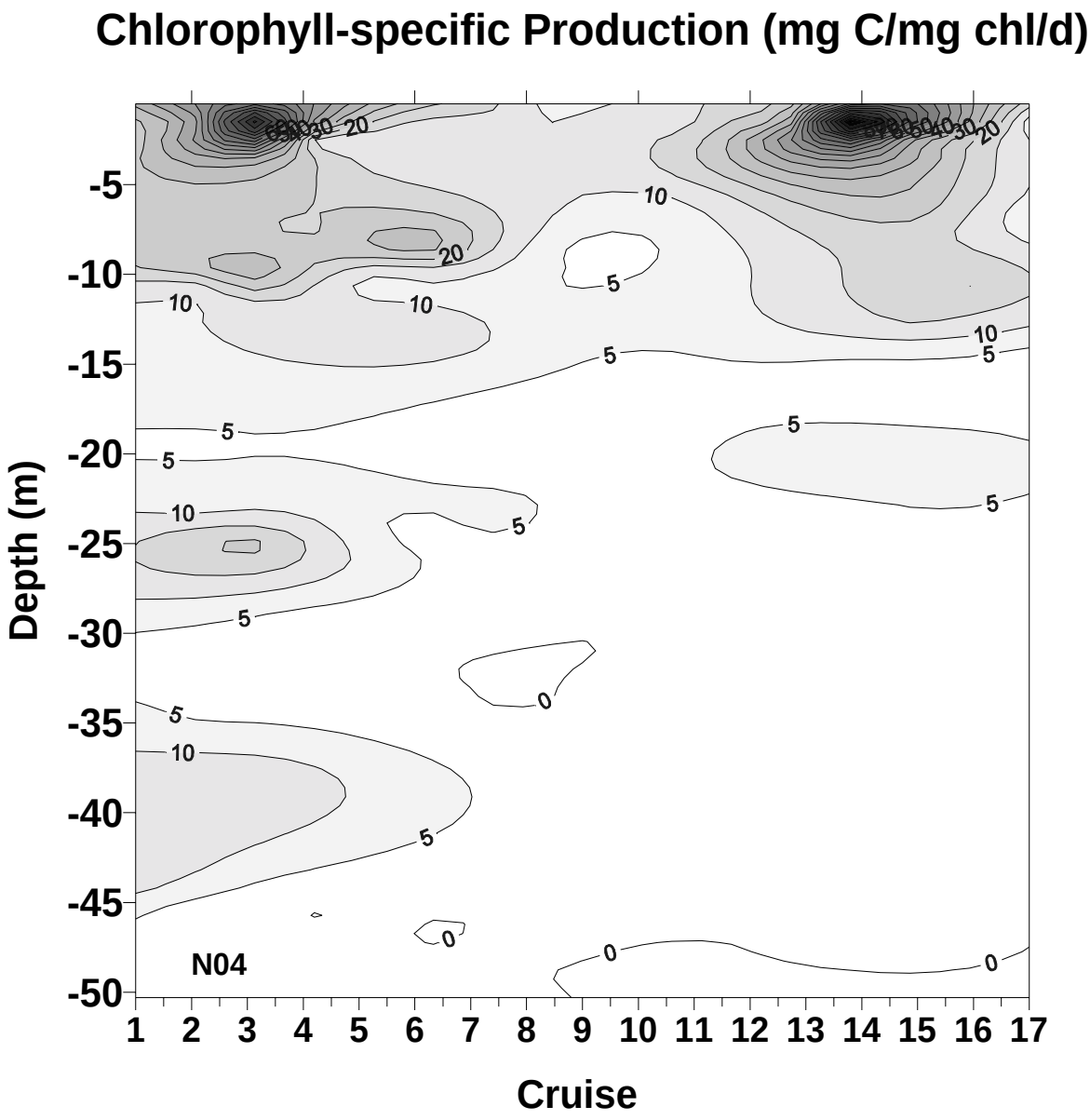


Figure 5-12. Time series of contoured chlorophyll-specific production (mgCmgChl*a*$^{-1}$d^{-1}) over depth (m) at station N04.

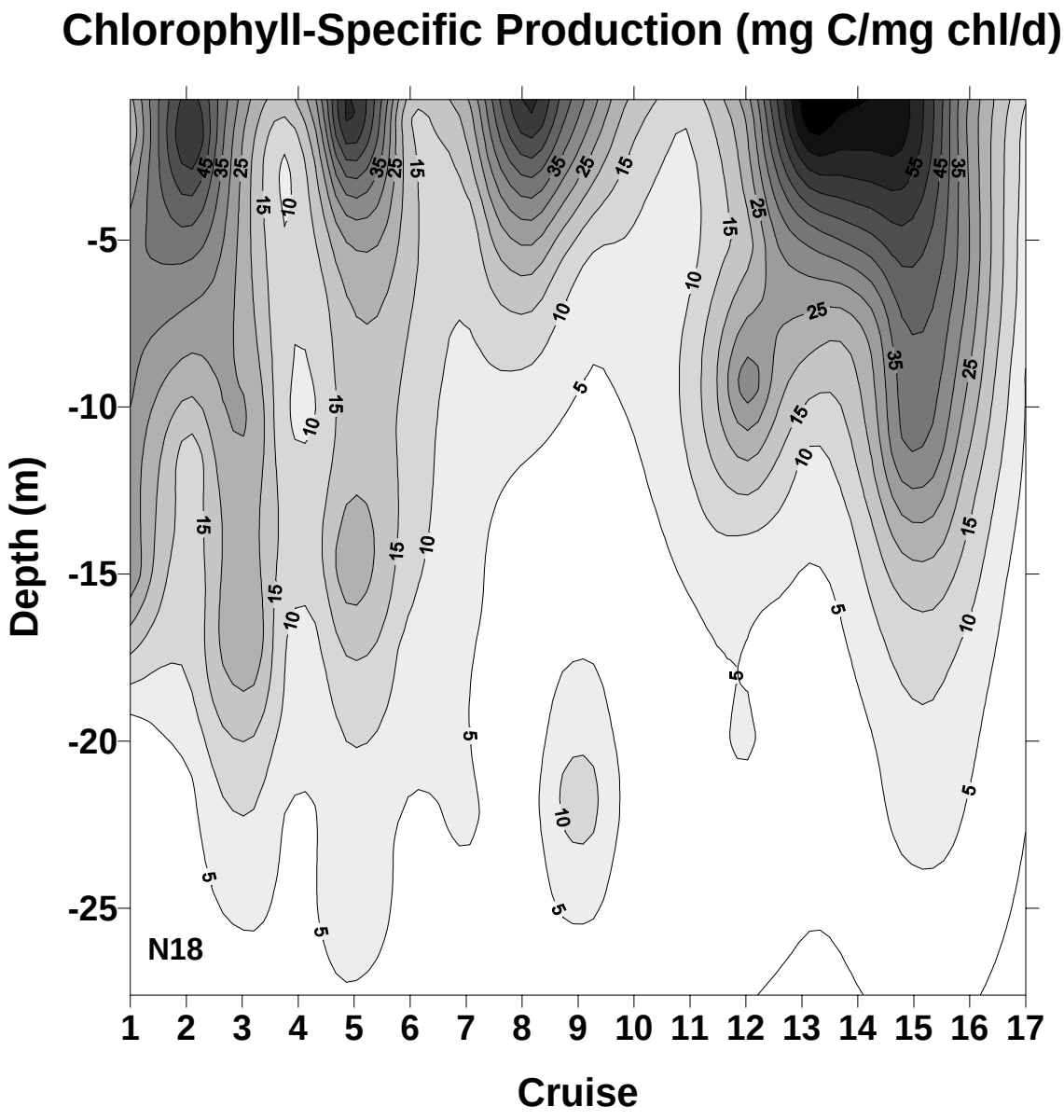


Figure 5-13. Time series of contoured chlorophyll-specific production (mgCmgChl*a*$^{-1}$d^{-1}) over depth (m) at station N18.

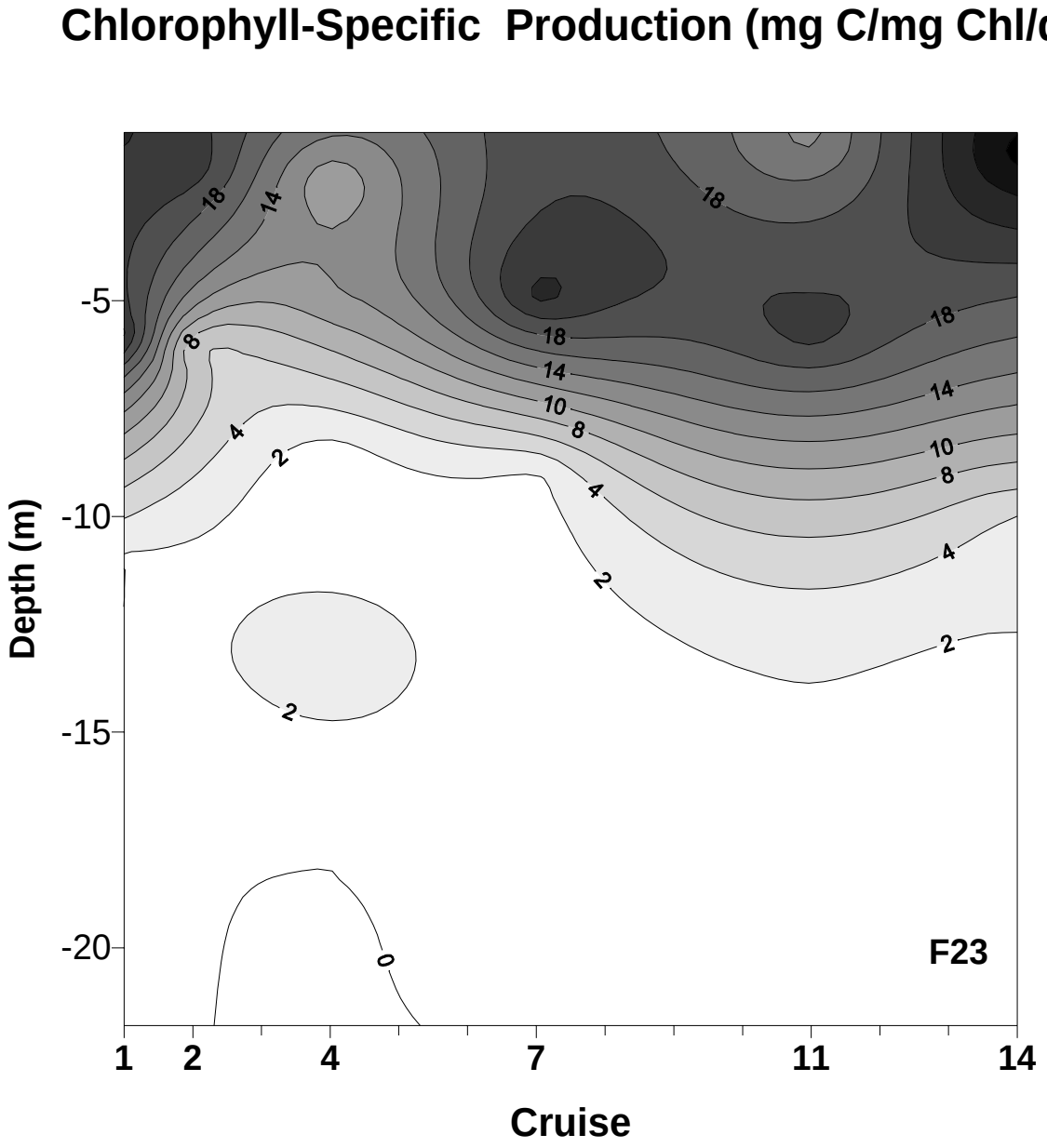


Figure 5-14. Time series of contoured chlorophyll-specific production (mgCmgChl*a*$^{-1}$d^{-1}) over depth (m) at station F23.

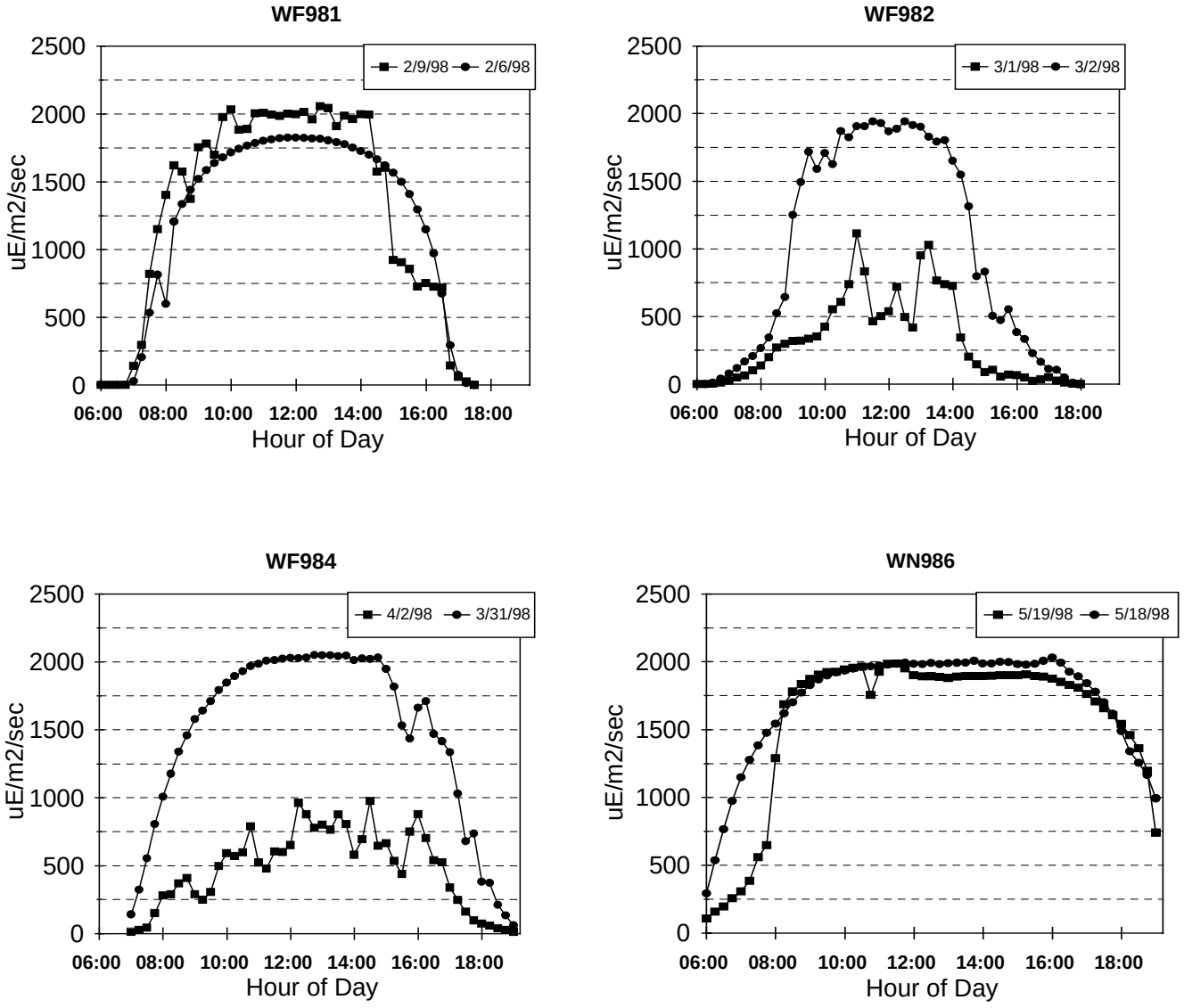


Figure 5-15. Photoperiod light field over the course of the day during the four surveys demonstrating the differences between observed light on the day of the survey and theoretical maximum light from a cloudless day close in time to the survey date (used to calculate potential production).

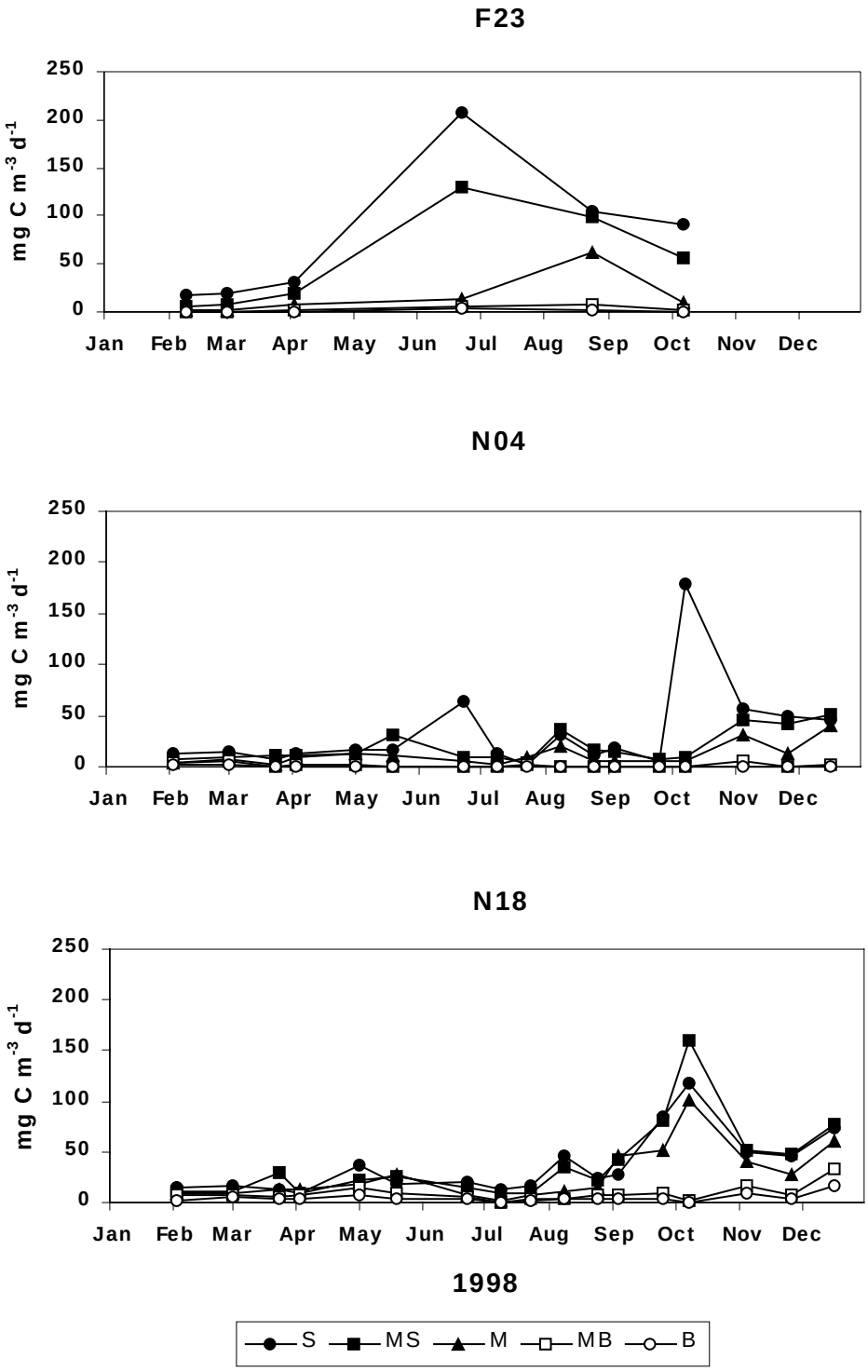


Figure 5-16. Potential production ($mgCm^{-3}d^{-1}$) calculated using incident light from a cloudless day over the annual cycle for each station and depth.

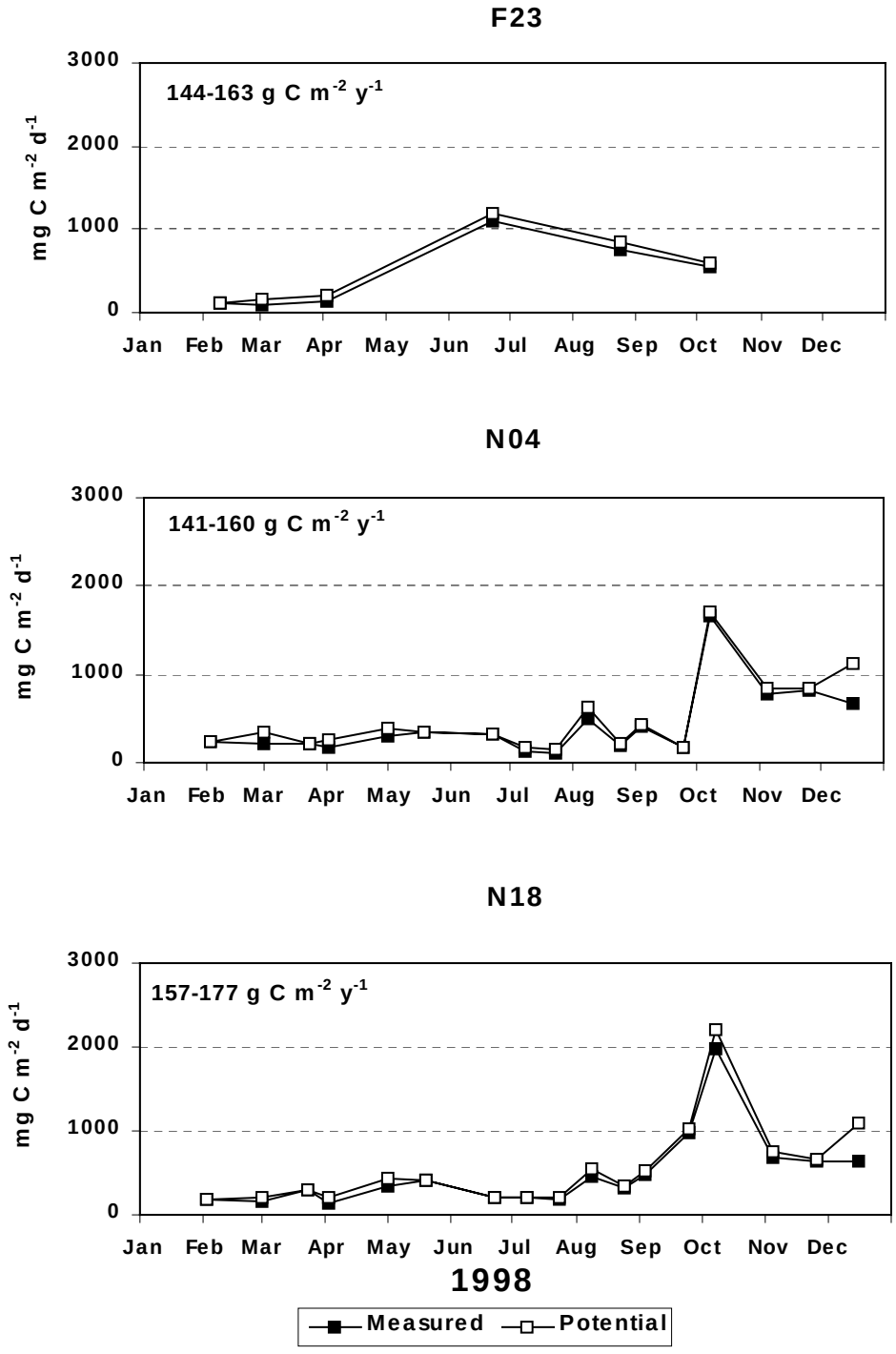


Figure 5-17. Measured and potential areal production ($mgCm^{-2}d^{-1}$) for the 1998 season. Annual and potential annual production ($gCm^{-2}y^{-1}$) are shown in the panel insets, with the higher value being the potential annual production at each station.

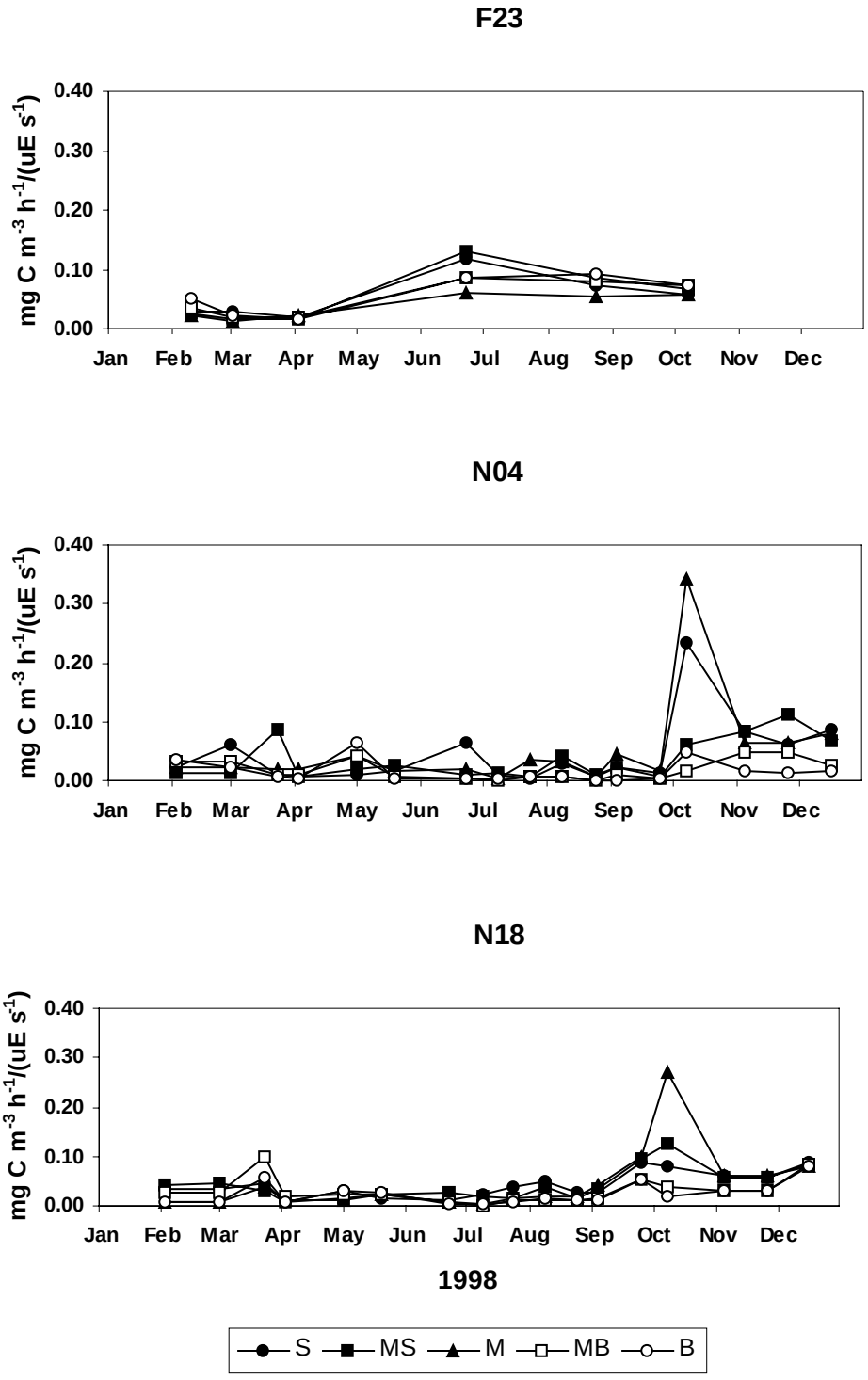


Figure 5-18. Alpha, α, [mgCm^{-3}h^{-1}(μE m^{-2} s^{-1})] in 1998 at stations F23, N04, and N18 at 5 depths.

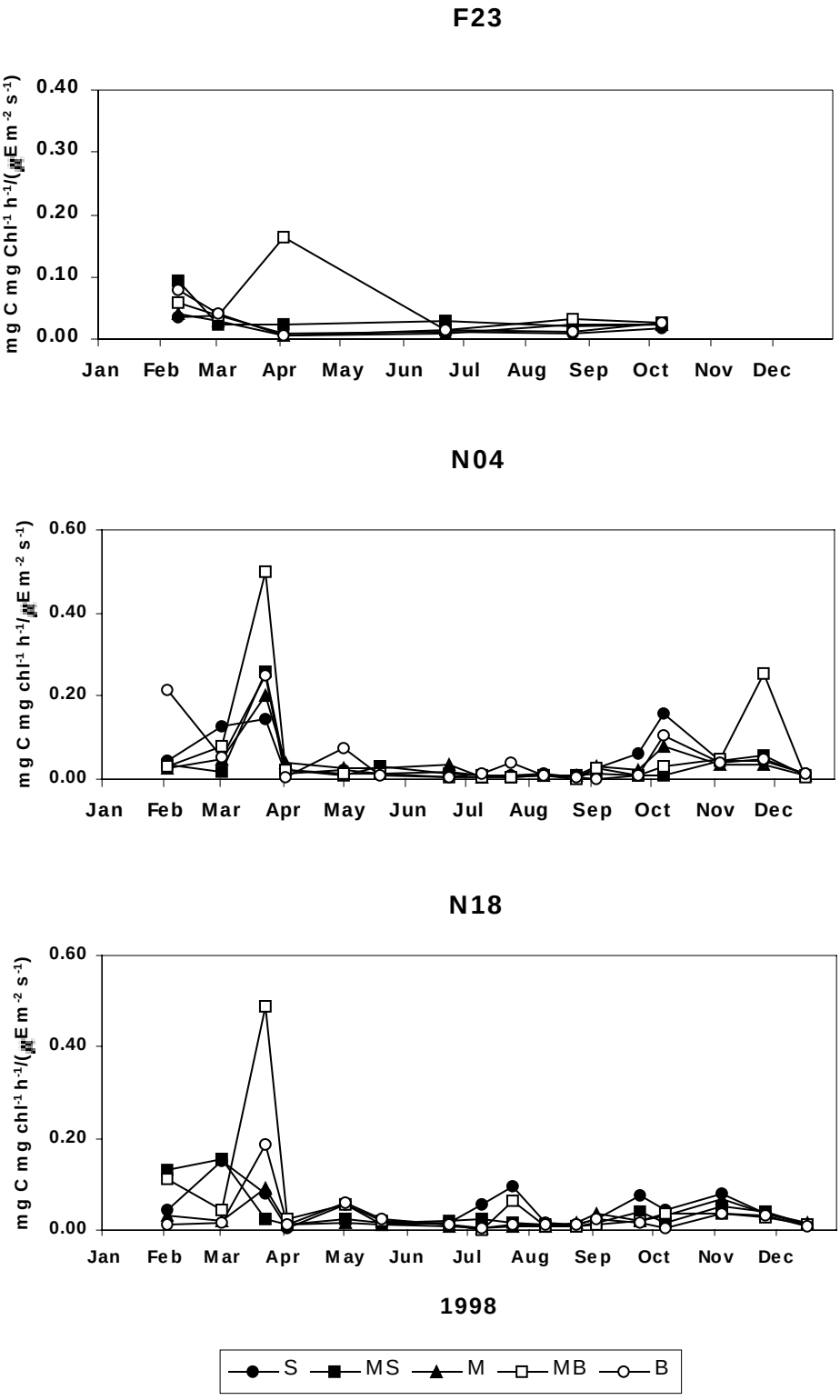


Figure 5-19. Chlorophyll-specific alpha, α^B, mgC(mgChl*a*)$^{-1}$h^{-1}(µEm^{-2}s^{-1})$^{-1}$ in 1998 at stations F23, N04, and N18 at 5 depths.

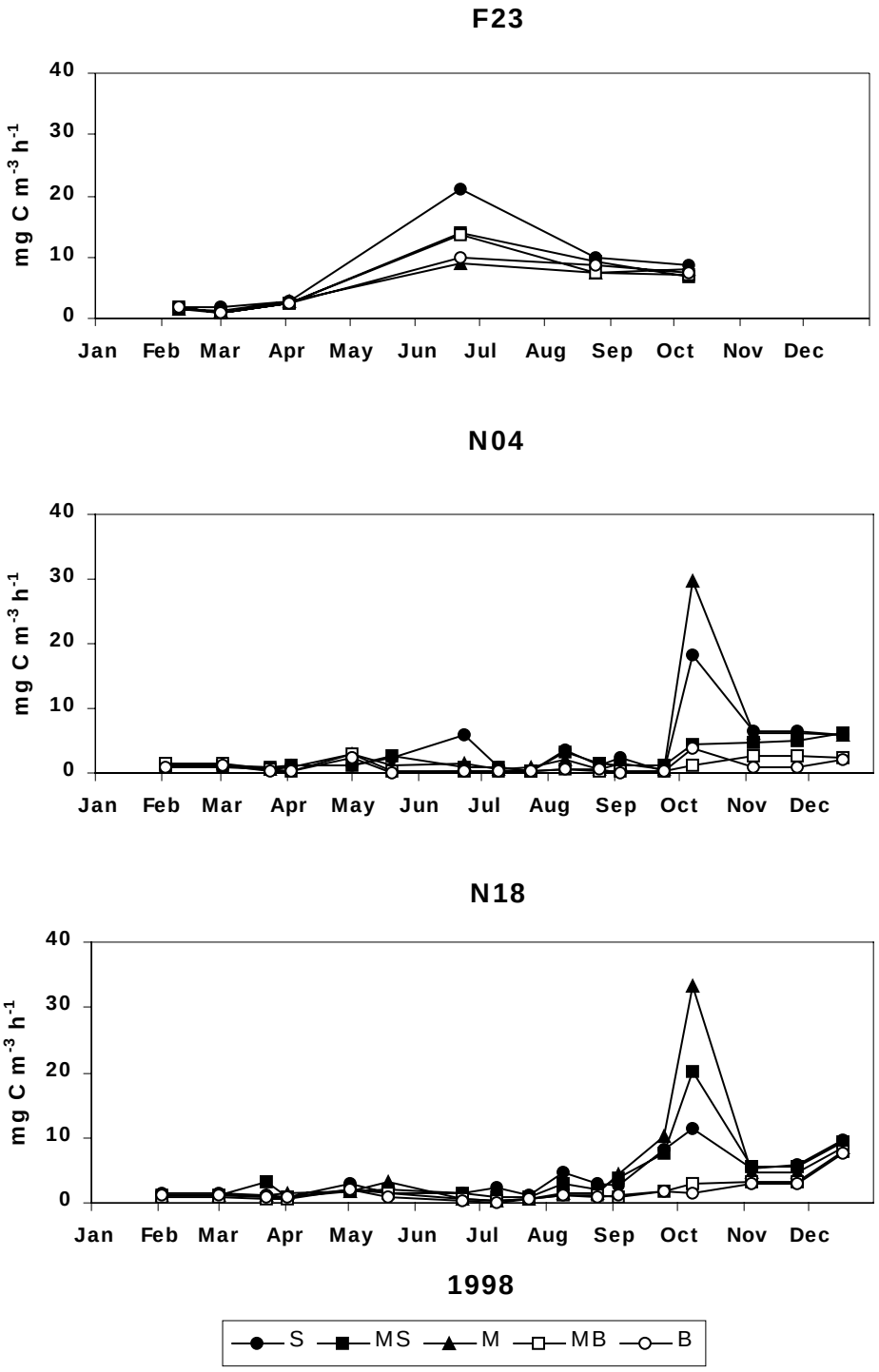


Figure 5-20. P_{max} ($mgCm^{-3}h^{-1}$) in 1998 at stations F23, N04, and N18 at 5 depths.

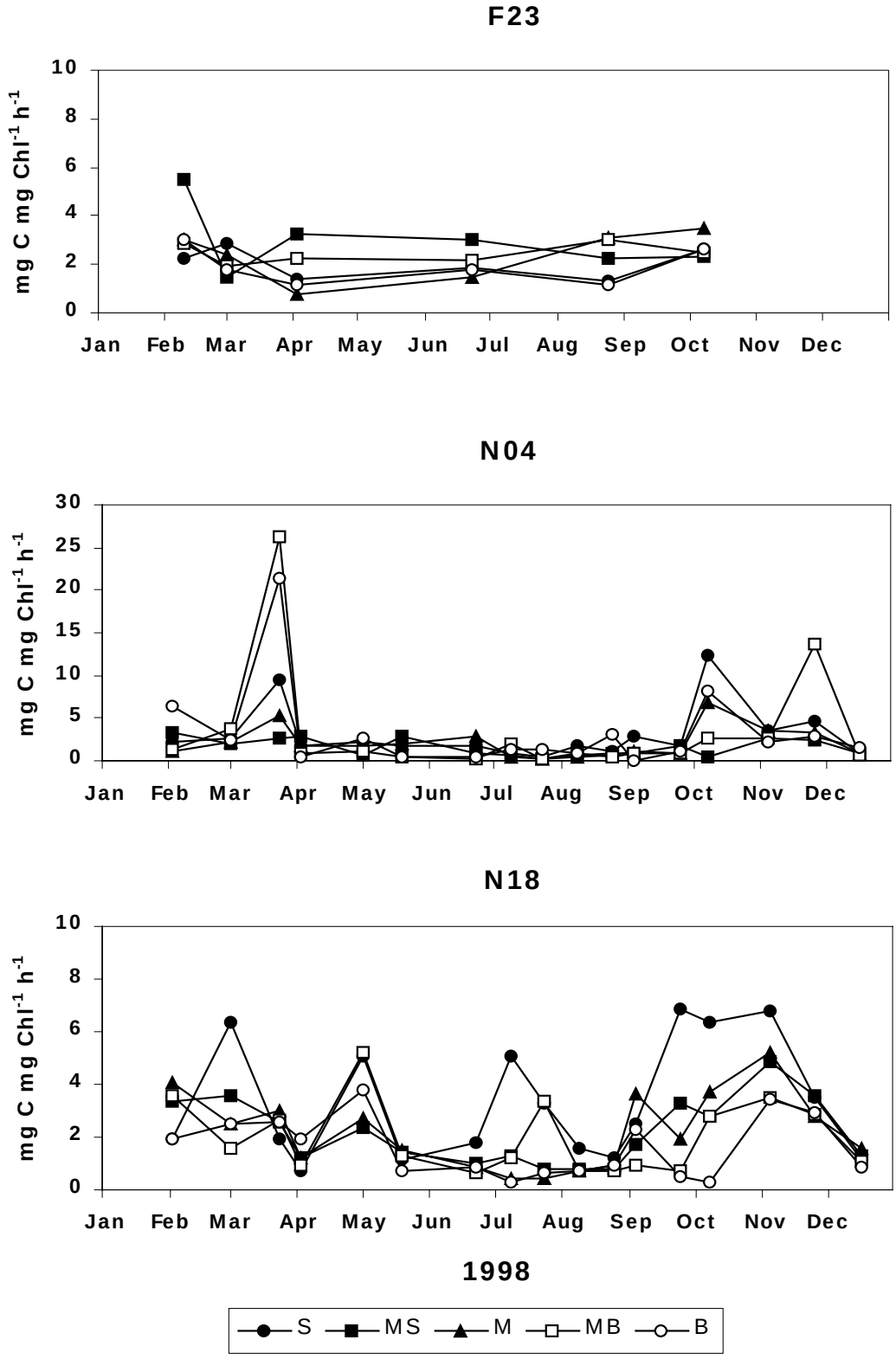


Figure 5-21. P^{B}_{max} (mgCmgChl*a*$^{-1}$h^{-1}) in 1998 at stations F23, N04, and N18 at 5 depths.

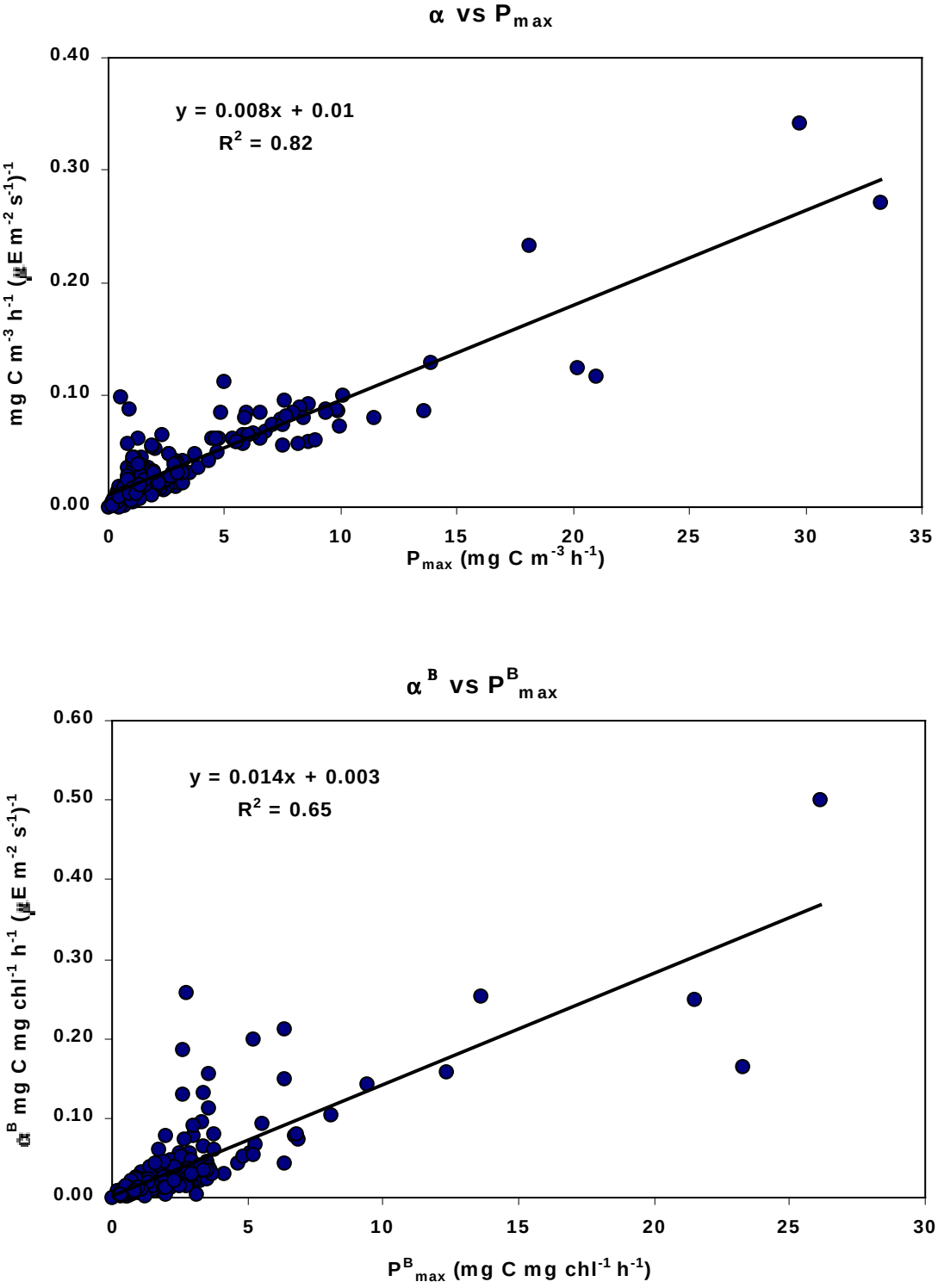
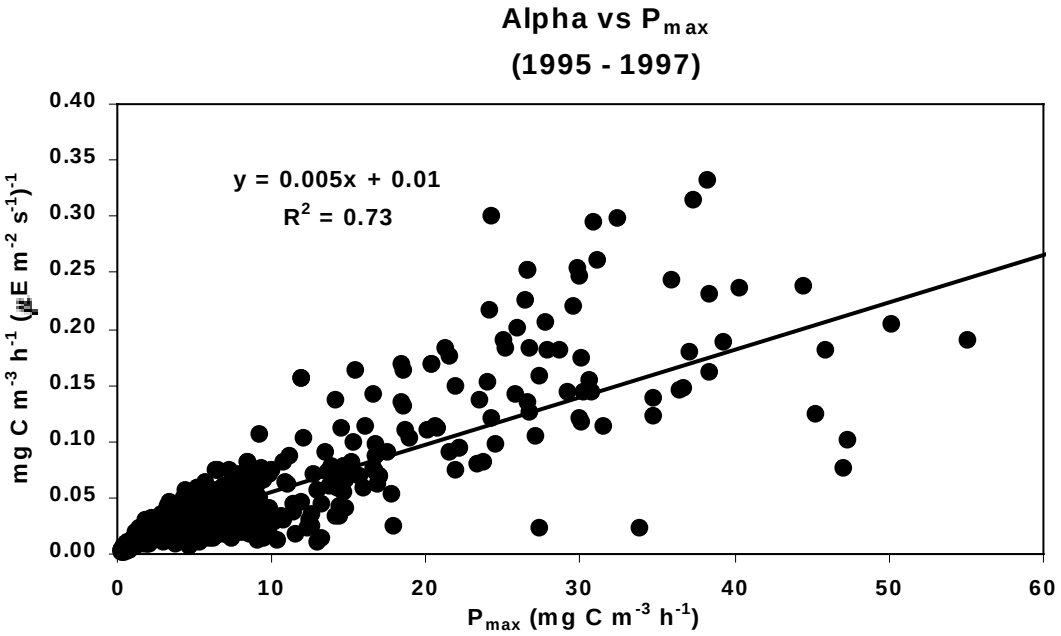


Figure 5-22. Relationship between the fitted values of the parameters of the P-I curves normalized (α^B and P^B_{max}) and not normalized (α and P_{max}) to phytoplankton biomass using the seasonal data for 1998.



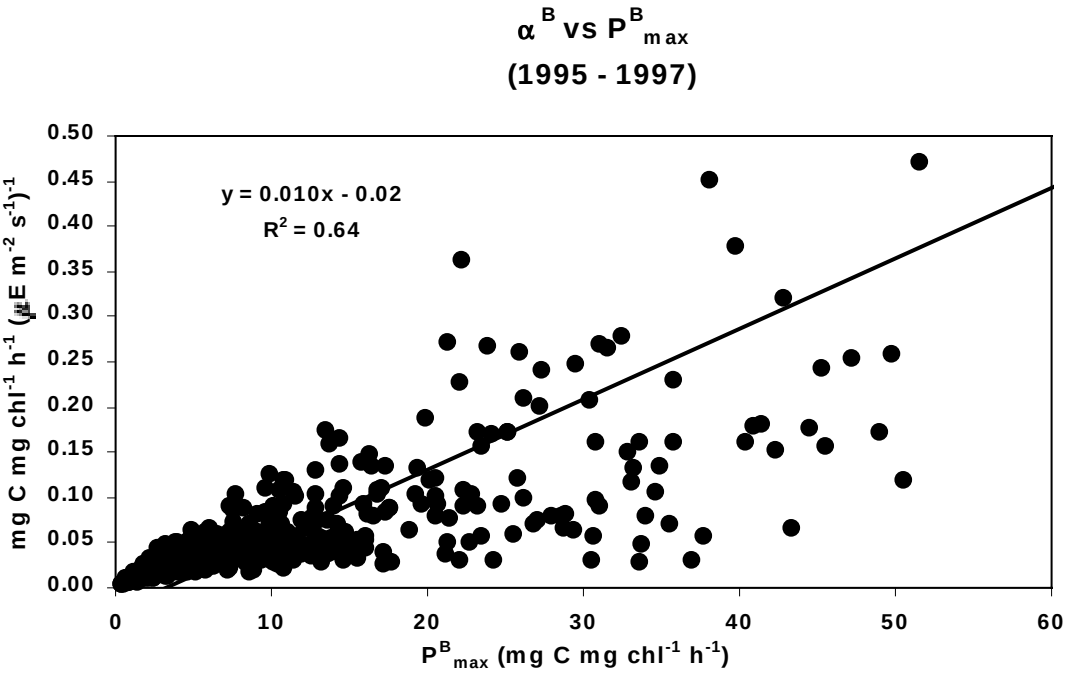


Figure 5-23. Relationship between the fitted values of the parameters of the P-I curves normalized (α^B and P^B_{max}) and not normalized (α and P_{max}) to phytoplankton biomass using the seasonal data for 1995-97.

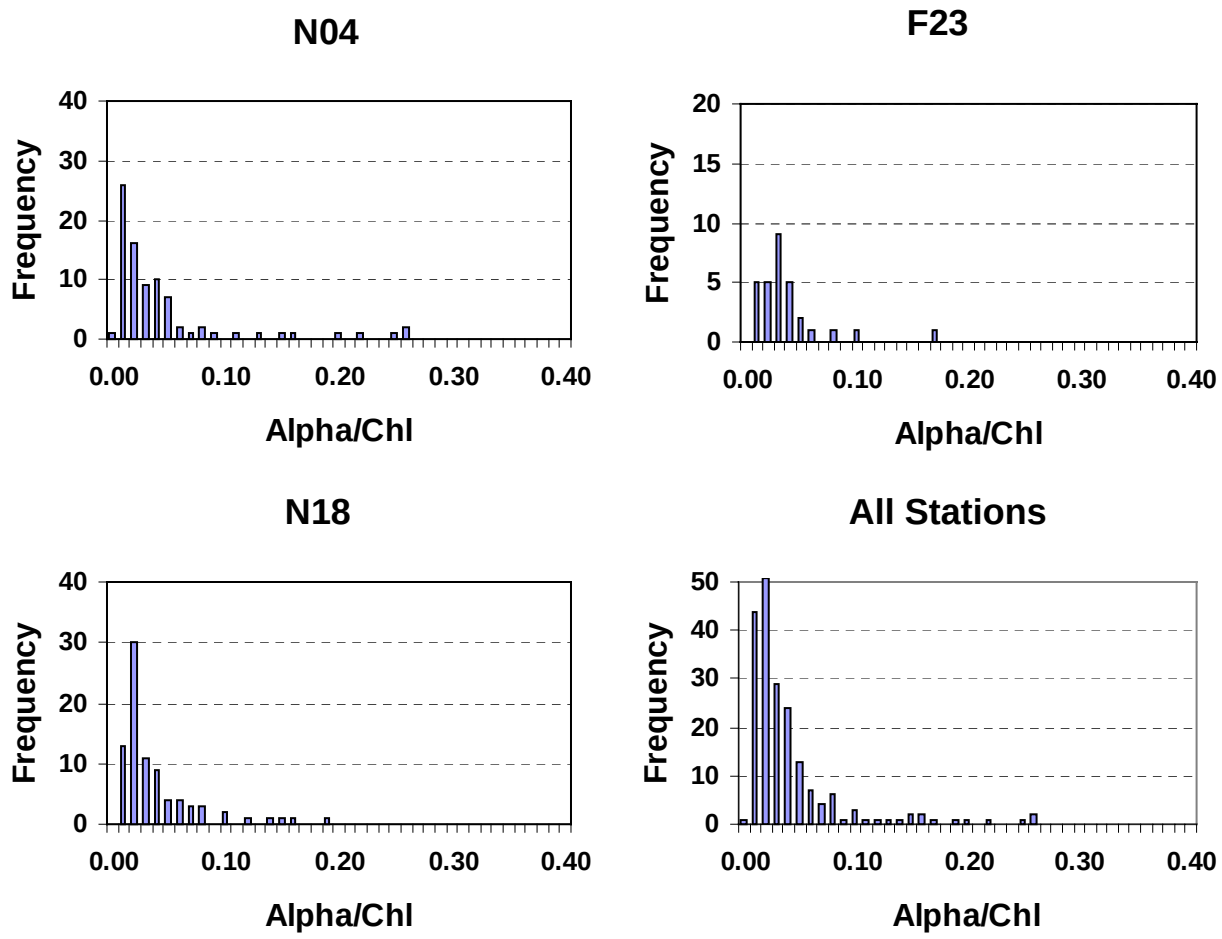


Figure 5-24. Frequency distributions for chlorophyll-specific alpha for stations F23, N04, N18 and the pooled data during 1998.

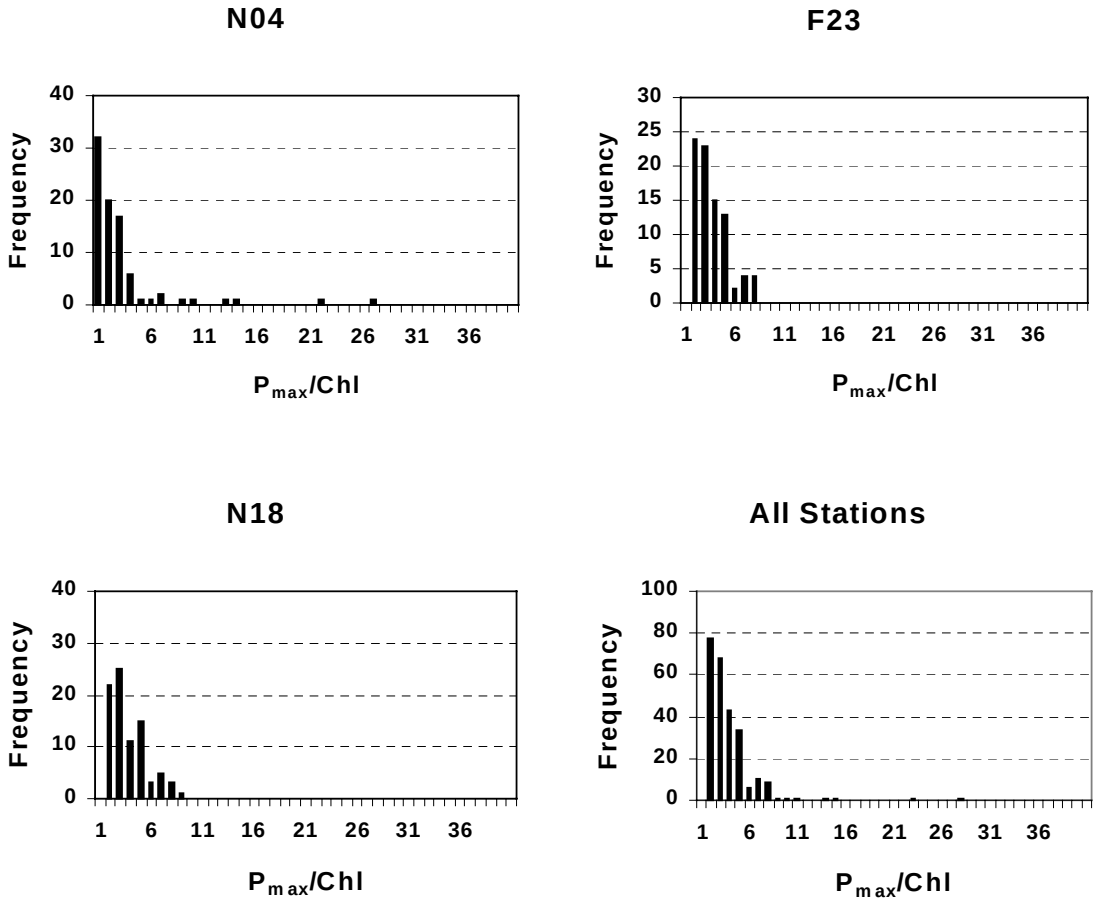
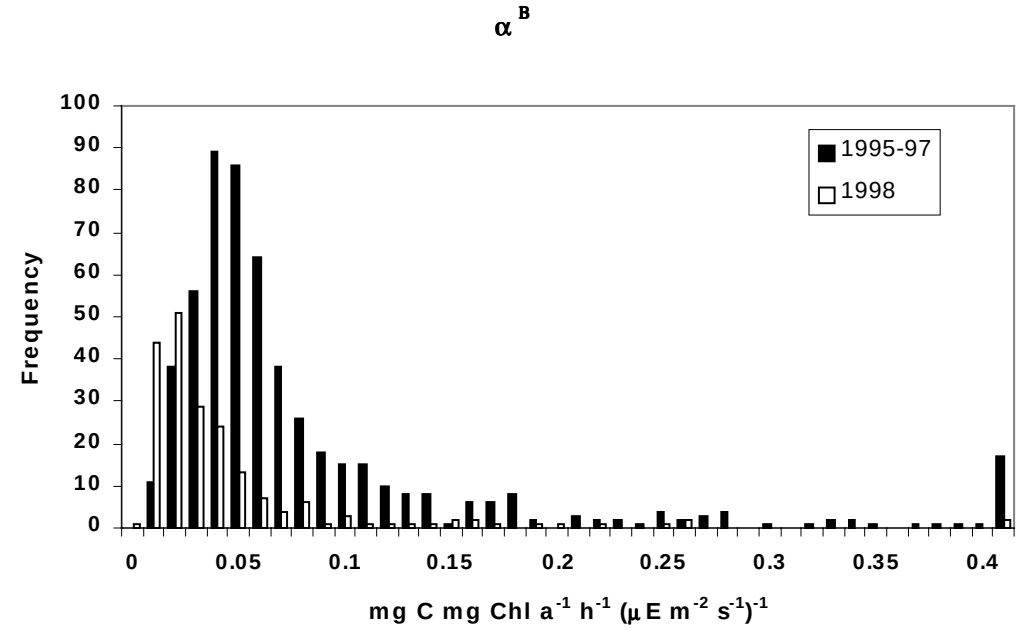


Figure 5-25. Frequency distributions for chlorophyll-specific P^B_{max} for stations F23, N04, N18 and the pooled data during 1998.



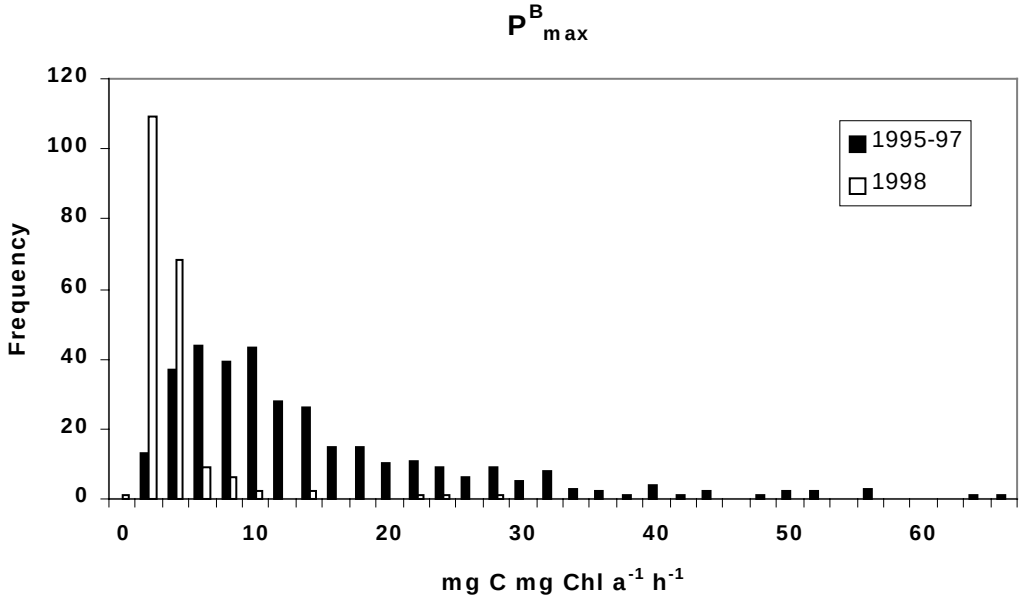


Figure 5-26. Frequency distributions for chlorophyll-specific alpha and P^B_{max} for stations F23, N04, N16 and N18 comparing the 1998 data with earlier years (1995-1997).

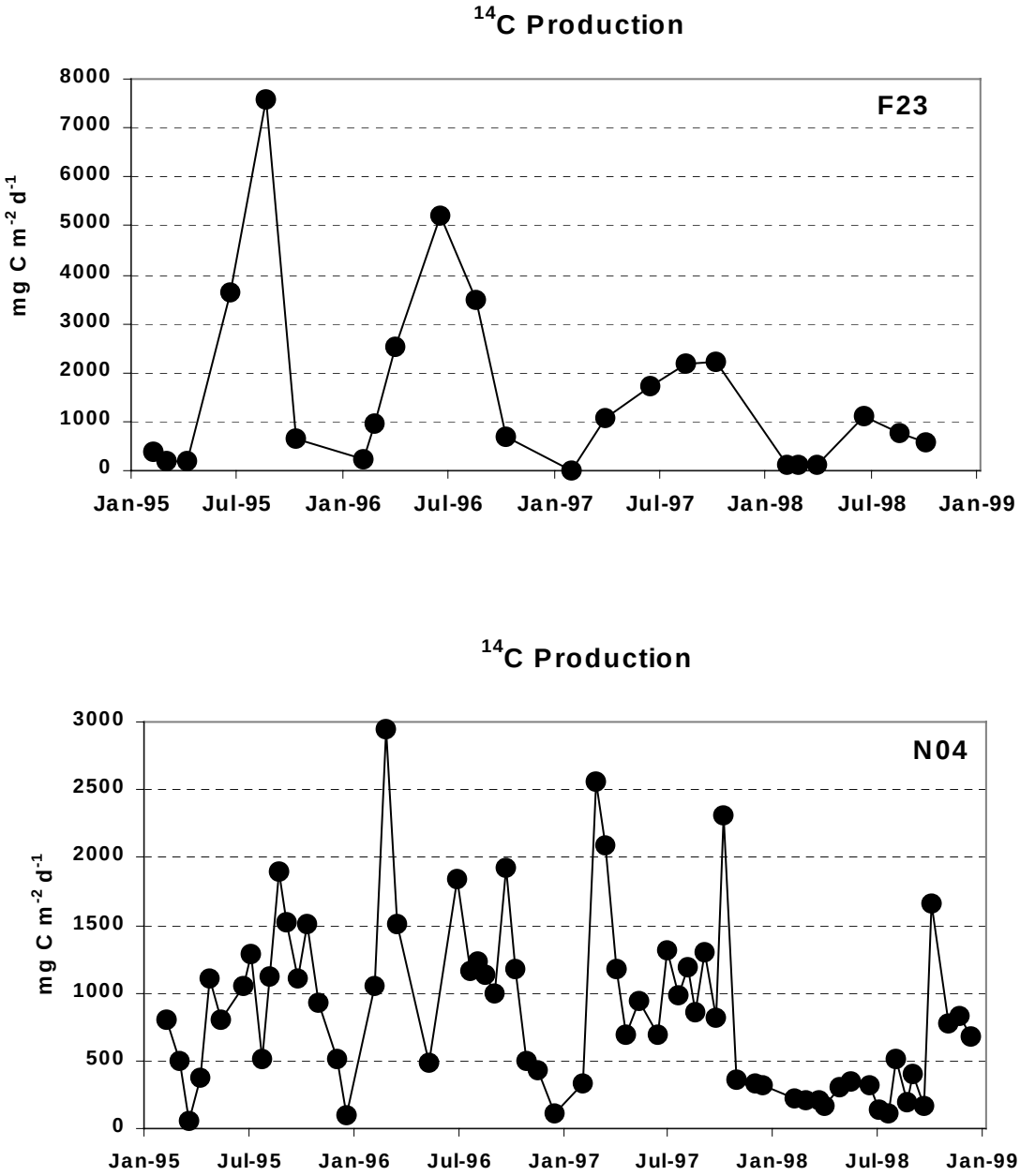


Figure 5-27. Measured phytoplankton production (mg C m^{-2} d^{-1}) from 1995-1998 for stations N04 and F23. Data for 1998, present study; data for 1995-97 from Cibik *et al.* 1996, 1998a, and 1998b.

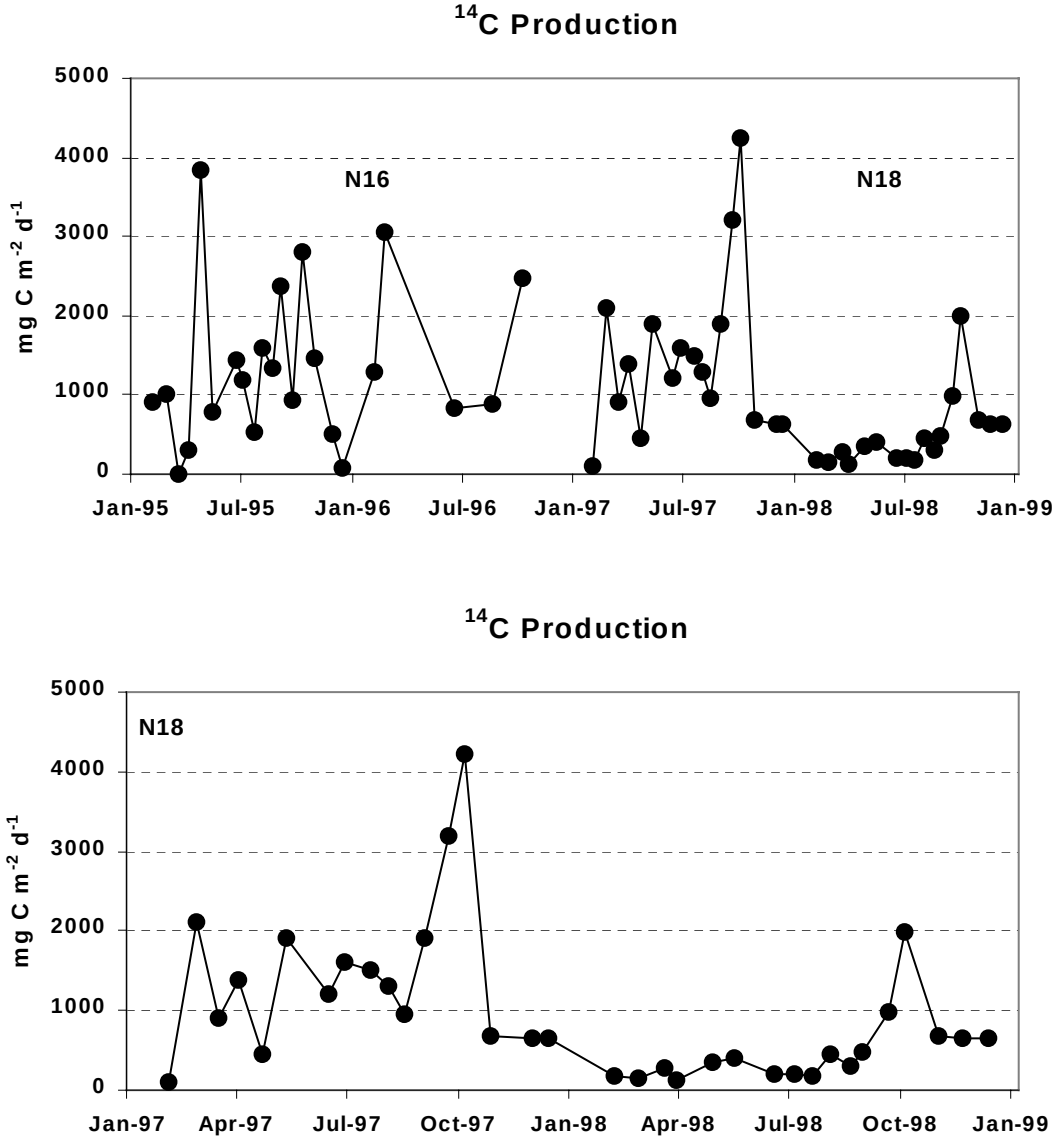


Figure 5-28. Measured phytoplankton production (mg C m^{-2} d^{-1}) from 1995-1998 for stations N16 and N18. Data for 1998, present study; data for 1995-97 from Cibik *et al.* 1996, 1998a, and 1998b.

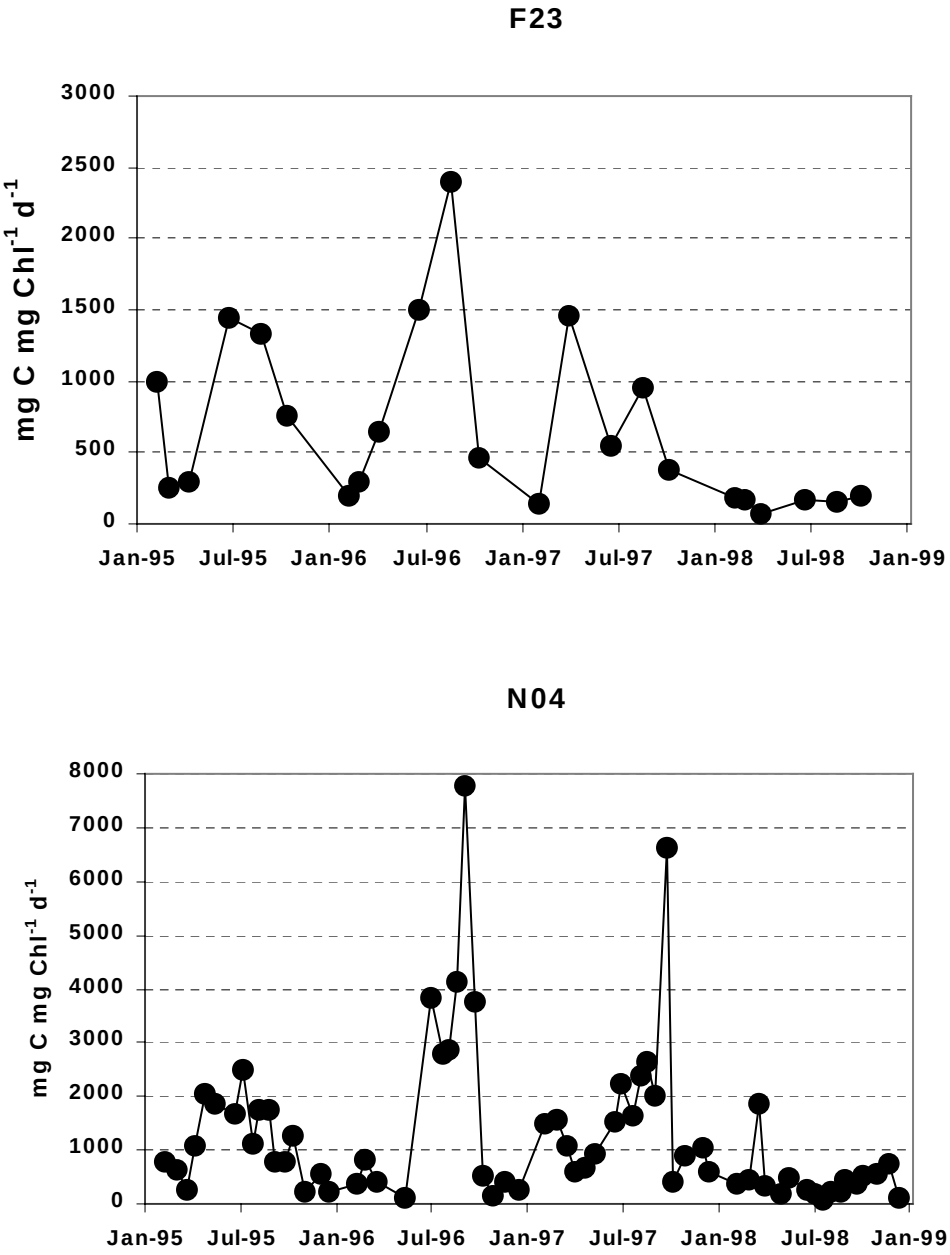


Figure 5-29. Measured chlorophyll-specific phytoplankton production (mg C mg Chl a^{-1} d^{-1}) from 1995-1998 for stations N04 and F23. Data for 1998, present study; data for 1995-97 from Cibik *et al.* 1996, 1998a, and 1998b.

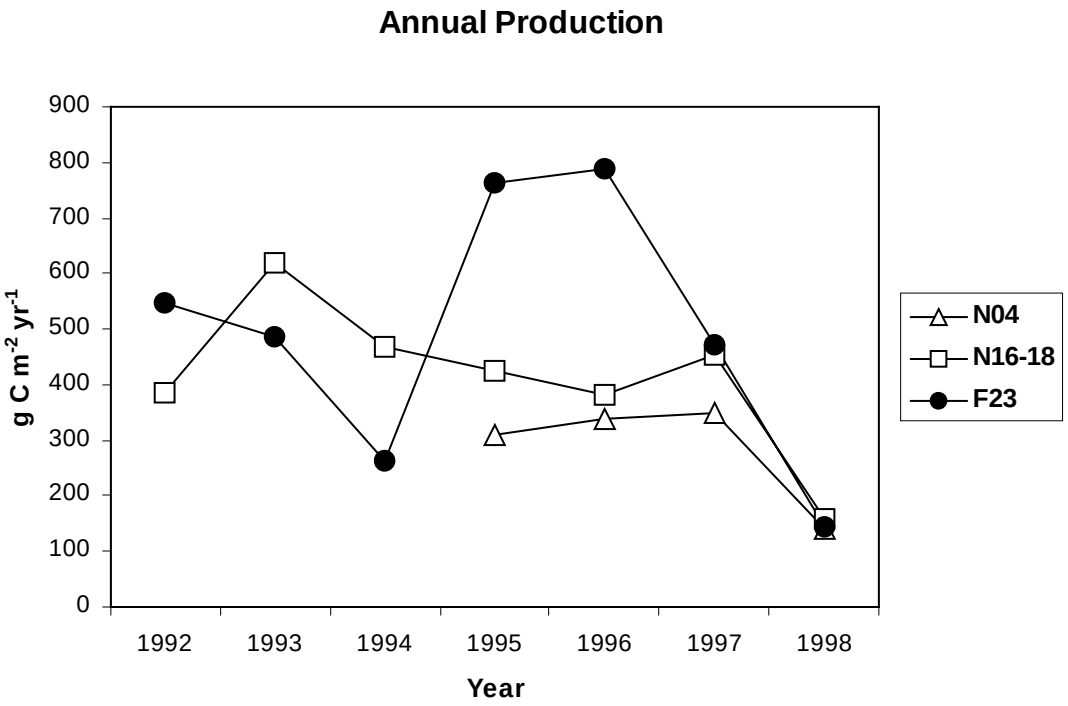


Figure 5-30. Annual production (g C m^{-2} y^{-1}) for stations F23, N04, N16 and N18 from 1992-1998. Data for 1998, present study; data for 1995-97 from Cibik *et al.* 1996, 1998a, and 1998b; data for 1992-94 from Kelly and Doering 1995.

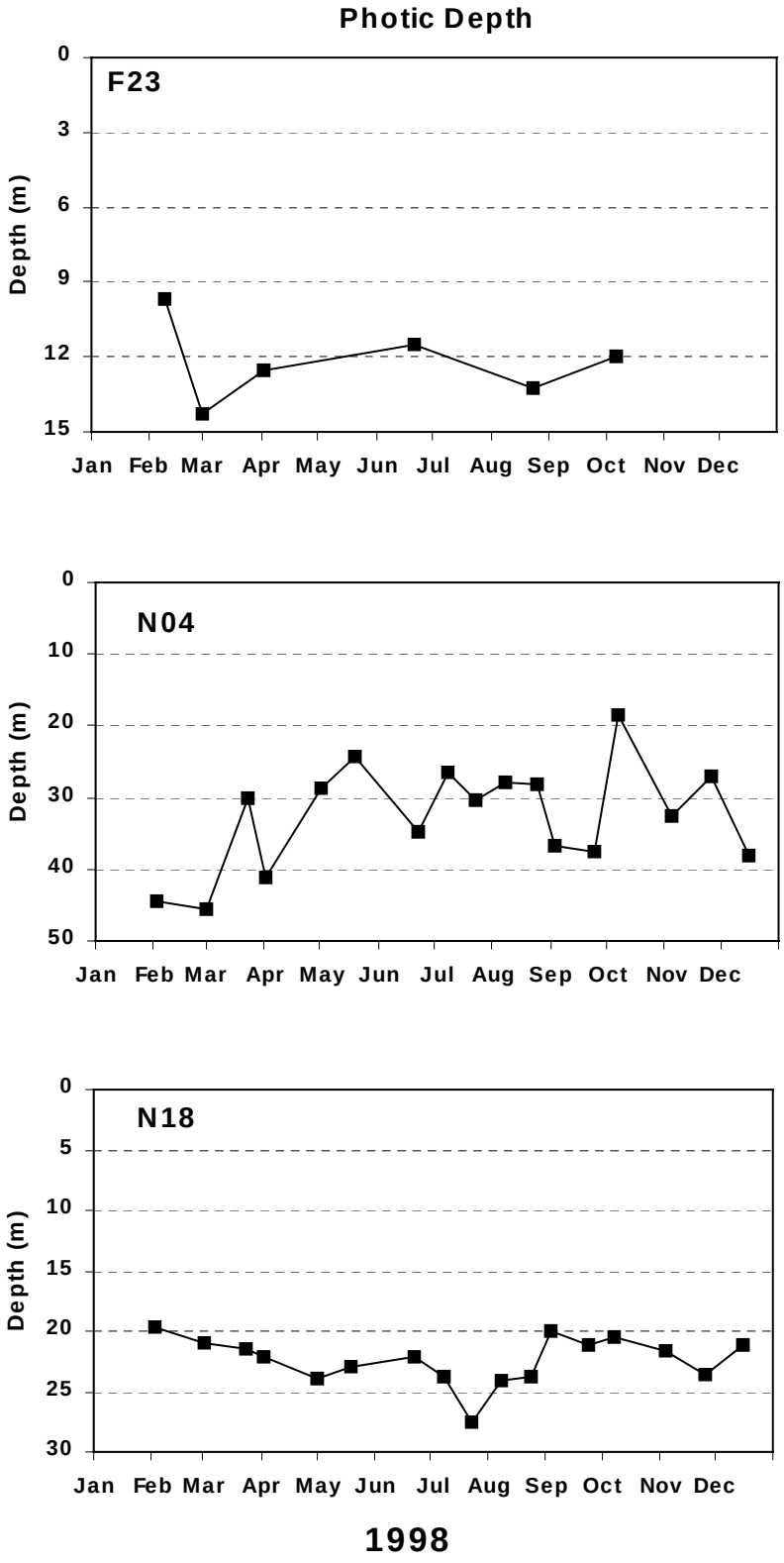


Figure 5-31. Depth (m) of the photic zone as defined by the 0.5% light level at stations F23, N04 and N18 during 1998.

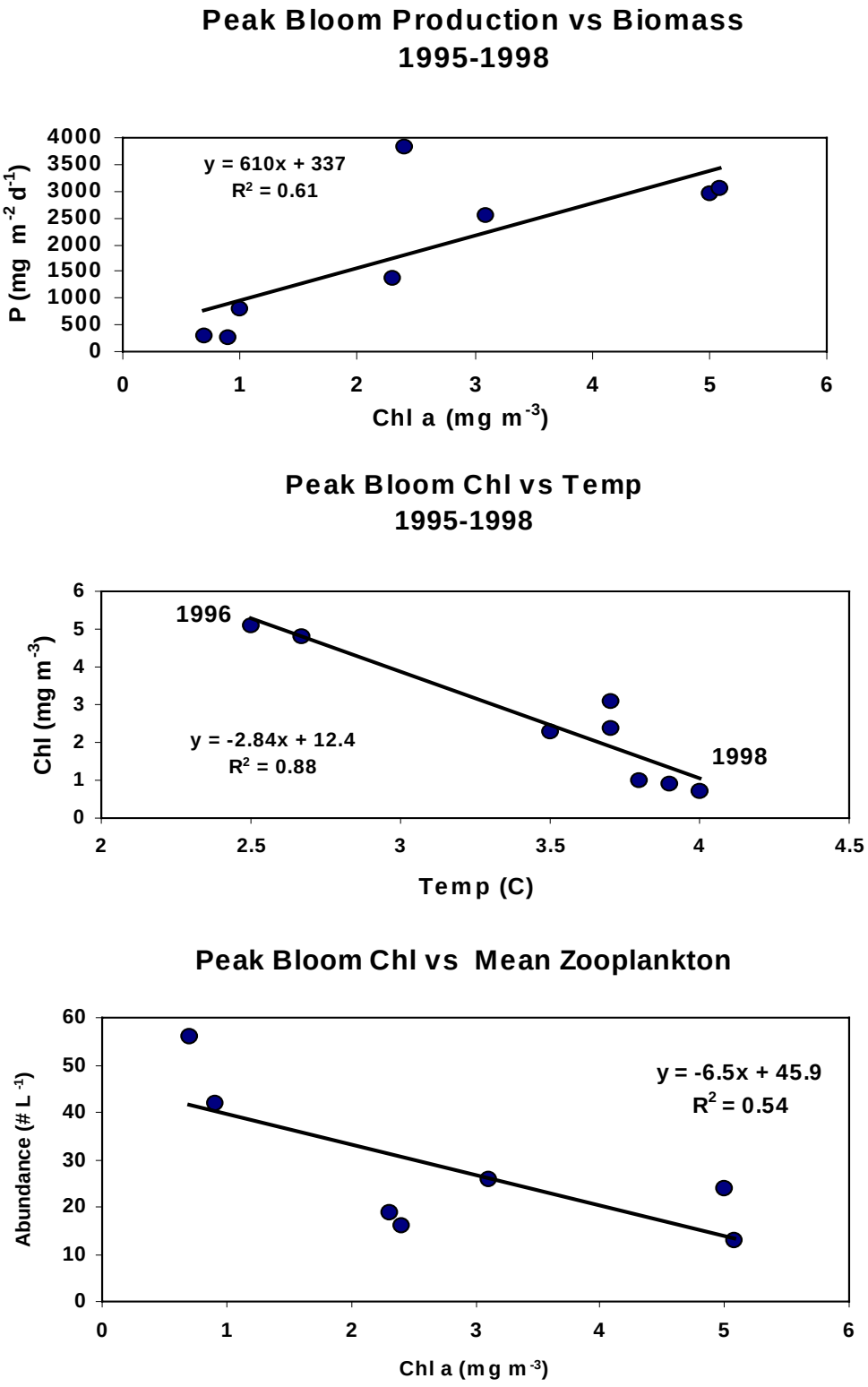


Figure 5-32. Relationships between the peak bloom production (mg C m^{-2} d^{-1}) or the peak bloom biomass (mg Chl a m^{-3}) and biomass, temperature and mean zooplankton abundance (number l^{-1}) over the bloom period for 1995-1998.

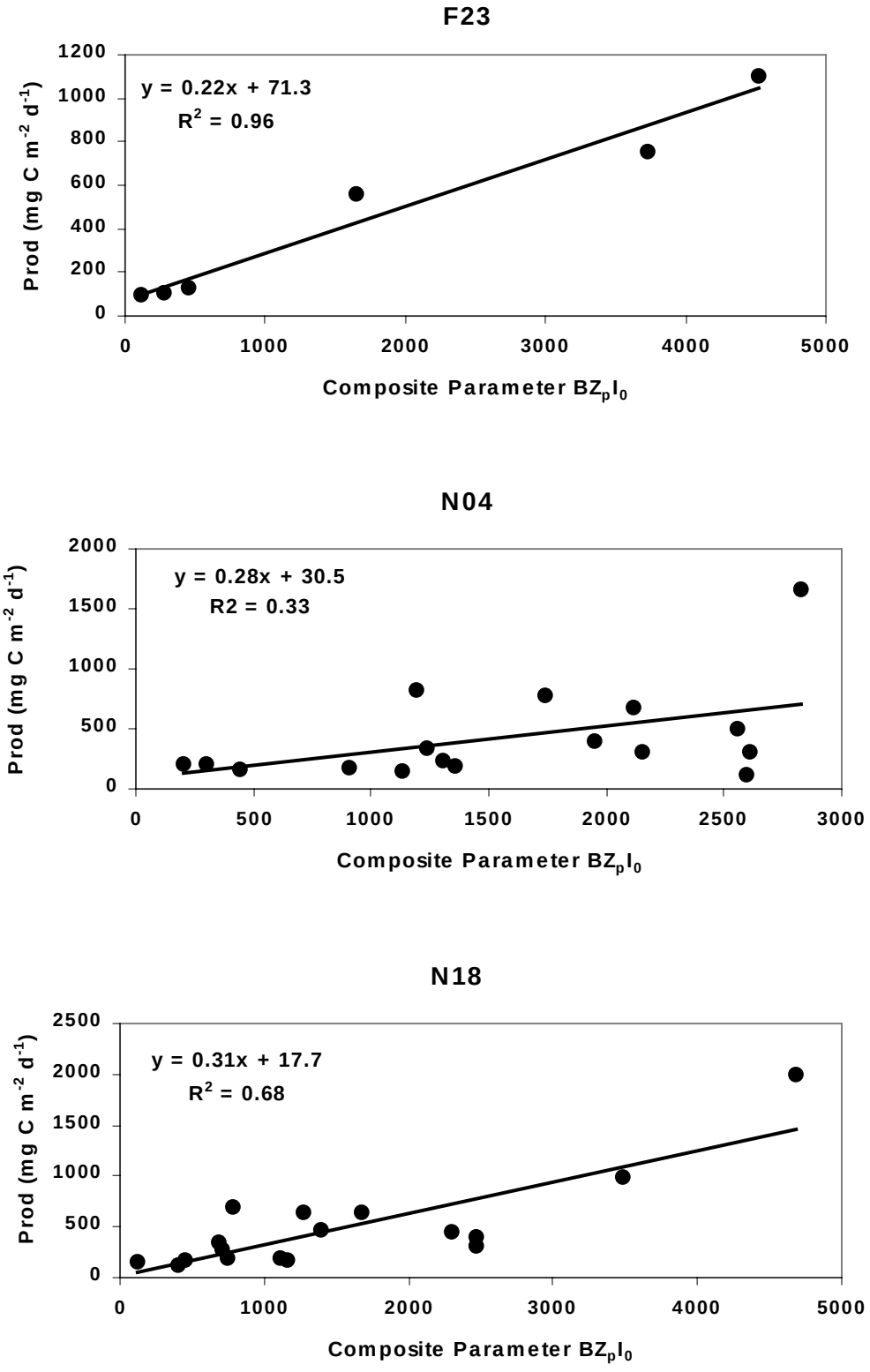


Figure 5-33. Relationships between areal production (mg C m^{-2} d^{-1}) and the composite function BZ_pI_0 (see text) for stations F23, N04 and N18 in 1998.

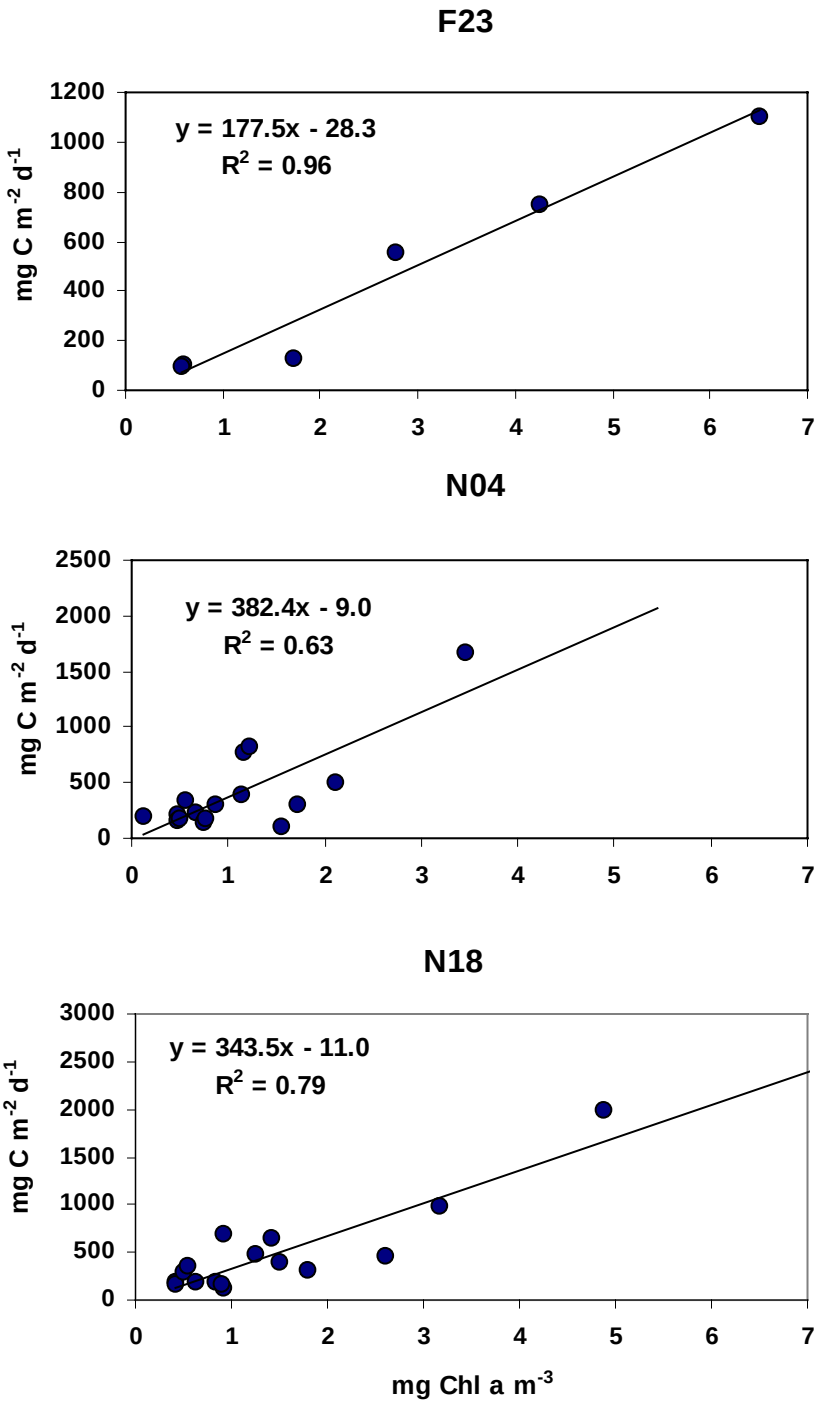


Figure 5-34. Relationships between areal production (mg C m^{-2} d^{-1}) and phytoplankton biomass (mg Chl a m^{-3}) for stations F23, N04 and N18 in 1998.

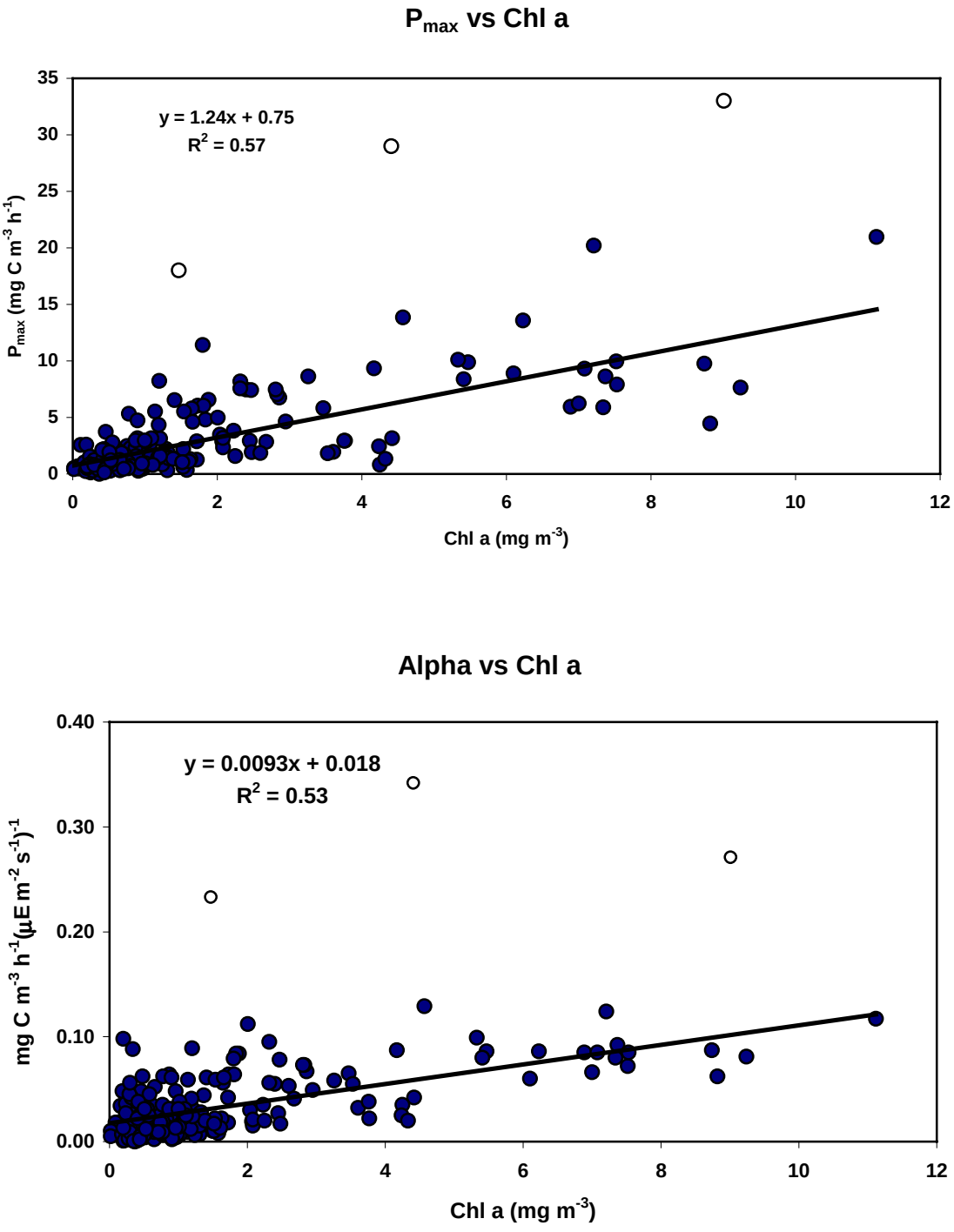


Figure 5-35. Relationship between the fitted values of the parameters of the P-I curves (α and P_{max}) and phytoplankton biomass (mg Chl a m^{-3}) using the seasonal data for 1998.

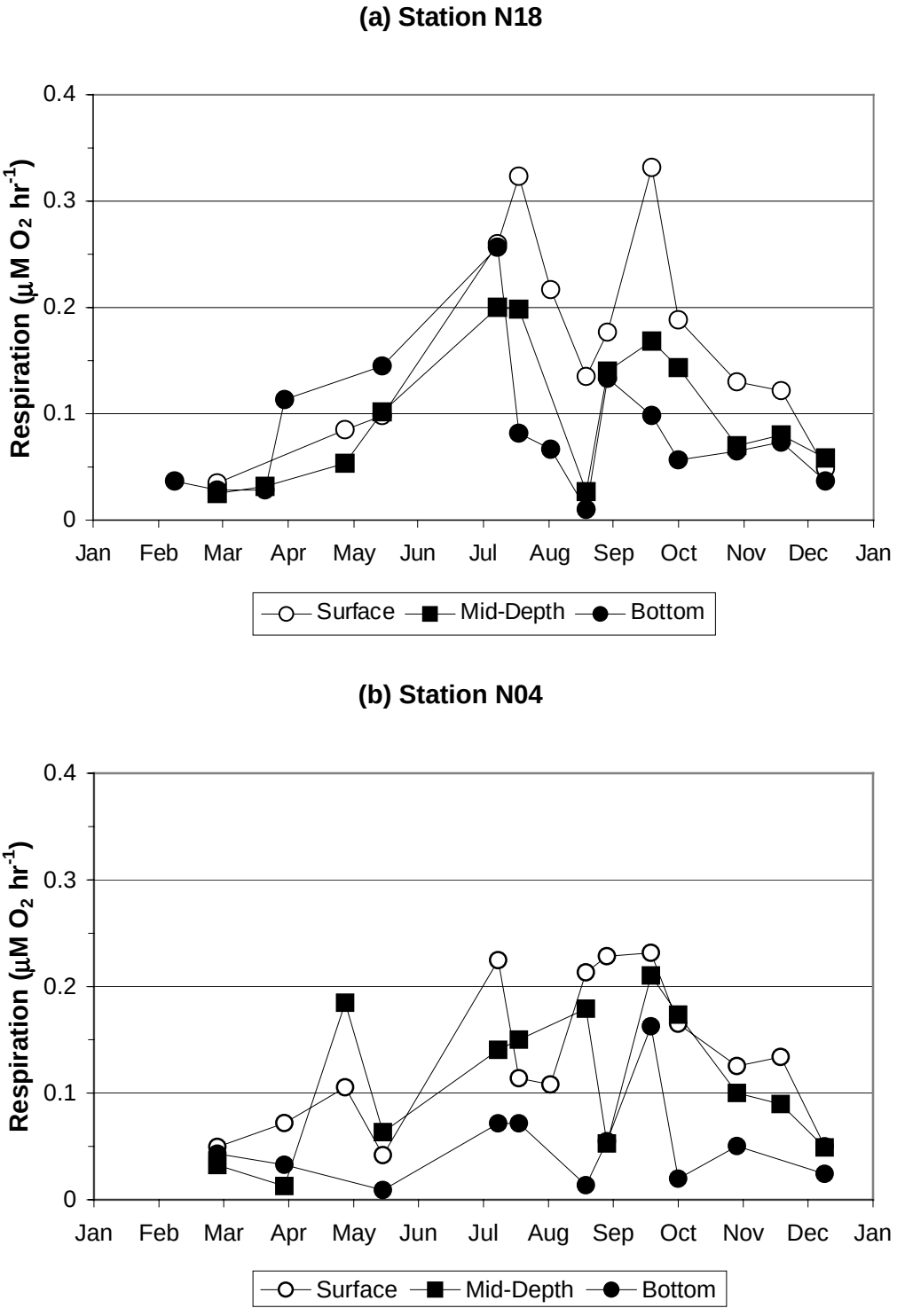


Figure 5-36. Time-series of respiration at stations N18 and N04.

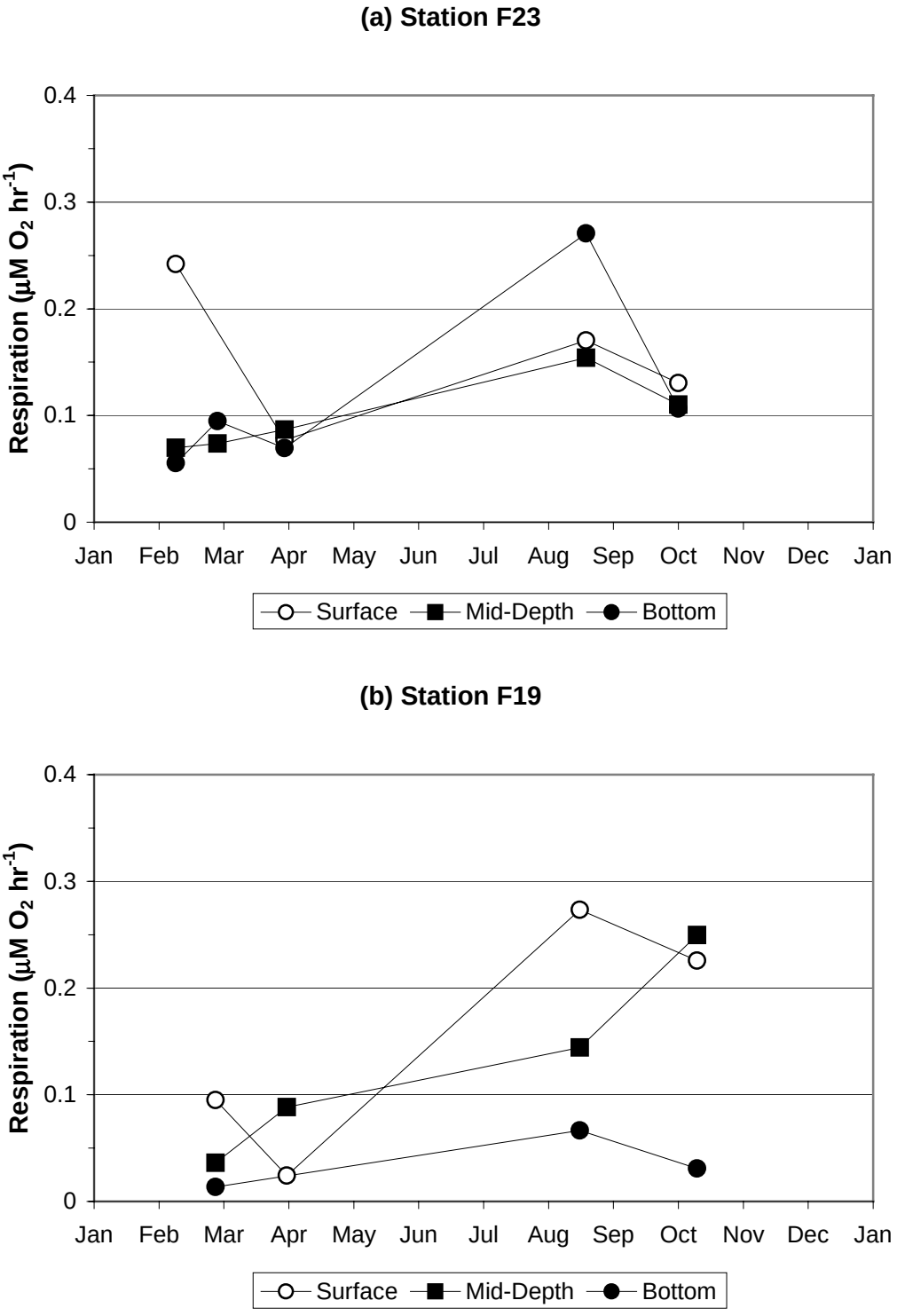


Figure 5-37. Time-series of respiration at stations F23 and F19.

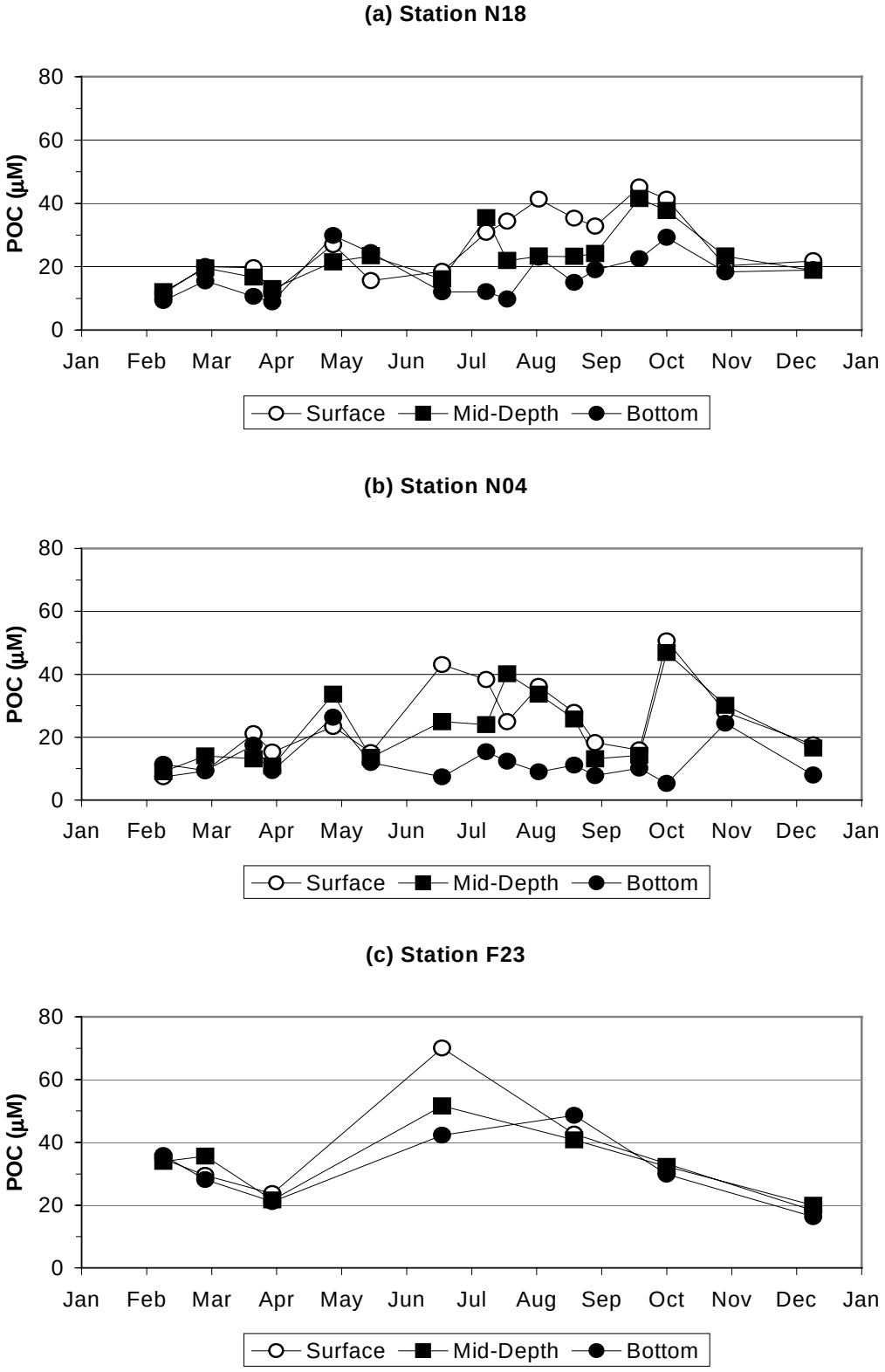


Figure 5-38. Time-series of POC at stations N18, N04 and F23.

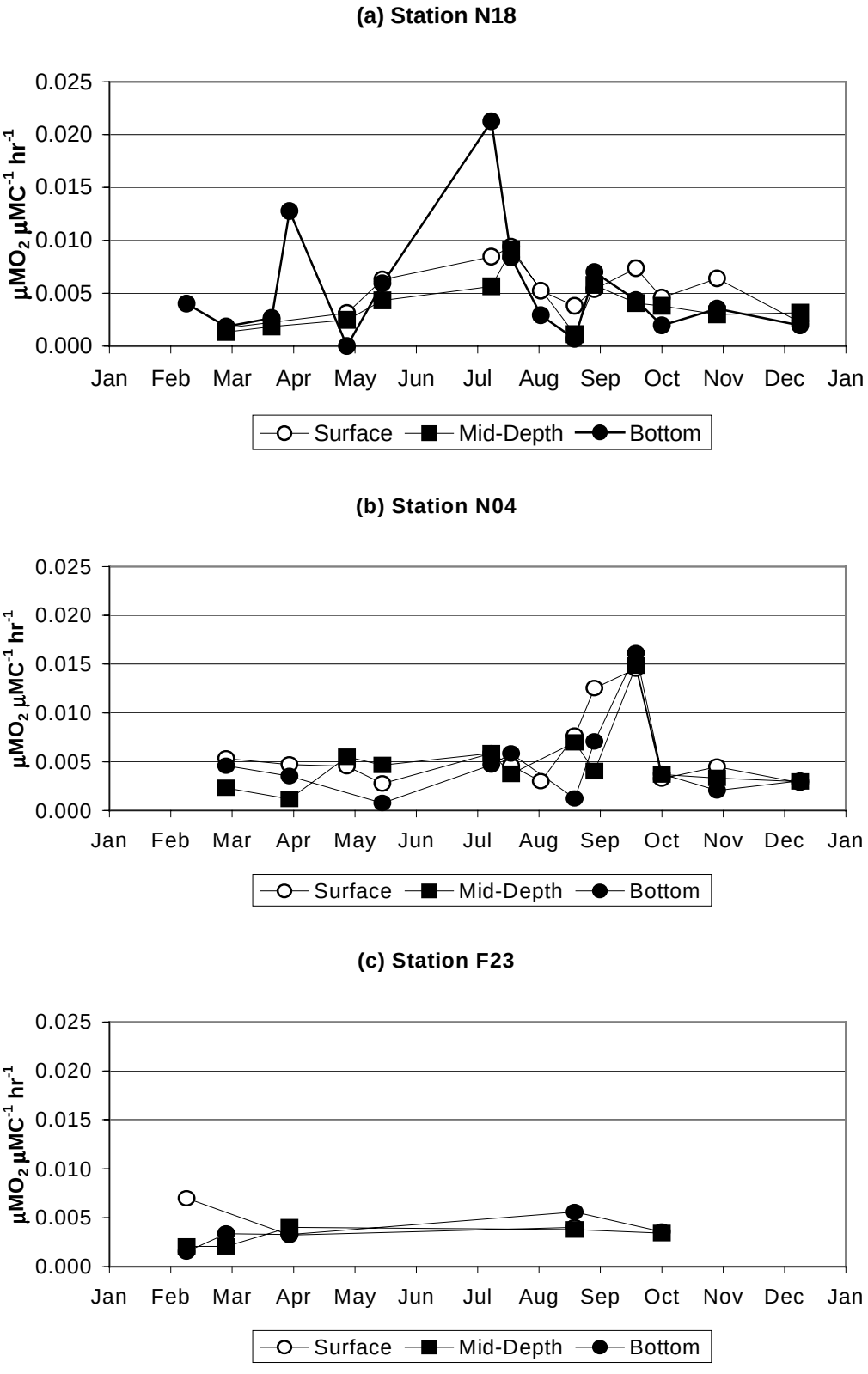


Figure 5-39. Time-series of carbon-specific respiration at stations N18, N04 and F23.

6.0 PLANKTON

Plankton samples were collected on each of the water column surveys conducted during 1998. 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 1998 (WF981, WF982, and WF984), 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 group 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 1998 semi-annual reports (Libby *et al.* 1999a and 1999b). A brief overview of highlights of patterns in the plankton in 1998 is presented below. Details are considered in Sections 6.1 and 6.2. A discussion of several points that emerge from the 1998 results and from previous attempts to summarize plankton patterns in Massachusetts Bay is provided in Section 6.3.

Whole-Water Phytoplankton — Unlike some other years, and the common paradigm, there was not a major winter/spring or fall bloom. Phytoplankton abundance steadily increased from low levels in February through April (means of 0.3-0.8 x 10^6 cells L^{-1}) to high levels in May through October (means of 0.7-3.5 x 10^6 cells L^{-1}), followed by declines in November and December (Nearfield means of 0.4-0.7 x 10^6 cells L^{-1}).

Phytoplankton assemblages were numerically dominated by microflagellates and cryptomonads (<10 μm), with subdominant contributions by various chain-forming diatoms such as *Chaetoceros socialis* and *Skeletonema costatum* (winter and spring), *Leptocylindrus minimus, L. danicus, Rhizosolenia fragilissima, Proboscia alata,* and *S. costatum* (summer), and *Chaetoceros spp., Leptocylindrus spp., S. costatum,* and *Pseudo-nitzschia* spp. in the fall.

There were no confirmed blooms of nuisance algae in 1998, although the fall *Pseudo-nitzschia* records for *P. "pungens"* could have included some of the domoic-acid-producing species *Pseudo-nitzschia multiseries*. However, total abundances of *Pseudo-nitzschia "pungens"* did not exceed 82 x 10^3 cells L^{-1}, which is well below the Canadian threshold of 5 x 10^5 cells L^{-1} for increased vigilance for domoic acid in shellfish.

Screened Water Phytoplankton (> 20 μm) — The silicoflagellate *Distephanus speculum* was dominant in February, with subdominant contributions by the dinoflagellates *Ceratium longipes* and *C. tripos*. From March onward, *C. longipes* and *C. tripos* were dominant, with subdominant contributions by other dinoflagellates such as *C. furca, C. fusus, C. lineatum, Dinophysis norvegica* and *Protoperidinium trochoidium*. A sustained bloom of *Ceratium longipes* and *C. tripos* from February to the fall was the major feature for screened-water taxa.

Zooplankton — The zooplankton were dominated, as typical in this coastal system, by copepod nauplii, adults and copepodites of the small copepods *Oithona similis* and *Pseudocalanus* spp., with seasonal subdominant contributions from gastropod and bivalve veligers, and a mixture of other normally-occurring taxa.

During the first three farfield surveys, zooplankton samples were collected at two additional stations in Cape Cod Bay (stations F32 and F33). On the first survey (WF981), the addition of these stations

provided additional data, which extended the range of total abundance recorded in Cape Cod Bay from 12-24 x 10^3 animals m^{-3} for stations F01and F02 to 28-56 x 10^3 animals m^{-3} for all 4 stations. The range of total abundance measured in Cape Cod Bay was extended from 15-24 to 27-29 x 10^3 animals m^{-3} for survey WF982 and from 13 to 19-28 x 10^3 animals m^{-3} for survey WF984. During the April survey (WF984), the abundance of *Calanus finmarchicus* copepodites comprised only 3-4% of the catch at F01 and F02, but 7-11% at F32 and F33. Thus, for this important forage item of right whales that feed in Cape Cod Bay at this time of the year, addition of the two new stations captured a three-fold increase in patchiness of this copepod that would have been missed by sampling only stations F01 and F02.

6.1 Phytoplankton

6.1.1. Seasonal Trends in Total Phytoplankton Abundance

Total phytoplankton abundances in nearfield whole water samples (surface and subsurface chlorophyll maximum depths) were low (0.055 – 0.614 x 10^6 cells L^{-1}) from February through early April (Figure 6-1; Table 6-1). Total abundances increased from May through July, to levels in August that were the highest observed during the year. Instead of a typical winter/spring phytoplankton bloom, there was a sustained increase from February through August. Total phytoplankton abundances in nearfield whole water samples (surface and subsurface chlorophyll maximum depths) remained high from August through early October (Table 6-1). By early November, however, phytoplankton abundance declined to levels generally half or less of the summer levels, remaining low in December.

Total phytoplankton abundance in farfield whole water samples (surface and subsurface chlorophyll maximum depths) showed similar trends to the samples collected in the nearfield (Figure 6-2 and Table 6-1). Total abundance was low through early April and had increased by June. The farfield mean reached a maximum value in August and decreased to lower levels in October. In October, higher total phytoplankton abundance was observed in the nearfield compared to the farfield area.

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. Nonetheless, similar seasonal increases, though of different taxa, were recorded. Screened phytoplankton increased from February through May achieving the highest levels in June and July (Figures 6-3 and 6-4, Table 6-2). These increases in screened phytoplankton abundance largely reflected a sustained bloom of the dinoflagellates *Ceratium longipes, Ceratium tripos*, and other species of this genus from February through July. Screened phytoplankton abundance fluctuated, but overall decreased from August through December. These decreases in screened phytoplankton abundance largely reflected a decline in the sustained bloom of the dinoflagellates *Ceratium fusus, Ceratium tripos*, and other species of this genus which had increased from February through July.

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

Survey	Dates (1998)	Nearfield Mean	Nearfield Range	Farfield Mean	Farfield Range
WF981	2/3-2/10	0.297	0.055-0.579	0.432	0.173-0.887
WF982	2/27-3/2	0.333	0.211-0.457	0.576	0.301-1.274
WN983	3/24	0.532	0.405-0.614	NA	NA
WF984	3/31-4/3	0.351	0.280-0.477	0.772	0.232-2.509
WN985	5/1	1.119	0.593-2.220	NA	NA
WN986	5/19	0.794	0.581-1.231	NA	NA
WF987	6/16-19, 6/22	0.890	0.148-2.033	2.042	0.158-4.932
WN988	7/8, 7/13	2.356	1.142-3.310	NA	NA
WN989	7/23	1.904	1.379-2.462	NA	NA
WN98A	8/7	2.266	1.501-3.432	NA	NA
WF98B	8/18-25	1.938	0.307-4.035	3.533	0.823-5.257
WN98C	9/3	1.312	0.544-2.203	NA	NA
WN98D	9/24	1.376	0.547-2.333	NA	NA
WF98E	10/5-17	1.904	0.950-2.802	0.843	0.208-1.445
WN98F	11/4	0.781	0.665-0.904	NA	NA
WN98G	11/25	0.446	0.346-0.702	NA	NA
WN98H	12/16	0.724	0.605-0.936	NA	NA

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

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

Survey	Dates (1998)	Nearfield Mean	Nearfield Range	Farfield Mean	Farfield Range
WF981	2/3-2/10	166	120-247	112	22-456
WF982	2/27-3/2	188	93-303	98	36-148
WN983	3/24	514	581-790	NA	NA
WF984	3/31-4/3	1,715	1,431-2,023	586	76-1,766
WN985	5/1	1,726	574-2,307	NA	NA
WN986	5/19	1,934	201-3,455	NA	NA
WF987	6/16-19, 6/22	4,238	1,116-13,757	2,289	314-11,796
WN988	7/8, 7/13	3,193	1,134-5,164	NA	NA
WN989	7/23	3,351	1,703-6,775	NA	NA
WN98A	8/7	4200	2183-6733	NA	22-456
WF98B	8/18-25	1516	566-2735	2452	283-8992
WN98C	9/3	809	369-1682	NA	NA
WN98D	9/24	488	135-852	NA	76-1,766
WF98E	10/5-17	744	452-1086	633	62-1940
WN98F	11/4	1670	1366-2075	NA	NA
WN98G	11/25	1556	621-2939	NA	NA
WN98H	12/16	3533	2469-4813	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 — In February and March (WF981 and WF982), nearfield whole-water phytoplankton assemblages from both depths were numerically dominated by unidentified microflagellates and cryptomonads < 10 µm in longest dimension (Figure 6-5a). Small centric diatoms < 10 µm in diameter were subdominants in surface samples from stations N04 and N18, whereas an unidentified species of the dinoflagellate genus *Gymnodinium* was subdominant at chlorophyll maximum depths at these same stations.

During March and April (WN983 and WF984), the overwhelming nearfield dominance of < 10 µm microflagellates and cryptomonads continued in the nearfield (Figure 6-5a). *Gymnodinium* sp. was again a subdominant at subsurface depths. In May (WN985), the nearfield samples were still dominated by small microflagellates and cryptomonads and a bloom of chain-forming diatoms such as *Chaetoceros socialis* and *Skeletonema costatum* was present. The increase in *Chaetoceros socialis* and *Skeletonema costatum* in the nearfield continued through late May during WN986, but with unidentified centric diatoms < 10 µm in diameter and a small (< 20 µm diameter) species of the diatom genus *Thalassiosira* and *Gymnodinium* sp. joining *Skeletonema costatum* as subdominants.

During the June survey (WF987), nearfield assemblages from both depths included a mixture of small microflagellates and chain-forming diatoms such as *Skeletonema costatum, Chaetoceros* spp., and *Pseudonitzschia delicatissima*. In early July (WN988), whole-water assemblages were dominated by microflagellates < 10 µm in size, and a mixture of subdominant diatoms such as *Leptocylindrus minimus, L. danicus, Rhizosolenia fragilissima, Proboscia* (formerly *Rhizosolenia*) *alata*, and *Skeletonema costatum*. In late July (WN989), surface assemblages were dominated by small microflagellates, and secondarily by the chain-forming diatoms *Leptocylindrus danicus* and *L. minimus*. Subdominance in subsurface chlorophyll-maximum depths had shifted, however, to an unidentified species of *Gymnodinium*.

During August (WN98A and WF98B), nearfield whole-water phytoplankton abundance from both depths was dominated by unidentified microflagellates and the diatom *Leptocylindrus danicus* (Figure 6-5a). Other diatoms, including *Leptocylindrus minimus, Skeletonema costatum* and *Pseudo-nitzschia delicatissima* made lesser contributions. In early September (WN98C), the dominance of < 10 µm microflagellates and cryptomonads continued in the nearfield, with *L. minimus* and the dinoflagellate *Gymnodinium* sp. as subdominants. By late September (WN98D) microflagellates were still dominant in the nearfield, but at station N18 dominance was shared with various diatoms, including *Chaetoceros didymus, L. danicus, L. minimus, S. costatum*, and a small centric < 10 µm in longest dimension. The increase in diatom abundance was coincident with increasing productivity and chlorophyll concentrations at station N18. The differences in the phytoplankton assemblage, productivity rate and chlorophyll concentration observed at stations N18 and N04 indicate that the nearfield fall bloom was initiated in the western nearfield in late September.

During early October (WF98E), microflagellate dominance was shared with chain-forming diatoms such as *Chaetoceros compressus, Eucampia zodiacus*, and *Skeletonema costatum* (Figure 6-5a). Diatoms characterized as *Pseudo-nitzschia "pungens*" (which could include the non-toxic *P. pungens* or the domoic-acid-producing *P. multiseries*, because these cannot be reliably distinguished using light microscopy) was present, comprising 5.7% of cells counted. The mixed phytoplankton assemblage did not exhibit as strong a fall bloom signal in cell abundance as was observed in the chlorophyll and productivity data. The 1998 fall bloom cell abundance did not approach the magnitude of major fall blooms (*i.e.*, 1993 *Asterionellopsis glacialis*) observed during the previous baseline monitoring years.

In early November (WN98F), microflagellate dominance was shared with cryptomonads, *E. zodiacus* and an unidentified species of the dinoflagellate genus *Gymnodinium*. By late November (WN98G),

microflagellate and cryptomonad abundance was shared only with the diatom *Rhizosolenia delicatula*.

The December assemblage (WN98H) was dominated by microflagellates, with lesser contributions by *Chaetoceros compressus*, another unidentified species of this genus, a centric diatom < 10 μm in longest dimension and (nominally) two species of *Pseudo-nitzschia* (*delicatissima* and "*pungens*"). These can be distinguished by criteria visible with standard light microscopy, so effectively the designation of "*delicatissima*" means "not *pungens* or *multiseries*." The latter comprised 5-13% of total cells counted in nearfield samples, with abundances of up to 82,000 cells L^{-1}.

Screened Phytoplankton — During WF981, nearfield screened samples were overwhelmingly dominated by the silicoflagellate *Distephanus speculum*. The thecate dinoflagellates *Ceratium tripos* and, at various stations, by *C. longipes* and *Dinophysis acuminata* were secondary dominants. The ciliate protozoan *Mesodinium rubrum* was also abundant.

Beginning in late February (WF982) and continuing through the rest of 1998 until December (WN98H), dinoflagellate assemblages in screened samples were dominated by *Ceratium longipes* and *C. tripos*. Subdominants included contributions by other *Ceratium* species such as *C. furca*, *C. macoceros*, and *C. lineatum*, and various other dinoflagellates such as *Protoperidinium trochoideum*, *Protoperidinium* spp., *Dinophysis norvegica*, and *Prorocentrum micans*.

6.1.3. Farfield Phytoplankton Assemblages

Whole-Water Phytoplankton — From late winter through early spring (WF981, WF982 and WF984), most farfield station assemblages were dominated at both depths by unidentified microflagellates and cryptomonads < 10 μm in cell size. In Cape Cod Bay, pennate and centric diatoms were dominant in late winter and early spring (Figure 6-5b). By June (WF987), dominance of assemblages at most farfield stations had shifted from microflagellates and cryptomonads to a mixture of chain-forming diatoms as illustrated in Figure 6-6 for Boston Harbor (stations F23, F30 and F31) and the near-harbor coastal area (stations F13, F24 and F25). The diatoms included were several species of the genus *Chaetoceros*, *Skeletonema costatum*, and others. In late August (WF98B), most farfield assemblages were again dominated by unidentified microflagellates and cryptomonads < 10 μm in cell size, and the diatoms *Leptocylindrus danicus* and *L. minimus*. The pennate diatoms *Pseudo-nitzschia delicatissima* and *P. pungens* were subdominants at most stations. The increase in pennate diatoms was observed at Boston Harbor and nearby coastal stations (Figure 6-6), but not in Cape Cod Bay (Figure 6-5b). The June and August assemblages observed in the harbor and coastal waters were different than those observed in the nearfield (Figure 6-5a). Nearfield abundance increased in the summer, but microflagellates remained dominant and diatoms did not achieve the high the levels observed at the harbor and coastal stations.

By early October (WF98E), microflagellate and cryptomonad dominance was shared with chain-forming diatoms, including *Leptocylindrus danicus*, *Eucampia zodiacus*, *Skeletonema costatum*, *Chaetoceros compressus* and *Pseudo-nitzschia pungens*. There were also unidentified centric diatoms of the genus *Thalassiosira* < 20 μm in individual cell diameter at several other stations. Generally, however, the abundance of diatoms had decreased relative to the microflagellates in the farfield (Figures 6-5b and 6-6). This was not the case in the nearfield were the abundance of diatoms increased due to the localized bloom of diatoms (mixed assemblage) in the nearfield (Figure 6-5a).

Screened Phytoplankton — Predominant taxa in screened samples from farfield stations generally paralleled those of the nearfield, but exhibited more diversity and differences in dominance at various stations, as detailed below.

In early February (WF981), 20 μm-screened surface phytoplankton samples were dominated by the silicoflagellates *Distephanus speculum* and *Dictyocha fibula*, and to a much lesser extent, at various

stations, by several species of the dinoflagellate genus *Ceratium* (*C. furca, C. fusus, C. longipes*, and *C. tripos*). An unidentified athecate dinoflagellate was the second most abundant component of the screened surface samples at station F23 in Boston Harbor. The ciliate protozoan *Mesodinium rubrum* was also abundant, comprising > 40% of cells counted at station F01 in Cape Cod Bay. These patterns from surface samples generally held for subsurface depths, except that the dinoflagellate *Prorocentrum micans* comprised > 22% of cells counted at station F25.

In late February – early March (WF982) *Distephanus speculum*, and to a lesser extent, *Mesodinium rubrum* were still abundant at both depths at most stations, but that dominance was shared with increasing proportions of *Ceratium longipes* and *C. tripos*. By late March – early April (WF984), surface and subsurface samples were overwhelmingly dominated by *Ceratium longipes*, and secondarily by *C. tripos, C. fusus*, and other species of this genus. An unidentified athecate dinoflagellate was subdominant at stations F30 and F31 in Boston Harbor.

From June (WF987) through both August (WF98B) and October (WF98E), screened assemblages were dominated by several species of the dinoflagellate genus *Ceratium* (*fusus, lineatum, longipes, tripos*). Secondary dominants included other dinoflagellates such as *Dinophysis norvegica, Prorocentrum micans, Protoperidinium pallidum*, and *P. trochoidium*.

6.1.4 Nuisance Algae

There were no confirmed blooms of harmful or nuisance phytoplankton species in Massachusetts and Cape Cod Bays during 1998. Some species that have caused harmful blooms in different seasons in previous years, such as *Phaeocystis pouchetti* (early spring) were unrecorded, or in the case of *Alexandrium tamarense* (late spring and summer), were recorded only in trace concentrations. 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. However, potentially toxic species of the diatom genus *Pseudo-nitzschia* were present, in some cases, in moderately high numbers.

Alexandrium tamarense was sporadically recorded for screened samples at a few stations during April and May, but only at trace abundances of 2-5 cells L^{-1}. This dinoflagellate was again recorded in June and July, but only at abundances of <10 cells L^{-1}. There was no paralytic shellfish poisoning (PSP) toxicity recorded in shellfish at the Massachusetts Bay stations monitored by the Massachusetts Division of Marine Fisheries.

Perhaps the singular phytoplankton event of the year was the bloom of *Ceratium longipes/C. tripos*, which began unusually early in February, and exhibited sustained increases through July. Observations by Turner during the sampling for the ECOHAB (Ecology and Oceanography of Harmful Algal Blooms) program in the Gulf of Maine revealed that this bloom extended far to the north and east along the coast of Maine into the Bay of Fundy in July and August of 1998. Although abundances of *C. longipes* and *C. tripos* recorded for screened samples during WF981 – WN983 (February – March) were < 515 cells L^{-1}, in April and May (WF984, WN985, WN986) maximum levels were 1-2 x 10^3 cells L^{-1}. In June and July (WF987, WN988, WN989) maximum abundances were 2.5-3.1 x 10^3 cells L^{-1}. Dominance of the 20 μm-screened phytoplankton by various *Ceratium* species (*C. tripos, C. longipes* and *C. fusus*) continued through the late summer and fall, into December. The sustained bloom of *Ceratium*, though significant, was 1-2 orders of magnitude lower in abundance than past blooms of these same species that have caused large-scale anoxia.

Ceratium longipes and *C. tripos* usually bloom in Massachusetts and Cape Cod Bays during the spring and summer, but the early initiation of this bloom in 1998 may relate to the unusually mild El Niño winter in New England in 1998. Nonetheless, abundances recorded here are well below those associated with the 1976 bloom of *C. tripos* blamed for widespread anoxia in the New York Bight.

During that bloom, early March levels of *C. tripos* were an order-of-magnitude higher than "normal" levels of 1-5 x 10^2 cells L^{-1} (Falkowski *et al.* 1980; Malone *et al.* 1979). By June 1976, abundances associated with anoxia reached 5 x 10^5 cells L^{-1}, although most values were 10-400 x 10^3 cells L^{-1} (average = 240 x 10^3 cells L^{-1}) (Malone, 1978). Thus, levels of *C. tripos* and *C. longipes* in Massachusetts Bay in 1998 (maxima < 3 x 10^3 cells L^{-1}) were far below those in the New York Bight in 1976.

Another non-toxic phytoplankton reported to cause anoxia as bloom biomass decays is the silicoflagellate *Distephanus speculum*. During an anoxia-inducing bloom in August 1983 in the Gulf of Trieste (Adriatic Sea), *D. speculum* abundances were 4-653 x 10^3 cells L^{-1} (Fanuko, 1989). Levels of this species in screened samples from Massachusetts Bay during 1998 were < 0.5 x 10^3 cells L^{-1}, and usually < 0.1 x 10^3 cells L^{-1}.

Pseudo-nitzschia spp. were identified in the nearfield rapid analysis samples in all surveys in February – July except WF981, but except for values of 2-3 x 10^3 cells L^{-1}during WN988, this genus was only present at approximate levels of 1.5 x 10^3 cells L^{-1}, and usually < 0.5 x 10^3 cells L^{-1}. Although the 20 μm-screened rapid analysis samples would conspicuously capture long chains of this genus, it was rarely abundant enough to be recorded in whole-water phytoplankton samples which were dominated by microflagellates and other diatoms during the first half of 1998. However, *Pseudo-nitzschia* spp. were abundant enough to be recorded for whole water samples during fall of 1998. It was also 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 counts on intercostal poroids on the underside of acid-washed thecae. Nonetheless, even if these were *P. multiseries*, their abundances were two orders of magnitude below the 5x10^5 cells L^{-1} associated with domoic acid toxicity in Canadian waters.

During the fall 1998 bloom of *Pseudo-nitzschia* spp., there was considerable discussion of issues regarding a threshold response mode for this genus. Accordingly, a detailed discussion of present taxonomy of this potentially toxic genus seems appropriate, and is presented below.

There are potentially four species of the genus *Pseudo-nitzschia* that could occur in the MWRA sampling area: *P. pungens, P. multiseries, P. delicatissima*, and *P. pseudodelicatissima*. Although there are reports of all four of these species producing domoic acid, either in field collections, or in culture (see Table 1 of Bates *et al.* 1998), the primary species that has been associated with domoic acid shellfish toxicity episodes in the North Atlantic is *P. multi-series*. The reports of domoic acid toxicity in the field for *P. pseudodelicatissima* and *P. delicatissima* are based upon only single occurrences, in either the Bay of Fundy or at Prince Edward Island, Canada, respectively. The only published report of domoic acid toxicity in the field attributed to *P. pungens* was from New Zealand, although there have apparently been recent unpublished reports (summarized by Bates *et al.*, 1998) from California and Washington (state). Several other species of the genus, which may or may not produce domoic acid occur in the Pacific. Based upon criteria given in the Hasle and Syvertsen (1997) chapter of a manual entitled "Identifying Marine Phytoplankton," it is possible to distinguish these four species using microscopy, but in some cases, only using scanning electron microscopy (SEM). Criteria are given below.

Members of the genus *Pseudo-nitzschia* form end-to-end chains, with adjacent cells overlapping. Individual cells vary in both length ("apical axis") and width ("transapical axis"). *P. pungens* and *P. multiseries* are not reliably distinguished by light microscopy because they are both of approximately the same length (74-142 μm for *P. pungens* and 68-140 μm for *P. multiseries*), the same width (3.0-4.5 μm for *P. pungens* and 4-5 μm for *P. multiseries*), with adjacent cells overlapping by one-third or more of cell length. The primary accepted way for distinguishing *P. pungens* from *P. multiseries* is to

count intercostal poroids, which are small holes that occur in rows between the ribs ("costae") on the inner surfaces of diatom thecae ("valves") that have been separated by treatment with acid or bleach. Since the diameters of these poroids are considerably less than 1 μm, the only way to see them well enough to count is with SEM. If poroids occur in pairs in rows, then the species is *P. pungens*. If, however, there are multiple poroids (3-4) in a row, then the species is *P. multiseries*. Effectively the designation of "*Pseudo-nitzschia pungens*" in our data (obtained thus far with light microscopy only) means either *P. pungens* or *multiseries* (but we do not know which), but not *P. delicatissima* or *P. pseudodelicatissima*. The reason is that the latter two species are distinguished from *P. pungens/multiseries* by their more narrow cells (1.5-2.5 μm), compared to widths of 3-5 mm for *P. pungens/multiseries*, and by overlapping of adjacent cells in chains in *P. delicatissima* or *P. pseudodelicatissima* by only about one-ninth of cell length, compared to by one-third or more of cell length with *P. pungens/multiseries*. The differentiation of *P. delicatissima* from *P. pseudodelicatissima* is facilitated by differences in length, in that *P. delicatissima* cells are much shorter (40-76 μm length) than those of *P. pseudodelicatissima* (59-140 μm length).

6.1.5 1992–1998 Interannual Comparisons

The phytoplankton assemblages in 1998 were generally similar to patterns found during other baseline monitoring years. In contrast to the paradigm, however, there was no clear winter/spring bloom in Massachusetts Bay in 1998. A review of the 1992 to 1998 phytoplankton and chlorophyll (see Section *4.2.3*) data suggests that the spring bloom may not be as common in Massachusetts Bay as once 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 1998. Further, in some previous years, the spring bloom appeared limited to Cape Cod Bay, and was not representative of most of the nearfield area. The fall bloom observed in the nearfield in 1998 was a localized event with elevated production rates and chlorophyll concentrations associated with a diatom dominated mixed phytoplankton assemblage.

A description of the common paradigm of "normal" seasonal succession is presented based upon the 1992-1998 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. In addition to microflagellates, the following are dominant in the periods identified below:

Winter (primarily February) — diatoms abundant, including *Chaetoceros debilis, C. socialis, Thalassiosira nordenskioldii,* and *T. rotula;*

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

Summer (June, July, August) — 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.

Screened-water dinoflagellate assemblages are normally dominated by the same non-toxic taxa that were abundant in 1998. 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. However, the frequency of sampling

for the HOM program may not adequately capture the occurrence of *A. tamarense*. For example, despite the relative absence of the species in HOM samples in 1993, shellfish PSP toxicity caused by *A. tamarense* was high in that year and extended to a section of the Cape Cod Bay (Sandwich, MA) that had never before recorded toxicity. In 1998, there was no shellfish PSP toxicity in the bays (pers. com. D. Anderson).

6.2 Zooplankton

6.2.1 Seasonal Trends in Total Zooplankton Abundance

Total zooplankton abundance at nearfield stations generally increased from February through April, reached the highest numbers in mid-May and remained moderately high in June, July and August (Figure 6-7). Total zooplankton abundance at nearfield stations fluctuated, but generally remained at high levels from August through December (Table 6-3).

Total zooplankton abundance at farfield stations was generally low (< 20 x 10^3 animals m^{-3}) in February (Figure 6-8, Table 6-3). However, at stations F02, F33 and particularly F32 in the eastern side of Cape Cod Bay, values were high, ranging from 24.3-56.2 x 10^3 animals m^{-3}. By late February to early March, total zooplankton abundance at farfield stations had generally increased, with values at half the stations >20 x 10^3 animals m^{-3}. Only at the three stations in Boston Harbor (F23, F30, and F31) were all values <10 x 10^3 animals m^{-3}. The spring increase in farfield zooplankton abundance continued through late March-early April, with most values >20-30 x 10^3 animals m^{-3}. By June, zooplankton abundance was high (>10 x 10^3 animals m^{-3}) at all stations, with an astonishing maximum of 289.8 x 10^3 animals m^{-3} at station F23 in Boston Harbor. The latter sample was dominated by copepod nauplii (30%), the marine cladoceran *Evadne nordmani* (14%) bivalve larvae (16%), and polychaete larvae (16%), all of which reflect normal summer pulses of reproduction for these taxa. Total zooplankton abundance at farfield stations was somewhat lower at most stations in October than in August, but there were no consistent trends of higher values during either survey for all stations in a given area compared to others. Maximum abundance in both periods occurred in Boston Harbor, but these were nearly matched by levels at other stations in the nearfield or in Cape Cod Bay in August.

6.2.2 Nearfield Zooplankton Community Structure

In early February (WF981), the nearfield zooplankton assemblages were dominated by copepod nauplii, and females and copepodites of *Oithona similis* (stations N16 and N04), although gastropod veligers comprised 19% of the assemblage at station N04. At station N18 copepod nauplii were 40% of the catch, but abundance of *O. similis* was low (<5%), whereas *Acartia hudsonica* females and copepodites had a combined total of 42% of animals counted.

During the late winter and early spring (WF982, WN983 and WN984), the nearfield was dominated by copepod nauplii and *Oithona similis* copepodites, with gastropod veligers as subdominants, and occasional subdominant abundances by *Calanus finmarchicus* copepodites, *Pseudocalanus* copepodites, and the appendicularian *Oikopleura dioica*. Nearfield stations during WN986 and WF987 were dominated by copepod nauplii with subdominants including bivalve veligers, and copepodites of *Oithona similis*, *Pseudocalanus* sp. and *Temora longicornis*. During WN988 and WN989 copepod nauplii and *O. similis* copepodites continued to dominate, with subdominant contributions by *Oikopleura dioica*, bivalve veligers and *Pseudocalanus* and *Temora longicornis* copepodites.

Table 6-3. Nearfield and Farfield Average and Ranges of Abundance (10^3 animals m^{-3}) for Zooplankton.

Survey	Dates (1998)	Nearfield Mean	Nearfield Range	Farfield Mean	Farfield Range
WF981	2/3-2/10	8.5	3.0-12.9	15.5	1.2-56.2
WF982	2/27-3/2	23.5	9.2-33.0	21.6	4.8-57.2
WN983	3/24	29.5	28.7-30.4	NA	NA
WF984	3/31-4/3	48.4	42.1-56.0	27.7	1.5-71.0
WN985	5/1	20.8	10.0-31.5	NA	NA
WN986	5/19	62.3	52.0-72.7	NA	NA
WF987	6/16-19, 6/22	48.8	23.3-69.8	59.2	14.6-289.8
WN988	7/8, 7/13	30.5	28.7-32.2	NA	NA
WN989	7/23	35.6	26.8-44.3	NA	NA
WN98A	8/7	45.9	33.5-58.3	NA	NA
WF98B	8/18-25	45.0	30.5-64.7	45.8	27.3-72.8
WN98C	9/3	12.9	11.9-13.9	NA	NA
WF98D	9/24	35.2	24.9-45.5	NA	NA
WF98E	10/5-17	44.9	35.8-59.2	35.0	15.9-83.2
WN98F	11/4	58.3	39.0-77.6	NA	NA
WF98G	11/25	64.5	61.9-66.9	NA	NA
WN98H	12/16	53.5	47.4-59.7	NA	NA

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

From early August through early October, the nearfield zooplankton assemblages were dominated by copepod nauplii, and females and copepodites of *Oithona similis*. Subdominants included copepodites of *Pseudocalanus* sp., *Temora longicornis*, and to a lesser extent bivalve and gastropod veligers, the marine cladoceran *Evadne nordmani* and the tunicate *Oikopleura dioica*. The copepod *Microsetella norvegica* and copepodites of the genus *Centropages* were subdominants in late September (WN98D).

In November (WN98F and WN98G), the dominance of copepod nauplii and *Oithona similis* was being supplanted by bivalve veligers, and to a lesser extent gastropod veligers. This was likely due to a combination of the seasonal decline in copepod abundance in the fall, along with a seasonal reproductive pulse by benthic bivalves and gastropods.

6.2.3 Farfield Zooplankton Assemblages

At farfield stations during survey WF981, copepod nauplii and *Oithona similis* females and copepodites were dominants. *Pseudocalanus* copepodites were also subdominants at most stations. *Acartia hudsonica* copepodites were 6-20% of the catch at stations F31 and F23, respectively, in Boston Harbor, and barnacle naupalii were 22% of the assemblage at stations F31, and gastropod veligers made up 36% at station F30.

In late February (WF982), copepod nauplii and *Oithona similis* copepodites were again dominant at farfield stations, but barnacle nauplii and/or gastropod veligers were subdominants at most stations. *Acartia hudsonica* were again subdominants at station F30 in Boston Harbor and, presumably reflecting the shallow depths in the harbor, polychaete larvae and harpacticoid copepods, likely of benthic origin, were subdominants at stations F30 and F31, respectively.

In April, copepod nauplii and *Oithona similis* copepodites were dominant at all farfield stations, except station F30, the most inshore station in Boston Harbor. As expected, *Acartia hudsonica* copepodites were most abundant in the harbor at station F30, but surprisingly, *A. hudsonica* was either unrecorded, or present only at trace levels at the other two harbor stations (F31 and F23, respectively). Barnacle nauplii were also abundant at most stations, and sporadically dominant at some (F13, F23, F01, F25, F30, and F31). Gastropod veligers were also dominant at most farfield stations, except for F23 and F30 in Boston Harbor.

During WF987 farfield zooplankton assemblages were dominated at most stations by copepod nauplii and bivalve veligers, with important subdominant contributions from copepodites of *Oithona similis, Temora longicornis* and *Pseudocalanus* spp. *Acartia* spp. copepodites were important subdominants at stations F30 and F31 in Boston Harbor as expected, but surprisingly, not at station F23. There, the cladoceran *Evadne nordmani* and polychaete larvae shared subdominance, whereas these latter taxa were much less prominent elsewhere.

The addition of stations F32 and F33 in Cape Cod Bay during WF981, WF982, and WF983, reinforces the dominance of copepod nauplii and *Oithona similis* copepodites recorded for the previously sampled stations F01 and F02. However, addition of F32 and F33 extended the range in total abundance recorded for F01 and F02 from approximately 12,000-24,000 animals m^{-3} to 28,000-56,000 animals m^{-3} in WF981, from approximately 15,000-24,000 animals m^{-3} to 27,000-29,000 animals m^{-3} in WF982, and from approximately 13,000 animals m^{-3} to 19,000-28,000 animals m^{-3} in WF984. Thus, addition of stations F32 and F33 in Cape Cod Bay revealed a greater level of variability in total abundance of assemblages that were generally dominated by the same suite of taxa. Further, during WF984, abundance of *Calanus finmarchicus* copepodites comprised only about 3-4% of the catch at stations F01 and F02, but approximately 7-11% at F32 and F33. Thus, for this important forage item of right whales that feed in Cape Cod Bay during this time of the year, addition of the two new stations captured a three-fold increase in the range of abundances of this copepod that would have been missed by sampling only stations F01 and F02.

At farfield stations during survey WF98B, copepod nauplii were dominants, with subdominant contributions at various stations by adults and copepodites of copepods such as *Oithona similis, Pseudocalanus* sp., *Temora longicornis* and *Microsetella norvegica*. Non-copepod subdominants at most stations included *Evadne nordmani*, *Oikopleura dioica*, and meroplankters such as bivalve and gastropod veligers. At stations in Boston Harbor (F23 and F30), dominants were the adults and copepodites *of Acartia tonsa* and polychaete larvae. Interestingly, there were sporadic occurrences of adults of *Acartia hudsonica* at Boston Harbor stations (F23, F30, and F31). *A. hudsonica* is generally thought to be a cold-season species, but careful examination confirmed that it does co-occur in Boston Harbor during the summer with its warm-season congener *A. tonsa*, although in lower abundances.

During WF98E, copepod nauplii and *Oithona similis* copepodites were again dominant at farfield stations, but bivalve veligers, *O. dioica*, and copepodites of *Pseudocalanus* sp. and *Temora longicornis* were subdominants at most stations. *Acartia hudsonica* were again abundant at stations F23 and F30 in Boston Harbor. Salps were conspicuous subdominants at several stations in the southern portion of the farfield (F01, F02 and F06).

6.3 Discussion of Plankton Results

There are several points that emerge from the 1998 results and from previous attempts to summarize plankton patterns in Massachusetts Bay that prompt further discussion. These include whether the lack of a 1998 spring bloom was due to unusual zooplankton grazing pressure, questions on the estimation of zooplankton biomass based on presently available indices, differences in characterization and grouping of plankton, and what, if any, "zooplankton threshold" would be appropriate for defining unusual effects of the new outfall.

6.3.1 Absence of a Winter/Spring Bloom in 1998

The lack of a "spring bloom" in 1998 begs for an explanation. One obvious possibility might be that high grazing pressure prevented a bloom. Since there are no data available on the zooplankton grazing rates in 1998, zooplankton abundance must be used as an implicit measure of grazing pressure. In Section *5.1.9*, a series of empirical relationships were discussed that were based on data collected during the winter/spring bloom periods in the nearfield from 1995-1998. Relatively strong correlations were observed between chlorophyll biomass and phytoplankton production, temperature and zooplankton abundance. The same data were used to show the positive correlation between zooplankton abundance and temperature (Figure 6-9). Though no grazing rate measurements were made, it has been established that grazing rates are temperature dependent. This analysis suggests that in 1998 warm winter water temperatures may have led to an increase in grazing pressure and the absence of a winter/spring bloom. In the absence of any zooplankton grazing rate data, however, speculation that the lack of a 1998 spring phytoplankton bloom was due to zooplankton grazing pressure is difficult to confirm.

The data set being used for these comparisons is limited. In comparison across the entire baseline-monitoring period, total zooplankton abundances in February, March and April of 1998 were generally within the broad envelope-of-variability seen in previous years and in most cases below 50×10^3 animals m^{-3}. In addition to these "normal" abundances in 1998, the taxonomic composition of the zooplankton assemblage was similar to other years. The zooplankton assemblage was dominated by copepod nauplii, *Oithona similis* adults and copepodites, and comparatively much lower abundances of adults and copepodites of several other copepod species such as *Pseudocalanu*s spp., *Centropages* spp. and *Calanus finmarchicus, Acartia hudsonica* in Boston Harbor, as well as meroplankters such as gastropod veligers.

No matter what the explanation for the lack of a 1998 spring bloom, the baseline monitoring data suggests that spring blooms are not as typical of Massachusetts Bay as was once thought. Large spring blooms as defined by chlorophyll data in past years (1992, 1997) were partly due to blooms of *Phaeocystis*, which does not bloom every year, and was not recorded in 1998. Further, in some previous years, the spring bloom appeared limited to Cape Cod Bay, and was not largely representative of most of the nearfield area. Also, in some previous years, the major bloom came in the fall, such as the 1993 bloom of *Asterionellopsis glacialis*. Thus, the presence or absence of a major spring phytoplankton bloom appears to be part of the large envelope-of-variability recorded for the MWRA sampling area since 1992.

6.3.2 *Oithona* and *Calanus* Biomass

As noted in Section *6.2.2* and *6.2.3, Oithona similis* is the numerical dominant at most stations at most times of the year. It was stated in the plankton issues report (Cibik *et al.*, 1998c) that though present in high abundance the contribution of *Oithona* to overall zooplankton biomass is less significant due to its small body size. This was based on a comparative analysis where zooplankton biomass was approximated as the product of abundance and adult body weight obtained from the

literature. From this analysis, it was determined that the most important species in terms of biomass is the large copepod *Calanus finmarchicus*, which reportedly dominates biomass during the winter/spring period. This analysis and the conclusion drawn from it are questionable due to the application of ADULT copepod biomass values to abundances of copepods almost totally dominated by smaller copepodites.

In the MWRA "zooplankton retrospective" report (Lemieux *et al.* 1998), there is a figure showing comparative sizes of adult and copepodite stages of the copepods *Calanus finmarchicus, Centropages typicus, Centropages hamatus, Pseudocalanus* sp., *Paracalanus parvus*, and *Oithona similis* (Figure 2-1 on p. 2-11, from Davis, 1987). Comparisons of sizes in this figure between younger copepodite stages of *Calanus finmarchicus* with those of adults of smaller copepod species reveal there is a strong potential for overestimation of *Calanus* biomass in the analysis of comparative copepod biomass presented by Cibik *et al.* (1998c). The figure in Lemieux *et al.* (1998) also shows that the range in size from C1 copepodite to adult is substantially larger for large Copepods than it is for smaller copepods. For instance, the adult *Calanus finamarchicus* is ~4 times the length of a C1 copepodite, while an *Oithona similis* adult is only ~2.5 times the length of its C1 copepodite. As mass approximately scales as a power function of length, a biomass estimate assuming adult mass would be much more biased for *Calanus* than for *Oithona*.

In Cibik *et al.* (1998c), the biomass calculations assumed a biomass for *Calanus* (*i.e.*, adults) of 125 µgC. However, since most of the "*Calanus*" recorded during the HOM baseline monitoring program are copepodites smaller than stage C3, comparisons of size (*i.e.*, length) should be made between these younger copepodites (rather than the adults) and adults/copepodites of smaller species. A *Calanus* C3 copepodite is approximately the same length as adults of *Centropages typicus, C. hamatus*, and *Pseudocalanus* sp. Biomass values used by Cibik *et al.* (1998c) for the latter three were 15, 10 and 10 µgC, respectively. A *Calanus* C2 copepodite is approximately the same length as a *Paracalanus parvus* adult, for which Cibik *et al.* (1998c) used a biomass value of 5 µg C. The length of a *Calanus* C1 copepodite approximates that of an *Oithona similis* adult, for which Cibik *et al.* used a biomass value of 1 µgC. Since a biomass value of 125 µgC was applied to all *Calanus* recorded, it would take 125 *O. similis* to equal the biomass of a single *Calanus finmarchicus* even though most were smaller copepodites. The application of the adult biomass factor for *Calanus* could result in an overestimate of *Calanus* biomass in comparison to Oithona biomass of 125 times, or over two orders-of-magnitude. In general, the abundance of *Oithona similis* adults and copepodites is two orders-of-magnitude higher than that of *Calanus* copepodites. This would then tend to more closely equilibrate their contributions to biomass.

Although *Calanus* specimens recorded from the MWRA samples have been recorded as adults versus copepodites, the copepodites have not been further characterized as to stage. Thus, while it is apparent that the biomass estimates presented by Cibik *et al.* (1998c) are overestimations, it is not clear by how much. It would be possible to discern this by re-examination of *Calanus* specimens in archived samples, and determination of comparative copepodite stage structure. The preponderance of small copepodites in the records of *Calanus finmarchicus* precludes the extrapolation of adult biomass values to assemblages dominated by small copepodites. Doing so overestimates the contribution of *Calanus* to copepod biomass, and may reverse the conclusions of Cibik *et al.* (1998c) that it is the biomass dominant during the first half of the year.

6.3.3 Zooplankton Identification Issues

Two zooplankton identification issues were raised in the plankton issues report (Cibik *et al.*, 1998c) that *Pseudocalanus newmani* was apparently identified incorrectly as *Paracalanus parvus* and *Acartia hudsonica* was identified incorrectly as *Acartia tonsa* (during late summer and fall) in 1992-1994. As this is the last annual report that will appear prior to initiation of discharge from the outfall

(scheduled for October 1999), it is important to address these issues. The objective is to provide consistency in the zooplankton species data for the baseline-monitoring period for future comparisons with post-outfall monitoring data. This is especially important for *Acartia* spp. given its potential importance as an MWRA threshhold.

6.3.3.1 Paracalanus/Pseudocalanus Grouping

In Cibik *et al.* (1998c), *Pseudocalanus newmani* and *Paracalanus parvus* abundance was reported as a combined total. This was done because of discrepancies in distinguishing between the two species and because there is a clear seasonal shift in the assemblage. It was reported that, since *Pseudocalanus* is a boreal species and *Paracalanus* is a warm water species, the abundances for the first half of the year are expected to be nearly all *Pseudocalanus* and the abundances for the second half of the year are a mix of the two species. This is an oversimplification of seasonal patterns of these copepods.

First, the grouping of *Pseudocalanus newmani* and *Paracalanus parvus* as a single generic entity (P*seudocalanus*/*Paracalanus*) would be imprecise, as there are at least two species of each of these two genera that occur in the MWRA sampling area. The *Paracalanus* include *P. parvus* and *P. crassirostris*, which differ greatly in size, habitat and presumably ecology. *Pseudocalanus newmani* and *P. moultoni* co-occur and are difficult to separate with light microscopy (Frost, 1989), though they are clearly distinguished with molecular techniques (Bucklin *et al.* 1998). Additionally, the assertion that the seasonality of the species allows the grouped data to be interpreted as *Pseudocalanus* for the first half of the year and a mix of the two species in the second half of the year is an oversimplification. The MWRA baseline monitoring data indicate that, although predominance by *Pseudocalanus* adults and copepodites is found in winter and spring, *Paracalanus* adults and later copepodites are clearly present throughout the year.

Most of the records in the MWRA database for *Paracalanus parvus* and *Pseudocalanus newmani* are for copepodites, and most of those are for young copepodites. While adults of these two species are readily distinguished, it is difficult to distinguish between the young copepodites of these two species. It became apparent early in HOM 3 that, depending on season, some or many of the "*Paracalanus parvus* copepodites" recorded during HOM 1 were almost certainly *Pseudocalanus* spp. copepodites. Thus, to handle this within the database and make multi-year comparisons consistent, it was recommended that records for copepodites of the two genera be combined as "*Paracalanus/Pseudocalanus* copepodites." This taxonomic combination of *Paracalanus* and *Pseudocalanus* copepodites is common in studies using fine-mesh nets in areas of northern Europe, where they both occur, and provides consistency in data presentation. Thus, it is recommended that records for COPEPODITES of *Paracalanus parvus* and *Pseudocalanus newmani* be combined, but that the adults of these two taxa continue to be recorded separately.

Based on recent research, it is also recommended that the species designation of *Pseudocalanus newmani* be replaced by *Pseudocalanus* spp. Using mitochondrial DNA analyses, it has been shown that two species of *Pseudocalanus* (*P. newmani* and *P. moultoni*), co-occur in Massachusetts and Cape Cod Bays and Georges Bank (Bucklin *et al.*, 1998). These two species are extremely difficult to distinguish, even as adults, using microscopy.

6.3.3.2 Acartia hudsonica and Acartia tonsa Identifications

Cibik *et al.* (1998c) state that *Acartia hudsonica* was identified incorrectly as *Acartia tonsa* during late summer and fall in 1992-1994. This is a misleading generalization and, as it reads, is incorrect because it implies that *Acartia tonsa* was not present in Boston Harobr during late summer and fall, when, in fact, it was not only present but abundant. In reality, some of the specimens identified as *Acartia tonsa* during 1992-1994 were likely *Acartia hudsonica*. Typically *Acartia tonsa* is a

dominant summer-fall component of the harbor zooplankton, just as *Acartia hudsonica* is during the winter and spring. However, this temporal classification is not absolute and *Acartia hudsonica* persist in the harbor throughout the warmer periods, co-occurring with *A. tonsa*. This was the case in August 1998 with *A. hudsonica* being observed at each of the Boston Harbor stations.

The co-occurrence of *A. tonsa* and *A. hudsonica* during warmer periods became apparent after the addition of station F30 in inner Boston Harbor during HOM2. During the 1992-94 sampling (HOM1), the only zooplankton station fully inside Boston Harbor was station F23. Although most *Acartia* specimens sorted from station F23 during HOM1 have dried out, and archived samples need to be re-examined, it is likely that some of the *Acartia* specimens recorded as *A. tonsa* during HOM1 were actually *A. hudsonica*. The vast majority of the *Acartia* specimens recorded throughout all phases of the MWRA study, however, were copepodites, which are indistinguishable when they co-occur. Further, comparisons of *Acartia* present during summer and fall during 1998 (HOM3) reveal that persistence of *A. hudsonica* adults (mostly males) through the warmer months is much more frequent at station F30 than at station F23. It is unclear why this pattern was observed.

Despite the co-occurrence (at low levels) of these species in summer in Boston Harbor and other waters north of Cape Cod, cycles of resting eggs in Narragansett Bay and elsewhere (Zillioux and Gonzalez, 1972; Sullivan and McManus, 1986) reveal that these species are sufficiently different in seasonality, physiology, and abundance throughout most of their range to preclude being lumped as "*Acartia* spp." as done by Cibik *et al.* (1998c) and Lemieux *et al.* (1998). A final caveat, however, is that comparisons of total abundances of *Acartia* adults + copepodites in Boston Harbor (Figure 6-10) reveals that *Acartia tonsa* is numerically far more abundant during the warmer months than *Acartia hudsonica* is during the colder months. This is because the absolute abundances of *Acartia* spp. are far higher in summer and fall than in winter and spring. It is also apparent that while Acartia spp. are sporadically present in the nearfield and Cape Cod Bay (Figure 6-11), the abundances in these areas are orders-of-magnitude lower than in Boston Harbor (Figure 6-10). These trends have major implications for the "MWRA *Acartia* hypothesis" discussed below.

6.3.4 Zooplankton Thresholds

6.3.3.1 *Acartia* Hypothesis

It has been suggested that effects of the MWRA outfall might be detected through a shift in zooplankton communities in the nearfield from those dominated by offshore taxa to those dominated by harbor taxa (Lemieux *et al.*, 1998). Copepods of the genus *Acartia*, which have been found predominantly in Boston Harbor during the HOM program, are the central components of this hypothesis.

The *Acartia* hypothesis is based on the supposition that this copepod requires high concentrations of food for maximal growth and egg production and is, therefore, restricted to the harbor environs. If the new outfall causes an increase in eutrophication in the nearfield and gives rise to an increase in phytoplankton density, then based on the hypothesis there would be a shift in the distribution of *Acartia* further offshore (Cibik *et al.*, 1998c).

The *Acartia* hypothesis is based on a paper by Paffenhofer and Stearns (1988) entitled: "Why is *Acartia tonsa* (Copepoda: Calanoida) restricted to nearshore environments?" The putative answer to this question was that *Acartia tonsa* was food limited, and could not obtain sufficient food for reproduction on the middle and outer continental shelf (off Georgia), where food concentrations were stated to be low, and because *Acartia tonsa* decreased clearance rates at lower algal food concentrations, compared to *Paracalanus* sp. which continued to increase its clearance rate when food levels were low. Paffenhofer and Stearns mentioned, but dismissed in a sentence each, the possibilities that *Acartia tonsa* was restricted to estuaries by temperature, salinity, or predation.

The conclusions of Paffenhofer and Stearns (1988) were challenged 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°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°C (Zillioux and Gonzalez, 1972). Tester and Turner confirmed that eggs held at 10°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.

Tester and Turner (1991) also compared clearance rates and food concentrations in the experiments of Paffenhofer and Stearns with others from the literature. This revealed that *Acartia tonsa* regularly contends in nature with food concentrations much lower than the minimum levels offered by Paffenhofer and Stearns, exhibits much lower clearance rates at these low natural food levels, but is still abundant under such conditions. Tester and Turner (1991) concluded that restriction of *Acartia tonsa* to estuarine waters by food limitation had not been actually tested, and was primarily due to proper combinations of warm water and low salinity for naupliar survival. In essence, the physiological tolerances of the younger instars determines the biogeographic distribution of the species, as with many other animals. Thus, it is unlikely that the higher salinity in Massachusetts Bay will allow this species to respond even if food were highly abundant.

6.3.3.2 Validity of Zooplankton Thresholds

The selection of an appropriate zooplankton threshold for the new MWRA outfall is difficult for several reasons. First, what type of change in the zooplankton might be considered bad? Second, how much of a change would be considered bad, and how would it be quantified? Lemieux *et al.* (1998) suggest that an appropriate zooplankton threshold for effects of the new outfall would be a shift in the nearfield from present zooplankton dominance by "offshore" assemblages dominated by *Calanus, Pseudocalanus* and *Centropages typicus* to an "inshore" community dominated by *Acartia, Eurytemora* and *Centropages hamatus*. Several additional factors must be considered and questions addressed in the evaluation of this proposed zooplankton threshold. These include:

- the relatively low and variable abundance of these species in Massachusetts Bay, Cape Cod Bay and surrounding waters (Gulf of Maine),
- the effect of confounding "inshore" factors (*i.e*. temperature and salinity),
- spatial variability in Massachusetts Bay that is driven by physical oceanography, and
- should there even be a zooplankton threshold?

Although *Acarti*a spp. are major components of the zooplankton only in Boston Harbor, other copepod species listed in the proposed threshold occur throughout nearfield, farfield and harbor areas. They occur in such low abundances, that their presence or absence in a given area would be based upon statistically insignificant percentages of the whole zooplankton assemblage, and would not be an unambiguous indication of any change in the habitat. For instance, *Centropages typicus* and *C. hamatus* as well as two species of *Pseudocalanus* occur throughout the MWRA sampling area (as well as the rest of the Gulf of Maine), but records at a given station are usually based on comparatively low actual raw counts of these animals, compared to the overwhelming preponderance of copepod nauplii, *Oithona similis*, and whatever meroplankters happen to be in season. Thus, these copepods are poor contenders for indicator species. It is true that *Calanus finmarchicus* is generally more abundant offshore than inshore, but again, it is a minor component of total abundance.

Eurytemora herdmani is the only "inshore" species other than the *Acartia*'s that appears to be limited to truly "inshore" locations. It is usually present only at Boston Harbor locations, and primarily in the

early spring. This is likely due to a combination of seasonality of resting egg cycles, and preference for brackish water. Interestingly, during a previous Battelle study (Newtown Creek) in waters around New York Harbor, Long Island Sound, and adjacent waters of the New York Bight and the Hudson River (West, 1995), the only location where *Eurytemora herdmani* was present, and was usually dominant, was up the Hudson River in brackish low-salinity waters. Thus, attempting to define a zooplankton threshold for "eutrophication" using *Eurytemora herdmani*, clearly mixes the effects of salinity with any putative eutrophication effects.

Should there be any zooplankton threshold for effects of the MWRA outfall? Probably not. The reason is that it is difficult to envisage any adverse effect on the system that would be reflected by zooplankton in Massachusetts Bay. The reason for that is that Massachusetts Bay and the rest of the Gulf of Maine system is highly advective. Water flows from the north and east along the coasts of Maine, New Hampshire, and Massachusetts, exiting the Massachusetts Bay system on both sides of Stellwagen Bank, and flowing to the east along the northern flank of Georges Bank (Bigelow, 1927). Therefore, zooplankton in the MWRA sampling area is as transient as cars at a given location on a freeway. Not only is this suspected from physical oceanography, but actually confirmed using molecular techniques which show that *Calanus finmarchicus* and the two species of *Pseudocalanus* in the Gulf of Maine are part of a genetically homogeneous population extending from the Gulf of St. Lawrence through the Scotian Shelf, Gulf of Maine, Massachusetts Bay and out to Georges Bank (Bucklin and Kocher, 1996; Bucklin *et al.* 1996; 1998).

Thus, any adverse effect on or by the zooplankton of Massachusetts Bay, even one as catastrophic as the trophic cascade caused by invasion of the Black Sea by the ctenophore *Mnemiopsis leidyii* (Zaitsev, 1992; Kideys, 1994), would likely be transient and insignificant in Massachusetts Bay. Before any such effects became pronounced, the zooplankton populations involved would likely be washed out of Massachusetts Bay toward Georges Bank, and restocked from the north by the Maine Coastal Current. Since Boston Harbor is physically sheltered from the Maine Coastal Current, its zooplankton assemblages are distinct from those in Massachusetts Bay even though tidal interaction with the coastal and nearfield waters is constant. The harbor assemblage is influenced by "embayment" parameters such as lower salinity due to runoff, warmer temperatures in summer, shallow depth which may influence copepod resting egg cycles and meroplankton retention, and higher turbidity. This is likely why *Acartia* spp., *Eurytemora herdmani*, and meroplankton dominate the harbor, whereas outside the harbor, plankton assemblages are similar from Nova Scotia to Georges Bank because they are all part of the same physical oceanographic conveyer belt.

In all likelihood, after the outfall goes on line, the copepod abundance in the nearfield, and farfield outside Boston Harbor will be dominated *by Oithona similis, Pseudocalanus* spp., and to a much lesser extent *Paracalanus parvus, Centropages typicus* and *C. hamatus,Calanus finmarchicus* and other typically "offshore" copepods just as it is now. Since these "non-*Acartia*'s" often co-occur at varying and, for all but *Oithona* and *Pseudocalanus* copepodites, low numbers throughout the nearfield and farfield, any thresholds based upon their numbers would not be clear-cut. However, if we see *Acartia* spp. ever comprising over half the copepods anywhere but inside the harbor, then we would know that, for whatever reason, there had been a significant change (for example a runoff pulse due to a hurricane). In terms of meroplankton (planktonic larvae of benthic invertebrates), while they often dominate the numbers in many zooplankton samples, their periods of abundance are ephemeral, and likely more related to reproductive cycles of their macrobenthic parents, than to processes in the plankton.

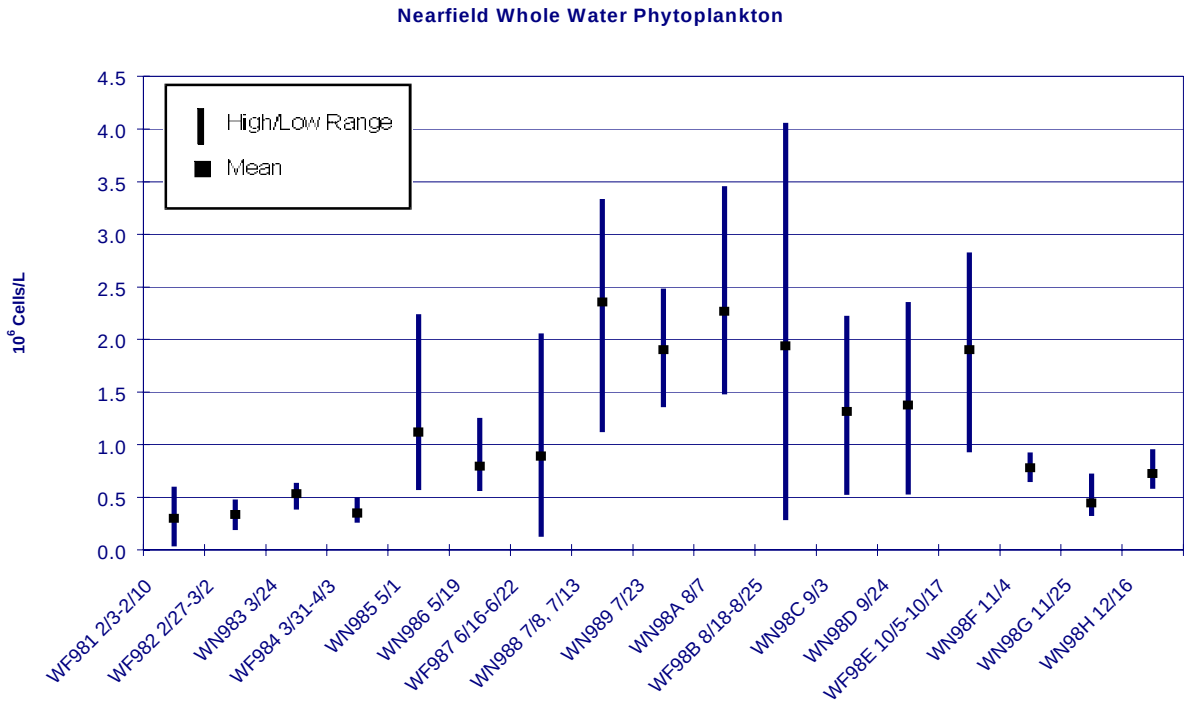


Figure 6-1. Total phytoplankton abundance for nearfield whole-water samples. Mean and range for all nearfield stations and depths sampled.

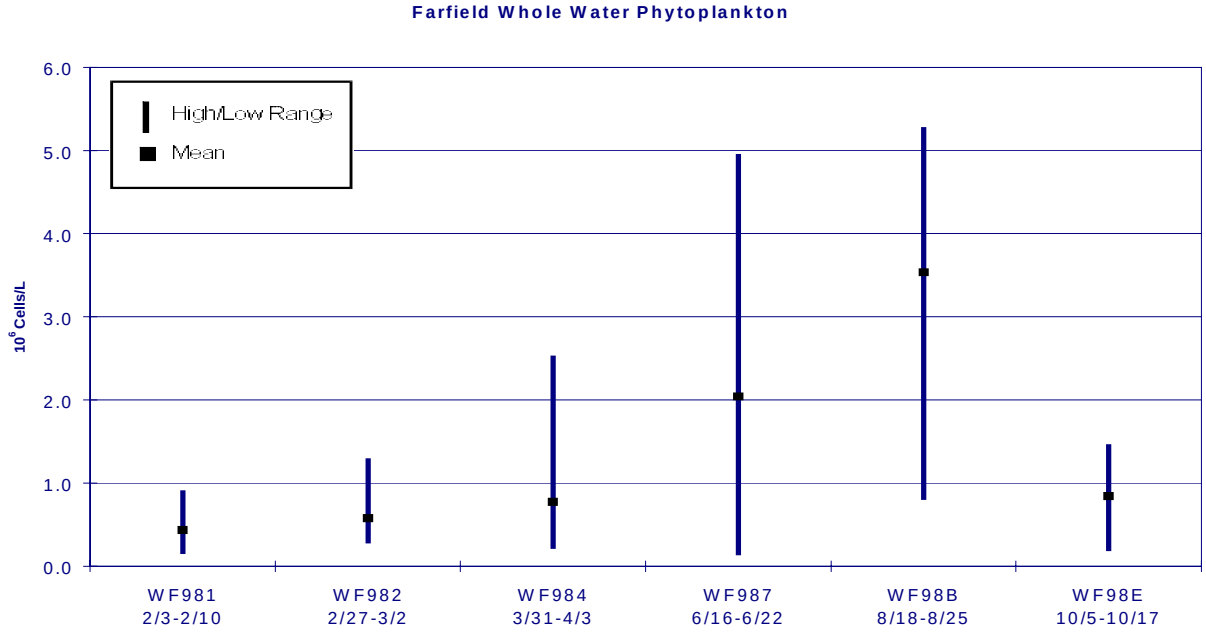


Figure 6-2. Total phytoplankton abundance for farfield whole-water samples. Mean and range for all farfield stations and depths sampled.

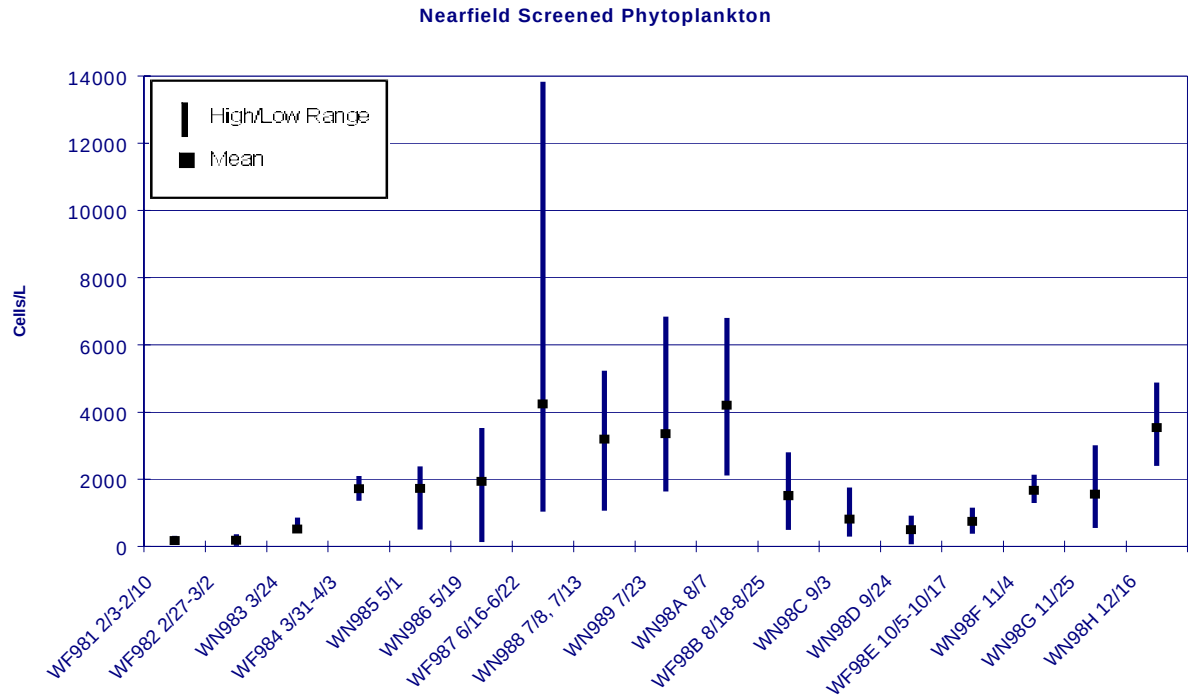


Figure 6-3. Total phytoplankton abundance for nearfield 20-µm screened samples. Mean and range for all Nearfield stations and depths sampled.

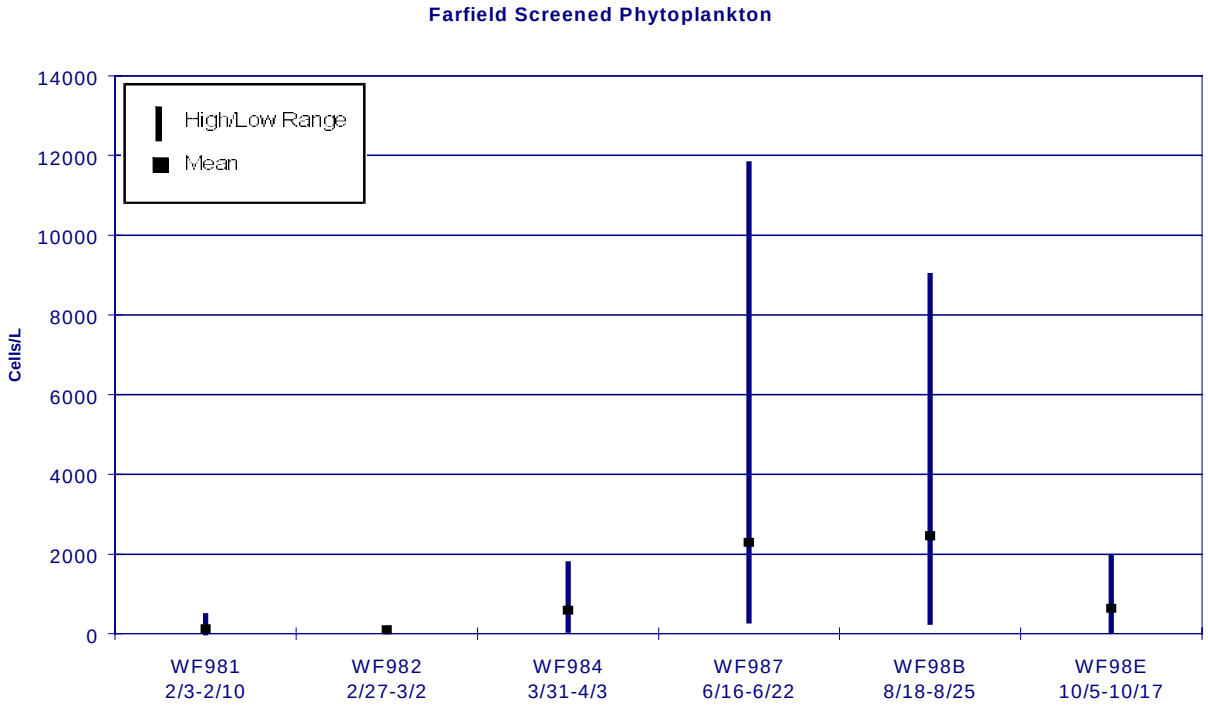


Figure 6-4. Total phytoplankton abundance for farfield 20-µm screened samples. Mean and range for all Farfield stations and depths sampled.

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.

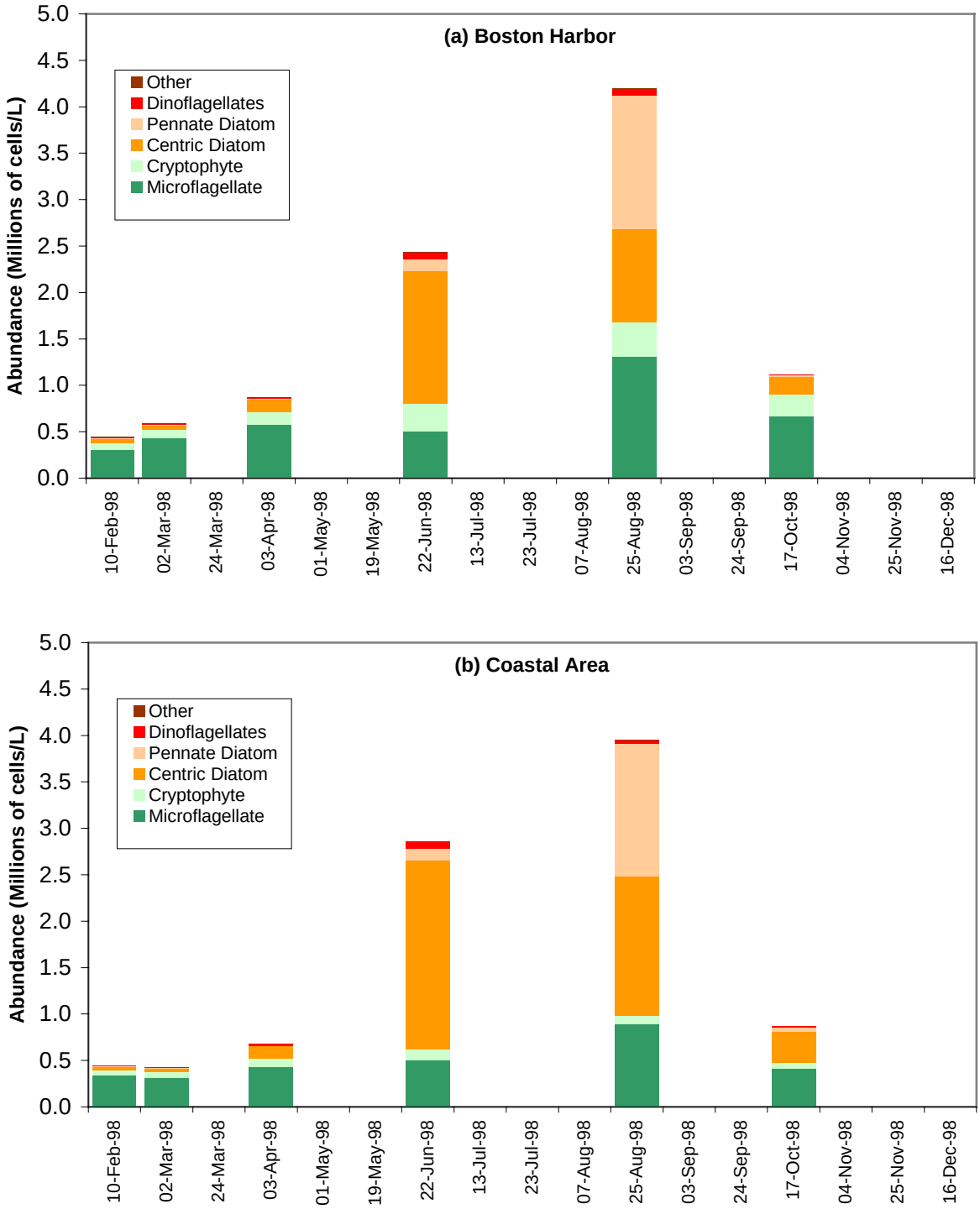


Figure 6-6. Average phytoplankton abundance by major taxonomic group, (a) Boston Harbor and (b) coastal area. Data are average of surface and mid-depth samples from F23, F30 and F31 and F13, F24 and F25, respectively.

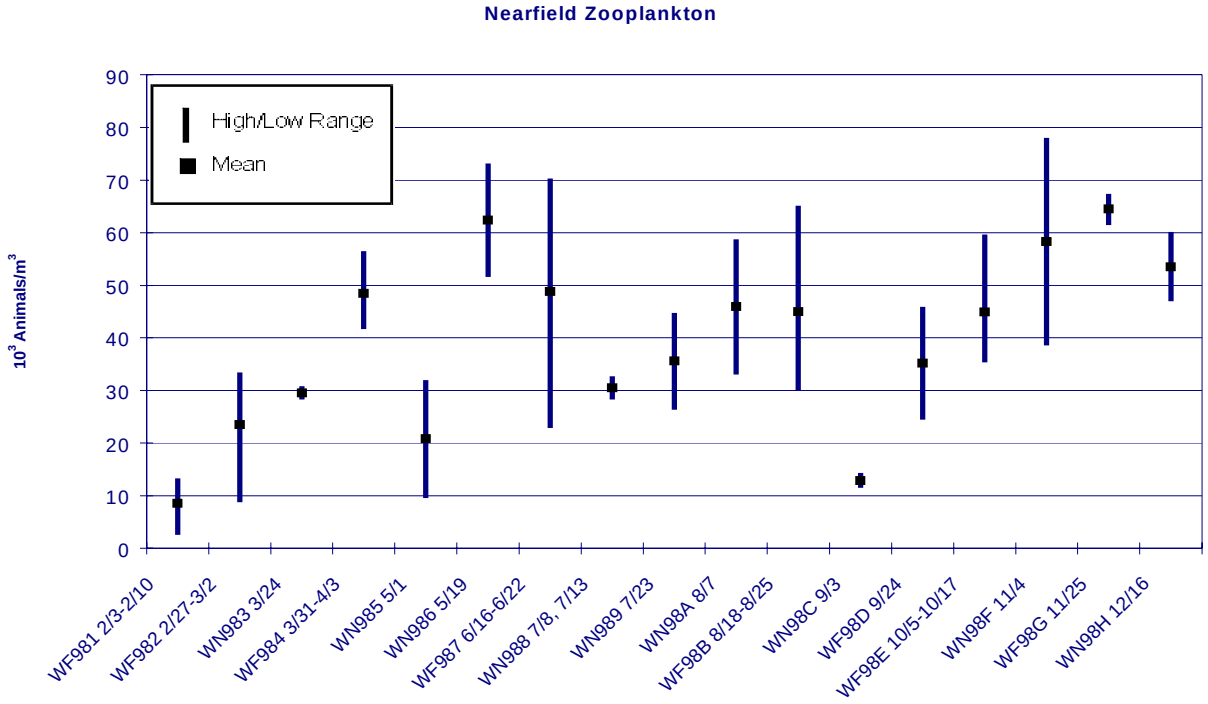


Figure 6-7. Total zooplankton abundance for nearfield. Mean and range for all nearfield stations and depths sampled.

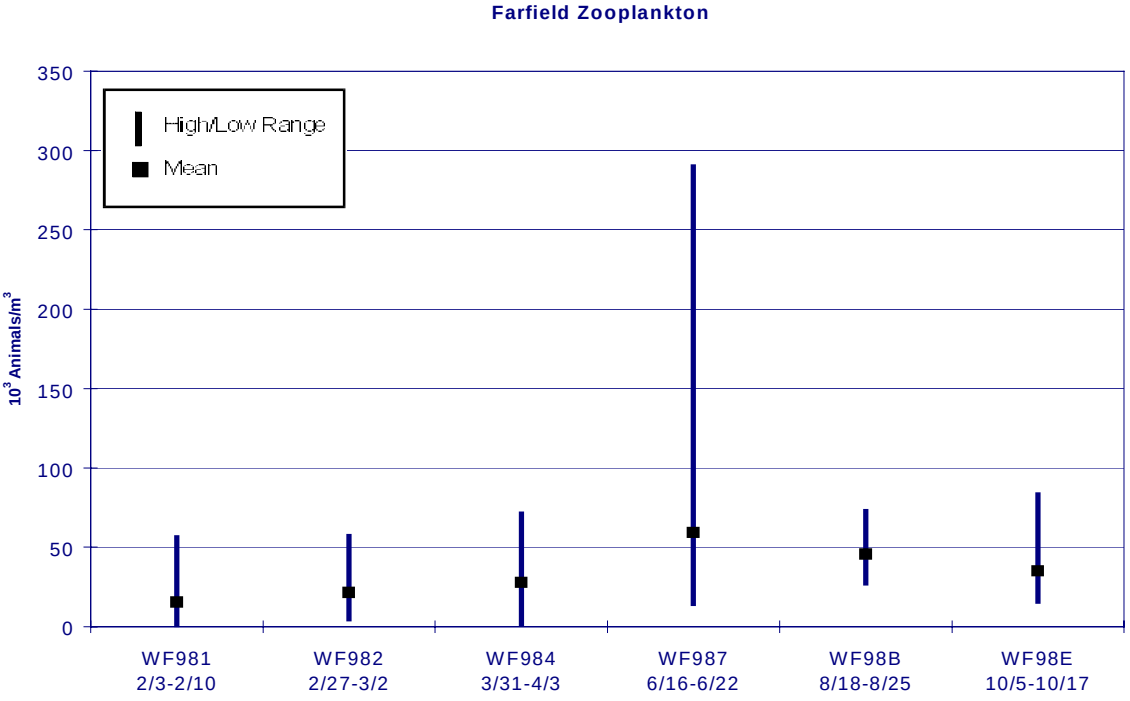


Figure 6-8. Total zooplankton abundance for farfield. Mean and range for all farfield stations and depths sampled.

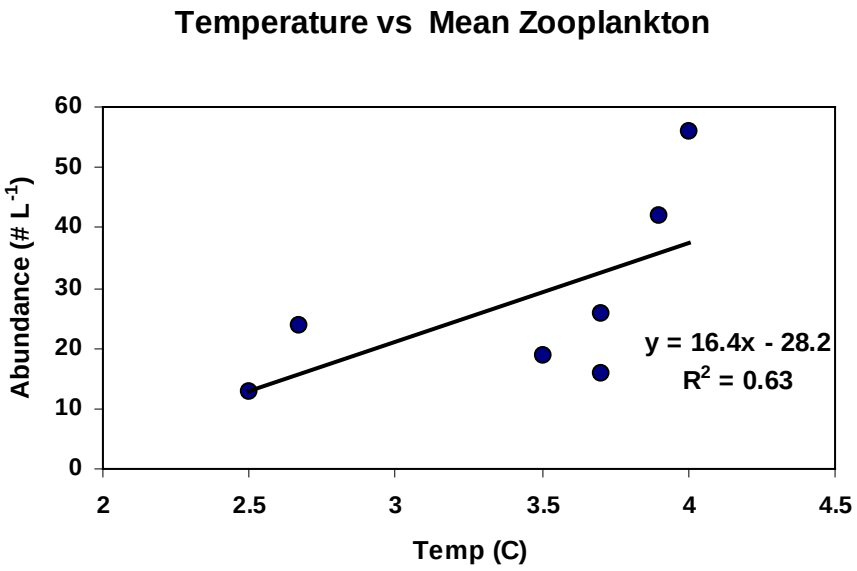


Figure 6-9. Relationship between temperature and zooplankton abundance during the "Spring" bloom period for 1995-1998. Data from productivity stations only.

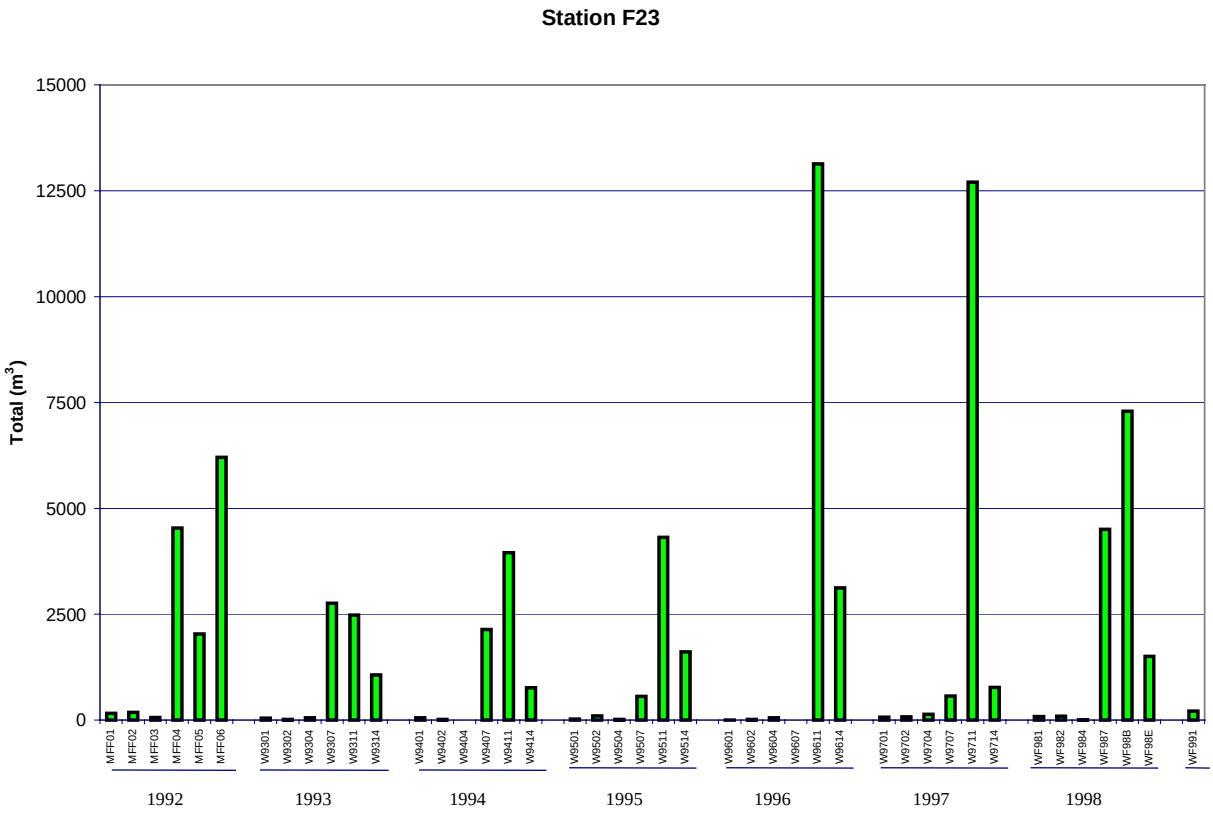


Figure 6-10. Total abundance of *acartia* spp. adults and copepodites at station F23, 1992-1998.

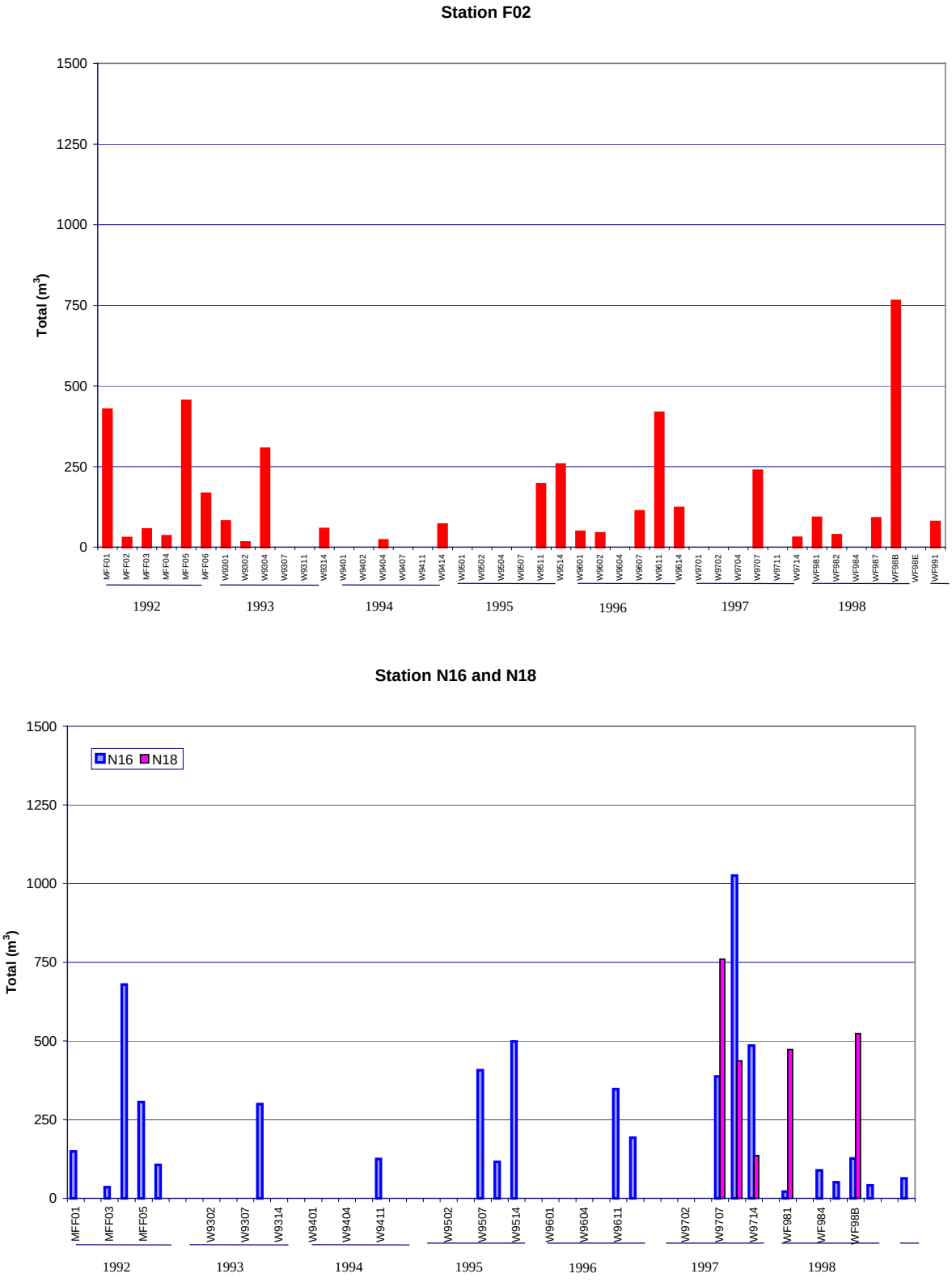


Figure 6-11. Total abundance of *acartia* spp. adults and copepodites at (a) Cape Cod Bay station F02 and (b) nearfield stations N16 and N18, 1992-1998. Note different scale than Figure 6-10.

7.0 SUMMARY OF 1998 WATER COLUMN MONITORING

In 1998, the weather conditions in the Massachusetts and Cape Cod Bays region were influenced, as was much of the country, by weather patterns associated with the El Niño event in the Equatorial Pacific. The winter of 1998 was relatively warm and the winter and spring seasons were disrupted by numerous storms and record rainfall events (particularly in June). These conditions resulted in warm water temperatures and high flow conditions in the early spring, which contributed a relatively early onset of stratification. Due to the high flow conditions in late winter/early spring and June, surface salinity was lower in western Massachusetts Bay during 1998 than any previous baseline-monitoring year. The unusually low surface salinity gave rise to strong stratification during the summer of 1998. Significant upwelling events were observed in July and August that transported cooler, nutrient-rich waters from the deeper waters of Massachusetts Bay into the coastal areas. Evidence of this was observed at coastal stations along the south shore and in the western nearfield. Stratification weakened in the fall but the overturn of the water column and the return to winter conditions was delayed until late in the year. The water column was still stratified in November throughout much of the nearfield and a deep halocline was present in December at the deeper eastern nearfield stations.

No spring bloom was observed in 1998 even though elevated nutrient concentrations persisted in the surface waters until May. Nutrient and production data indicate that bloom conditions existed and that the phytoplankton community may have started to bloom (nutrient draw down between February and March and high productivity), but an increase in biomass was not achieved. Potential factors influencing the occurrence of a spring phytoplankton bloom include nutrient limitation, light availability, photic depth, temperature and predation. In 1998, nutrients were available and irradiance and photic depth were not significantly different than those observed in previous years. A preliminary analysis suggests that in 1998 warm winter water temperatures may have led to an increase in grazing pressure that prevented a winter/spring bloom. In the absence of any zooplankton grazing rate data, however, speculation that the lack of a 1998 spring phytoplankton bloom was due to zooplankton grazing pressure is difficult to confirm.

Regardless of the reasons for the lack of a 1998 spring bloom, the baseline monitoring data suggest that spring blooms may not be as typical of Massachusetts Bay as was once thought. Large spring blooms as defined by chlorophyll data in past years (1992 and 1997) have been partly due to blooms of *Phaeocystis*, which does not bloom every year and was not recorded in 1998. Further, in some previous years, the spring bloom appeared limited to Cape Cod Bay and was not largely representative of most of the nearfield area. Thus, the presence or absence of a major spring phytoplankton bloom appears to be part of the large envelope-of-variability for the MWRA sampling area.

Due to the absence of a winter-spring bloom, annual productivity at stations N04, N18 and F23 was lower than in prior years. Typically, the spring phytoplankton bloom accounts for greater than 30% of the annual production at the monitoring sites. In 1998, the fall bloom dominated the seasonal productivity pattern. As with the winter/spring bloom, the fall bloom is not a consistent annual characteristic in the bays. The intensity of the fall bloom and the phytoplankton species that bloom varied from year to year during the baseline-monitoring period. In 1998, the fall bloom was not a single species bloom, but rather a general increase in the numbers of a variety of chain-forming diatoms. The bloom was more clearly observed in increased chlorophyll concentrations and peak production rates that were measured in the nearfield than in phytoplankton abundance.

The overturn of the water column and the return to winter conditions was delayed in 1998 compared to previous baseline monitoring years. The water column was stratified until November throughout much of the nearfield and a deep halocline was still present in December at the deeper eastern nearfield stations. The strength and duration of stratification are important factors in the decline of

bottom water dissolved oxygen concentrations. Due to the persistence of stratified conditions in 1998, bottom water DO concentrations decreased over the entire June to December time period in the nearfield area. The delay in mixing led to the annual minimum in bottom water DO concentration in December. Relatively high bottom water DO concentrations observed at the setup of stratified conditions in June kept the minima from reaching extremely low levels that had been observed during previous years.

In November and December 1998, anomalously high concentrations of ammonium and phosphate were observed in the western nearfield that correlated with high concentrations observed by the MWRA in northern Boston Harbor. The source of the anomalously high nutrient concentrations has not been determined, but was likely due to the transfer of south system sewage flow from Nut Island to the Deer Island and increased secondary treatment capacity at the Deer Island facility. The transfer of sewage flow from Nut Island to Deer Island increased discharge volume by a third, but did not immediately result in increased ambient nutrient concentrations in the harbor. The harbor's summer biological community may have been able to adapt and utilize the increased nutrient input initially, but once the system shut down in September/October elevated nutrient concentrations were measured both in the harbor and nearby coastal waters.

Instead of being dominated by a major winter/spring or fall bloom, phytoplankton abundance steadily increased from low levels in February to a maximum during the summer and fall followed by declines in November and December. The phytoplankton assemblages were numerically dominated by microflagellates and cryptomonads, with subdominant contributions by various chain-forming diatoms. *Chaetoceros socialis* and *Skeletonema costatum* were subdominants during the winter and spring. During the summer, *Leptocylindrus minimus, L. danicus, Rhizosolenia fragilissima, Proboscia alata,* and *S. costatum* were abundance. The localized fall bloom in the nearfield was due to an increase in mixed assemblage of diatoms – *Chaetoceros spp., Leptocylindrus spp., S. costatum,* and *Pseudo-nitzschia* spp., which was also abundant in the nearfield during December.

Perhaps the singular phytoplankton event of the year was the bloom of *Ceratium longipes/C. tripos,* which began unusually early in February, and exhibited sustained increases through July. Observations in the Gulf of Maine revealed that this bloom extended far to the north and east along the coast of Maine into the Bay of Fundy in July and August of 1998. *Ceratium longipes* and *C. tripos* usually bloom in Massachusetts and Cape Cod Bays during the spring and summer, but the early initiation of this bloom in 1998 may relate to the unusually mild El Niño winter in New England in 1998. Dominance of the 20 μm-screened phytoplankton by various *Ceratium* species (*C. tripos, C. longipes* and *C. fusus*) continued through the late summer and fall, into December. This bloom of *Ceratium*, however, was 1 to 2 orders of magnitude less abundant than past blooms of these species that have caused large-scale anoxia in the New York Bight in 1976.

In 1998, the zooplankton were dominated, as typical in this coastal system, by copepod nauplii, adults and copepodites of the small copepods *Oithona similis* and *Pseudocalanus* spp., with seasonal subdominant contributions from gastropod and bivalve veligers, and a mixture of other normally-occurring taxa. Zooplankton abundance generally increased from February through April, reached the highest numbers in mid-May in the nearfield. By June, zooplankton abundance was unusually high at all stations, with an astonishing maximum of 290 x 10^3 animals m^{-3} at station F23 in Boston Harbor. The harbor sample was dominated by copepod nauplii, the marine cladoceran *Evadne nordmani*, bivalve larvae, and polychaete larvae, all of which reflect normal summer pulses of reproduction for these taxa. Total zooplankton abundance at nearfield stations fluctuated, but generally remained at high levels from August through December.

During the first three farfield surveys, zooplankton samples were collected at two additional stations in Cape Cod Bay (stations F32 and F33). The addition of these stations extended the range of total zooplankton abundance measured in Cape Cod Bay by approximately a factor of two. During the

April survey, the abundance of *Calanus finmarchicus* copepodites comprised only 3-4% of the catch at stations F01 and F02, but 7-11% at stations F32 and F33. Thus, for this important forage item of right whales that feed in Cape Cod Bay at this time of the year, the addition of the two new stations captured a three-fold increase in patchiness of this copepod that would have been missed by sampling only stations F01 and F02.

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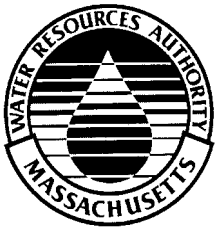

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