2001 annual water column monitoring report

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) has collected water quality data in Massachusetts and Cape Cod Bays for the Harbor and Outfall Monitoring (HOM) Program since 1992. This monitoring is in support of the HOM Program mission to assess the environmental effects of the relocation of effluent discharge from Boston Harbor to Massachusetts Bay. The data from 1992 through September 5, 2000 were collected to establish baseline water quality conditions and to provide the means to detect significant departure from the baseline after the outfall becomes operational. 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). The 2001 data represent the first full year of conditions in the bays since initiation of discharge from the bay outfall on September 6th, 2000. This annual report evaluates the 2001 water column monitoring results, assesses spatial, and temporal trends in the data, compares 2001 data against seasonal and annual water quality thresholds, and examines responses in the nearfield to the transfer of effluent discharge from the Boston Harbor outfall to the bay outfall.

Over the course of the HOM program, a general sequence of water quality events has emerged from the data collected in Massachusetts and Cape Cod Bays. The trends are evident even though the timing and year-to-year manifestations of these events are variable. In general, but not always, a winter/spring phytoplankton bloom occurs as light becomes more available, temperature increases, and nutrients are readily available. Later in the spring, the water column transitions from well mixed to stratified conditions, which serves to cut off the supply of nutrients to the surface waters and terminate the spring bloom. The summer is generally a period of strong stratification, depleted nutrients, and a relatively stable mixed-assemblage phytoplankton community. In the fall, stratification deteriorates and supplies nutrients to surface waters often contributing to the development of a fall phytoplankton bloom. The lowest bottom water dissolved oxygen concentrations are observed prior to the fall overturn of the water column – usually in October. By late fall or early winter, the water column becomes well mixed and resets to winter conditions.

The physical processes in 2001 closely followed climatology and none of the forcing parameters or physical variables showed extreme behavior. Surface water temperatures were relatively warm over the first three months of 2001 in comparison to previous years. Winds in March were somewhat anomalous in the propensity of downwelling-favorable winds, which would have had a tendency to increase the transport of Gulf of Maine waters through Massachusetts Bay at this time. The warm air temperatures and lack of major storms resulted in a prolonged period of weak stratification during the fall of 2001. The dry conditions in the fall of 2001 could significantly impact the conditions in early 2002 because of the lag between freshwater inflow and the response of the water column.

The various water quality parameters in 2001 followed the general sequence of events observed over the baseline period. The main deviations from baseline trends were observed in February and December. Nutrient, biomass, and production data suggest that the winter/spring bloom had peaked prior to the early February 2001 survey in Massachusetts Bay. The decline of this bloom and an influx of nutrients (precipitation, runoff, and advection) led to elevated spring nutrient concentrations in spite of the minor bloom of *Phaeocystis pouchetii* in April. The *Phaeocystis* bloom marked the second consecutive year that this nuisance species was observed in Massachusetts Bay. The calm weather and warm temperatures led to a delay in destratification of the water column and resulted in a late fall bloom. The fall bloom normally occurs in September and October, but in 2001 the bloom occurred from October to December with peak production rates and highest biomass concentrations being measured in early December.

From 1992 to 2000, there was a general trend of increasing annual mean nutrient concentrations in the regions in Massachusetts Bay. This did not continue in 2001 as a decrease in annual mean concentrations was observed throughout the bays, except that NO_3 and especially NH_4 increased from 2000 to 2001 in the nearfield. The largest change that was seen was in annual mean NH_4 concentrations in Boston Harbor that dropped from a high of 10 µM in 2000 to 2 µM in 2001. This was directly due to the transfer of MWRA discharge from the harbor to the bay. A sharp decrease in NH_4 concentration was also seen at the coastal stations, which are strongly influenced by transport of water from Boston Harbor. The increase in annual mean NH_4 in the nearfield was not as dramatic as the harbor and coastal water decrease. This is due to relatively high dilution in the nearfield and the inclusion of 4 months of post-discharge data in the 2000 annual mean NH_4 concentration. Since 1999, the annual mean NH_4 levels have almost doubled in the nearfield. There was little if any change in NH_4 concentrations in offshore, boundary, or Cape Cod Bay waters from 2000 to 2001. In fact, annual mean NH_4 concentrations in Cape Cod Bay have decreased from 1999 to 2001.

The decrease in nutrient concentrations from 2000 to 2001 was commensurate with a decrease in biomass as estimated by chlorophyll and POC measurements. The 2000 annual mean chlorophyll concentrations were the highest observed over the monitoring period and continued a trend of increasing chlorophyll from 1997 to 2000. The lack of major winter/spring and fall blooms in 2001 resulted in decreases in annual chlorophyll concentrations of ≥50% in Boston Harbor, coastal, nearfield and Cape Cod Bay waters. The decrease was not as sharp at the offshore and boundary stations where the 2001 annual concentrations were highest. The presence of elevated chlorophyll at the offshore and boundary stations suggests that chlorophyll concentrations in Massachusetts Bay continue to be influenced by regional factors from the Gulf of Maine. Satellite imagery suggests the trend of increasing concentrations from 1997 to 2000 and then decreasing in 2001is not directly related to local factors, but represent trends observed over much of the western Gulf of Maine.

The annual minimum DO concentrations and percent saturations observed in October 2001 were relatively high in comparison to baseline values. It might be expected that DO concentrations would be high given the relatively low biomass concentrations measured in 2001 (assuming that this correlates to a low organic loading to the bottom waters and benthos). The fact that similar DO minima were observed in 2001 and 2000 when annual biomass concentrations were at or near maximum baseline levels suggests that interannual variations in organic loading play a relatively minor role in controlling bottom water DO. An examination of the connection between physical oceanographic conditions and DO concentrations indicates that regional processes and advection are the primary controlling factors governing bottom water DO concentrations in Massachusetts Bay.

There were no exceedances of Contingency Plan thresholds for water quality parameters in 2001. The dissolved oxygen concentration and percent saturation survey mean minimums for June – October of 2001 were above the threshold standards for both the nearfield and Stellwagen Basin. The nearfield mean areal chlorophyll values were all well below (~50%) each seasonal and annual threshold. Although there was a minor *Phaeocystis* bloom in April 2001, the nearfield mean abundance was well below the threshold. *Alexandrium* and *Pseudo-nitzschia* were observed intermittently, but at very low abundance.

The outfall monitoring results from 2001 do not show any apparent negative impacts upon the water column. Although the effluent nutrient signature is clearly observed in the vicinity of the outfall, it is diluted to background levels over a few days and tens of kilometers. In this area of elevated nutrients there are at most subtle increases in chlorophyll and productivity. There is no apparent change in dissolved oxygen or plankton. The natural variability that has been observed on seasonal and interannual time scales and across the spatial expanse of Massachusetts and Cape Cod Bays is so large it is a challenge to detect outfall effects.

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1.0 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) has implemented a long-term Harbor and Outfall Monitoring (HOM) Program for Massachusetts and Cape Cod Bays. The objective of the HOM Program is to (1) verify compliance with National Pollutant Discharge Elimination System (NPDES) permit requirements; (2) evaluate whether the impact of the discharge on the environment is within the bounds projected by the EPA Supplemental Environmental Impact Statement (SEIS; EPA 1988), and (3) determine whether change within the system exceeds the Contingency Plan thresholds (MWRA 2001). The 2001 data represent the first full year of conditions in the bays since initiation of discharge from the bay outfall on September 6th, 2000. A time line of major upgrades to the MWRA treatment system is provided for reference in **Table** 1-1.

Table 1-1. Major Upgrades to the MWRA Treatment System.

Date	Upgrade
December 1991	Sludge discharges ended
January 1995	New primary plant on-line
December 1995	Disinfection facilities completed
August, 1997 to March, 2001	Secondary treatment phased in
July 9, 1998	Nut Island discharges ceased: south system flows transferred to Deer Island
September 6, 2000	New outfall diffuser system on-line

The 2001 water column monitoring data have been reported in a series of survey reports, data reports, and semiannual interpretive reports (Libby *et al.,* 2002a and 2002b). The purpose of this report is to present a compilation of the 2001 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 2001 data have also been compared to previous baseline monitoring data to characterize trends or departure from trends that may be related to discharge from the bay outfall.

The water column data presented in this report include physical characteristics – temperature, salinity, and density (Section 3) and water quality parameters – nutrients, chlorophyll, dissolved oxygen, production and respiration, and phytoplankton and zooplankton (Section 4). Unlike previous annual reports, this report is focused on a few topics pertinent to the 2001 monitoring data rather than reanalysis of the detailed dataset presented in the semiannual reports. Those interested in an extensive presentation of all 2001 monitoring results are referred to the semiannual reports (Libby *et al.*, 2002a and 2002b). The final section (Section 5) completes this integration and provides an overview of the major themes from the 2001 water column data including comparisons of data against the established Contingency Plan (MWRA 2001) thresholds.

2.0 2001 WATER COLUMN MONITORING PROGRAM

This section provides a summary of the 2001 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: 1998-2001 (Albro *et al*., 2002). 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 2001 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 four times per year. The 2001 results have also been presented in semiannual water column reports that provide full descriptions of physical, chemical, and biological conditions in the bays over the course of the year (Libby *et al*., 2002a and 2002b). The semiannual 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 semiannual reports, and are discussed in this report are available in the MWRA HOM Program Database.

2.2 2001 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 17 surveys that were conducted in 2001 (**Table** 2-1). The surveys have been designed to evaluate water quality on both a high-frequency basis for a limited area (nearfield surveys) and a low-frequency basis for an extended area (farfield). A total of 48 stations are distributed throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay in a strategic pattern that is intended to provide a comprehensive characterization of the area (**Figures** 2-1 and 2-2). The nearfield stations, located in Massachusetts Bay in the vicinity of the outfall site, were sampled during each of the 17 surveys. The farfield stations, located throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay, were sampled during the 6 combined farfield/nearfield surveys.

The 21 nearfield stations are located in a grid pattern covering an area of approximately 100 km^2 centered on the MWRA bay outfall (**Figure** 2-1). The 28 farfield stations are located throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay (**Figure** 2-2). Station N16 is sampled twice during the combined surveys as both a farfield and a nearfield station.

The stations for the farfield surveys have been further separated into regional groupings according to geographic location to simplify regional data comparisons. These regional groupings include Boston Harbor (three stations), coastal (six stations along the coastline from Nahant to Marshfield), offshore (eight deeper-water stations in central Massachusetts Bay), boundary (five stations in an arc from Cape Ann to Provincetown and in or adjacent to the Stellwagen Bank National Marine Sanctuary),

Table 2-1. Water quality surveys for 2001 (WF011-WN01H).

Survey #	Type of Survey	Survey Dates
WF011	Nearfield/Farfield	February 7-9, 12
WF012	Nearfield/Farfield	February 27 – March 2
WN013	Nearfield	March 26
WF014	Nearfield/Farfield	April 4-6, 9
WN015	Nearfield	April 26
WN016	Nearfield	May 18
WF017	Nearfield/Farfield	June 19-21, 25
WN018	Nearfield	July 12
WN019	Nearfield	July 25
WN01A	Nearfield	August 9
WF01B	Nearfield/Farfield	August 27-30
WN01C	Nearfield	September 17
WN01D	Nearfield	October 9
WF01E	Nearfield/Farfield	October 19-22, 25-27
WN01F	Nearfield	October 29
WN01G	Nearfield	December 7
WN01H	Nearfield	December 19

and Cape Cod Bay (five stations, two of which are only sampled for zooplankton during the three farfield surveys from February to April). The regional nomenclature is used throughout this report and regional comparisons are made by partitioning the total data set by these groupings. 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 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).

- Dissolved inorganic nutrient (DIN) samples were collected at type E stations
- DIN and dissolved oxygen (DO) samples were collected at type F stations
- DIN, DO, dissolved and particulate organic nutrients, chlorophyll, and total suspended solids (TSS) were collected at type A and D stations
- Additional samples for plankton and urea analyses were also collected at type D stations
- Type G stations are similar to the type D stations except that samples were only collected at three depths at these shallow harbor stations
- The full suite of analyses plus productivity and respiration measurements were conducted at the three type P stations.
- Respiration measurements were also conducted at one type R station.

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. In 2000, the sampling schema at stations F19, F22, and F26 was modified to collect more data ‘upstream’ of the nearfield. Additional nutrient and plankton parameters were added at stations F22 and F26 (Type D) to better define biological conditions at the northeastern boundary of Massachusetts Bay. In August 2000, additional nutrient samples were also added at station F19 (Type A+R) to provide ancillary data on dissolved and particulate organic nutrients coincident with respiration measurements. The added parameters at stations F19, F22, and F26 have become a permanent part of the program and were measured during each farfield survey in 2001.

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	**6**	**10**	**24**	**2**	**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 A station F19 (prior to 2000 a type F station)

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

Station Type	Number	Station Number
A	6	N01, N07, N10, N16, N20, and F19
D	10	F01, F02, F06, F13, F22, F24, F25, F26, F27, and N16 (on farfield survey day)
E	24	F03, F05, F07, F10, F14-F18, F28, N02, N03, N05, N06, N08, N09, N11-N15, N17, N19, and N21
F	2	F12 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 A station F19

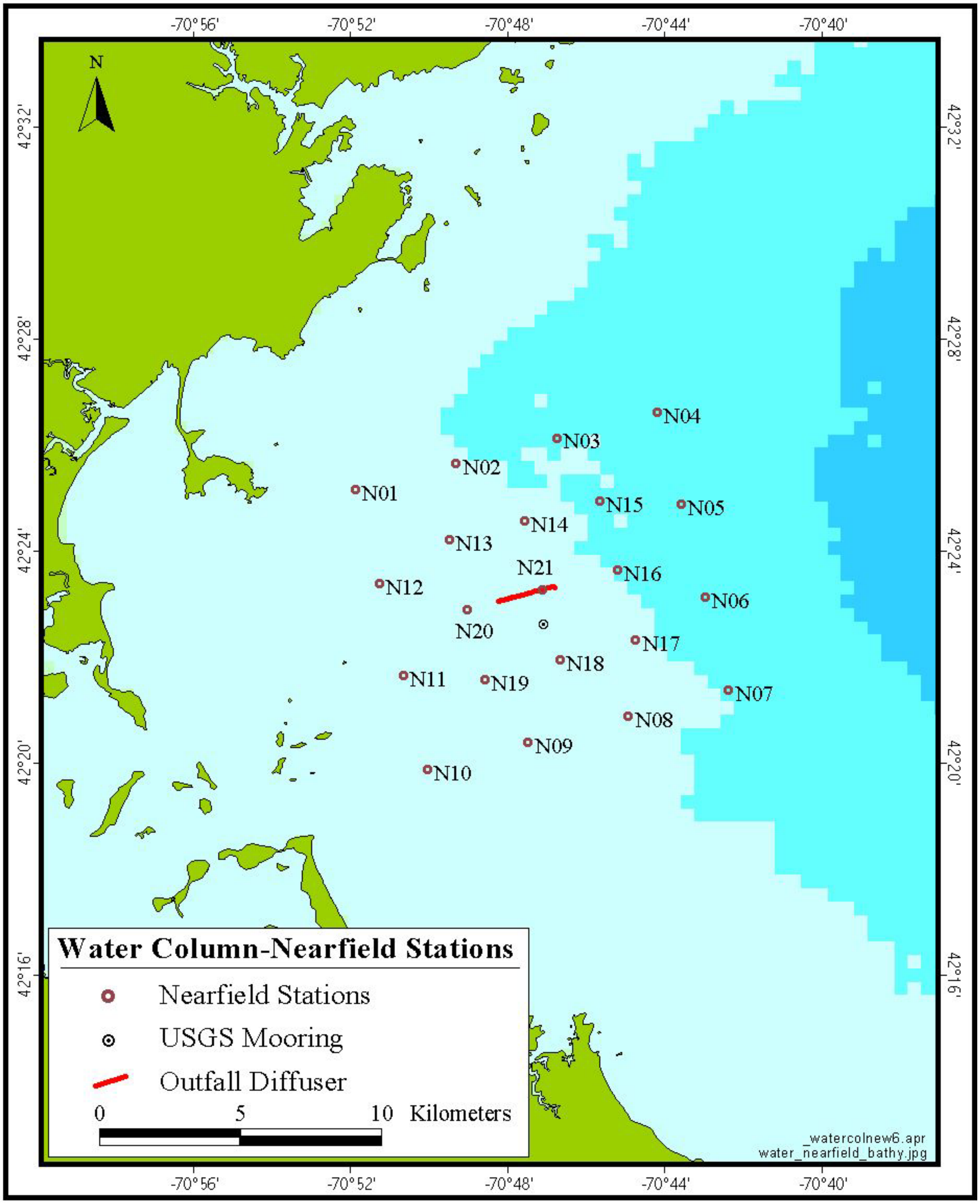


Figure 2-1. Locations of nearfield stations, MWRA offshore outfall, and USGS mooring.

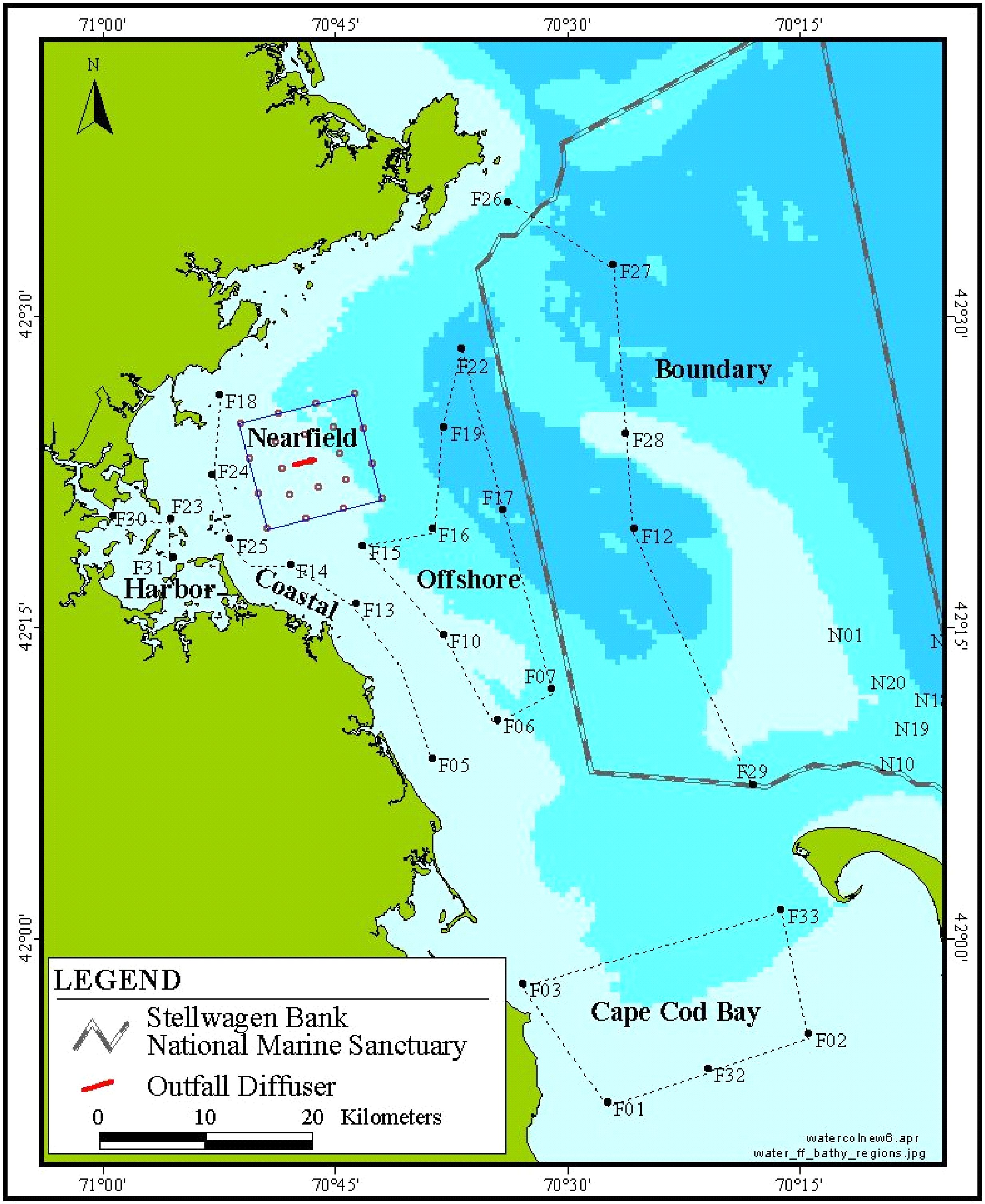


Figure 2-2. Locations of farfield stations and regional station groupings.

3.0 PHYSICAL CHARACTERIZATION

3.1 Forcing Variables

3.1.1 River Discharge

The two principal freshwater sources influencing the outfall site are the Charles and the Merrimack Rivers. The river discharge records (**Table** 3-1; **Figures** 3-1 and 3-2) indicate that the freshwater inflow was low mid March of 2001. River flow was normal through the spring freshet and summer. Drought conditions ensued in September, and the last 4 months of 2001 were unusually dry. The fall of 2001 was the driest since the beginning of the monitoring program.

Table 3-1. River discharge summary for the Charles and Merrimack Rivers 1990-2001.

Year	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Charles River Discharge (m^3s^{-1})				
1991	13	7	3	10
1992	10	8	2	9
1993	15	15	1	5
1994	15	11	3	7
1995	11	5	1	7
1996	16	12	4	16
1997	12	13	1	4
1998	21	21	8	7
1999	18	7	4	9
2000	13	16	4	7
2001	**14**	**14**	**4**	**2**
mean	14	12	3	8
Merrimack River Discharge (m^3s^{-1})				
1990	333	366	164	331
1991	289	237	117	295
1992	254	266	100	174
1993	200	393	51	198
1994	253	380	74	164
1995	295	154	45	292
1996	409	487	127	401
1997	296	404	70	123
1998	401	454	122	116
1999	328	175	103	180
2000	292	410	104	160
2001	**196**	**392**	**55**	**58**
mean	295	343	94	208

3.1.2 Winds

Previous analysis has indicated that the most important aspect of the wind forcing is the average north-south component of wind stress, which determines the preponderance of upwelling or downwelling conditions in western Massachusetts Bay. During early 2001, more northerly wind conditions than usual resulted in stronger than average downwelling conditions (**Table** 3-2; **Figure** 3-3). The spring and summer were close to average, and the fall had weaker than average downwelling conditions. The wind speeds were also typical, but slightly weaker than average (**Table** 3-3).

Table 3-2. Southerly (upwelling) Wind Stress, 1990-2001. Calculated seasonally averaged stress in Pa*10^3 at the Boston Buoy (Large and Pond, 1981).

	Jan.-Mar.	Apr.-Jun.	Jul.-Sep.	Oct.-Dec.
1990	-0.0	1.4	0.8	0.1
1991	-1.6	-0.2	1.0	-4.2
1992	-3.8	-0.4	1.0	-3.4
1993	-4.5	-0.0	1.3	-1.3
1994	-3.5	1.0	0.4	-1.7
1995	-0.1	0.0	-0.0	-0.9
1996	-2.8	0.5	-0.2	-1.3
1997	-0.1	-0.8	0.5	-2.2
1998	-4.3	-0.8	0.9	-0.5
1999	-2.1	-0.2	0.7	-0.9
2000	-3.3	0.0	-0.1	-2.6
2001	**-4.6**	**-0.3**	**0.6**	**-0.1**
mean	-2.6	0.0	0.6	-1.6

Table 3-3. Wind Speed, 1990-2001. Seasonally averaged speed in m/s at the Boston Buoy (USGS).

	Jan.-Mar.	Apr.-Jun.	Jul.-Sep.	Oct.-Dec.
1990	7.0	5.8	4.4	7.9
1991	7.6	5.8	5.3	7.5
1992	7.9	5.8	5.1	7.0
1993	7.7	5.8	4.9	6.9
1994	7.4	5.9	5.6	6.8
1995	6.6	4.6	4.6	7.2
1996	7.3	5.1	4.5	6.6
1997	7.6	5.3	5.1	6.6
1998	6.9	4.6	3.9	6.8
1999	7.3	4.5	4.3	6.8
2000	7.3	5.4	4.6	7.2
2001	**7.1**	**4.5**	**4.2**	**6.4**
mean	7.3	5.3	4.7	7.0

3.2 Air Temperature

The annual progression of air temperature was within the normal range until the fall of 2001 (**Figure** 3-4). The air temperatures were warmer than average for the last 3 months of 2001. Previous analysis has indicated that the average wintertime temperature influences the bottom-water temperature at the onset of stratification (Libby *et al*., 1999). **Table** 3-4 indicates that in 2001, the average wintertime temperature was only a degree below its climatological average.

Table 3-4. Winter Air Temperature, 1992-2001. Average temperature in °C at the Boston Buoy. Data from NOAA National Data Buoy Center (http://scaboard.ndbc.noaa.gov/data).

Year	Dec. 1 - Feb. 28
1992-1993	-0.4
1993-1994	-1.4
1994-1995	1.7
1995-1996	-0.4
1996-1997	2.3
1997-1998	2.6
1998-1999	2.2
1999-2000	0.8
2000-2001	**0.0**
mean	0.8

3.3 Water Temperature

3.3.1 Nearfield description

The time series of near-surface water temperature near the outfall site for 2001 follows the typical seasonal curve until the fall, during which it is warmer than average (**Figure** 3-5). November and December of 2001 had the highest winter near-surface temperatures of the Outfall Monitoring observation period. Near-bottom temperatures were colder than average during the stratified period, based on the shipboard survey data (**Figure** 3-6). One of the observations occurred just after a strong cooling event in June, which may bias the seasonal average toward a cooler temperature. Average upwelling conditions over the summer would have been expected to result in average near-bottom temperatures. In the fall, a sharp increase in bottom water temperature in early October occurred following a strong mixing event that led to a short-lived period of warmer bottom waters. This was clearly seen in temperature data from the USGS mooring in the vicinity of the Boston Buoy (**Figure** 3-7). Nearfield bottom waters returned to cooler temperatures by mid October (buoy and survey data) suggesting an influx of cooler bottom waters to the region.

3.3.2 Spatial Temperature Structure

The spatial variability of temperature is exemplified by cross-sections from the mouth of Boston Harbor across Stellwagen Basin to the Gulf of Maine (**Figure** 3-8). The principal gradients are in the vertical, associated with the seasonal progression of thermal stratification. The top panel shows conditions in April, at the beginning of seasonal stratification. The stratification increases in June and remains strongly stratified through August. Horizontal gradients tended to be weak with generally cooler temperatures in the surface waters closer to shore and increasing to the east. In October, surface temperature is decreasing, but the bottom water is continuing to warm.

3.4 Salinity

3.4.1 Nearfield Description

The salinity showed a normal seasonal progression in 2001 (**Figure** 3-9). The drought conditions had not persisted for long enough for a salinity anomaly to show up in the fall of 2001.

3.4.2 Spatial Salinity Structure

The salinity structure across Massachusetts Bay (**Figure** 3-10) showed persistent E-W gradients in April and June, due to local freshwater inputs into Boston Harbor and from the Gulf of Maine at station F27. In April, the freshwater inputs initiate the establishment of vertical and horizontal salinity gradients with largest gradients occurring near Boston Harbor and at the offshore stations F19 and F27. Flow through the bay outfall peaked prior to the early April survey and reached levels comparable to freshwater flow from the Charles River to Boston Harbor (**Figure** 3-11). Although it may be counterintuitive, bottom waters in the vicinity of the outfall mix with the effluent resulting in a buoyant plume and a well mixed water column with higher salinity surface waters (relative to surface waters in the vicinity). Significant salinity gradients continued to be observed in June and persisted through August. The lower salinity signature of the outfall discharge was seen in August and was coincident with elevated NH_4 concentrations (see **Figure** 4-5) along a transect extending from the nearfield south to stations off of Marshfield.

3.5 Stratification

3.5.1 Nearfield Description

In 2001, stratification, as defined by the density gradient between surface and bottom waters, generally fell within the range observed from 1992 to 2000 (**Figure** 3-12). The strong downwelling favorable conditions in the spring did not appear to delay in the onset of stratification. Conditions in the fall, however, which are normally downwelling favorable, ranged from upwelling favorable in October to relatively neutral conditions in November and December (see **Figure** 3-3). The calm weather and lack of mixing due to seasonal storms led to prolonged stratification into early December 2001.

3.5.2 Spatial Variations in Stratification

The stratification early in 2001 reflected the salinity structure (see **Figure** 3-10), with strong stratification near Boston Harbor and offshore and weak stratification in the nearfield (**Figure** 3-13). The strongest stratification occurred in June, with contributions from both temperature and salinity. Strong stratification persisted through August though it was dominated by the temperature structure. By October, surface cooling eliminated the stratification above 20-m depth, but there was still stratification between 20 and 40-m depth due both to temperature and salinity variations.

3.6 Comparison of Shipboard and Timeseries Data

One issue affecting the evaluation of the survey data is the unresolved temporal variability in the water properties due to the relatively low frequency of shipboard observations. To examine the unresolved variability associated with shipboard sampling, a comparison was made of average seasonal temperature based on the continuous timeseries from the Boston Buoy and from the near-surface data at station N21. Two comparisons were performed using data collected from the upper 2 m of the water column (buoy data from 0.6 m and survey data from 1-2 m) during both the winter (February and March) and summer (July-August). The average near-surface temperature values for each season are presented along with the buoy timeseries data in **Figure** 3-14. The regression analysis of survey versus buoy data indicates that the correspondence is high (r^2=0.89; **Figure** 3-15a) for the winter comparison, indicating that the interannual differences in temperature are well characterized by the shipboard measurements. However the July-August data show an insignificant correlation (r^2=0.11; **Figure** 3-15b), indicating that there is actually no information in the shipboard data with respect to the time-mean temperature during this time period, and thus the shipboard data cannot be used to ascertain interannual variations in summertime near-surface temperature. The results of this analysis are independent of which nearfield station is used for the comparison, as station-to-station correlation in the nearfield is very high relative to interannual variability. For instance, the results of the comparison using station N18 surface data (which is also located in close proximity to the Boston Buoy; see **Figure** 2-1) yield correlations of 0.87 for the winter and 0.15 for the summer.

The explanation of this is simple—there are large, short-term fluctuations in summertime temperature (**Figure** 3-5). The shipboard temperature record depends on which days happen to be sampled, introducing a random error that is comparable or larger than the actual interannual variation in the mean. In the winter, the day-to-day fluctuations are smaller relative to the interannual variations, so the sparse shipboard observations still provide a meaningful estimate of the mean.

Some types of analysis are severely compromised by this sampling problem, and others are only slightly affected. Estimates of stratification are significantly degraded, because they are sensitive to the large fluctuations of near-surface temperature. Bottom water properties also appear to experience large fluctuations during summer months, due to upwelling-downwelling processes as well as possibly mixing events or internal waves. Near-bottom dissolved oxygen is likely to exhibit significant short-term variability, because of the east-west gradients in dissolved oxygen that are advected past the outfall site by upwelling and downwelling bottom currents. These short-term variations in dissolved oxygen would degrade the estimates of interannual variation measured by the shipboard program.

Although the maintenance of timeseries measurements represents a significant expense, and it cannot replicate the biological and chemical measurements obtained in shipboard surveys, timeseries measurements are essential to providing statistically robust measures of the long-term variability of water properties. Thus the existing moorings (USGA and NOAA) near the outfall should be continued. The recent deployment of the Gulf of Maine Ocean Observing (GoMOOS) buoy in northeastern Massachusetts Bay provides a great opportunity to obtain high-resolution physical oceanographic data at the boundary. A sensible addition to the monitoring program would be to add a near-bottom dissolved oxygen sensor to the instrument array currently deployed on the USGS mooring. An oxygen sensor was added to the GoMOOS array during the summer of 2002. These timeseries will provide an excellent characterization of the variability of water properties at the outfall and the forcing conditions that may be driving that variability.

3.7 Summary

There were no significant anomalies in physical forcing in 2001. The winds in March 2001 were somewhat anomalous in the propensity of downwelling-favorable winds (**Figure** 3-3), which would have had a tendency to increase the transport of Gulf of Maine waters through Massachusetts Bay at this time. Decreased residence time due to the rapid transport could be a possible explanation for a reduced spring bloom, but such a causal link would be highly speculative. The warm air temperatures and lack of major storms resulted in a prolonged period of weak stratification during the fall of 2001. The dry conditions in the fall of 2001 could significantly impact the conditions in early 2002 because of the lag between freshwater inflow and the response of the water column.

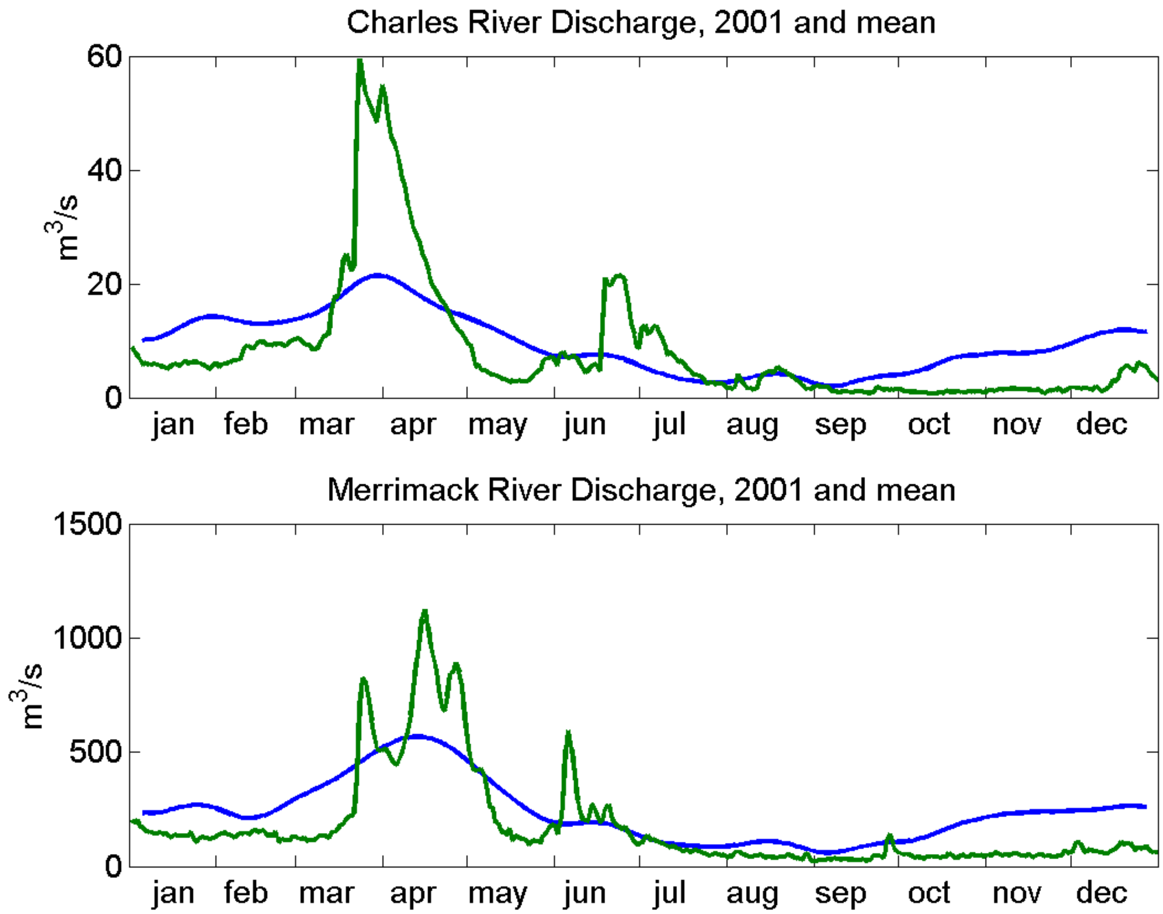


Figure 3-1. Charles River (at Waltham) and Merrimack River (at Lowell) discharge for the year 2001 (green curve), compared to the 12-year average (smoothed blue curve).

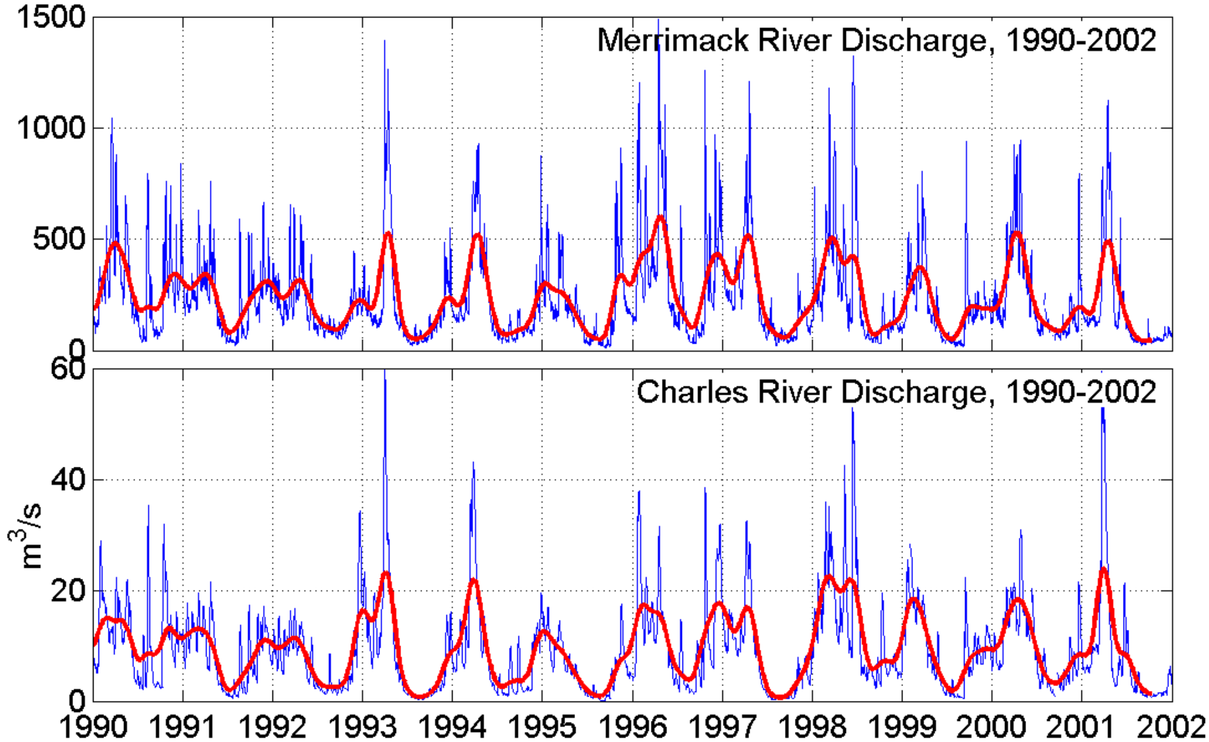


Figure 3-2. Merrimack River (at Lowell) and Charles River (at Waltham) discharge, 1990–2001 (data from USGS). Blue lines indicate 5-day running mean. Thick red lines indicate 3-month moving averages.

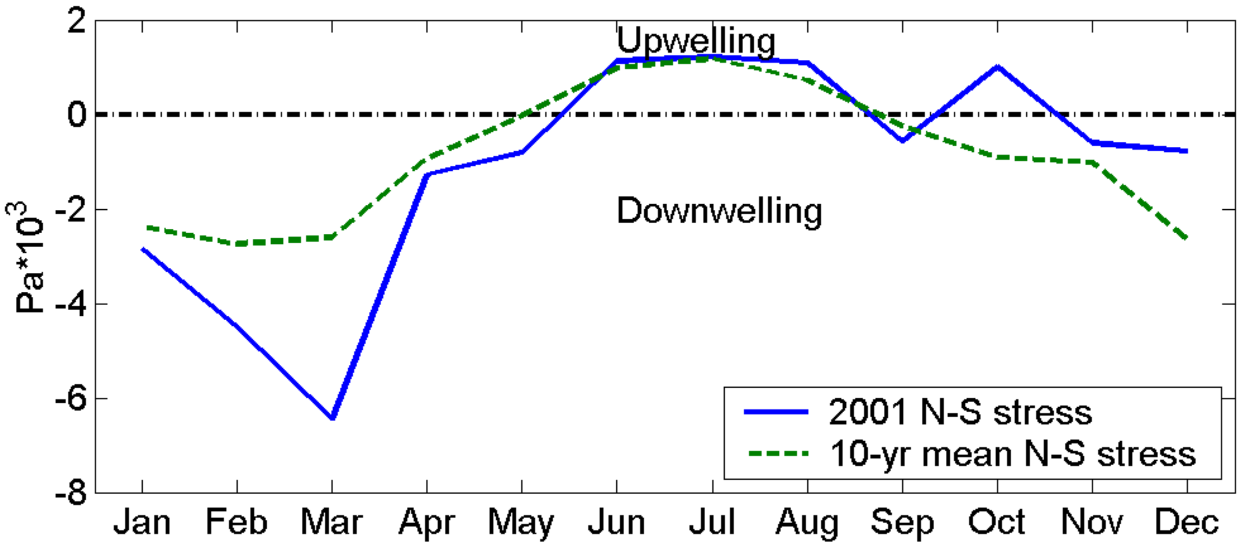


Figure 3-3. Monthly average N-S wind stress at Boston Buoy for 2001 compared with 10-year average. Positive values indicate northward-directed, upwelling-favorable wind stress.

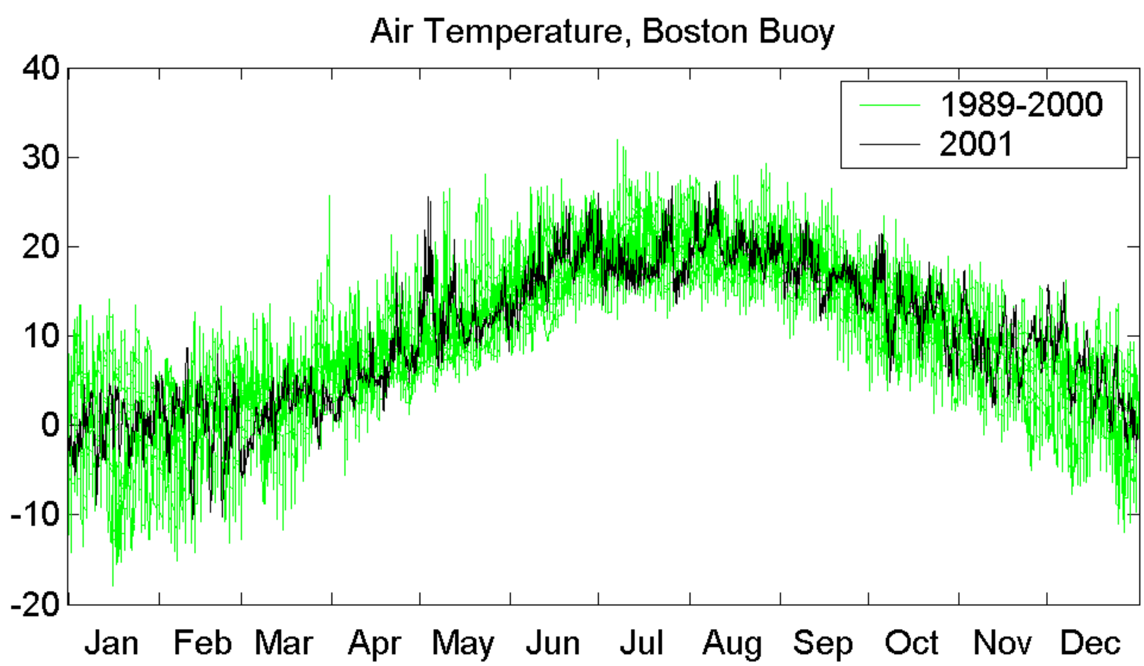


Figure 3-4. Hourly surface air temperature in 2001 (Black) measured at the Boston Meteorological Buoy compared to data from the last 12 years.

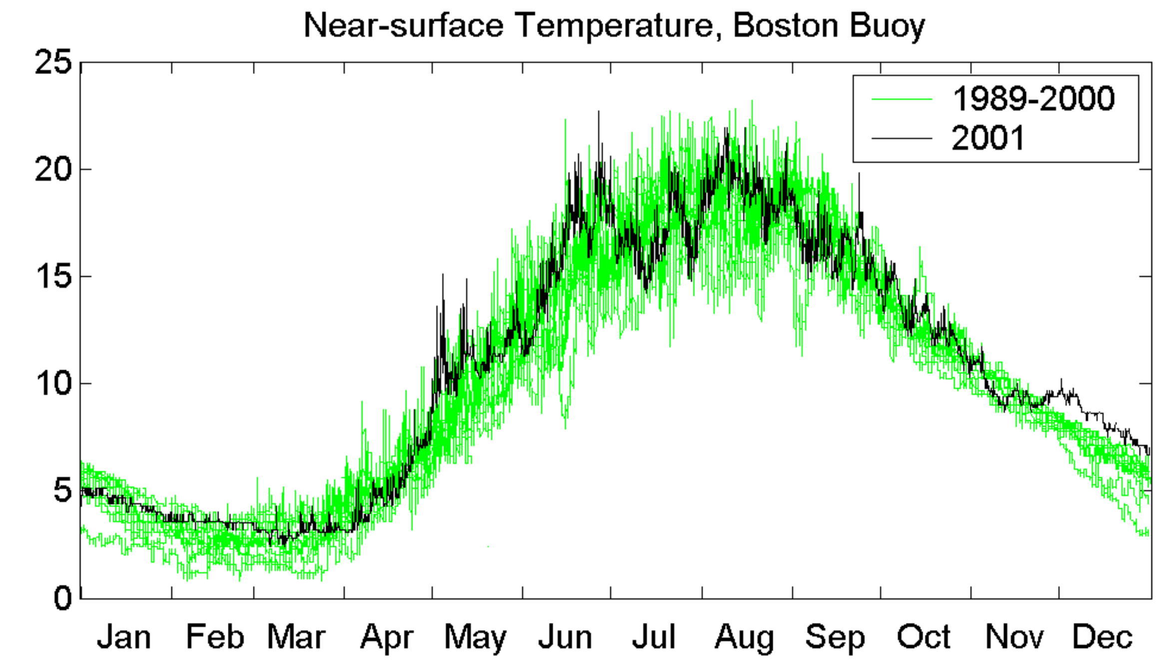


Figure 3-5. Hourly water temperature at the Boston Buoy (Black) superimposed on the data from the previous 12 years (green). Data collected from 0.6 m depth.

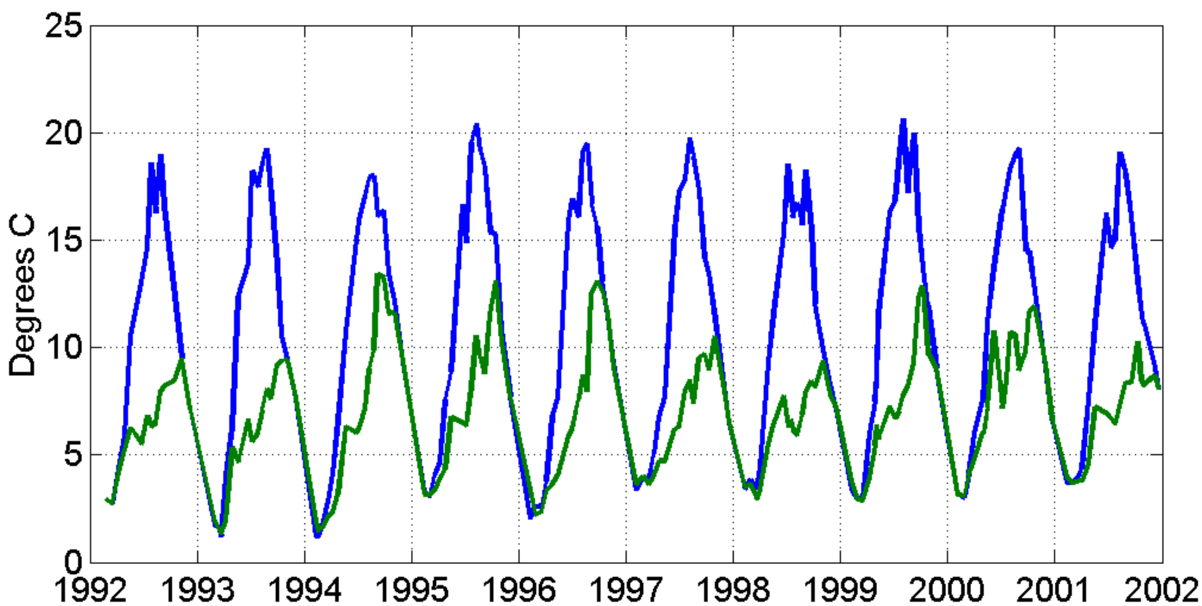


Figure 3-6. Near-surface (blue line) and near-bottom (green line) temperature observed in the vicinity of the outfall site (averaging the data from stations N13, N14, N18, N19, N20 and N21).

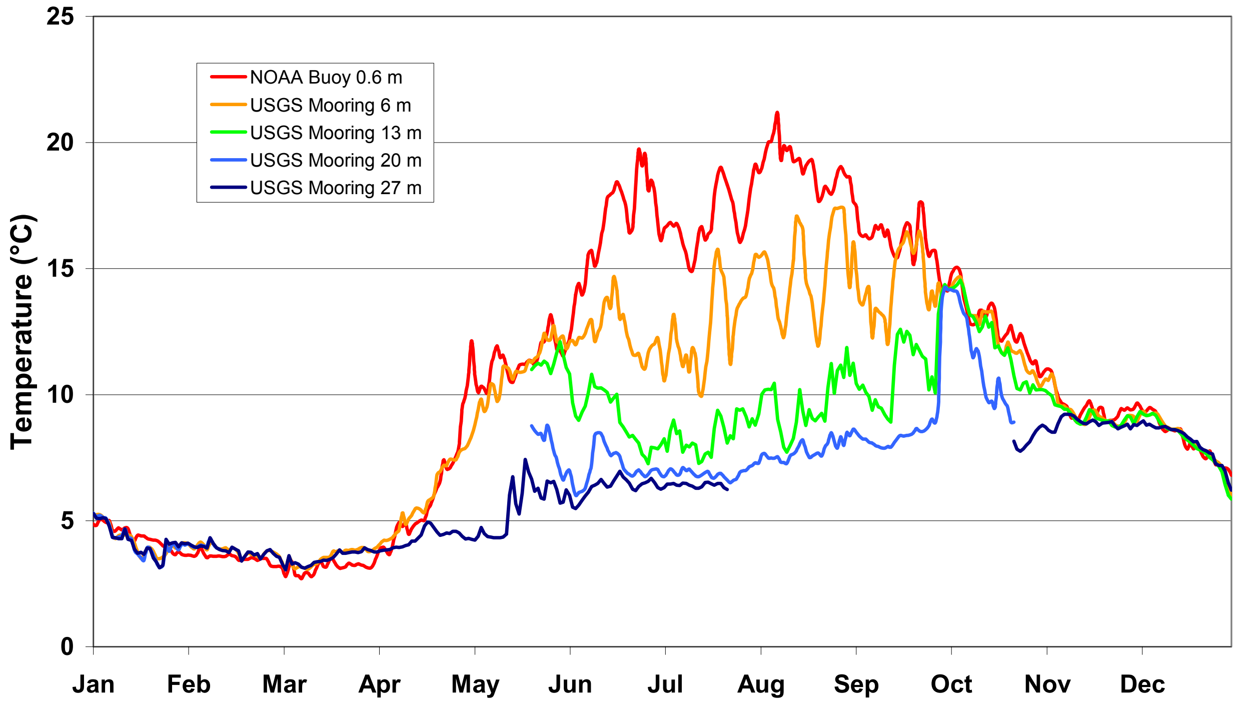


Figure 3-7. NOAA and USGS temperature mooring data in the nearfield.

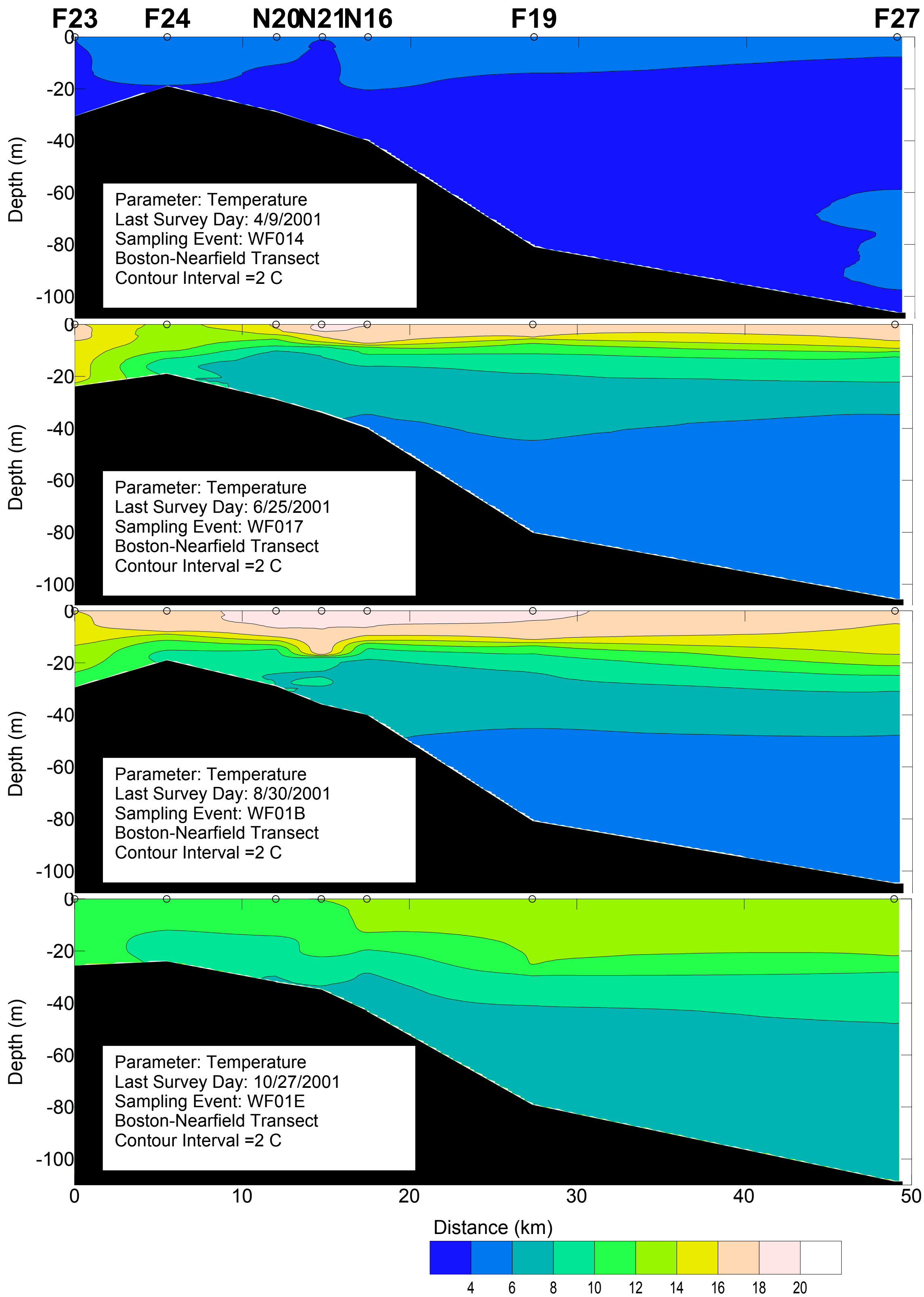


Figure 3-8. Temperature along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April-October 2001.

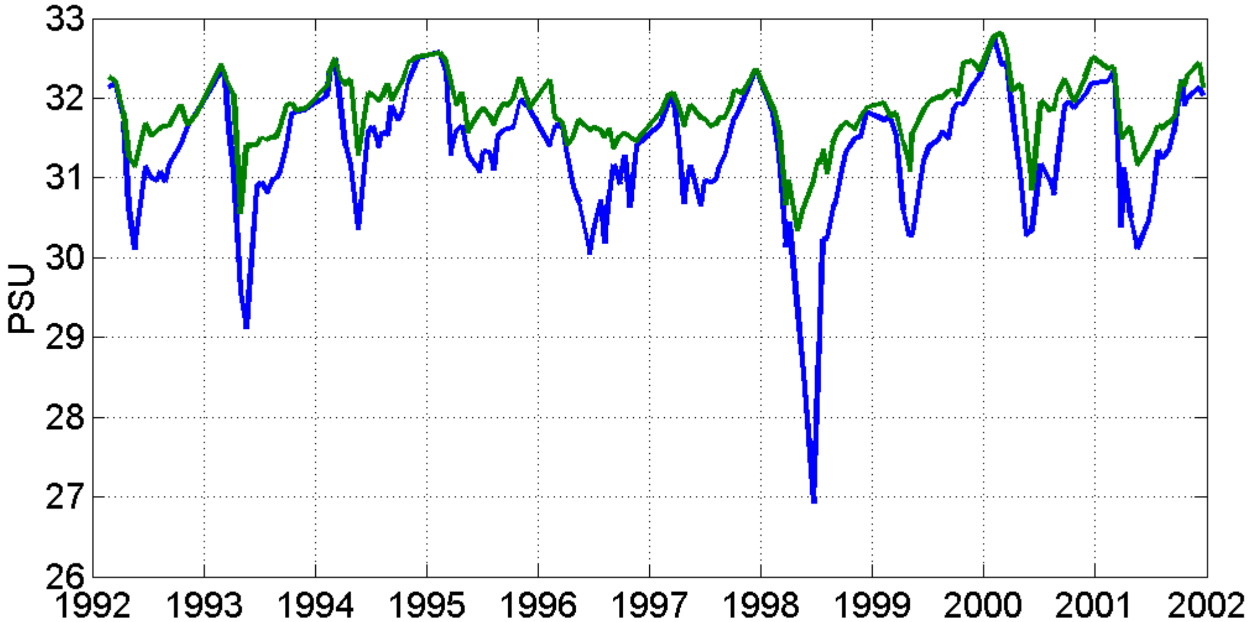


Figure 3-9. Near-surface (blue line) and near-bottom (green line) salinity observed in the vicinity of the outfall site (averaging the data from stations N13, N14, N18, N19, N20 and N21).

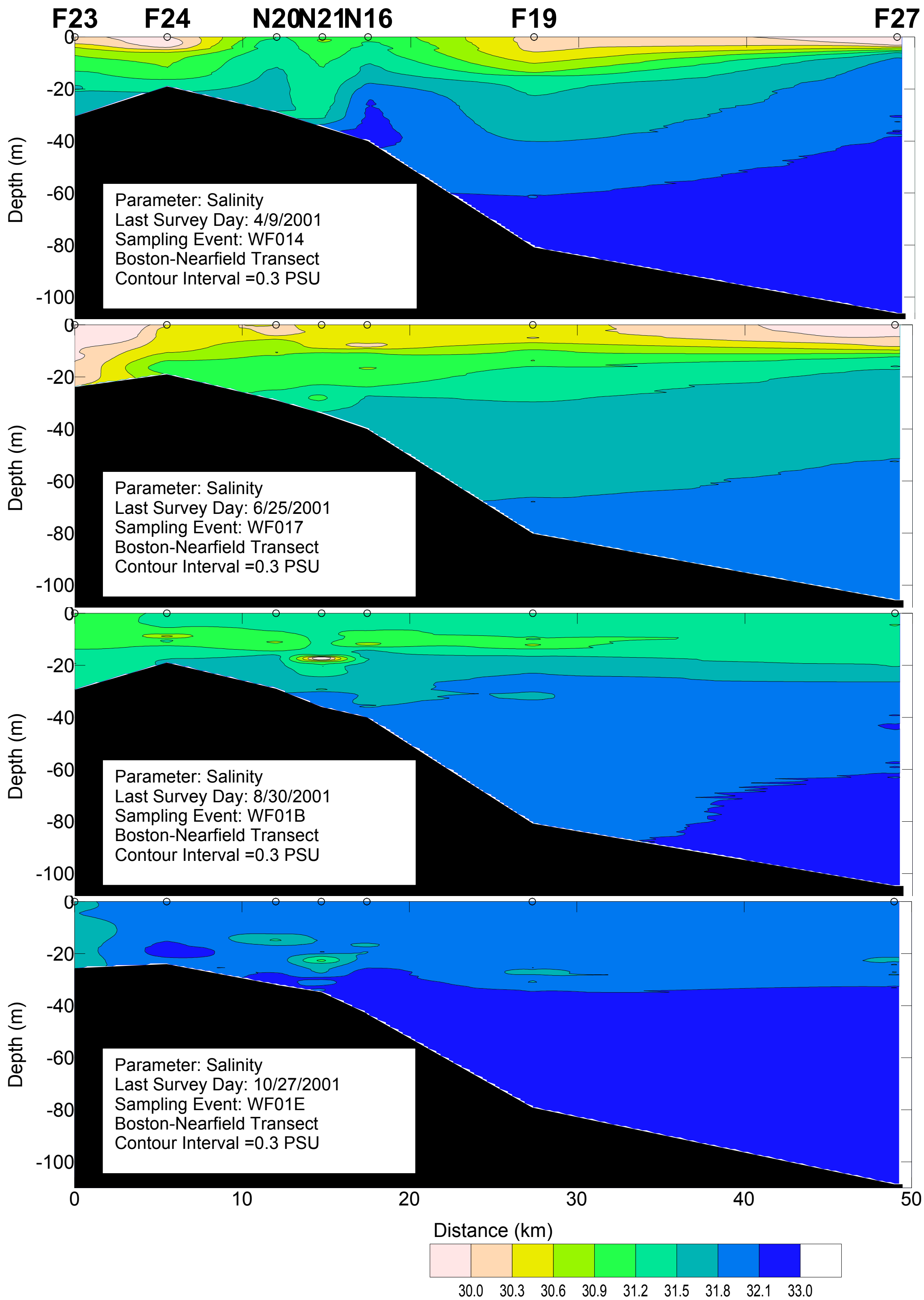


Figure 3-10. Salinity along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April-October 2001.

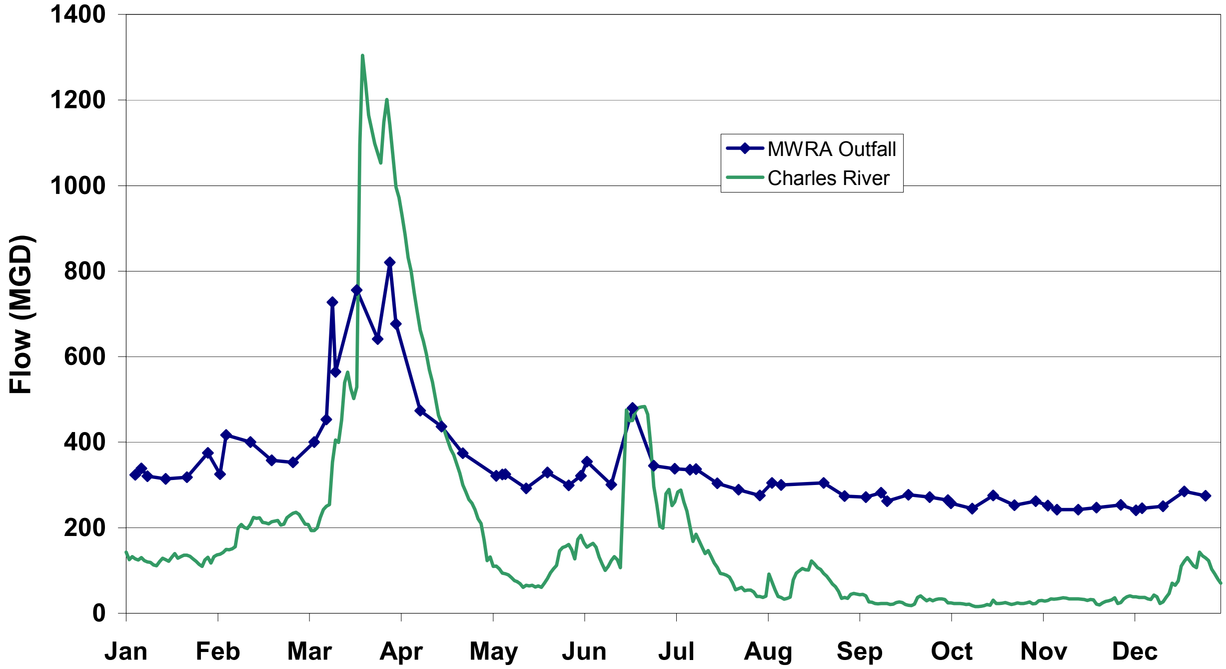


Figure 3-11. Charles River and MWRA outfall flows for the year 2001.

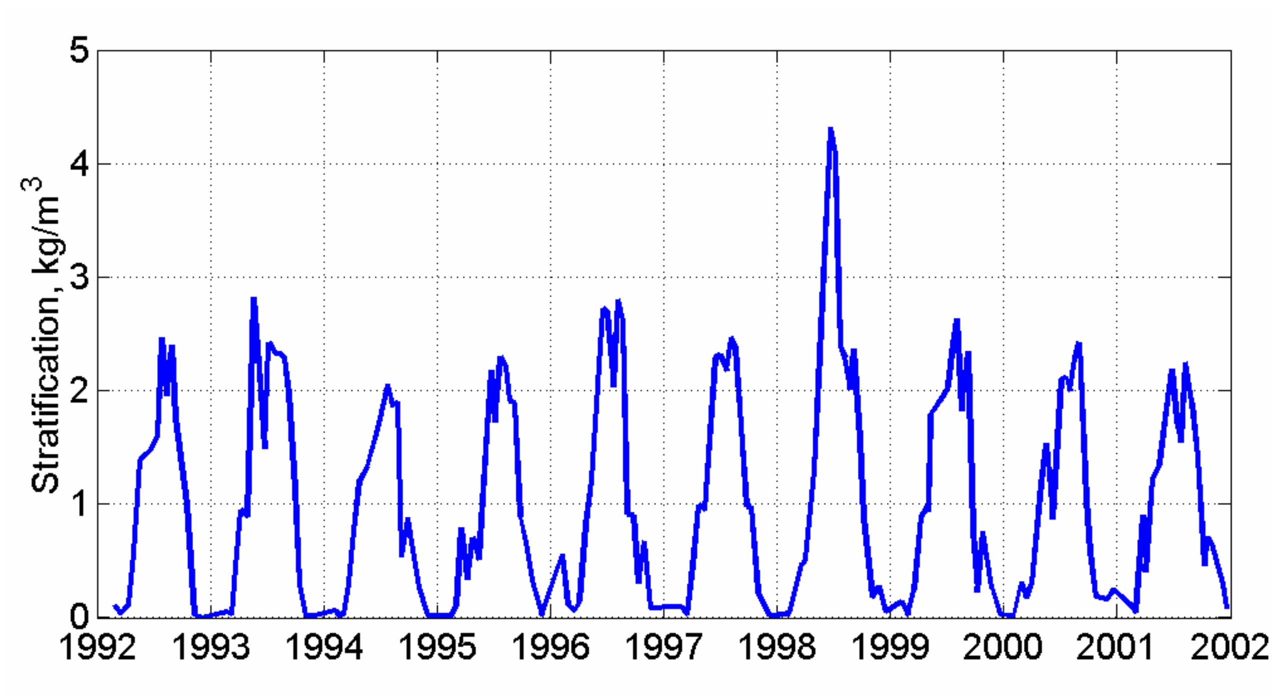


Figure 3-12. Density difference between surface and bottom observed in the vicinity of the outfall site (averaging the data from stations N13, N14, N18, N19, N20, and **N21**).

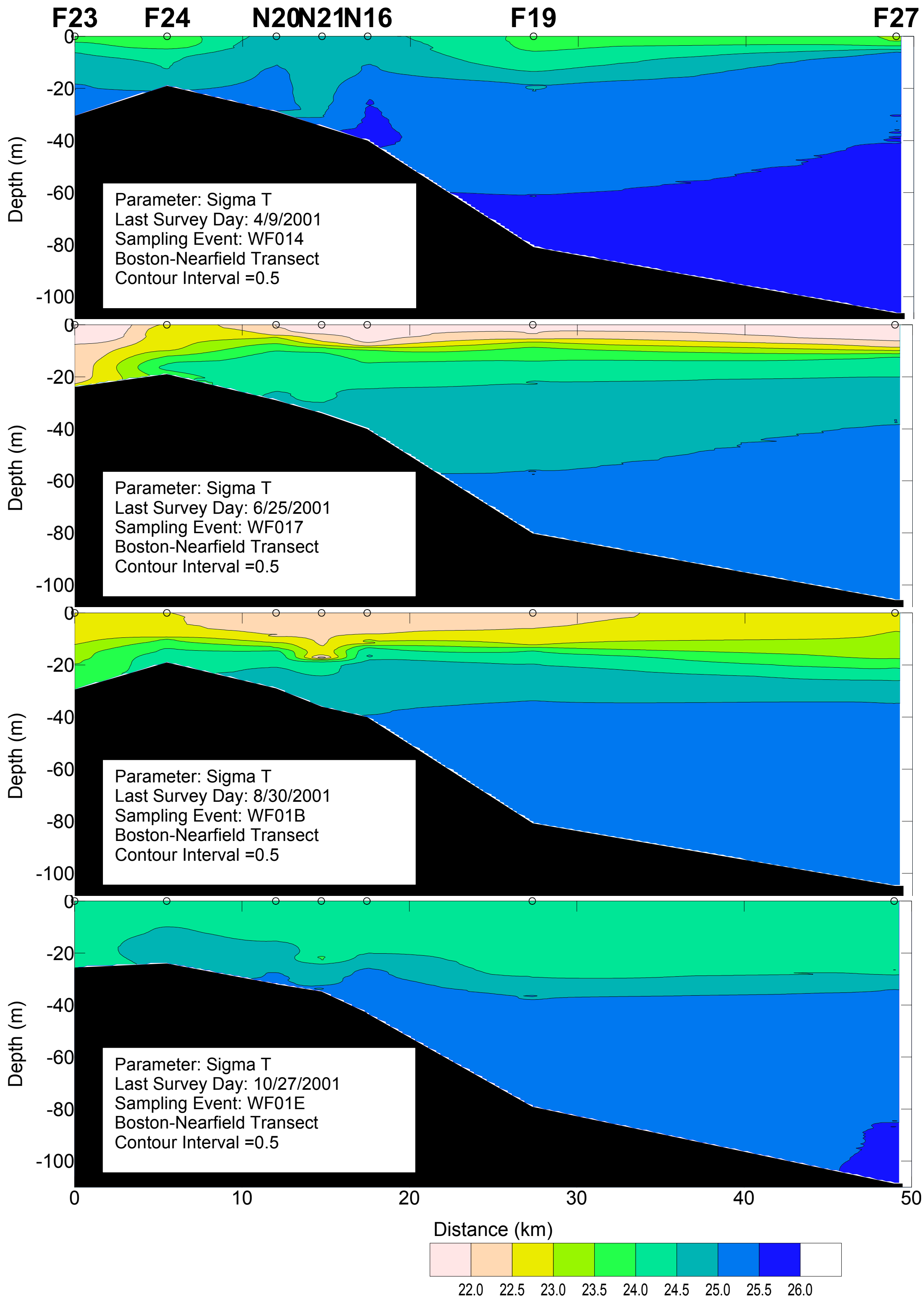


Figure 3-13. Density along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April-October 2001.

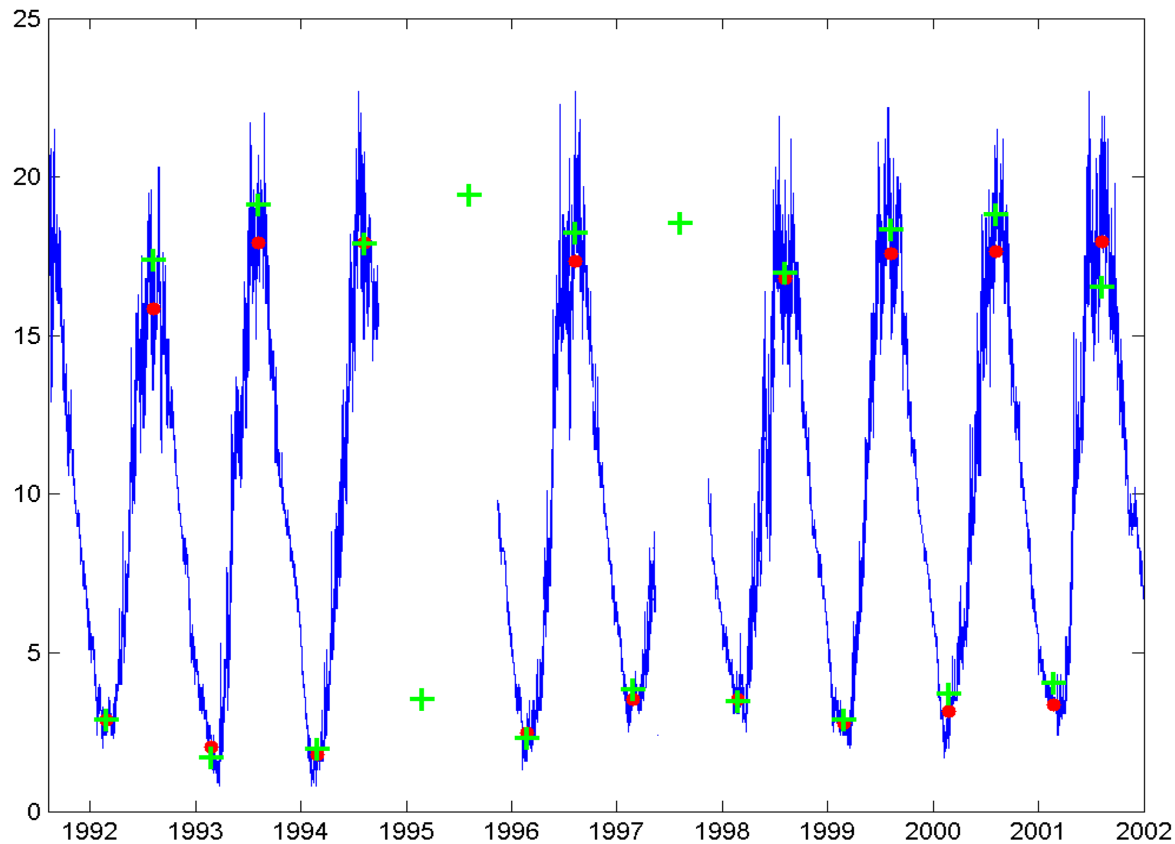


Figure 3-14. Timeseries of winter (February-March) and summer (July-August) mean near-surface temperature at the Boston Buoy (red dots) and station N21 (green crosses) superimposed on the hourly near-surface water temperature at the buoy. Data collected from 0.6 m depth at the buoy and from 1-2 m at station N21.

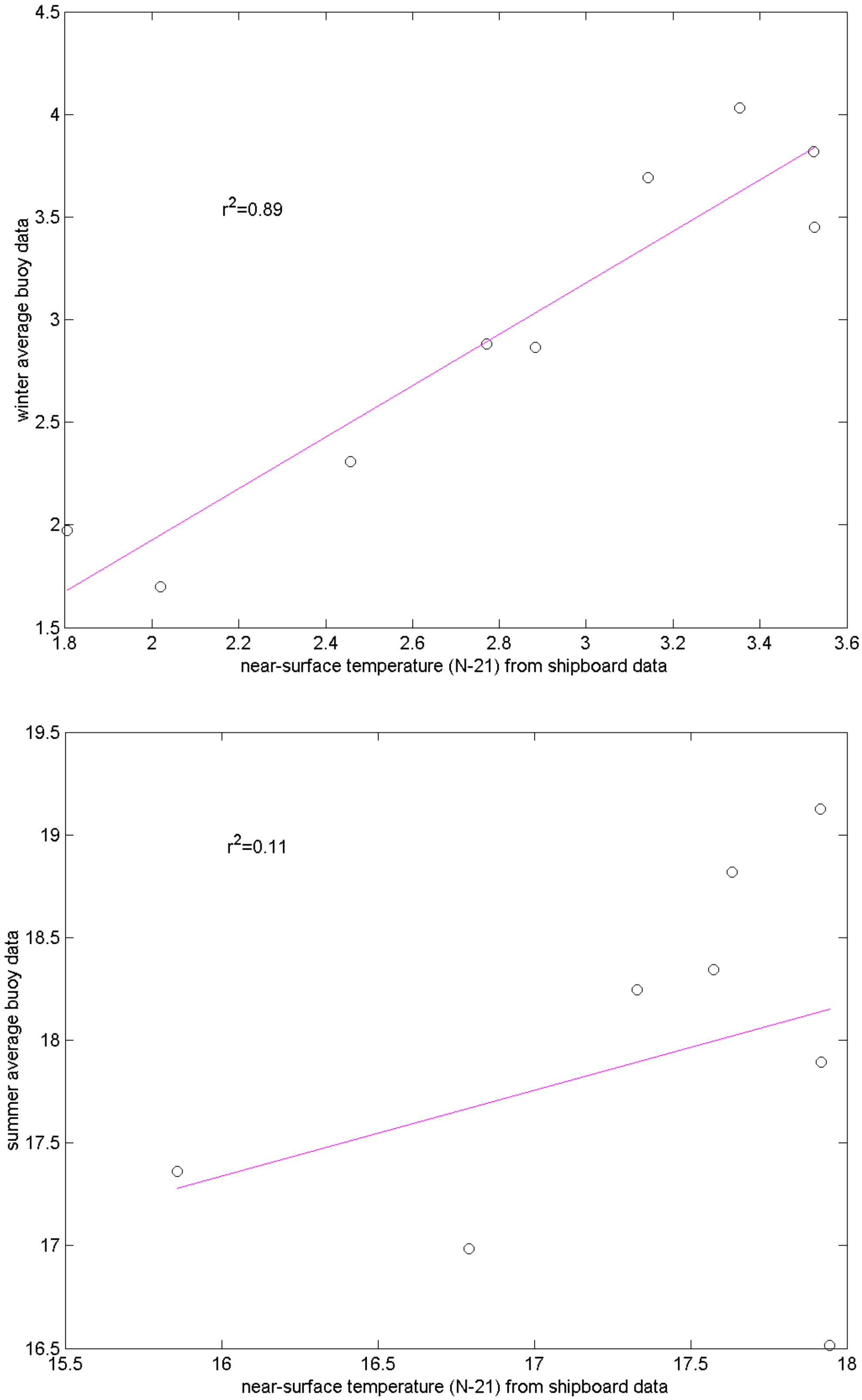


Figure 3-15. Comparisons of (a) winter and (b) summer mean near-surface temperature at the Boston Buoy and station N21. Data from 1992 to 2001 as presented in Figure 3-12.

4.0 WATER QUALITY

In this section, temporal trends in the data are presented on narrow (nearfield) and broad (regional) spatial scales and compared on an interannual basis versus the entire baseline monitoring period – February 1992 to September 2000. The physical data on temperature, salinity, and density presented in the previous section provide the stage upon which discussions of the main water quality parameters are developed. These parameters include nutrients, chlorophyll/biomass, plankton, production, and dissolved oxygen. This section begins with a review of 2001 monitoring results, and then evaluates these results in comparison to baseline data.

4.1 2001 Water Quality Monitoring Results

The trends and distribution of nutrients, biomass, plankton, productivity, and dissolved oxygen in Massachusetts and Cape Cod Bays in 2001 are presented with particular focus on the nearfield area. The higher frequency sampling in the nearfield allows for a more detailed examination of the temporal trends in Massachusetts Bay. The data are presented as individual values at representative stations, as mean survey values across the area, and as annual means. The farfield data are grouped by geographic region (see **Figure** 2-2) as in previous annual reports to examine regional variability in nutrient distribution.

Over the course of the HOM program, general trends in water quality events have emerged from the data collected in Massachusetts and Cape Cod Bays. The trends are evident even though the timing and year-to-year manifestations of these events are variable. The winter to spring transition in Massachusetts and Cape Cod Bays is usually characterized by a series of physical, biological, and chemical events: seasonal stratification, the winter/spring phytoplankton bloom, and nutrient depletion. The summer is generally a period of strong stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community dominated by microflagellates. In the fall, stratification breaks down supplying nutrients to surface waters that often results in the development of a fall phytoplankton bloom. The lowest dissolved oxygen concentrations are usually observed in the nearfield bottom water in October prior to the fall overturn of the water column. By late fall or early winter, the water column is usually well mixed and has returned to winter conditions.

These trends were generally evident in 2001 although no major blooms were observed in Massachusetts Bay, and there was a delay in the breakdown of stratification in the fall. A winter/spring bloom of centric diatoms was observed in Cape Cod Bay. The chlorophyll and production data suggest that the end of the winter/spring bloom was captured in Massachusetts Bay in early February. In March and April, a minor bloom of *Phaeocystis pouchetii* that was most prominent in northeastern Massachusetts Bay was observed. The appearance of *Phaeocystis* in back-to-back years (2000 and 2001) deviates from the ~3-year cycle of *Phaeocystis* blooms that had been observed previously. In the fall of 2001, there was a delay in the deterioration of stratification due to the calm, warm weather that predominated. The water column remained weakly stratified in the nearfield until December, and this led to the development of a late fall/early winter bloom and a seasonal peak in production rates and chlorophyll concentrations in early December.

The physical oceanographic conditions in 2001 are discussed in Section 3 and in the semiannual reports (Libby *et al.*, 2002a and 2002b). A summary of these findings is presented to set stage for the water quality results. In 2001, stratified conditions were first observed in early April at Boston Harbor, offshore, and boundary stations. The development of stratification at these stations was driven by a decrease in surface salinity due to March/April runoff. At coastal and Cape Cod Bay stations, density and salinity decreased from early March to April. The decrease was similar in both surface and bottom waters resulting in weaker April stratification than observed further offshore. In the nearfield, the water column began to stratify in late March at the deeper eastern nearfield stations, but remained well mixed further inshore. In early April, a localized mixing event in the nearfield was observed, which may have been due to increased flow from the outfall discharge. By late April, the water column had become weakly stratified across all of the nearfield area. By June, surface water temperatures had increased by >10°C throughout the bays, and a strong density gradient was present throughout most of Cape Cod and Massachusetts Bays. Stratified conditions continued late into the fall. In the nearfield, mooring data indicated that there was a strong mixing event in late September. However, the water column did not remain well mixed as both the mooring, and nearfield monitoring data from mid October show that the water column was once again weakly stratified. The weak density gradient continued to be observed from late October to early December in the nearfield. The water column finally returned to well-mixed winter conditions over the entire nearfield in late December. Mild meteorological conditions contributed to the lingering stratification into early December.

4.1.1 Nutrients

The nutrient data for 2001 generally followed the "typical" progress of seasonal events in Massachusetts and Cape Cod Bays, but there were clear deviations from the usual trends (**Figure** 4-1). The early February survey is normally conducted prior to the occurrence of the winter/spring bloom in Massachusetts Bay. The winter nutrient concentrations are usually at annual maximum as the water column is well mixed and biological uptake of nutrients is limited. Pre-bloom nitrate (NO_3) and silicate (SiO_4) concentrations are typically 8 µM and 10 µM, respectively. In 2001, early February nutrient concentrations, although relatively high in comparison to later surveys, were lower than typically seen. Nitrate concentrations were 6±1 µM in each of the areas and silicate concentrations were even lower ranging from 2.5 to 4 µM in Massachusetts Bay and 1.5 µM in Cape Cod Bay. A winter/spring 'diatom bloom' that occurred in Cape Cod Bay sharply reduced nutrient concentrations in that area from early to late February (**Figure** 4-1). A decrease was also observed in Massachusetts Bay although at different rates in various areas, even though plankton data were not indicative of bloom conditions. The relatively low concentrations of SiO_4 in Massachusetts Bay suggest that the winter/spring bloom may have been in progress and peaked prior to the first survey. Evidence for an early February bloom in the nearfield was also suggested by the productivity data (see Section 4.1.2).

There was a sharp increase in nutrient concentrations from February to April. A number of physical and biological factors contributed to this increase. An increase in freshwater flows resulting from near-record precipitation (NWS Logan Station) in March combined with influx of waters from the Gulf of Maine (northerly wind component and strong downwelling suggest this was the case) provided additional sources of nutrients to the bays. At the same time, the failure or decline in the winter/spring diatom bloom likely reduced the rates of biological uptake. Nutrient concentrations in April were higher than early February values for many of the areas of the bays (**Figure** 4-1). This was especially evident for SiO_4 concentrations, which increased from annual minima throughout the bays in late February to seasonal maxima in April. The exception to the trend of increasing nutrient concentrations was in offshore and boundary waters where NO_3 concentrations decreased by 0.5-1 µM from late February to April. There was also a large decrease in NO_3 in the nearfield from late March to early April. The decrease in NO_3 in these areas of Massachusetts Bay was coincident with elevated abundance of *Phaeocystis pouchetii*, which was present in lower numbers in Cape Cod Bay, Boston Harbor, and coastal waters. Silicate is not a major nutrient requirement for *Phaeocystis*, which accounts for the contrasting trends in SiO_4 and NO_3 concentrations in offshore and boundary waters.

From April to June, nutrient concentrations decreased sharply. This was most pronounced for NO_3 with survey mean concentrations of <2 µM for each of the areas (**Figure** 4-1), as NO_3 was essentially removed from the surface waters by the June survey. In the nearfield, for example, seasonal stratification led to NO_3 depleted conditions in surface waters by late April and these conditions persisted through the summer to early October (**Figure** 4-2). Survey mean nutrient concentrations remained low in Boston Harbor, coastal, and Cape Cod Bay waters from July to August, while there was an increase in concentrations over this time period at the deeper offshore and boundary stations. This trend was also evident in the nearfield, and it was driven by higher nutrient concentrations in mid-depth and bottom waters (e.g. NO_3 and SiO_4; **Figure** 4-2) as rates of respiration and remineralization of organic matter increased.

Except for low NO_3 concentrations in Cape Cod Bay, October nutrient levels were relatively high. Typically, fall survey mean NO_3 and SiO_4 concentrations are about half that observed in October 2001. In the nearfield, following the mid October survey, there was a sharp drop in NO_3 concentrations in surface and mid-depth waters, and they remained low relative to bottom waters until late December (**Figure** 4-2). By early December, SiO_4 concentrations had decreased by almost 4 µM in the surface and mid-depth waters. This decrease occurred as the water column remained weakly stratified and corresponded to peak production rates and high chlorophyll (and POC) concentrations at both of the nearfield stations during the late fall/winter diatom bloom.

Ammonium (NH_4) concentrations continued to be a good tracer, albeit not a conservative tracer, of the effluent plume in the nearfield. When the water column is well mixed the signature reaches the surface waters (**Figure** 4-3a). During periods of stratification, the NH_4 signature of the plume is contained below the pycnocline (**Figure** 4-3b). Elevated NH_4 (and PO_4) concentrations were measured in the surface waters on June 25th (**Figure** 4-4) suggesting that high flow rates during a June 17th rain event (>2 in) may have resulted in the plume reaching the surface waters though this warrants further investigation. Using NH_4 as a tracer also provides an indication of the horizontal advection of the plume within and out of the nearfield. In August, salinity and NH_4 data suggested the effluent plume was advected from the nearfield to the south (**Figure** 4-5). A similar displacement of the plume (direction and distance) was observed in July 2001 during the plume tracking survey as the plume was followed over a period of three days as it moved from the nearfield to waters off of Scituate (Hunt *et al*., 2002). Comparisons of NH_4 and chlorophyll concentrations (**Figure** 4-5) in the vicinity of the plume suggest this source of nitrogen may have contributed to localized increases in chlorophyll concentrations. The effectiveness of NH_4 concentrations as a tracer of the plume and the possible ecological impact of the elevated NH_4 concentrations are evaluated in more detail in Section 5.3.

4.1.2 Productivity and Biomass

Areal production at the nearfield stations in 2001 followed patterns observed in prior years. Both nearfield stations sampled were characterized by spring and fall blooms, with variable productivity during the summer. However, timing of events was somewhat different from earlier years, with an early onset of the spring bloom and a delay in peak fall productivity. Additionally, some differences in the magnitude of productivity were noted, including increased productivity at depth in the fall at station N18 and the relative magnitude of the late fall bloom at station N04 versus N18.

Potential areal productivity (**Figure** 4-6) indicated the winter/spring bloom of 2001 was underway in Massachusetts Bay when seasonal sampling was initiated in early February. Measured productivity was lower due to cloud cover on the day of the survey and did not indicate that the bloom was underway. Potential and measured productivity matched closely over the remainder of 2001. A second productivity peak was observed at both nearfield stations in April during the *Phaeocystis* bloom. The magnitude of the winter/spring bloom in the nearfield in 2001 was lower than earlier years (except for 1998, a year with no spring bloom) and may be related to warm surface water temperature during February – March (see **Figure** 3-5).

Productivity at both nearfield sites throughout the summer period was similar to values observed in earlier years. In general, nearfield stations are characterized by the occurrence of a fall bloom. In 2001, distinct fall phytoplankton blooms were observed as increases in production at both nearfield stations (**Figure** 4-6). The fall bloom in 2001 reached peak values of >3250 mg C m^{-2} d^{-1} at both stations and occurred from early October through early December. From 1995 – 2000, the fall bloom peak has been consistently higher at station N18 compared with N04. In 2001, the peak fall productivity was similar at both sites. In addition, the second peak in fall productivity occurred later than usual. Typically the timing of the fall bloom has been tied to a decrease in stratification. Thus, the late fall peak in productivity may be related to the extended period of stratification that occurred in 2001.

The seasonal trend in productivity at Boston Harbor station F23 in 2001 was similar to the pattern observed in 2000, with the occurrence of spring and fall productivity peaks (**Figure** 4-6). As noted in 2000, this represents a change in the previously observed productivity cycle for the harbor, which prior to 2000 was characterized by increasing productivity throughout the summer, followed by a fall decline. The pattern observed in 2000 and 2001 more closely resembles the seasonal cycle observed at the nearfield stations. In 2001, the fall peak dominated the annual cycle, while in 2000 the seasonal maximum occurred in spring. The altered seasonal productivity cycle may be tied to reduced nutrient availability in the harbor in recent years during the summer-stratified period.

Chlorophyll concentrations throughout the bays in 2001 were much lower than seen in the previous two years. Chlorophyll concentrations peaked in early February and were highest in Cape Cod Bay coincident with the winter/spring diatom bloom (**Figure** 4-7). Chlorophyll concentrations decreased in the nearfield from February to March, but increased coincident with productivity in the nearfield in early April. The increase was coincident with the minor *Phaeocystis* bloom, but not large in magnitude. Chlorophyll concentrations remained low throughout the bays during the summer except in Boston Harbor where the annual maximum was observed in June. Chlorophyll was relatively low in the fall in each of the areas, but reached atypically high levels in the nearfield during the late fall/winter bloom from early October to early December. Fall 2001 was a departure from the trend during the two previous years. During September and October of 1999 and 2000, substantial and prolonged fall blooms were observed, but in 2001 the bloom was minor and was observed from October to early December.

Chlorophyll is an imperfect measure of biomass. Although it is relatively easy to measure and provides high-resolution data, chlorophyll concentrations are not a direct indicator of carbon biomass as it varies with light, phytoplankton species, and nutrient availability. A more direct measure of biomass – particulate organic carbon (POC) – is made at a subset of the MWRA monitoring stations. The POC pattern in 2001 was generally similar to that of chlorophyll (**Figure** 4-8). High POC concentrations were observed in Cape Cod Bay in February in association with the winter/spring diatom bloom. The highest survey mean POC concentrations for 2001 occurred in the nearfield in early December (**Figure** 4-8) coincident with peak production and high chlorophyll concentrations. The main difference between the patterns for POC and chlorophyll is the elevated POC concentrations observed in the summer. Limited nutrient availability and high light intensity in the summer lead to relatively low chlorophyll concentrations per unit carbon.

The difference in potential and measured productivity observed during the spring bloom period in 2001 emphasizes the importance of potential productivity. It is recommended that future discussion of productivity focus on potential production. Although annual potential productivity generally represent only a ~10% increase over annual measured productivity, potential production is particularly important on cloudy days to avoid missing key features of the annual cycle (i.e. early February bloom in **Figure** 4-6).

4.1.3 Plankton

The 2001 nearfield phytoplankton cycle featured relatively low phytoplankton abundance over most of the year. Whole-water phytoplankton assemblages were dominated by unidentified microflagellates and several species of centric diatoms except during the April *Phaeocystis* bloom. During the February surveys, nearfield abundance was ≤0.5 x 10^6 cells L^{-1}, and similarly low counts were found throughout Massachusetts Bay (**Figures** 4-9, 4-10 and 4-11). As suggested by the production, biomass and nutrient data the winter/spring bloom may have occurred prior to the early February survey. In Cape Cod Bay, the winter/spring bloom was evident by the relatively high abundance of centric diatoms observed (**Figure** 4-9). In April, a bloom of *Phaeocystis pouchetii* was observed throughout the bays with the highest concentrations found at the boundary stations (**Figure** 4-10) and elevated abundances in the nearfield and offshore areas. The *Phaeocystis* bloom in April 2001 was much less abundant than the bloom of this species during the same period the previous year, and it was also a departure from the 3-year cycle for these blooms that had been observed during the baseline period.

By June, phytoplankton abundance was relatively low in Cape Cod Bay and most of Massachusetts Bay, but high in coastal and harbor waters. These inshore stations exhibited relatively high abundances of centric diatoms during both the June and August surveys. Nearfield phytoplankton abundance was highest in late July and generally decreased through December. The decrease in phytoplankton abundance from fall to early winter is typical for this time of year. Compared to most years the late fall and early winter abundance levels in 2001 were relatively high. Levels of >10^6 cells L^{-1} in the nearfield (mostly the centric diatoms *Thalassiosira* spp., *Guinardia delicatula, Leptocylindrus danicus, Skeletonema costatum*) from October to early December were coincident with high chlorophyll and POC concentrations and peak production rates.

There were no blooms of harmful or nuisance phytoplankton species in Massachusetts and Cape Cod Bays during this time period, other than the April bloom of *Phaeocystis pouchetii*. This alga was present in April at levels up to 3 x 10^6 cells L^{-1}, but its abundance in 2001 did not approach the levels of the April 2000 bloom (>12 x 10^6 cells L^{-1}). The suggestion from previous "*Phaeocystis*" years, such as 1992, 1994, 1997, and 2000 of blooms in ~3 year cycles was thwarted by back-to-back April blooms in 2000 and 2001. The dinoflagellates *Alexandrium tamarense* and *Alexandrium* spp. were sporadically recorded for screened samples in May, June, and July at abundances of ≤ 35 cells L^{-1} (only 2 samples >20 cells L^{-1}), which is well below the threshold abundance of 100 cells L^{-1}. There were no incidences of shellfish toxicity associated with *Alexandrium tamarense* in Massachusetts and Cape Cod Bays in 2001. Potentially toxic diatoms of the genus *Pseudo-nitzschia* were present in both spring and fall. Diatoms designated as *P. pungens* (which could also include some toxic *P. multiseries*) were frequently present in the first half of the year, but never abundant (< 25 x 10^3 cells L^{-1} and usually <10 x 10^3 cells L^{-1}). *P. pseudodelicatissima* was frequently present in the second half of the year, reaching a maximum of 278 x 10^3 cells L^{-1} at station N04 in late July. Otherwise, values for this species did not exceed 72 x 10^3 cells L^{-1}.

Zooplankton abundance and community composition in 2001 was similar to previous years. Total zooplankton abundance did not increase from February through July as has usually been the case (**Figure** 4-12), and zooplankton counts were considerably lower than for the same period in 1999 and 2000. The relatively low abundance of zooplankton may have been due to bottom-up control because phytoplankton were also relatively sparse in comparison to the two previous years. Zooplankton abundance reached annual maximum levels in late August and progressively declined through September and October and into December. Copepod nauplii, *Oithona similis* copepodites and adults, and *Pseudocalanus* spp. copepodites and adults as usual, dominated zooplankton assemblages. Subdominant contributions came from other calanoid copepods (*Centropages typicus* and *C. hamatus, Temora longicornis, Calanus finmarchicus*, and in Boston Harbor, *Acartia hudsonica* and *A. tonsa*), and sporadically from various meroplankters such as barnacle nauplii, bivalve and gastropod veligers, and polychaete larvae. Zooplankton abundance in Boston Harbor reached unprecedented low levels during October 2000 due to decimation of zooplankton populations by ctenophore (*Mnemiopsis leidyi*) predation. Although zooplankton abundances were low in the fall of 2001, they did not decrease to the levels observed in 2000. Anecdotal evidence indicates that there were dense assemblages of ctenophores of the Beroida order in Boston Harbor in the fall of 2001. These ctenophores mainly feed on other ctenophores such as *Mnemiopsis* and their presence may have reduced the grazing pressure on copepods in 2001.

4.1.4 Dissolved Oxygen

DO concentrations in 2001 were within the range of values observed during previous years and followed the typical trends. Maximum concentrations occurred in February when the water column was well mixed (**Figure** 4-13). In general, there was a steady decrease in bottom water DO concentrations from February to October. In contrast, DO concentrations in the nearfield and offshore areas remained relatively constant from April to June, and at the boundary stations bottom water concentrations actually increased over this period, likely due to an influx of waters from the Gulf of Maine. The June bottom water DO concentrations throughout most of Massachusetts and Cape Cod Bays were higher than those measured during the two previous years. The lack of a major winter/spring bloom in Massachusetts Bay and the regional influence of the Gulf of Maine may have led to relatively high bottom water DO concentrations in June. The lowest bottom water DO concentrations in June were found in Boston Harbor and Cape Cod Bay, which is not strongly influenced by the Gulf of Maine and had a winter/spring diatom bloom in February. *In situ* DO values for the August surveys were suspect, but concentrations determined via Winkler titration indicated that DO values remained relatively high (~9 mg L^{-1}) through the summer-stratified period. By September, DO concentrations in the nearfield had decreased to below 8 mg L^{-1}. The increase in bottom water percent saturation from September to early October was the result of a mixing event in late September (see **Figure** 3-7). The mixing event did not lead to an increase in DO concentration, but rather a slightly lower DO concentration and warmer temperature, which directly affects the determination of DO percent saturation.

As typically observed, the annual minimum DO concentrations and percent saturations were observed during the October survey (**Figure** 4-13). These annual minima were relatively high in comparison to previous years (Nearfield survey mean minimum DO = 7.4 mg L^{-1}). However, even though 2001 DO minimum concentrations were relatively high, bottom water DO concentrations did not increase to typical winter values until late December because of persistent stratified conditions. The bottom water DO survey minimum values were comparable to those measured in the fall of 2000. It might be expected that 2001 DO values would be high given the relatively low chlorophyll concentrations measured in 2001 and subsequently the presumed low level of organic loading to the bottom waters and benthos. The fact that similar DO minima were observed in two very different 'biological' years – major spring and fall blooms in 2000 and minor blooms in 2001 – suggests that either loading plays a relatively minor role in controlling bottom water DO or that the presumption that high chlorophyll concentrations are indicative of high loading is incorrect. An examination of the connection between physical oceanographic conditions and DO concentrations suggests that it is the former and that regional processes and advection are the primary controlling factors governing bottom water DO concentrations in Massachusetts Bay (Geyer *et al*., 2002).

4.2 Interannual Comparison – 2001 vs. Baseline

The year-to-year variability in nutrient concentrations and biological parameters depends on a variety of physical and biological processes. This section focuses on characterizing the year-to-year variability and evaluating the trends that were observed in 2001 versus baseline data (1992 to September 6, 2000). The 2001 versus baseline comparisons focus primarily on the nearfield and Boston Harbor where changes due to the diversion of effluent are expected to have the greatest effect on water quality. Data are presented as survey means and annual means for each area (as defined in **Figure** 2-2). The baseline data are presented as the range and average of survey mean values.

4.2.1 Nutrients

A phytoplankton bloom and an associated increase in chlorophyll of varying intensities often characterize the winter/spring period in Massachusetts and Cape Cod Bays. The presence of elevated nutrient concentrations, increasing light and water temperatures, and the onset of seasonal stratification establish conditions that are conducive for a bloom to occur in the bays. The intensity of the winter/spring nutrient draw down is related to the strength of the bloom – the more intense the bloom, the lower the concentrations of nutrients in the surface waters. During the summer-stratified period, nutrients are generally depleted in the surface waters and tend to increase at depth as organic material is degraded and nutrients remineralized. During years when upwelling conditions are favorable, nutrient concentrations may increase in July and August in western Massachusetts Bay at western nearfield and coastal stations. The fall is often a period of increasing nutrient concentrations as the water column returns to well-mixed winter conditions. This fall trend may be punctuated by decreases in nutrient concentrations during strong fall blooms (*i.e. Asterionellopsis glacialis* bloom in the fall of 1993). The input of bottom water nutrients into the surface layer as stratification breaks down is one of the primary factors that initiate fall blooms in these temperate coastal waters. The inputs of nutrients and the continued availability of light provide the fuel for these blooms. The interannual variability is much less than the seasonal concentration range that results from spring draw down and fall increases each year. There are, however, interannual differences in the timing and extent of the nutrient dynamics.

This general trend in nutrient concentrations was observed in 2001 (**Figures** 4-14 and 4-15). In comparison to baseline data, the concentrations NO_3, SiO_4, and PO_4 were relatively low in early February, high in March, close to baseline mean over the summer, high in fall and low in December. In early February, nutrient concentrations were near (NO_3) or below (SiO_4 and PO_4) the baseline minima indicating a relatively early draw down of nutrients due to the winter/spring bloom. The low concentrations were coincident with elevated levels of chlorophyll and productivity (see **Figures** 4-6 and 4-7). The winter/spring draw down of nutrients was not as sharp as observed in 1992, 1994, 1996, and 2000 when substantial blooms led to a sharp decline in NO_3 concentrations in both surface and bottom waters from February to March. Although the overall draw down was less intense, it does not suggest, as in 1998, that there was no winter/spring bloom. Rather, the low concentrations observed in early February indicate that it occurred earlier than previously observed. There was an increase in nutrients following the end of the winter/spring bloom and prior to the April *Phaeocystis* bloom that resulted in NO_3 and PO_4 concentrations exceeding the baseline maxima for the March nearfield survey. The *Phaeocystis* bloom in April led to a decrease in some nutrient concentrations, which then remained comparable to the baseline mean values through the summer. Nitrate concentrations were higher than baseline maximum values in September and late October due to the lack of an early fall bloom. The persistence of weakly stratified conditions and the occurrence of a late fall bloom resulted in NO_3 and SiO_4 concentrations below the baseline minima in December 2001.

A plot of survey mean NH_4 (**Figure** 4-16a) show that trends in the concentration of this nutrient do not follow the same pattern governed by physical and biological processes. Although NH_4 is preferentially taken up by phytoplankton over NO_3, elevated NH_4 concentrations were observed in the nearfield over much of 2001 especially in the summer, when NO_3 concentrations were lowest. This was due to the continued supply of NH_4 to the nearfield from the bay outfall. The high concentrations in the summer were primarily the result of the stratified water column trapping the effluent derived NH_4 below the pycnocline where it was underutilized by phytoplankton. It should be noted, however, that this is not a 'new' source of nutrients to the nearfield; rather it is reaching the nearfield area via a new pathway – the subsurface outfall vs. surface tidal flow from the harbor. The use of the NH_4 signal as a tracer of the effluent plume will be discussed in detail in Section 4.5. In comparison to baseline data, nearfield NH_4 concentrations were comparable to the maximum values observed during the winter/spring and late fall surveys, which were conducted when the water column was either weakly stratified or well-mixed. Under stratified conditions during the summer and fall (June – October), nearfield NH_4 concentrations were well above baseline maxima reaching a maximum mean value of 4.5 µM in June. This is about three times the maximum level measured at this time during the baseline period and is the highest survey mean NH_4 concentration measured from 1992 to 2001.

In contrast, NH_4 concentrations in Boston Harbor, as expected, were below or near baseline minima for the entire year (**Figure** 4-16b). In 2001, NH_4 concentrations in the harbor were 25% to 50% of the baseline mean and only 10 to 25% of the maximum concentration that had been seen in Boston Harbor during 1998 to 2000 when the discharge of secondary treated effluent led to elevated harbor NH_4 concentrations. Water quality changes in Boston Harbor are the focus of intensive study by MWRA and are summarized in Taylor 2002. Continued monitoring should provide additional insight into changes in nutrient and biological dynamics in the harbor that result from relocation of the outfall.

The annual mean nutrient concentrations for each of the regions in Massachusetts Bay show a general trend of decreasing annual means from 2000 to 2001 except for NO_3 and NH_4 in the nearfield (**Figures** 4-17 and 4-18). In Cape Cod Bay, NO_3 concentrations increased while the other nutrients remained unchanged from 2000 levels. In general, trends of increasing nutrient concentrations were observed from 1992 to 1999 for the bays (Libby *et al.*, 2000). Since 1999 SiO_4 and PO_4 annual mean concentrations have decreased across the bays. The pattern for NO_3 has been more variable from 1999 to 2001, but concentrations decreased for most of Massachusetts Bay from 2000 to 2001. As discussed in the comparison of 2001 survey means versus baseline data for the harbor, there was a very sharp decrease in annual mean NH_4 concentration from 2000 to 2001 in Boston Harbor (10 to 2 µM). This was coincident with a commensurate decrease in PO_4 (1.0 to 0.6 µM). A sharp decrease in NH_4 concentration was also seen at the coastal stations, which are strongly influenced by water quality conditions in Boston Harbor. The increase in annual mean NH_4 in the nearfield was not as dramatic as the harbor and coastal water decrease. This is due to greater dilution in the nearfield and the inclusion of 4 months of post-discharge data in the 2000 mean NH_4 concentration. Since 1999, the annual mean NH_4 levels have almost doubled in the nearfield. There was little if any change in NH_4 concentrations in offshore, boundary, and Cape Cod Bay waters from 2000 to 2001. In fact, annual mean NH_4 concentrations in Cape Cod Bay have decreased from a maximum of 1.7 µM in 1999 to 1.1 µM in 2000 and 2001. The impact of the changes in the nutrient regimes in both the harbor and nearfield are discussed in the next section.

4.2.2 Productivity and Biomass

One of the potential effects of the relocated effluent discharge could be a change in areal productivity. This was assessed by comparing production measurements at the nearfield stations N04 and N18 and Boston Harbor station F23 in 2001 to the baseline productivity data collected from February 1995 to August 2000 (**Figures** 4-19 and 4-20). In general, areal production at the nearfield sites in 2001 fluctuated near the baseline mean for most of the annual cycle. The major deviations from the baseline data include an increased magnitude of the fall bloom at station N04 relative to prior years (and relative to station N18) and the late occurrence of the second fall production peak at both stations. Productivity in early December 2001 was the highest ever measured at station N04. At station N18, the early December peak in production was lower than observed during major blooms, but was more than 4 times the baseline maximum for December surveys. The deviations from the baseline data are most likely related to the presence of stratified conditions late into the fall and may also be enhanced by increased nutrient availability related to the outfall (see **Figure** 4-16a). In Boston Harbor, productivity in 2001 generally fell well below the baseline mean and always within the baseline range (**Figure** 4-20). The decrease in productivity in the harbor is most likely tied to decreased nutrient availability (see **Figure** 4-16b) as also suggested by the altered seasonal productivity pattern.

Nearfield chlorophyll concentrations exhibited little difference in the patterns of volumetric ($\mu g\ L^{-1}$) and areal ($mg\ m^{-2}$) values for 2001 or over the baseline. Areal chlorophyll is useful for comparisons between areas and it is also used as a nearfield threshold value. In 2001, chlorophyll concentrations were generally at or below the baseline mean for most of the year. The two deviations from this trend were in early February and December when chlorophyll concentrations exceeded baseline maxima (**Figure** 4-21). The high concentrations in early February were coincident with elevated production rates that were close to the baseline maximum at station N04 and above the mean at station N18. In December 2001, mean survey chlorophyll concentration reached its annual maximum coincident with peak production at both stations N04 and N18 (see **Figure** 4-19). Although the early February and December 2001 chlorophyll values were relatively high (150 $mg\ m^{-2}$) in comparison to baseline for those surveys, they were well below the maximum values observed during major winter/spring and fall blooms. During the March 2000 *Phaeocystis* bloom, the mean chlorophyll concentration was 3-fold higher than the winter/spring bloom of 2001 (450 $mg\ m^{-2}$) and was the highest survey mean chlorophyll concentration observed for the baseline. The fall blooms in both 1993 and 1999 resulted in chlorophyll levels that were twice as high (~300 $mg\ m^{-2}$) as that measured in December 2001.

The POC data showed a similar pattern to chlorophyll in the comparison of 2001 versus baseline (**Figure** 4-22). POC concentrations generally followed the baseline mean with deviations from the mean evident in June/July and late October/December. Unlike chlorophyll during the early winter/spring bloom, POC concentrations were higher than the baseline mean, but below the maximum in early February. Following the first survey of the year, mean POC concentrations were below the baseline mean until June when they were well above the maximum value and remained high into early July. These elevated POC values were not coincident with an increase in chlorophyll, production or plankton abundance. An increase in POC concentrations from mid October to December was concomitant with high productivity and chlorophyll levels associated with the late fall bloom. From late October to December 2001, POC levels were higher than baseline maxima and reached an annual survey mean maximum of 45 µM in early December. This value was nearly double the baseline maximum for December and approached the fall bloom maximum of 54 µM seen in 1999.

Comparisons of 2001 chlorophyll and POC concentrations in Boston Harbor versus baseline data are presented **Figure** 4-23. The survey mean chlorophyll data closely follow the same trend seen for areal production in the harbor – at baseline maximum values for February and close to baseline minima for the remainder of the year. POC concentrations did not exhibit high values in February corresponding to the relatively high production and chlorophyll concentrations (compared to baseline at least) and remained below the baseline mean for all of 2001. The production and chlorophyll data suggest the harbor may be moving away from the baseline trend of increasing production and POC concentration from winter to summer and then decreasing in fall.

Chlorophyll-specific production averaged over depth at stations N04, N18 and F23 was also examined for 2001 versus baseline (**Figures** 4-24 and 4-25). The baseline period for this parameter is shorter (1998 – 2000) due to questions about the comparability of methods used prior to 1998. Depth-averaged chlorophyll-specific productivity was calculated for 1997 using *in situ* fluorescence data, but it was elevated compared to 1998 through 2001. For example, at station N04, the 1997 values for each of the surveys exceeded the upper range of the 1998-2000 baseline data shown in **Figure** 4-24. For station N18, 15 of the 17 values in 1997 were greater than the upper range. Differences in techniques (i.e. chlorophyll measurement and integration depth) prior to 1998 most likely contributed to the high values observed in 1997. The differences between data from the pre-1998 and 1998 to 2000 periods need to be further examined before including earlier chlorophyll-specific production data in the baseline dataset.

The pattern of chlorophyll-specific production indicates that the efficiency of production was high relative to the amount of biomass present at the nearfield stations, particularly during the *Phaeocystis* bloom in April and prior to the fall period (**Figure** 4-24). At both stations N04 and N18, the peak depth-averaged chlorophyll-specific production (>50 mgC $mgChla^{-1}$ d^{-1}) occurred in April when production was elevated relative to the rest of the winter/spring surveys and *Phaeocystis* abundance was high, but there was relatively low chlorophyll biomass. These rates were about double the maximum observed over the abbreviated baseline period. Chlorophyll-specific production remained elevated in comparison to the baseline data at station N18 over the summer (station N04 was close to the baseline mean over this period). The late summer/early fall peaks preceded a period of increased areal production and elevated chlorophyll *a* at station N18 and N04. Efficiency of production was lower at harbor station F23 (**Figure** 4-25) relative to the nearfield sites and remained relatively constant over 2001. Except for the early February survey, Boston Harbor depth-averaged chlorophyll-specific production was above baseline maxima. To improve the evaluation of changes in harbor and nearfield production efficiency, it will be necessary to extend the baseline data set to include 1995-1997 by rectifying the data inconsistencies.

Measured annual productivity estimates in 2001 were similar at all three stations and intermediate to values observed in 1995 - 2000 (**Figure** 4-26a). Annual productivity at station F23 was lower than the values recorded at the nearfield sites, as was similarly noted in 2000. Prior to 2000, annual productivity at F23 was consistently higher than stations N04 and N18. Potential annual productivity shows a similar trend with time, although the values are elevated compared to measured production (**Figure** 4-26b). Since 1997, the increase in potential annual productivity over measured at the nearfield stations has been low (10 – 15%; **Figure** 4-27). In 1995 and 1996, the increase in potential annual productivity was greater (25 – 60%). The annual productivity values suggest that productivity in the harbor is declining; however, there is no evidence that annual productivity at the nearfield sites has increased despite the observed increased magnitude of the fall bloom.

The annual mean chlorophyll and POC concentrations (based on calendar years) for each of the six areas are presented in **Figure** 4-28. These values were calculated as the average of the survey means using all data collected during each of the surveys from each sampling depth. There was a precipitous decline in annual mean chlorophyll from maxima in 2000 to values less than half that in 2001 for many areas. The 2000 annual mean chlorophyll concentrations were the highest observed over the monitoring period and continued a trend of increasing chlorophyll from 1997 to 2000. The primary reason for the decline in chlorophyll from 2000 to 2001 was the lack of major winter/spring and fall blooms in 2001. Annual chlorophyll concentrations decreased by ≥50% in Boston Harbor, coastal, nearfield and Cape Cod Bay waters. The decrease was not as sharp at the offshore and boundary stations in eastern Massachusetts Bay where the 2001 annual concentrations were highest. The annual mean chlorophyll concentrations in 2001 were also lower than observed in 1999 (another year with substantial winter/spring and fall blooms) and marked a return to chlorophyll levels observed in 1995-1998 for Boston Harbor, coastal, and nearfield waters. Annual mean POC concentrations also decreased from 2000 to 2001 except at eastern Massachusetts Bay offshore and boundary stations where there was a slight increase (**Figure** 4-28b). Unlike chlorophyll, this continued a trend of decreasing POC from 1999 maxima.

The continued presence of elevated chlorophyll at the offshore and boundary stations suggests that chlorophyll concentrations in Massachusetts Bay continue to be influenced by regional factors from the Gulf of Maine. The trend of increasing concentrations from 1997 to 2000 and then decreasing in 2001 is not directly related to local factors. The regional trend for fall blooms is clearly illustrated in **Figure** 4-29. These images are monthly composites of SeaWiFS images for the southwestern Gulf of Maine [courtesy of J. Yoder (URI) and J. O'Reilly (NOAA)]. The September image for 1998 shows relatively low concentrations of chlorophyll over most of Massachusetts and Cape Cod Bays. There is an obvious increase in chlorophyll concentrations from 1998 to 1999 to 2000 and then a decline in 2001. The interpretation of these images is qualitative, but the relative trends are unambiguous. Furthermore, the blooms are not restricted to Massachusetts Bay, but rather are occurring throughout southwestern Gulf of Maine.

4.2.3 Plankton

Phytoplankton communities are mixtures of many species, with the abundance and composition of the community changing in response to each species response to prevailing environmental influences on the phytoplanktonic habitat (i.e., annual change in irradiance, temperature, nutrient, grazer abundance). Differences in the 2001 nearfield phytoplankton annual cycle, relative to baseline observations, may be identified by hierarchical examination (i.e., from total phytoplankton to specific groups) of the major components of the nearfield phytoplankton. Using this approach, questions of how the 2001 phytoplankton cycle differed from the baseline pattern, and which phytoplankton taxa were responsible for any observed deviations, may be addressed.

The whole-water phytoplankton assemblages in 2001 were generally similar to those found during other baseline monitoring years. A description of the common paradigm of "normal" seasonal succession is presented based upon the 1992-2000 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 taxa are dominant in Massachusetts and Cape Cod Bays during the periods identified below:

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

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

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

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

Superimposed over the background dominance of microflagellates and common diatoms, in some years there are outbursts of a single species such as *Asterionellopsis glacialis* in fall of 1993, or *Phaeocystis pouchetii* in spring of 1992, 1994, 1997, 2000, and 2001, or congeners such as the frequent summer-fall blooms of *Ceratium longipes/tripos*. Although such blooms may be intermittent, they can be dramatic. Why such species bloom in some years but not others is unclear.

Compared to baseline observations, the 2001 nearfield phytoplankton cycle featured lower phytoplankton abundance throughout most of the year, with the exception of elevated phytoplankton abundance in late July, and a prolonged late October through December diatom bloom (**Figure** 4-30). Compared to the baseline data, 2001 exhibited lower winter/spring abundance (even during the minor *Phaeocystis* bloom), summer abundance that was near the baseline mean (with the exception of the late July microflagellate bloom), and a late fall bloom with abundance levels higher than the baseline maxima. The late fall bloom persisted from late October through mid December and was the dominant feature of the 2001 nearfield phytoplankton cycle.

Diatom abundance was low during much of 2001. Nearfield diatom abundance was less than 50% of the corresponding nearfield baseline mean diatom level in ten of seventeen 2001 surveys (**Figure** 4-30b). However, in early February 2001, during a bloom dominated by *Thalassiosira nordenskioldii* and *Guinardia delicatula*, diatom abundance was approximately 1.7-times the mean baseline level. The next time nearfield diatom abundance exceeded baseline mean levels was in mid May during a *Skeletonema costatum* bloom. This *Skeletonema* bloom exceeded the highest May nearfield baseline *Skeletonema* record by approximately 25%, and contributed to a May total diatom abundance that was approximately 1.5 times the mean baseline level. This May diatom bloom was brief, being observed only in a single survey. Diatom abundance remained low, relative to baseline levels, through the summer and early autumn of 2001. September and October diatom abundance was comparable to the baseline minima and drastically below the abundance maxima associated with the major fall blooms in 1993, 1995, and 1997. In late October diatom abundance rebounded to baseline mean levels. While there was no nearfield phytoplankton sampling in November 2001, early and late December surveys found an abundant nearfield diatom community. This late fall bloom was delayed approximately six weeks from the baseline fall diatom bloom, which typically occurs in mid October. Productivity data suggests that it may have begun in October (see **Figure** 4-6). The late-fall diatom bloom was not limited to a single species or even genus, but consisted of a diverse phytoplankton assemblage. *Skeletonema costatum*, *Leptocylindrus danicus*, *L. minimus*, *Thalassiosira* spp. and *Rhizosolenia* spp all displayed December 2001 abundance levels that matched or vastly exceeded mean baseline levels for these taxa. The result was a December 2001 nearfield diatom abundance that was nearly 6-fold higher than the mean baseline level for early December (**Figure** 4-30b).

Dinoflagellates were also present at levels exceeding baseline means throughout the late fall of 2001 (**Figure** 4-31). Compared to baseline levels, the increases in dinoflagellate abundance preceded the diatom increase by approximately one month. Dinoflagellate abundance was approximately 50% below baseline levels throughout most of the winter and spring of 2001. In late July and early August, nearfield dinoflagellate abundance increased to levels unprecedented in baseline sampling. In late July 2001 dinoflagellate abundance (225,000 cells l^{-1}) was nearly 4-times the late July nearfield mean baseline value of 59,000 cells l^{-1}. Some of this increase was due to the abundances of *Ceratium* spp. (especially *C. longipes* and *C. fusus*), which persisted at greater than baseline maximum levels (up to 20,000 cells l^{-1}) for June and July of 2001 (**Figure** 4-31b). *Ceratium* abundance was near baseline minimums for the remainder of 2001, except for an early October peak of 7,000 cell l^{-1} that was near the baseline mean and an early December peak (up to nearly 4,000 cell l^{-1}) that exceeded the range of observed nearfield baseline *Ceratium* abundance. This elevated autumn *Ceratium* abundance was consistent with the pattern of elevated dinoflagellate abundance observed during most of the autumn of 2001.

Microflagellate abundance was near baseline levels for February through June of 2001. In late July, microflagellate abundance increased to 2.4 x 10^6 cells l^{-1}, a level that was 2.4-times the mean baseline level (**Figure** 4-32). However, this late July microflagellate peak was well within the range of observed microflagellate baseline abundance for that period. Following the late July increase, microflagellate abundance was near baseline levels in August through mid October. In late October, microflagellate abundance increased to near 1.5 x 10^6 cells l^{-1}, a level that was nearly three-times the baseline mean. Microflagellate abundance increased as part of the late-fall bloom, with elevated nearfield microflagellate abundance of greater than the maximum nearfield baseline observations for the corresponding period of October through December.

The 2001 nearfield phytoplankton annual cycle featured an atypical late autumn bloom. The autumn diatom peak, which typically would be expected in September or October, occurred in early December in 2001 (**Figure** 4-30b). The late autumn bloom was primarily a diatom bloom (6-fold increase over baseline mean), however, nearly all components of the nearfield phytoplankton were present in increased abundance in December 2001, with >2-fold increase in early December in dinoflagellate abundance, and a nearly 3-fold increase in early October in microflagellate abundance. The community-wide late autumn bloom is suggestive of an increase of the late autumn phytoplankton carrying capacity above those levels usually observed during the baseline period. Whether this change reflects a change in phytoplankton habitat parameters, or is representative of a shift in the timing of the 2001 nearfield phytoplankton cycle is unknown.

The major feature of the 2001 nearfield phytoplankton cycle was the prolonged late autumn bloom. This feature was part of a regional autumn increase in chlorophyll as confirmed by SeaWiFS images (see **Figure** 4-29). On average, the southwestern Gulf of Maine (including Massachusetts and Cape Cod Bays) displays its annual chlorophyll biomass peak in the autumn (O'Reilly and Zeitlin, 1998). Further, western Gulf of Maine chlorophyll levels in autumn are usually higher than those anywhere else on the northeast US continental shelf except the southern Mid-Atlantic Bight. O'Reilly and Zeitlin (1998) noted that western Gulf of Maine phytoplankton photosynthetic efficiency is not at its annual maximum near the summer solstice (maximum light availability), but rather, in autumn. The fall bloom in the western Gulf of Maine appears to be a lifting of the sub-surface chlorophyll maximum layer (usually at 15 to 30 m depth in the stratified summer season) toward the previously nutrient-limited surface layers in response to decreases in water column stability. Such a scenario is consistent with the elevated late-autumn 2001 nearfield phytoplankton abundance. Such an increased photosynthetic efficiency (see **Figure** 4-24) and related declines in C:Chl ratios associated with autumn blooms in the western Gulf of Maine (O'Reilly and Zeitlin, 1998) are also consistent with the elevated chlorophyll and primary production levels observed in the nearfield during late autumn 2001.

An increase in late autumn phytoplankton carrying capacity is not limited to an increase in resource availability, but may be due to a decrease in loss processes. Nearfield zooplankton abundance was down to levels at or below the minimum baseline levels during much of the autumn of 2001 (**Figure** 4-33). For example, in October 2001 mean nearfield zooplankton abundance (24,000 animals m^{-3}; samples from 8, 19 and 29 October) was only about half of the corresponding nearfield baseline mean level of 46,000 animals m^{-3}. An increase in phytoplankton abundance above baseline levels, such as that seen in the late autumn nearfield is suggestive of a decrease in zooplankton community grazing pressure that may be associated with the nearly 50% reduction (versus baseline) in zooplankton abundance observed in autumn 2001. However, the absence of zooplankton grazing data precludes further insight on such speculation.

Zooplankton community composition in 2001 was similar to previous years. Total zooplankton abundance was generally lower than the baseline mean (**Figure** 4-33). The most abundant taxa in the zooplankton assemblage were, as usual, copepod nauplii and adults and copepodites of the copepod *Oithona similis*. Other abundant taxa included *Pseudocalanus* copepodites and various pulses of meroplankters. Larger zooplankters such as copepods of the genera *Calanus* and *Centropages* were generally present outside Boston Harbor, albeit in much lower abundance than the small copepods. As usual, copepods of the genus *Acartia* were generally confined to Boston Harbor.

The MWRA baseline monitoring program has highlighted the numerical importance of small copepods, and is one of the first of an increasing number of studies that are able to do so because of the consistent use of fine mesh nets (102-µm). Recent studies have shown that when net mesh of 100 µm or less is used, small copepods vastly exceed the abundance and sometimes the biomass of larger copepods. These studies have focused on waters all over the globe including studies from Long Island estuaries (Turner, 1982), the continental shelf (Turner & Dagg, 1983) and slope of the northeastern United States (Roman *et al*., 1985), the Sargasso Sea (Roman *et al*., 1993), the continental shelf off the southeastern United States (Paffenhöfer, 1985; 1993; Paffenhöfer *et al*., 1995), Jamaica (Chisholm & Roff, 1990;

Hopcroft & Roff, 1998; Hopcroft *et al*., 1998; Webber & Roff, 1995a, 1995b), the North Sea (Nielsen & Sabatini, 1996), the Mediterranean (Siokou-Frangou *et al*., 1997; Calbet *et al*., 2001), the equatorial Pacific (Roman & Gauzens 1997), and Japan (Uye, 1994; Uye & Sano 1998; Uye *et al*., 2002).

Small copepods (< 1 mm length) are undoubtedly the most abundant metazoans on Earth. Included in this size class are adults and copepodites of calanoid genera such as *Paracalanus, Pseudocalanus, Acartia* (embayments), and *Clausocalanus* (offshore); cyclopoid genera such as *Oithona* (ubiquitous), and *Oncaea* and *Corycaeus* (offshore, and most abundantly in the tropics); planktonic harpacticoids of the genus *Microsetella*; and nauplii of almost all copepod species. The MWRA data for nearfield zooplankton reveal that copepods and copepod nauplii comprise the major components of total zooplankton abundance (**Figure** 4-34). Of the non-nauplii component of copepods, the most abundant components include adults and copepodites of *Oithona similis* and *Pseudocalanus/Paracalanus* (**Figure** 4-35). The *Pseudocalanus/Paracalanus* community abundance consists primarily of copepodites.

Failure to adequately account for small copepods may cause serious underestimations of zooplankton abundance, biomass, production, copepod grazing impact on phytoplankton primary production, zooplankton-mediated fluxes of chemicals and materials, and trophic interactions in the sea. A recent paper by C. P. Gallienne and D. B. Robins (2001) examined the effects of mesh selection on zooplankton abundance, biomass, production, and copepod grazing impact. Gallienne and Robins (2001) found that the conventional 200-µm mesh net is likely to catch only 7% of the organisms between 200 µm and 20 mm body length. The under sampled zooplankton are primarily mesozooplankton in the 200-800 µm size class. Because of the relationship of volume to body length, the effect on biomass is less severe with these missed small organisms consisting of one-third of the total biomass. However, the effect of this loss on estimates of secondary production is about 67% because of the decrease in weight-specific growth with body size – the smaller zooplankton incorporate more carbon per unit biomass than the larger zooplankton. Gallienne and Robins (2001) conclude that a considerable proportion of the zooplankton size range ~200-800 µm length is not represented in either the microzooplankton or the "mesozooplankton" net samples in many studies (nominally 62-µm and >200-µm mesh, respectively). This poses serious limitations on understanding zooplankton-mediated fluxes and their role in ecosystem dynamics.

The feeding ecology of small copepods is less well known than that of adults of larger copepod species, such as the genus *Calanus* (Marshall & Orr, 1955). Most feeding information for small copepods is for coastal genera such as *Acartia*, rather than for offshore taxa. Although it is generally assumed that small copepods, including nauplii, feed primarily upon small-sized phytoplankton cells (Berggreen *et al.*, 1988; Marshall & Orr, 1955; Uye & Kasahara, 1983), most such information comes from rearing or feeding studies on limited laboratory diets (reviewed by Turner, 1984; 2000). There have been few examinations of actual copepod feeding on mixed diets of natural phytoplankton and microzooplankton found in the sea, and some of these have produced surprises. Some species of *Oithona* (Nakamura & Turner 1997; Lonsdale *et al.*, 2000) and *Paracalanus* (Suzuki *et al.*, 1999), and even nauplii of Arctic *Calanus* spp. (Turner *et al.*, 2001) may feed primarily as predators upon heterotrophic protists, rather than as grazers of phytoplankton. Nauplii of various copepod species have been shown to feed upon bacterioplankton (Turner & Tester 1992, Roff *et al.*, 1995). Other small cyclopoids such as *Corycaeus amazonicus* appear to feed primarily as carnivores upon copepod nauplii (Turner *et al.*, 1984), or as in the case of Antarctic *Oncaea curvata* upon entire gelatinous *Phaeocystis* colonies (Metz, 1998). Thus, numerous basic questions remain as to the feeding ecology and grazing/predation impact of small copepods in the sea.

Despite limited knowledge of what small copepods eat, it is clear that many higher-trophic-level consumers eat them. Numerous studies have shown that copepod nauplii, *Oithona* spp. and other small copepods are important prey of fish larvae, and other planktivores (Turner, 1984; Lough & Mountain, 1996; Conway *et al.*, 1998, and references therein). Thus, small copepods are important links in marine food webs, serving as major grazers of phytoplankton, as components of the microbial loop (Turner & Roff, 1993) by preying upon bacterioplankton and heterotrophic protists, and as prey for ichthyoplankton and other larger pelagic carnivores. The present understanding of the true abundance, biomass, trophic ecology, and role of small copepods in biogenic fluxes is inadequate and precludes full understanding of the ecology of the Massachusetts and Cape Cod Bays.

4.2.4 Dissolved Oxygen

The survey mean bottom water DO concentrations and percent saturation in 2001 closely followed the cycle observed for the baseline mean in both the nearfield and Stellwagen Basin (**Figures** 4-36 and 4-37). In 2001, as during the baseline, the DO cycle follows a repetitive pattern of higher concentrations in late winter/early spring, decreasing concentrations through the summer to the fall, and then increasing concentrations following the overturn of the water column in the fall. No measurements were made in Stellwagen Basin after October to verify the return to winter conditions. The only clear deviation from the baseline trend and range was for nearfield bottom water percent saturation in early February and mid December when the 2001 survey means were greater than the baseline maximum percent saturation values (**Figure** 4-37a). These relatively high percent saturation values likely had more to do with elevated temperatures than elevated production as DO concentrations were only slightly above (early February) or at (mid December) baseline means.

Bottom water DO concentrations were well above the contingency plan threshold values in both the nearfield and Stellwagen Basin and percent saturation values were below the 80% caution threshold, but well above warning and background levels. This is highlighted in a presentation of annual survey mean minima for the two areas (**Figures** 4-38 and 4-39). The annual DO concentration minimum in 2001 was on the upper end of the spectrum and well above the lowest baseline values observed in 1999 of 5.9 mgL^{-1} and 6.25 mgL^{-1} in the nearfield and Stellwagen Basin, respectively. Percent saturation minima in 2001, while below the caution threshold value of 80%, were also relatively high in comparison to previous years. These figures also highlight the regional continuity of interannual minima between the nearfield area and Stellwagen Basin. Linear regressions of the two datasets indicate that percent saturation and DO concentration in these two areas are significantly correlated (r^2 of 0.86 and 0.96, respectively). The correlation between nearfield, Stellwagen Basin and boundary station DO levels has been shown by both model and statistical analysis (HydroQual, 2001 and Geyer *et al.*, 2002).

Based on high correlations between temperature and DO and salinity and DO that were observed over the baseline period (Libby *et al.*, 2000), a statistical model was developed according to the formula

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

where T' and S' are the near-bottom temperature and salinity anomalies (relative to the 9-year mean for Sept.-Oct., A=7.46 mg/l, B=0.22, and C=1.9). In prior reports, the model was used to hindcast the variability of the fall, deep water DO levels to provide insight into the processes affecting interannual variations in bottom water DO. The lower panel in **Figure** 4-40 indicates which of the factors, salinity or temperature, contributed more to the predicted anomaly in a given year. For example in 1994, the low dissolved oxygen was related to both salinity and temperature anomalies, whereas in 1999 it was due principally to the salinity effect. For this report, it is used in a ‘forecast’ mode to see how well the result matches the measured DO concentration minimum. The statistical model predicted the bottom water DO minima for an inner set of nearfield stations almost exactly for 2001 (**Figure** 4-40). The measured and modeled DO concentrations were also close to the 10-year mean, so there was little information to be garnered from the relative contributions of temperature and salinity, but the result reaffirms the correlations between these parameters and bottom water DO concentrations.

4.3 Water Quality Summary

The various water quality parameters in 2001 followed the general trends observed over the baseline period. The main deviations from baseline trends were observed in February and December. Nutrient, biomass and production data suggest that the winter/spring bloom had peaked prior to the early February 2001 survey in Massachusetts Bay. The failure of this bloom and an influx of nutrients (precipitation, runoff and advection) led to elevated spring nutrient concentrations in spite of the minor bloom of *Phaeocystis pouchetii* in April. The *Phaeocystis* bloom marked the second consecutive year that this nuisance species was observed in Massachusetts Bay, which is a departure from the ~3 year cycle of occurrence that was noted over the baseline period. The calm weather and warm temperatures led to a delay in destratification of the water column and resulted in a late fall bloom. The fall bloom normally occurs in September and October, but in 2001 the bloom occurred from October to December with peak production rates and highest biomass concentrations being measured in early December. The dynamics associated with these blooms (winter/spring, *Phaeocystis*, and fall) are discussed in more detail in Section 5.

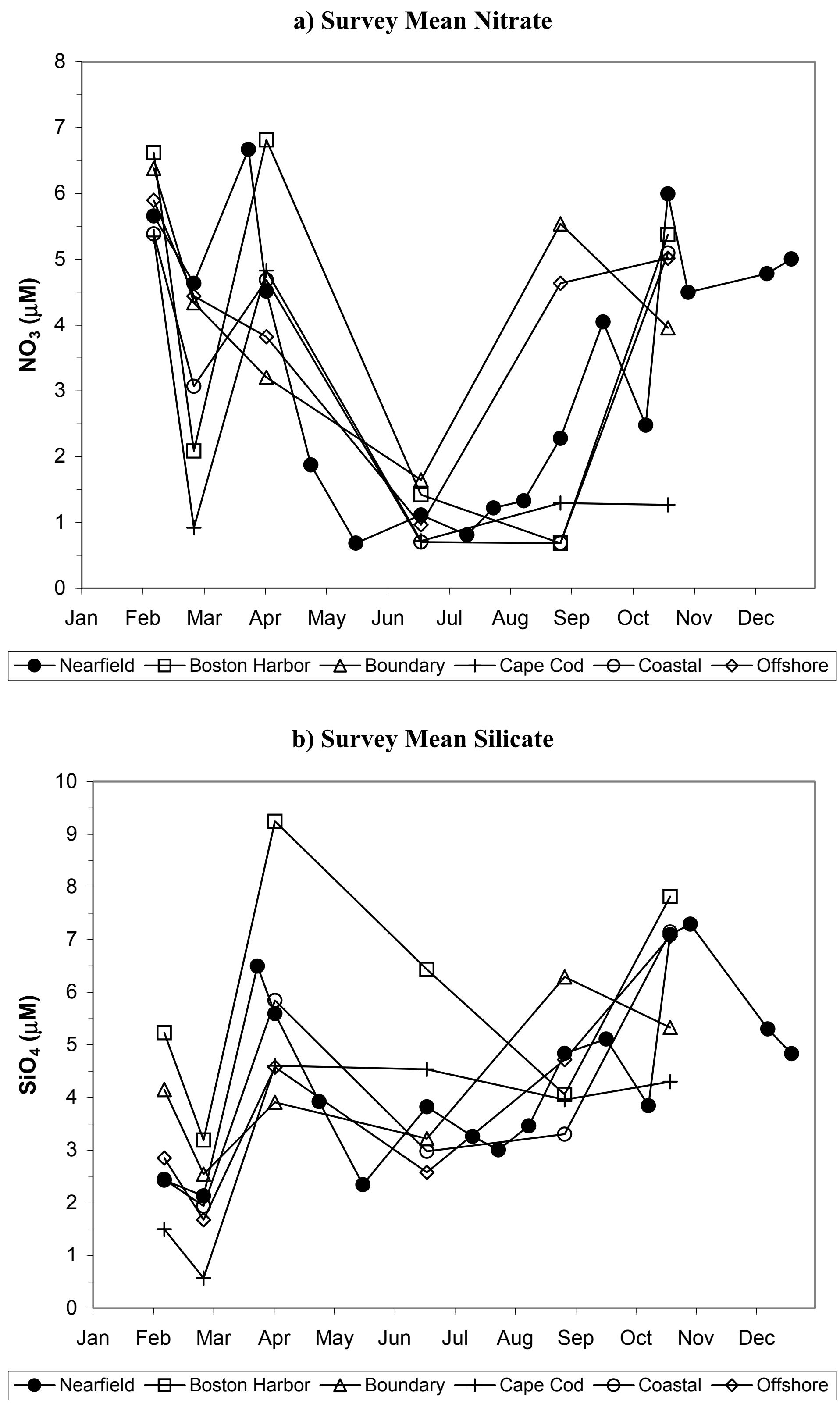
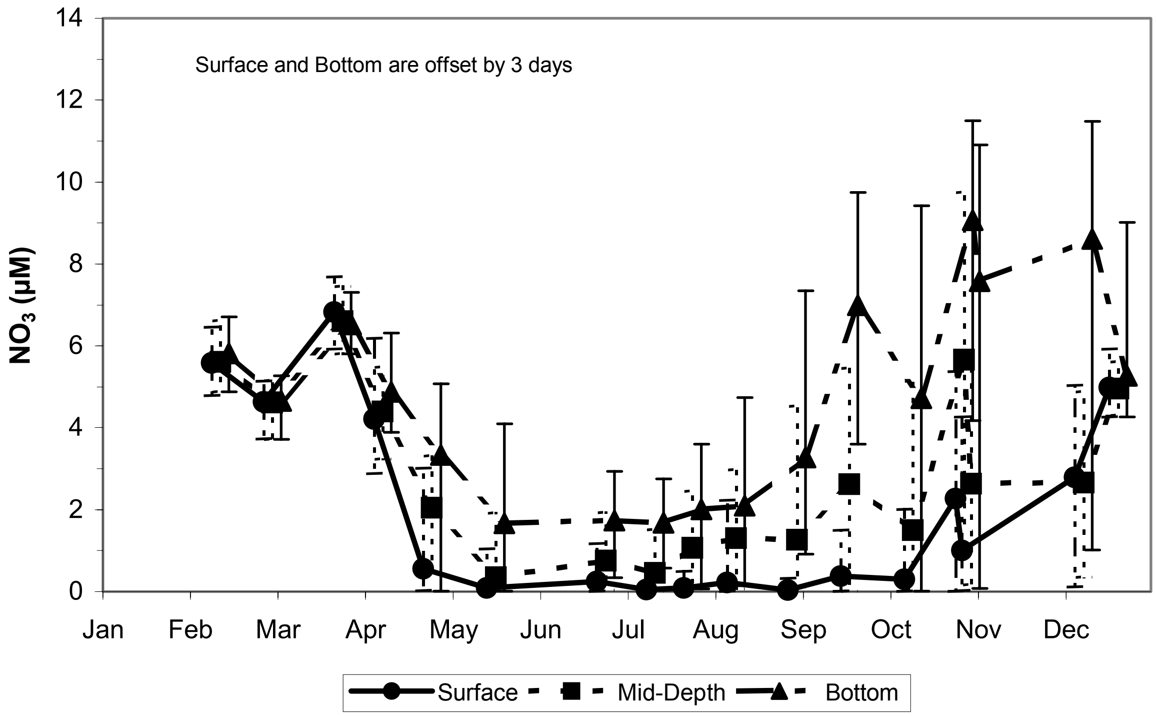


Figure 4-1. Time-series of survey mean (a) NO_3 and (b) SiO_4 concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region.

(a) Nitrate



(b) Silicate

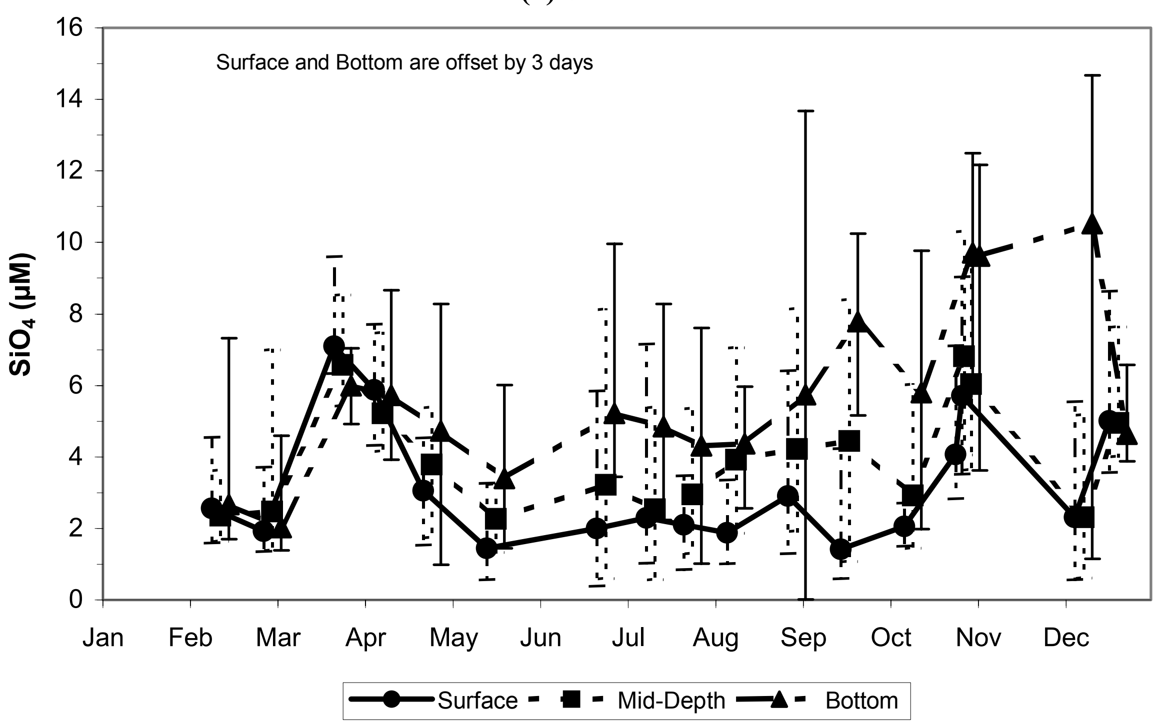


Figure 4-2. 2001 nearfield nutrient cycles for (a) NO_3 and (b) SiO_4. Survey average and range for surface, mid-depth and bottom samples collected during each nearfield survey. Surface and bottom data offset for clarity.

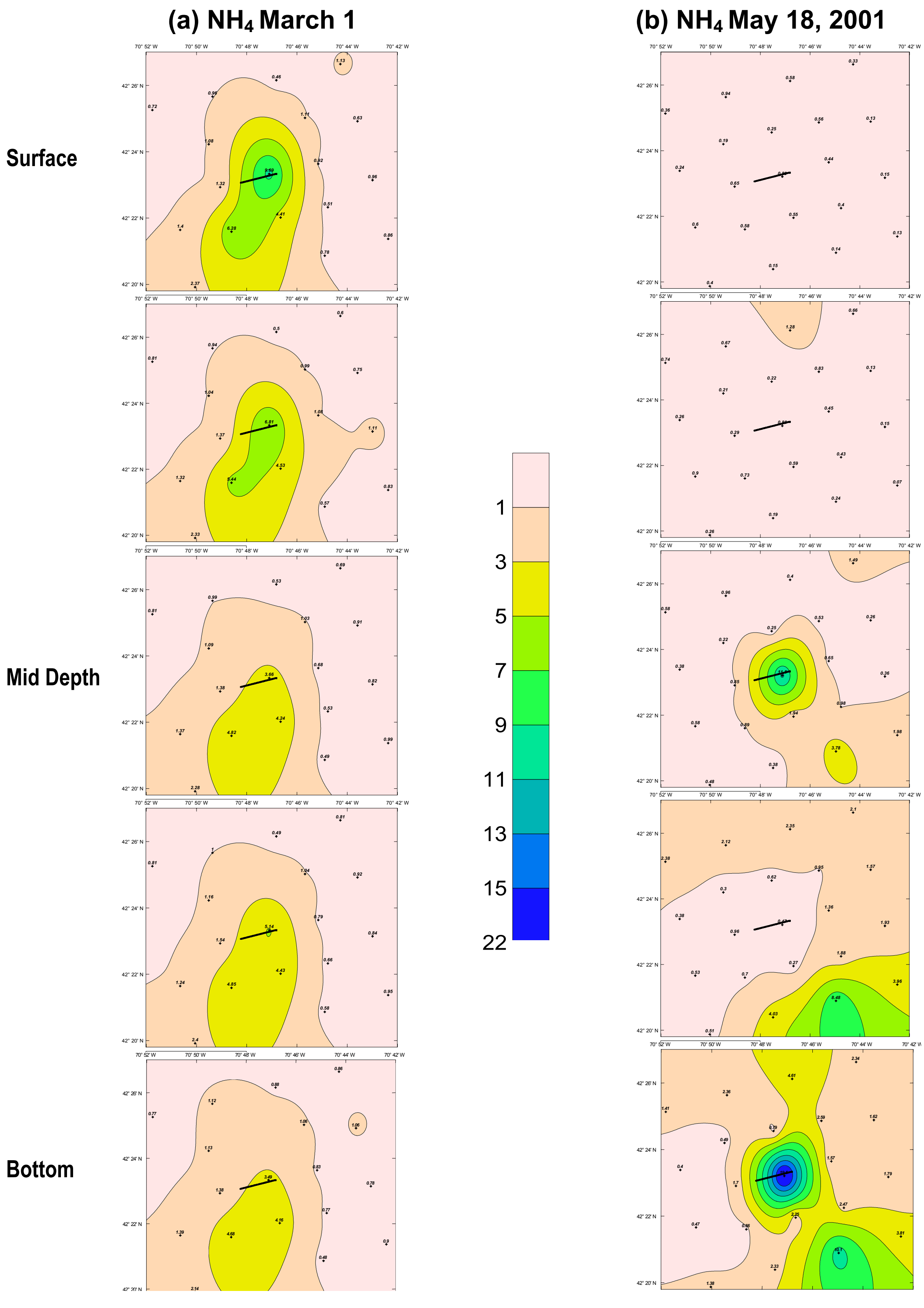


Figure 4-3. NH_4 distribution in the nearfield by depth for (a) March 1 and (b) May 18, 2001. Plots displayed from surface to bottom.

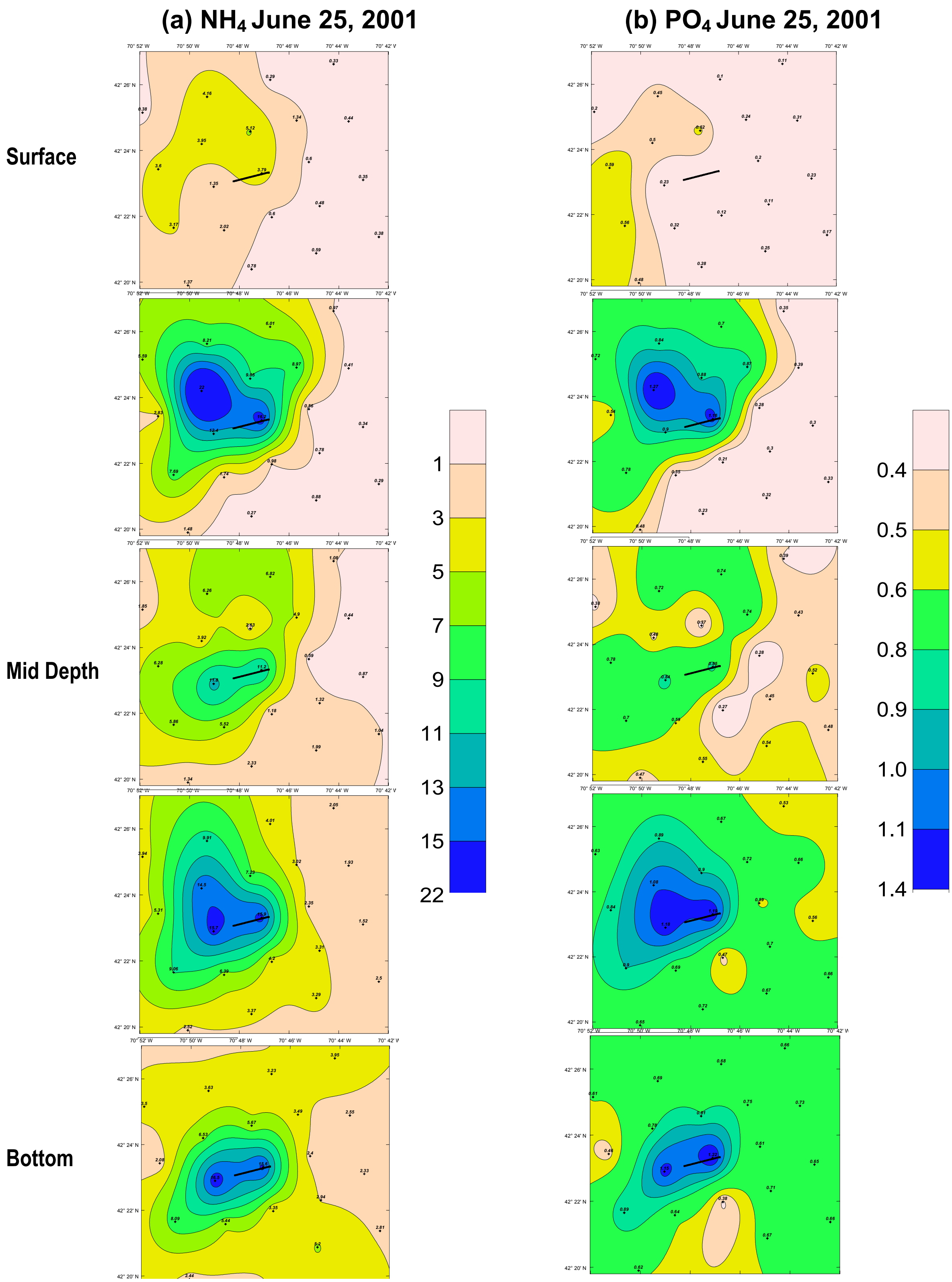


Figure 4-4. Distribution in the nearfield by depth of (a) NH_4 and (b) PO_4 on June 25, 2001. Plots displayed from surface to bottom.

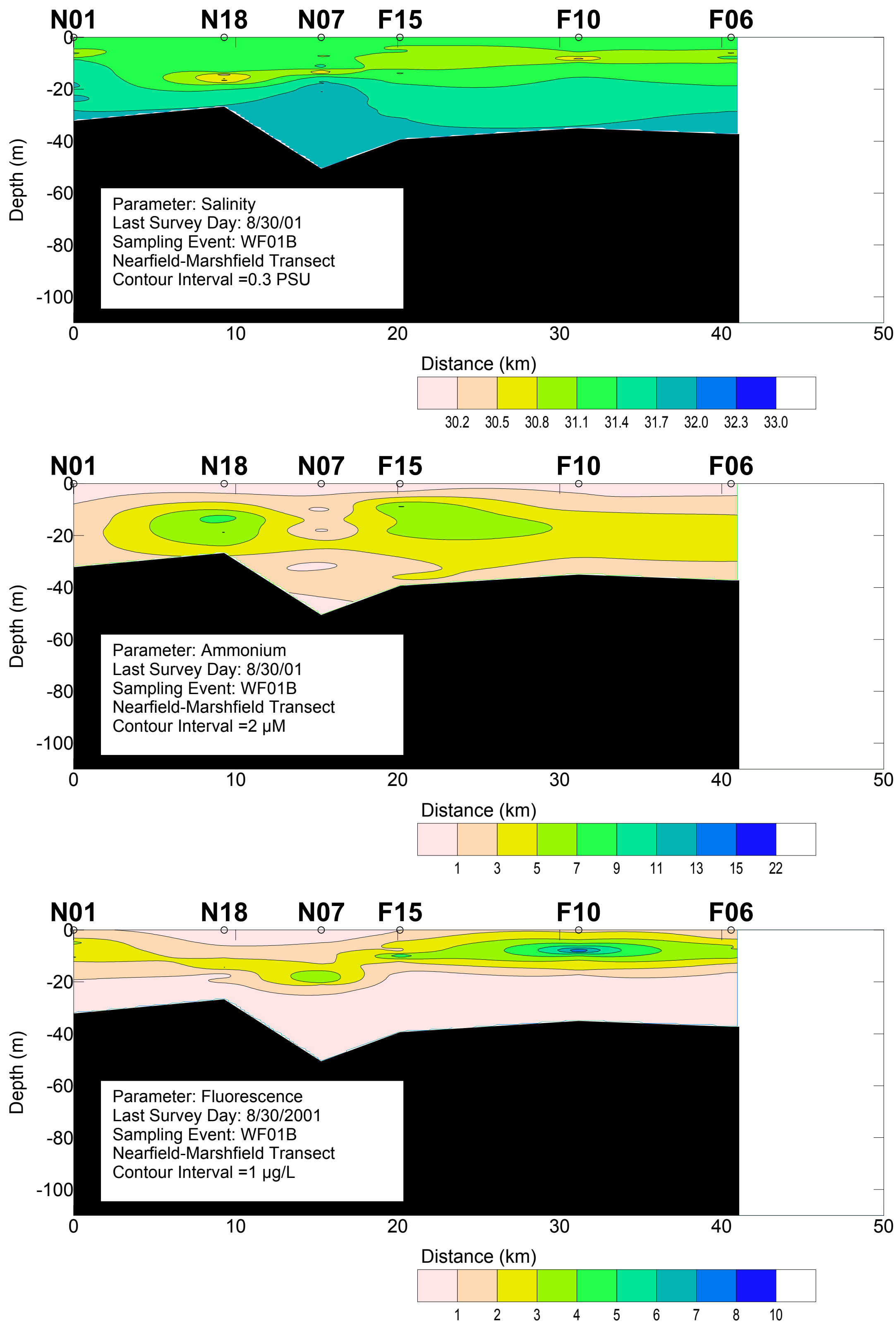


Figure 4-5. Salinity, NH_4, and fluorescence along Nearfield-Marshfield transect in August 2001.

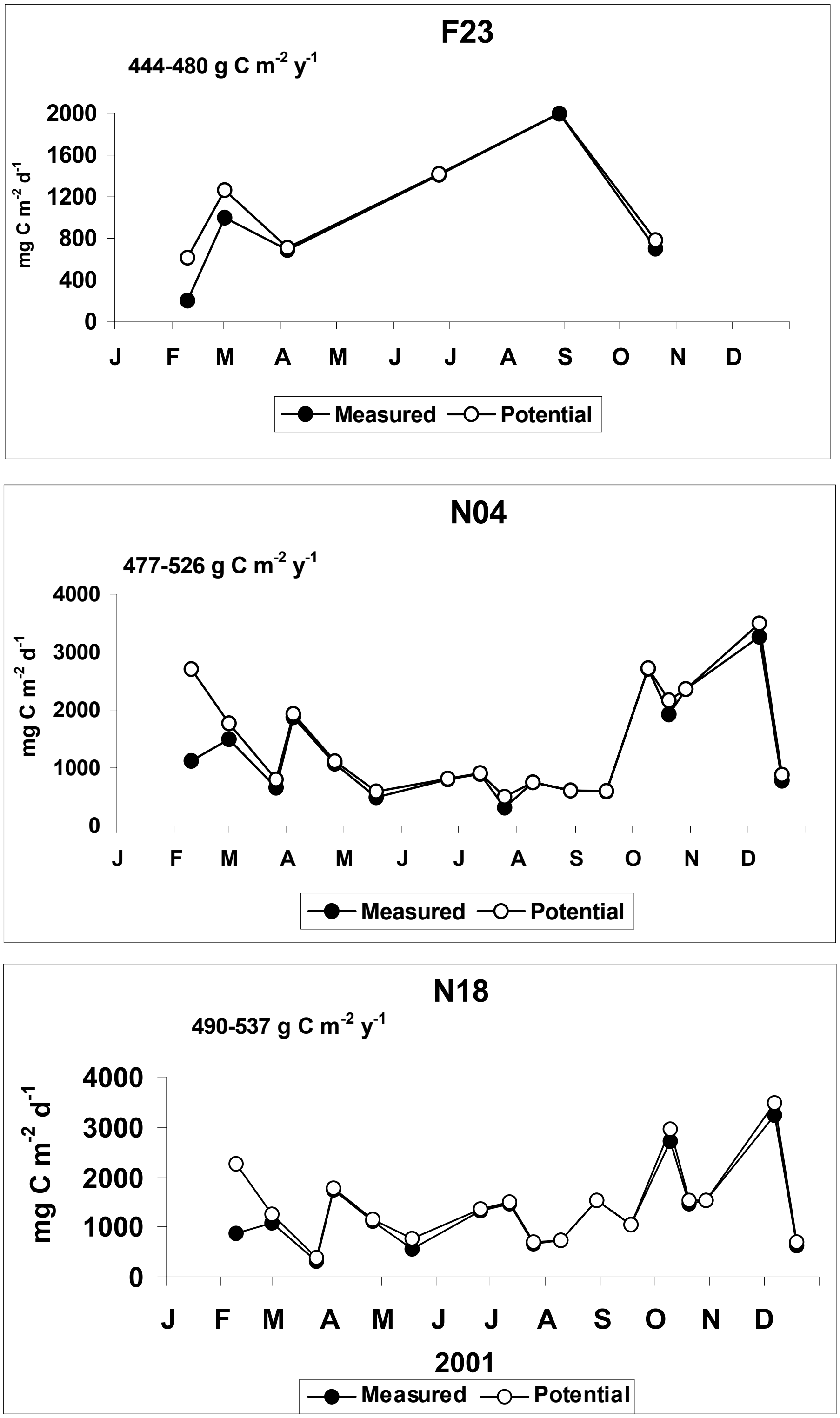


Figure 4-6. Measured and potential areal production ($mgCm^{-2}d^{-1}$) for 2001 at stations F23, N04, and N18. Annual and potential annual production ($gCm^{-2}y^{-1}$) are shown in the panel insets, with the higher value being the potential annual production at each station.

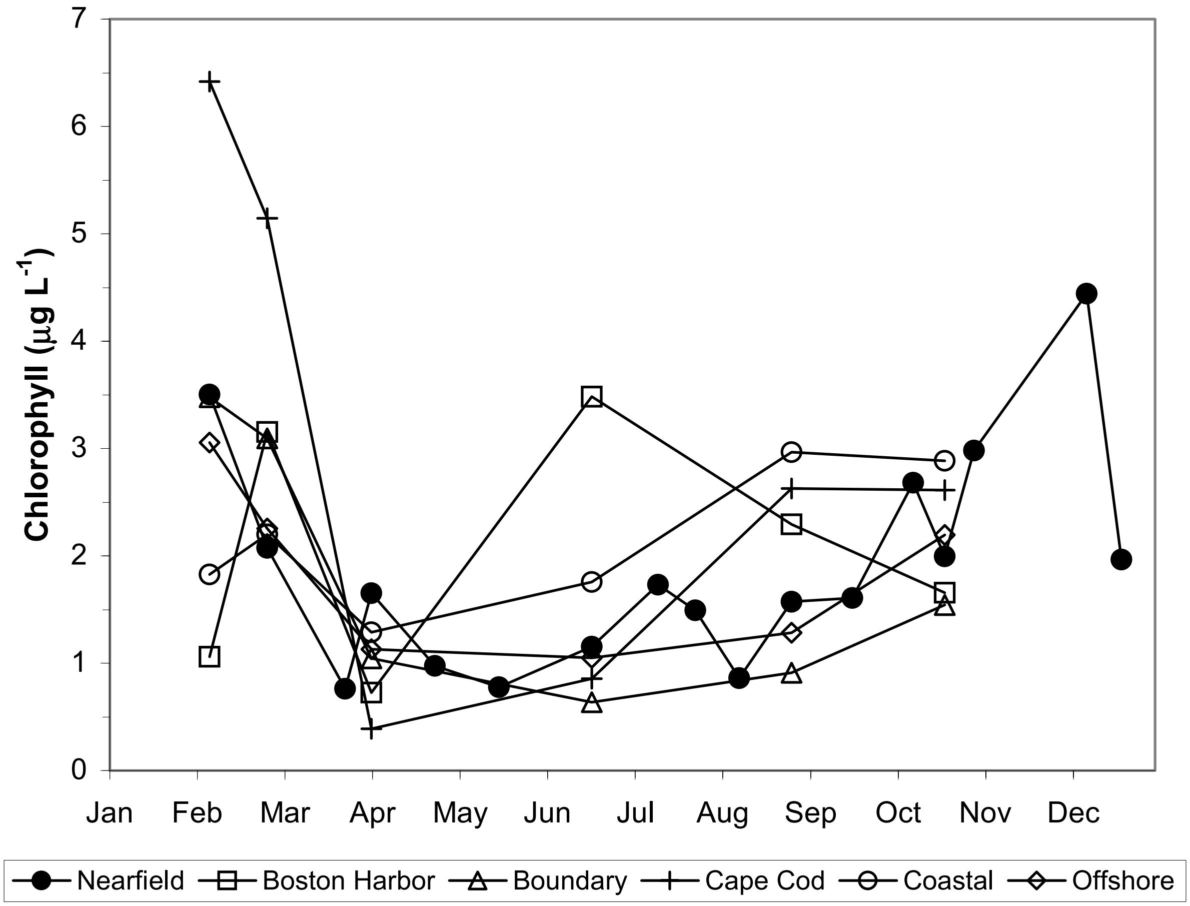


Figure 4-7. Time-series of survey mean chlorophyll concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region.

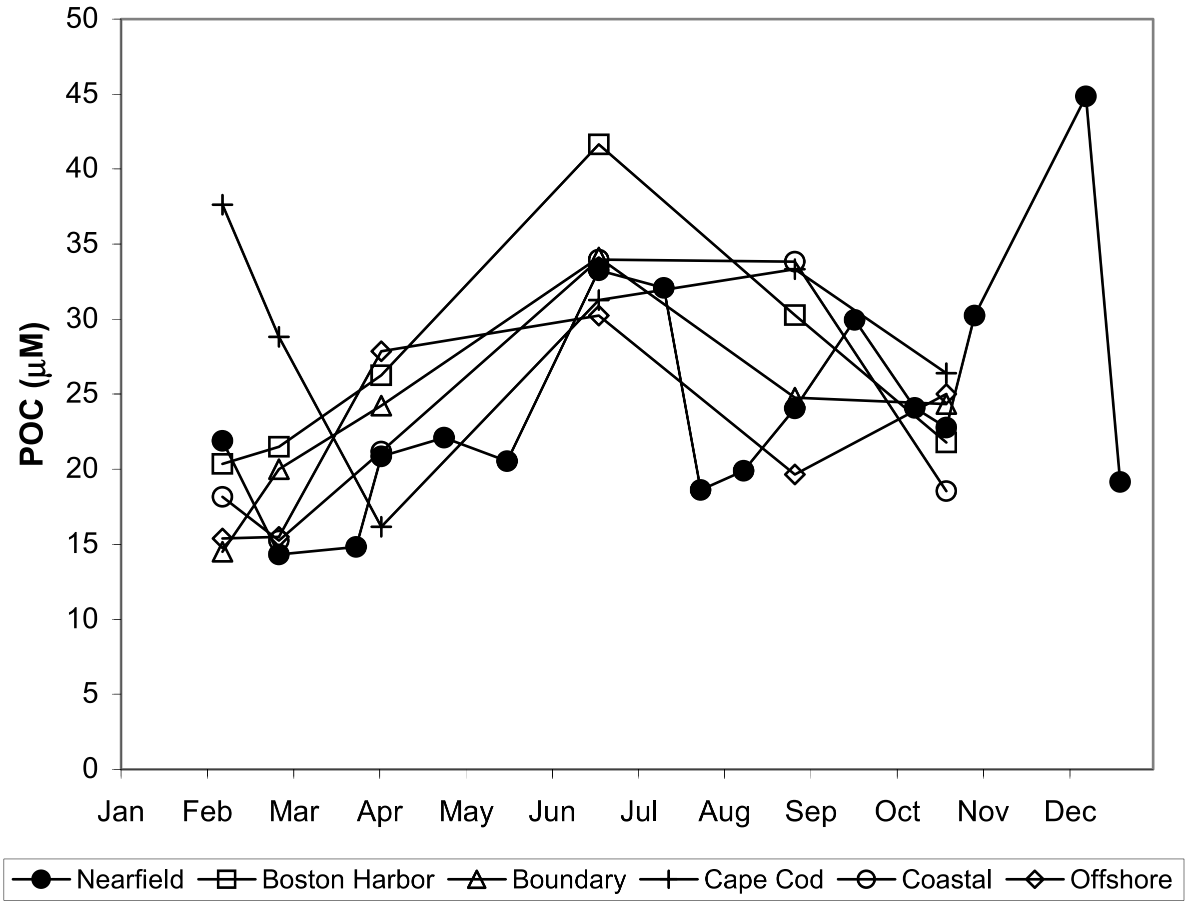


Figure 4-8. Time-series of survey mean POC concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region.

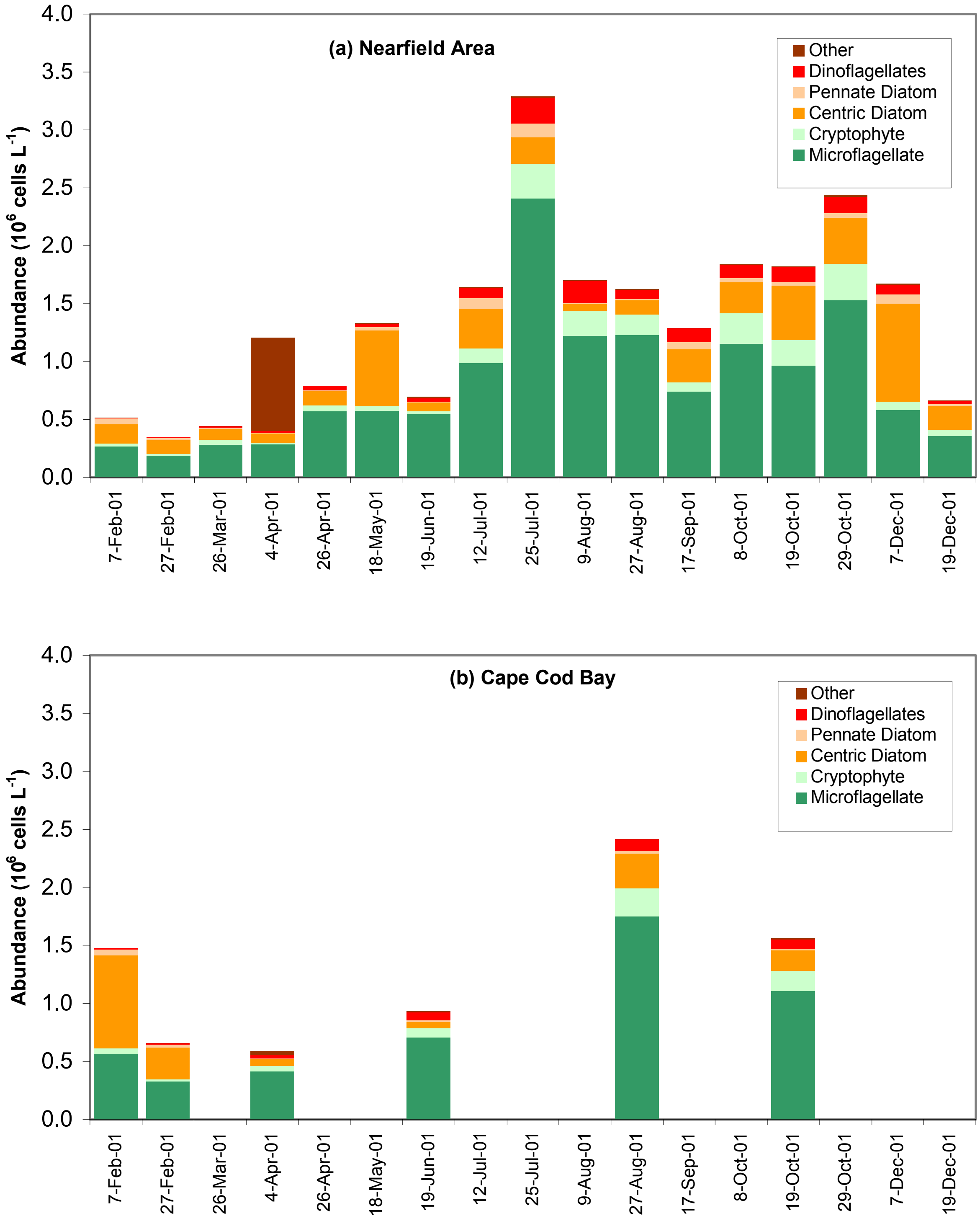
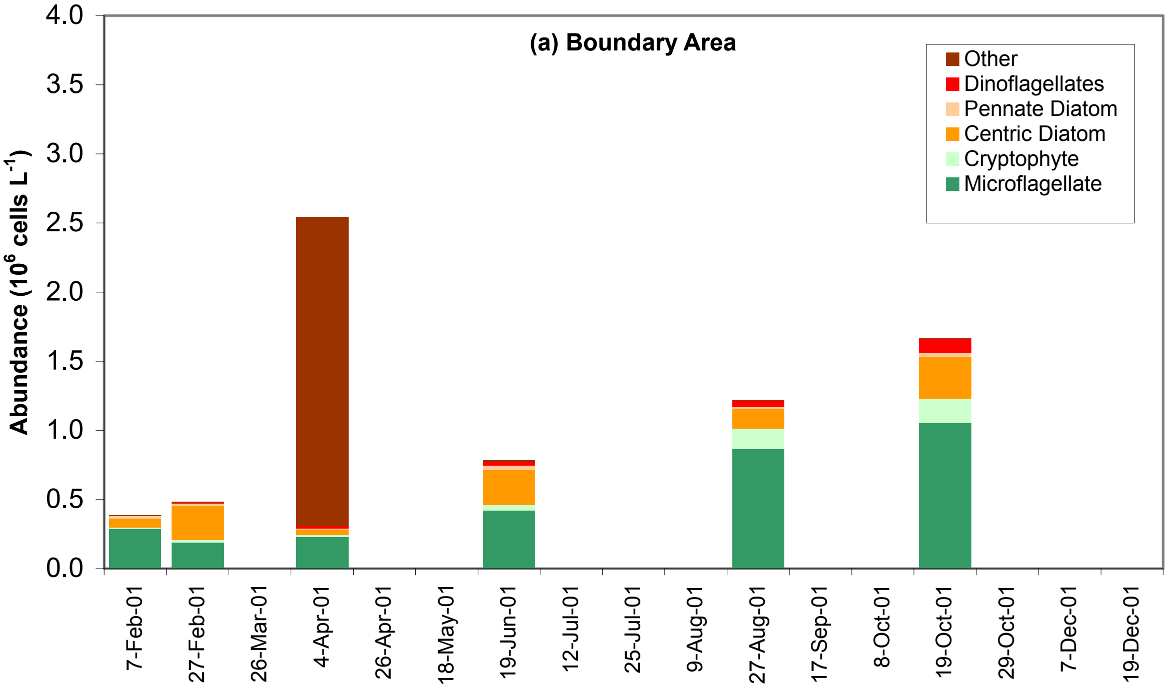


Figure 4-9. Average phytoplankton abundance by major taxonomic group, (a) nearfield area and (b) Cape Cod Bay. Data are average of surface and mid-depth samples from N04, N16, and N18, and F01 and F02, respectively.



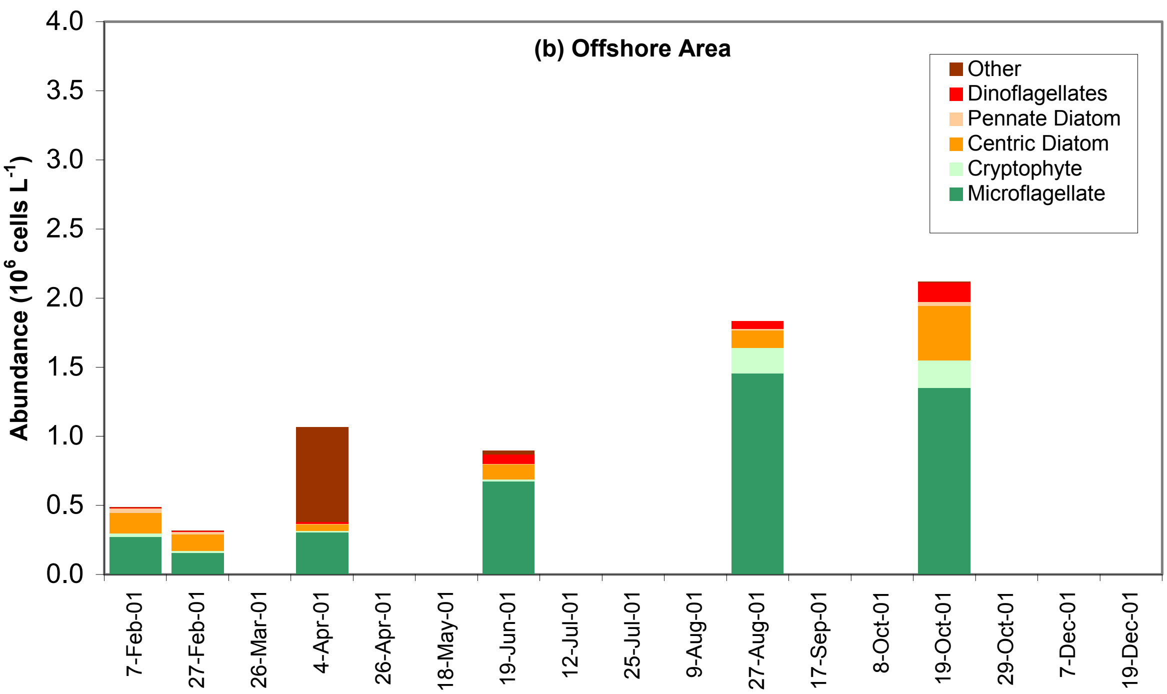


Figure 4-10. Average phytoplankton abundance by major taxonomic group, (a) boundary and (b) offshore area. Data are average of surface and mid-depth samples from F26 and F27, F06 and F22 respectively.

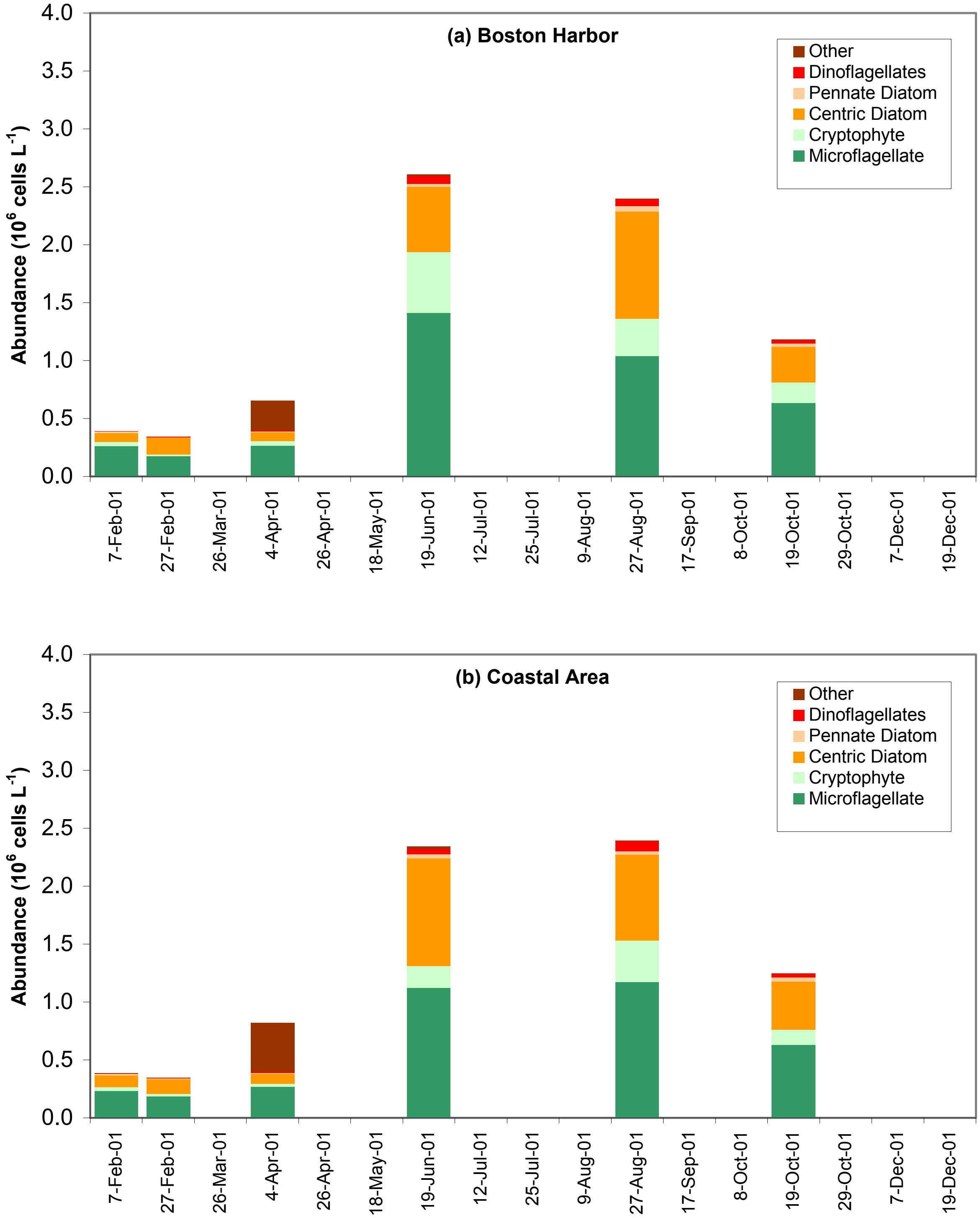


Figure 4-11. Average phytoplankton abundance by major taxonomic group, (a) Boston Harbor and (b) coastal area. Data are average of surface and mid-depth samples from F23, F30, and F31, and F13, F24, and F25, respectively.

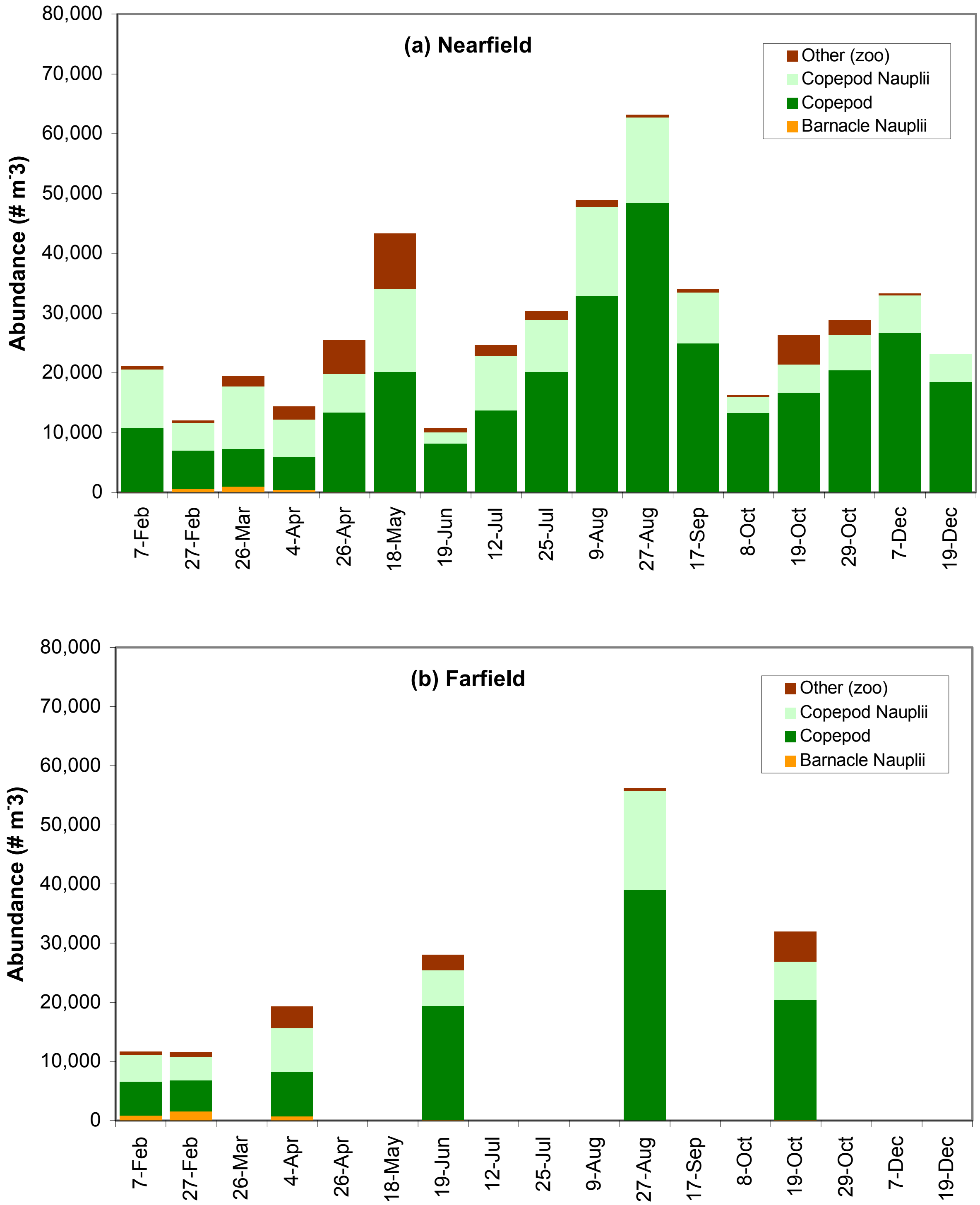


Figure 4-12. Average zooplankton abundance by major taxonomic group, (a) nearfield area and (b) farfield area.

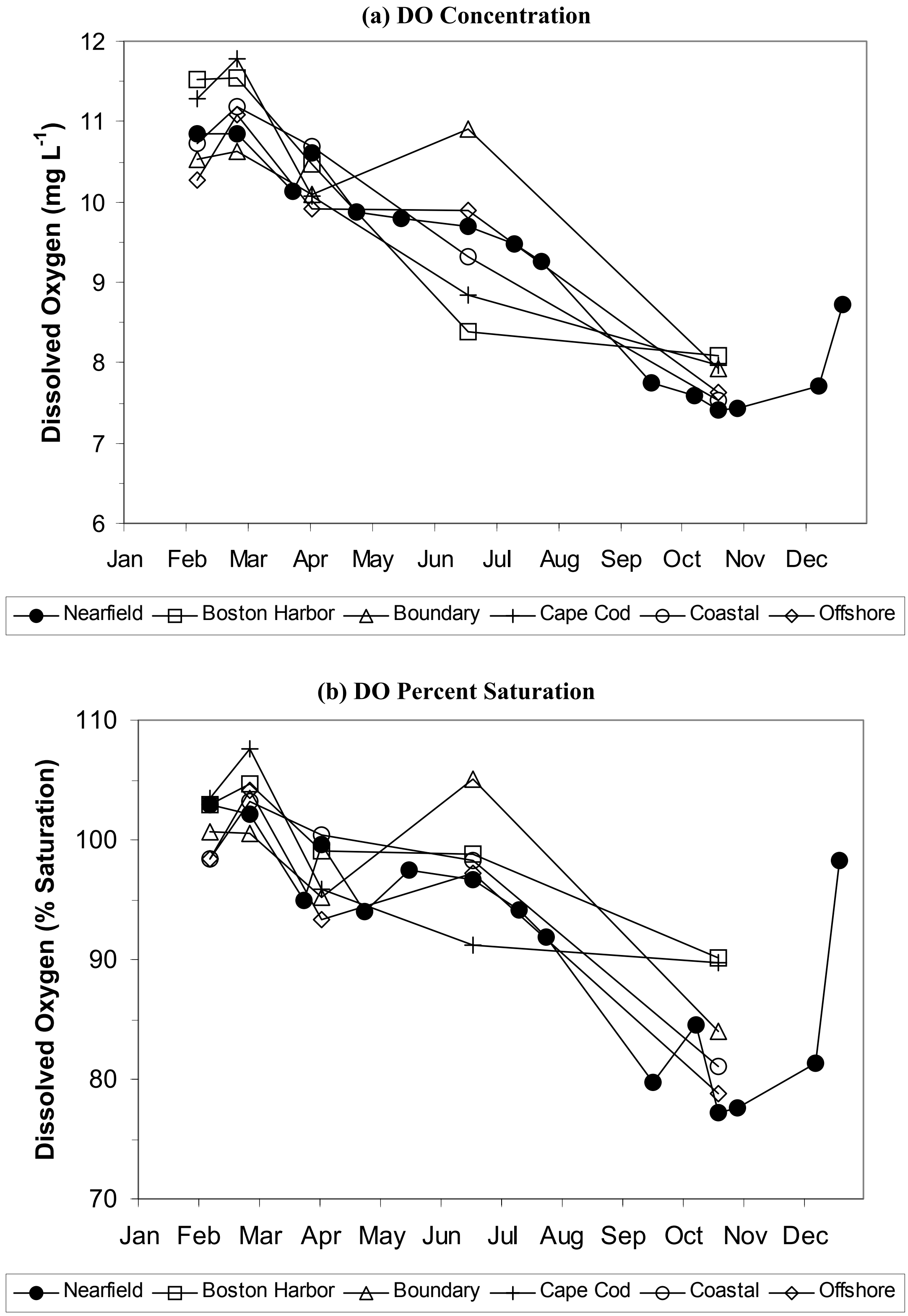
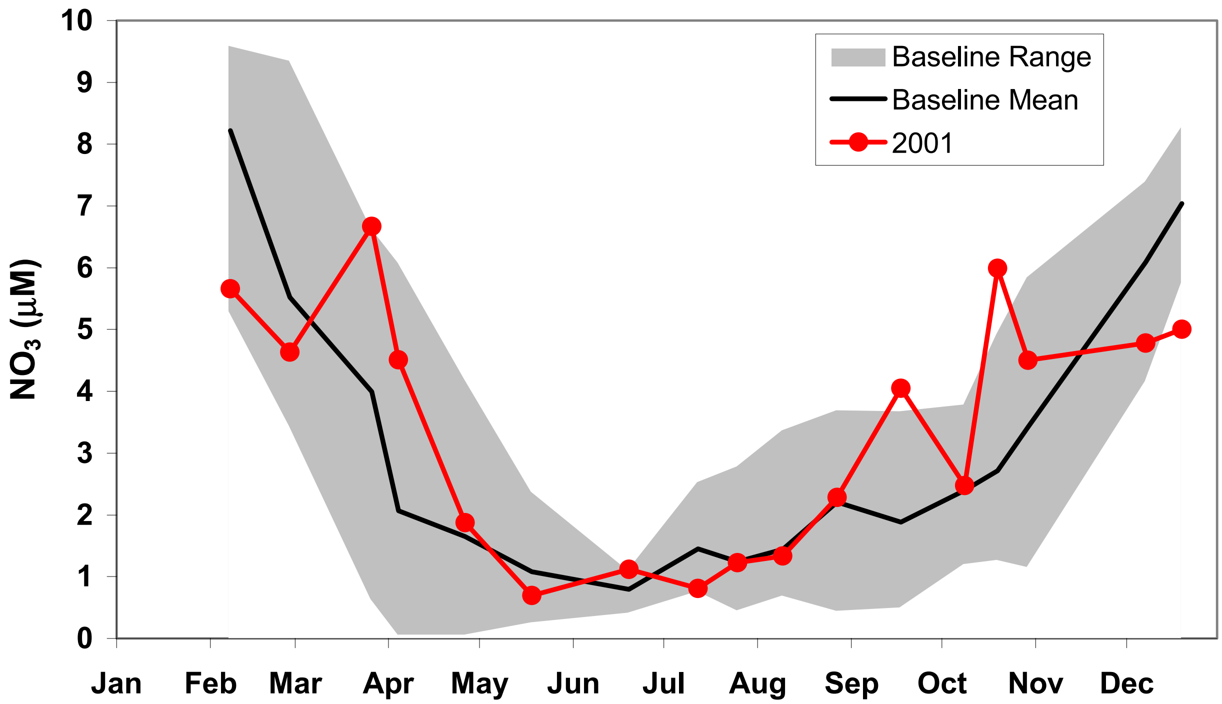


Figure 4-13. Time-series of average bottom dissolved oxygen (a) concentration and (b) percent saturation for 2001 in Massachusetts and Cape Cod Bays (data collected from all stations in the six areas).

(a) Nitrate



(b) Silicate

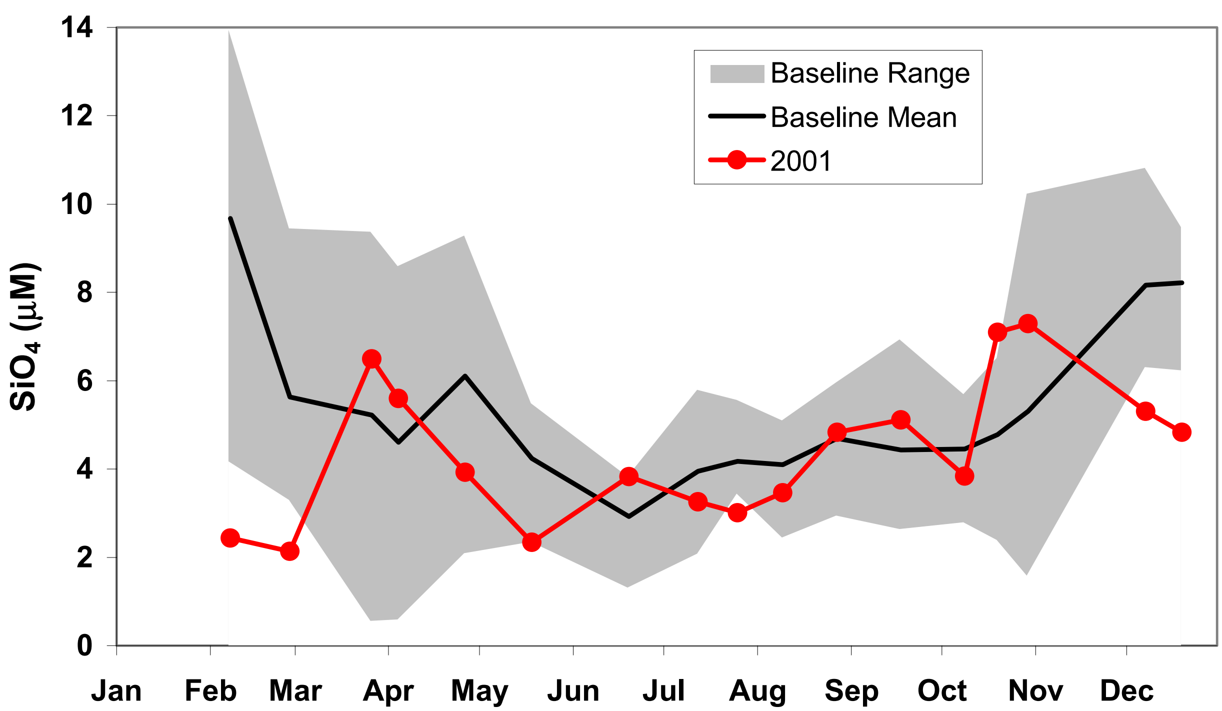


Figure 4-14. Time-series of survey mean (a) NO_3 and (b) SiO_4 concentrations in the nearfield in 2001 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.

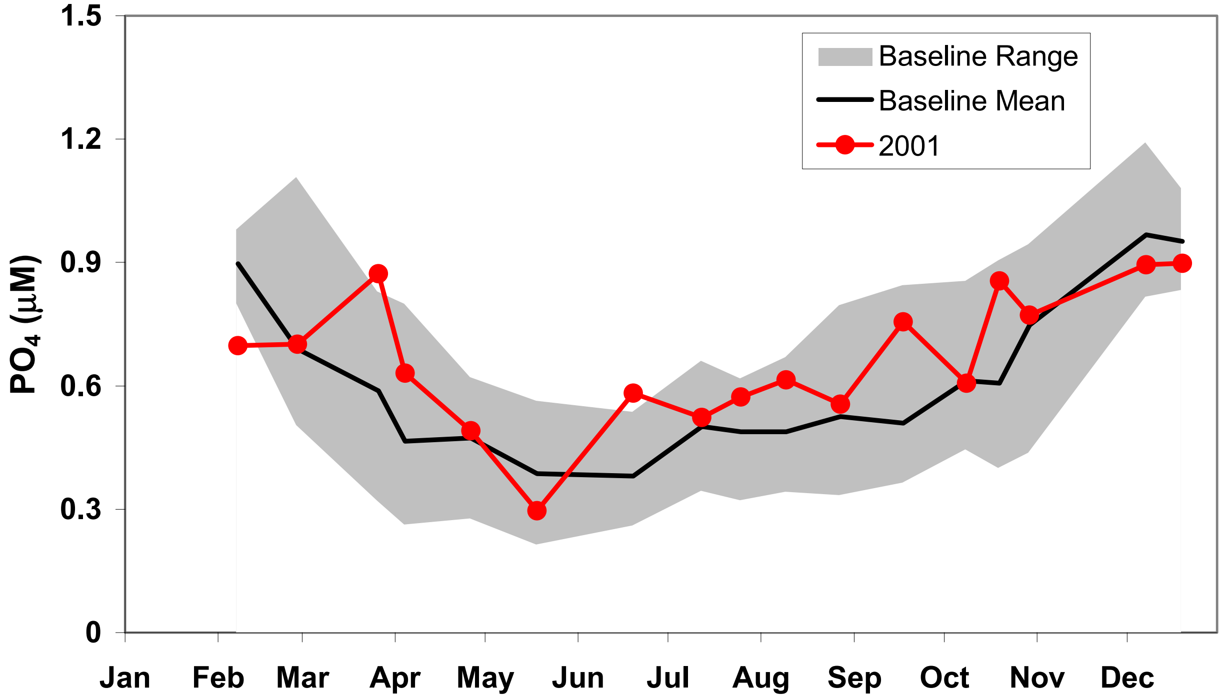
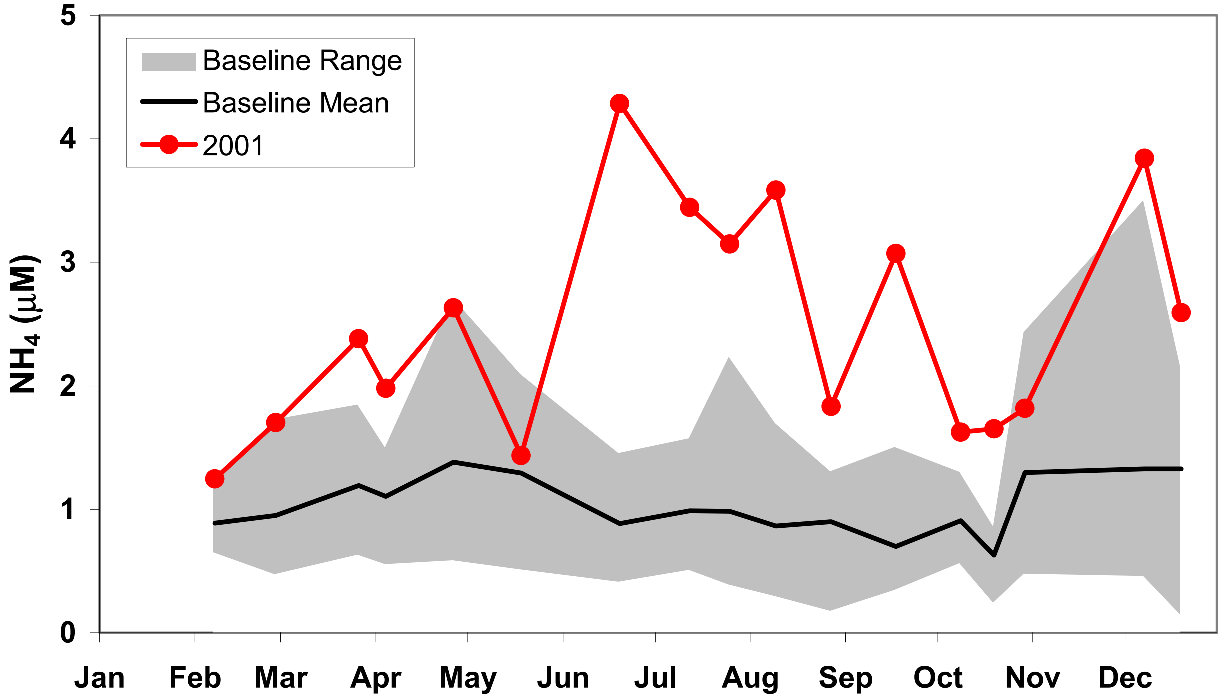


Figure 4-15. Time-series of survey mean PO_4 concentration in the nearfield in 2001 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.

(a) Nearfield



(b) Boston Harbor

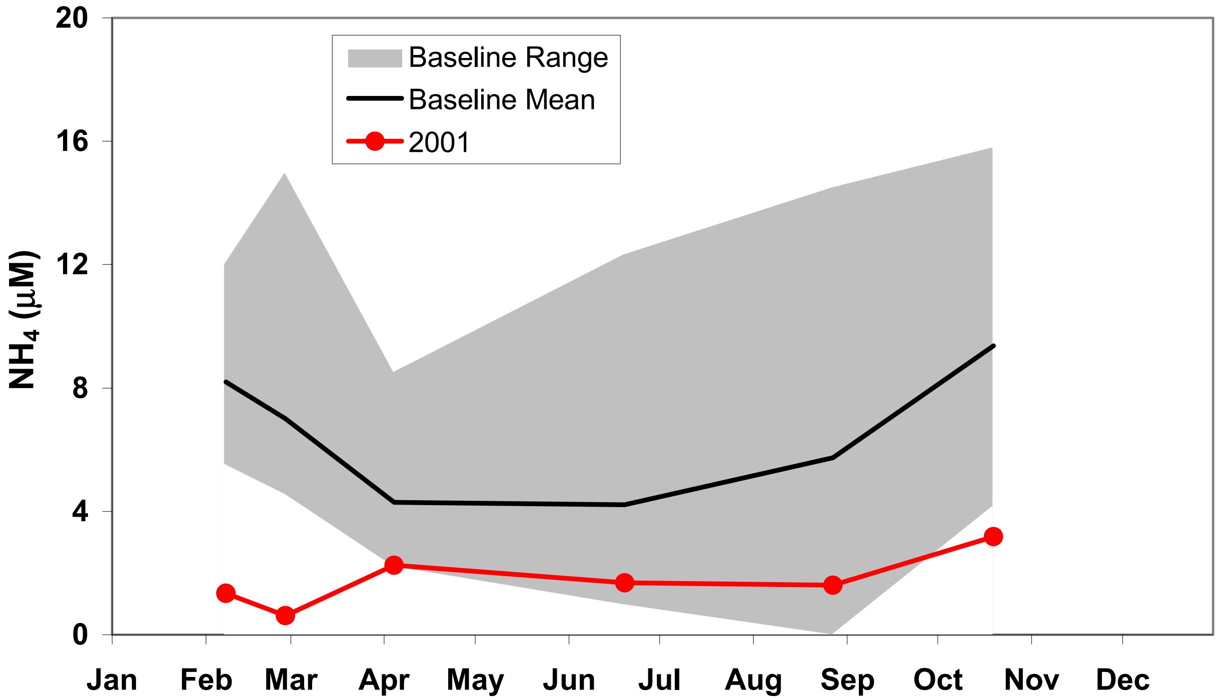


Figure 4-16. Time-series of survey mean NH_4 concentrations in (a) the nearfield and (b) Boston Harbor in 2001 compared against the baseline range and mean. Data collected from all depths and all nearfield stations. Note change in axis between nearfield and harbor plots.

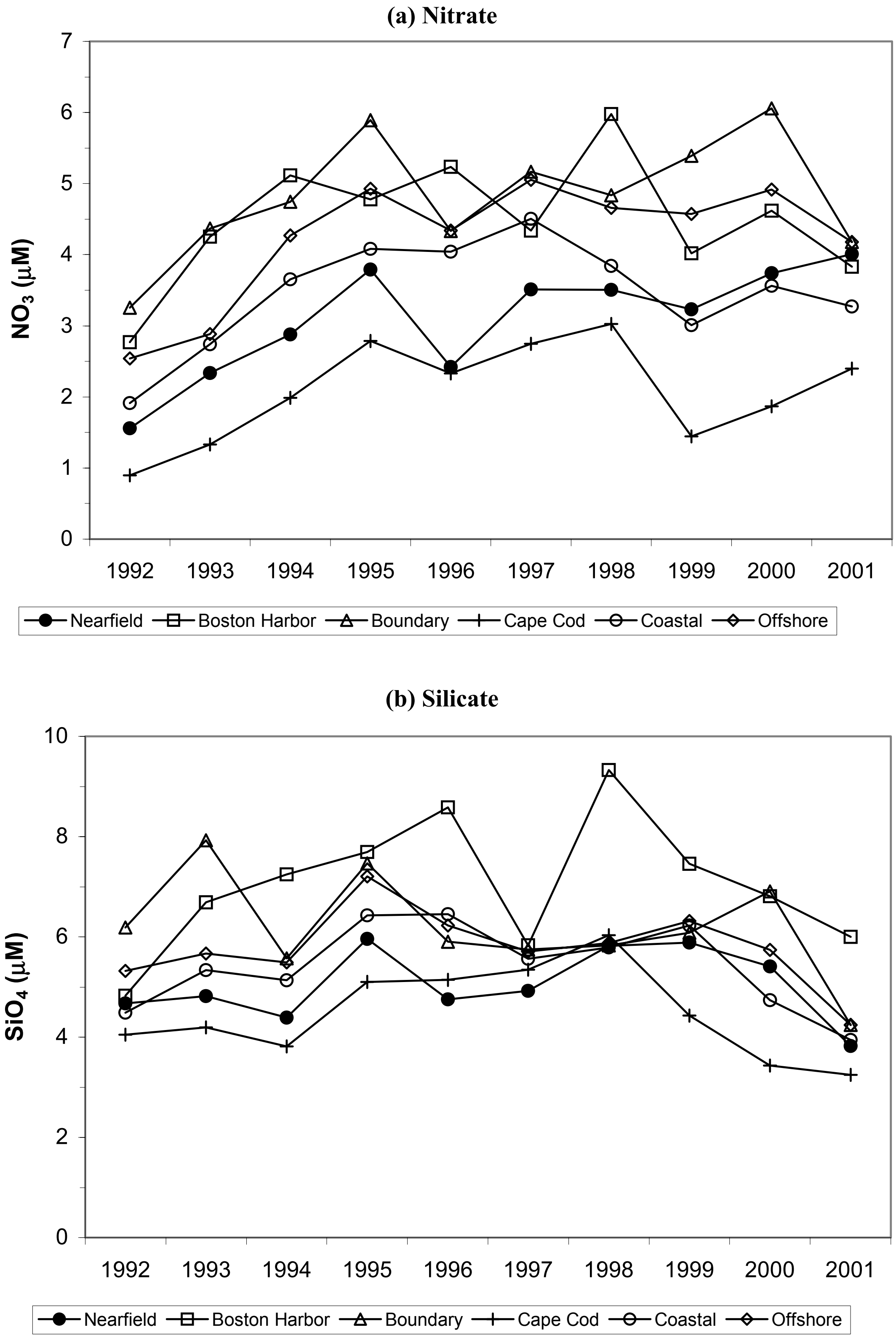
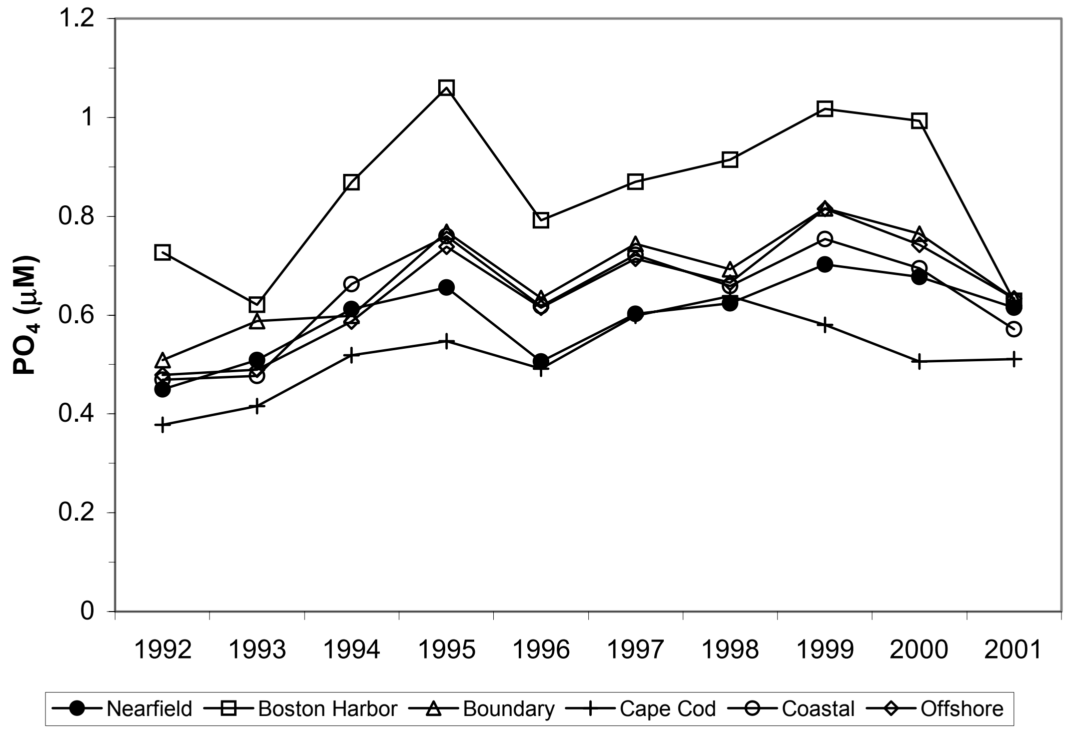


Figure 4-17. Annual mean (a) NO_3 and (b) SiO_4 concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

(a) Phosphate



(b) Ammonium

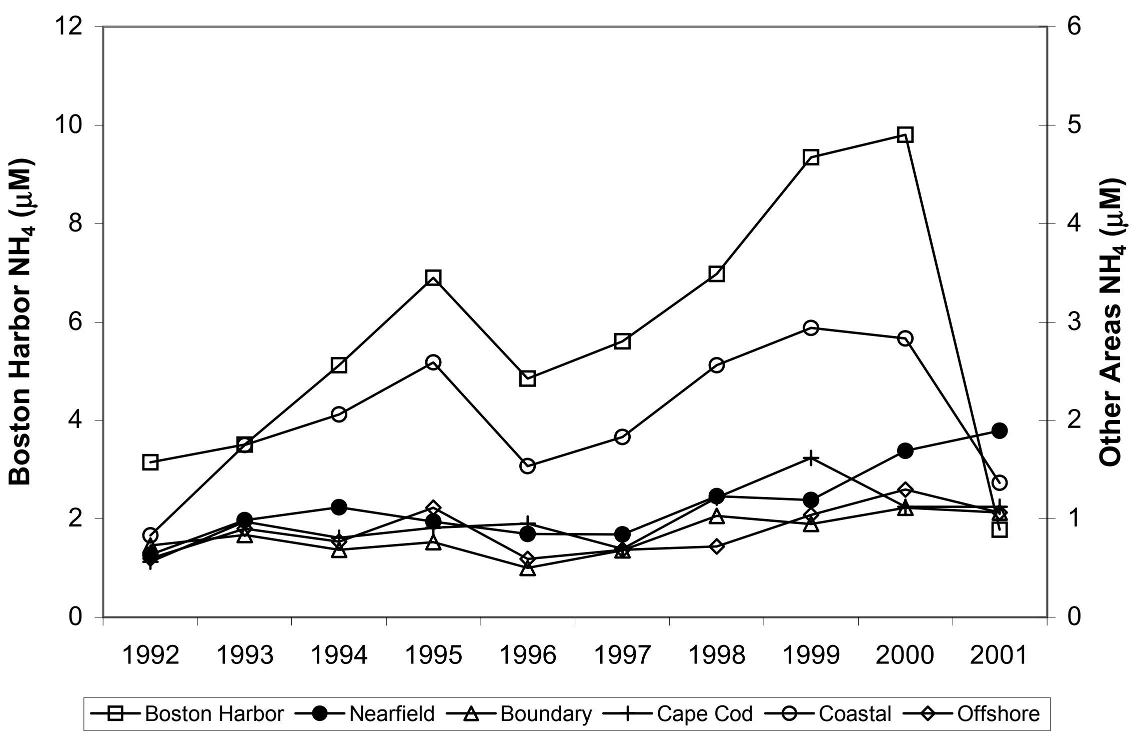
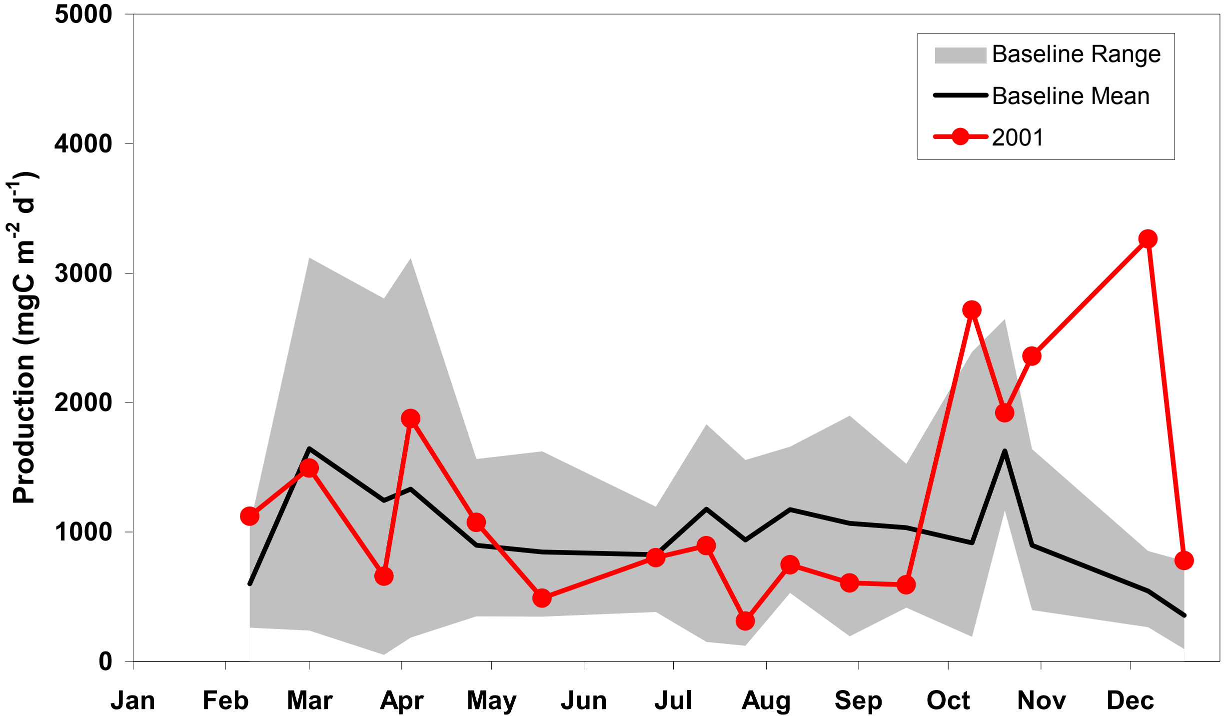


Figure 4-18. Annual mean (a) PO_4 and (b) NH_4 concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

(a) Station N04



(b) Station N18

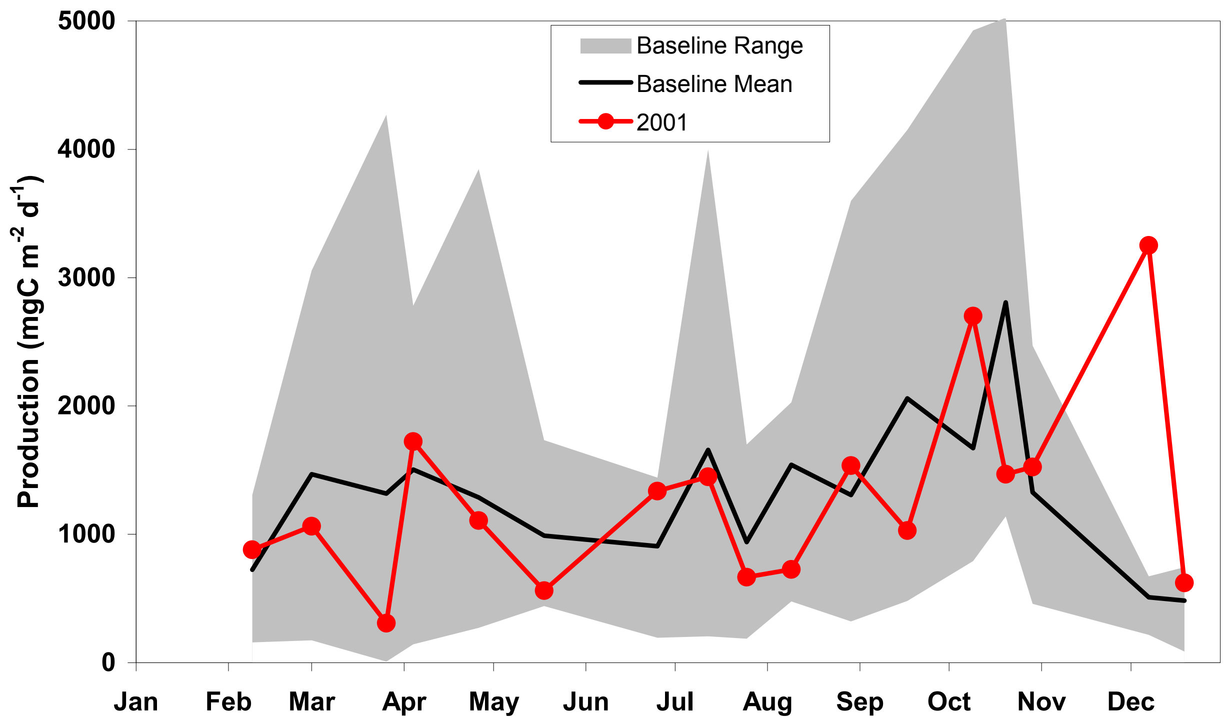


Figure 4-19. Time-series of areal production ($mgCm^{-2}d^{-1}$) at nearfield stations (a) N04 and (b) N18 for 2001 compared against the baseline range and mean.

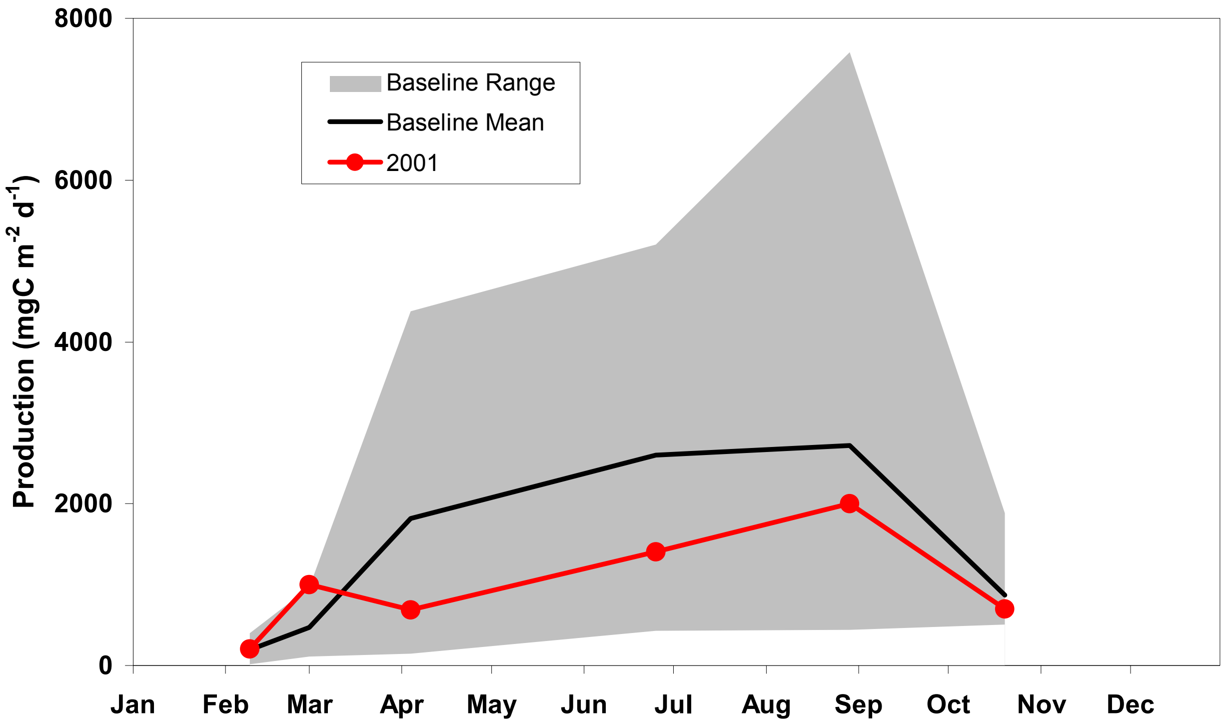


Figure 4-20. Time-series of areal production (mgCm^{-2}d^{-1}) at Boston Harbor station F23 for 2001 compared against the baseline range and mean.

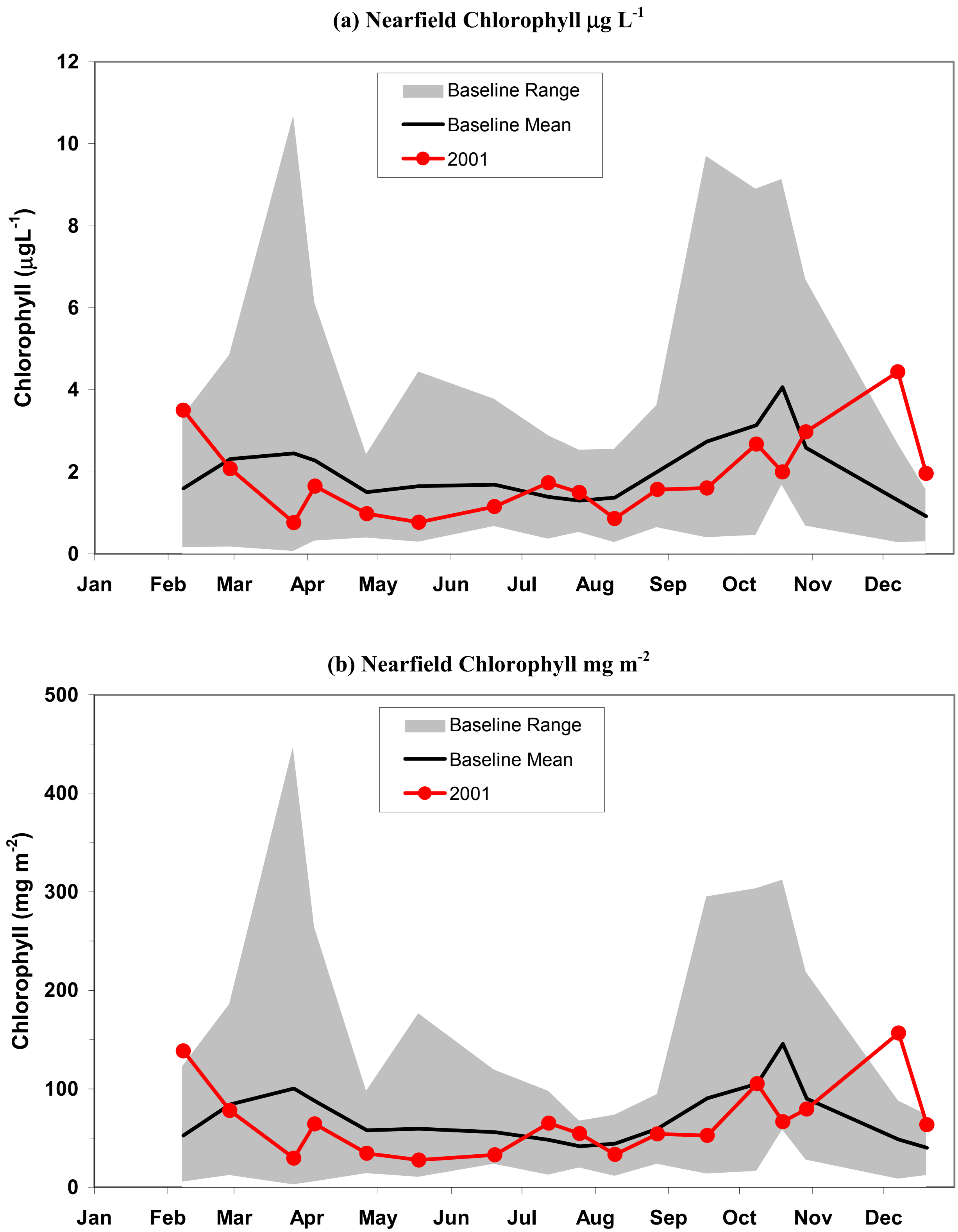


Figure 4-21. Time-series of survey mean chlorophyll (a) volumetric and (b) areal concentrations in the nearfield in 2001 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.

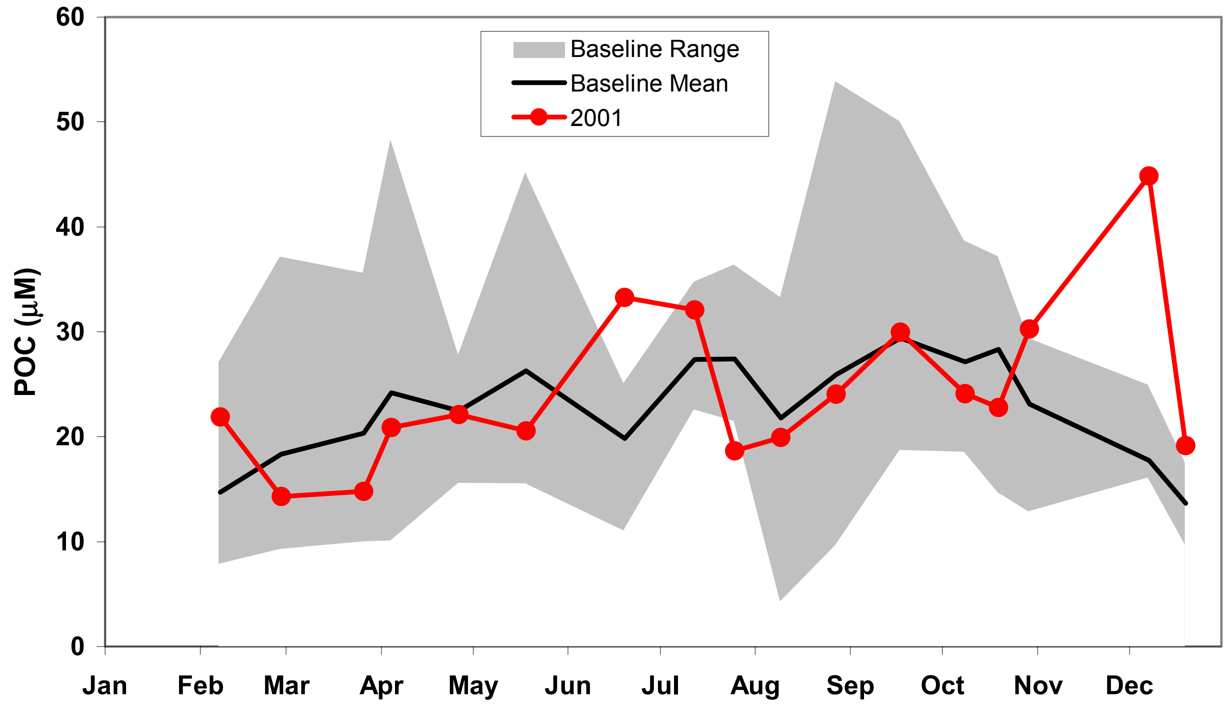
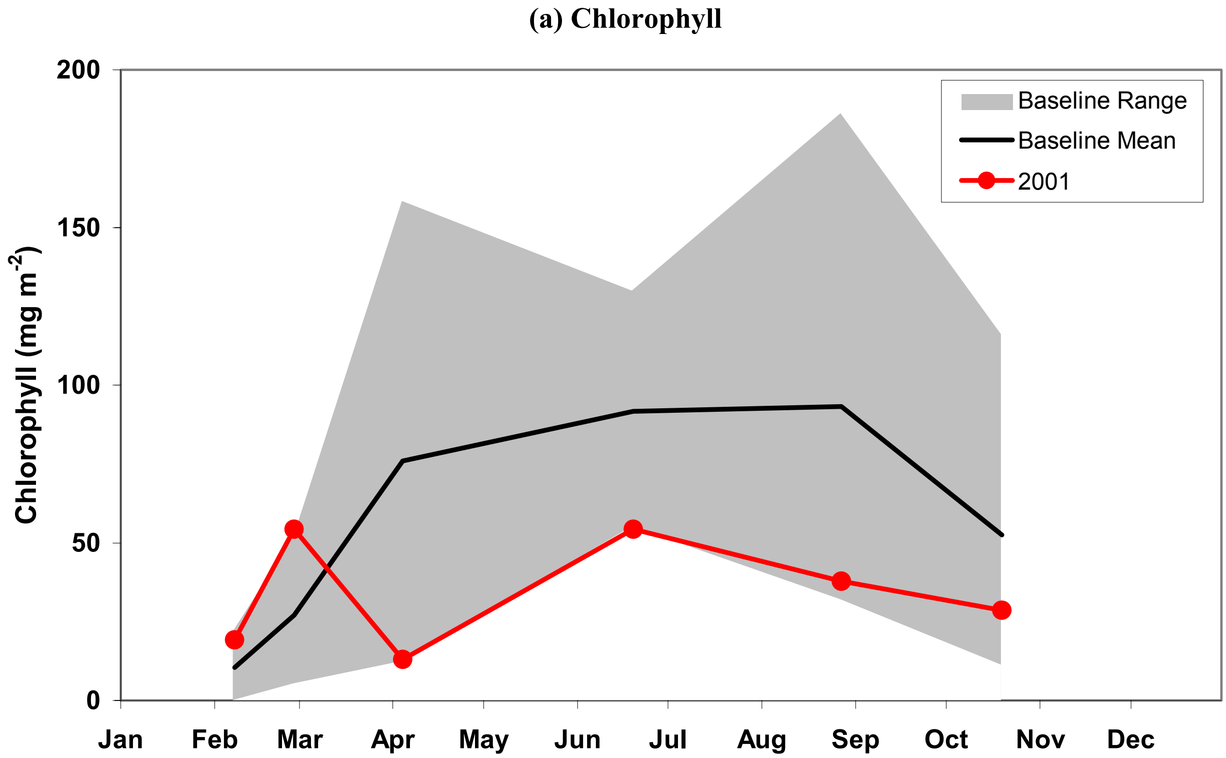


Figure 4-22. Time-series of survey mean POC concentrations in the nearfield in 2001 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.



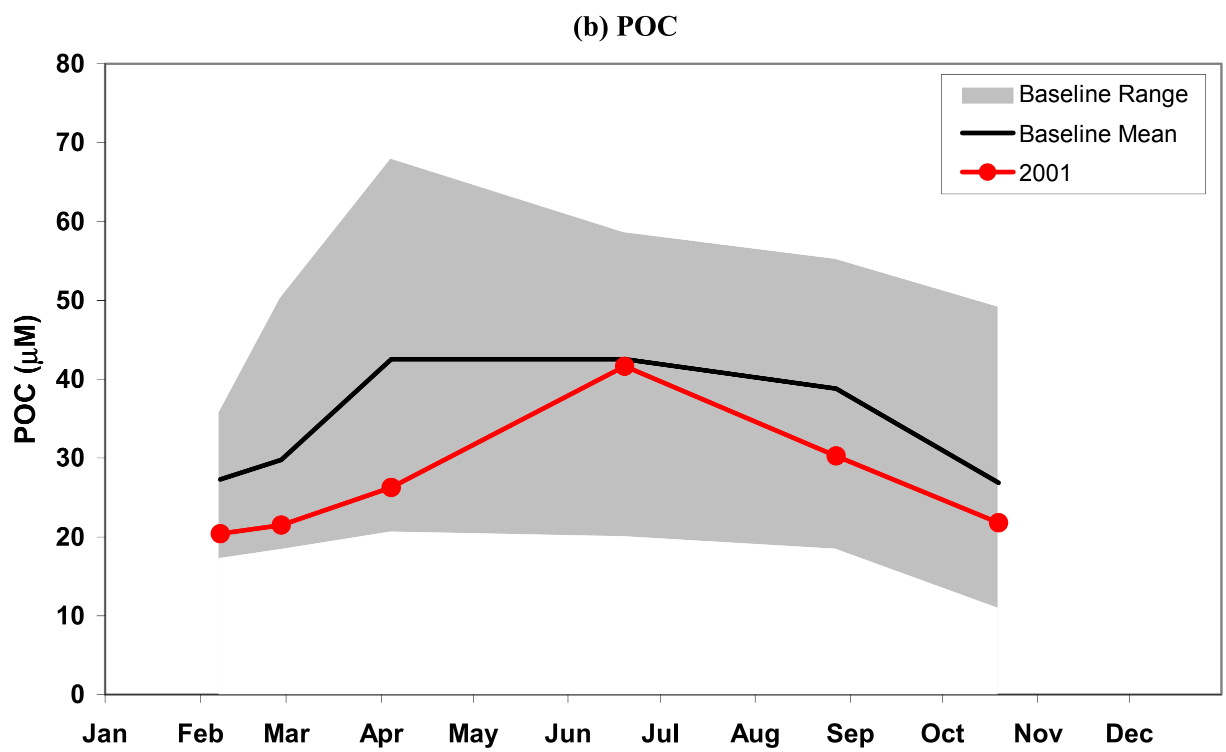
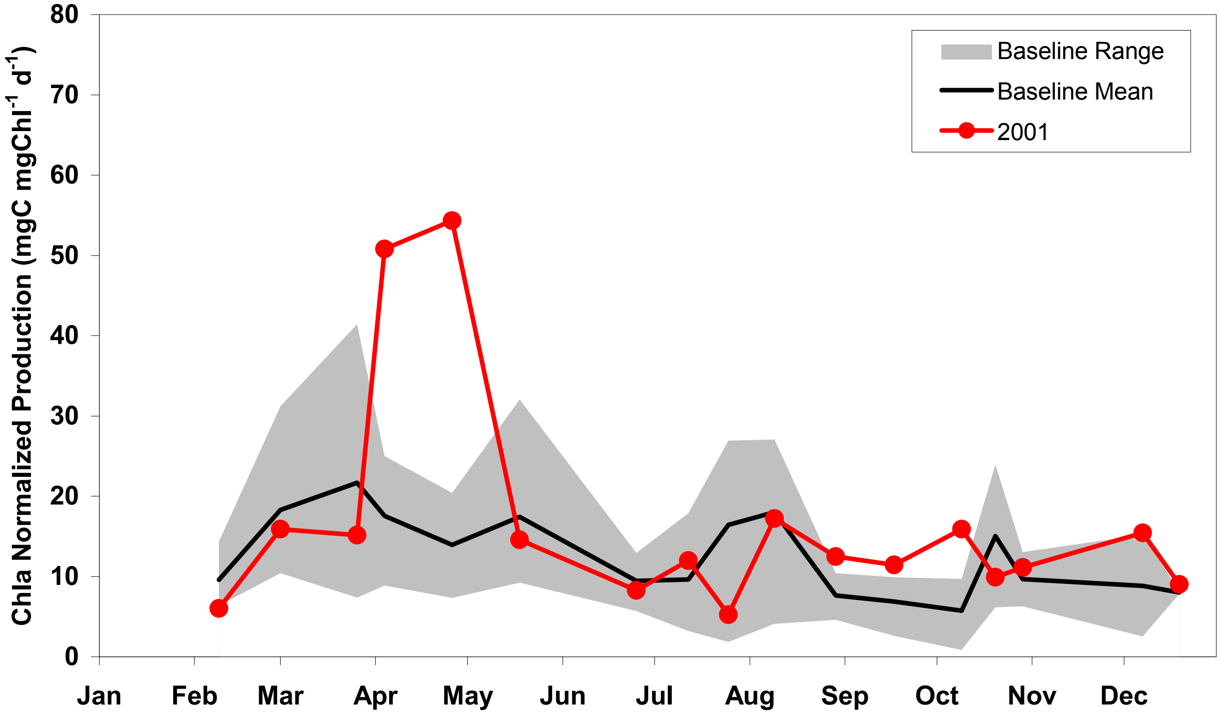


Figure 4-23. Time-series of survey mean (a) chlorophyll and (b) POC concentrations in Boston Harbor in 2001 compared against the baseline range and mean. Data collected from all depths and all harbor stations.

(a) Station N04



(b) Station N18

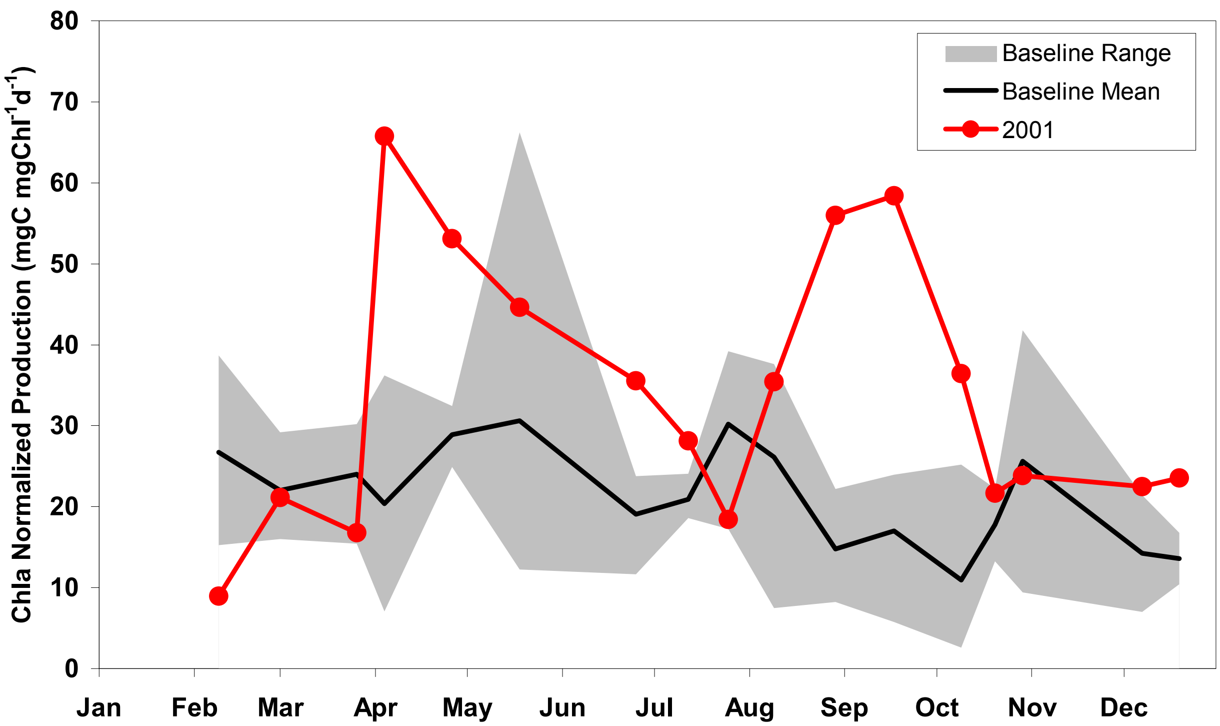


Figure 4-24. Time-series of depth-averaged chlorophyll-specific production (mgCmgChla^{-1}d^{-1}) at nearfield stations (a) N04 and (b) N18 for 2001 compared against the baseline range and mean.

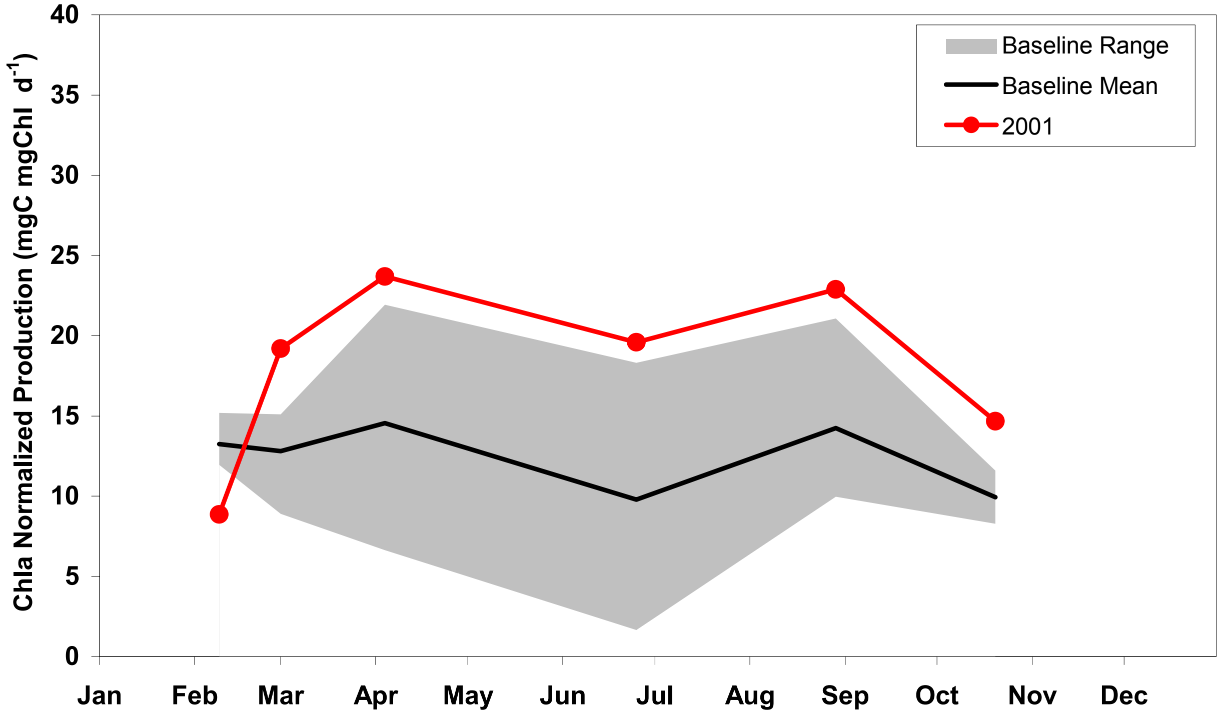


Figure 4-25. Time-series of depth-averaged chlorophyll-specific production (mgCmgChla^{-1}d^{-1}) at Boston Harbor station F23 for 2001 compared against the baseline range and mean.

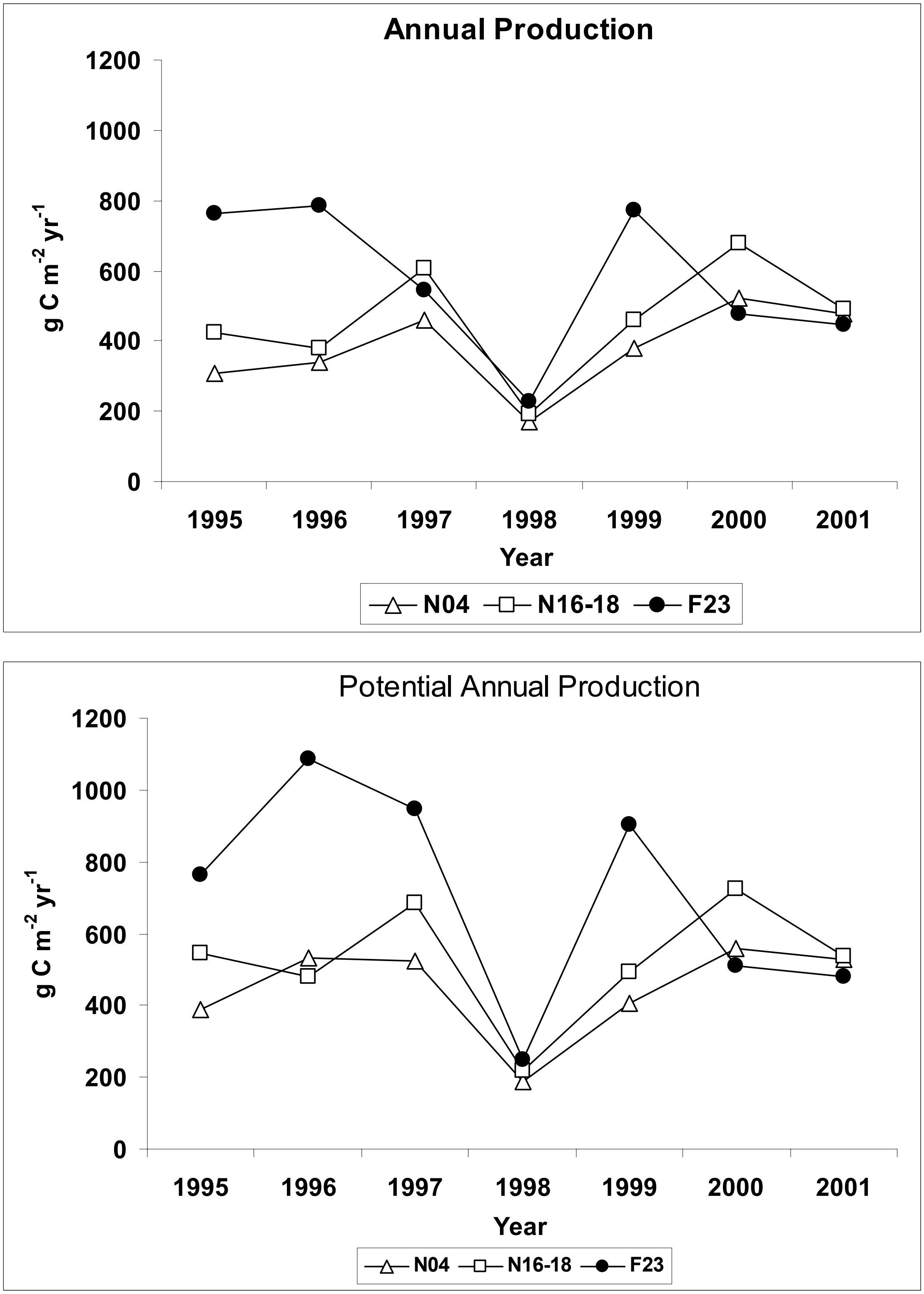


Figure 4-26. Annual measured and potential production (g C $m^{-2}yr^{-1}$) for stations F23, N04, and N16/N18 from 1995–2001.

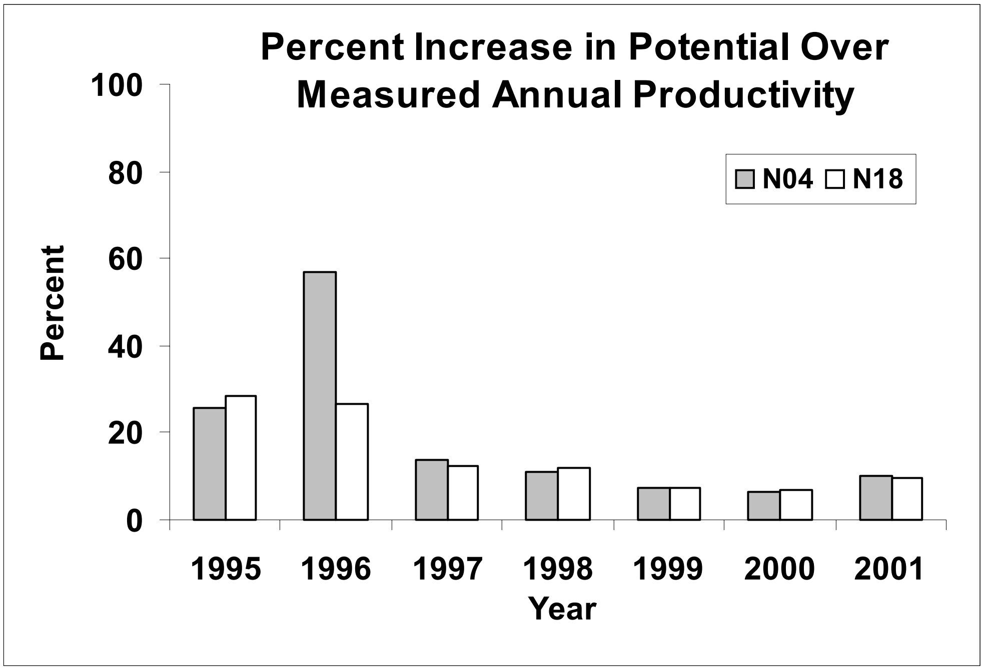
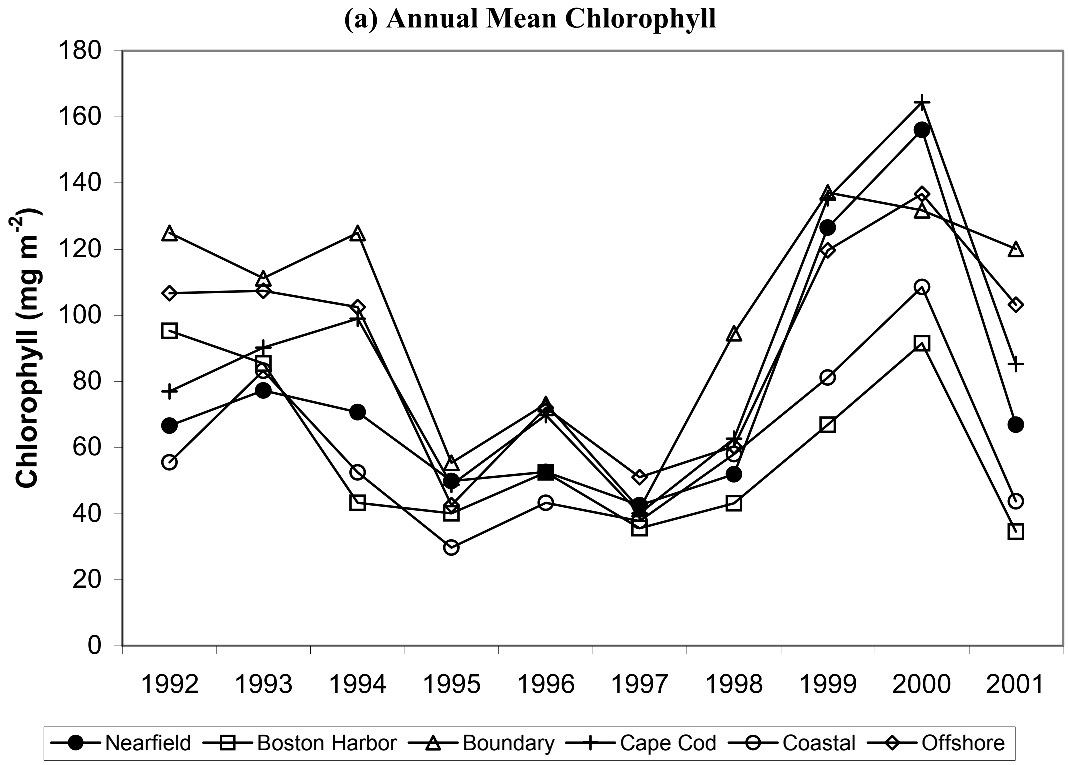


Figure 4-27. Percent increase in potential over measured annual production for stations N04 and N16/N18 from 1995–2001.



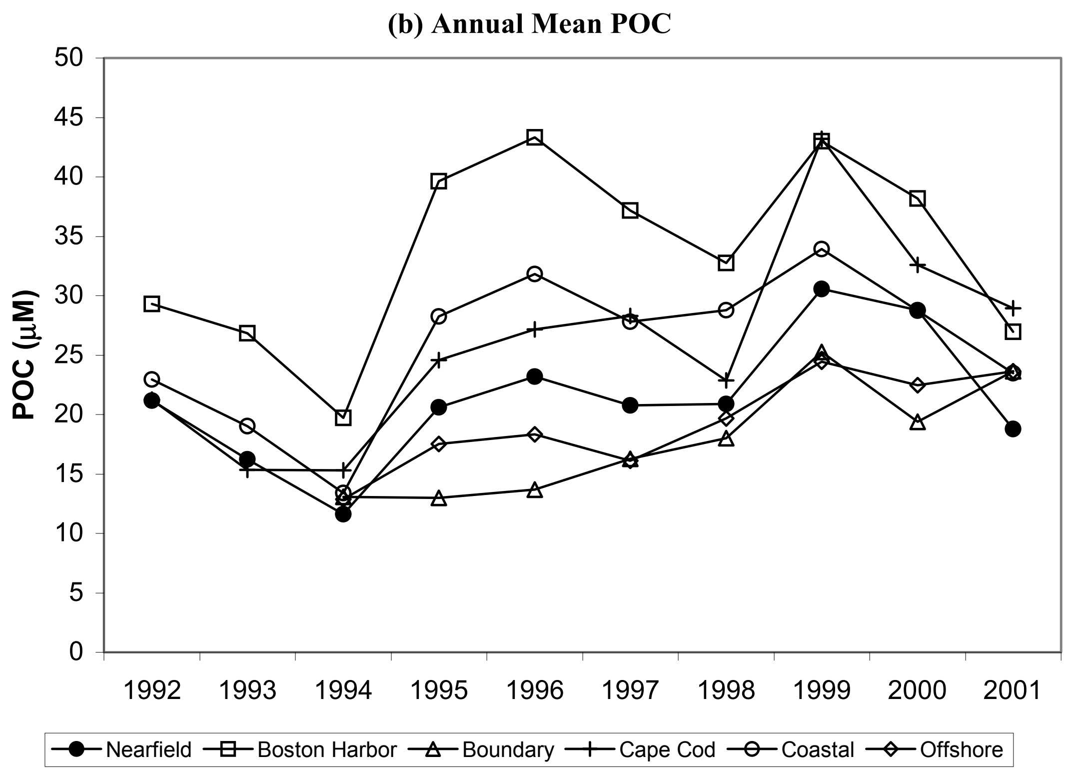


Figure 4-28. Annual mean (a) chlorophyll and (b) POC concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

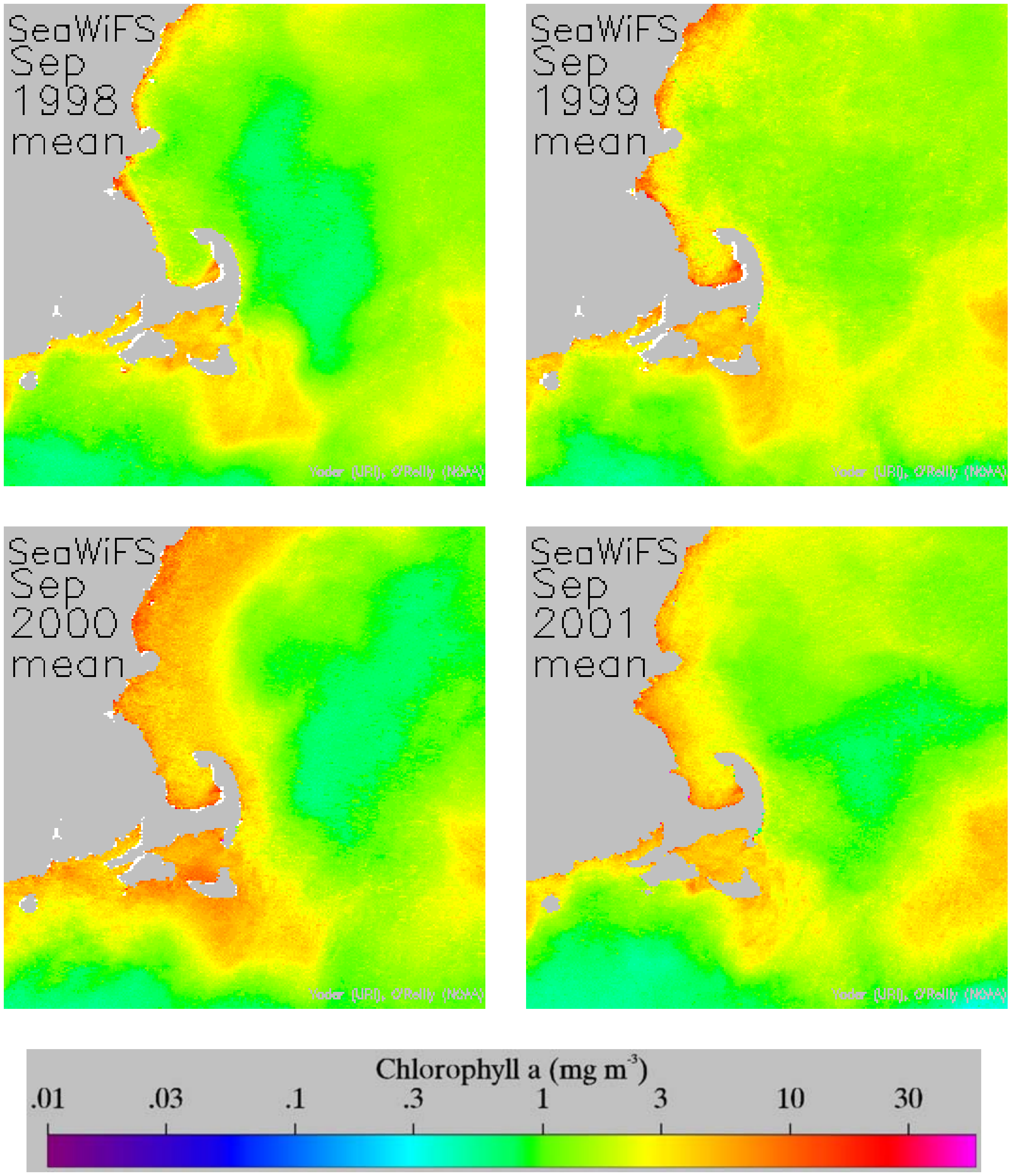
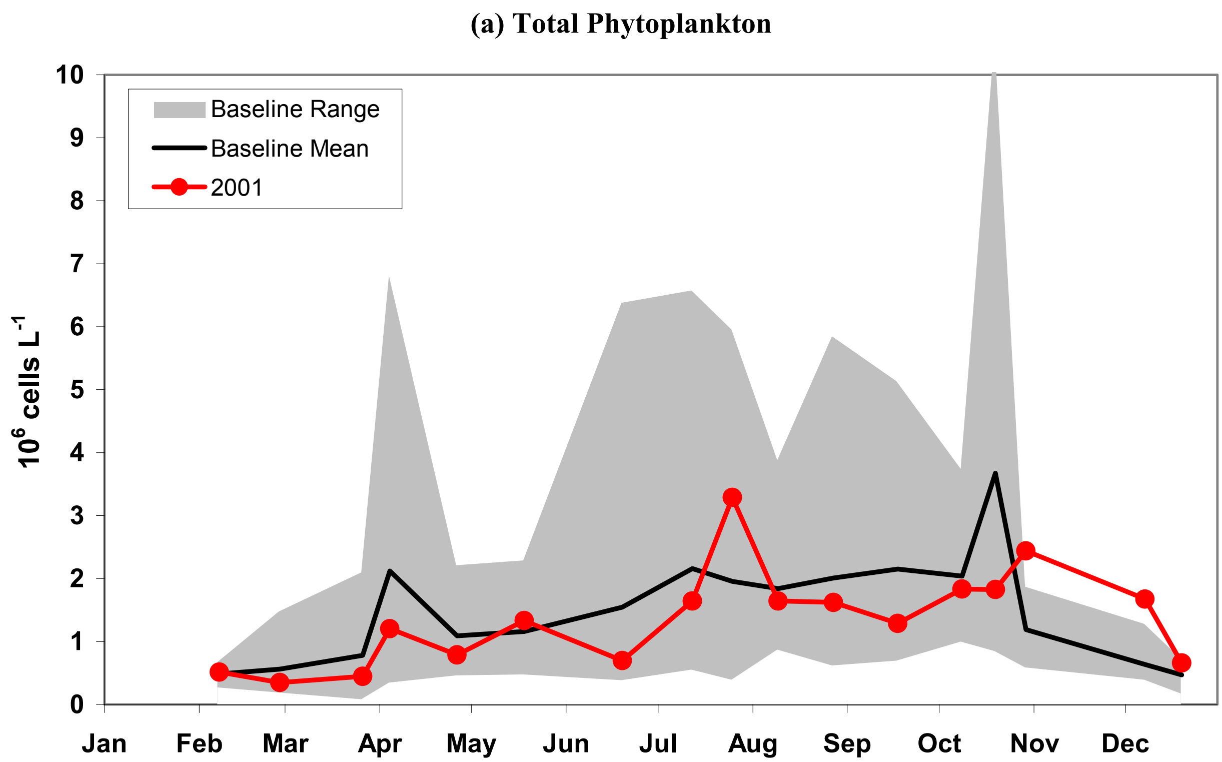


Figure 4-29. Monthly composite of SeaWiFS chlorophyll images for the southwestern Gulf of Maine for September in 1998 to 2001 [J. Yoder (URI) and J. O'Reilly (NOAA)].



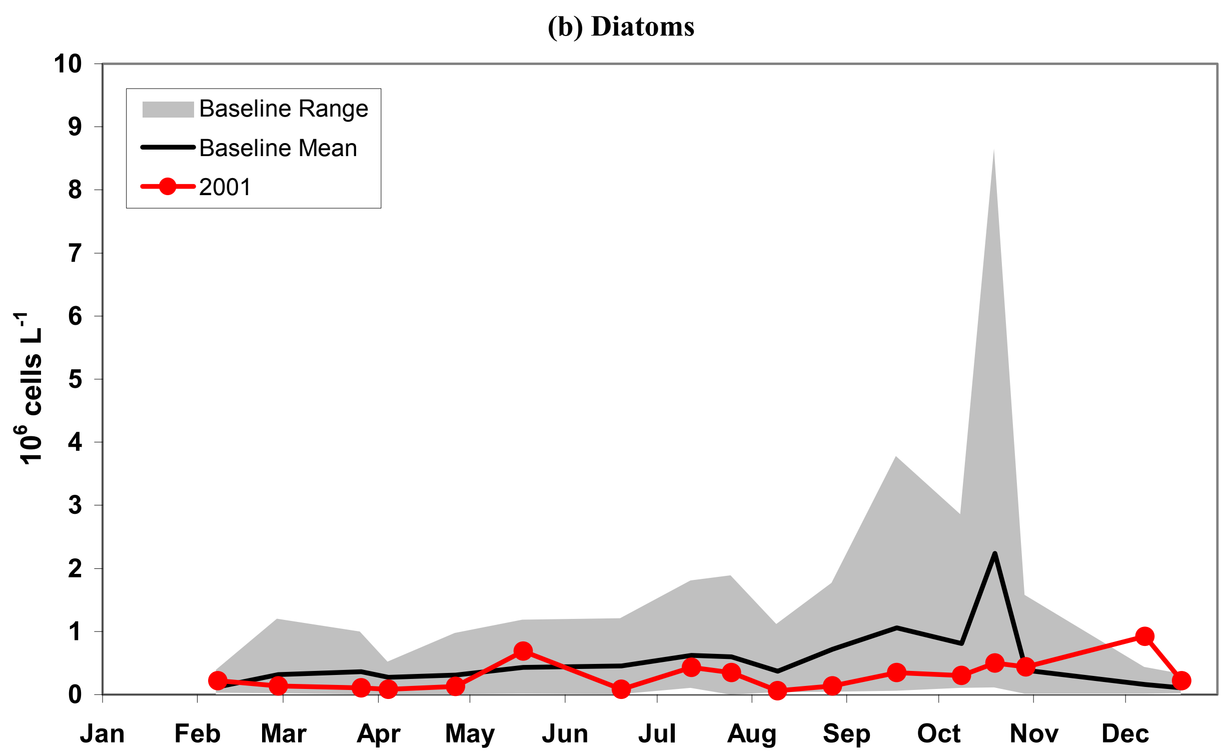


Figure 4-30. Time-series of survey mean (a) total phytoplankton and (b) diatom abundance in the nearfield in 2001 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled.

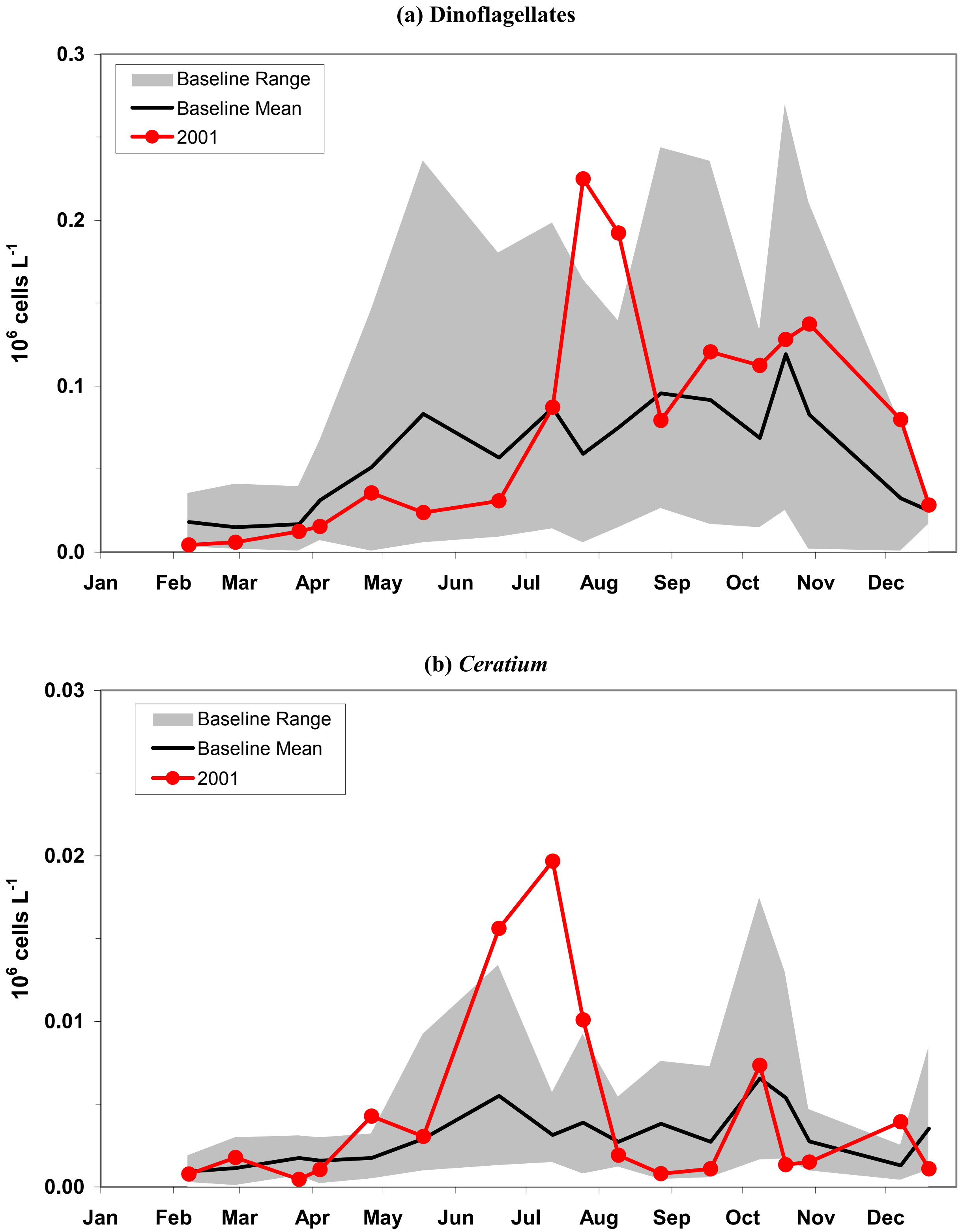


Figure 4-31. Time-series of survey mean (a) dinoflagellate and (b) *Ceratium* abundance in the nearfield in 2001 compared against the baseline range and mean. Data from 20-µm screened samples collected from both surface and mid depths, and all nearfield stations sampled.

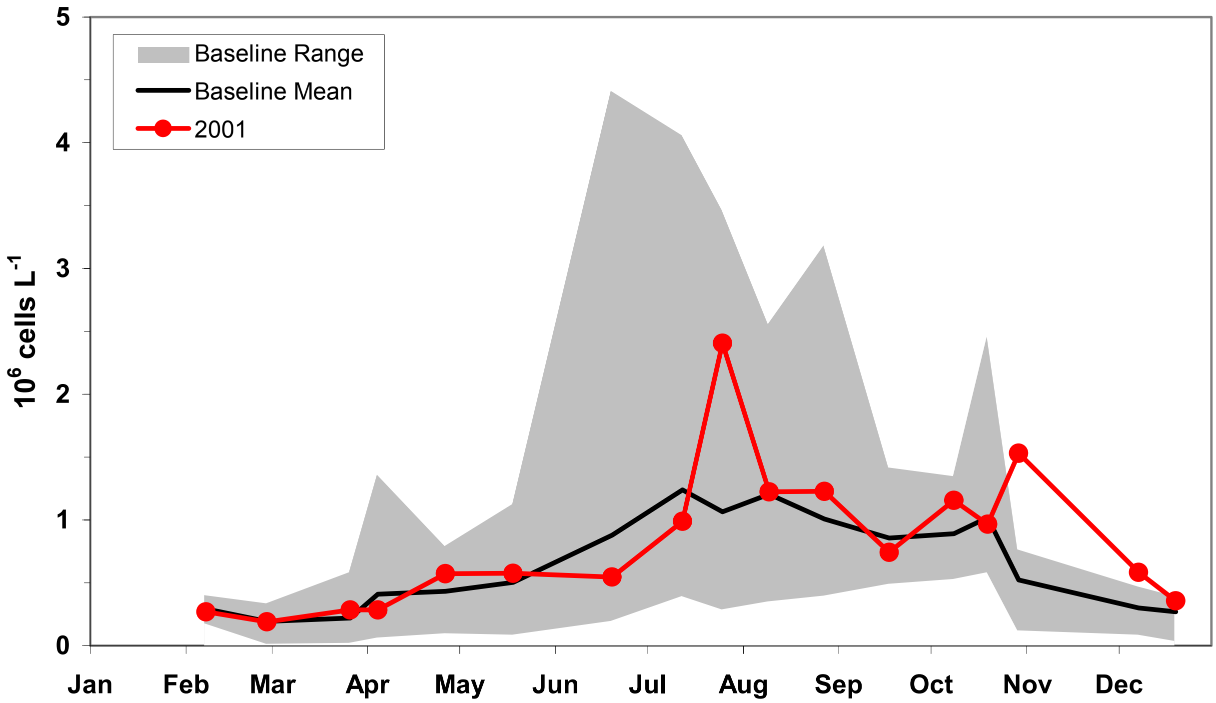


Figure 4-32. Time-series of survey mean microflagellate abundance in the nearfield in 2001 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled.

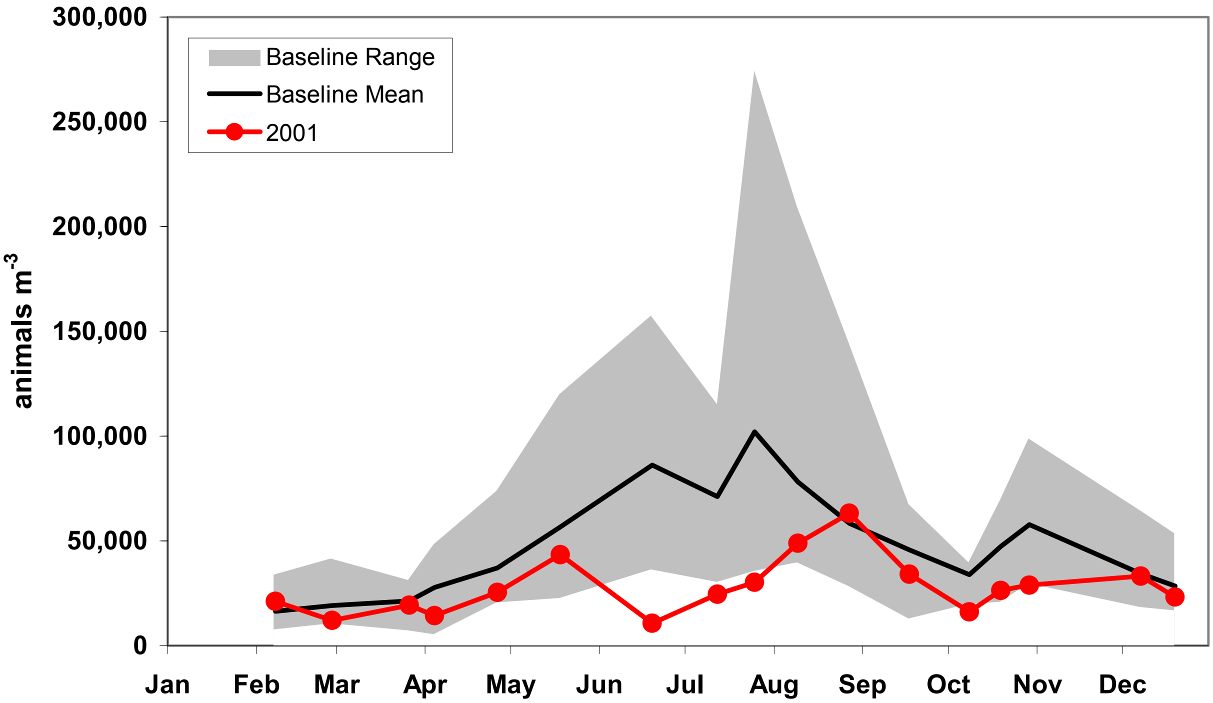


Figure 4-33. Time-series of survey mean zooplankton abundance in the nearfield in 2001 compared against the baseline range and mean. Data collected from all nearfield stations sampled.

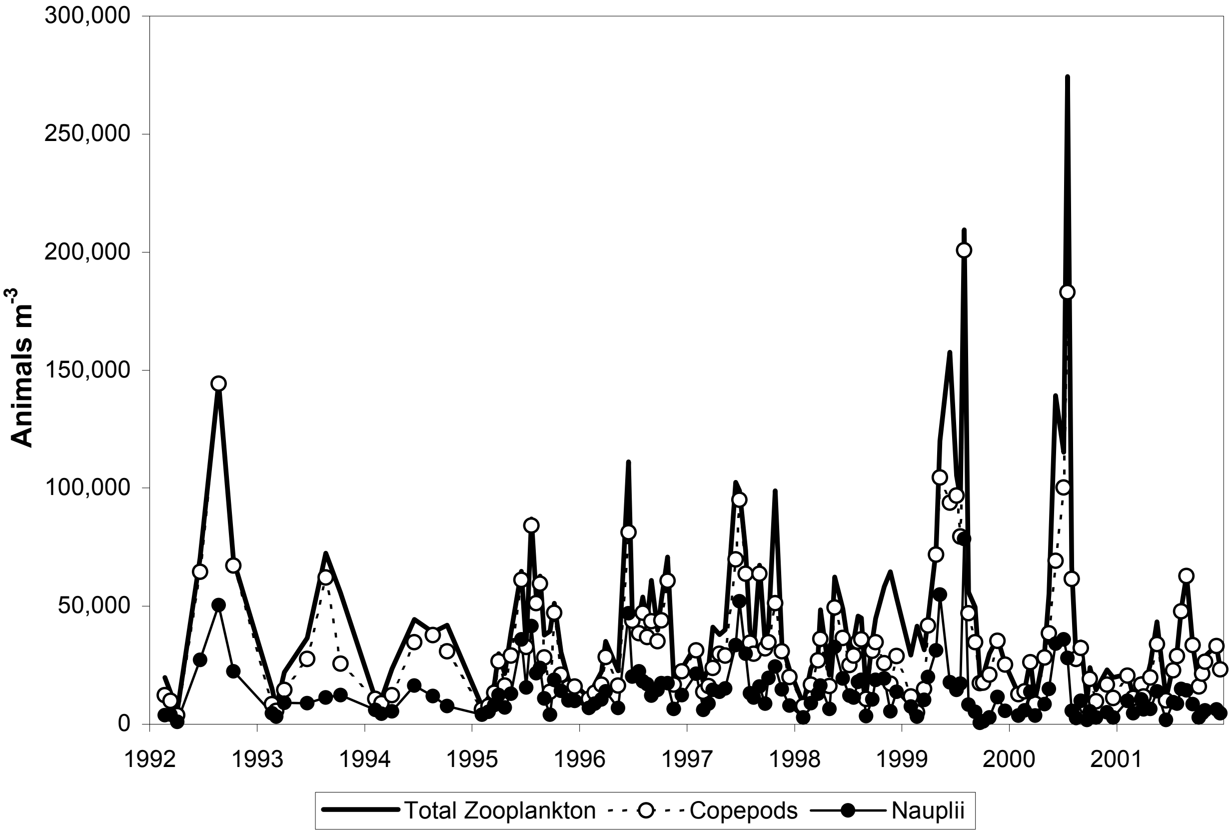
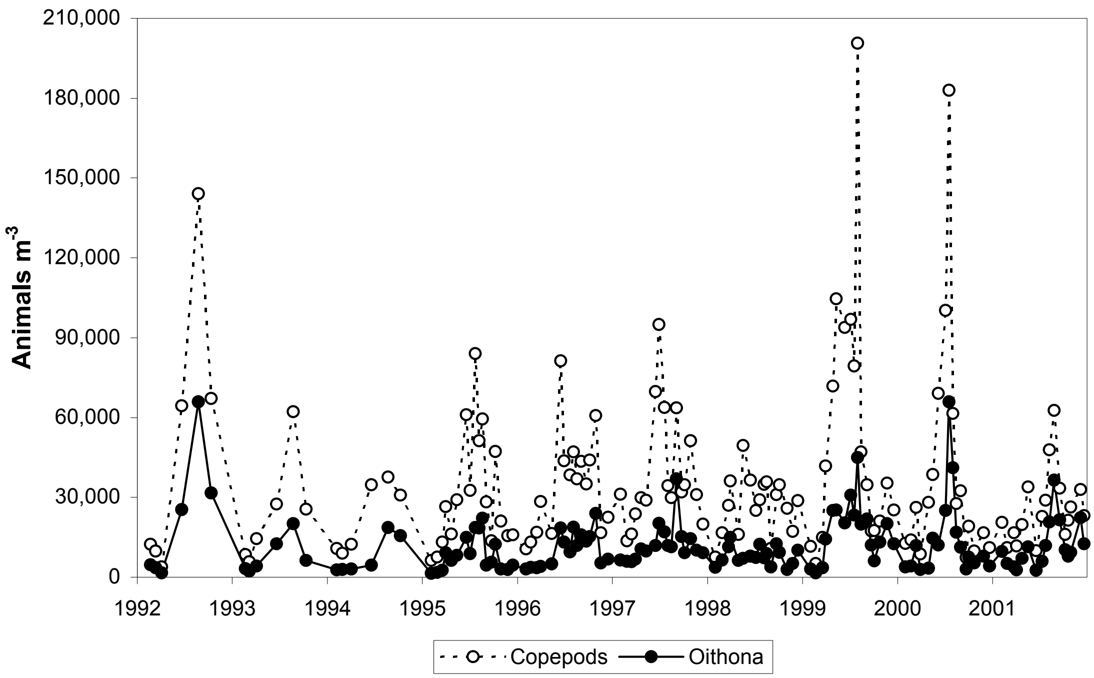


Figure 4-34. Comparison of total zooplankton, copepods, and nauplii abundance in the nearfield from 1992-2001. Mean value for all stations sampled by survey.

(a) *Oithona*



(b) *Paracalanus and Pseudocalanus*

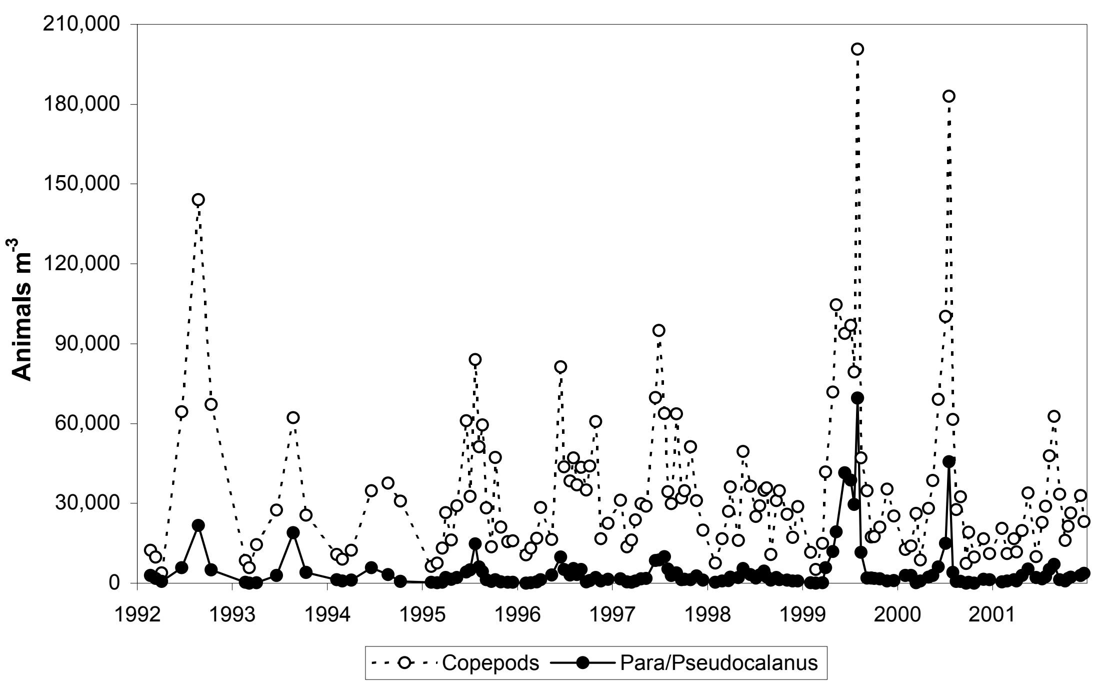
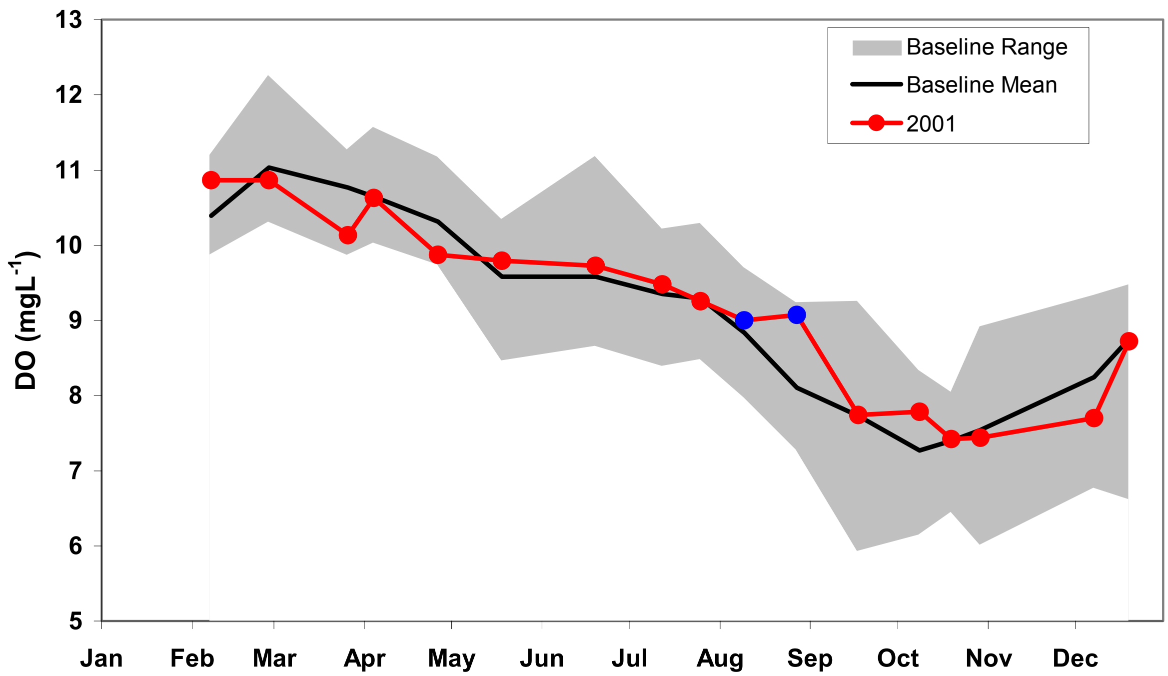


Figure 4-35. Comparison of total copepods and (a) *Oithona* (adults and copepodites) and (b) *Paracalanus/Pseudocalanus* (adults and copepodites) abundance in the nearfield from 1992-2001. Mean value for all stations sampled by survey.

(a) Nearfield



(b) Stellwagen Basin

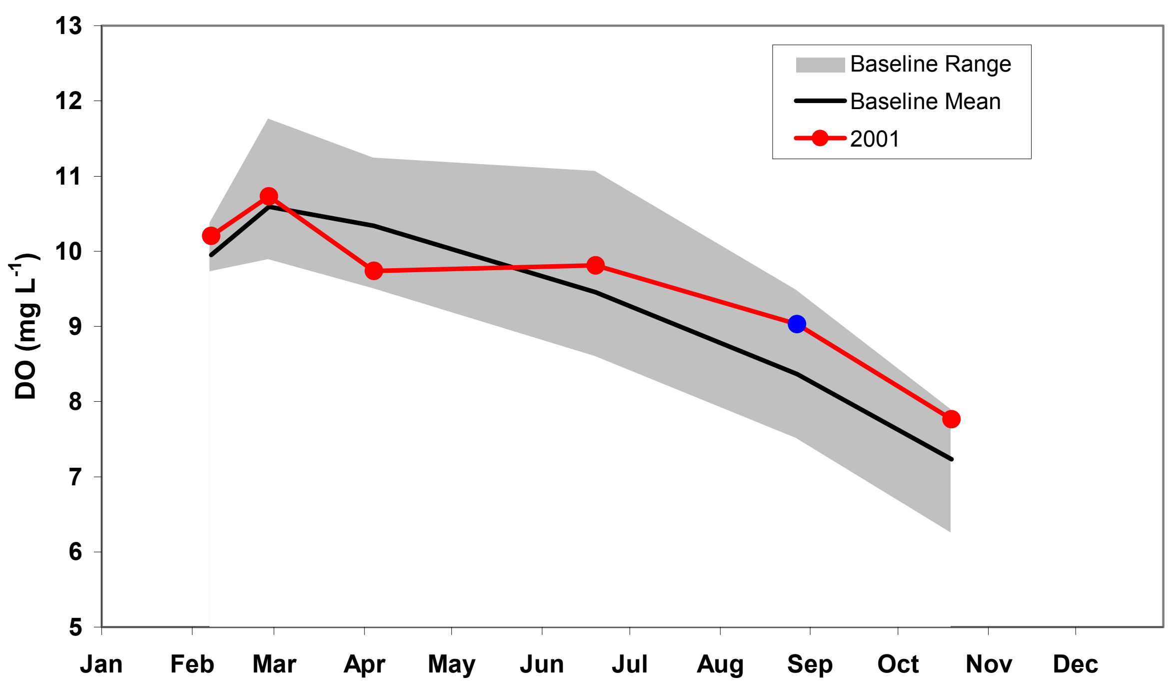


Figure 4-36. Time-series of survey mean bottom water DO concentrations in (a) the nearfield and (b) Stellwagen Basin in 2001 compared against the baseline range and mean. Stellwagen Basin data collected from stations F12, F17, F19, and F22. August data (blue dots) from Winkler titrations.

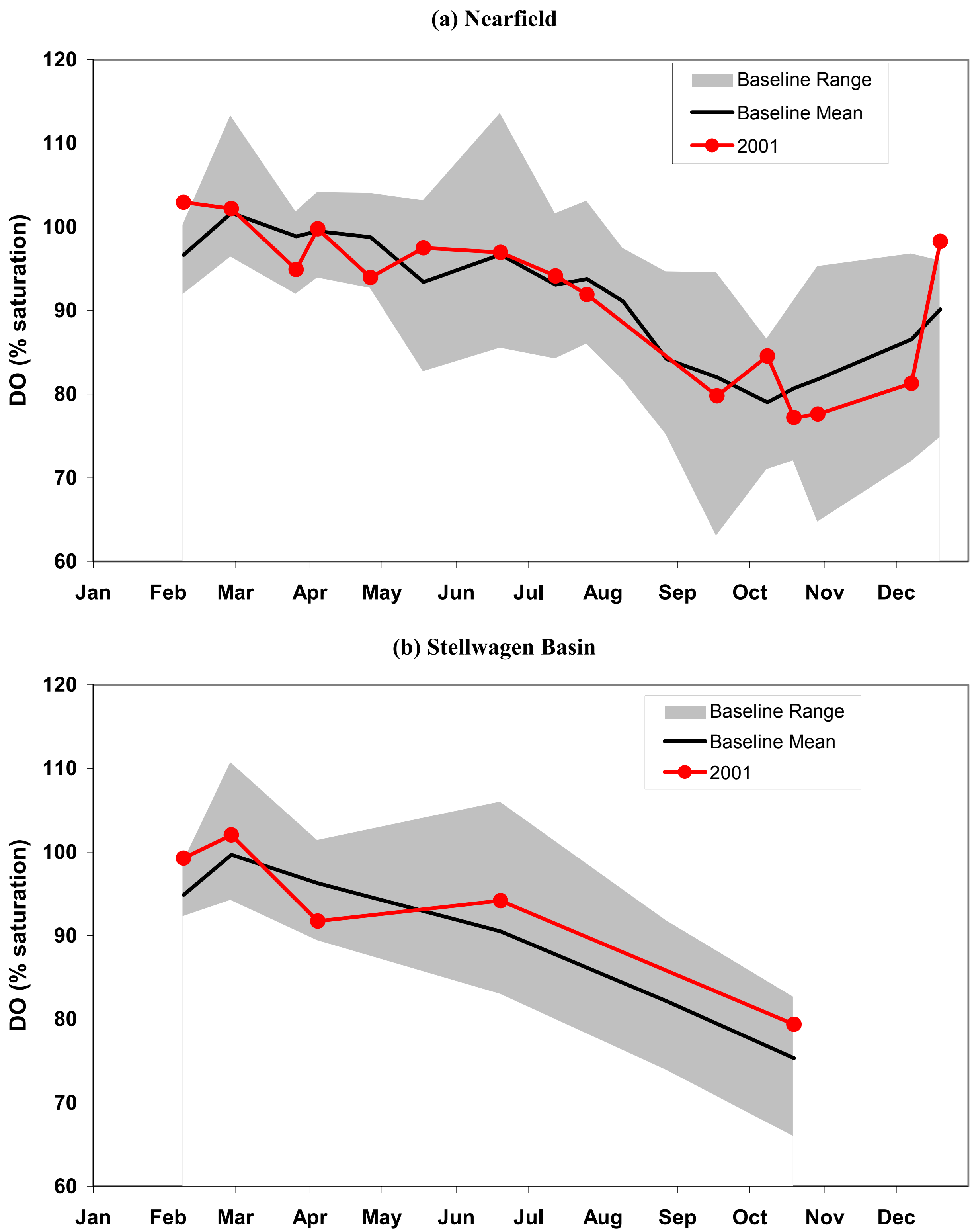


Figure 4-37. Time-series of survey mean bottom water DO percent saturation in (a) the nearfield and (b) Stellwagen Basin in 2001 compared against the baseline range and mean. Stellwagen Basin data collected from stations F12, F17, F19, and F22.

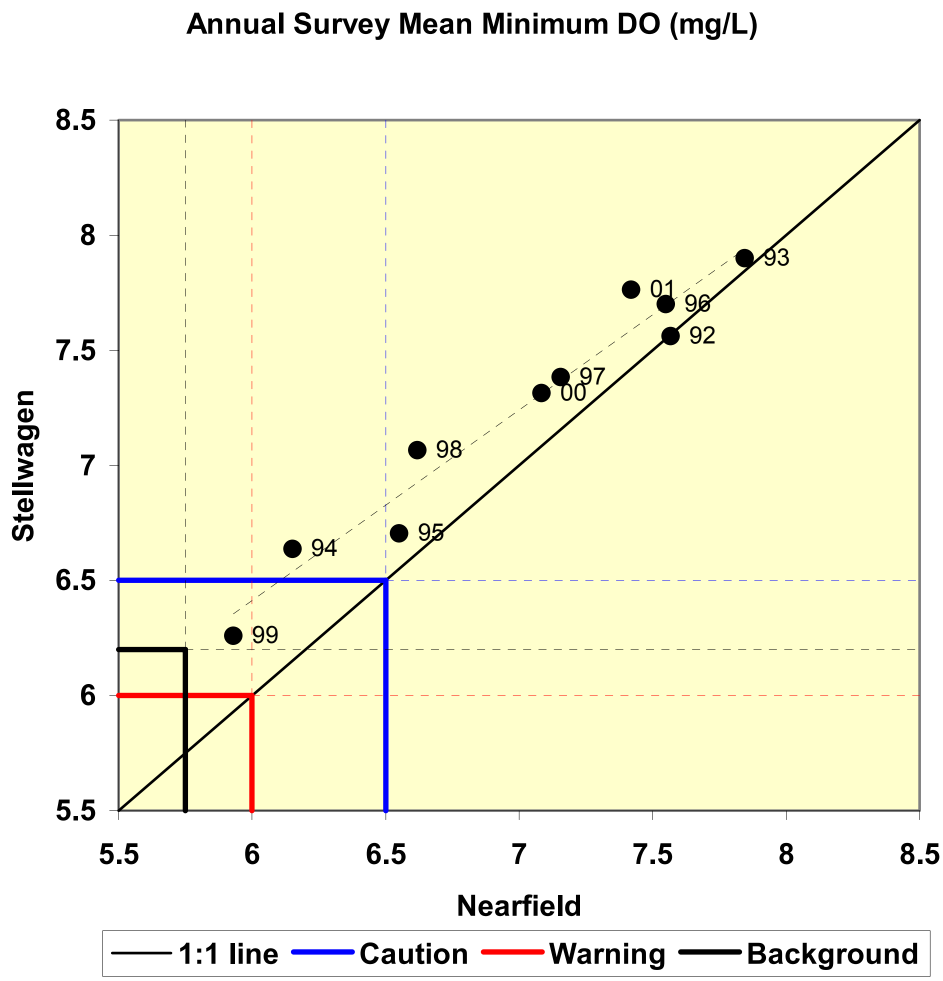


Figure 4-38. Comparison of annual minimum survey mean bottom water DO concentration in the nearfield and Stellwagen Basin for 1992 to 2001. Linear regression (dotted line) yields r^2=0.96.

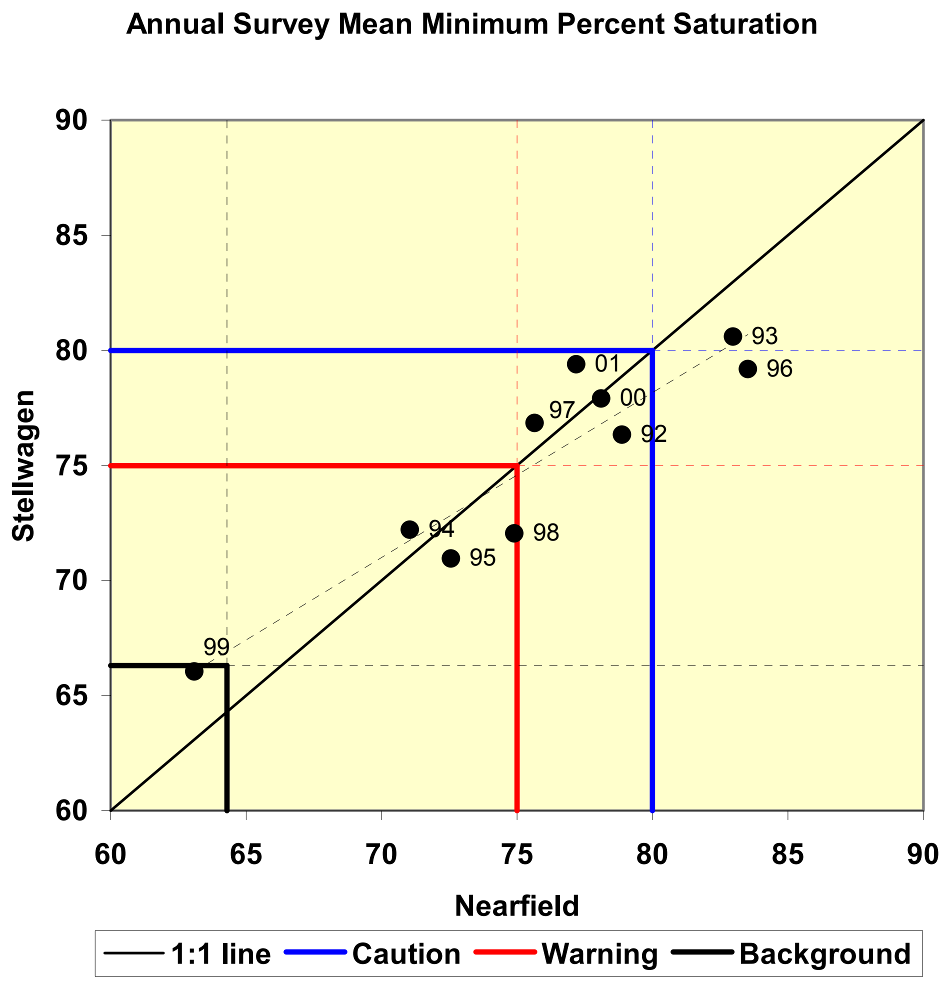


Figure 4-39. Comparison of annual minimum survey mean bottom water DO percent saturation in the nearfield and Stellwagen Basin for 1992 to 2001. Linear regression (dotted line) yields r^2=0.86.

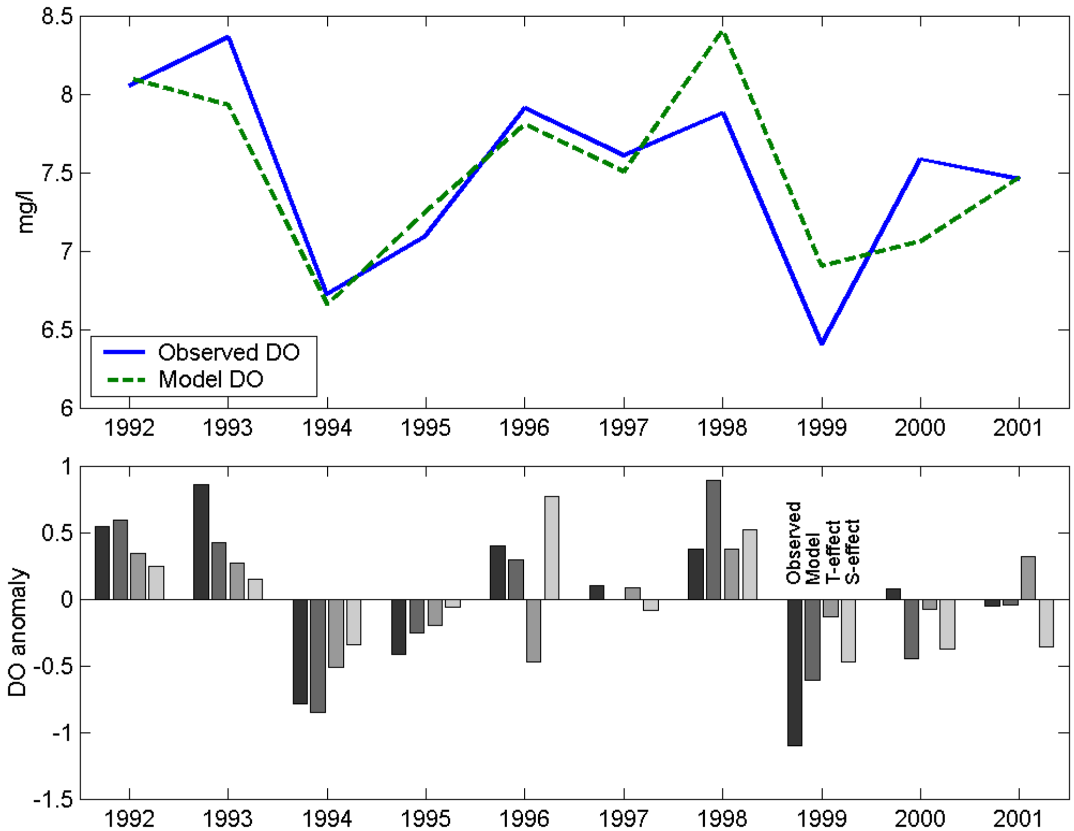


Figure 4-40. Comparison of observed and model results for bottom water dissolved oxygen. The bar plot in lower panel shows the individual contributions due to temperature and salinity for each of the years. The observed data are the mean values for September-October surveys from nearfield stations N13, N14, N18, N19, N20, and N21.

5.0 SUMMARY OVERVIEW OF 2001

This section summarizes trends in water quality and the major water column events of 2001. Four main themes were evident in the 2001 data: 1) physical processes and water quality generally followed typical patterns seen during baseline monitoring, 2) the primary deviations from the norm were related to phytoplankton bloom dynamics, 3) the outfall effluent plume has a clear signature, and 4) none of the water quality thresholds were exceeded in 2001.

Over the course of the Harbor and Outfall Monitoring Program 1992-2001, a general sequence of water quality events has emerged from the data collected in Massachusetts and Cape Cod Bays. The trends are evident even though the timing and year-to-year manifestations of these events are variable. These include trends in stratification of the water column, nutrients, light, and chlorophyll, and changes in the dissolved oxygen in the deep waters of the bay. In general, but not always, a winter/spring phytoplankton bloom occurs as light becomes more available, temperatures increase, and nutrients are readily available. Later in the spring, the water column transitions from well mixed to stratified conditions, which serves to cut off the supply of nutrients to the surface waters and terminate the spring bloom. The summer is generally a period of strong stratification, depleted nutrients, and a relatively stable mixed-assemblage phytoplankton community. Dissolved oxygen declines in the bottom waters over the course of the summer as increasing temperatures lead to higher respiration rates and stratification isolates these waters from the surface water sources of dissolved oxygen. In the fall, stratification deteriorates and supplies nutrients to surface waters often developing into a fall phytoplankton bloom. The lowest dissolved oxygen concentrations are observed prior to the fall overturn of the water column – usually in October. By late fall or early winter, the water column becomes well mixed and resets to winter conditions.

5.1 Summary of 2001 Conditions

The physical processes in 2001 closely followed climatology and none of the forcing parameters or physical variables showed extreme behavior. Surface water temperatures were relatively warm over the first three months of 2001 in comparison to previous years. Winds in March were somewhat anomalous in the propensity of downwelling-favorable winds, which would have had a tendency to increase the transport of Gulf of Maine waters through Massachusetts Bay at this time. The warm air temperatures and lack of major storms led to a prolonged period of weak stratification during the fall of 2001. The dry conditions in the fall of 2001 could significantly impact the conditions in early 2002 because of the lag between freshwater inflow and the response of the water column.

The various water quality parameters in 2001 followed the general trends observed over the baseline period. The main deviations from baseline trends were observed in February and December. Nutrient, biomass and production data suggest that the winter/spring bloom had peaked prior to the early February 2001 survey in Massachusetts Bay. The decline of this bloom and an influx of nutrients (precipitation, runoff and advection) led to elevated spring nutrient concentrations in spite of the minor bloom of *Phaeocystis pouchetii* in April. The *Phaeocystis* bloom marked the second consecutive year that this nuisance species was observed in Massachusetts Bay. The calm weather and warm temperatures led to a delay in destratification of the water column and resulted in a late fall bloom. The fall bloom normally occurs in September and October, but in 2001 the bloom occurred from October to December with peak production rates and highest biomass concentrations being measured in early December.

From 1992 to 2000, there was a general trend of increasing annual mean nutrient concentrations in the regions in Massachusetts Bay (Libby *et al.*, 2001). This did not continue in 2001 as a decrease in annual mean concentrations was observed throughout the bays, except that NO_3 and especially NH_4 increased from 2000 to 2001 in the nearfield. The largest change that was seen was in annual mean NH_4

concentrations in Boston Harbor that dropped from a high of 10 µM in 2000 to 2 µM in 2001. This was directly due to the transfer of MWRA discharge from the harbor to the bay. A sharp decrease in NH_4 concentration was also seen at the coastal stations, which are strongly influenced by water quality conditions in Boston Harbor. The increase in annual mean NH_4 in the nearfield was not as dramatic as the harbor and coastal water decrease. This is due to relatively high dilution in the nearfield (Hunt *et al*., 2002) and the inclusion of four months of post-discharge data in the 2000 annual mean NH_4 concentration. Since 1999, the annual mean NH_4 levels have almost doubled in the nearfield. There was little if any change in NH_4 concentrations in offshore, boundary, or Cape Cod Bay waters from 2000 to 2001. In fact, annual mean NH_4 concentrations in Cape Cod Bay have decreased from a maximum of 1.7 µM in 1999 to 1.1 µM in 2000 and 2001.

The decrease in nutrient concentrations from 2000 to 2001 was commensurate with a decrease in biomass as estimated by chlorophyll and POC measurements. The 2000 annual mean chlorophyll concentrations were the highest observed over the monitoring period and continued a trend of increasing chlorophyll from 1997 to 2000. The lack of major winter/spring and fall blooms in 2001 resulted in decreases in annual chlorophyll concentrations of ≥50% in Boston Harbor, coastal, nearfield, and Cape Cod Bay waters. The decrease was not as sharp at the offshore and boundary stations; the 2001 annual concentrations were highest in these two regions. The presence of elevated chlorophyll at the offshore and boundary stations suggests that chlorophyll concentrations in Massachusetts Bay continue to be influenced by regional factors from the Gulf of Maine. Satellite imagery suggests that the trend of increasing concentrations from 1997 to 2000 and then decreasing in 2001is not directly related to local factors, but represent trends that were observed over much of the western Gulf of Maine.

The annual minimum DO concentrations and percent saturations observed in October 2001 were relatively high in comparison to baseline values. It might be expected that DO concentrations would be high given the relatively low biomass concentrations measured in 2001 (assuming that this correlates to a low organic loading to the bottom waters and benthos). The fact that similar DO minima were observed in 2001 and 2000 when annual biomass concentrations were at or near maximum baseline levels suggests that interannual variations in organic loading play a relatively minor role in controlling bottom water DO. An examination of the connection between physical oceanographic conditions and DO concentrations indicates that regional processes and advection are the primary controlling factors governing bottom water DO concentrations in Massachusetts Bay (Geyer *et al*., 2002).

5.2 2001 Phytoplankton Bloom Dynamics

In general, Massachusetts Bay (and the nearfield in particular) is characterized by the periodic occurrence of a winter/spring phytoplankton bloom, variable production during the summer, and a fall bloom. Boston Harbor (as measured at station F23) had been characterized by a seasonal productivity cycle markedly different from the nearfield that tended to gradually increase from spring through summer and decrease in the fall. Starting in 2000 and continuing in 2001, the productivity pattern in Boston Harbor more closely followed the pattern typically observed at the nearfield stations characterized by a spring or fall peak and relatively low summer production. The following subsections focus on the winter/spring, *Phaeocystis* and late fall blooms as they occurred in 2001, but also in general as to their occurrence during previous monitoring years 1992-2000.

5.2.1 Late Winter/Early Spring Bloom

In early February 2001, relatively high (potential) production and chlorophyll concentrations in the nearfield suggested a winter/spring bloom was underway and nearfield phytoplankton abundance (and diatom abundance) though low was relatively high in comparison to baseline values for the early February survey (see **Figure** 4-30). The peak of the winter/spring diatom bloom may have occurred prior to the earliest 2001 survey (February), but nearfield winter/spring diatom abundance was only half of mean baseline levels later in the spring (March, April, and May). In terms of productivity, there were two peaks in productivity during the winter/spring bloom in 2001. The first occurred in February and the second higher peak in April in association with the *Phaeocystis pouchetii* bloom. The peak production during the 2001 winter/spring period was low in comparison to previous years, (except for 1998, a year with no bloom; **Figure** 5-1a). Although the reason for the failure of the winter/spring diatom bloom to achieve higher production and phytoplankton abundance in 2001 cannot be definitively determined, there were a number of physical and biological factors that may have contributed to its failure to achieve bloom levels of phytoplankton abundance.

There are three essential phases of phytoplankton bloom development: bloom initiation, bloom maintenance, and bloom termination. During bloom initiation phytoplankton population growth exceeds all loss processes such that "bloom" abundance levels are eventually achieved. During bloom maintenance organism- and environment-specific combinations of growth and loss processes (i.e., fast zooplankton grazing but faster phytoplankton growth, slow phytoplankton growth but slower wash-out and zooplankton grazing, etc.) act to keep phytoplankton levels at or above the bloom threshold level. Eventually (usually time-scale of weeks), loss processes will exceed phytoplankton growth and the bloom terminates. Bloom termination refers to a series of eco-physiological events resulting in end of a phytoplankton bloom. In 2001, the winter/spring diatom bloom failed to reach bloom abundance levels. Phytoplankton growth may have been rapid as the (potential) production values indicated, but biomass/abundance accumulation was never achieved likely due to higher loss processes.

Winter/spring phytoplankton blooms occur due to elevated growth related to seasonal stratification of the physical environment, prior to temperature-related increases in mortality due to grazing. Variation in winter/spring temperature, light, and degree of stratification results in variation in the timing of the winter/spring bloom (Townsend *et al.*, 1994). In winter of 2001, especially February, water temperature at the Boston Buoy was among the warmest observed in the 1989 to 2001 winter period (see **Figure** 3-5). Further, winter/spring water column stratification was reduced relative to the long-term mean pattern. Two factors led to reduced early spring stratification: (1) freshwater inflow was reduced relative to the long-term mean over the first 3 months of 2001, and (2) the February-March wind regime resulted in strong downwelling during that period (see **Figures** 3-1 and 3-3). Elevated winter water temperatures and reduced stratification, as observed in 2001, are expected to repress winter/spring bloom formation (Townsend *et al.*, 1994), and Massachusetts Bay winter/spring phytoplankton bloom magnitude is negatively correlated with water temperature (Keller *et al.*, 2001). Elevated zooplankton abundance, and presumed increased zooplankton grazing, is the inferred mechanism of winter/spring bloom repression in Massachusetts Bay (Keller *et al.*, 2001). In spring 2001, reduced stratification and elevated zooplankton grazing associated with warmer water temperatures may have acted to reduce the rate of phytoplankton population growth and eventual biomass accumulation.

It should be noted that in early February 2001 zooplankton abundances were not elevated although they were higher than the baseline mean for the nearfield. There are at least two possible interpretations here. One possibility is that as zooplankton abundance in February 2001 was not elevated zooplankton grazing must not have been elevated, so something else repressed phytoplankton abundance (i.e. caused winter/spring bloom failure). Another possibility is that while zooplankton abundance was not elevated, temperature-dependent zooplankton grazing rate may have been elevated to the point that it exceeded phytoplankton growth rates. Zooplankton grazing pressure is the cross product of zooplankton abundance times grazing (clearance) rate. Zooplankton clearance rate may be more temperature sensitive than is phytoplankton growth rate. For example phytoplankton growth rate has a Q10 of ca. 2.5 (Eppley, 1972) while zooplankton clearance rate, using *Acartia hudsonica* as an example, has a Q10 of near 3.2 (Deason, 1980). Thus while zooplankton abundance was not higher in February 2001, warm temperatures may have resulted in increased grazing pressure. Information on temperature-dependent filtering or clearance data for key zooplankton species would be needed to assess whether fluctuations in zooplankton abundance or temperature-dependent fluctuations in grazing rate were more important in explaining winter/spring bloom development or lack thereof in Massachusetts Bay.

5.2.2 *Phaeocystis pouchetii* 'bloom'

In April 2001, *Phaeocystis pouchetii* was observed in Massachusetts Bay for the second year in a row. This species had appeared to bloom in spring in two- to three-year cycles, with blooms recorded in the bays in 1992, 1994, 1997, and 2000. The suggestion of an intermittent interannual "cycle" was complicated by the reappearance of *Phaeocystis* in 2001 and data indicate that it was also present in March and April of 2002. The nearfield *Phaeocystis* abundance in April 2001 was much lower than during the 2000 bloom. Data from the farfield indicate that there was a gradient in abundance from a maximum of >2.5 million cells L^{-1} at boundary stations F26 and F27, decreasing to 1.5 million cells L^{-1} at offshore station F22, a million cells L^{-1} in the nearfield, and under a million in coastal and harbor waters. This gradient suggests that the 2001 *Phaeocystis* bloom was part of a regional event and may have been advected into Massachusetts Bay from the Gulf of Maine. This is supported by the distribution patterns of chlorophyll in SeaWiFS imagery from late March to early April 2001 (**Figure** 5-2). During the spring of both 2000 and 2001, *Phaeocystis* blooms were observed in the Gulf of Maine on surveys for the ECOHAB (ECology and Oceanography of Harmful Algal Blooms) program. In 1994, a concurrent *Phaeocystis* bloom was observed in Buzzards Bays (Turner *et al*., 2000). It is unclear if any substantial change in the plankton of Massachusetts Bay will occur in the wake of the outfall coming on line in fall of 2000, but, in regards to *Phaeocystis* blooms, the apparent change from a 2-3 year cycle seen during the baseline to three consecutive years with blooms seems to be due to regional phenomena.

5.2.3 Late Fall/Early Winter Diatom Bloom

In comparison to previous years, the magnitude of the fall bloom was not extraordinary, but the timing of the bloom was unprecedented. Typically, the fall bloom occurs in September and October. In 2001, total phytoplankton abundance peaked in late October, but diatom abundance reached a maximum in early December. Chlorophyll, POC and production all peaked in early December. Typically the timing of the fall bloom has been tied to decreased stratification. The extended period of stratification that was observed in the nearfield into December may have contributed to the delay in the timing of the fall bloom in 2001.

During fall blooms in 1995 to 2000, production rates in the nearfield ranged from 1600 to 5000 mgC m^{-2} d^{-1} (**Figure** 5-1b), with blooms typically lasting 3-4 weeks in September and October. The bloom in 2001 reached peak values of >3250 mg C m^{-2} d^{-1} at both nearfield stations (**Figure** 5-1b) and occurred from October through early December. From 1995 to 2000, the fall bloom peak has been consistently higher at station N18 compared with N04, however, this year the peak fall productivity was similar at both sites.

A short period of intense mixing was noted in the USGS mooring data in the nearfield in late September and early October (see **Figure** 3-7). This mixing event and influx of nutrients may be associated with the initial fall productivity peak, which occurred on October 9th. Production was elevated and relatively uniform throughout the water column at station N18 during this initial fall bloom peak (**Figure** 5-3). As a result, maximum productivity for the bottom water at station N18 was greater than values observed in earlier years (**Figure** 5-4). Mean productivity in the bottom waters at station N18 was also somewhat elevated relative to earlier years even though annual productivity in 2001 was not. A slight increase in maximum bottom productivity was also noted at station N04. The increase in bottom water productivity in early October is likely to have resulted from the mixing event. The coincident increase in bottom water production and the comparable fall peak production rates at the nearfield stations argues against an attributable outfall effect as station N04 is nominally upstream and station N18 downstream of the discharge.

The late fall bloom was the dominant feature of the phytoplankton cycle in 2001. Phytoplankton bloom criteria range from commonly applied biomass (as carbon or chlorophyll) thresholds to community- and species-specific abundance criteria (Smayda, 1997). The late autumn 2001 bloom peaked at a nearfield mean abundance of approximately 2.5 x 10^6 cells l^{-1}, well below the baseline fall maximum of 10 x 10^6 cells l^{-1} (see **Figure** 4-30). In this context, the phytoplankton abundance levels achieved in autumn 2001 appear unexceptional. However, application of site-specific, season-specific and species-specific bloom-defining criteria, as advocated by Smayda (1997), identifies the exceptional nature of the 2001 late autumn bloom. This bloom featured a community-wide increase in phytoplankton abundance, with total phytoplankton elevated to approximately 2- to 2.5-times the early December baseline mean level (see **Figure** 4-30). Diatoms, present at 6-times the early December baseline mean level and dominated by increased *Skeletonema, Leptocylindrus, Thalassiosira* and *Rhizosolenia* abundance, displayed the greatest increase. Late autumn dinoflagellate, microflagellate and even silicoflagellate abundances were increased two- to three-fold above the corresponding nearfield baseline mean levels. Autumn blooms frequently achieve the annual biomass peak in open coastal ecosystems (Cebrian & Valiela, 1999), including western Gulf of Maine and Massachusetts Bay (O'Reilly & Zeitlin, 1998) and have usually occurred as stratification is breaking down (nutrients becoming available). In 2001, the late-autumn bloom observed in Massachusetts Bay reached abundance levels that rivaled, but did not exceed the summer bloom peak. However, given the elevated phytoplankton levels observed in late autumn 2001, compared to their corresponding baseline levels, this late-autumn event represents a deviation from the expected pattern of Massachusetts Bay phytoplankton abundance. This atypical pattern was likely due to the persistence of a weakly stratified water column into early December.

5.3 Discharge Signature

The MWRA effluent discharge was transferred from the harbor outfall to the offshore outfall in Massachusetts Bay on September 6, 2000. The most obvious change observed in the monitoring data that resulted from the transfer of discharge to the bay was the decrease in NH_4 concentration in the harbor and coastal waters and the increase of this anthropogenic signal offshore in the nearfield. Although it is not a conservative tracer due to biological utilization, NH_4 proved to be an excellent tracer of the influence of Boston Harbor on coastal and western nearfield waters over the course of the baseline monitoring program, and it now appears to be a clear indicator of the effluent plume in the nearfield. The discharge also has a visible signature in the winter when buoyant plumes from each diffuser head are visible at the surface during calm conditions. White flocculent material was observed in the vicinity of the upwelling plumes on a number of occasions, and samples of the material were collected for analysis in March 2001 and June 2002. These signatures of the effluent plume are discussed in more detail in the following subsections.

5.3.1 NH_4 Tracer

A comparison of model predictions and monitoring results was presented in the 2000 annual water column monitoring report (Libby *et al*., 2001). Model simulations predicted that the concentrations of effluent would be greatly reduced in the harbor, would increase locally within the plume in the nearfield, and have little impact on concentrations in the rest of Massachusetts and Cape Cod Bays (Signell *et al*., 1996). The overall spatial patterns in NH_4 concentrations during October 1999 (harbor outfall) and October 2000 (bay outfall) surveys clearly confirmed the model dilution simulations of harbor and bay outfall effluent distributions. Although NH_4 is not a truly conservative tracer of the effluent plume due to biological utilization, it is a good indicator of the effluent plume over relatively short spatial (<20 km) and temporal (hours to days) scales.

A more quantitative approach was taken by Mickelson *et al.* (2002) using changes in NH_4 concentrations before and after the diversion to the bay outfall to estimate relative farfield dilution of the effluent. Because the temporal monitoring results were strongly autocorrelated, the data were grouped to avoid pseudoreplication. Because there are clear annual cycles for many stations, the data was divided into two seasons within each year (summer = April through October, winter = November through March). The mean seasonal NH_4 concentration at each monitoring station for each year was calculated by first averaging the station data by depth, then each station across the surveys within a given month, and lastly each station by the months within a season (summer and winter). Because 2000 was a transition year (offshore discharge began in September) the station means from 1992 to 1999 (n=8 for each station) were compared with the mean from 2001 (n=1 for each station). Statistical analysis rejected the hypothesis that the mean NH_4 concentration for 2001 was equal to the mean of the means for 1992-1999 when $p<0.05$ (t-test).

The station average data showed a striking change in the pattern of NH_4 concentrations after the outfall was moved offshore. Ammonium decreased significantly in the harbor at most stations and increased in the bay at only those stations within 20 km of the new outfall. Many of the changes were statistically significant, even with only one complete year of monitoring data after the new outfall began discharging (**Figures** 5-5 and 5-6). The magnitude of change in Boston Harbor was greater in winter whereas the magnitude of change in the bay was greater in summer. Summer stratification decreases the plume rise height, and therefore decreased the dilution, but stratification can also affect currents and thus far field dilution. Wind-driven momentum transfer across the pycnocline is less in summer resulting in greater surface currents and lessened bottom currents (Butman *et al.*, 2001). The higher surface currents in summer sweep more NH_4 from water tidally exchanging with the harbor, while the slow bottom currents as well as stratification in summer decrease dilution of the bottom-trapped plume at the new outfall site.

Hydrodynamic modeling (Signell *et al.*, 2000) of a conservative tracer predicted an identical seasonal and spatial pattern to the observed NH_4 concentrations. However, the magnitude of the values between the model results and field results differ by a factor of two. Using a typical effluent concentration of 1300 µM NH_4, a modeled tracer concentration of 1% corresponds to about 13 µM NH_4. The observed average values are about 6 µM. This difference may be due to differences in the way the model and observations are aggregated in the plots. For example, the model values are the maximum value over depth (versus depth-average in the observed NH_4 data) and are average model predictions over a single month (observed NH_4 data are a 6-month average). Also, the model predictions were based on hydrographic conditions measured in 1992, while the NH_4 data are from all monitoring years. Another factor for the decrease in observed versus model-calculated NH_4 concentrations is utilization of the nutrient by phytoplankton.

The patterns of the NH_4 and chlorophyll concentrations along the Nearfield-Marshfield transect in **Figure** 4-5 suggest that there was an increase in chlorophyll associated with the elevated NH_4 concentrations in the plume. The availability and preferential uptake of NH_4 by phytoplankton might be expected to lead to a localized increase in chlorophyll, but the chlorophyll maximum is usually located in the vicinity of the pycnocline during the summer-stratified period. The observed patterns are likely the result of the contouring and limited sampling resolution (vertically and horizontally), which does not allow for a more quantitative analysis of a potential connection between NH_4 availability and increases in chlorophyll/production.

Findings from the plume tracking survey in July 2001 (Hunt *et al.*, 2002) suggest that the distribution of the plume can be characterized not only by fluorescent dye, but also in varying degrees by water quality parameters (NH_4, salinity, and beam attenuation). The use of towed instruments would provide high-resolution (temporal and spatial) data with which to better characterize the plume. Collection of *in situ* data and discrete samples (pumping system on towed array) over shorter temporal and spatial scales may provide insight as to the impact of increased NH_4 availability on localized chlorophyll levels. If the monitoring focus were to shift to that scale, towed instruments might be the appropriate tool to quantify distribution of the effluent plume and potential ecological effects.

5.3.2 *Thalassionema nitzschoide*s

A more direct observation of the effluent plume was first made in December 2000. Under relatively calm conditions, individual upwelling plumes from each diffuser head are visible at the surface during winter months when the water column is not stratified. During the nearfield survey in March 2001, in addition to seeing the plume, a surface slick consisting of white flocculated material was observed near the edges of the outfall plume and qualitative grab samples of this material were collected. Microscopic examination of the material revealed that it was predominantly cells of the colonial pennate diatom *Thalassionema nitzschoides* (**Figure** 5-7). While *T. nitzschoides* was the overwhelming dominant taxon in the surface slick, it was a minor component of the nearfield phytoplankton community. *Thalassionema nitzschoides* is a cosmopolitan coastal diatom (Smayda, 1958) that is common in Massachusetts Bay and is a regular component of the southern New England nearshore marine phytoplankton communities (Staker *et al.*, 1978; Karentz & Smayda, 1984). It is usually present at relatively invariant low- to moderate-abundance levels. However, the appearance of *T. nitzschoides* surface slicks near the edges of the outfall plume is consistent with its tendency to be abundant near coastal upwelling fronts (Barcena & Abrantes, 1998). The observation of surface *T. nitzschoides* in winter/spring 2001 was likely due to transient environmental conditions (upwelling of the outfall plume) resulting in relatively high growth and physical aggregation of these phytoplankton cells along the outfall plume front. White flocculants were also observed in February 2002 and anecdotal evidence indicates that they have been seen during other surveys suggesting that this is a relatively common phenomenon and attributable to the bay outfall. Another sample of the material was collected in June 2002 for analysis by MWRA. It was determined that the material consisted of grease, a variety of different bacteria, and unidentified algae. The bacteria were not types usually associated with sewage and secondary treatment. It is unknown if the two samples consisted of the same materials. If necessary, a more quantitative sampling effort focused on the flocculants would provide additional information on frequency, composition, and fate of the material.

5.4 Contingency Plan Thresholds

September 6, 2000 marked the end of the baseline period, completing the data set for MWRA to calculate the threshold values used to compare monitoring results to baseline conditions. The water quality parameters included as thresholds are dissolved oxygen concentrations and percent saturation in bottom waters of the nearfield and Stellwagen Basin, annual and seasonal chlorophyll levels in the nearfield, seasonal averages of the nuisance algae *Phaeocystis pouchetii* and *Pseudo-nitzschia pungens* in the nearfield, and individual sample counts of *Alexandrium tamarense* in the nearfield (**Table** 5-1). The DO values compared against thresholds are calculated based on the mean of bottom water values for surveys conducted from June to October. The chlorophyll values are calculated as survey means of areal chlorophyll (mg m^{-2}) and then averaged over seasonal and annual time periods. For chlorophyll and nuisance algae the seasons are defined as the following 4-month periods: winter/spring from January to April, summer from May to August, and fall from September to December. The *Phaeocystis* and *Pseudo-nitzschia* seasonal values are calculated as the mean of the nearfield station means (each station is sampled at surface and mid-depth). For *Alexandrium* each individual sample value is compared against the threshold of 100 cells L^{-1}.

Table 5-1. Contingency plan threshold values for water column monitoring.

P	Time Period	Caution Level	Warning Level	Background	2001
Bottom Water DO concentration	Survey Mean in June-October	< 6.5 mg/l (unless background lower)	< 6.0 mg/l (unless background lower)	Nearfield - 5.75 mg/l Stellwagen - 6.2 mg/l	7.4 mg/L 7.8 mg/L
Bottom Water DO %saturation	Survey Mean in June-October	< 80% (unless background lower)	< 75% (unless background lower)	Nearfield - 64.3% Stellwagen - 66.3%	77% 79%
Chlorophyll	Annual	107 mg/m^2	143 mg/m^2	--	67 mg/m^2
	Winter/spring	182 mg/m^2	--	--	69 mg/m^2
	Summer	80 mg/m^2	--	--	45 mg/m^2
	Autumn	161 mg/m^2	--	--	85 mg/m^2
Phaeocystis pouchetii	Winter/spring	2,020,000 cells l^{-1}	--	--	186,400 cells l^{-1}
	Summer	334 cells l^{-1}	--	--	None
	Autumn	2,370 cells l^{-1}	--	--	None
Pseudo-nitzschia pungens	Winter/spring	21,000 cells l^{-1}	--	--	5,700 cells l^{-1}
	Summer	38,000 cells l^{-1}	--	--	100 cells l^{-1}
	Autumn	24,600 cells l^{-1}	--	--	5,900 cells l^{-1}
Alexandrium tamarense	Any nearfield sample	100 cells l^{-1}	--	--	35 cells l^{-1}

The dissolved oxygen concentration survey mean minimum for June – October of 2001 was well above the threshold standard for both the nearfield and Stellwagen Basin. The percent saturation values were slightly below the caution threshold of 80% in each area, but the survey mean minima that were measured were well above the background values. Thus, the threshold was not exceeded. The nearfield mean areal chlorophyll values were all well below (~50%) each seasonal and annual threshold. Although there was a minor *Phaeocystis* bloom in April 2001, the nearfield mean abundance was well below the threshold. *Alexandrium* and *Pseudo-nitzschia* were observed intermittently, but at very low abundance. There were no threshold exceedances for water quality parameters in 2001.

A number of topics have been highlighted in this report that should be addressed in a more detailed analysis. These topics are presented here as recommendations for future focus:

- Timeseries measurements are essential to providing statistically robust measures of the long-term variability of water properties. The addition of a near-bottom dissolved oxygen sensor to the USGS mooring in the nearfield combined with data from the DO sensor recently added to the GoMOOS buoy in northern Stellwagen Basin would provide a dataset with which to better characterize the variability of water properties at the outfall and the forcing conditions that may be driving that variability. Next year's report will examine this data in more detail.

- An action item for next year's report is to extend the baseline data set for chlorophyll-specific production to include 1995-1997 by rectifying data comparability issues.

- The failure of the winter/spring diatom bloom to reach "bloom" abundance levels and the late fall increase in phytoplankton abundance are both suggestive of top down control due to increasing or decreasing zooplankton community grazing pressure, respectively. Variations in zooplankton abundance have been inferred to mean variations in grazing pressure, but the absence of any actual zooplankton grazing data precludes further insight on such speculation. Our present inadequate understanding of the role of zooplankton grazing/predation rates (especially for small copepods) limits interpretation of trophic interactions between primary and secondary producers. A set of experiments focused on measuring the grazing rates for each of the major components of the zooplankton community (i.e. nauplii, *Oithona*, and *Pseudo/Paracalanus* copepodites) and phytoplankton removal rates might provide a critical link for understanding these trophic interactions in Massachusetts and Cape Cod Bays.

- Patterns of the NH_4 and chlorophyll concentrations in the vicinity of the effluent plume suggest that there may have been a localized increase in chlorophyll associated with the elevated NH_4 concentrations. An action item for next year's report is to critically examine the limited evidence for this. The current sampling resolution (vertically and horizontally) may not be adequate to detect a connection between NH_4 availability and increases in chlorophyll.

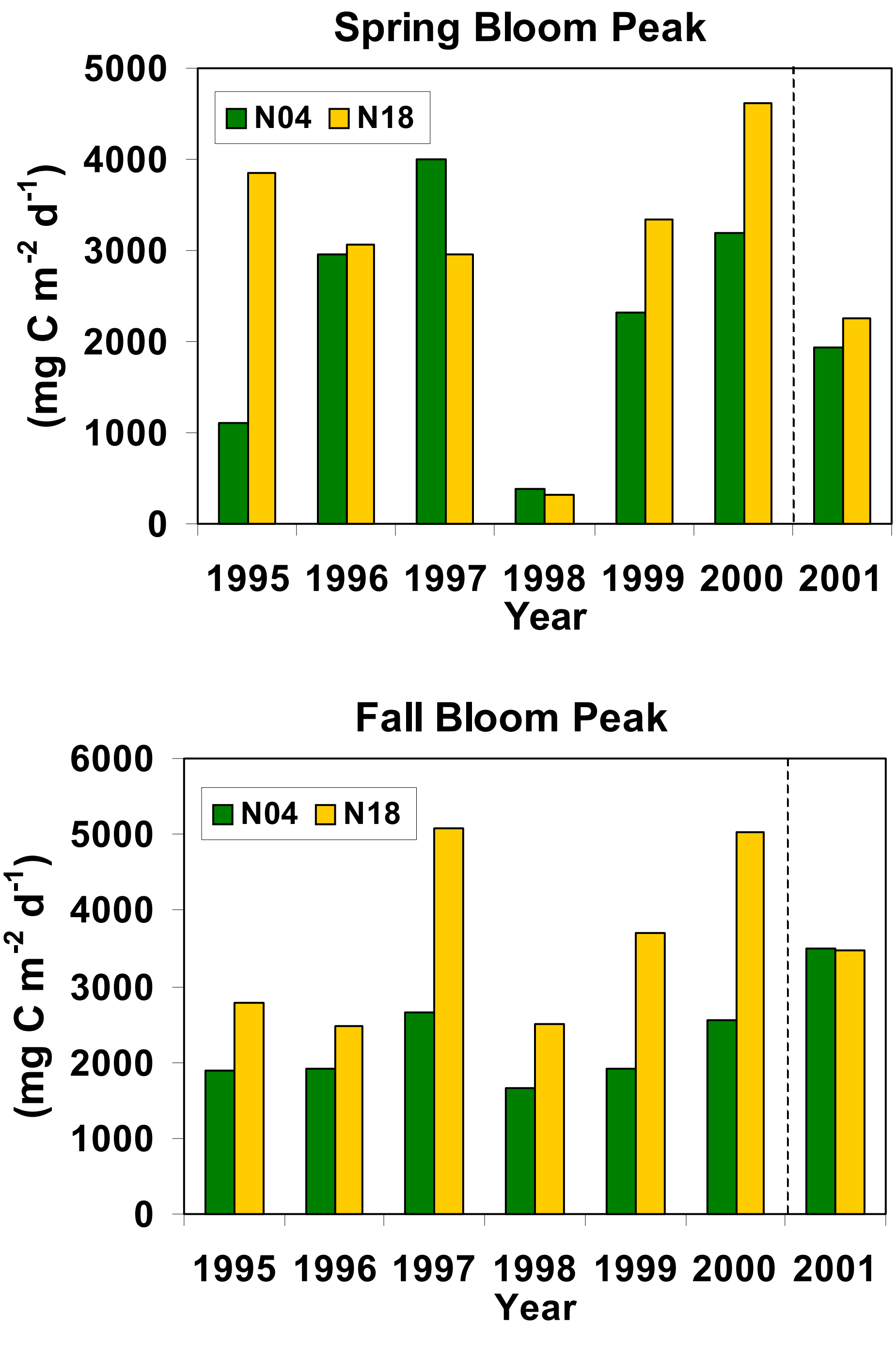


Figure 5-1. Production ($mgCm^{-2}d^{-1}$) at nearfield stations N04 and N16/N18 from 1995 to 2001 showing the (a) spring and (b) fall bloom peaks.

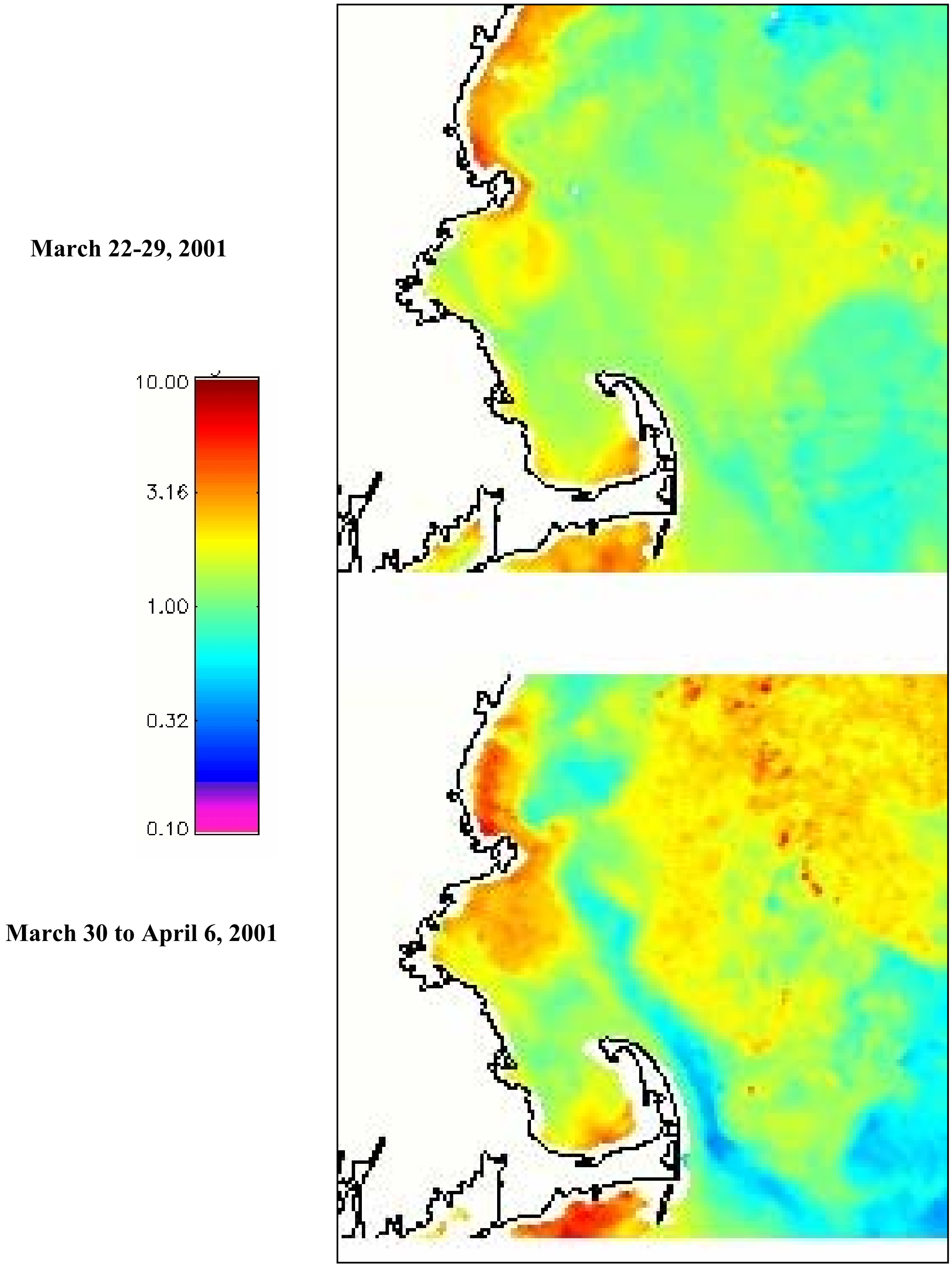


Figure 5-2. Eight-day composites of SeaWiFS chlorophyll (mg m^{-3}) images for the southwestern Gulf of Maine for late March and early April 2001. [Image courtesy of Dr. Andrew Thomas, School of Marine Sciences, University of Maine].

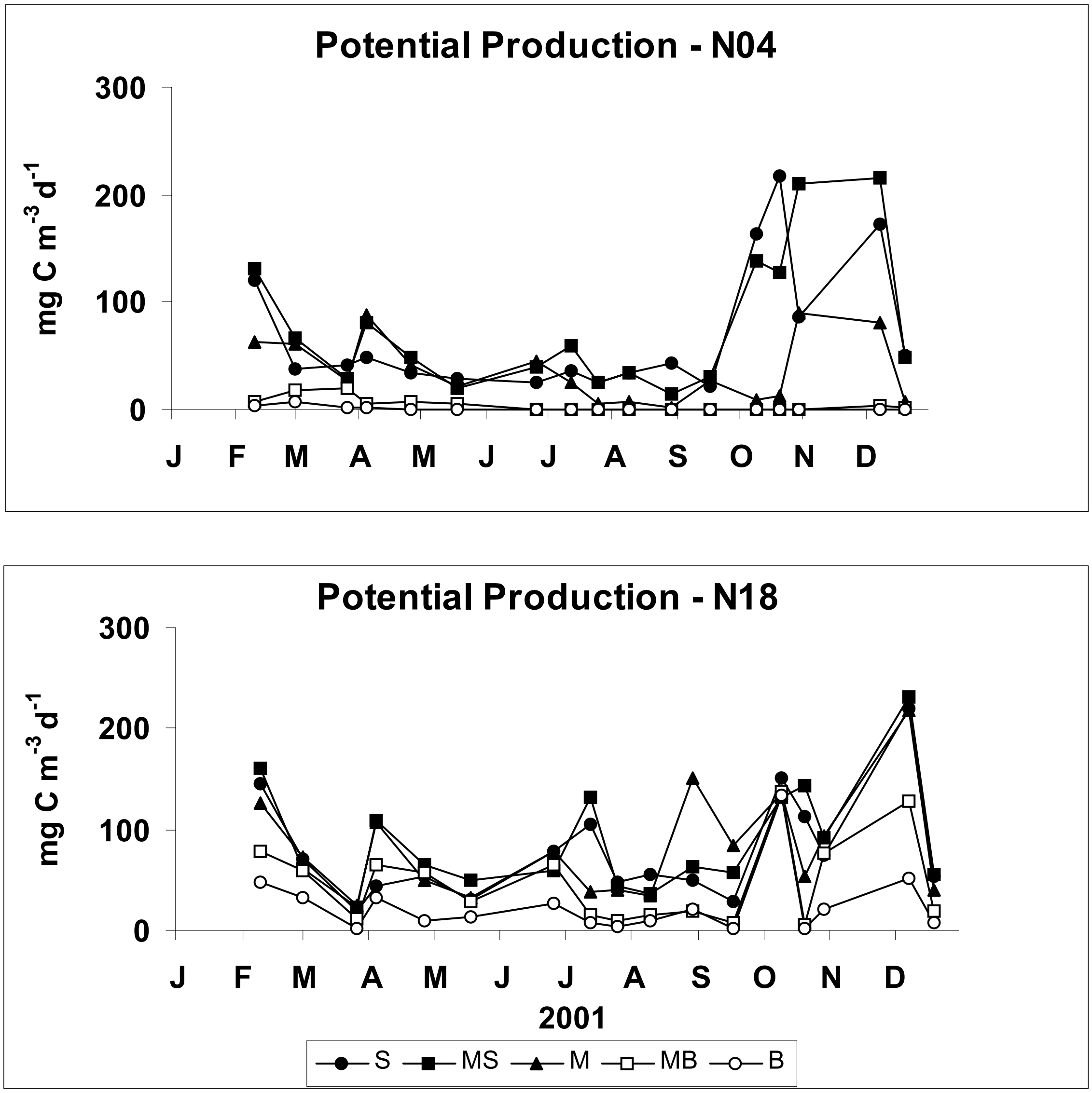


Figure 5-3. Potential production ($mgCm^{-3}d^{-1}$) calculated using incident light from a cloudless day over the annual cycle for each station and depth at stations N04 and N18.

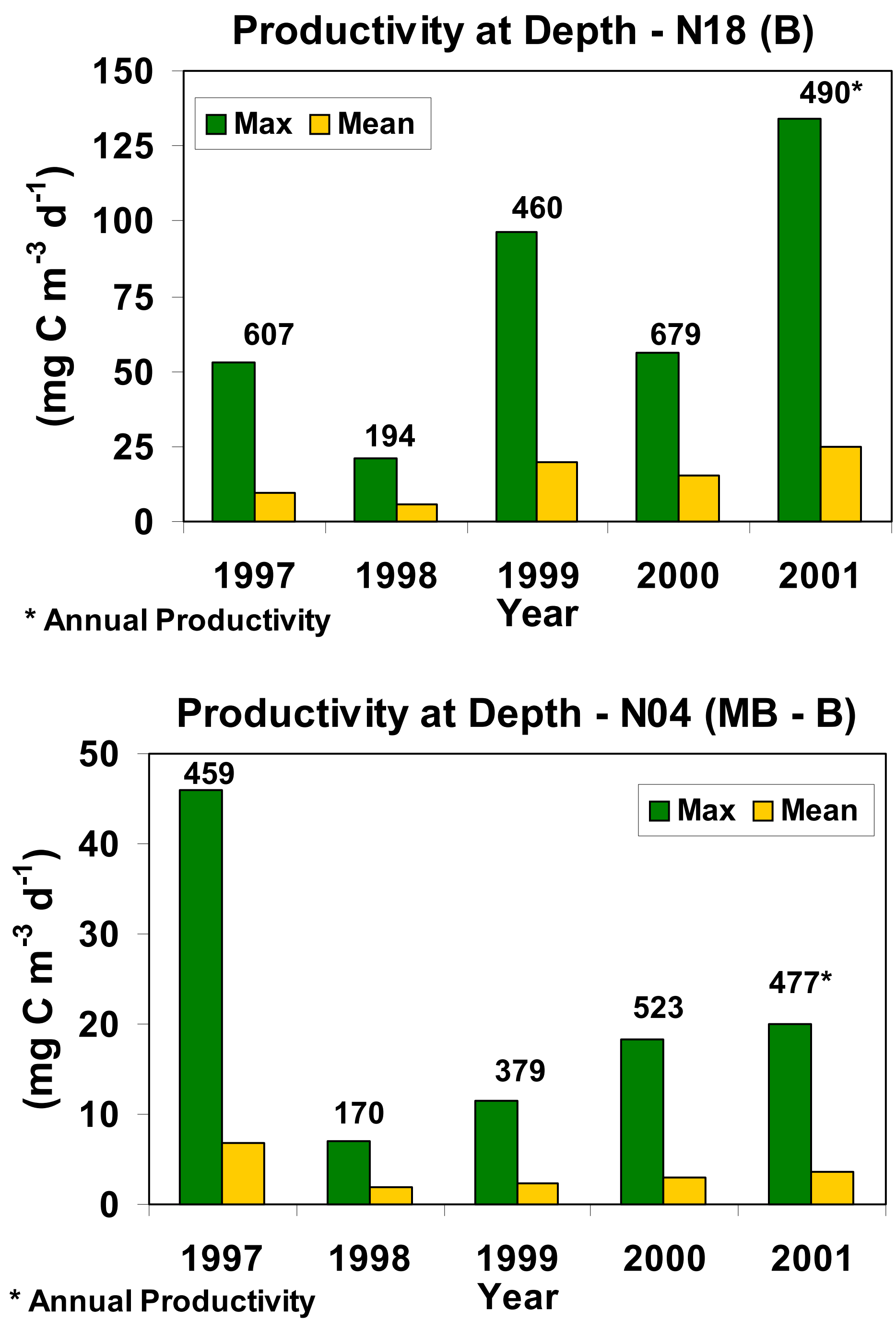


Figure 5-4. Maximum and mean productivity (mgCm^{-3}d^{-1}) in the bottom water at nearfield stations (a) N18 and (b) N04 from 1997 to 2001. Annual station production (gCm^{-2}yr^{-1}) is provided for reference. Note that station N04 data includes both bottom and mid-bottom data.

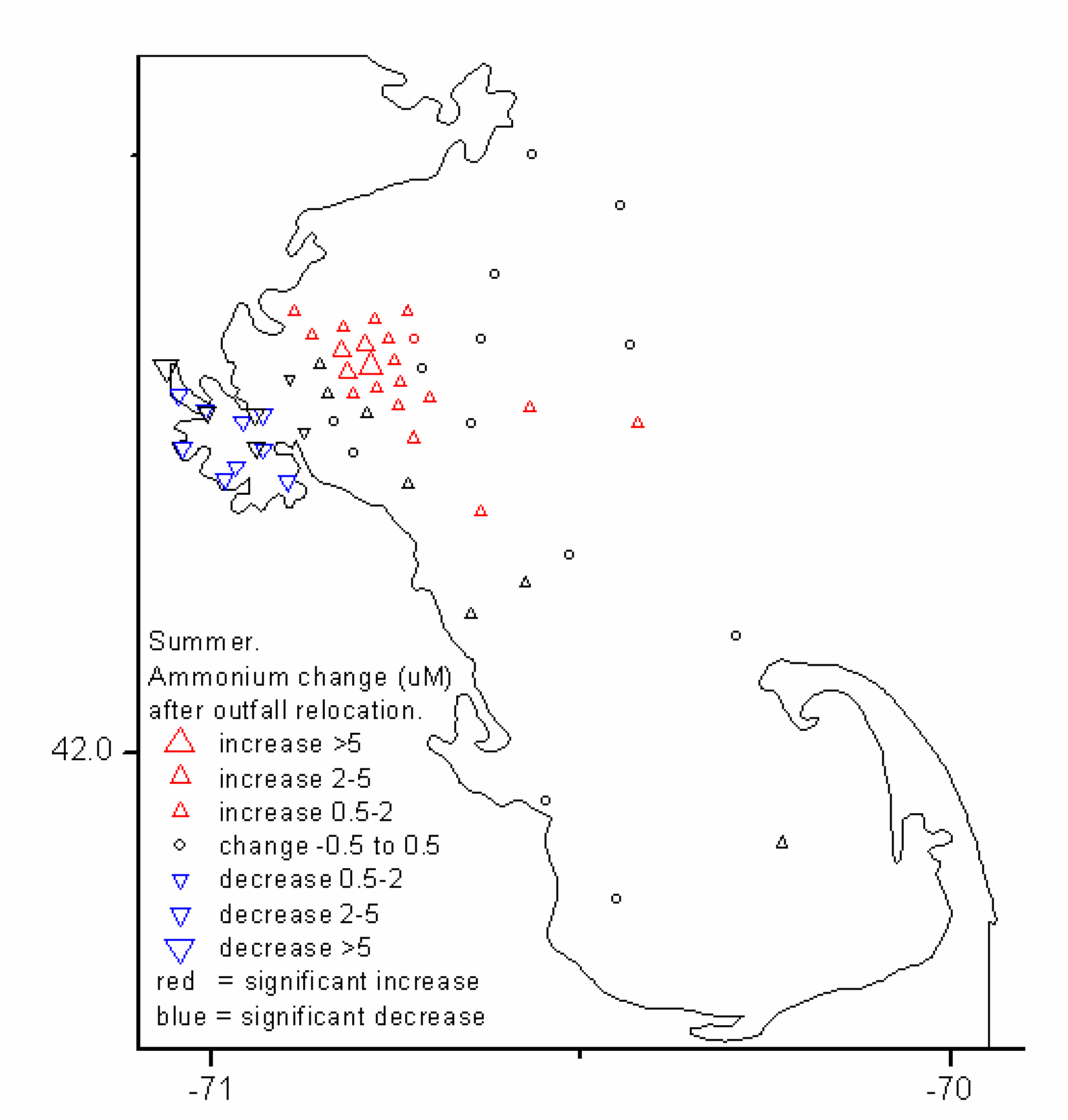


Figure 5-5. Change NH_4 concentration 2001 versus baseline in summer (April – October).

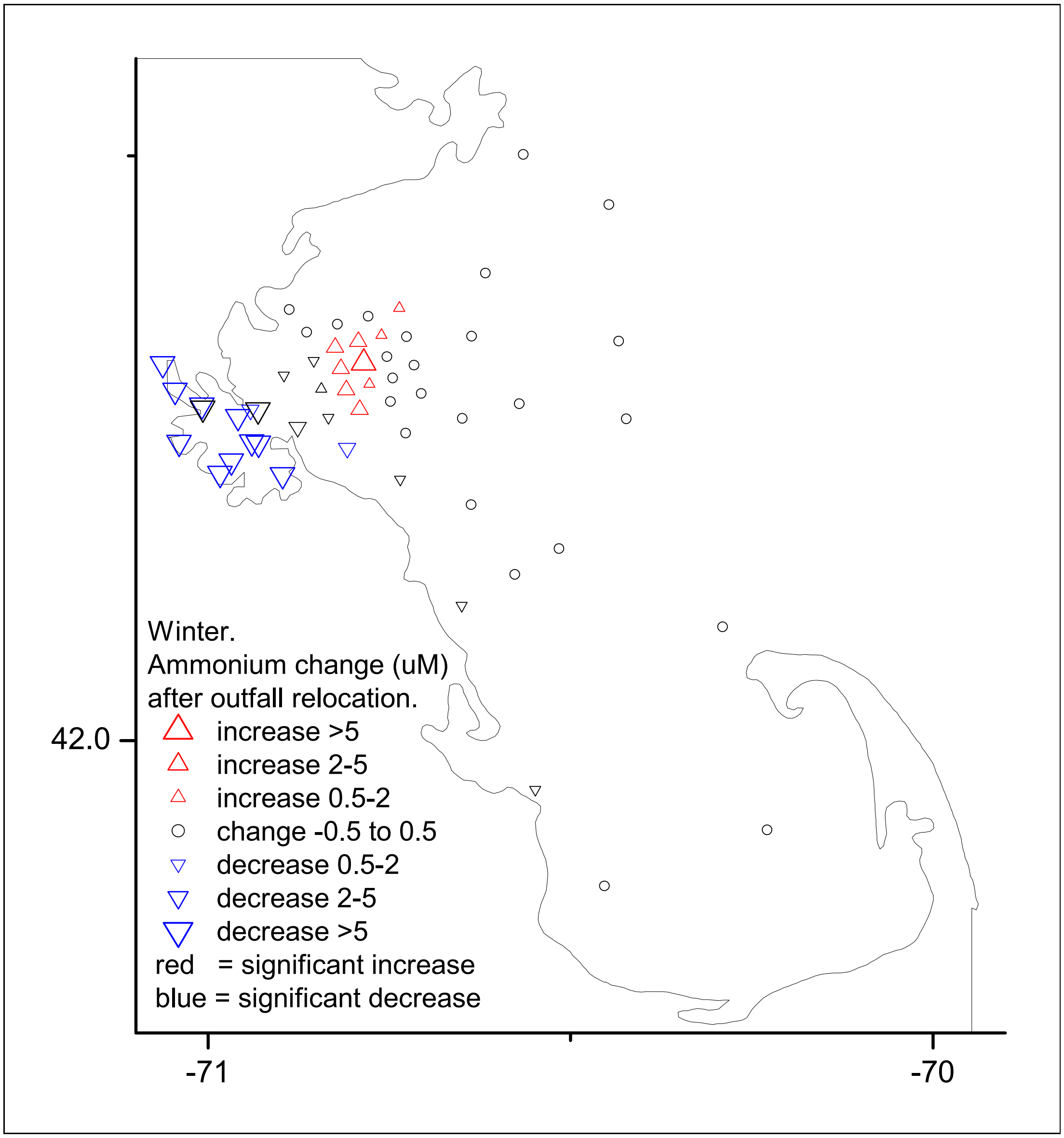


Figure 5-6. Change NH_4 concentration 2001 versus baseline in winter (November – March).

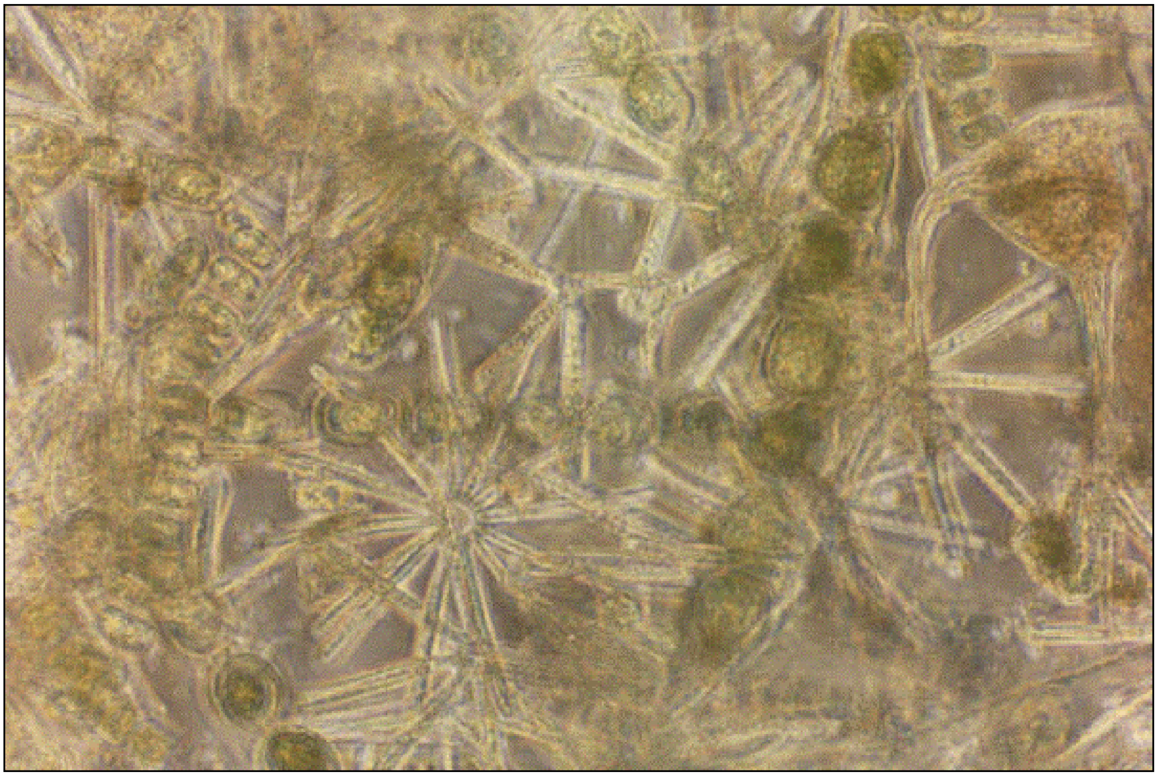


Figure 5-7. Photomicrograph of *Thalassionema nitzschoides* in a grab sample from station N21 (March 2001). The image was taken at 250X magnification by Dave Borkman, URI. *Thalassionema nitzschoides* is the long, thin diatom joined at one end forming fan-shaped colonies.

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