2002 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 bay outfall becomes operational. The surveys are 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 2002 data represent the second full year of conditions since initiation of discharge from the bay outfall on September 6th, 2000. This annual report evaluates the 2002 water column monitoring results, assesses spatial and temporal trends in the data, compares 2002 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. Water quality conditions in the bays are evaluated in the context of questions posed in the ambient monitoring plan (MWRA 1991).

2002 Water Quality:

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. This serves to cut off the supply of nutrients to the surface waters and terminates the spring bloom. The summer is generally a period of strong stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community. In the fall, stratification deteriorates and supplies nutrients to surface waters, which often contributes to the development of a fall phytoplankton bloom. Dissolved oxygen concentrations are lowest in the bottom waters 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.

This sequence has continued since the bay outfall became operational on September 6, 2000 and was generally evident in 2002. The major features and differences from the baseline in 2002 include:

- Dry conditions in fall 2001 continued into 2002 and significantly impacted conditions in early 2002. Meteorological conditions led to a delay in the onset of stratification (June) and decreased transport of Gulf of Maine waters into Massachusetts Bay in the spring.
- The winter/spring bloom started prior to the first survey in early February as indicated by the productivity, chlorophyll, and nutrient data. This is the second year in a row that the bloom was underway by early February and marks a departure from winter/spring bloom initiation in late February that had been observed during the 1995-2000 time period.
- A minor *Phaeocystis pouchetii* bloom was observed throughout most of Massachusetts and Cape Cod Bays in April.
- These blooms did not deplete nutrient levels in the surface waters until June as the waters were weakly stratified until this survey.
- The weak stratification in late spring and early summer also contributed to the relative scarcity of *Ceratium*, which usually increases in abundance as the water column

becomes more stratified and their mobility gives them a competitive advantage over other phytoplankton.

- A substantial bloom was observed in August/September, which is earlier than usual for Massachusetts Bay and may have been associated with the decimation of zooplankton populations by ctenophore (*Mnemiopsis leidyi*) predation.
- A late fall bloom was also observed, but only in the chlorophyll and production data as phytoplankton abundance did not increase.
- Annual minimum DO levels were measured in October in the nearfield (6.43 mgL^{-1} and 71.25%) with comparably low minima throughout Massachusetts Bay. The DO minima in the nearfield and Stellwagen Basin did not go below contingency thresholds.
- Although relatively large winter/spring and fall blooms were observed in 2002, seasonal and annual mean chlorophyll levels in the nearfield were well below contingency thresholds.
- The nuisance algae *Alexandrium* spp. and *Pseudo-nitzschia pungens* were observed intermittently at abundances well below threshold values.
- The minor *Phaeocystis* bloom in March and April was well below threshold values for the winter/spring, but, as the bloom was still present on May 1st, the summer *Phaeocystis* threshold value was exceeded. This was not indicative of any problem or impact associated with the outfall rather due to the timing of the survey and the very low summer threshold value.

Monitoring Questions:

When the outfall site was chosen and the outfall monitoring plan originally designed, MWRA expected to discharge primary treated effluent through the outfall for a number of years before full secondary treatment was available. As outfall completion was delayed, it became clear that effluent discharged in Massachusetts Bay would receive more thorough treatment. The primary concerns shifted from effects of high-organic-material discharge on dissolved oxygen levels and on the benthic community to the effects of a nutrient-rich discharge into the bottom waters of the bay. Secondary sewage treatment effectively removes organic material, but only removes about 20% of the nitrogen. The biological treatment process also changes the nitrogen in the wastewater from primarily organic nitrogen to dissolved inorganic forms (primarily NH_4), which may be more readily taken up by marine algae. Therefore, concern over water column impacts has shifted from those associated with biological oxygen demand to a focus on the potential for eutrophication and for subtle ecosystem shifts in Massachusetts Bay, due to relocating the nutrient-rich discharge from the shallow, well-mixed, turbid waters of Boston Harbor to the deep, clear waters of Massachusetts Bay. These concerns were addressed in a set of the monitoring questions (MWRA 1991) that focused on circulation in the system and MWRA effluent's effect on water quality in the bays with respect to nutrients including eutrophication impacts such as nuisance algal blooms and hypoxia, and ecosystem impacts on planktonic communities

Over the course of the HOM program much has been learned about the Massachusetts and Cape Cod Bays system. Our understanding of the circulation and importance of the Gulf of Maine to both water properties and biology of the system has led to changes in the way we envision the bay outfall might impact the bays. No longer is the system viewed as a simple upstream to downstream conveyor belt, but rather one that has a weak and seasonal counterclockwise circulation pattern that is often obscured by tidal and local/regional wind forcing. The influence of the Gulf of Maine has been observed on circulation, nutrient loading, dissolved oxygen, and nuisance species in the bays. Improved understanding of these linkages remains critical for assessing the relative impact of the bay outfall on water quality in Massachusetts and Cape Cod Bays.

Changes in the nutrient regimes following diversion are unambiguous – NH_4 has dramatically decreased in Boston Harbor and nearby coastal waters while increasing in the nearfield. Although the effluent plume is consistently observed in the nearfield, detectable levels are confined to an area within 20 km of the outfall. The higher nearfield NH_4 concentrations have not translated into increased biomass whether measured as chlorophyll, POC, or phytoplankton abundance. On a station specific basis, there has been a slight increase in winter/spring and fall bloom production and biomass in the nearfield. In Boston Harbor, a dramatic decrease in NH_4 has been concomitant with decreases in chlorophyll, POC, and production, and preliminary results indicate that the seasonal pattern in productivity may be changing from a eutrophic to a more normal temperate coastal pattern. Further study is necessary before statistically significant change can be documented and conclusions drawn as to the impact, or lack thereof, that the transfer of discharge from the harbor to the bay outfall has on the Massachusetts and Cape Cod Bay system.

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1.0 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) is conducting 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 2002 data represent the second full year of measurements 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 2002 water column monitoring data have been reported in a series of survey reports, data reports, and semiannual interpretive reports (Libby *et al.,* 2002a and 2003). The purpose of this annual report is to present a compilation of the 2002 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 2002 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 post diversion data from September 6, 2000 thru December 2002 are also examined in context of the monitoring questions posed in 1991 that describe a series of possible environmental responses to the transfer of the discharge from the harbor to the bay outfall (MWRA 1991). These questions were originally conceived as a basis for evaluating changes and possible responses, but not necessarily actual or the only responses that could occur. A summary of the questions pertaining to the water column monitoring effort is provided below.

Water Circulation

- What are the nearfield and farfield water circulation patterns?

Nutrients

- Have nutrient concentrations changed in the water near the outfall?
- Have nutrient concentrations changed in Massachusetts Bay or Cape Cod Bay and, if so, are they correlated with changes in the nearfield?

Biology and Productivity

- Has phytoplankton biomass changed and, if so, can changes be correlated with ambient water nutrient concentrations?
- Has phytoplankton biomass changed in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?
- Have production rates changed in the vicinity of the outfall or Boston Harbor and, if so, can these changes be correlated with changes in ambient water nutrient concentrations?
- Have phytoplankton or zooplankton species composition changed in the vicinity of the outfall and, if so, can these changes be correlated with ambient water nutrient concentrations?
- Have phytoplankton or zooplankton species composition changed in Massachusetts Bay or Cape Cod Bay and, if so, can the changes be correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?
- Has the abundance of nuisance or noxious phytoplankton species changed?

Dissolved Oxygen

- Has dissolved oxygen in the nearfield changed relative to baseline and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?
- Has dissolved oxygen changed in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?
- Does dissolved oxygen in the water column meet the State Water Quality Standard in the nearfield and farfield?

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 phytoplankton and zooplankton community composition (Section 4). Unlike previous annual reports, this report focuses on addressing the 1991 monitoring questions rather than a reanalysis of the detailed dataset presented in the semiannual reports. Those interested in an extensive presentation of all 2002 monitoring results are referred to the semiannual reports (Libby *et al.*, 2002a and 2003). A summary of the current understanding of the system serves as an introduction to both Sections 3 and 4 and serves as a basis for discussion of topics pertinent to the post discharge data in general and 2002 monitoring data specifically. The final section (Section 5) completes this integration and provides an overview of the major findings from the 2002 water column data including comparisons of data against the established Contingency Plan (MWRA 2001) thresholds and a summary of the current status for addressing the monitoring questions (MWRA 1991).

2.0 2002 WATER COLUMN MONITORING PROGRAM

This section provides a summary of the 2002 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: 2002-2005 (Libby *et al*., 2002b). 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* water quality data, >20 µm phytoplankton species abundance, whale watch information, and any deviations from the plan were summarized in a survey report.

Results for 2002 water column surveys have been presented in data reports: nutrient (including calibration information, sensor and water chemistry data), plankton (phytoplankton and zooplankton), and productivity/respiration. These data reports were submitted to the MWRA four times per year. The 2002 results have also been presented in semiannual water column reports that provide descriptions of physical, chemical, and biological conditions in the bays over the course of the year (Libby *et al*., 2002a and 2003). 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 from MWRA.

2.2 2002 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 17 surveys that were conducted in 2002 (**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 six 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 27 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), 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, subsets of the data have also been grouped to focus on the deep-water stations off of Cape Ann (F26 and F27 – Northern Boundary) and in Stellwagen Basin (F12, F17, F19 and F22 – see **Figure** 2-2). Details on the sampling protocols can be found in the CW/QAPP (Libby *et al.*, 2002b).

Table 2-1. Water quality surveys for 2002 (WF021-WN02H).

Survey #	Type of Survey	Survey Dates
WF021	Nearfield/Farfield	February 5-9
WF022	Nearfield/Farfield	February 26-28, March 1
WN023	Nearfield	March 25
WF024	Nearfield/Farfield	April 5, 10-12
WN025	Nearfield	May 1
WN026	Nearfield	May 22
WF027	Nearfield/Farfield	June 10, 11, 14, 18
WN028	Nearfield	July 12
WN029	Nearfield	July 25
WN02A	Nearfield	August 9
WF02B	Nearfield/Farfield	August 19-22
WN02C	Nearfield	September 19
WN02D	Nearfield	September 25
WF02E	Nearfield/Farfield	October 7, 9, 10, 15
WN02F	Nearfield	November 4
WN02G	Nearfield	November 20
WN02H	Nearfield	December 11

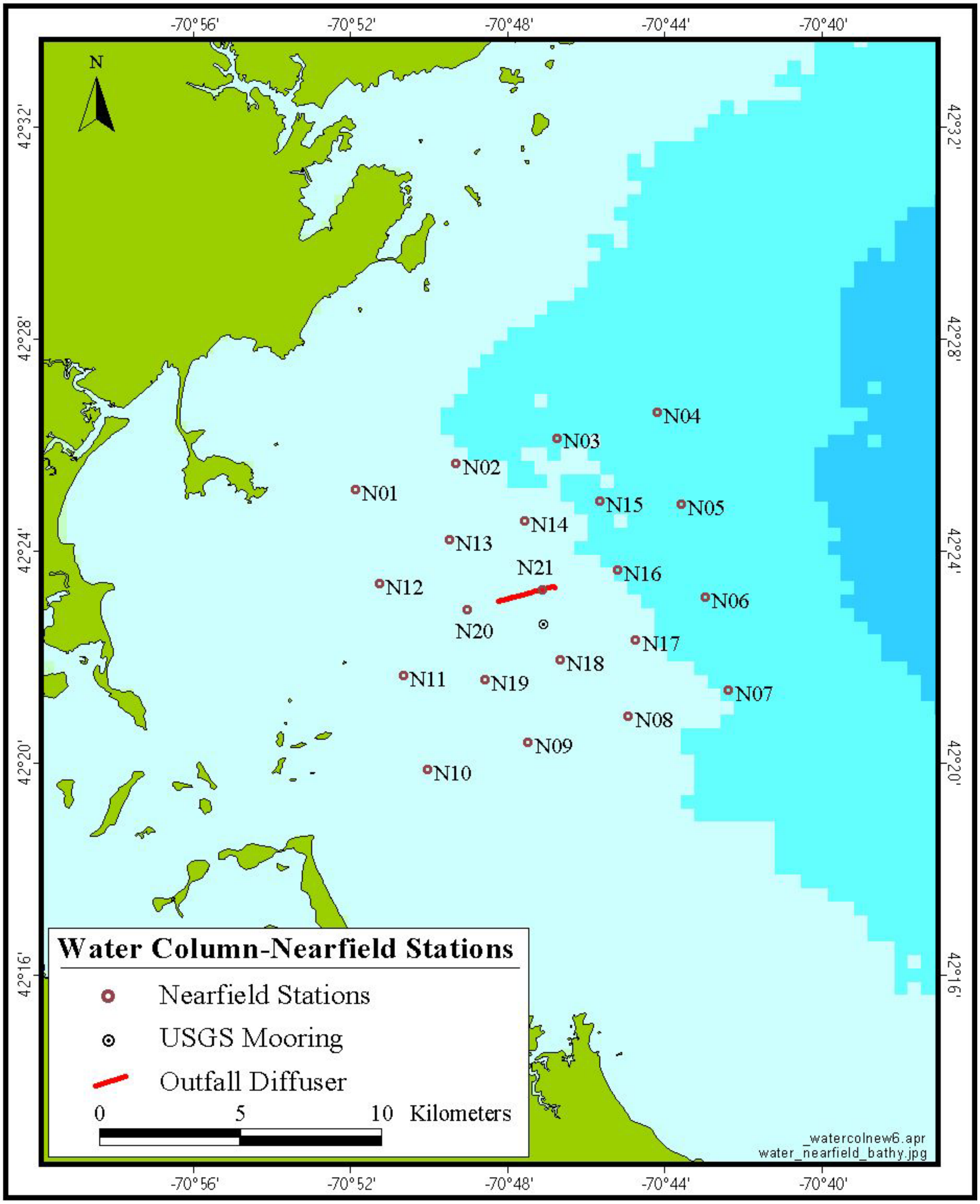


Figure 2-1. Locations of nearfield stations, MWRA offshore outfall, and USGS mooring.

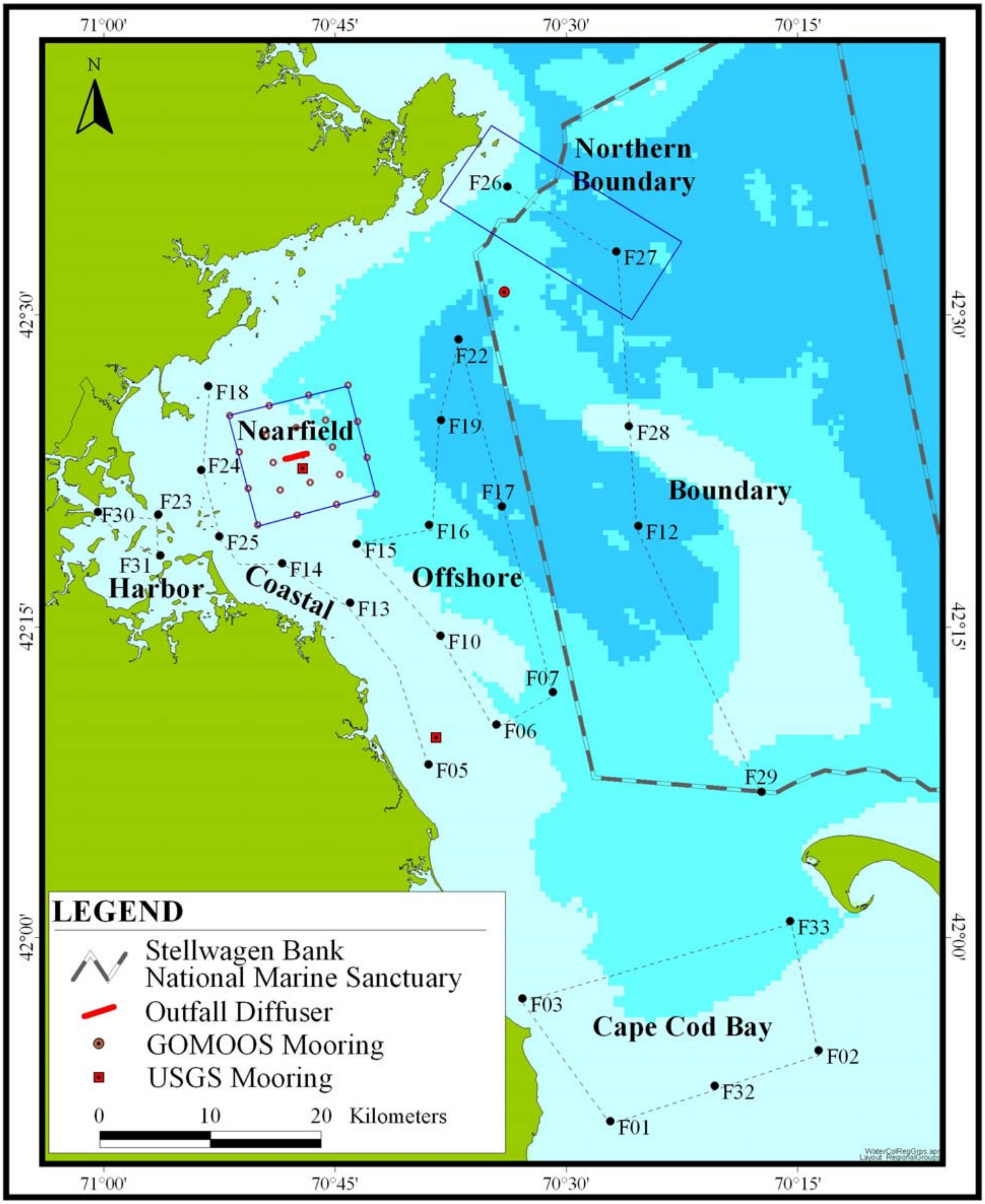


Figure 2-2. Locations of farfield stations and regional station groupings.

3.0 PHYSICAL CHARACTERIZATION

3.1 Circulation and General Physical Properties

3.1.1 Massachusetts and Cape Cod Bays

Circulation, water properties, and consequently, the biology of Massachusetts and Cape Cod bays are often affected by the larger pattern of water flow in the Gulf of Maine (Beardsley *et al.*, 1997). The western Maine coastal current usually flows southwestward along the coast of Maine and New Hampshire and may enter Massachusetts Bay south of Cape Ann. Water entering under these conditions eventually exits the bays north of Race Point at the tip of Cape Cod. Winds strongly influence the direction of circulation and the connectivity between the Gulf of Maine and the Bay. The optimal conditions for input of Gulf of Maine waters are winds from the northeast, combined with significant freshwater inflow from the Gulf. Winds from the south impede the surface water inflow, although they cause upwelling, which pushes surface water offshore and allows deep waters to enter from the Gulf. During the spring, when fresh water enters the bay from the north and northerly winds are prevalent, the transport often follows the counterclockwise path in **Figure** 3-1, around the perimeter of Massachusetts Bay, into Cape Cod Bay and out around Race Point. In late spring and summer, Cape Cod Bay becomes isolated from this circulation. During the summer, southerly winds usually predominate, which is conducive to upwelling conditions.

The Merrimack River and rivers further north in the Gulf of Maine provide most of the freshwater inflow to Massachusetts Bay (Manohar-Maharaj and Beardsley, 1973). Although they don’t empty directly into the bay, their flow is much greater than the Charles River and other Massachusetts Bay rivers. The spring freshet results in salinity stratification in early April. As the surface waters warm up in May and June, temperature stratification dominates over that due to the freshwater input. During the summer there is a strong and persistent pycnocline throughout most of Massachusetts and Cape Cod bays, occasionally punctuated by storm mixing events. The waters remain stratified until late October or early November, when surface cooling and wind stress cause the water column to become vertically mixed. **Figures** 3-2 through 3-4 show the seasonal progression of temperature, salinity and density across the Boston-Nearfield transect in northern Massachusetts Bay for 2002.

Wind-induced upwelling and downwelling causes large variations in the water properties at the outfall site by advecting the waters on- and offshore. Persistent, strong southerly or southwesterly winds in summer lead to upwelling. Upwelling causes a decrease in both surface and bottom water temperature, but most notably the surface water. Downwelling causes a significant increase in bottom water temperature. Upwelling and downwelling have some influence on vertical exchange, but their main influence is the horizontal advection of gradients. Wind effects also include temporary destratification of the water column by large summer storms (for example, Hurricane Bob in 1990). A stormy early autumn can also lead to early fall turnover.

3.1.2 Nearfield and Effluent Distribution

The combination of the general circulation within Massachusetts Bay and local conditions and mixing determine the fate and transport of effluent discharged from the outfall. There are a number of different possible trajectories of the flow (see **Figure** 3-1), depending on the density distribution in the system and the winds. The residence time of the bay varies with the inflow from the Gulf, and Cape Cod Bay is at times somewhat isolated from Massachusetts Bay. The bay is stratified from about April through October, which leads to trapping of the effluent plume below the pycnocline. Density- and wind-driven flow determine the horizontal transport of effluent within and out of the nearfield area.

The extent of horizontal exchange is illustrated by **Figure** 3-5, which presents a set of progressive vector diagrams provided by USGS (Woods Hole, MA). The plots indicate 1-day trajectories[1] over a one-month period, at near-surface and deep water levels, based on analysis of current meter data. The trajectories include the effects of tides, which cause east-west excursions of several kilometers, as well as motions due to winds and other factors. There is essentially no mean flow at the outfall location; bottom currents of around 6 cm/s are very variable in direction (Butman *et al.*, 2002). The primary temporal and spatial scales of variability near the outfall are those of the tides and of local weather patterns. These representations show that that although the long-term average, net velocity is small at the outfall site, there is considerable "random" motion, which causes water parcels to be exchanged freely between the outfall site and other parts of the bay. The largest displacements in **Figure** 3-5 are in surface waters in summer. The vertical density gradient present in summer allows surface waters to slip relative to bottom waters, and thus surface waters move more readily in response to wind and tide.

The impact of the effluent is minimized by dilution. A 2-km long diffuser with 271 ports disperses the effluent into the 30 m deep waters in the bay, where the effluent mixes rapidly with large volumes of seawater to achieve very low concentrations of any contaminants that remain after secondary treatment. This was documented by a study conducted during the summer of 2001 that used rhodamine dye to track the distribution and estimate dilution of the effluent plume (Hunt *et al*., 2002). During the study, there was moderate stratification of the water column, as is typical of the early summer. The field results confirmed model predictions that the initial dilution of the effluent is about 100:1 at the edge of the hydraulic mixing zone and that it is rapidly diluted by oceanographic processes beyond this zone (Hunt *et al.*, 2002). After initial dilution the effluent is dispersed more gradually throughout western Massachusetts Bay. Drifter and model studies indicate that effluent constituents may move toward the shore, or offshore where they are incorporated into the general circulation of the bays (Geyer *et al.*, 1992).

3.2 2002 Physical Oceanographic Conditions

3.2.1 Forcing Variables

3.2.1.1 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; **Figure** 3-6) indicate that the freshwater flow was unusually low in early 2002 due to low rainfall—in fact 2001/2002 was the driest winter of the entire monitoring program (**Table** 3-1). This was a continuation of drought conditions that were noted from September to December 2001 (Libby *et al.*, 2002c). The spring was dryer than normal but not extreme. The summer was again the driest of the monitoring program based on the Merrimack discharge (**Table** 3-1). The fall was also drier than normal but not extreme. Overall, 2002 was the driest year of the decade, with approximately 65% of the normal freshwater inflow.

3.2.1.2 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 the winter of 2002, the winds were upwelling-favorable (from the southerly direction) on average (**Figure** 3-7), which is considerably different from the normal wind pattern (from the north/northeast) that induce downwelling. This weather pattern contributed to the low river flow in that there were fewer storms than usual, which usually produce downwelling-favorable winds. The summer was unusual in the absence of net upwelling conditions on a

[1] Note that the currents were measured only at the USGS mooring near the outfall site; progressive vector diagrams would only represent real water parcel trajectories if currents were uniform throughout western Massachusetts Bay. Nevertheless this data presentation is a useful visualization of the variability of the flow at the outfall site.

monthly basis. Temperature data from the USGS mooring indicates that there was an upwelling event in the nearfield in mid August 2002 (**Figure** 3-8), but on the whole, conditions were not conducive to upwelling during this period. The rest of the year showed typical wind conditions. The wind speeds were close to the mean for each of the seasons in 2002 (**Table** 3-2).

3.2.2 Air Temperature

Air temperatures in early 2002 continued the trend of warmer than average values that was seen over the last three months of 2001 (Libby *et al.*, 2002c). From January thru April 2002, air temperatures remained elevated in comparison to 1989 to 2001 levels (**Figure** 3-9). Previous analysis has indicated that the average wintertime temperature influences the bottom-water temperature at the onset of stratification (Libby *et al*., 1999). **Table** 3-3 shows that in 2002, the average wintertime temperature (3.6°C) was well above its climatological average and was the warmest observed over the 1992-2002 period. Summer and fall temperatures tended to fall in the middle of the range (**Figure** 3-9).

Table 3-1. River discharge summary for the Charles and Merrimack Rivers 1990-2002.

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
2002	**6**	**10**	**1**	**9**
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
2002	**121**	**307**	**42**	**146**
mean	282	340	90	203

Table 3-2. Wind Speed, 1990-2002. 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
2002	**6.9**	**5.4**	**4.6**	**7.8**
Mean	7.3	5.3	4.7	7.0

Table 3-3. Winter Air Temperature, 1992-2002. 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
2001-2002	**3.6**
Mean	1.1

3.2.3 Water Temperature

The surface water temperature at the Boston Buoy for 2002 follows the pattern observed for air temperature - unusually warm through April, close to average during the summer, and warm in the fall (**Figure** 3-10). Comparison of surface and bottom water temperatures from 1992-2002 indicates that 2002 was unusually warm from February to April in the surface waters and through to July in the bottom waters (**Figure** 3-11). These winter temperatures continued the pattern of elevated values in both the surface and bottom waters that had been observed during the fall of 2001 and were the highest winter temperatures observed during the Outfall Monitoring observation period. Near-bottom temperatures remained above average during the remainder for the summer and fall in 2002 before approaching minimum values in late fall and winter.

The warm surface and bottom water temperatures during the first half of 2002 led to a relatively small vertical gradient in temperature from February through June (see **Figure** 3-2). Along the Boston-Nearfield transect the temperature gradient between surface and bottom waters was only 5-8°C in June 2002, which is low compared to previous years when it is usually >10°C.

3.2.4 Salinity

In 2001, salinity showed a normal seasonal progression as the drought conditions had not persisted for long enough for a salinity anomaly to show up in the fall of 2001. By 2002, however, surface and bottom water salinity was the highest on average in comparison to 1992-2001 (**Figure** 3-12). The 2001-2002 drought and the small amount of freshwater input that ensued led to high salinity throughout the monitoring period in 2002.

As observed for temperature, vertical gradients in salinity were relatively weak in April and June of 2002 (see **Figure** 3-3). Normally spring storms and freshwater inputs result in relatively low salinity in the surface waters of Massachusetts Bay – either due to direct precipitation or influence of the freshet from the Gulf of Maine. In 2002, however, the low freshwater inputs led to a weak salinity gradient in April which is normally the period when stratification of the water column is initiated.

3.2.5 Stratification

As would be expected based on the temperature and salinity data, stratification, as defined by the density gradient between surface and bottom waters, was unusually weak during the first half of 2002 (**Figure** 3-13). This was due to lack of freshwater inputs and the unusually warm bottom temperatures during that period. There was no evidence, however, that this weak stratification resulted in reduced water-column stability during this period (*e.g.,* episodes of strong vertical mixing). A density gradient of >1 sigma-t units (σ_t) has been used to indicate that the water column is stratified. In 2002, the density gradient did not become >1 σ_t in the nearfield until June (**Figure** 3-13). This is a relatively late onset of stratification. In comparison to previous years, the density gradient along the Boston-Nearfield transect in April 2002 was <1 σ_t while in April 2001 it was 1-2 σ_t over most of the transect (**Figure** 3-14).

3.3 Summary

The dry conditions in the fall of 2001 continued into 2002 and significantly impacted conditions in early 2002. The lack of storms and associated freshwater inflow in early 2002 and the relatively warm surface and bottom water temperatures led to a delay in the onset of stratification until June of 2002. The lack of storms was also expressed in the lack of northerly winds and slightly upwelling favorable conditions over the first half of the year. The predominance of southerly rather than northerly winds during the spring of 2002 also would have a tendency to decrease the transport of Gulf of Maine waters through Massachusetts Bay at this time. As noted at the start of this section, these anomalous physical conditions in early 2002 are not only manifested as changes in water properties and circulation, but also impact biological properties in the bays.

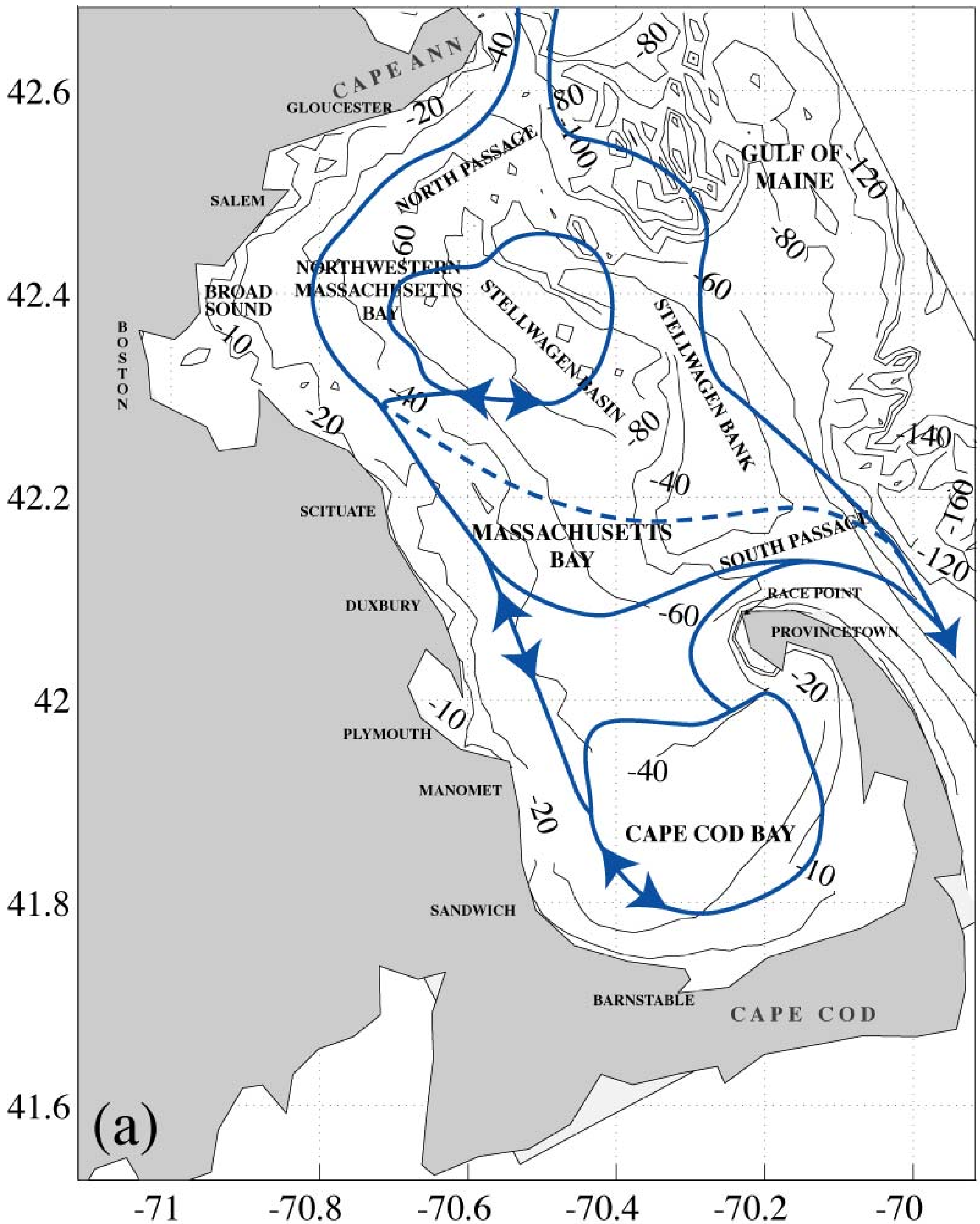


Figure 3-1. Summary of circulation within Massachusetts Bay (Lermusiaux 2001).

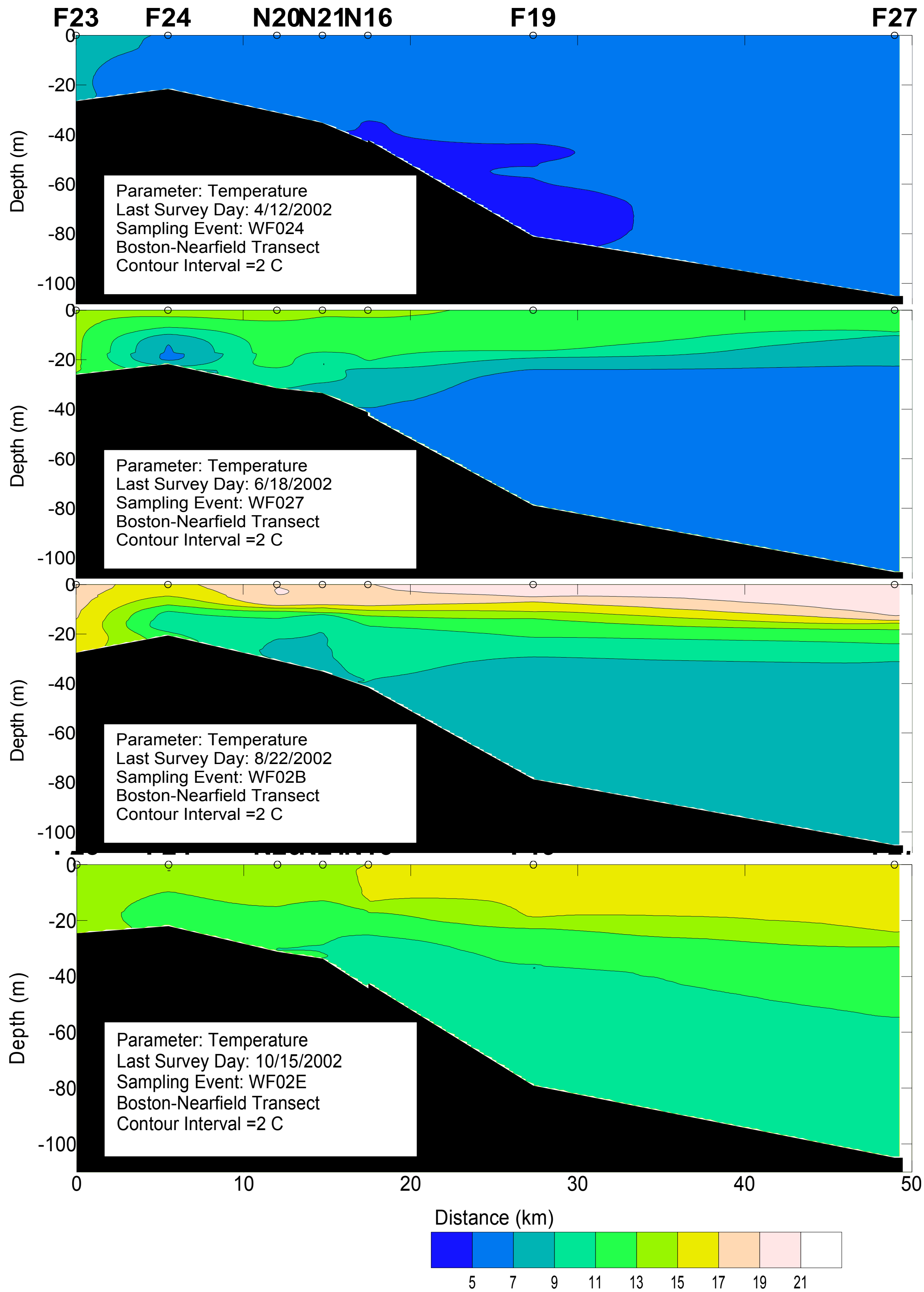


Figure 3-2. Temperature along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April-October 2002.

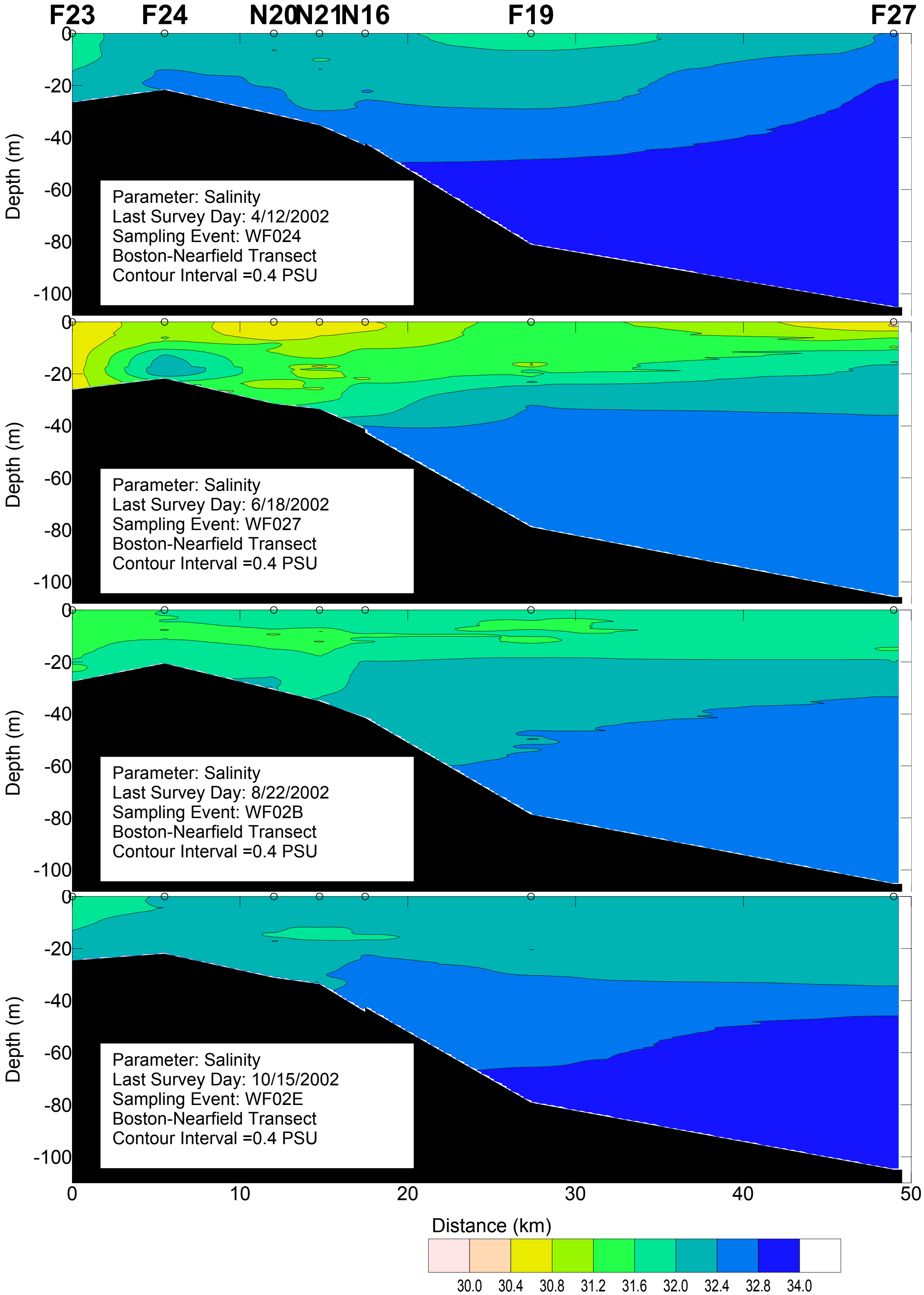


Figure 3-3. Salinity along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April-October 2002.

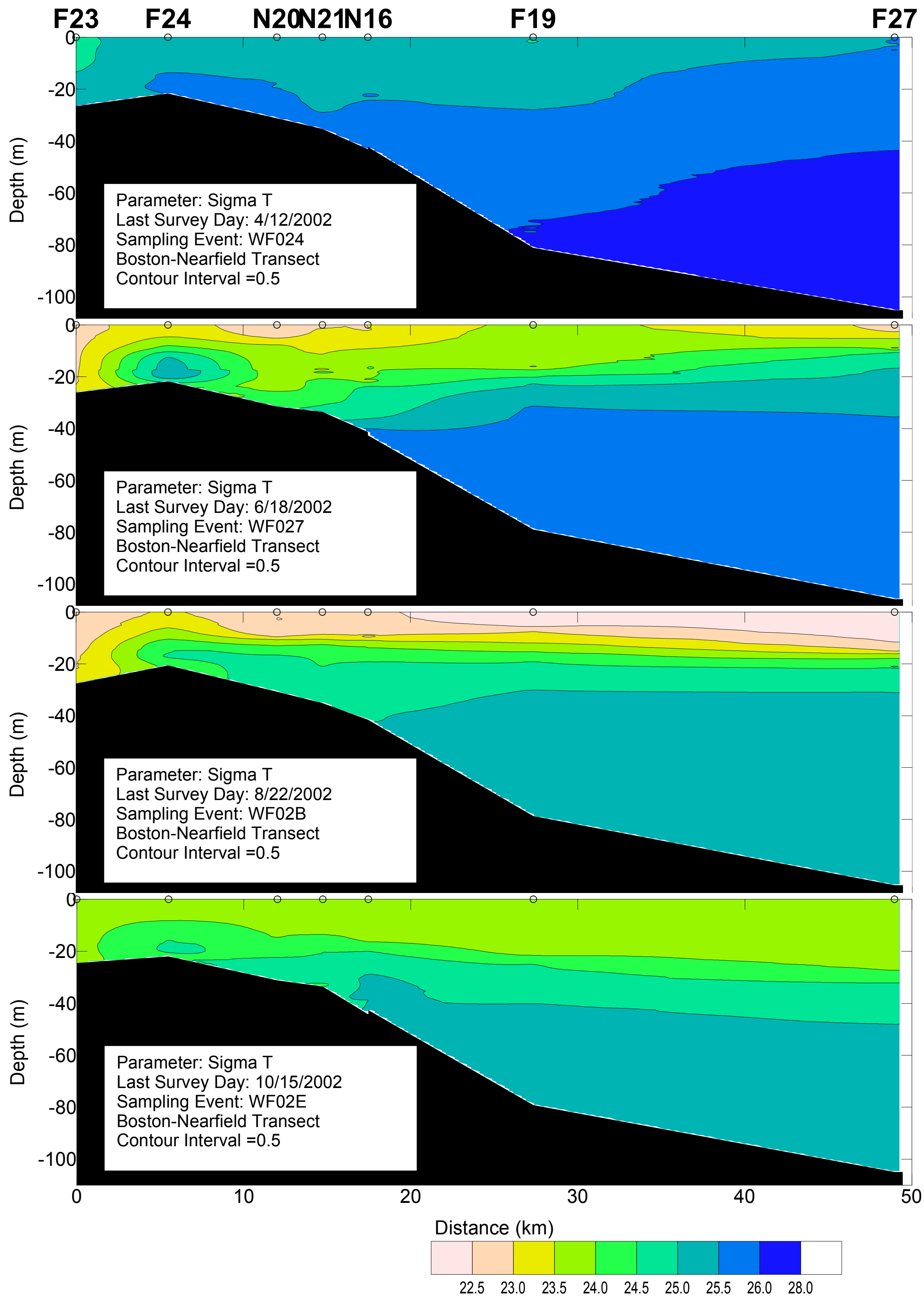


Figure 3-4. Density along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April-October 2002.

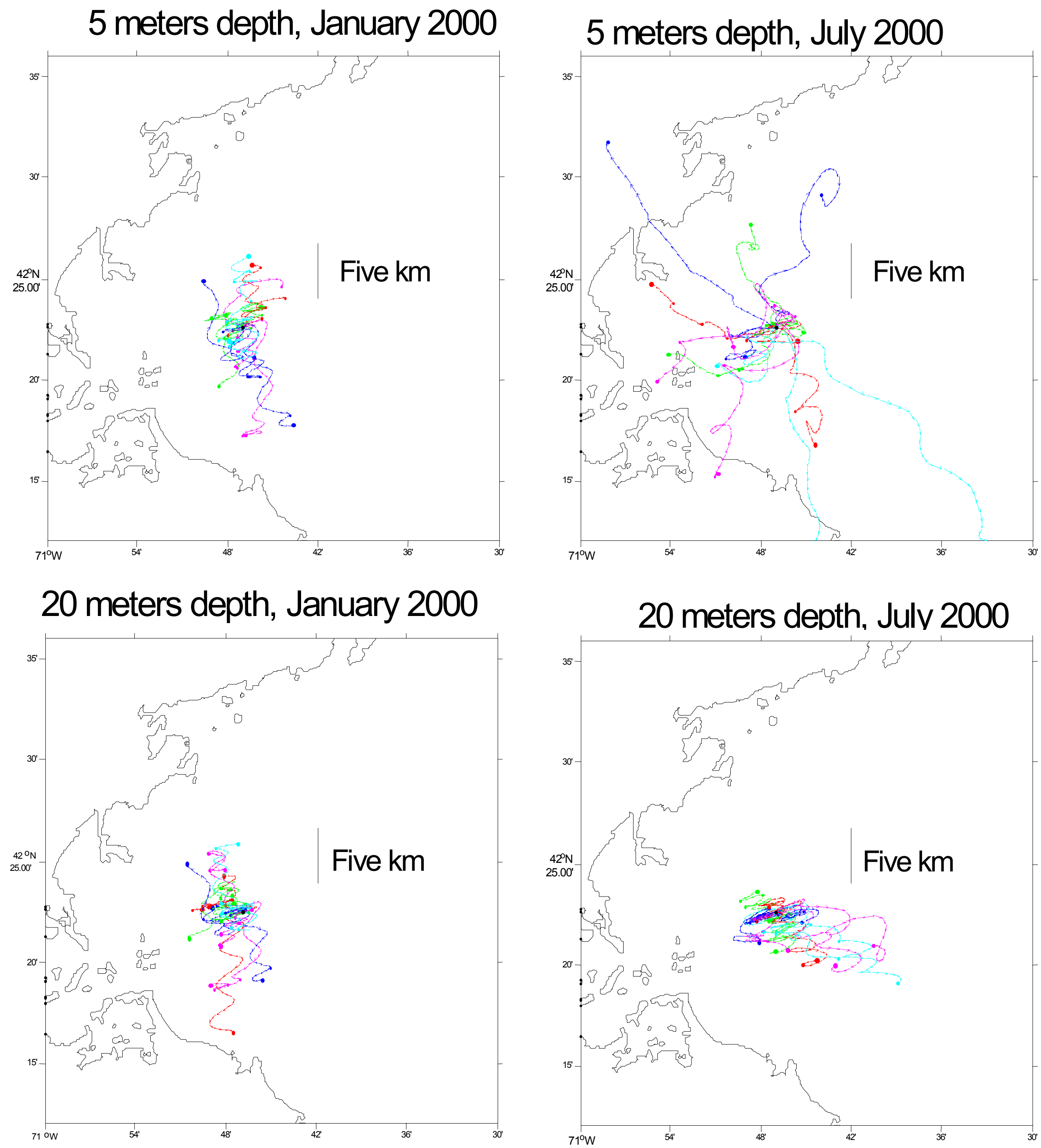


Figure 3-5. Progressive vector diagrams of currents near outfall site.

Trajectories illustrate 24-hour variation in currents from January 2000 (left) and July 2000 (right), near the surface (top panels) and near-bottom (bottom panels.) The Acoustic Doppler Current Profiler on the USGS mooring measured currents. Figures courtesy Soupy Alexander and Brad Butman, USGS.

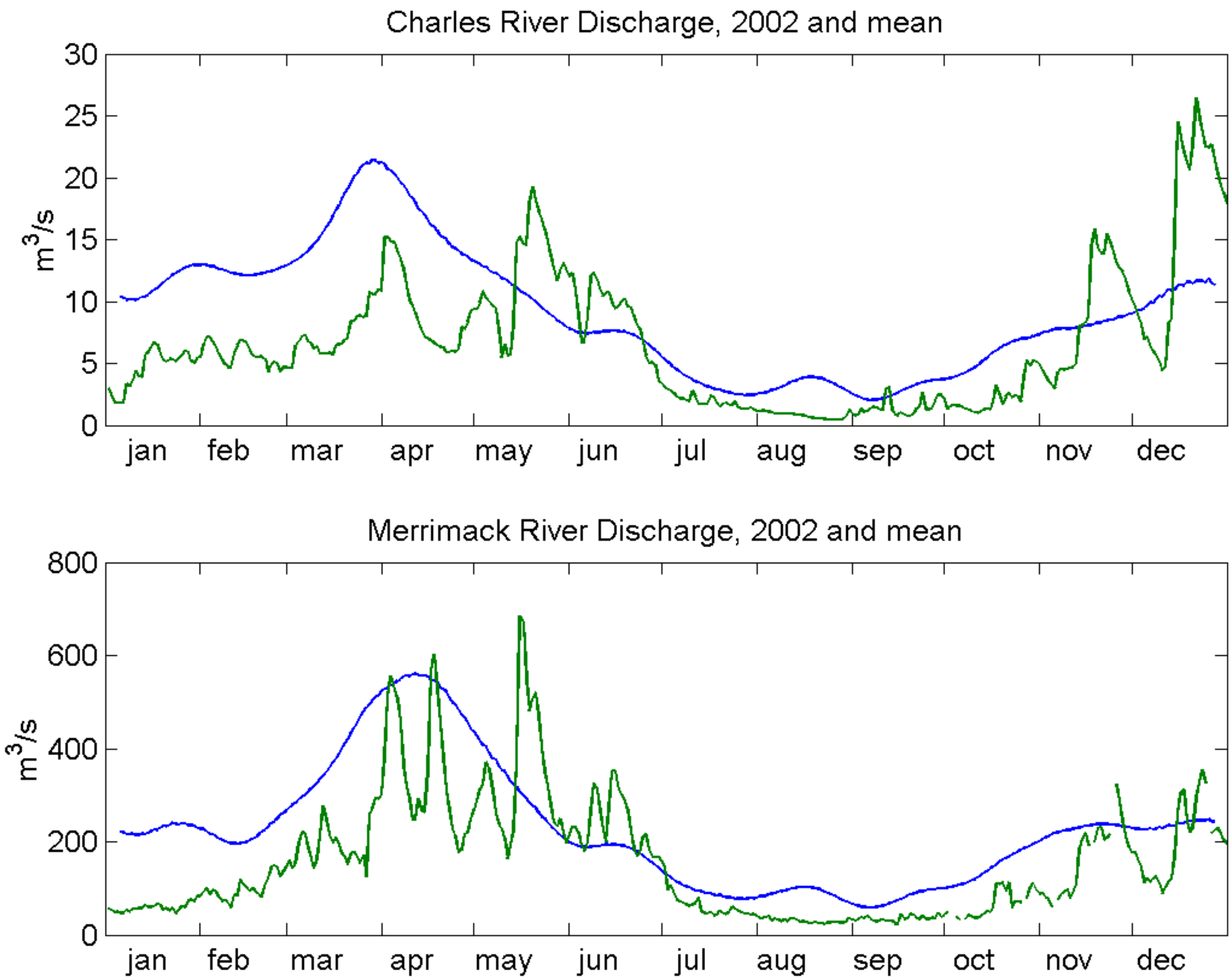


Figure 3-6. Charles River (at Waltham) and Merrimack River (at Lowell) discharge for the year 2002 (green curve), compared to the 12-year average (smoothed blue curve).

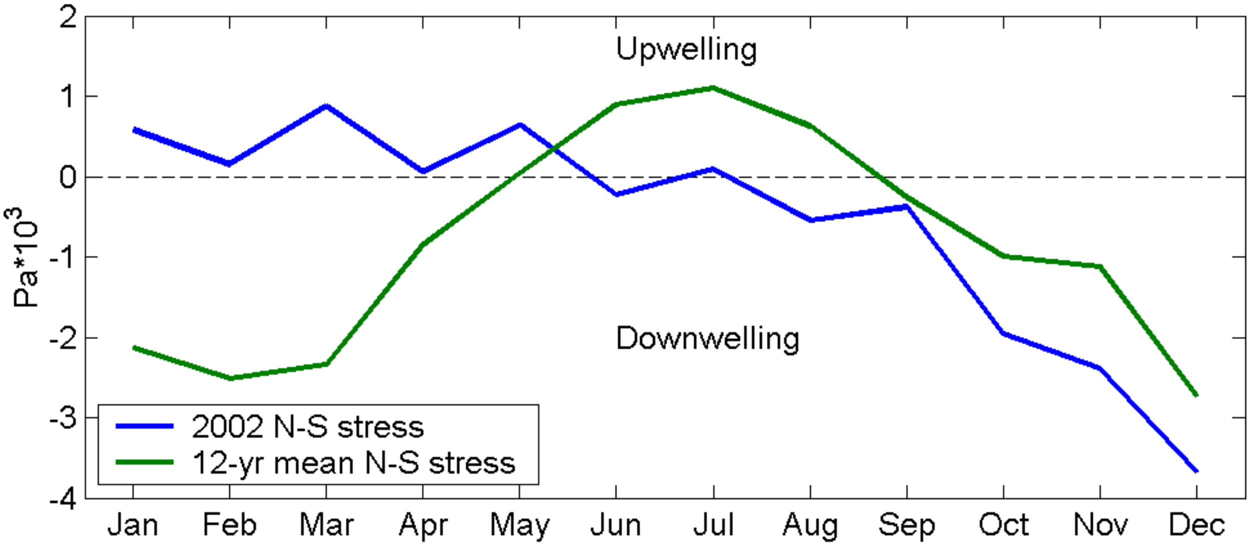


Figure 3-7. Monthly average N-S wind stress at Boston Buoy for 2002 compared with 12-year average. Positive values indicate northward-directed, upwelling-favorable wind stress.

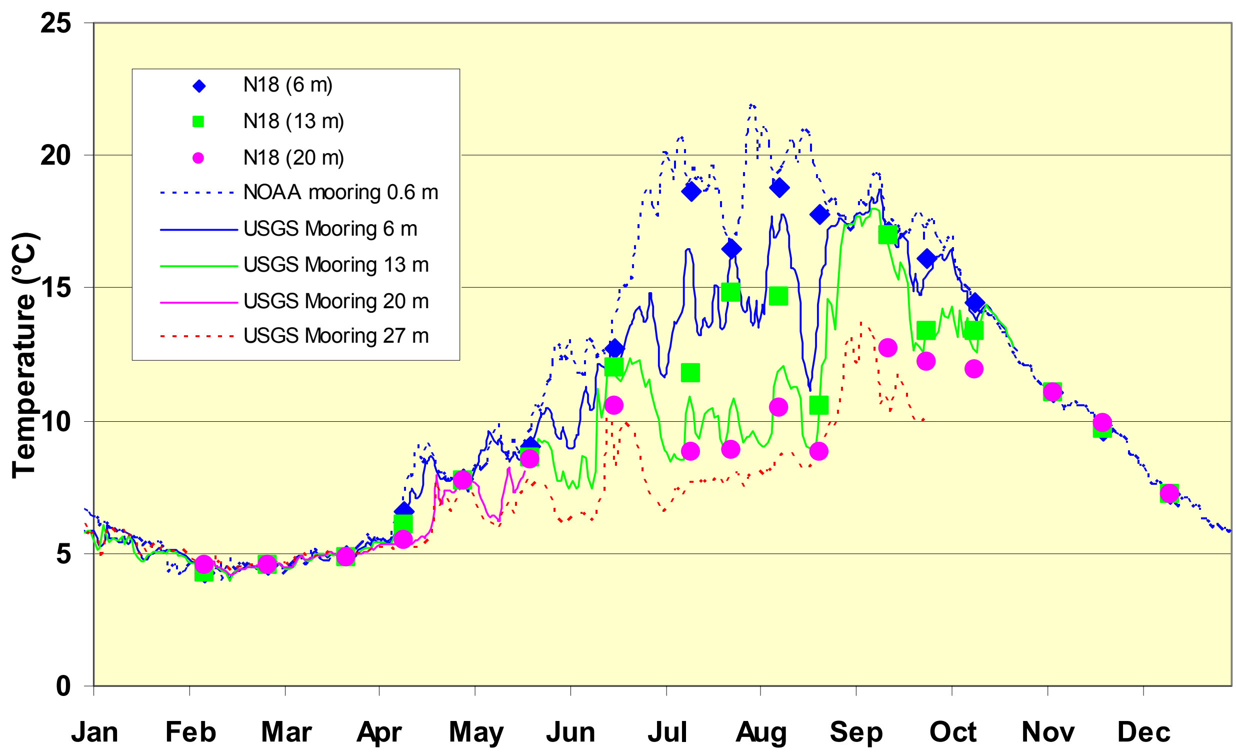


Figure 3-8. Boston Buoy NOAA and USGS temperature mooring data in the nearfield.

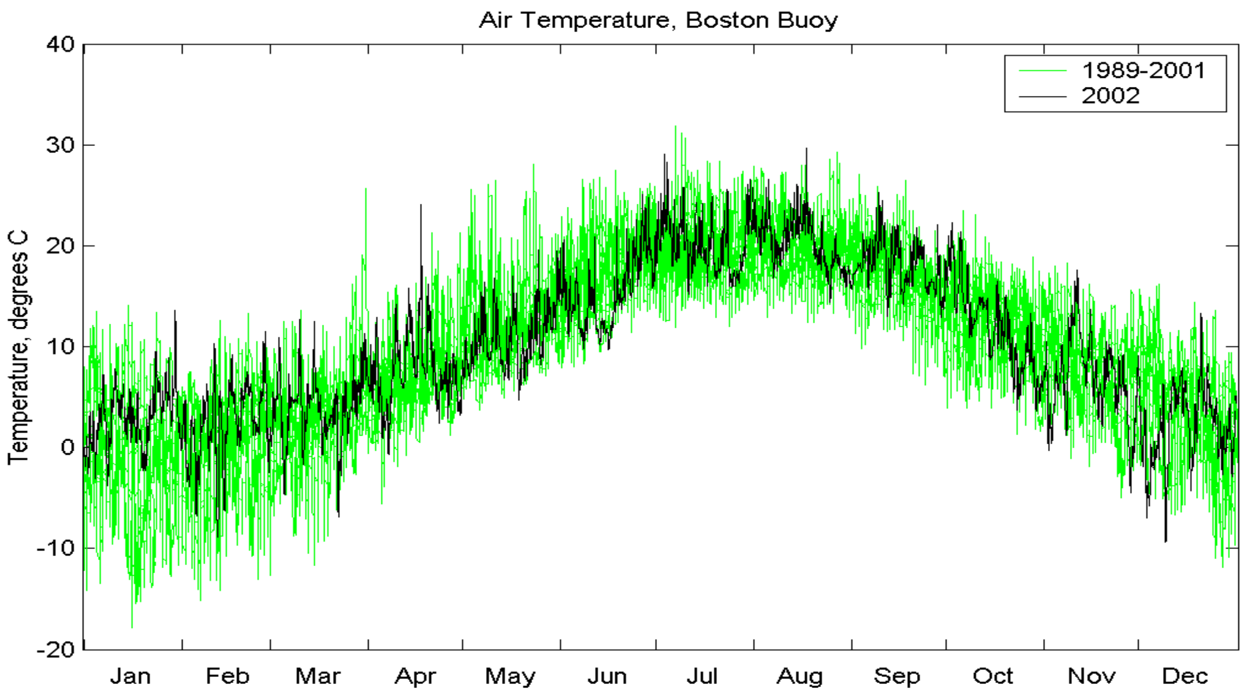


Figure 3-9. Hourly surface air temperature in 2002 (Black) measured at the Boston Meteorological Buoy compared to data from the last 13 years.

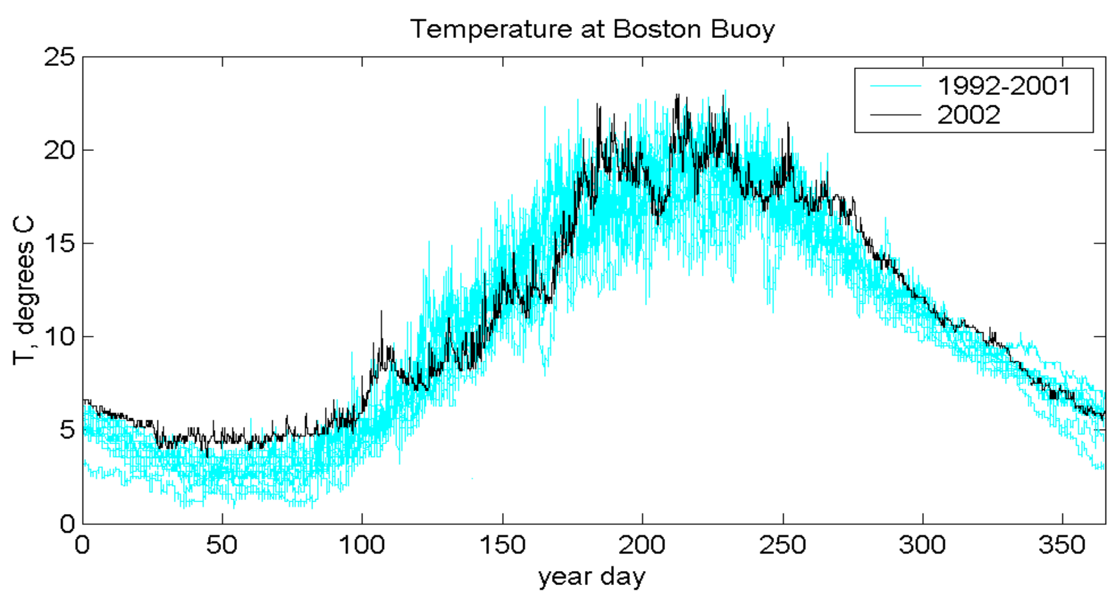


Figure 3-10. Hourly water temperature at the Boston Buoy (Black) superimposed on the data from the previous 10 years (blue). Data collected from 0.6 m depth.

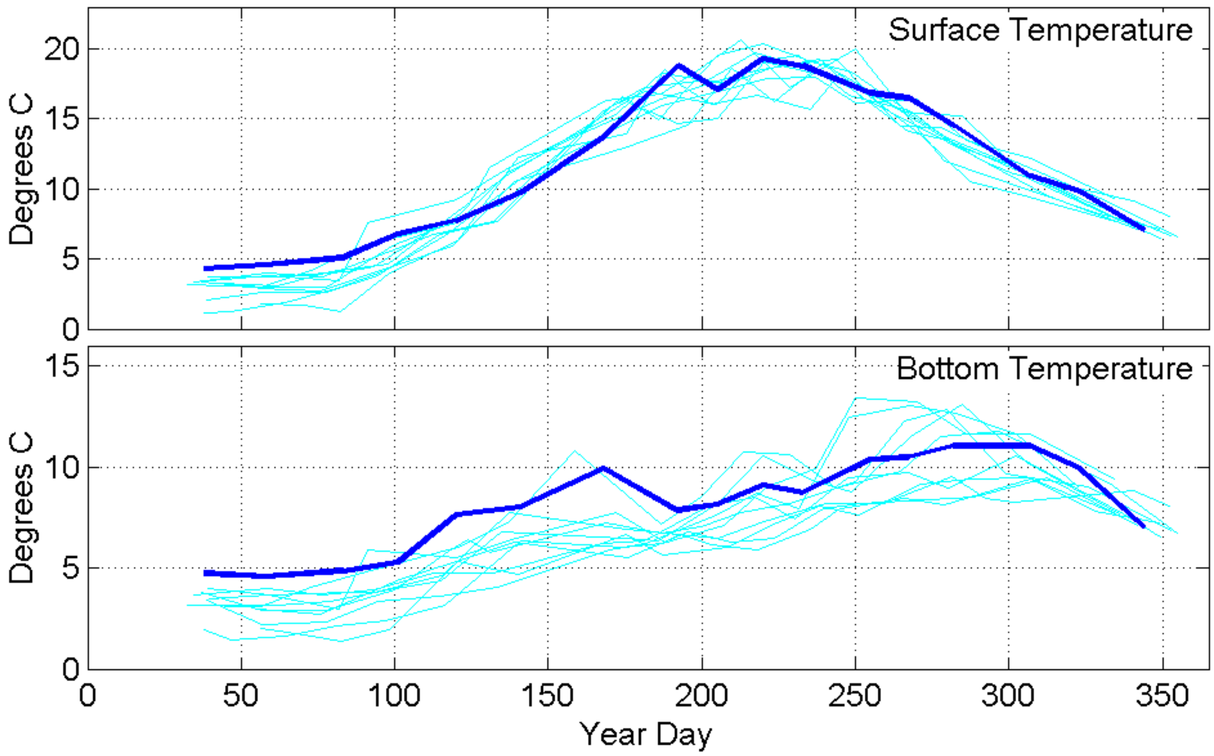


Figure 3-11. The annual cycle of surface and bottom temperature in the nearfield (average of data from stations N13, N14, N18, N19, N20 and N21), with the 2002 data shown in bold.

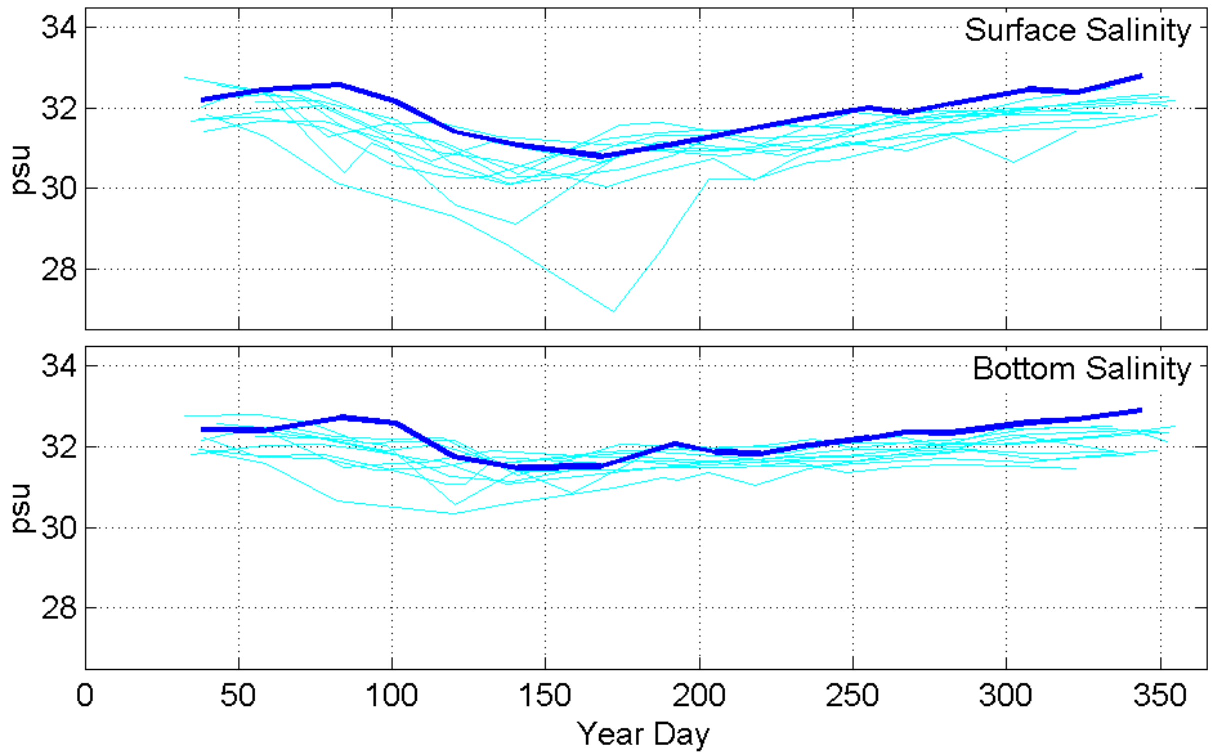


Figure 3-12. The annual cycle of surface and bottom salinity in the nearfield (same stations as Figure 3-11), with the 2002 data shown in bold.

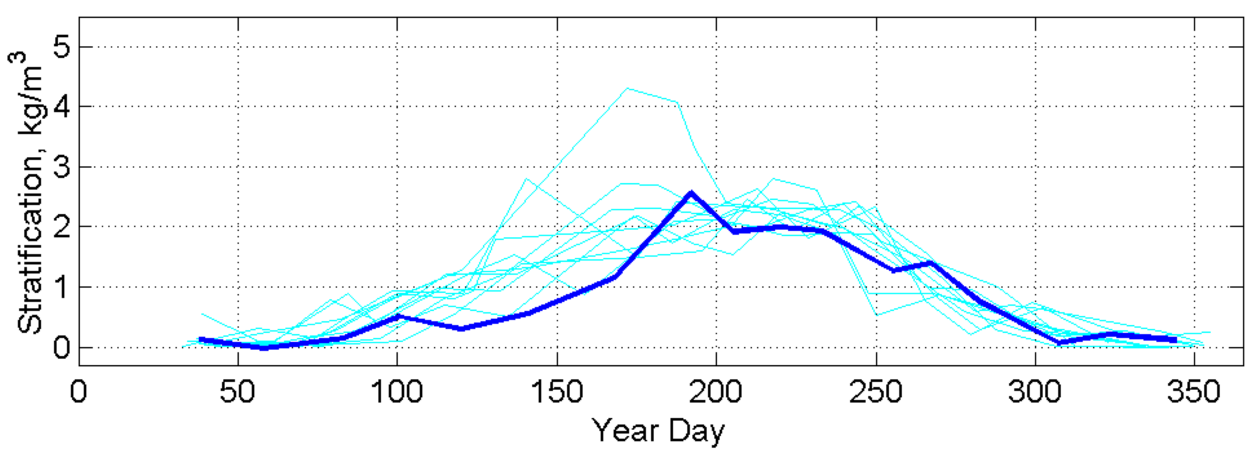


Figure 3-13. The annual cycle of stratification in the nearfield (same stations as Figure 3-11), with the 2002 data shown in bold.

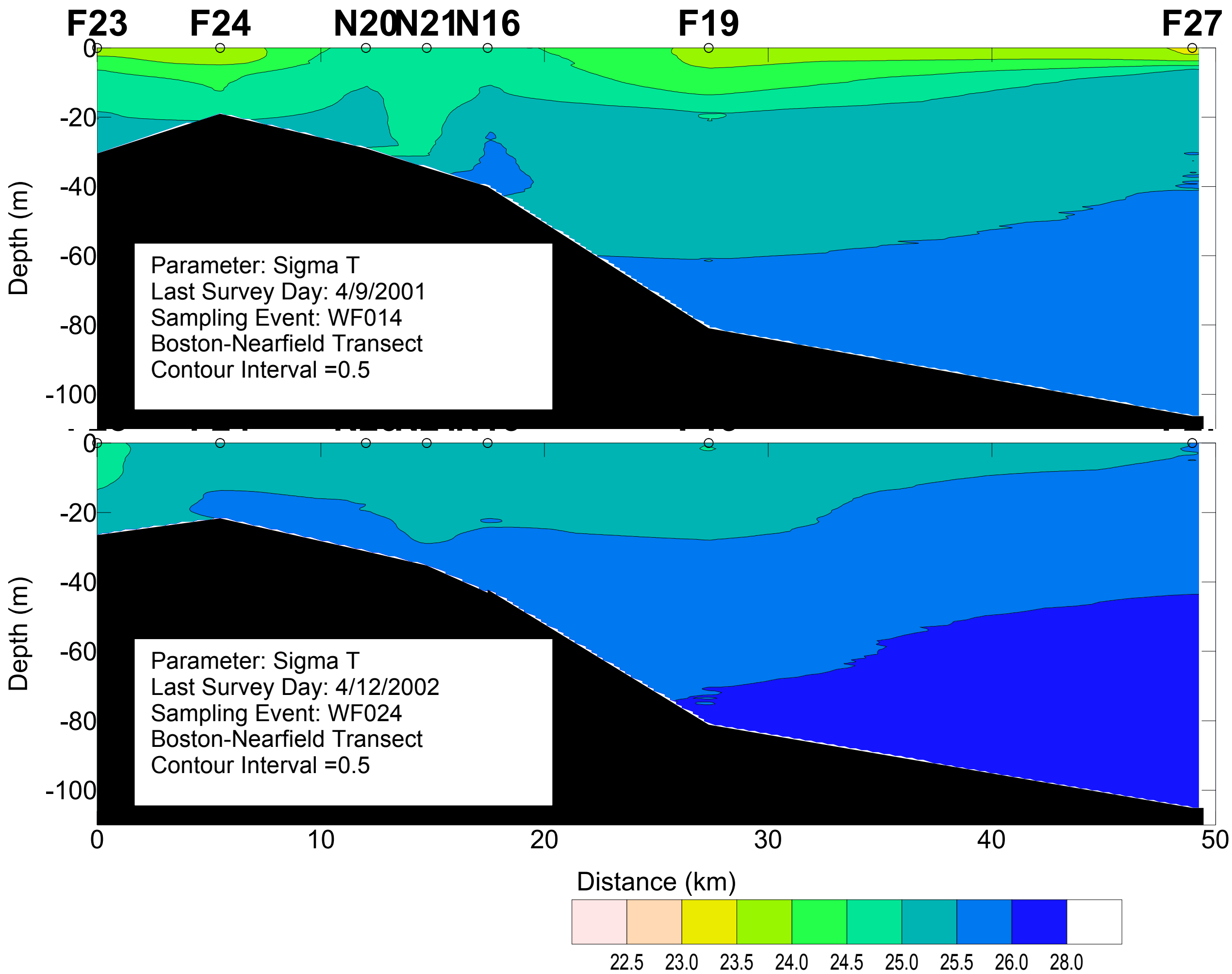


Figure 3-14. Density along Boston-Nearfield transect from Boston Harbor to the Gulf of Maine through the outfall zone, April 2001 and 2002.

4.0 WATER QUALITY

Over the course of the HOM program, general temporal and spatial trends in water quality characteristics have emerged from the data collected in Massachusetts and Cape Cod Bays. The trends are evident even though the timing, year-to-year manifestations and spatial extent of these events are variable. The physical dynamics of the system that were discussed in Section 3 are the primary influences on the occurrence, timing and extent of water quality events in the bays. A summary of these trends and spatial variability of water quality in Massachusetts and Cape Cod Bays is presented in Section 4.1 based on data collected during both the baseline and post-diversion periods. In Section 4.2, the 2002 monitoring results are discussed in comparison to these trends and versus baseline data with an emphasis on addressing the questions laid out in the 1991 Ambient Water Monitoring Plan (MWRA 1991).

4.1 Water Quality Trends and Characteristics

Massachusetts and Cape Cod Bays generally follow an annual cycle typical for temperate coastal waters (**Figure** 4-1), but the timing of events over the cycle are influenced by regional meteorological and oceanographic conditions (see Section 3). In the winter, the water column is well mixed, nutrient levels are high, and plankton biomass is low. The transition from winter to spring in Massachusetts and Cape Cod Bays is characterized by a series of physical, biological, and chemical events. A phytoplankton bloom often occurs as light increases, temperatures rise, and nutrients are available in the well-mixed water column. Centric diatoms often dominate early winter/spring blooms (February), while blooms of *Phaeocystis pouchetii* have tended to occur later in the spring (April). Winter/spring diatom blooms, when they occur, usually begin in the shallower waters of Cape Cod Bay. Blooms in the deeper waters of Massachusetts Bay usually begin two to three weeks later. Spring phytoplankton blooms are typically followed by an increase in zooplankton abundance. Later in the spring, stratification effectively separates the surface and bottom waters, preventing replenishment of nutrients to the surface and of oxygen to the bottom waters. Phytoplankton in the surface waters deplete the available nutrients and then undergo senescence. Phytoplankton abundance is also depleted by grazing.

The 'red tide' organism, *Alexandrium tamarense*, is rarely found in the bays; when present it is restricted to late spring. The presence or absence of *Alexandrium* is influenced by local forcing conditions, which, as described in Section 3.1, control the relative input of Gulf of Maine waters into Massachusetts Bay. Winds, currents and spring runoff in May determine whether blooms of *Alexandrium* (that are often present in GOM waters during this time of year) enter Massachusetts Bay or are transported out to sea (Anderson, 1997, Anderson *et al.* 2002).

The summer is generally a period of strong stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community dominated by microflagellates. Dissolved oxygen declines in the bottom waters over the summer as stratification prevents bottom water oxygen from being replenished from the surface and respiration consumes DO present in the bottom waters. Advection has been shown to greatly influence bottom DO concentrations (Geyer *et. al*., 2002). Nearfield bottom water DO tends to be lowest when these waters are warm and salty, reflecting slower currents and higher residence time, which results in stronger drawdown of dissolved oxygen in this region. Temperature also has a direct effect on DO levels in that there is a positive correlation between temperature and respiration rates.

In the fall, cooling surface waters and strong winds promote mixing of the water column. Stratification breaks down, oxygen is replenished in the bottom waters, and nutrients are supplied to surface waters usually stimulating a fall phytoplankton bloom. In many years, the fall bloom is stronger than the spring bloom. Typically, fall blooms end by early winter, when declining light levels limit photosynthesis. The lowest bottom water dissolved oxygen concentrations are observed just prior to the overturn of the water column – usually in October. By early winter, the water column is well mixed, and reset to winter conditions.

Inshore to offshore gradients for water quality parameters have also been a consistent feature in the HOM data. The spatial variability in biological and chemical parameters is driven by a combination of bathymetry and proximity to inputs including rivers, outfalls, and the Gulf of Maine. Over the baseline period, Boston Harbor and nearby coastal waters consistently had higher levels of nutrients than offshore waters (**Figure** 4-2a). The gradient was due to nutrient sources associated with rivers/runoff and the harbor outfall and a combination of dilution and biological utilization as the harbor waters were transported offshore. Moving the outfall offshore has caused a shift in the spatial distribution of some nutrients (i.e. NH_4 and PO_4) in the vicinity of the outfall but little change further afield (**Figure** 4-2b).

Phytoplankton biomass as characterized by chlorophyll also exhibits spatial gradients, which tend to be more variable than observed in the nutrient data. The spatial distribution of chlorophyll is closely tied to nutrient and light availability. During well mixed conditions shallow, inshore waters tend to have elevated chlorophyll concentrations. During stratified conditions chlorophyll concentrations show a distinctly different pattern, with high concentrations in nearshore surface waters and low concentrations in offshore surface waters with a distinct chlorophyll maximum near the pycnocline. This gradient between nearshore and offshore patterns results from limited availability of nutrients during stratified conditions. In the nearshore, the main nutrient sources are land based inputs and upwelling while offshore nutrients are only available at depth near pycnocline.

Within the bay system, spatial distributions of chlorophyll are basin specific. In the winter/spring, Cape Cod Bay often has higher chlorophyll as diatom blooms develop in the bay's shallow waters earlier than in the deeper waters of Massachusetts Bay. In the summer, chlorophyll often displays a gradient of decreasing surface water concentrations away from Boston Harbor, due to the availability of nutrients to spur on phytoplankton growth. In the fall, nearshore waters become mixed before offshore waters and the availability of nutrients often initiates a bloom and an inshore to offshore gradient of decreasing chlorophyll is observed. Satellite imagery (SeaWiFS) allows examination of the distribution of surface chlorophyll both within and outside of the bays. In **Figure** 4-3, the inshore to offshore gradient in chlorophyll from shallow coastal waters to deeper offshore waters is evident as is the influence of the Gulf of Maine waters north of Cape Ann. This highlights the regional nature of blooms in these waters.

Phytoplankton and zooplankton species composition and abundance tend to vary on a bay wide or regional scale. Except in Boston Harbor, species observed are typical of the open waters of the northwest Atlantic Ocean. Some have predictable seasonal cycles, while others (such as the nuisance species *Phaeocystis* and *Alexandrium*) appear only intermittently.

This general sequence of events and spatial distribution of features has continued to be observed since the bay outfall became operational on September 6, 2000. Water quality trends are strongly influenced by both local and regional oceanographic and meteorological conditions. Spatial gradients in water quality characteristics are also governed by these physical conditions and by the location of sources and availability of nutrients. Massachusetts and Cape Cod Bays are clearly part of and are influenced by the Gulf of Maine. Understanding this connection and taking it into account is critical in assessing the relative impact that the bay outfall may (or may not) have on water quality in Massachusetts and Cape Cod Bays.

4.2 Water Quality Monitoring Results

4.2.1 Nutrients

The nutrient data for 2002 generally followed the "typical" progress of seasonal events in Massachusetts and Cape Cod Bays. The seasonal trends in nutrient concentrations are closely linked with both physical and biological factors. Physical mixing or stratification combined with biological utilization and remineralization act to increase and decrease the concentrations of nutrients over the course of each year. Nutrient concentrations are high in the winter, decrease during the winter/spring bloom and onset of stratification, are generally depleted in surface waters and increasing at depth in the summer, and then return to elevated levels following the fall bloom and mixing of the water column. These cycles have been observed year-in and year-out to varying degrees. The monitoring questions are focused on understanding whether or not the transfer of the MWRA effluent discharge from the harbor outfall to the bay outfall has any impact on nutrient concentrations. Note that this transfer did not create a new source of nutrients to the system, rather changed where the effluent is discharged both in location and water depth.

In 2002, maximum nutrient concentrations were observed in early February as shown for nitrate (NO_3) and silicate (SiO_4) in **Figure** 4-4. Nutrient concentrations were lowest in Cape Cod Bay in early February likely due to an early winter/spring bloom occurring there prior to the first survey. Except for harbor and coastal areas, Massachusetts Bay nutrient concentrations decreased from early February through April. Silicate concentrations increased at the nearfield and boundary stations in April that is attributed to a change from a diatom bloom to one dominated by *Phaeocystis pouchetii*. In the nearfield, nutrient levels continued to decrease from April to early May when concentrations in nearfield waters were depleted. As discussed in Section 3, the onset of stratification was delayed until late May in the nearfield. Under weak stratification, the water column is relatively well mixed and nutrients are supplied to and utilized in the surface waters. This continued supply of nutrients may have contributed to the prolonged presence of *Phaeocystis* (from March to early May) in the nearfield. By June, NO_3 (and SiO_4 and PO_4) concentrations had reached minimum levels for 2002 at all but the Boston Harbor stations, which were lowest in August (**Figure** 4-4). Area mean NO_3 concentrations increased from June to October (except in the harbor) even in the face of the major bloom in August and September. The collapse of the early fall bloom, the weakening stratification, and increased mixing in October led to higher nutrient concentrations. The increase in nutrients due to mixing appeared to be offset somewhat in November by elevated rates of production and nutrient utilization. By December, nutrient concentrations had returned to typical winter levels.

Nearfield survey mean concentrations NO_3, SiO_4, and PO_4 in 2001 and 2002 generally follow baseline trends and are comparable in magnitude to the levels observed over the baseline period. The primary differences since diversion are that concentrations were relatively low in early February, high in October, and low in December (**Figures** 4-5 and 4-6a). In early February, NO_3 concentrations were below the baseline mean and SiO_4 concentrations were near or below the baseline minima indicating a relatively early draw down of nutrients due to the winter/spring bloom in both 2001 and 2002. The low concentrations were coincident with elevated levels of chlorophyll and productivity (see **Figures** 4-14 and 4-22). The 2001 and 2002 winter/spring draw down of nutrients were 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 nutrient drawdown 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 in 2001 and 2002 than previously observed. Nitrate concentrations were higher than baseline maximum values in September and late October 2001 due to the lack of an early fall bloom in 2001 and were elevated in October 2002 because the fall bloom was early. In 2001, weakly stratified conditions persisted into November and a late fall bloom resulted in NO_3 and SiO_4 concentrations below the baseline minima in December 2001. In 2002, the water column was well mixed in October, but elevated production rates and chlorophyll concentrations indicated that there was a late bloom in 2002 as well, which is corroborated by the low NO_3 and SiO_4 concentrations observed during these months.

The continued supply of NH_4 to the nearfield from the bay outfall caused nearfield NH_4 concentrations to be higher than the maximum values observed during the baseline period for the majority of the 2001 and 2002 surveys (**Figure** 4-6b). In contrast, NH_4 concentrations in Boston Harbor were below or near baseline minima for the entire year (**Figure** 4-7a). Harbor NH_4 concentrations 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. The other nutrients followed a pattern similar to that for NO_3 in the harbor in 2001 and 2002 – well below the baseline minimum during both the winter/spring and fall blooms (**Figure** 4-7b).

The change in NH_4 concentrations in the nearfield and Boston Harbor are consistent with model simulations which predicted that the transfer of effluent from Boston Harbor to Massachusetts Bay would greatly reduce nutrients in the harbor and increase them locally in the nearfield (**Figure** 4-8; Signell *et al*., 1996). This change was predicted to have little impact on concentrations in the rest of Massachusetts and Cape Cod Bays. The spatial patterns in NH_4 concentrations in the harbor, nearfield and bays since the diversion in September 2000 consistently confirm this (see **Figure** 4-2).

These spatial changes in NH_4 are also manifest in annual mean concentrations for these areas. For example, the annual mean NH_4 concentration in Boston Harbor dropped sharply from 2000 to 2001 (**Figure** 4-9a). A similar sharp decrease was also seen at the coastal stations, which are strongly influenced by water quality conditions in Boston Harbor. In contrast, the increase in annual mean NH_4 in the nearfield was not as dramatic as the harbor and coastal water decrease. Compared to 1999, the last full year before the bay outfall came online, annual mean NH_4 levels in the nearfield have almost doubled. Harbor, coastal, and nearfield NH_4 concentrations remained stable from 2001 to 2002. Unlike these regions, little if any change in NH_4 concentrations was measured in offshore, boundary, and Cape Cod Bay waters from 1992 to 2002. In fact, annual mean NH_4 concentrations in Cape Cod Bay decreased from a maximum of 1.7 μM in 1999 to <1 μM in 2002. The trends in annual mean concentration for other inorganic nutrients are more erratic as seen in **Figure** 4-9b for NO_3. Year to year variability in NO_3, SiO_4, and PO_4 may have more to do with timing of sampling and occurrence of blooms than any clear trends in background levels.

Ammonium in the water column has proven to be an excellent tracer of the effluent plume in the nearfield since the outfall came online in September 2000 (Libby *et al*., 2002c). The effluent plume, as defined by the distribution of elevated NH_4 concentrations, surfaced in the well-mixed waters from early February through early May 2002 and continued to surface under weak stratification in late May (**Figures** 4-10 and 4-11). Once seasonal stratification was established, the pycnocline prevented the effluent and elevated NH_4 concentrations from reaching surface waters (**Figure** 4-12). In addition to illustrating the vertical extent of the plume, the NH_4 distribution in late May highlights the variability of currents in the area. During this survey, the plume was observed to the northwest of the outfall. As discussed in Section 3, currents in the nearfield tend to be random depending upon a variety of factors.

One concern is that the effluent plume and nutrients contained therein may be advected outside of the nearfield. In August 2001, salinity and NH_4 data suggested the effluent plume was advected from the nearfield to the south (Libby *et al*., 2002c). A similar displacement of the plume (direction and distance) was observed in July 2001 during a 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). As discussed in Section 3, the predominant circulation pattern in Massachusetts Bay is counterclockwise, but currents are quite variable and highly dependent upon winds. Although the effluent plume has been observed to extend beyond the nearfield occasionally, the plume as characterized by NH_4 concentrations is usually confined to or in close proximity to the nearfield. An analysis of concentrations before and one year after the diversion indicated that there was an increase in NH_4 concentrations only at stations within 20 km of the new outfall (Mickelson *et al.* 2002).

In October, elevated NH_4 concentrations (7.5 µM) were measured in the surface water at offshore and boundary stations (stations F16 and F12, respectively). However, there was no concomitant pattern of elevated PO_4 concentrations or lower salinity at these stations. Moreover, the distances between the outfall and these boundary stations on Stellwagen Bank and no indications of strong offshore currents in the physical oceanographic data argue against any impact due to advection of an effluent plume. Thus, it is highly unlikely that the elevated NH_4 was due to advection of outfall discharge.

4.2.2 Phytoplankton Biomass

Trends in chlorophyll and POC in 2002 were comparable to those observed during previous years. The main exceptions were that the winter/spring bloom started prior to the first survey, the 'fall' bloom occurred earlier than usual (August/September), and there was a late fall bloom evident in the biomass and productivity data. Seasonal trends in phytoplankton biomass as measured by chlorophyll and POC are tied to physical conditions, nutrient availability, and ecosystem dynamics. The phytoplankton biomass seasonal signal in Massachusetts and Cape Cod Bays is dominated by winter/spring and fall blooms. Winter/spring phytoplankton blooms occur due to elevated growth related to increased light availability, nutrient replete conditions and seasonal stratification of the physical environment, prior to temperature-related increases in mortality due to grazing. Typically the timing of the fall bloom has been tied to decreased stratification and increased inputs of nutrients into the surface waters. The monitoring questions are focused on understanding whether or not changes in nearfield and farfield nutrient levels due to the transfer to the bay outfall has an impact on these seasonal trends and concentrations of phytoplankton biomass.

The highest chlorophyll levels for 2002 were recorded in Boston Harbor in early February (**Figure** 4-13a). However, regional chlorophyll maxima fluctuated throughout the winter/spring period and elevated chlorophyll levels were found in each of the regions at various times. Chlorophyll concentrations were high in the harbor, coastal waters, nearfield and Cape Cod Bay in early February during the winter/spring diatom bloom. This coincided with peak production at harbor station F23 and elevated production at the nearfield stations. In late February, there was a sharp drop in chlorophyll levels at these nearshore stations that coincided with decreased productivity. Particulate organic carbon (POC) concentrations (**Figure** 4-13b), however, increased in coastal and Boston Harbor waters. The largest increase in POC concentrations in late February was coincident with increasing chlorophyll concentrations at boundary stations F26 and F27 off of Cape Ann. The SeaWiFS images for this time period suggest that these elevated chlorophyll values were due to entrainment of waters from the Gulf of Maine into northwestern Massachusetts Bay (see **Figure** 4-3).

By early April, chlorophyll concentrations had decreased throughout most of Massachusetts Bay, but increased in both the nearfield and Cape Cod Bay in conjunction with the *Phaeocystis* bloom. Chlorophyll concentrations decreased from April to June across the bays and remained relatively low in the nearfield through the summer until increasing in August and September during the early fall bloom (**Figure** 4-13a). Particulate organic carbon concentrations followed a similar trend of increasing from July to September. Maximum POC concentrations were measured during the late August survey and remained high till late September (**Figure** 4-13b). Nearfield phytoplankton abundance and productivity also peaked in early and late August, respectively. This early fall bloom was also evident in nearshore areas of Massachusetts and Cape Cod Bay during the late August survey when relatively high levels of chlorophyll, POC, production and phytoplankton abundance were observed throughout the bays. A late fall bloom was apparent in the biomass and production data, but did not result in a large increase in phytoplankton abundance.

In 2001 and 2002, nearfield chlorophyll concentrations were consistent with the baseline mean and seasonal pattern. The main deviations from the baseline were in early February and late fall (**Figure** 4-14a). High concentrations in early February of 2001 and 2002 coincided with elevated production rates and early winter/spring blooms. The highest survey mean chlorophyll concentration in 2001 was in December coincident with peak production in the nearfield. In 2002, the fall bloom was early (August and September), but the highest chlorophyll levels occurred during a secondary fall bloom in November. These relatively high (150 - 200 mg m^{-2}) chlorophyll values were well below the maximum values observed during major winter/spring and fall blooms during the baseline. The highest survey mean chlorophyll values that have been observed during the monitoring program were measured in fall 2000 (~500 mg m^{-2}).

Although fall 2000 chlorophyll concentrations were extraordinary, the lack of similarly atypical POC concentrations suggests that it was more of a "chlorophyll" bloom than an extraordinary increase in phytoplankton biomass (**Figure** 4-14b). This is corroborated by plankton counts, which were elevated, but not exceedingly high. The fall 2000 bloom was regional in scope and encompassed most of the Gulf of Maine coastal waters, as evident in SeaWiFS satellite imagery (Libby *et al*., 2001). Particulate organic carbon concentrations in 2001 and 2002 generally followed the baseline means and trends except for peaks corresponding to fall blooms (**Figure** 4-14b). During all three years after diversion, fall to early winter (October to December) chlorophyll and POC concentrations were close to or above baseline maxima. Although phytoplankton abundance was not high, production values during these surveys was also at or above baseline maxima.

In Boston Harbor, 2001 and 2002 areal chlorophyll (**Figure** 4-15a) closely follow the nearfield trend. Values were at or above baseline maxima in February, then were close to baseline minima for the remainder of the year except for a peak in August 2002 that coincided with the early fall bloom observed throughout the near coastal waters of Massachusetts Bay. The early February 2002 areal chlorophyll concentration was the highest ever seen in Boston Harbor. Harbor POC concentrations were relatively low in 2001, and similar to baseline trends (**Figure** 4-15b). In 2002, however, elevated POC concentrations were coincident with high chlorophyll and productivity. The chlorophyll and POC data (along with production data presented in Section 4.3) suggest the harbor may be changing from its previous pattern of biomass levels peaking in summer to a more typical temperate coastal water trend dominated by spring and fall blooms. It should be noted that data collected for the more highly resolved (spatially and temporally) MWRA Harbor Monitoring Program confirmed that there was a substantial chlorophyll bloom in Boston Harbor in February 2002, but also indicated that summertime chlorophyll levels peaked in July rather than August (Taylor 2003). Thus, although HOM data did not capture the summer peak, it was present in 2002 albeit later than usually observed during HOM baseline monitoring.

Variations in the strength of the spring and fall blooms are the major factors affecting the annual average chlorophyll (**Figure** 4-16). The highest annual mean values occur in 1999 and 2000 when major blooms were observed in both spring and fall. However, because annual mean POC concentrations in 1999 and 2000 were not unusually high, phytoplankton biomass may not have been substantially higher. Boston Harbor and coastal areas tend to have lower areal averaged chlorophyll because of shallower depths although chlorophyll concentrations are often higher in those regions. In 2002, however, the blooms were primarily nearshore events and the highest annual mean areal chlorophyll was in Boston Harbor. The 2002 coastal blooms also resulted in the highest annual mean POC concentrations observed in the harbor and coastal waters to date. The nearfield annual mean POC concentrations were relatively stable in 2001 and 2002 and comparable to baseline values.

4.2.3 Dissolved Oxygen

DO concentrations in 2002 followed trends that have been observed consistently since 1992 and concentrations were relatively low but within the range of values observed previously. Bottom water DO levels are typically at a maximum in the winter, decrease over the course of the summer during seasonal stratification, and reach annual minimum levels just prior to stratification breaking down in the fall – usually October. The monitoring questions are focused on assessing whether or not the transfer to the bay outfall has an impact on dissolved oxygen levels in the bays. The primary areas of interest with respect to DO levels are the bottom water minima in nearfield and Stellwagen Basin. An adverse impact due to the transfer would be expected to result in decreased DO levels and DO bottom water minima well below those observed during the baseline.

In 2002, maximum bottom water DO concentrations occurred in February when the water column was well mixed (**Figure** 4-17). In general, DO concentrations remained relatively constant (10-11 mgL^{-1}) from February to April, decreased over the course of the summer, and reached minimum values of 7-8 mgL^{-1} in October. The only exceptions were in Boston Harbor, where there was an increase from June to August, and Cape Cod Bay, which exhibited a minimum value in August rather than October. The high, supersaturated levels of DO in Boston Harbor in August were associated with elevated production during the bloom. Cape Cod Bay is relatively shallow and the water column had already overturned and mixed by the October survey.

The combination of warm bottom water temperatures, high salinity, and limited advection into the system from the Gulf of Maine (i.e. no spring freshet due to drought and low river inputs) likely contributed to the steady decline and low October DO concentrations in Massachusetts Bay. As is typically observed, the annual minimum DO concentrations and percent saturations were observed during the October survey (**Figure** 4-17). The lowest survey mean DO concentration and percent saturation (6.43 mgL^{-1} and 71.25%, respectively) were measured in the nearfield. Comparably low minima were also observed at the coastal, offshore and boundary stations.

Since the bay outfall came on line, there has been little change in the DO cycle in the nearfield and Stellwagen Basin (**Figures** 4-18 and 4-19). DO levels were close to the baseline mean in 2001 in both areas and below the mean during 2002. The bottom water minima in these areas in 2002 were much lower than minima observed in 2000 and 2001, but higher than the baseline minimum that was measured in 1999 (**Figures** 4-20 and 4-21). Over this four year period, there is no apparent connection between the magnitude of winter/spring or fall blooms and annual DO minima. For example, 2000 and 2001 were two very different 'biological' years – major spring and fall blooms in 2000 and minor blooms in 2001 – yet relatively high DO minima that were observed during both years. The fact that both 1999 and 2002 had low DO minima and relatively large blooms winter/spring and early fall blooms suggests that organic loading may play at least a minor role in controlling bottom water DO. However, droughts occurred in both 1999 and 2002, and it was an examination of the 1999 data that led to the finding of a significant relationship between Merrimack River flow, bottom water salinity and temperature, and bottom water dissolved oxygen at the outfall site (Libby *et al*., 2000). An examination of the connection between these 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).

4.3 Productivity

Areal production at the nearfield stations in 2002 followed patterns observed in prior years. Both nearfield stations were characterized by spring and fall blooms, with variable productivity during the summer. In general, patterns observed at the nearfield sites were consistent with those observed from 1995 – 2002. However, timing of events was somewhat different from earlier years, with an early onset of both the spring and fall blooms. Additionally, some differences in the magnitude of productivity were noted, including elevated productivity during the spring and fall blooms at stations N18 and N04, relative to most years. It is these apparent changes in productivity both between the nearfield stations and at the harbor station that are the focus of the monitoring questions regarding production rates.

4.3.1 2002 Productivity

The winter/spring bloom in 2002 started in January as evident by the productivity peak in early February (**Figure** 4-22). A second productivity peak was observed at both stations in April corresponding with a *Phaeocystis* bloom occurring at the nearfield sites. The termination of the 2002 spring bloom occurred by mid-May, the typical timing observed in prior years. Because of early initiation, the duration of the winter/spring bloom (January to May) was longer than observed previously. From 1995 to 2000 initiation of the spring bloom generally occurred during late February – early March. In both 2001 and 2002, the bloom was underway when sampling was initiated in early February.

A major bloom occurred during the late summer (August) 2002 at both nearfield stations rather than during the fall period. The late summer peak in productivity may be related to a decrease in grazing pressure as there was a precipitous decline in zooplankton abundance from early to late August suggesting a link between the early occurrence of the bloom and decreased grazing via zooplankton. The typical October bloom observed in 5 of the last 7 years was not present in 2002. The late summer bloom peaks were similar in magnitude to peak fall bloom values observed during the post outfall period but greater than most values from 1995 to 1999, particularly at station N04. A late fall bloom was apparent in the production data coincident with elevated phytoplankton biomass concentrations, but did not result in a large increase in phytoplankton abundance.

The productivity pattern at Boston Harbor station F23 in 2002 was similar to the pattern observed in 2000 and 2001, with the occurrence of spring and fall productivity peaks (**Figure** 4-22). 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 2002 more closely resembles the seasonal cycle observed at the nearfield stations. The altered seasonal productivity cycle may be tied to reduced nutrient availability in the harbor in recent years during the summer-stratified period. The timing of the late summer bloom in the harbor also appears related to relaxation of grazing pressure due to decreased abundance of zooplankton.

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 and 2002 to the baseline productivity data collected from February 1995 to August 2000 (**Figures** 4-23 and 4-24). In Boston Harbor, productivity in 2001 and 2002 generally fell well below the baseline mean and always within the baseline range except for the winter/spring bloom in 2002 (**Figure** 4-23). The decrease in productivity in the harbor is most likely tied to decreased nutrient availability (see **Figure** 4-7) as also suggested by the altered seasonal productivity pattern.

In general, areal production at the nearfield sites in 2001 fluctuated near the baseline mean for most of the annual cycle (**Figure** 4-24). The major deviations from the baseline in 2001 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. In 2002, areal production in the nearfield was highly variable and was both greater than the baseline maximum and lower than the baseline minimum on multiple surveys. These major deviations from the baseline data, as noted previously, include the elevated magnitude of the winter/spring diatom and *Phaeocystis* blooms, the early occurrence of the fall bloom, and the lack of the more typical fall bloom in October (below baseline minimum).

4.3.2 Seasonal Cycles

The importance of the winter/spring and fall blooms in the annual productivity cycle has been noted over the baseline period. An increase or decrease in the magnitude or timing of these peaks in production could be indicative of a change due to changes in ambient nutrient concentrations. This is examined by comparing seasonal peak potential productivity rates. Potential productivity depends on the calculation of productivity as if all measurements were taken on full sunlight days and thus provides a maximum estimate of spring and fall peak bloom magnitudes. Both spring and fall bloom peaks have increased in the nearfield during the post outfall period. During the spring at station N18, the station nearest the outfall, primary productivity rates increased from about 3000 to 3600 mg C m^{-2} d^{-1} (**Figure** 4-25a). At station N04 the rates increased from 2300 to 3200 mg C m^{-2} d^{-1}. During the fall, a similar pattern of increased productivity occurred for the two nearfield stations (**Figure** 4-25b).

The timing and magnitude of the spring bloom is a function of numerous ecological and physical factors. An evaluation of the relationships between these factors suggests that the magnitude of the winter/spring bloom is correlated with the temperature during the bloom period (Townsend *et al*., 1994 and Keller *et al*., 2001; **Figure** 4-26). The warmer the winter temperature the more reduced the biomass of phytoplankton during the bloom period. This relationship was initially hypothesized to be associated with increased grazing pressure due to higher zooplankton abundance at higher temperatures. As data availability increased, however, the zooplankton vs. temperature relationship appeared less significant (**Figure** 4-27). It was noted, however, that from 2000 to 2002 blooms of *Phaeocystis pouchetii* occurred during the winter/spring period. Typically *Phaeocystis* is not grazed by zooplankton either because of its size or phenolic content. By separating the data into years with and without *Phaeocystis* blooms in the regression analysis, the reduced magnitude of the bloom and increases in zooplankton abundance were highly related to warmer temperatures (**Figures** 4-26 and 4-27). Likewise in non *Phaeocystis* years, zooplankton abundance is highly negatively correlated with production and chlorophyll during the spring bloom (**Figure** 4-28). This correlation is consistent with zooplankton grazing control of the magnitude of the spring bloom.

A bloom magnitude analysis is not presented for the Boston Harbor station since the annual cycle was not characterized by the occurrence of spring or fall blooms during the baseline period. Over the seasonal cycle the pattern of productivity appears to be changing at the mouth of Boston Harbor. Productivity exhibited a eutrophic pattern during the baseline period with high summer time rates as shown for 1999 in **Figure** 4-29. Data from 2001 and 2002 suggest a pattern more typical of temperate waters with winter/spring peaks, lower summer time rates, and at least in 2002 elevated levels during the late summer/early fall bloom (**Figure** 4-29). Spring and fall peaks approach 3000 mg C m^{-2} d^{-1} and summer rates have decreased from 3000 to 1000 mg C m^{-2} d^{-1}. As noted in Section 4.2.2, a July peak in chlorophyll in the harbor was missed due to the HOM sampling schedule. The 2002 seasonal pattern in the harbor clearly differs from the steady increase in production from February through the summer that was seen during the baseline, but it is unclear if the August 2002 peak is related to a delayed summer peak in harbor production or the early fall bloom observed in Massachusetts Bay.

4.3.3 Annual Productivity

Potential annual productivity (g C m^{-2} y^{-1}) was previously calculated (1997 – 2001) by integrating potential daily productivity (mg C m^{-2} d^{-1}) over the sample period (February to mid December) then weighting the data for the number of days in the annual cycle. This approach assumes that productivity during the period not sampled is equivalent to the average daily productivity during the portion of the year that was sampled. There was a concern that this approach may overestimate annual production. An alternate approach that could be used would assume that the initial and final measured values over the annual cycle are acceptable estimates for the corresponding periods not measured. During most years the new approach did result in a decrease in annual productivity; on occasion, however, increases occur if the initial or final samples were collected during bloom conditions such as occurred in early February 2001 and 2002 (**Table** 4-1).

Table 4-1. Comparison of potential annual productivity (g C m^{-2} y^{-1}) calculated using the original approach (a) and the alternate approach (b).

Year	Stations							
	N04 (a)	N04 (b)		N18 (a)	N18 (b)		F23 (a)	F23 (b)
1997	523	480		683	612		945	862
1998	192	191		221	213		250	224
1999	406	395		507	503		904	658
2000	557	511		726	665		510	494
2001	526	569		537	559		466	404
2002	489	646		542	783		556	582

Potential annual productivity during pre and post outfall years was compared utilizing both methods of calculation (**Figure** 4-30; note that potential annual productivity for 1995 and 1996 were not recalculated since data were unavailable and data from 2000 are not included in the analysis since the outfall became operational that year). Utilizing the original approach the estimates of potential annual productivity indicated an increase in values at nearfield sites of about 100 g C m^{-2} y^{-1} and a decrease at the mouth of Boston Harbor of about 350 g Cm^{-2} y^{-1}. Utilizing the new approach the increase at the nearfield sites and the decrease at Boston Harbor are about 200 g C m^{-2} y^{-1}.

Although there were no significant differences between pre and post diversion production, the data do show higher post diversion mean production at the nearfield stations and lower mean production in Boston Harbor in comparison to the baseline values (**Figure** 4-30). Similar changes are apparent in mean chlorophyll *a* and particulate organic carbon concentrations at the nearfield stations (**Figure** 4-31). In Boston Harbor, however, there was a decrease in POC while chlorophyll concentrations increased. This may be an artifact of the sampling schedule rather than a real change in Boston Harbor. Farfield sampling is focused on capturing the winter/spring bloom and the switch to a more typical temperate productivity pattern following diversion has resulted in higher winter/spring bloom chlorophyll concentrations in the harbor (see **Figure** 4-15a) and in turn higher annual values. Others conducting more routine monitoring focused on Boston Harbor have found significant decreases in chlorophyll levels in the two years after diversion to the bay outfall (Taylor 2003). All of these changes are coincident with an increase in NH_4 concentrations in the nearfield and a decrease in the harbor (see **Figures** 4-6b and 4-7a).

At the nearfield stations there is also an apparent increase in the amount of dissolved inorganic nitrogen (DIN) utilized during the spring bloom. By comparing early February nutrient concentrations to post bloom concentration, an apparent decrease or delta value can be calculated to indicate relative biological utilization (**Figure** 4-32). At nearfield stations the change in delta DIN over the spring bloom period was ~8 µM prior to diversion to the bay outfall. After diversion, delta DIN increased to 11.5 µM at N18 and 8.8 µM at N04. This increase was primarily due to increases observed in delta NH_4 for both stations from less than 1 µM NH_4 to about 6 µM at N18 and 2.5 µM at N04. There is a significant and positive relationship between the winter spring productivity peak and the change in surface nitrogen concentration over the bloom period (**Figure** 4-33). The transfer of the NH_4-rich effluent from Boston Harbor to the nearfield could be fueling the apparent, localized increase in production observed during the first two years of the bay outfall. The changes observed in pre and post outfall production and nutrient utilization during the spring bloom are the focus of ongoing examination.

4.4 Plankton

Trends in plankton in 2002 generally followed patterns observed in prior years. Notable exceptions to the typical trends include an early winter/spring diatom bloom, low *Ceratium* abundances in the summer, an early "fall" diatom bloom, and extremely low zooplankton abundances in the late summer and fall due to predation by the ctenophore *Mnemiopsis leidyi*. The monitoring questions are focused on understanding whether or not changes such as the timing of these seasonal events or in the species composition of the phytoplankton or zooplankton communities could be related to changes in nutrient levels due to the transfer to the bay outfall.

4.4.1 Phytoplankton

Phytoplankton communities are mixtures of many species, with the abundance and composition of the community changing in response to each species' response to changing environmental influences on the habitat (e.g. annual change in irradiance, temperature, nutrient, grazer abundance). A "normal" seasonal succession in Massachusetts and Cape Cod Bay has been observed in 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 blooms of a single species such as *Asterionellopsis glacialis* in fall of 1993 or *Phaeocystis pouchetii* in spring of 1992, 1994, 1997, 2000, 2001, and 2002. The interannual variability associated with both magnitude and occurrence of blooms as represented by total phytoplankton abundance is shown in **Figure** 4-34. Although such blooms may be intermittent, they tend to occur regionally and are usually observed throughout Massachusetts and Cape Cod Bay and beyond. Why such species bloom in some years but not others remains unclear.

2002 Phytoplankton Results:

In 2002, the winter/spring bloom of centric diatoms was observed in February 2002. Chlorophyll and production data indicated that the bloom was already underway in Boston Harbor, coastal, nearfield and Cape Cod Bay waters by the first survey in early February (see **Figures** 4-13 and 4-22). Phytoplankton abundance, however, continued to increase from February to April when a *Phaeocystis pouchetii* bloom was observed throughout most of Massachusetts and Cape Cod Bays (**Figure** 4-35). The exception being a maximum in phytoplankton abundance at the northern boundary stations in late February. The phytoplankton community at these stations off Cape Ann was dominated by *Skeletonema costatum*. The SeaWiFS images for this time period suggest that these elevated chlorophyll and Skeletonema values were due to entrainment of waters from the Gulf of Maine into northwestern Massachusetts Bay (see **Figure** 4-3).

The abundance of dinoflagellates, *Ceratium* in particular, was low during the summer months rather than peaking during this time frame as was typically the case during previous years. The delay in the onset of stratification during the spring and the relatively weak density gradient that was observed from May to July may have led to the low *Ceratium* abundance. Without a strong density gradient, these dinoflagellates were hindered in exploiting their motile capabilities and unable to out compete other phytoplankton. This is discussed in more detail below.

There was an atypically early "fall" bloom in August and September. This early fall bloom was evident in nearshore areas of Massachusetts and Cape Cod Bay during the late August survey when relatively high levels of chlorophyll, POC, production and phytoplankton abundance were observed throughout the bays. The major centric diatom bloom was constrained to the harbor, coastal, and nearfield waters with a minor diatom bloom evident in Cape Cod Bay. Total phytoplankton and diatom abundances at the offshore and boundary stations were relatively low. The early fall bloom may have been associated with a reduction in grazing pressure due to decimation of zooplankton populations by ctenophore (*Mnemiopsis leidyi*) predation. A late fall bloom was apparent in the chlorophyll and production data, but did not result in increased phytoplankton abundance.

Interannual Phytoplankton Comparisons:

The differences in the 2002 nearfield phytoplankton annual cycle, relative to baseline observations, were explored by hierarchical examination (*i.e.,* from total phytoplankton to specific groups) of the major components of the nearfield phytoplankton. Assemblages in 2001 and 2002 were generally similar to those found during other baseline monitoring years. During both post-diversion years, nearfield total phytoplankton abundance was usually at or slightly below the baseline mean value (**Figure** 4-36). The primary exceptions were the late summer/early fall diatom bloom in 2002, relatively low phytoplankton abundance in October 2002 (during a period when fall blooms are often observed), and a prolonged late October through December diatom bloom in 2001

In 2002, a sustained summer-fall diatom bloom occurred in August through late September consistent with chlorophyll and productivity data (**Figure** 4-36b). Early August 2002 diatom abundance (2.5×10^6 cells l^{-1}) was more than double the observed baseline maximum (1×10^6 cells l^{-1}). In early August, the diatom bloom was primarily comprised of *Dactyliosolen fragilissimus*. By late August *Leptocylindrus danicus* was the dominant species reaching levels comparable to the baseline maximum for this species in August (~0.8×10^6 cells l^{-1}). In September, the bloom was dominated by *Skeletonema costatum*, which was present at levels well above the baseline maximum for this species. By October, however, diatom abundance dropped dramatically and was below the baseline minimum and remained low for the remainder of 2002. The increase in chlorophyll and primary productivity in November 2002 was not evident in phytoplankton data, but may have been partly related to increased proportions of the large chain-forming diatoms *Eucampia zoodiacus* and lower light availability which can lead to increased chlorophyll levels on a per cell basis.

The early fall bloom was the dominant feature of the 2002 nearfield phytoplankton cycle and may have been due to a decrease in grazing pressure caused by predation of zooplankton by ctenophores (*Mnemiopsis leidyi*), which were observed in high numbers from late August through November. There was a sharp decline in nearfield zooplankton abundance from early to late August 2002 to abundances lower than observed during the baseline (see **Figure** 4-41). The very low zooplankton abundances imply that grazing pressure on phytoplankton was minimal, conducive to a bloom. The availability of nutrients in nearshore waters via the outfall and/or upwelling, which may have entrained both nutrient-rich bottom waters and the effluent plume into the upper water column, may have enhanced phytoplankton growth during the early fall bloom (see **Figure** 3-8). A similar combination of decreased zooplankton abundance (ctenophore predation) and nutrient availability was suggested as one of the factors leading to a prolonged, atypical late fall bloom in 2001 (Libby *et al*., 2002c).

Abundances of dinoflagellates were generally close to or below baseline means in 2002 except in late August (**Figure** 4-37a). In particular, abundances of members of the genus *Ceratium*, which usually dominate screened-water phytoplankton assemblages during warmer periods, were below the range of observed baseline values from March through early August of 2002 (**Figure** 4-37b). In 2002, *Ceratium* abundance was reduced to ca. one-third of the baseline level (on an annual basis) and were as low as 1% of the baseline mean level in June 2002 (**Table** 4-2).

Table 4-2. Comparison of 2002 nearfield Ceratium abundance (screened water) to baseline values.

Month	Baseline (cells L^{-1})	2002 (cells L^{-1})	% of Baseline
2	88	140	159
3	235	33	14
4	259	28	11
5	685	24	3
6	1959	10	1
7	1486	91	6
8	949	163	17
9	1578	267	17
10	1531	1479	97
11	865	531	61
12	478	234	49
Annul Mean	938	273	29

Ceratium:

Ceratium are large and have a relatively high respiration to photosynthesis ratio of ca. 25% compared to rates of 5 to 10% for diatoms, resulting in relatively low growth rate of ca. 0.3 div day-1 (Cushing, 1989). Under well-mixed conditions the *Ceratia* are easily out-competed by more efficient diatoms. However, under stratified conditions the mobile *Ceratia* (capable of swim speeds of 0.5 m h-1; Holligan, 1987) have developed a strategy of vertical migration across the pycnocline of stratified seas to maximize their ability to photosynthesize above the pycnocline and assimilate nutrient below the pycnocline. In the North Sea, annual variation in degree and spatial extent of stratification due to variation in freshwater input and wind conditions has been used to successfully explain long-term variation in *Ceratium* abundance (Dickson *et al.*, 1992).

As discussed in Section 3, 2002 was a dry year in Massachusetts Bay with low river flows resulting in elevated salinity and relatively weak stratification in the nearfield (see **Figures** 3-6, 3-12 and 3-13). Given the relationship observed in other systems (Cushing, 1989; Dickson *et al*., 1992), the relation between stratification and *Ceratium* abundance in Massachusetts Bay was investigated. The difference between near bottom and surface density was used as a simple index of stratification, with greater delta density values indicative of increased stratification. Nearfield averaged, screened water counts of *Ceratium* were used as an indicator of *Ceratium* abundance. Available data were pooled into monthly averages over the 1992 to 2002 period, and simple correlation analyses were employed to identify relationships between stratification and Massachusetts Bay *Ceratium* abundance. Because of *Ceratium*'s slow growth and the premise that stable (stratified) conditions may be required for >1 month in order for the *Ceratium* population to respond, direct and 1-, 2-, and 3- month time-lagged correlation analyses were examined.

Significant (at p=0.05) positive correlations were found between stratification and *Ceratium* abundance with a time lag of one month for April, June and September *Ceratium* abundance (**Figure** 4-38). As expected, all significant correlations were positive indicating increased *Ceratium* abundance coincident with increased stratification. The correlation coefficients for these comparisons indicate that the previous month's stratification alone may explain ~50% of the variance in *Ceratium* abundance in the months of April, June and September. Temporally coarser correlation analyses, such as mean annual or seasonal stratification and *Ceratium* abundance yielded no significant correlation, possibly due to variation in other factors (grazing, competition) that were not included in the simple stratification-*Ceratium* correlation model.

Given *Ceratium*'s slow growth and stratification-dependent vertical migration strategy, continuous stratification is a requirement (Cushing 1989) for *Ceratium* populations to develop the higher abundance that is usually observed during the summer in Massachusetts Bay. Given this, *Ceratium* are sensitive to reduction in stratification (Cushing, 1989, Dickson *et al*., 1992) with this modification of their physical environment being reflected in their population abundance. Reduced stratification in the spring-summer of 2002 appears to have resulted in the extremely low levels of *Ceratium* observed in Massachusetts Bay in the summer of 2002. The correlative relationship between stratification and *Ceratium* abundance provides some predictive power that may be useful for differentiating the effects of climate variation (*i.e.,* wet vs. dry years and annual variation in freshwater input) from anthropogenic effects on Massachusetts Bay phytoplankton variation.

Nuisance Species:

Examination of frequency and abundance of nuisance species over the baseline for *Alexandrium*, *Phaeocystis*, and *Pseudo-nitzschia* reveals no consistent increases in the abundances of nuisance phytoplankters since the outfall began discharge in September, 2000. *Alexandrium* made its normal seasonal appearance in late spring-early summer of each year, but at abundance levels well below previous maxima. Normal seasonal appearances of *Phaeocystis* (April) and *Pseudo-nitzschia* (fall) were at lower levels of abundance than prior to outfall discharge. The only change since outfall diversion is the apparent increase in frequency of the *Phaeocystis* blooms. The change in frequency, however, is more likely to be related to regional factors rather than any influences within the bays. In 2001, the highest *Phaeocystis* abundance was observed at the northern boundary stations, decreasing to the nearfield. This gradient suggests that the 2001 *Phaeocystis* bloom was regional and may have been advected into Massachusetts Bay from the Gulf of Maine, consistent with patterns of chlorophyll in SeaWiFS imagery. During the springs of 2000 and 2001, *Phaeocystis* blooms were observed in the Gulf of Maine on surveys for the ECOHAB program. Given these regional factors, it will be difficult to determine if substantial change in the phytoplankton of Massachusetts Bay has or will occur as a result of the outfall diversion.

4.4.2 Zooplankton

Zooplankton communities in Massachusetts and Cape Cod Bays are dominated by numerous species of copepods, all of which have widespread distributions in the Gulf of Maine, and some of which are found throughout the east coast of the United States. MWRA zooplankton monitoring is unusual in its use of finer mesh nets (0.1 mm) than are routinely used in other studies (0.3 mm and larger). Because of this, MWRA data are dominated by smaller zooplankters such as unidentifiable copepod nauplii and small copepodites, and adults of the small copepod *Oithona similis*, which are not captured at all or are under-reported in other studies. Larger taxa seen in MWRA monitoring as well as other studies in the bays include the estuarine species *Acartia tonsa, Acartia hudsonica*, and *Eurytemora herdmani,* as well as oceanic species *Calanus finmarchicus*, *Paracalanus parvus,* and species in the genera *Centropages* and *Pseudocalanus*.

Total zooplankton abundance tends to follow a predictable temporal pattern, with abundance peaking in mid-summer and lower levels in spring and fall (**Figure** 4-39). The seasonal timing for individual species is, however, variable. For example, *Calanus finmarchicus* tends to peak in the nearfield in April and May, while *Oithona similis* peak abundances occur in mid-late summer (**Figure** 4-40). There is, however, no clear seasonality in terms of dominant zooplankton taxa in the region. Zooplankton is usually dominated year-round by copepod nauplii (of various species) and adults and copepodites of the small cyclopoid copepod *Oithona similis*. Other abundant year-round small-copepod taxa included copepodites of *Pseudocalanus* spp. and adults and copepodites of *Paracalanus parvus*, and *Microsetella norvegica*. Adults and copepodites of larger copepods such as *Calanus finmarchicus* are present year-round, but most abundant in winter/spring. Adults and copepodites of other larger copepod taxa present year-round, mainly in offshore waters, include *Centropages typicus, Temora longicornis,* and *Metridia lucens*. Copepod taxa generally found only in inshore or embayment locations include the copepods *Acartia tonsa* (summer-fall), *Acartia hudsonica* (present year-round, but most abundant in winter-spring), *Eurytemora herdmani*, *Tortanus discaudatus*, and *Centropages hamatus*.

Non-copepod zooplankton that are sporadically abundant include the marine cladocerans *Penilia avirostris, Evadne nordmani* and *Podon polyphemoides* (mainly in summer and fall), salps (summer-fall), and the appendicularian *Oikopleura dioica* (year-round). Various pulses of meroplankton can be seasonally important, such as barnacle nauplii in winter and spring, and sporadic abundance of larval polychaetes, bivalve and gastropod veligers. Pulses of the ctenophore *Mnemiopsis leidyi* in summer and fall can result in substantial declines in the abundance of the rest of the zooplankton community, primarily through ctenophore predation on copepods and other zooplankton.

Interannual Zooplankton Comparisons:

For the first half of 2002, total zooplankton abundance exhibited patterns generally similar to levels observed previously with increased abundance from winter to summer (**Figure** 4-41). There was, however, a precipitous decrease in total zooplankton abundance from a nearfield mean of 96,000 to 24,000 animals m^{-3} between the early and late August surveys. Although very low relative to historic values and below the baseline minima (**Figure** 4-42), the nearfield zooplankton abundance was relatively high in comparison to harbor and some coastal stations where abundance ranged from only 200 to 3,000 animals m^{-3}. These very low abundances imply that grazing pressure on phytoplankton was minimal and conducive to the increases in phytoplankton abundance that were observed during the summer/fall diatom bloom in 2002.

The sharp decline in zooplankton abundance in August 2002 was primarily due to predation by unusually abundant ctenophores. Effects of ctenophores in reducing abundances of other zooplankters are well-known (see references in Deason & Smayda, 1982). In fact, it has been proposed by Deason & Smayda (1982) that the ctenophore *Mnemiopsis leidyi* is a "keystone predator" in Narragansett Bay, regulating the abundances of both zooplankton, and through reduction of grazing pressure, phytoplankton in summer. There has even been the suggestion that recent extension and prolonging of the periods of abundance of this ctenophore in Narragansett Bay is due to global warming (Sullivan *et al*. 2001).

The period of ctenophore dominance in 2002 was much longer (July-November) than in 2000 (October), the only previous year in which ctenophores were abundant in the bays. Unfortunately, since *Mnemiopsis* disintegrates upon formalin preservation, there are no abundance or displacement volume data for ctenophore populations during these two blooms. A linkage between increased ctenophores and the outfall diversion is unlikely, in view of independent observations that ctenophores were also abundant in Buzzards Bay and the Cape Cod Canal during the same periods of 2000 and 2002 when they were abundant in Massachusetts Bay and, particularly, Boston Harbor. Given their important roll in the plankton dynamics of the ecosystem, more effort should be devoted to quantifying fluctuations of ctenophores and their effects in the MWRA sampling area.

Zooplankton "Conveyor Belt" Hypothesis:

Because of their importance to the food web in general and as important prey for right whales specifically, issues relating to potential impacts of the discharge on zooplankton abundance or community structure have received significant attention. As part of that ongoing process, OMSAP recommended in July 2000 that

> "Since the Massachusetts and Cape Cod Bays system flows like a "conveyor belt" from north to south, MWRA should develop a method for analyzing the current data spatially and temporally to contrast differences between the northern boundary stations and Cape Cod Bay." (OMSAP 2000).

The "conveyor belt" hypothesis referred to by OMSAP suggested that MWRA zooplankton data might reflect the overall counterclockwise circulation in the bays, such that a population of zooplankton would be advected in at the northern boundary, transported through the nearfield (potentially receiving an inoculum of effluent nutrients), and be transported southward, ultimately into Cape Cod Bay. OMSAP suggested that the timing of peaks in important zooplankton species could be sequential, with taxa peaking first at the northern boundary, later in the nearfield and southern Massachusetts Bay, and ultimately reaching Cape Cod Bays.

An examination of MWRA zooplankton data (Kropp *et al*., 2003) does not support the hypothesis that conveyor belt circulation consistently transports "pulses" of zooplankton from north to south within the bays. Time series of *Calanus finmarchicus* and *Oithona similis* abundance were examined from 1995 through 2002 at station F27 at the northern boundary, N16 in the nearfield, F06 from southern Massachusetts Bay, and F01 in Cape Cod Bay (**Figure** 4-43). Peak *C. finmarchicus* abundances are often coincident at all stations, or may occur earlier at the southern stations than northern. Similarly, there is no consistent north-south sequence in peak abundances for *O. similis*, nor for other important copepod species that were examined including adults of *Paracalanus parvus, Pseudocalanus* spp., *Paracalanus/Pseudocalanus* copepodites, and *Centropages typicus*.

To further evaluate community composition in MWRA zooplankton data, both spatially and temporally, a series of principal components analyses (PCA) were carried out on the entire 1992-2002 dataset (Kropp *et al*., 2003). The input data included zooplankton species abundance and five abiotic factors, temperature, salinity, chlorophyll fluorescence, dissolved oxygen, and transmissivity. The PCA analyses document two major influences on zooplankton community structure – seasonality (explained 13% of the variation) and an estuarine versus offshore gradient (explained another 8% of the variation). Temperature and dissolved oxygen, which are negatively correlated, seemed to anchor two ends of the spectrum for the seasonality factor. This factor separated cold-water taxa which are abundant relatively early in the year, such as cirripede larvae and *Calanus finmarchicus* from taxa with summer peaks in abundance like *Oithona similis*. The 'estuarine/offshore' factor was anchored by salinity and transmissivity, which are also negatively correlated. This factor separated taxa based on proclivity for estuarine or offshore conditions - taxa abundant in somewhat turbid, low salinity, harbor waters like *Acartia hudsonica* versus taxa more abundant in higher salinity, clearer offshore waters like *Oithona similis* and *Paracalanus parvus*. Inspection of PCA output based on regional station groupings continued to exhibit seasonal and estuarine/offshore influences, but did not support the linear conveyor belt hypothesis. The zooplankton assemblages at the boundary stations do not "predict" the communities found at stations in the nearfield or in Cape Cod Bay on subsequent surveys (Kropp *et al.*, 2003).

Preliminary results from an ongoing investigation of the zooplankton data indicate that there may be a significant correlation between the abundance of important zooplankton taxa and the North Atlantic Oscillation (NAO). One early finding found a negative correlation between NAO and *Calanus finmarchicus* (**Figure** 4-44). The impact of such wide scale forcing factors on zooplankton in Massachusetts and Cape Cod Bays is just beginning to be examined and certainly seem to play a larger role in zooplankton dynamics in the system than that due to the transfer of the MWRA outfall from Boston Harbor to the bay.

4.5 Summary

Over the course of the HOM program, general trends in water quality 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 the events are variable. Water qualifty conditions and the biological cycle in the bays in 2002 generally followed those observed previously. The main differences were the early winter/spring bloom starting prior to the first survey, delay in establishment of stratified conditions in the spring, and the early 'fall' bloom in August and September 2002. The winter/spring bloom of centric diatoms observed in February 2002 was most prominent in the nearshore waters of Boston Harbor, coastal waters, and near Cape Ann. A minor *Phaeocystis pouchetii* bloom was observed throughout most of Massachusetts and Cape Cod Bays in April. Even with the occurrence of these blooms, nutrient levels were not depleted in the surface waters until June as the waters were only weakly stratified until May/June. This weak late spring and early summer stratification also contributed to the relative scarcity of *Ceratium*, which usually increases in abundance as the water column becomes more stratified and their mobility gives them a competitive advantage for nutrients over other phytoplankton. The early occurrence of the fall bloom may have been associated with the decimation of zooplankton populations by ctenophore (*Mnemiopsis leidyi*) predation. A late fall bloom was also observed, but only in the chlorophyll and production data and did not result in increased phytoplankton abundance.

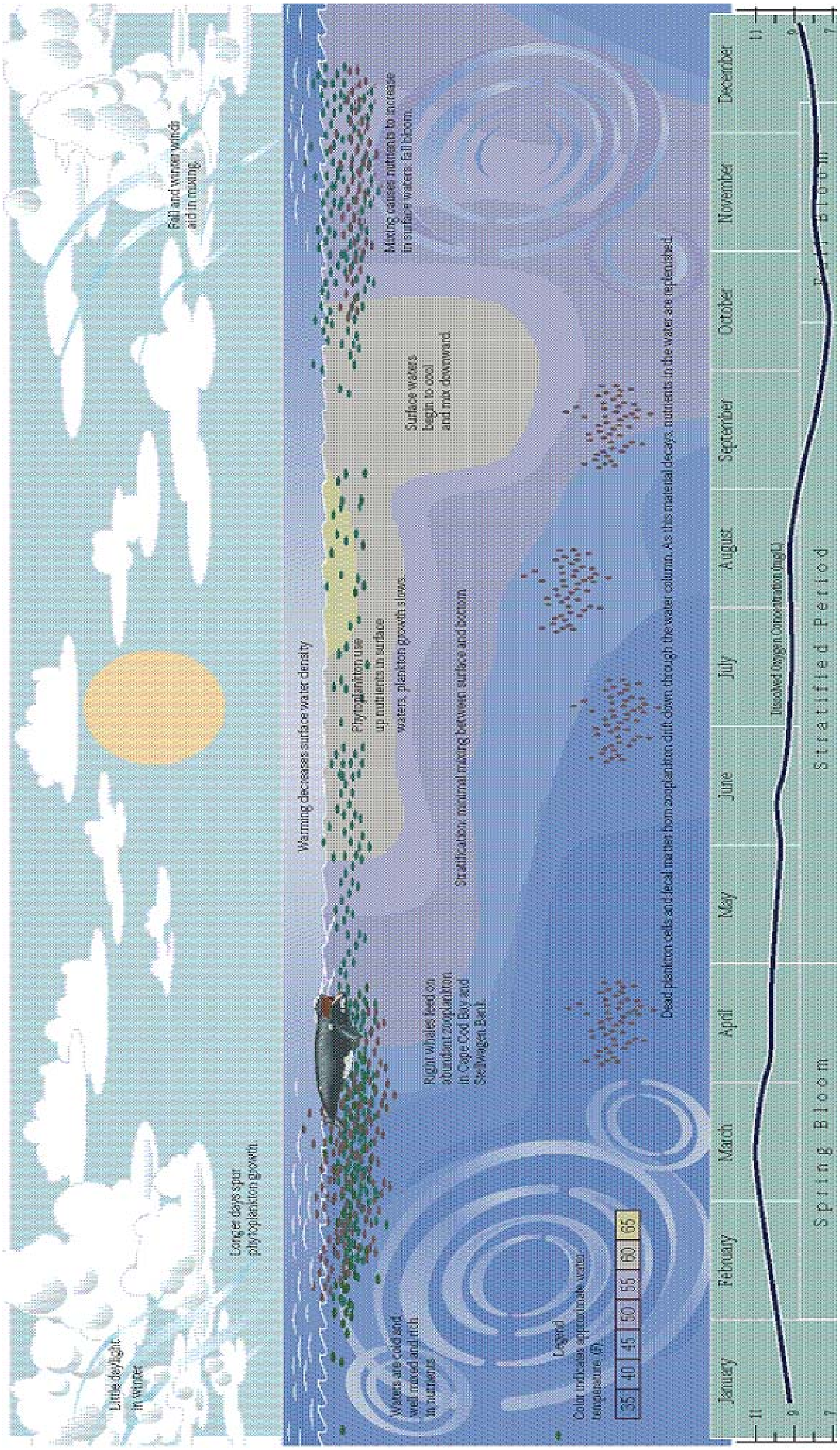


Figure 4-1. Seasonal cycle of coastal New England waters.

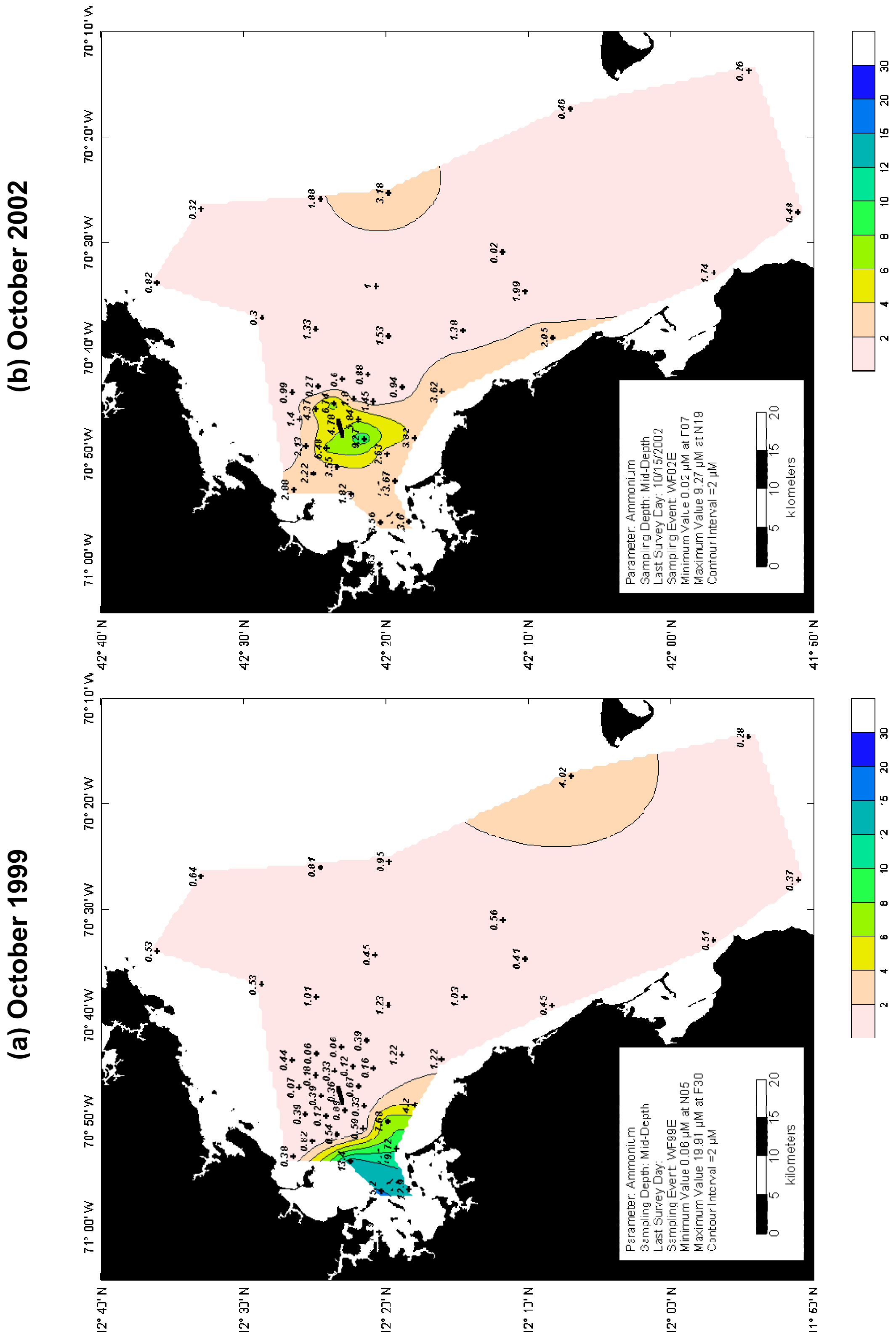


Figure 4-2. Mid-depth contour of NH_4 concentrations in (a) October 1999 and (b) October 2002.

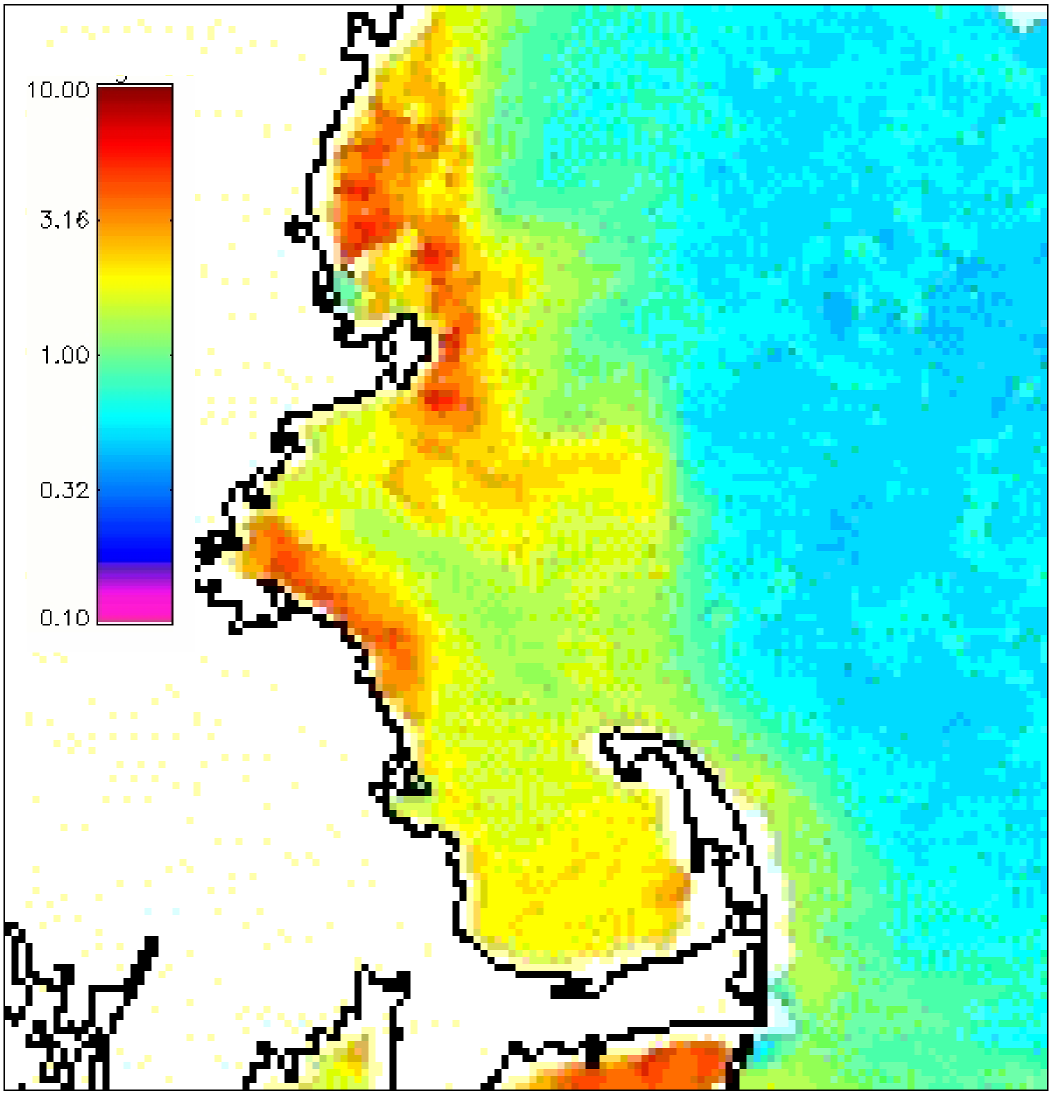
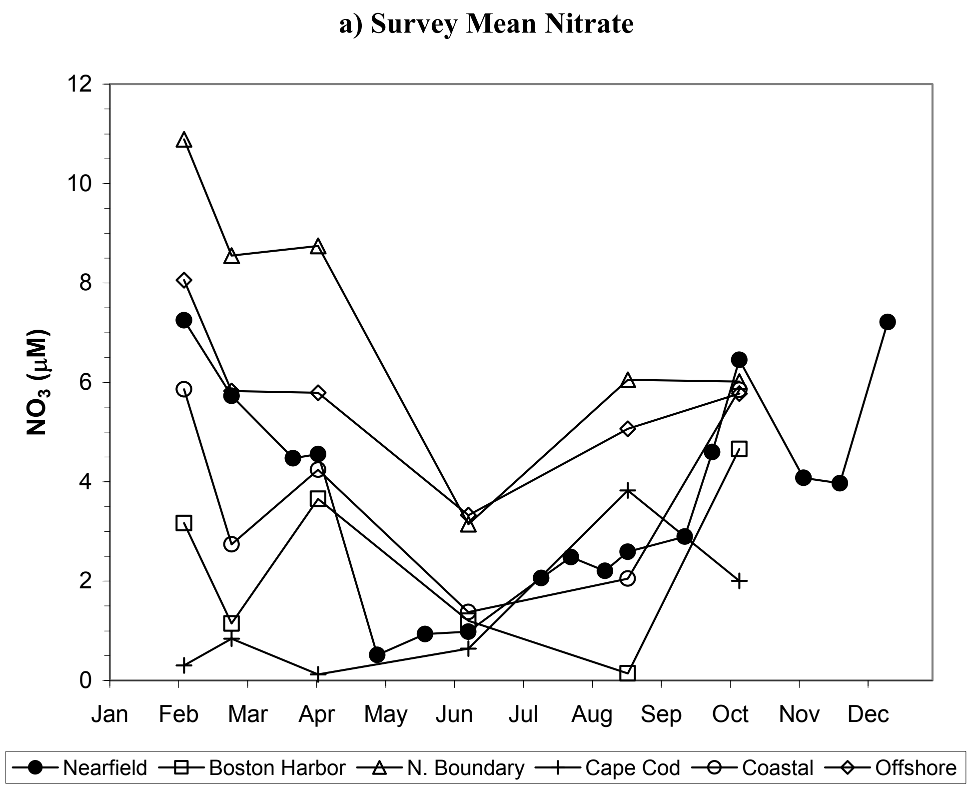


Figure 4-3. Eight-day composite of SeaWiFS chlorophyll (mg m^{-3}) images for the southwestern Gulf of Maine for February 26 to March 5 2002. [Image courtesy of Dr. Andrew Thomas, School of Marine Sciences, University of Maine]



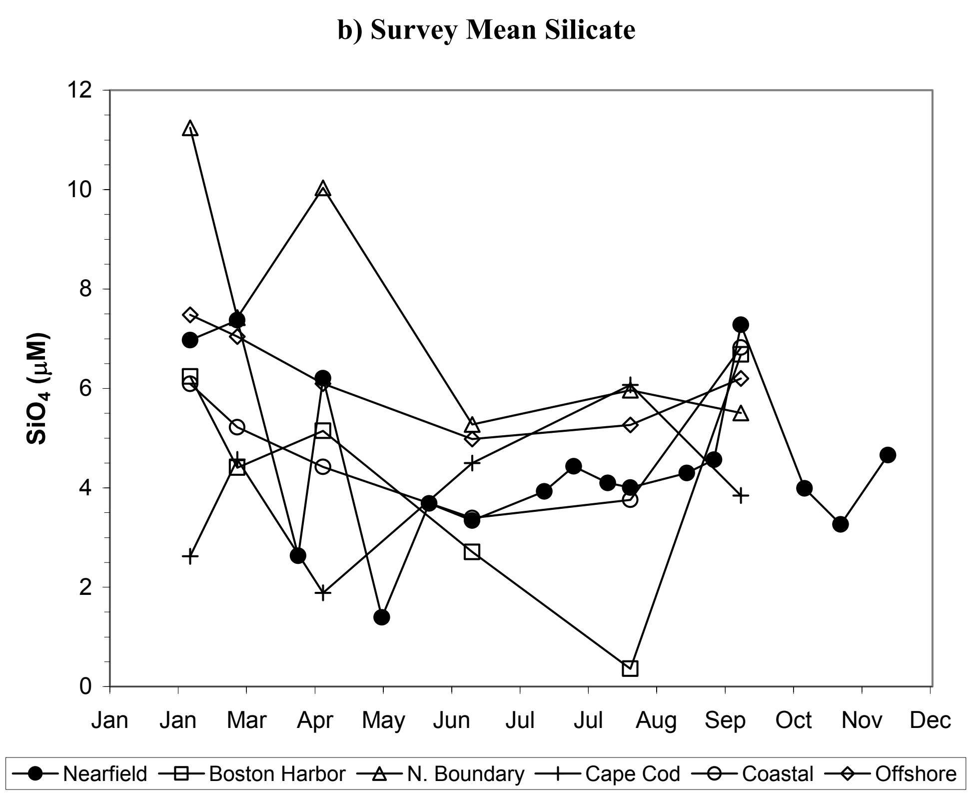
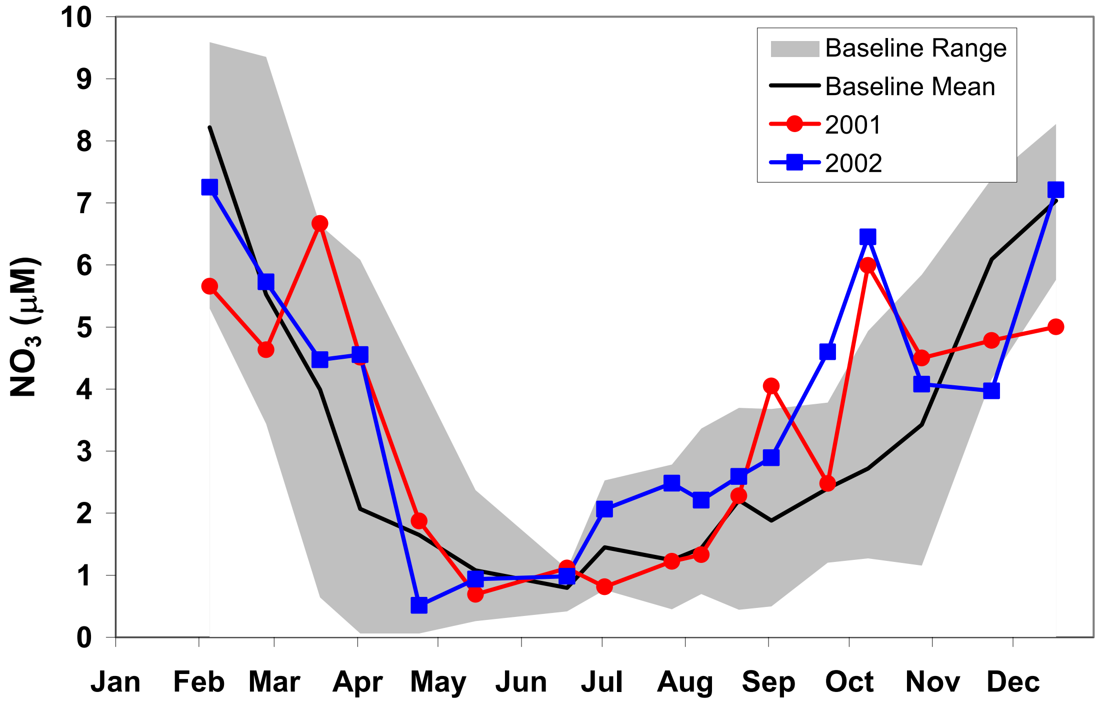


Figure 4-4. Time-series of survey mean (a) NO_3 and (b) SiO_4 concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region.

(a) Nitrate



(b) Silicate

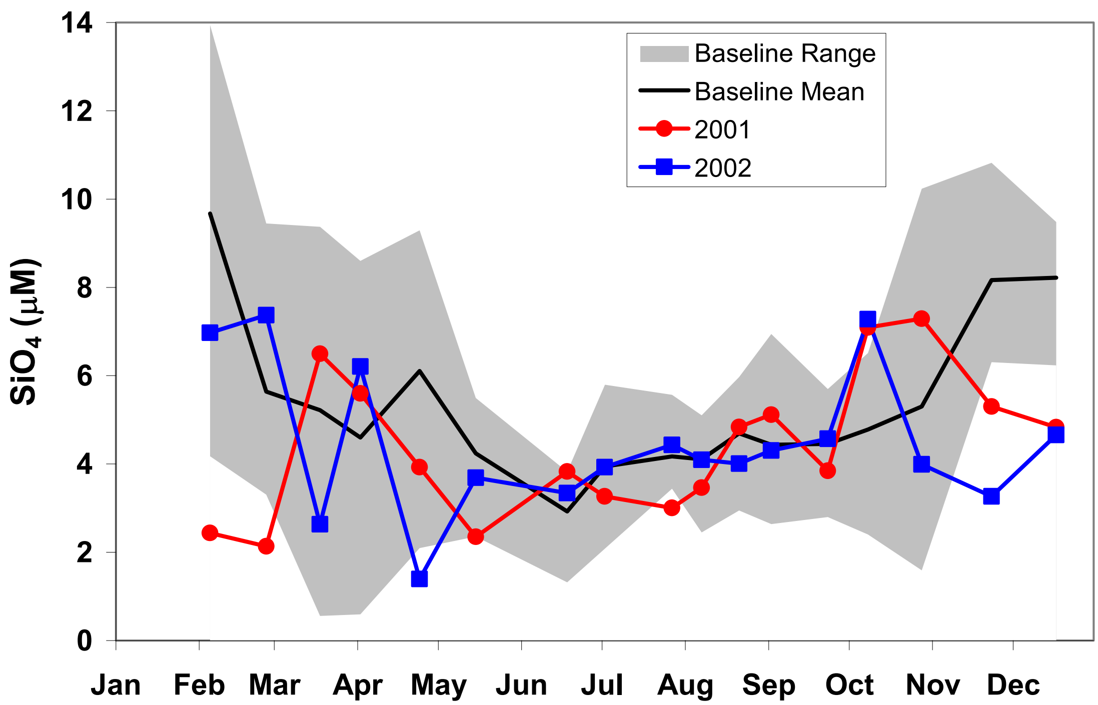
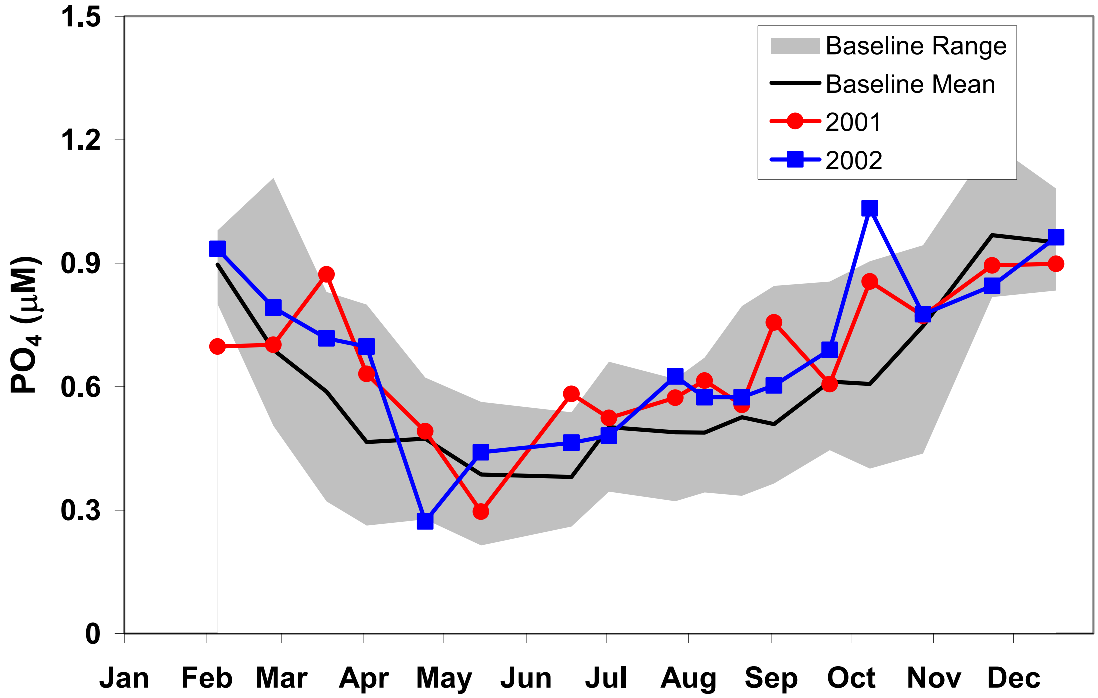


Figure 4-5. Time-series of survey mean (a) NO_3 and (b) SiO_4 concentrations in the nearfield in 2001 and 2002 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.

(a) Phosphate



(b) Ammonium

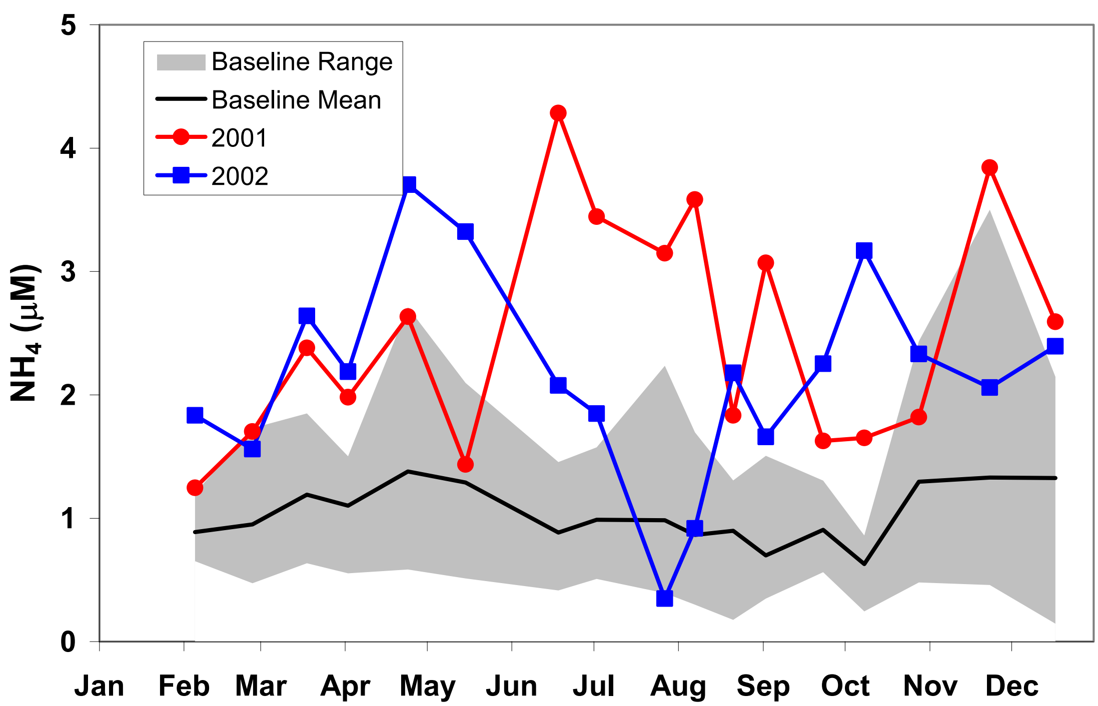
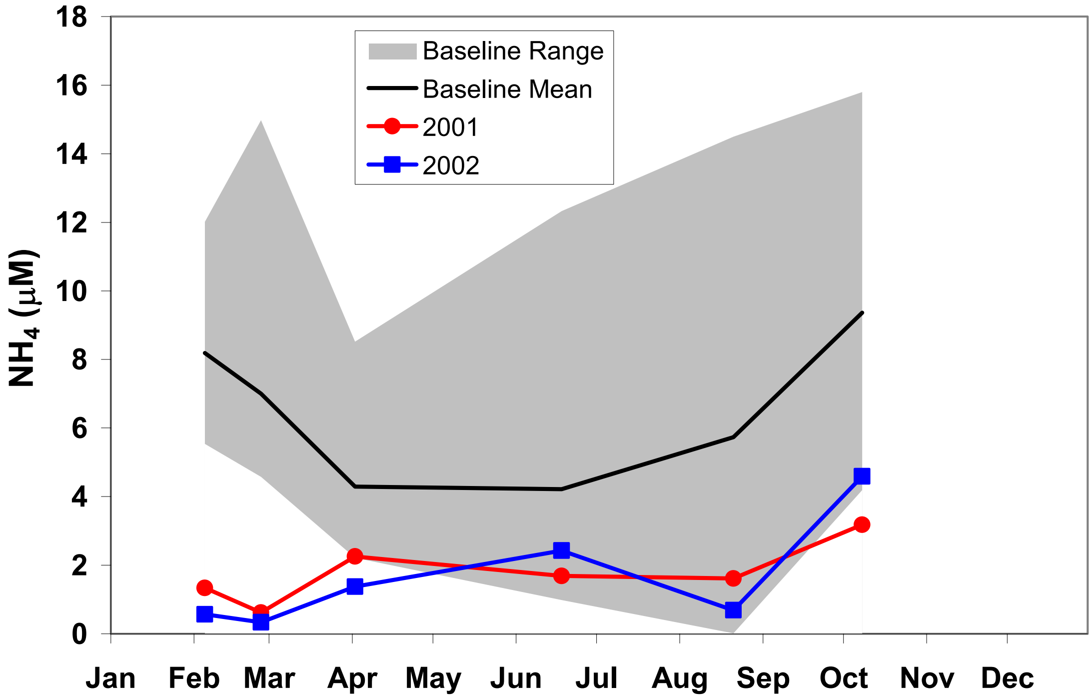


Figure 4-6. Time-series of survey mean (a) PO_4 and (b) NH_4 concentration in the nearfield in 2001 and 2002 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.

(a) Ammonium



(b) Nitrate

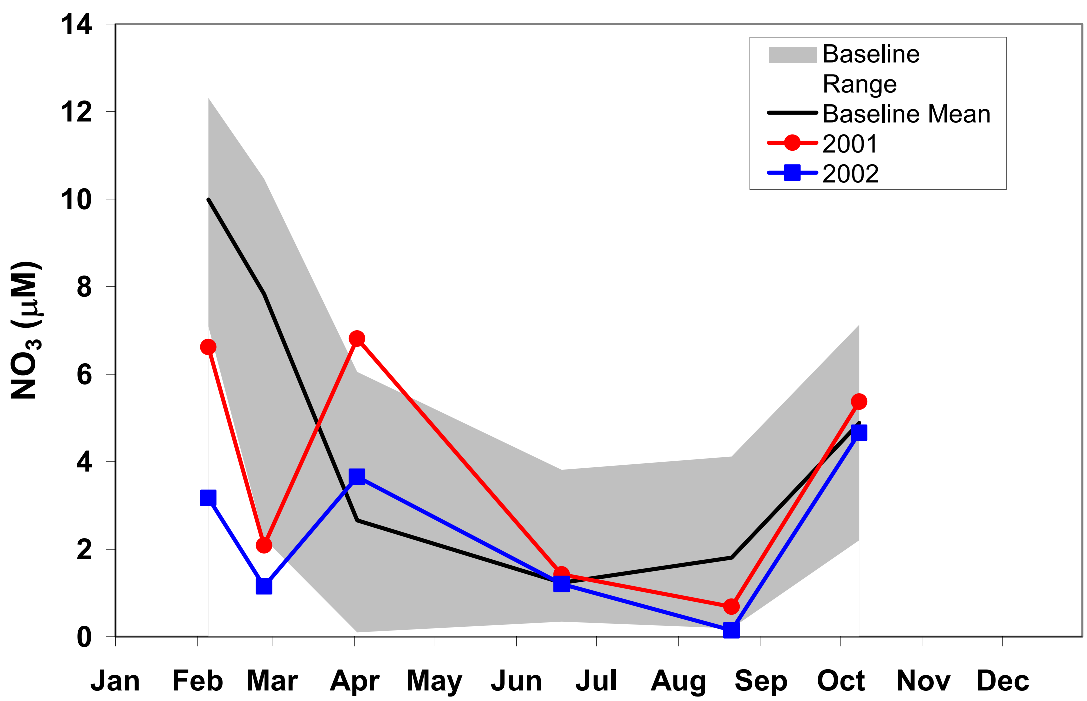


Figure 4-7. Time-series of survey mean (a) NH_4 and (b) NO_3 concentrations in Boston Harbor in 2001 and 2002 compared against the baseline range and mean. Data collected from all depths and all harbor stations.

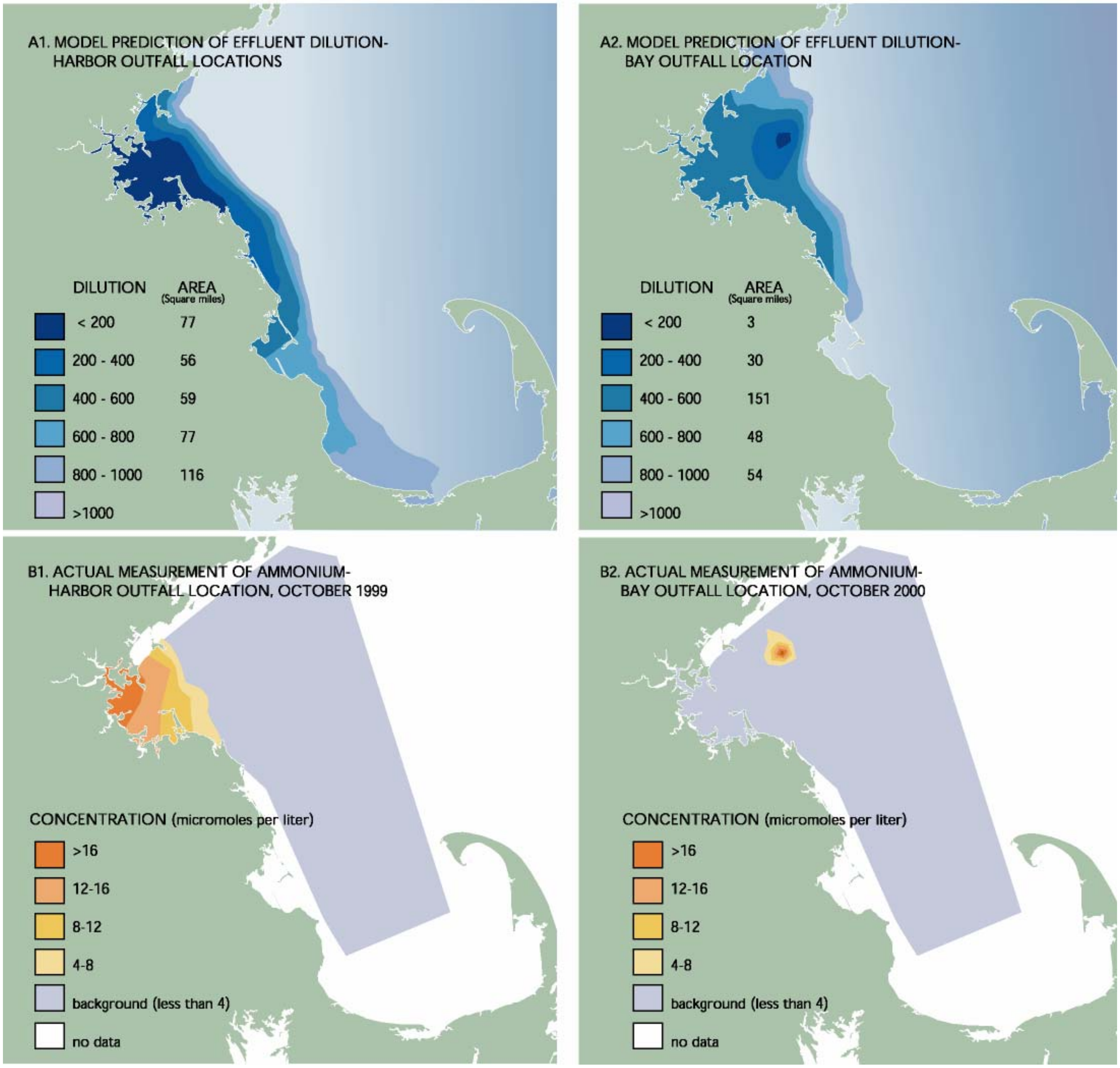
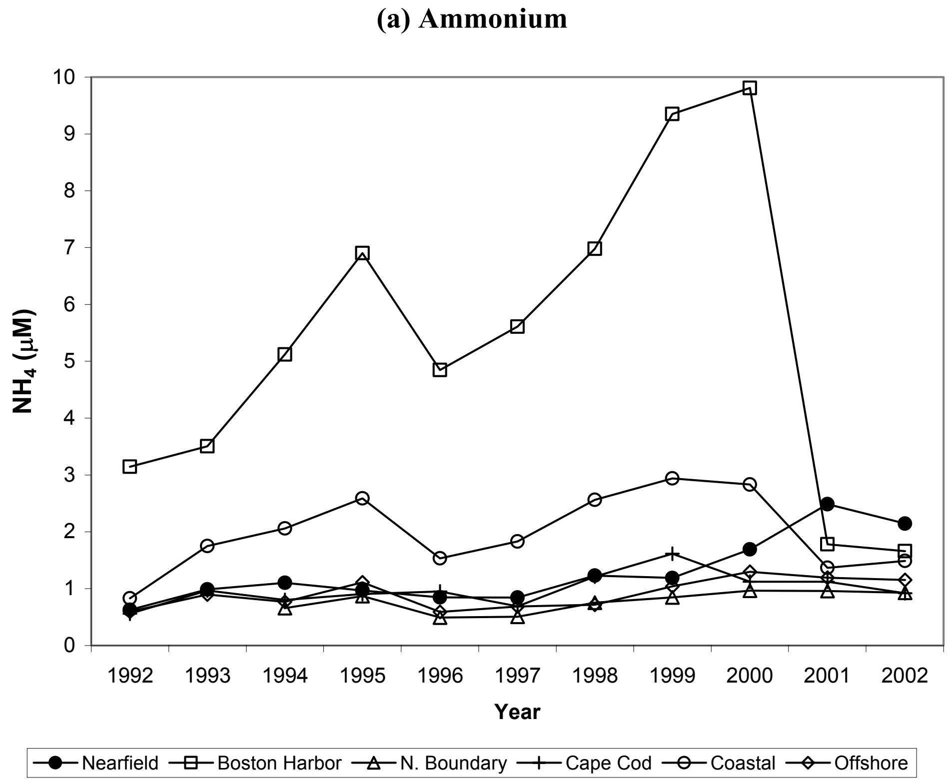


Figure 4-8. Comparison between (a) model predictions for dilution for the harbor and bay outfall and (b) actual NH_4 concentration measurements before and after September 6, 2000.



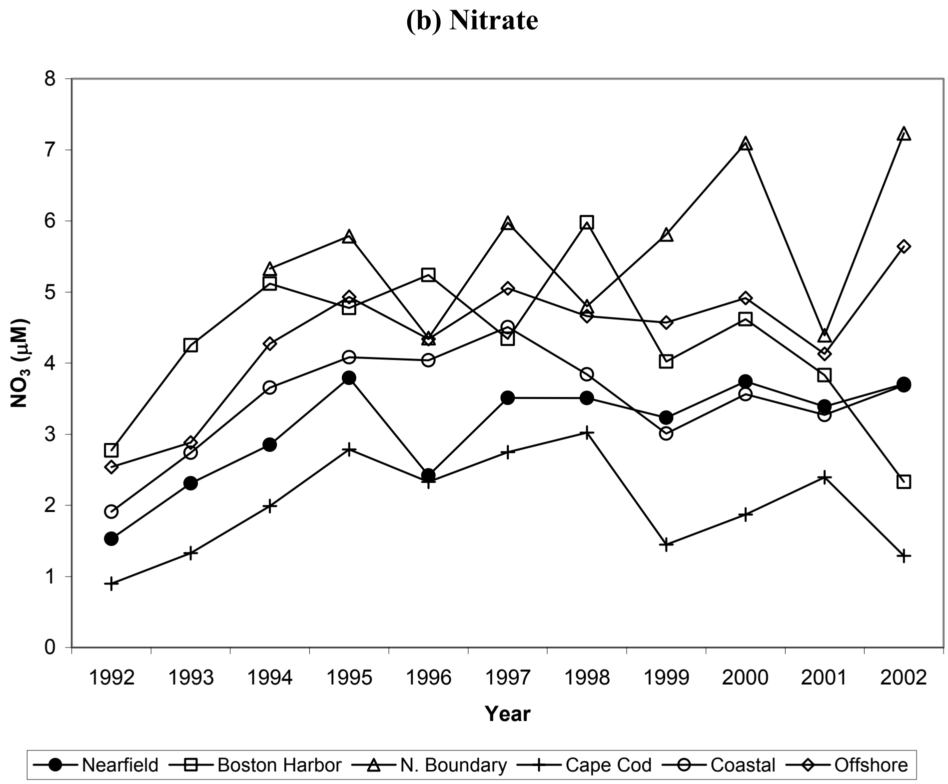


Figure 4-9. Annual mean (a) NH_4 and (b) NO_3 concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

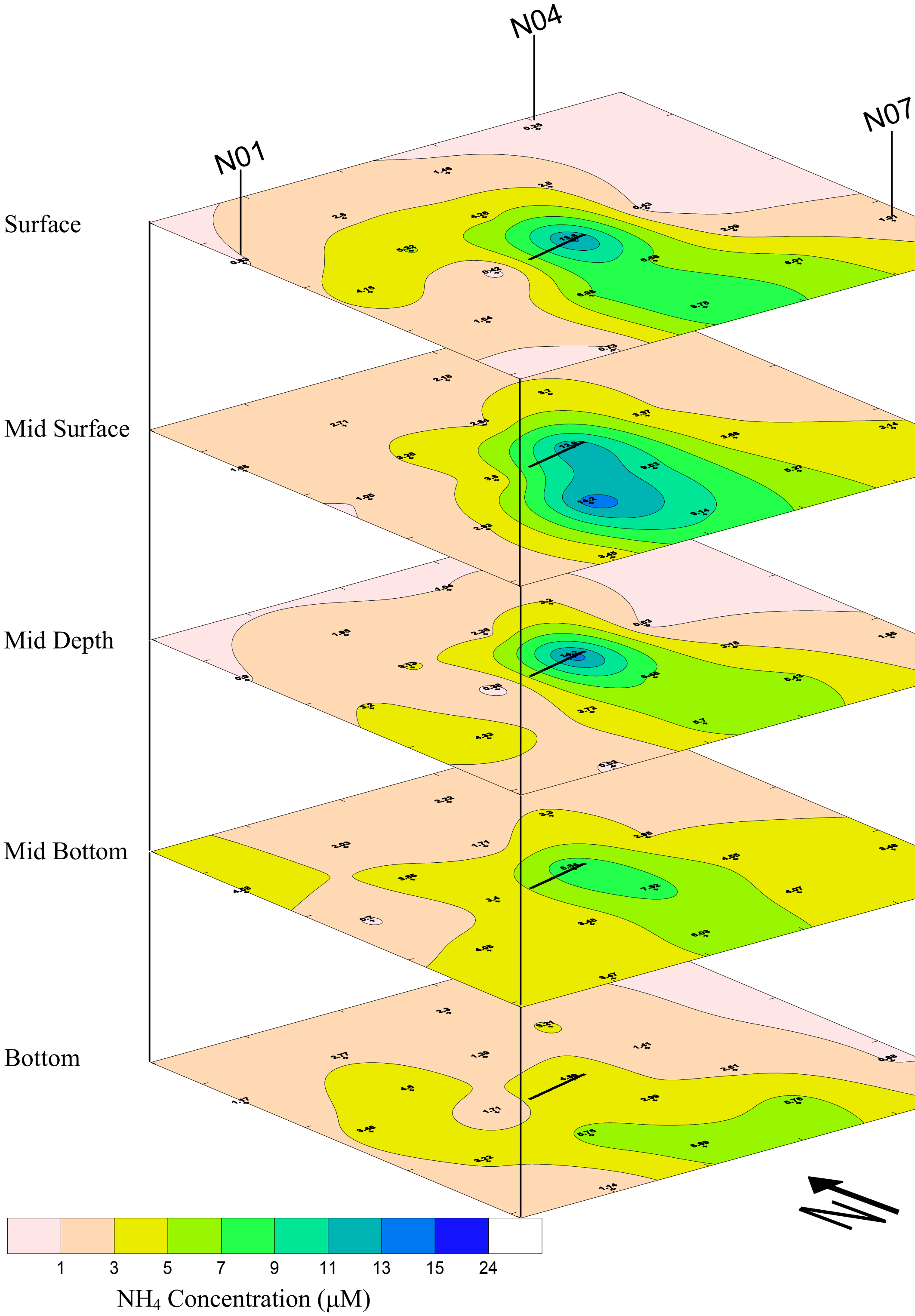


Figure 4-10. Ammonium concentrations at each of the five sampling depths for all nearfield stations during WN025

(Note: displayed depths are a representation, actual sampling depths vary for each station)

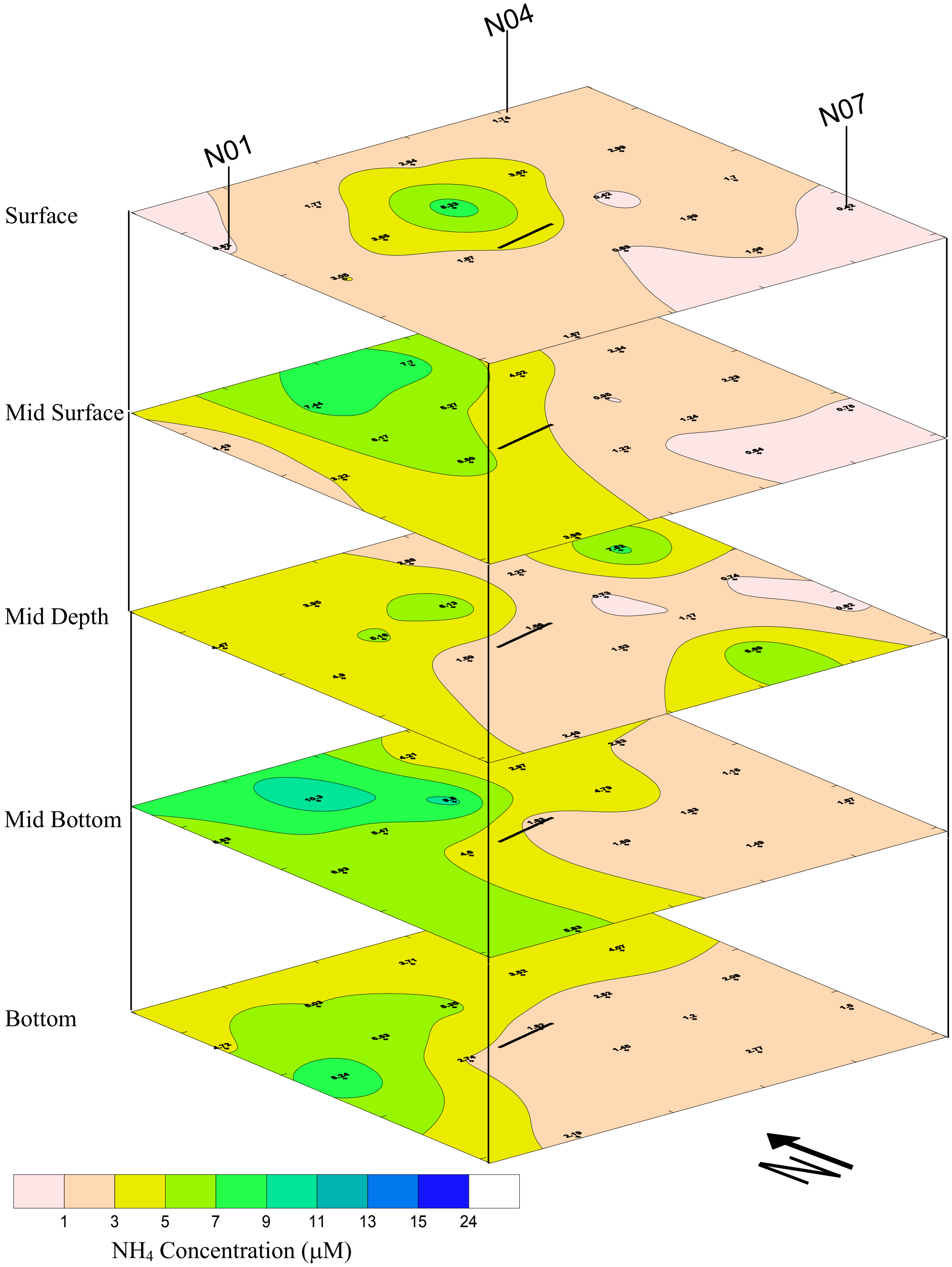


Figure 4-11. Ammonium concentrations at each of the five sampling depths for all nearfield stations during WN026

(Note: displayed depths are a representation, actual sampling depths vary for each station)

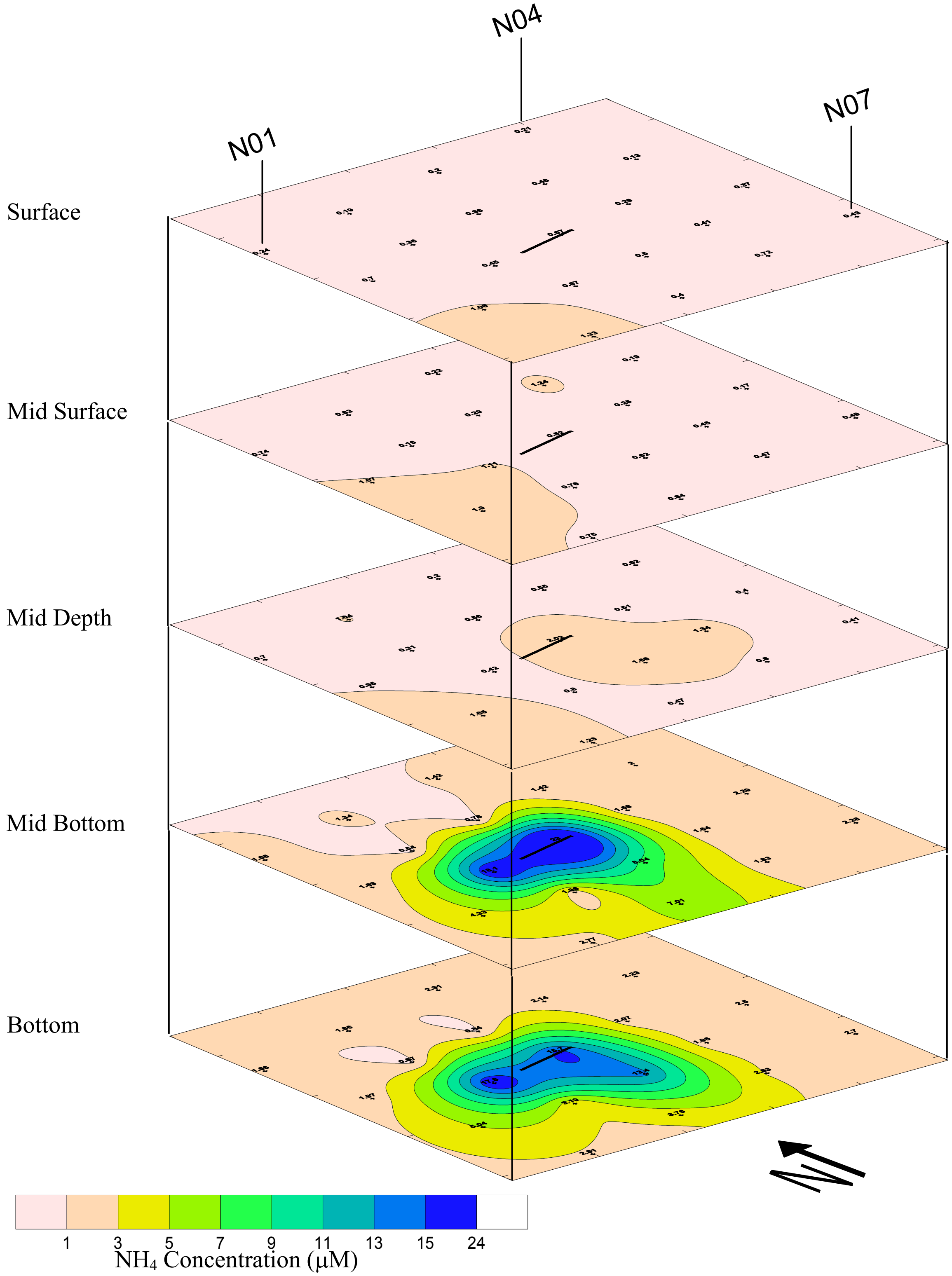
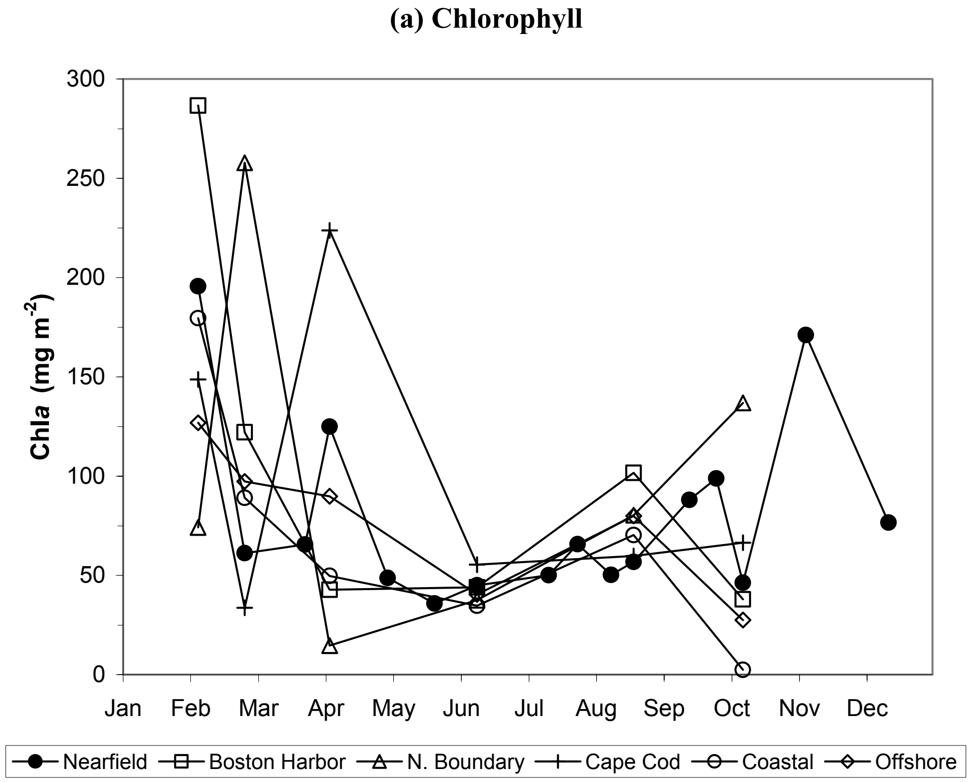


Figure 4-12. Ammonium concentrations at each of the five sampling depths for all nearfield stations during WN027

(Note: displayed depths are a representation, actual sampling depths vary for each station)



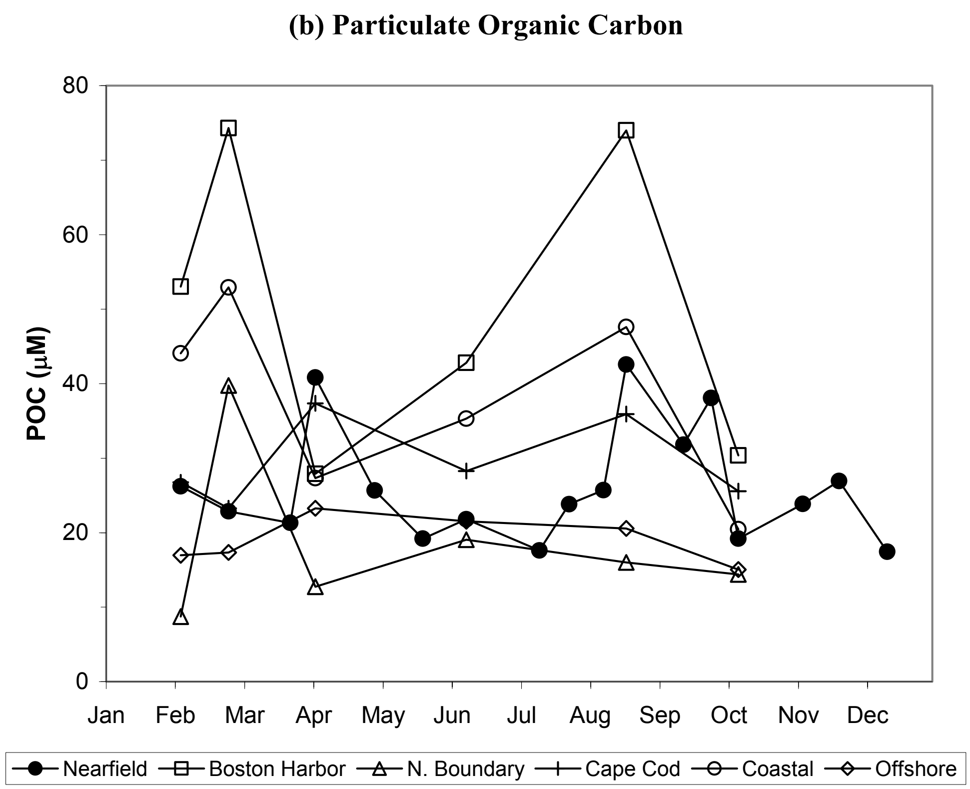
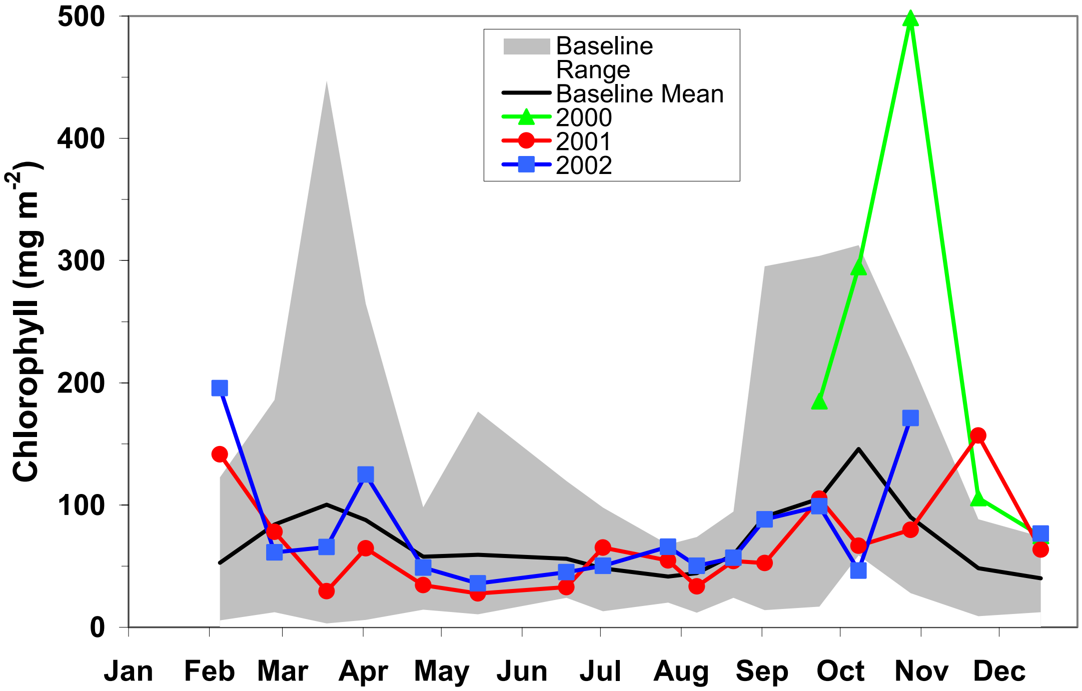


Figure 4-13. Time-series of survey mean (a) chlorophyll and (b) POC concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region.

(a) Chlorophyll



(b) Particulate Organic Carbon

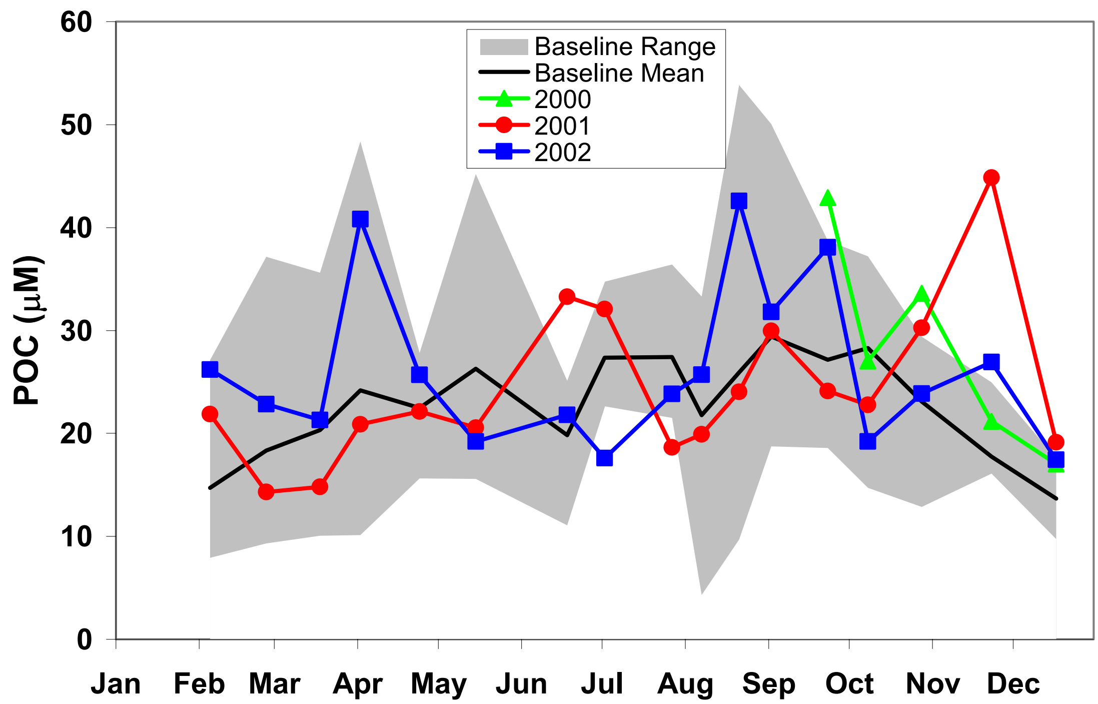
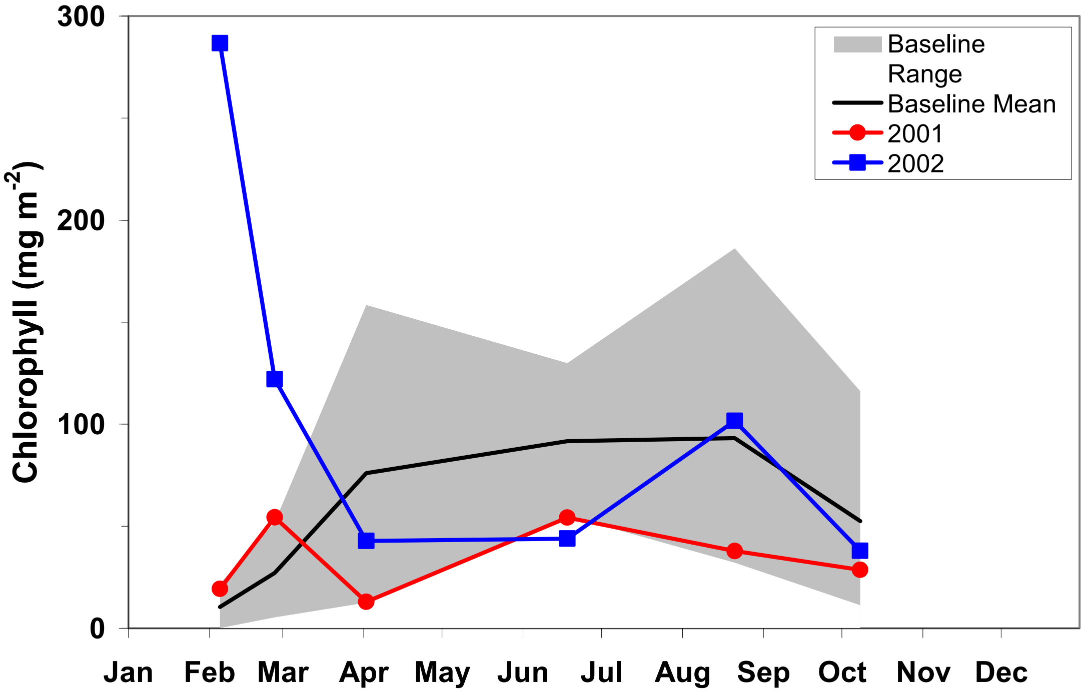


Figure 4-14. Time-series of survey mean (a) chlorophyll and (b) POC concentrations in the nearfield in 2001 and 2002 compared against the baseline range and mean. Data collected from all depths and all nearfield stations.

(a) Chlorophyll



(b) POC

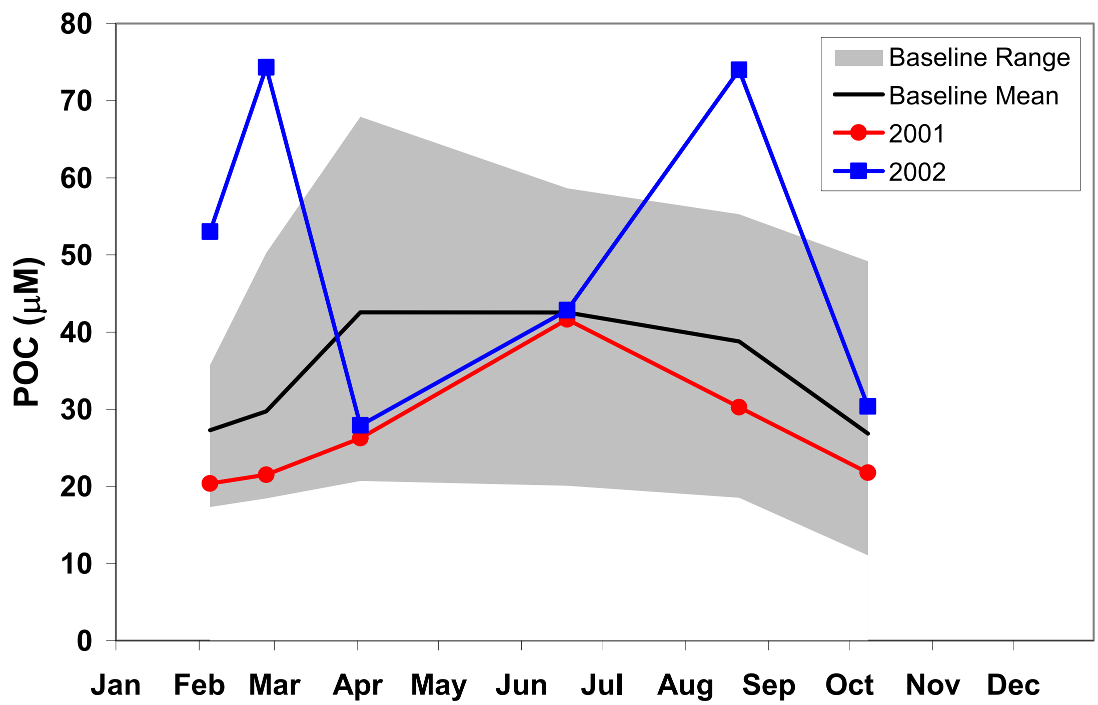
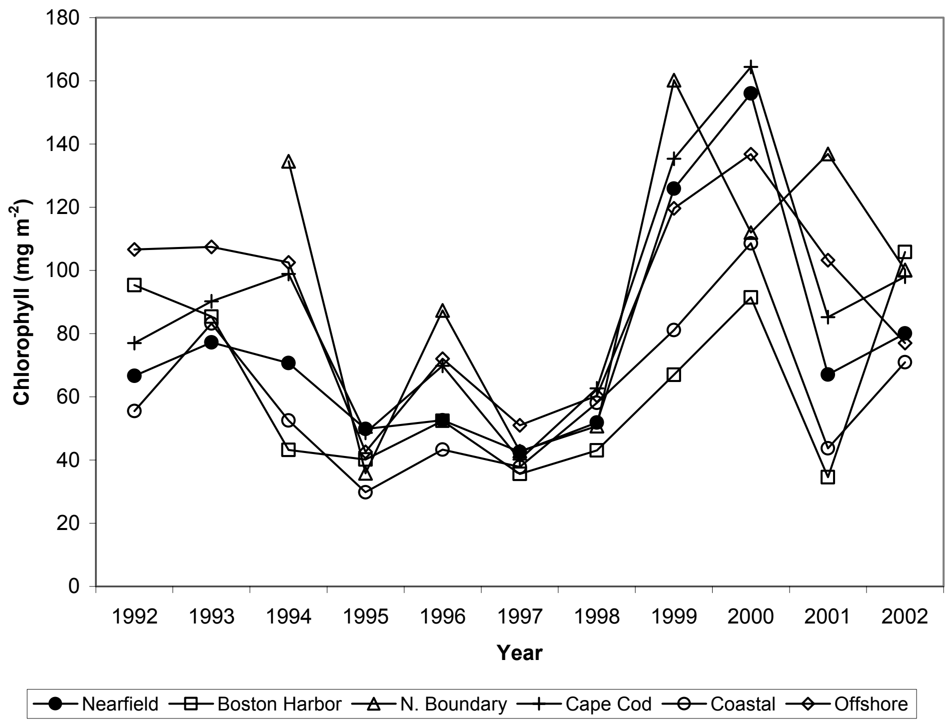


Figure 4-15. Time-series of survey mean (a) chlorophyll and (b) POC concentrations in Boston Harbor in 2001 and 2002 compared against the baseline range and mean. Data collected from all depths and all harbor stations.

(a) Annual Mean Chlorophyll



(b) Annual Mean POC

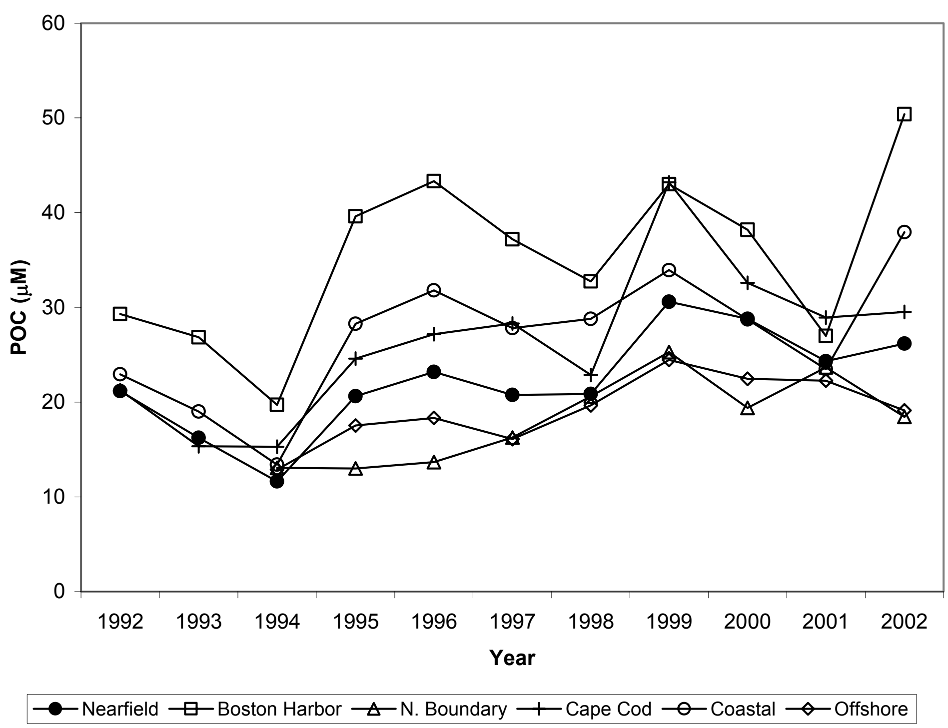


Figure 4-16. Annual mean (a) chlorophyll and (b) POC concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

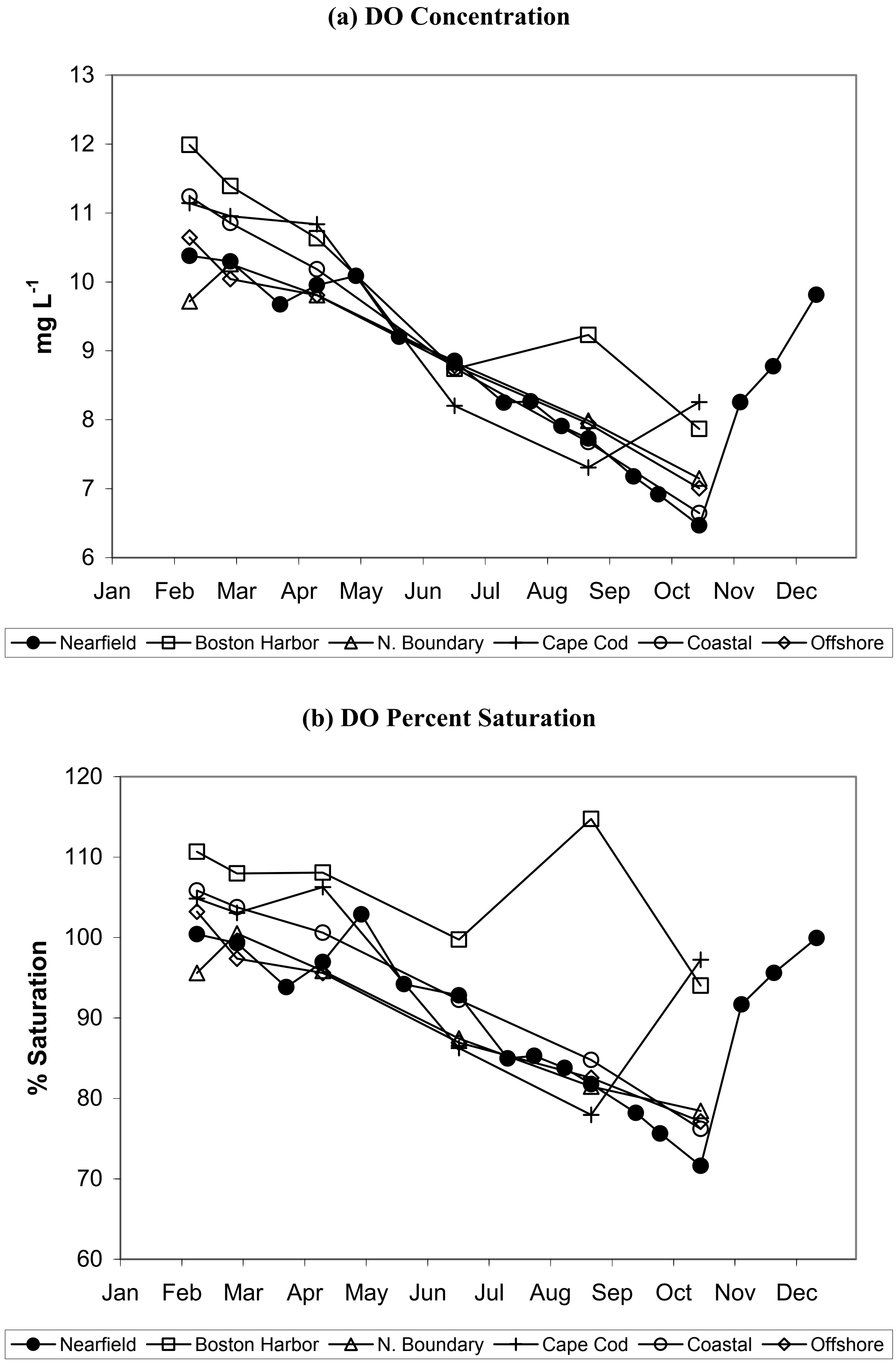


Figure 4-17. Time-series of average bottom dissolved oxygen (a) concentration and (b) percent saturation for 2002 in Massachusetts and Cape Cod Bays (data collected from all stations in the six areas).

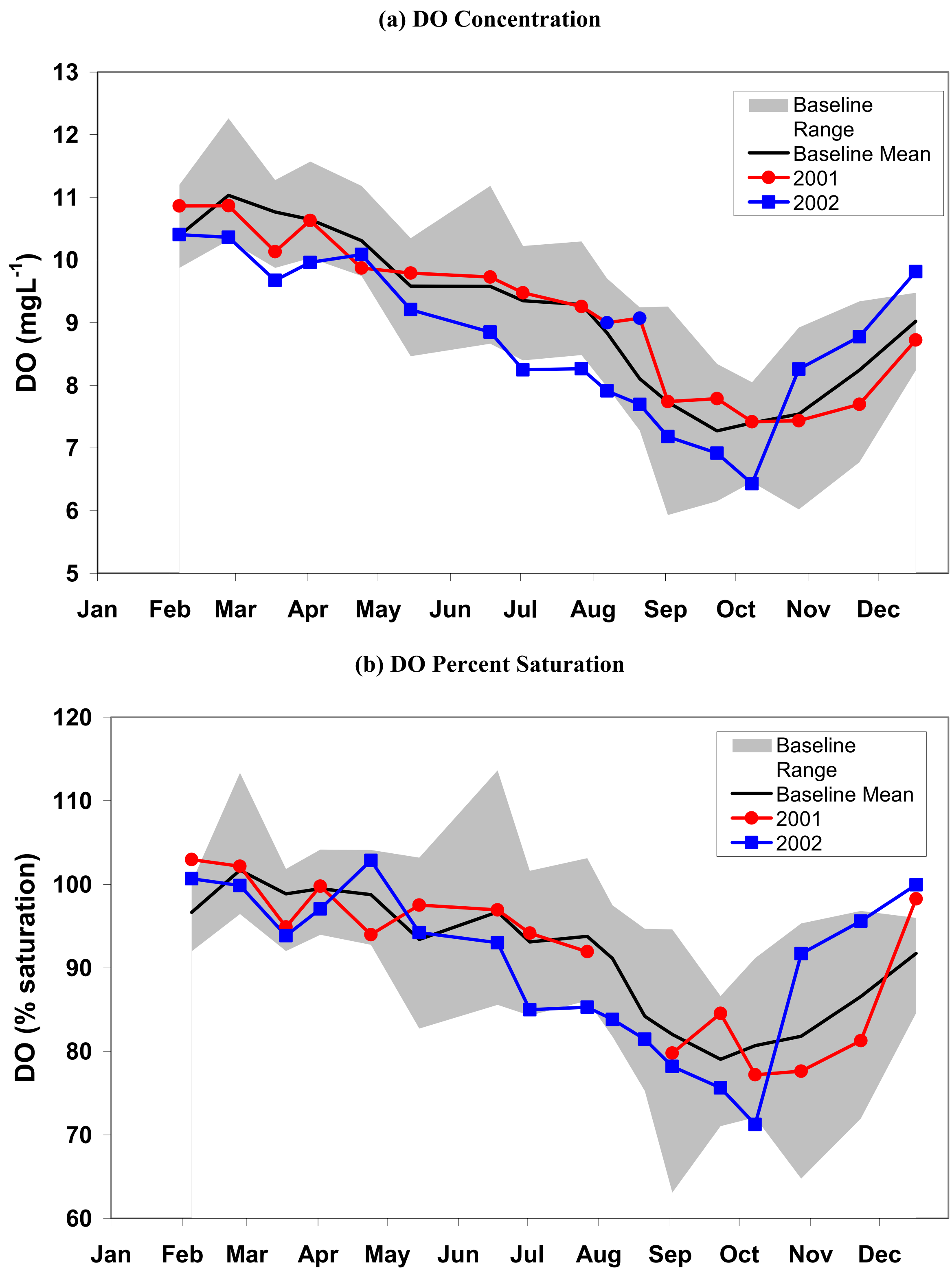


Figure 4-18. Time-series of nearfield survey mean bottom water (a) DO concentrations and (b) DO %saturation in 2001 and 2002 compared against the baseline range and mean. August data (blue dots) from Winkler titrations.

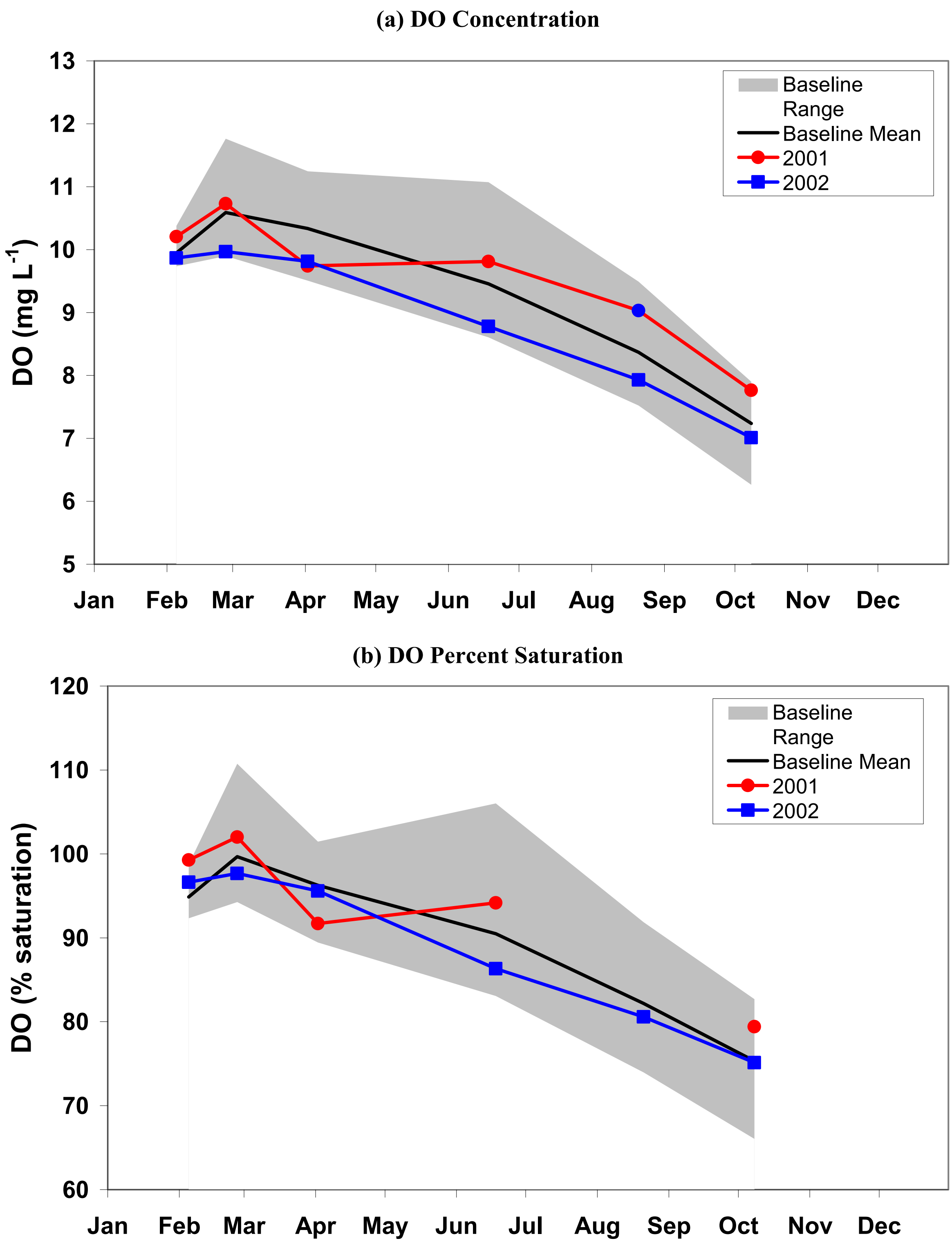
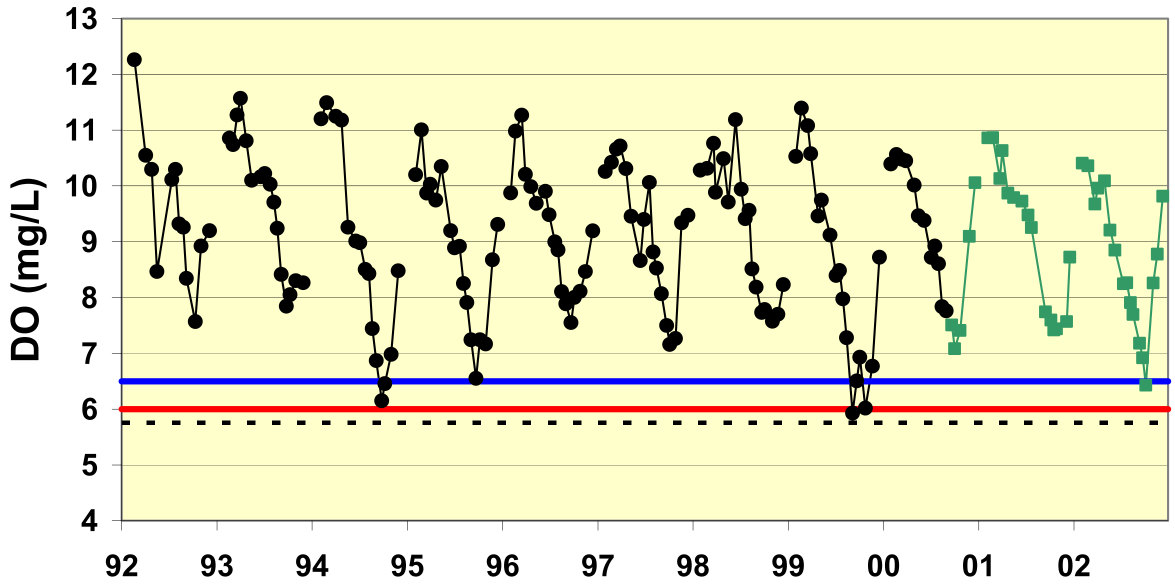


Figure 4-19. Time-series of Stellwagen Basin survey mean bottom water (a) DO concentrations and (b) DO %saturation in 2001 and 2002 compared against the baseline range and mean. August data (blue dots) from Winkler titrations. Data collected from stations F12, F17, F19, and F22.

(a) DO concentration



(b) DO Percent Saturation

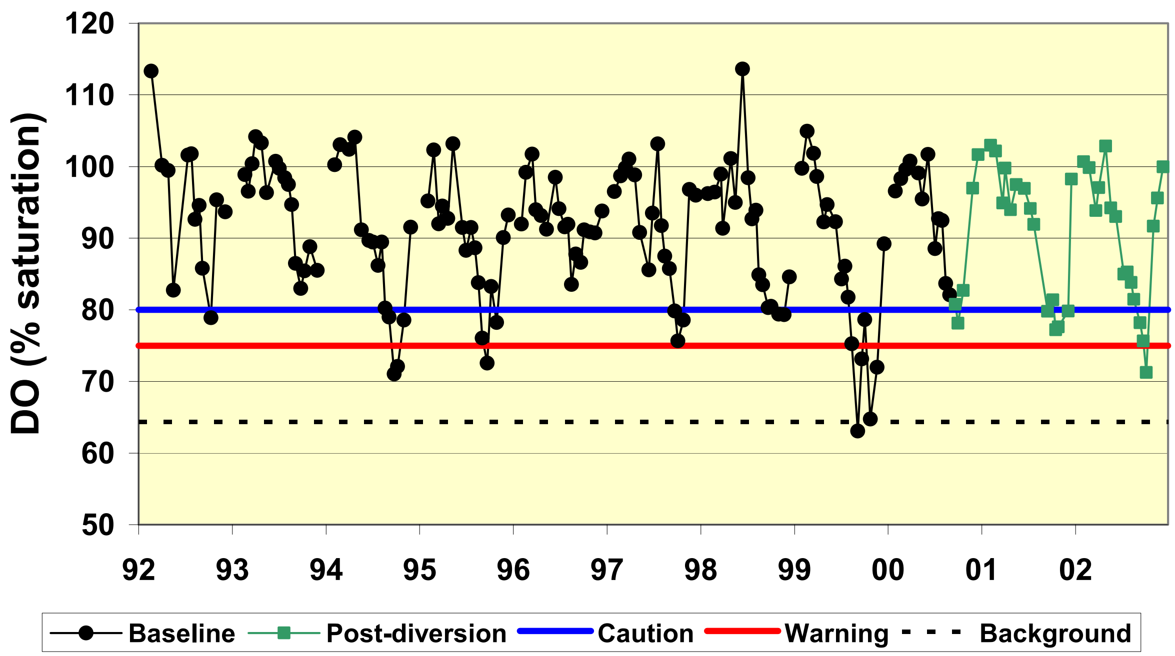
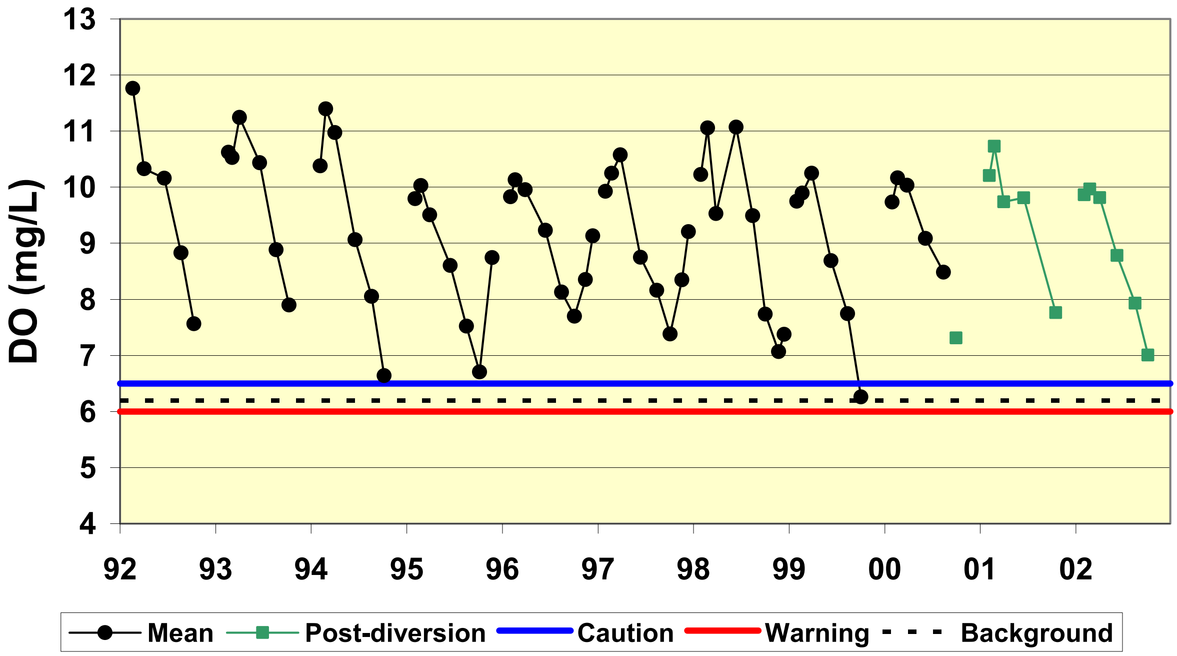


Figure 4-20. Survey mean bottom water dissolved oxygen (a) concentration and (b) percent saturation in the nearfield compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares.

(a) DO concentration



(b) DO Percent Saturation

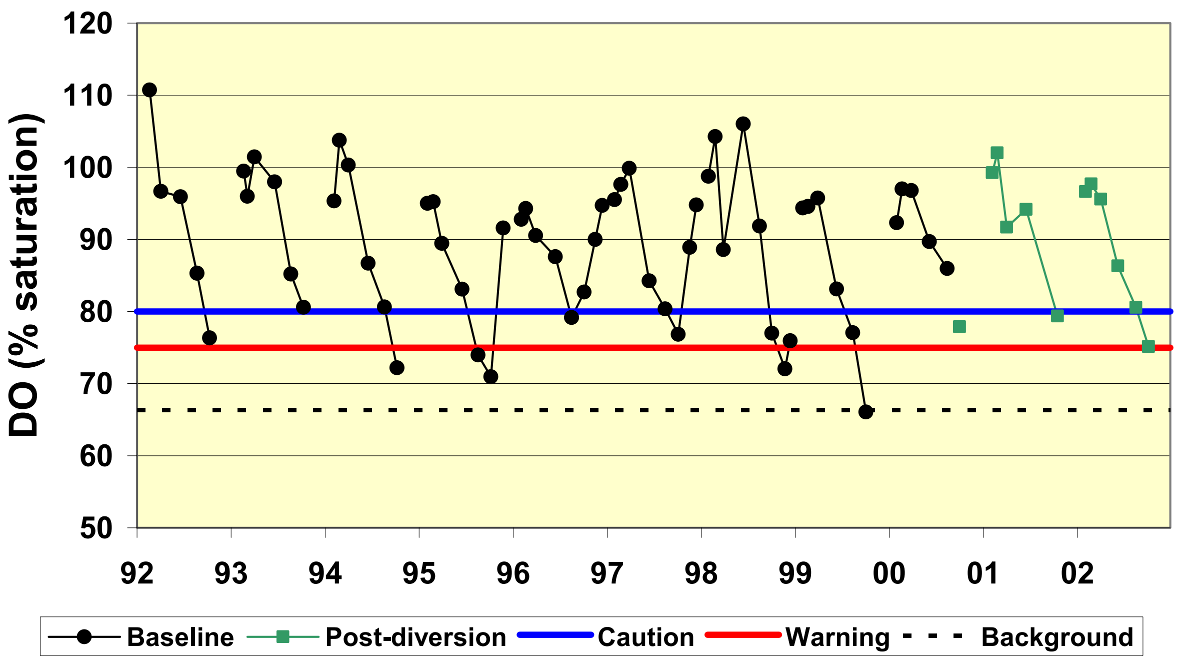


Figure 4-21. Survey mean bottom water dissolved oxygen (a) concentration and (b) percent saturation in Stellwagen Basin compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares. Data collected from stations F12, F17, F19, and F22.

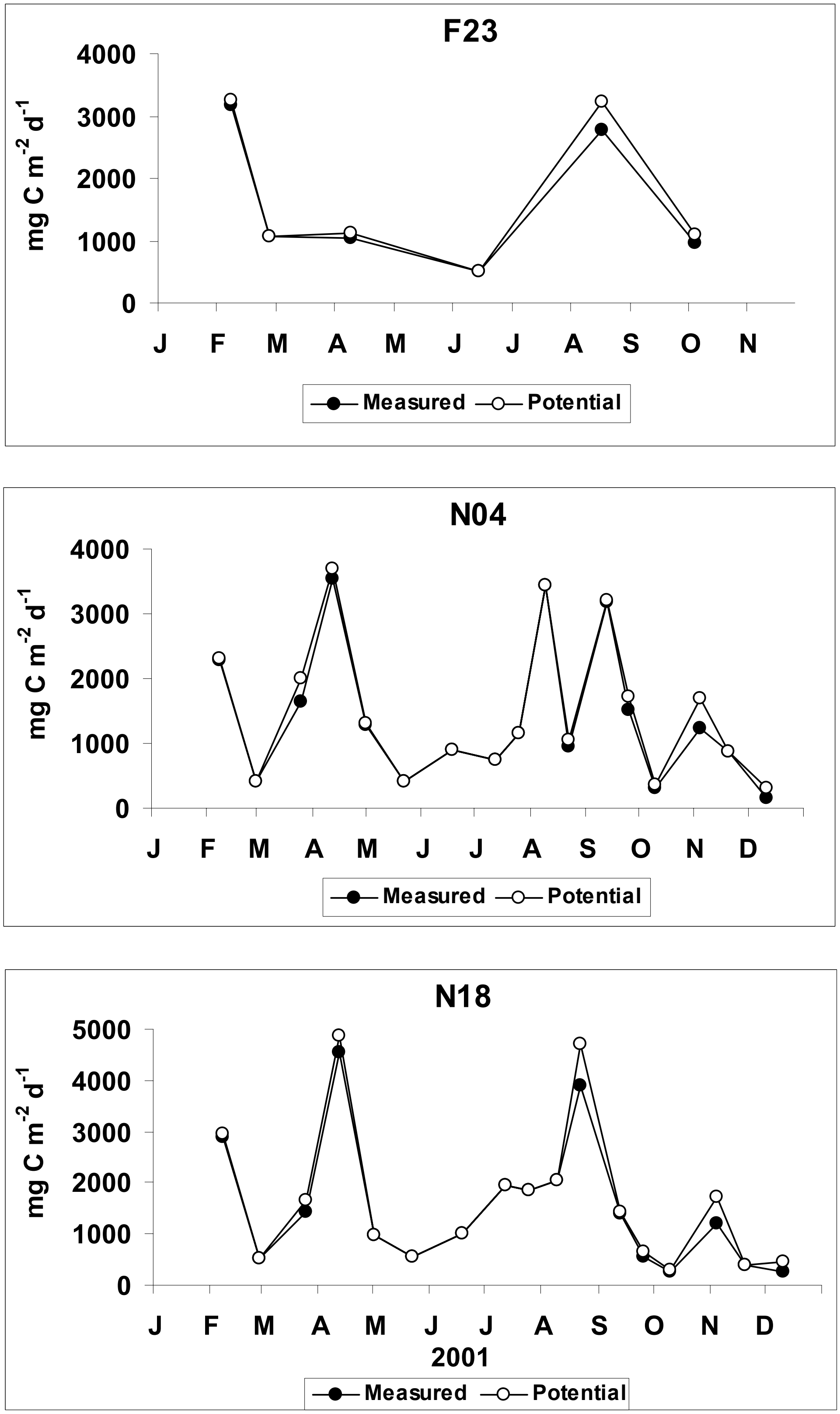


Figure 4-22. Measured and potential areal production ($mgCm^{-2}d^{-1}$) in 2002 at stations F23, N04 and N18.

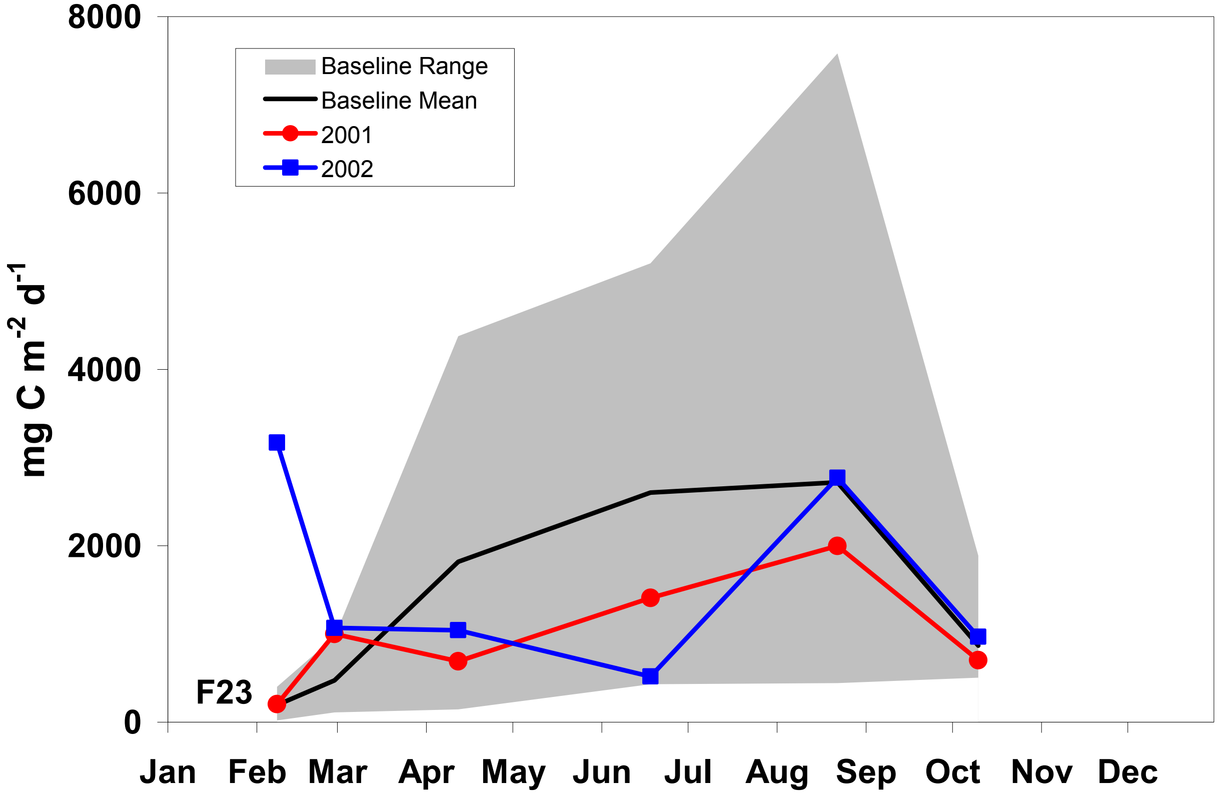
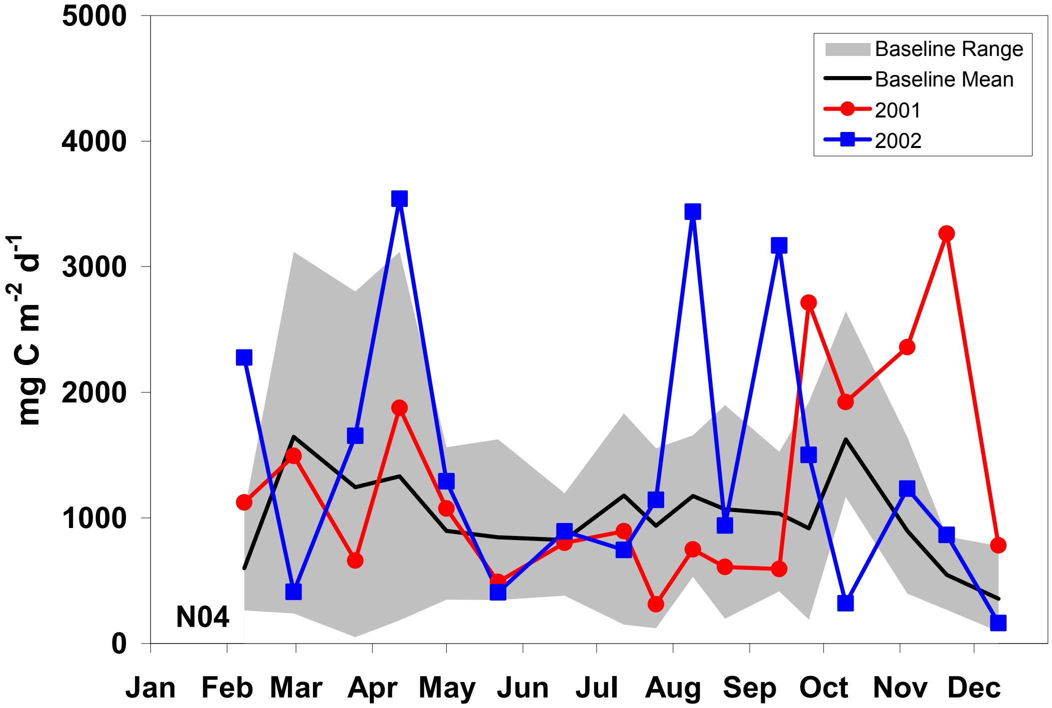


Figure 4-23. Time-series of areal production ($mgCm^{-2}d^{-1}$) at Boston Harbor station F23 for 2001 and 2002 compared against the baseline range and mean.

(a) Station N04



(b) Station N18

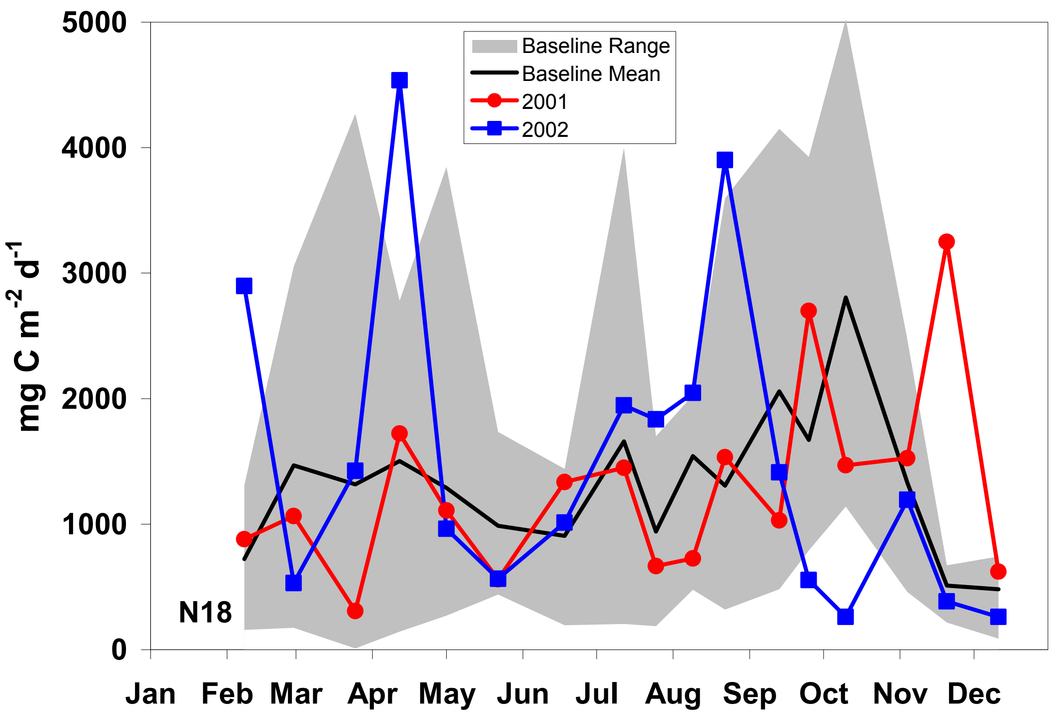


Figure 4-24. Time-series of areal production ($mgCm^{-2}d^{-1}$) at nearfield stations (a) N04 and (b) N18 for 2001 and 2002 compared against the baseline range and mean.

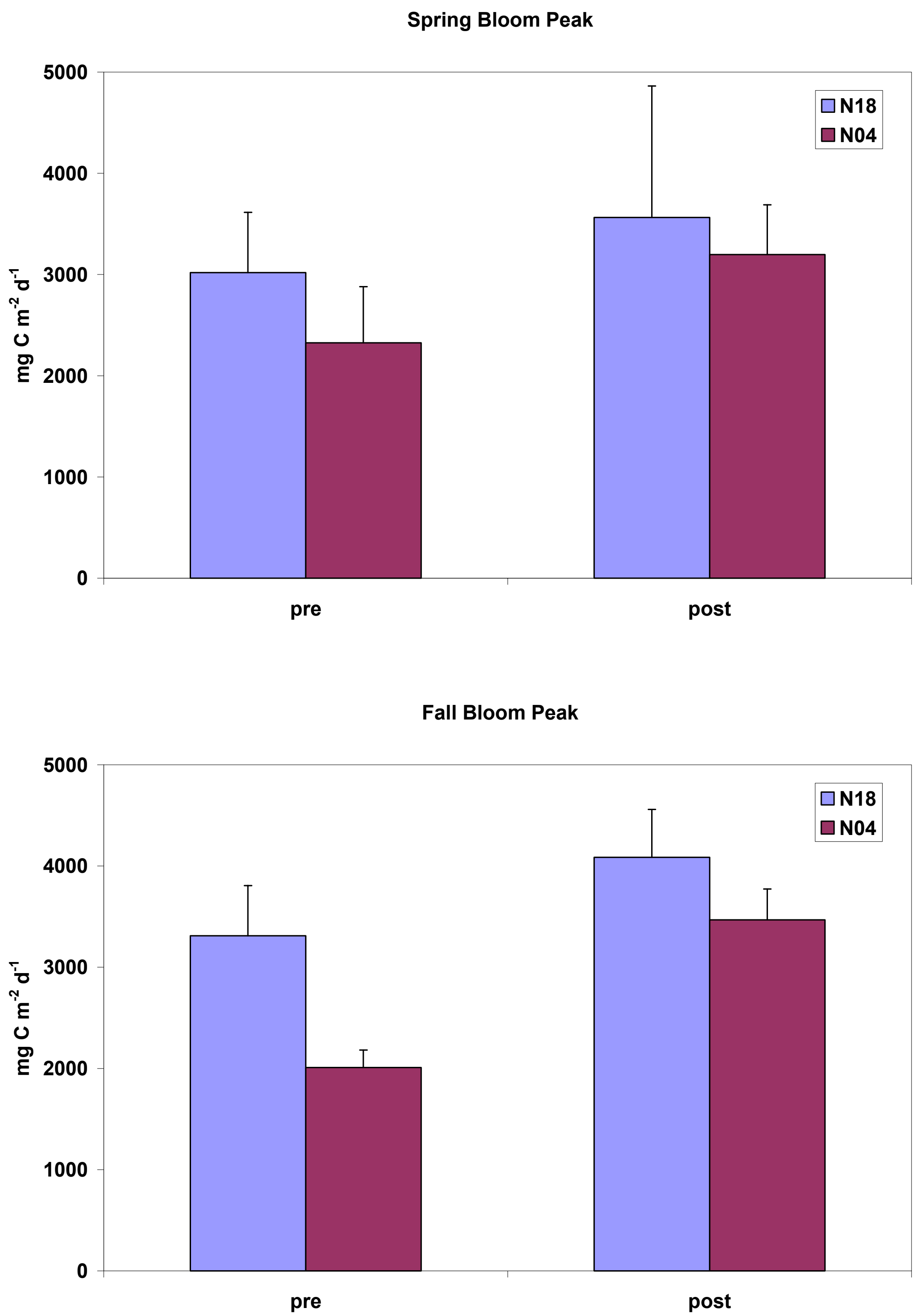


Figure 4-25. Spring and fall bloom peak production (mgCm^{-2}d^{-1}) at nearfield stations N04 and N16/N18. Pre versus post outfall diversion – spring 97-00 vs. 01-02 and fall 97-99 vs. 00-02.

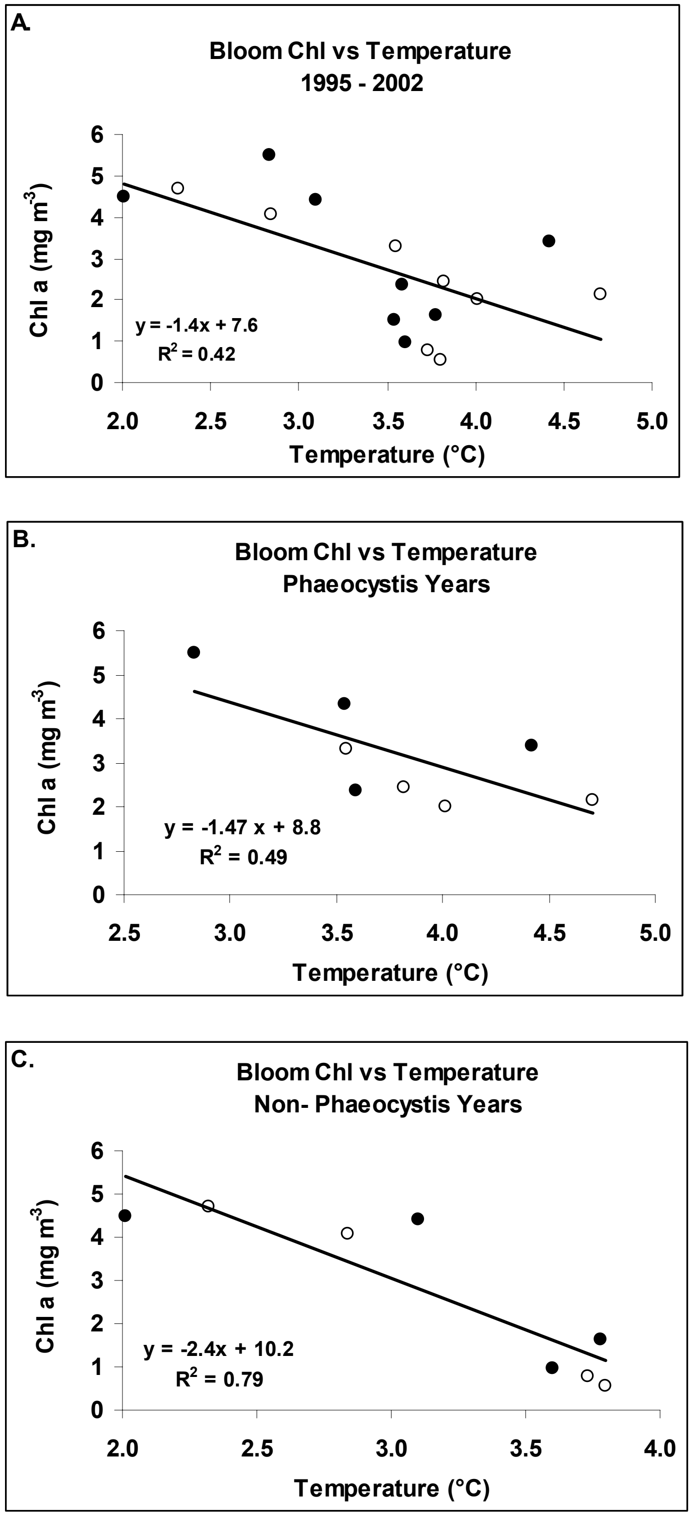
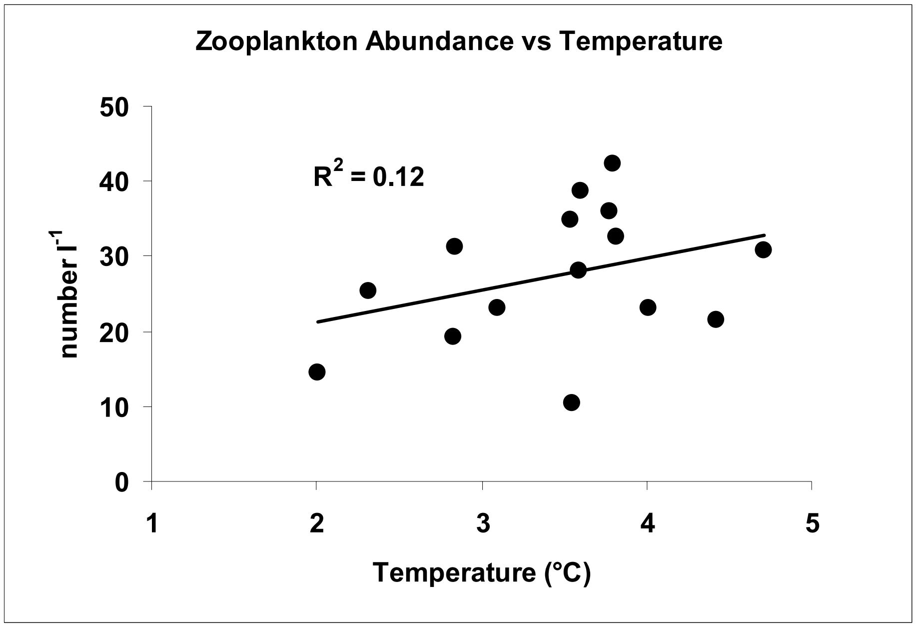


Figure 4-26. Nearfield peak chlorophyll vs. surface temperature during the spring bloom period. Empty circles are station N04 data and filled circles are station N18 data.



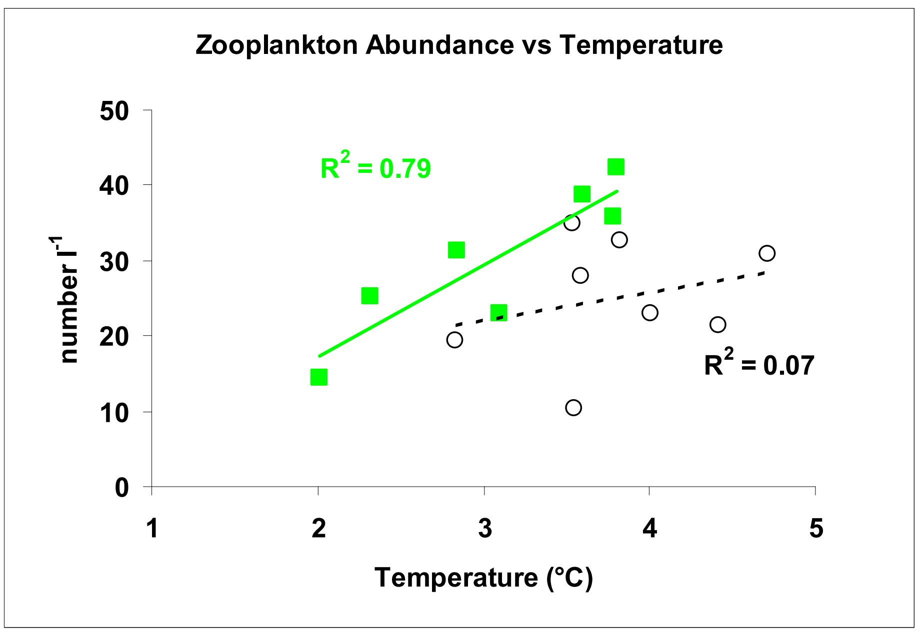


Figure 4-27. Total zooplankton vs. surface temperature both averaged over the spring bloom period at stations N04 and N18. Non *Phaeocystis* year data (95, 96, 98, and 99) green squares and *Phaeocystis* year data (97, 00, 01, and 02) open circles.

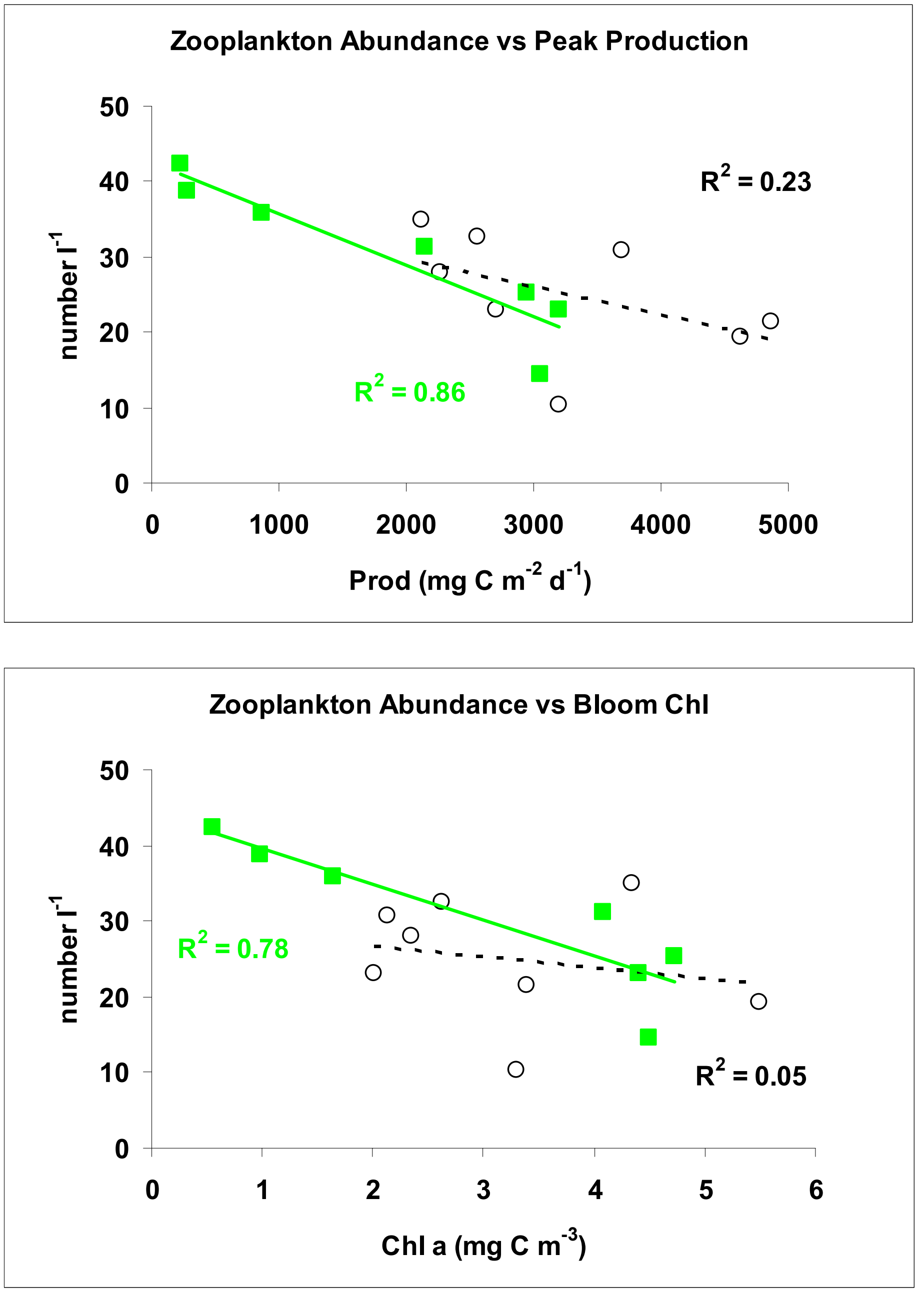


Figure 4-28. Spring bloom period average total zooplankton vs. peak production and average chlorophyll at stations N04 and N18. Non-*Phaeocystis* year data (95, 96, 98, and 99) green squares and *Phaeocystis* year data (97, 00, 01, and 02) open circles.

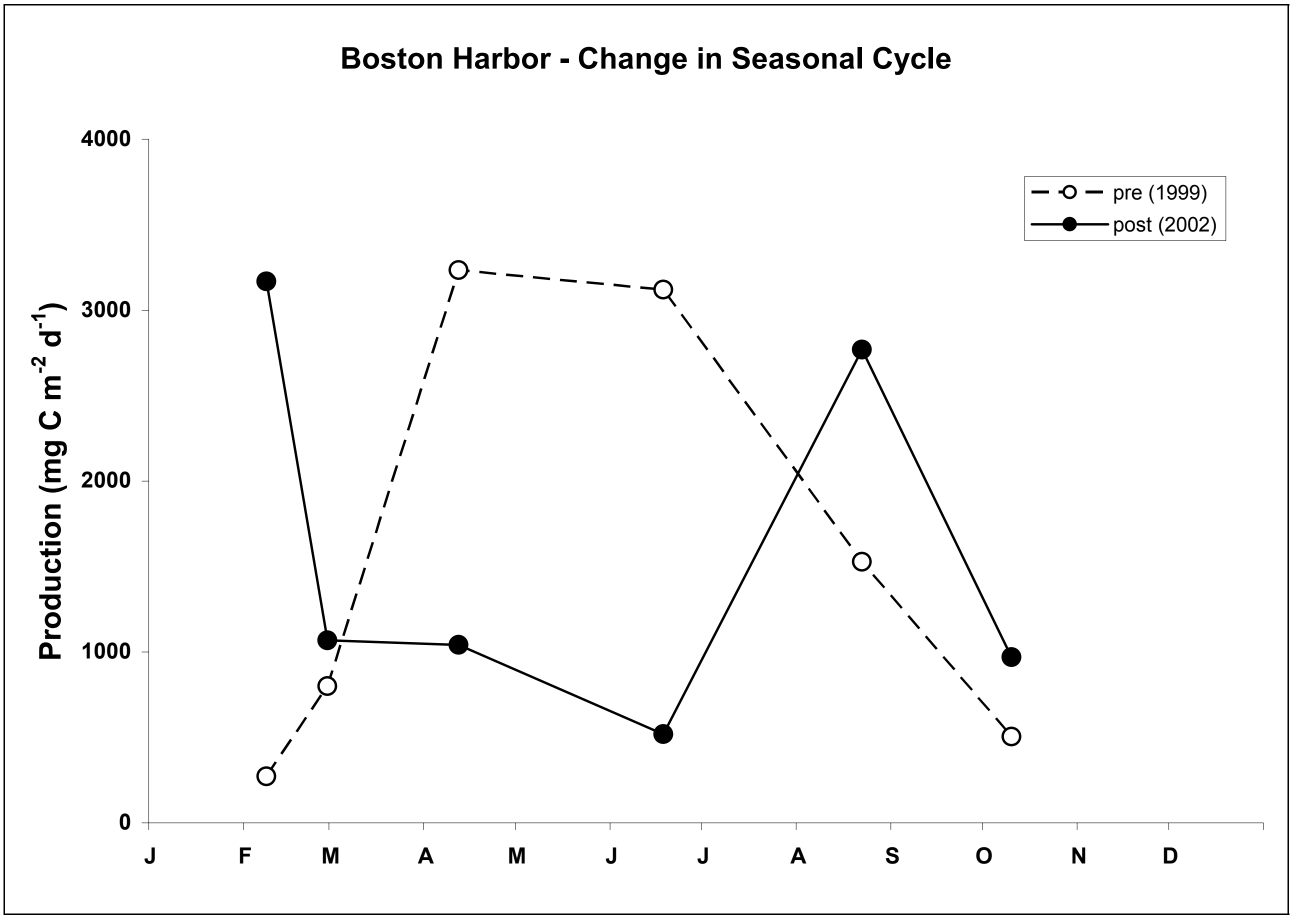
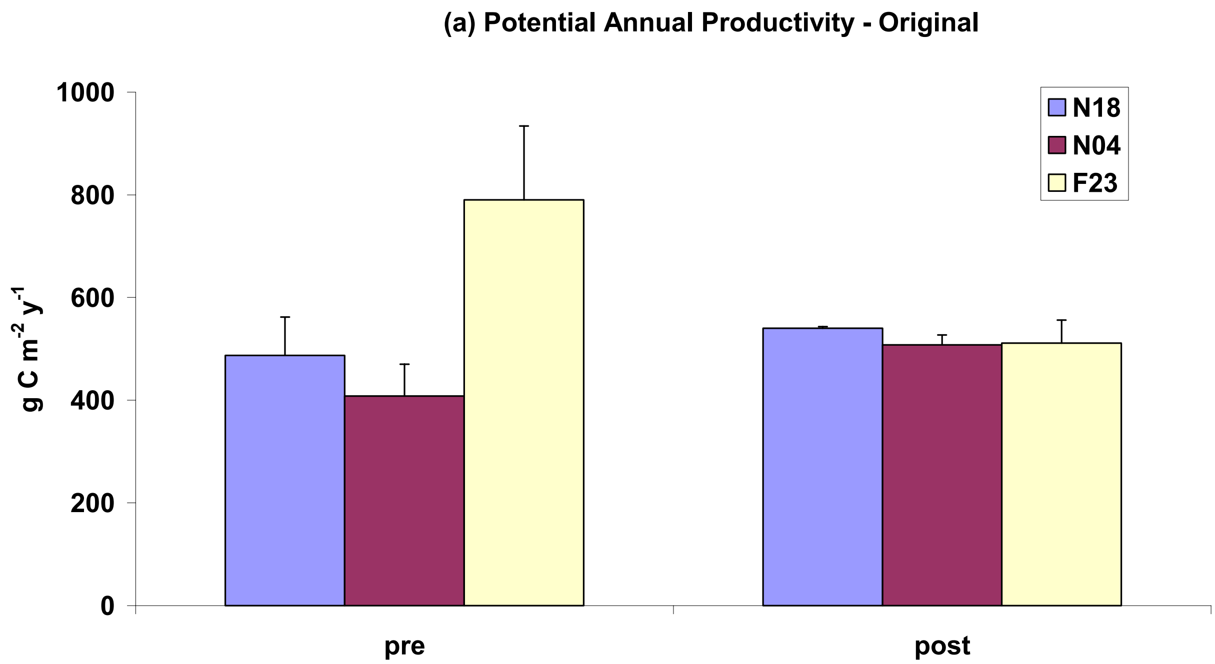


Figure 4-29. Seasonal patterns of productivity pre and post outfall at Boston Harbor Station F23.



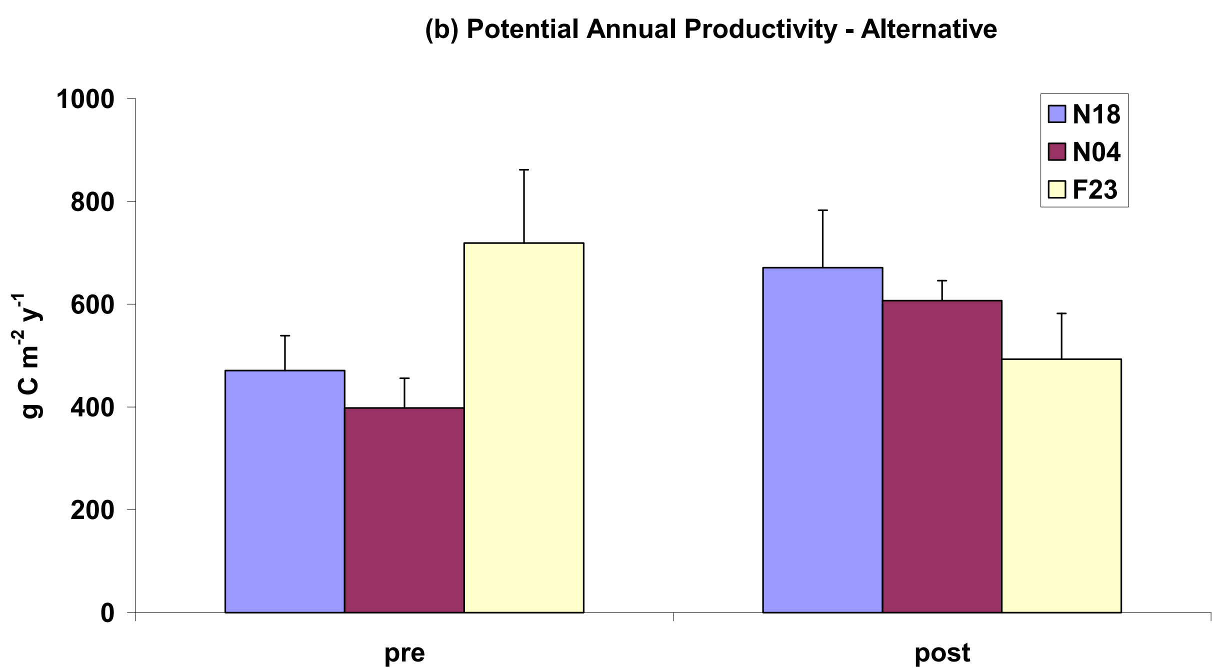
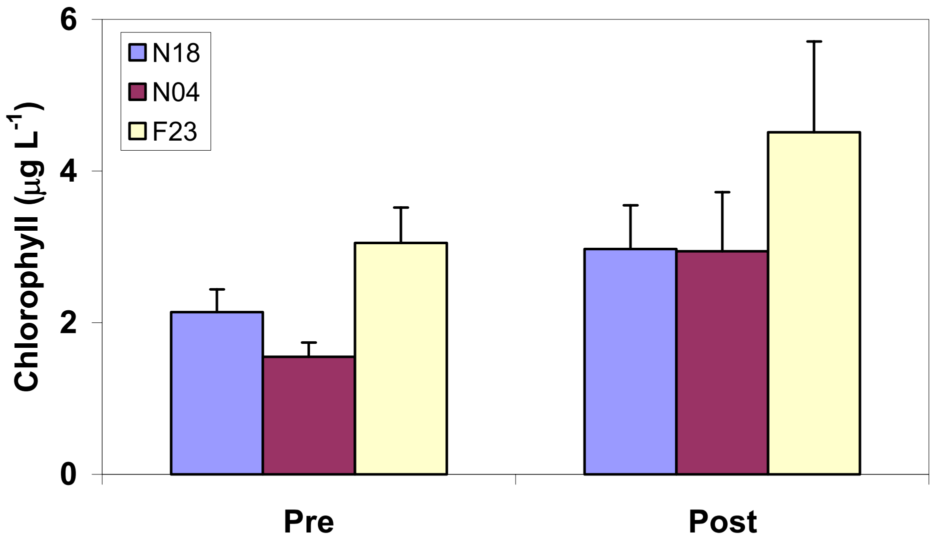


Figure 4-30. Annual potential production (g C $m^{-2}yr^{-1}$) for stations F23, N04, and N16/N18 pre and post outfall diversion. (a) original calculation and (b) alternative approach.

(a) Chlorophyll



(b) POC

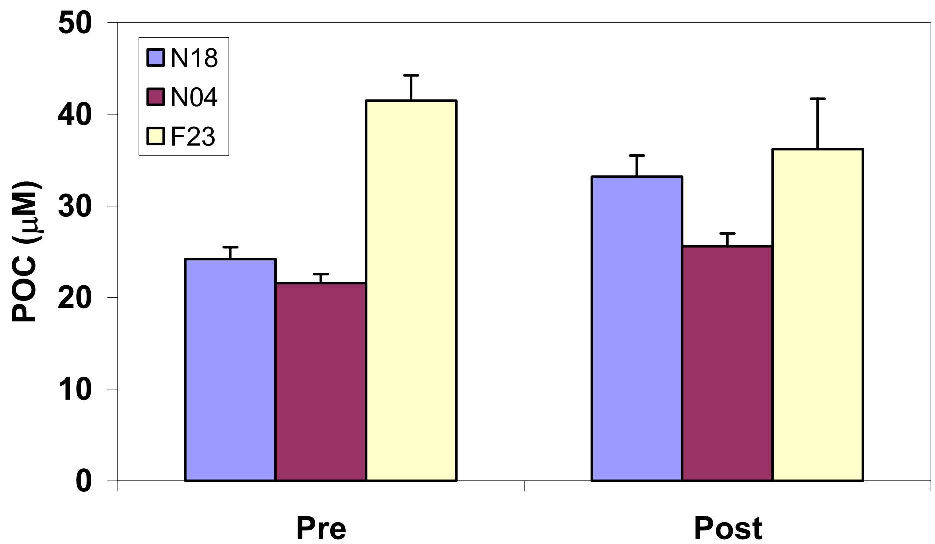
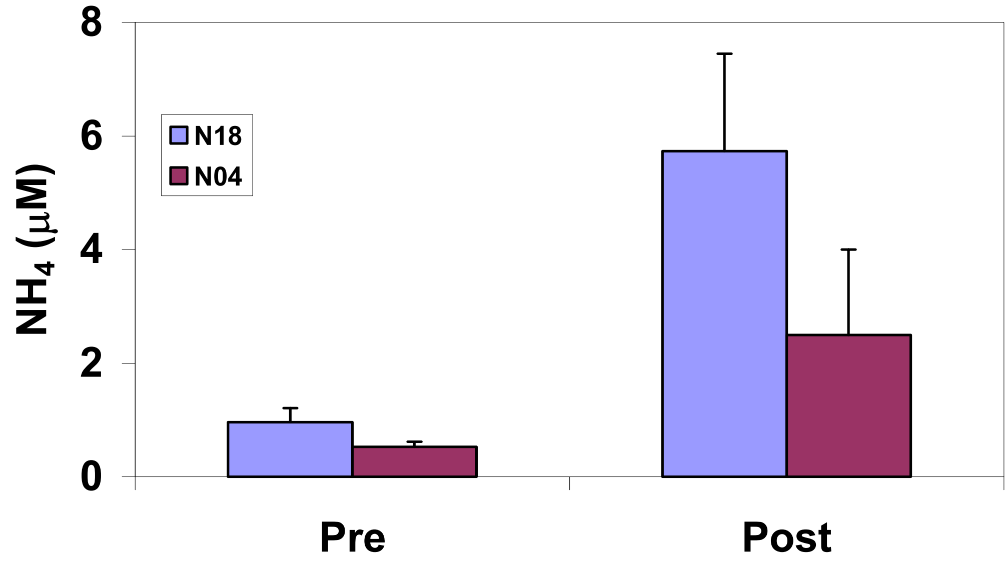


Figure 4-31. Surface water concentrations of (a) chlorophyll and (b) POC for stations F23, N04, and N16/N18 pre and post outfall diversion.

(a) Delta NH_4



(b) Delta DIN

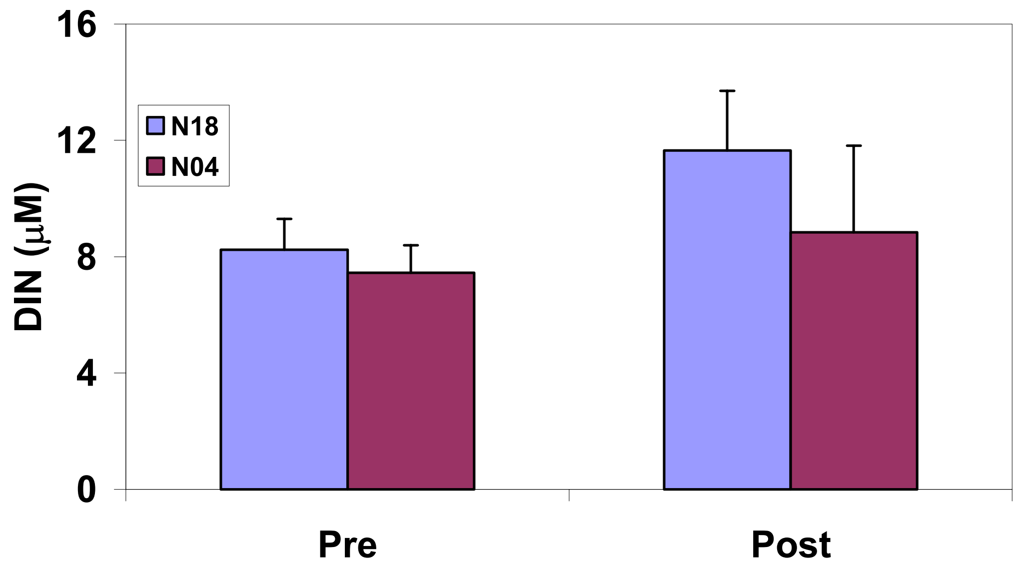


Figure 4-32. Change in mean water concentrations over spring bloom period of (a) NH_4 and (b) DIN for stations N04, and N16/N18 pre and post outfall diversion.

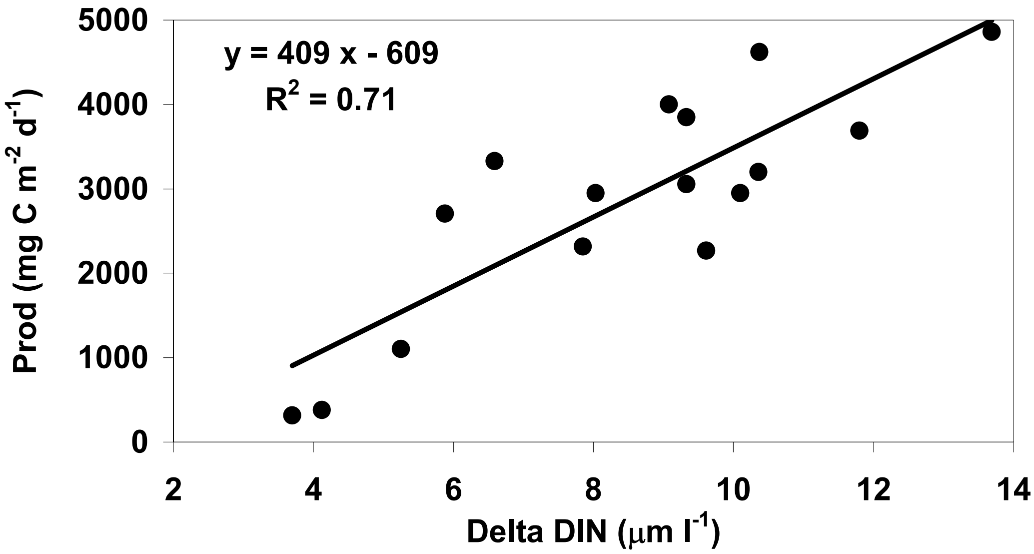


Figure 4-33. Delta DIN versus peak production over the spring bloom period stations N04 and N16/N18 from 1995-2002.

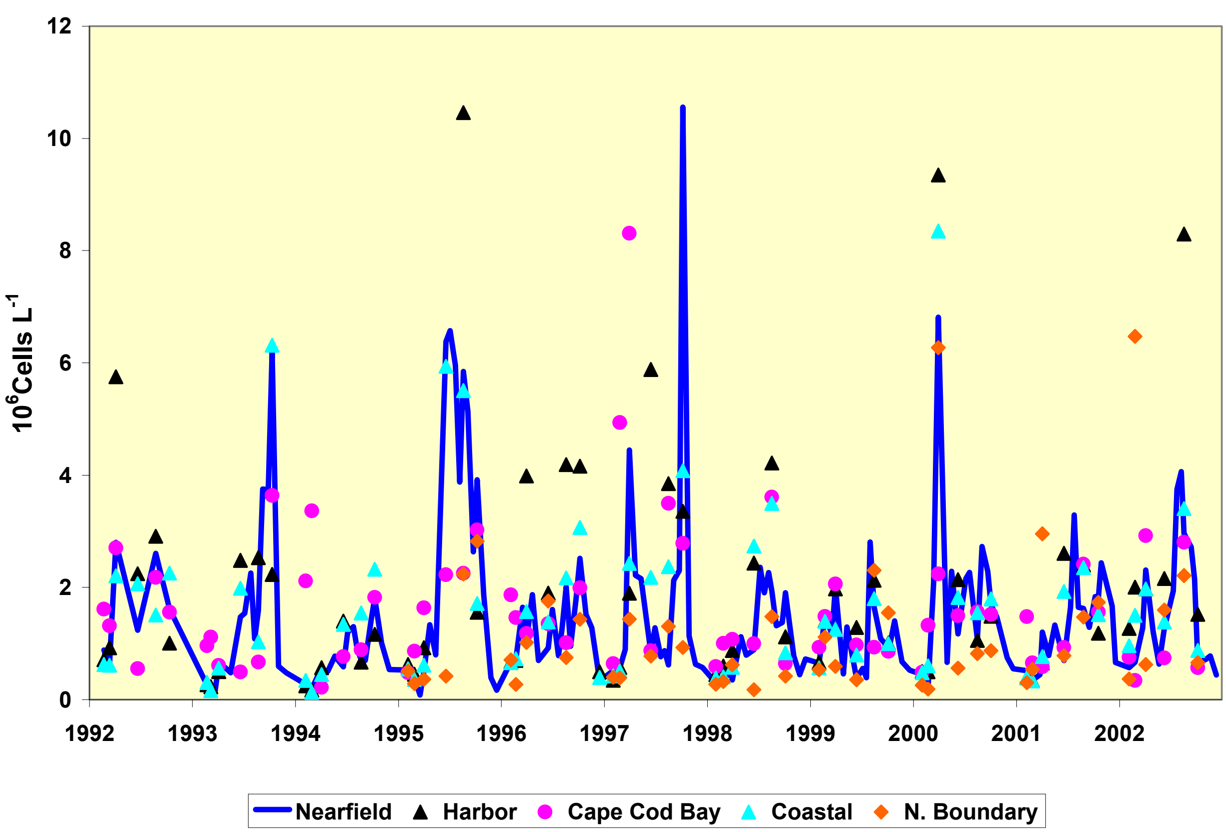
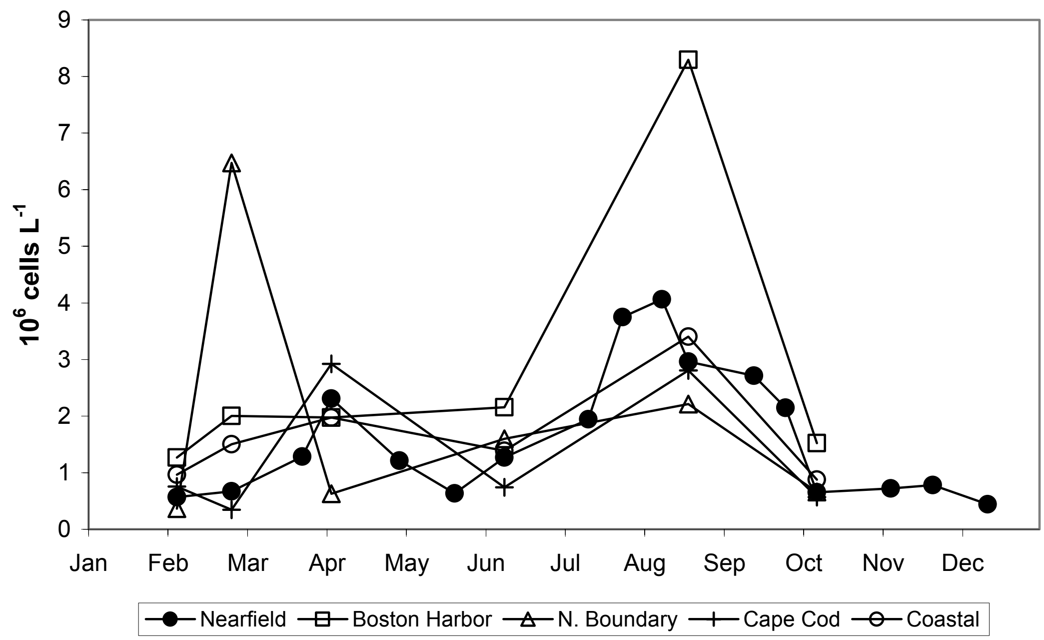


Figure 4-34. Total phytoplankton abundance by region, 1992-2002.

(a) Total Phytoplankton



(b) Total Diatoms

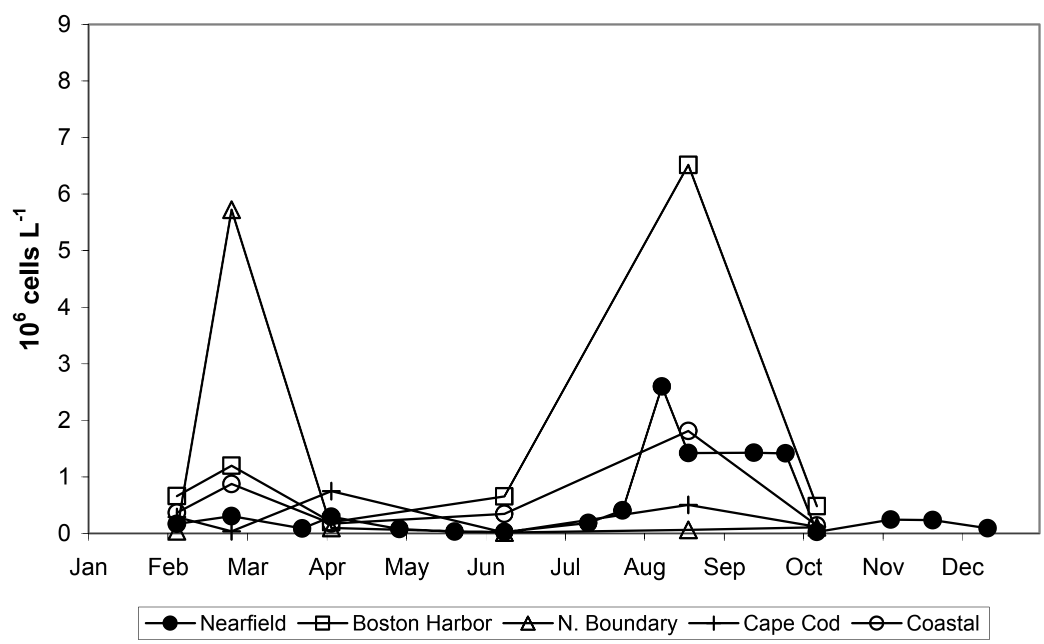


Figure 4-35. Time-series of (a) total phytoplankton and (b) total diatom abundance in Massachusetts and Cape Cod Bays. Mean of surface and mid-depth abundance and stations within each region.

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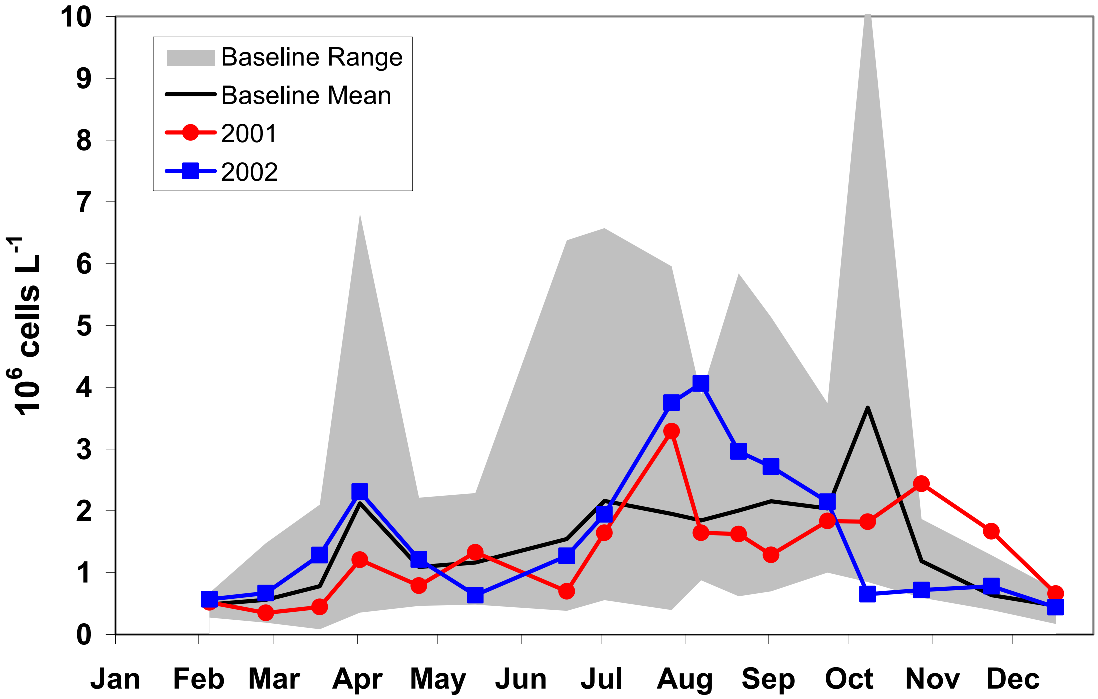
(a) Total Phytoplankton



(b) Diatoms

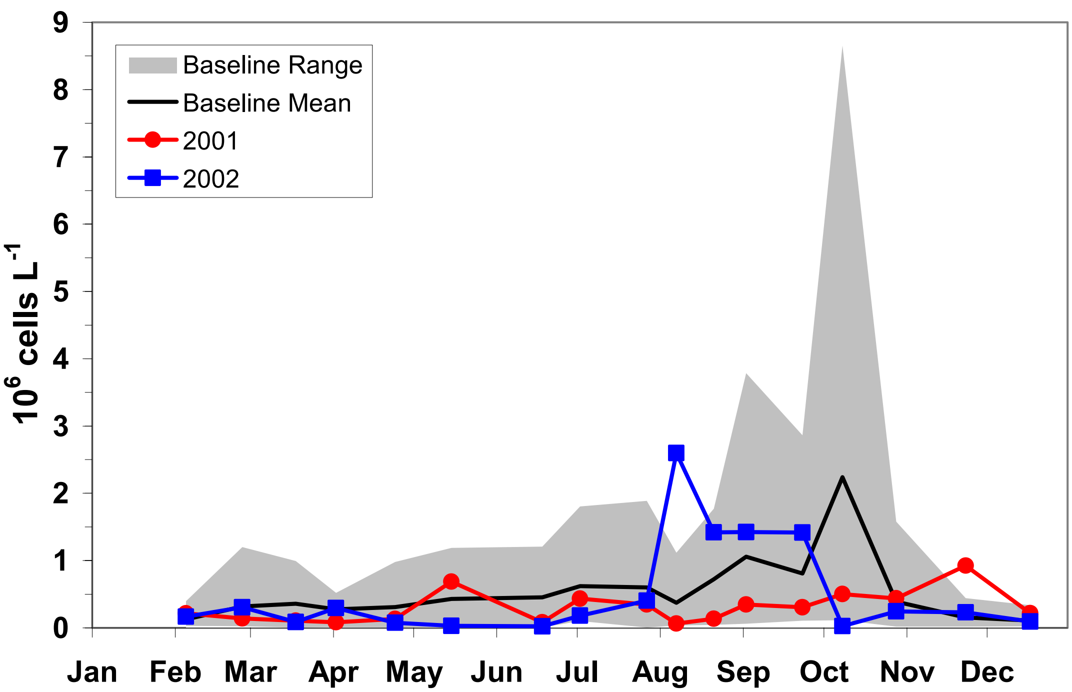
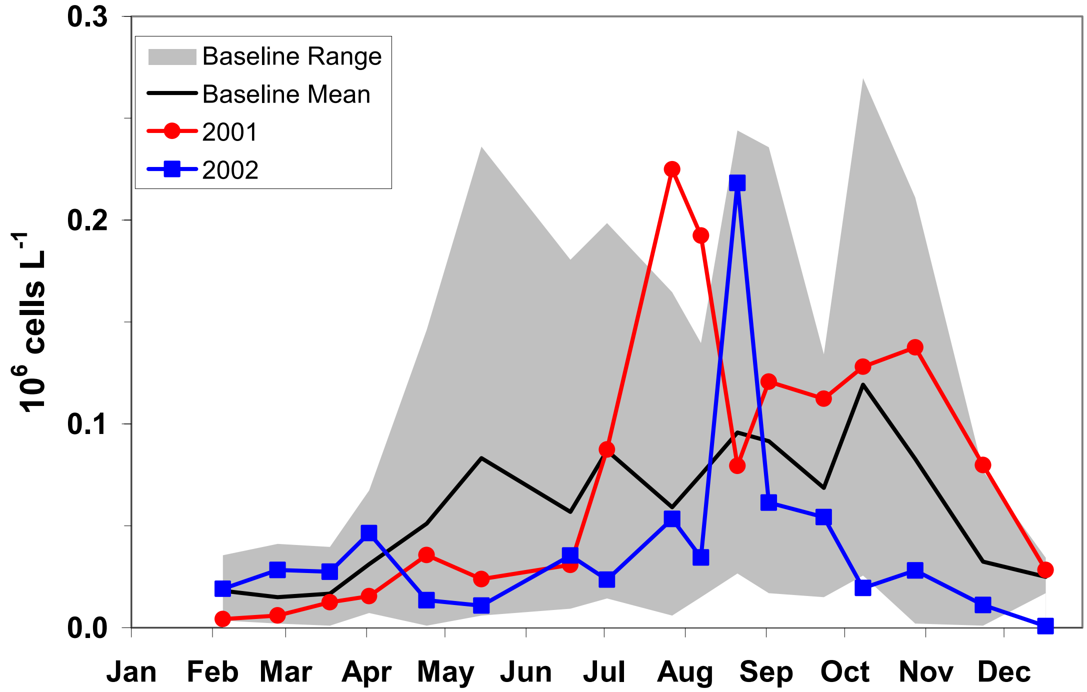


Figure 4-36. Time-series of survey mean (a) total phytoplankton and (b) diatom abundance in the nearfield in 2001 and 2002 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled.

(a) Dinoflagellates



(b) *Ceratium*

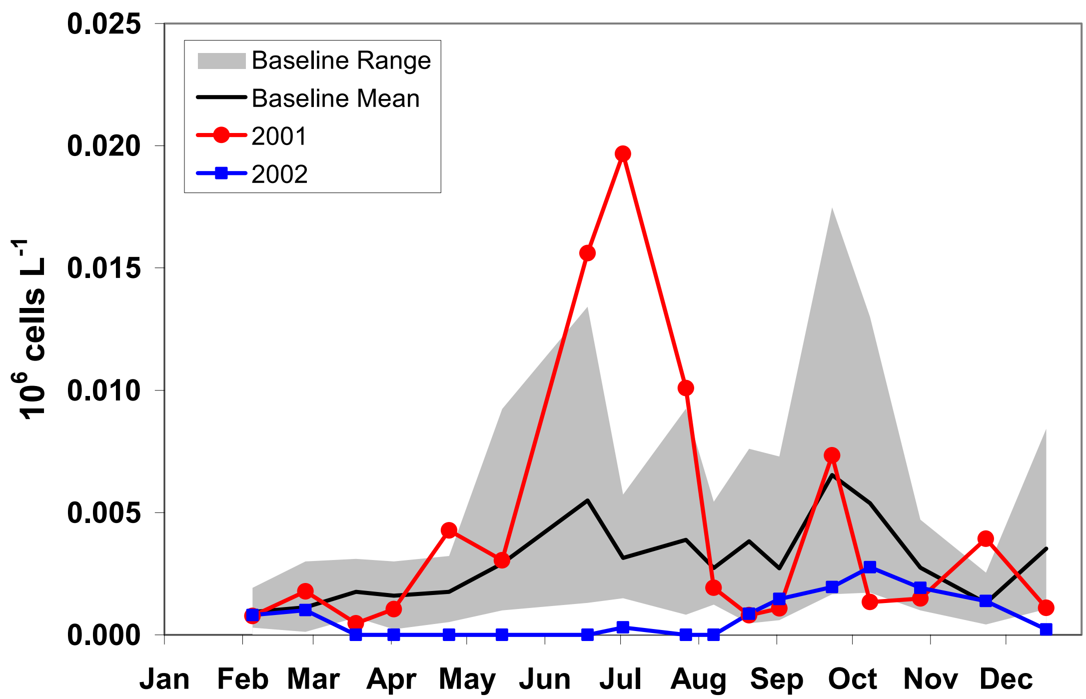


Figure 4-37. Time-series of survey mean (a) dinoflagellate and (b) *Ceratium* abundance in the nearfield in 2001 and 2002 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled.

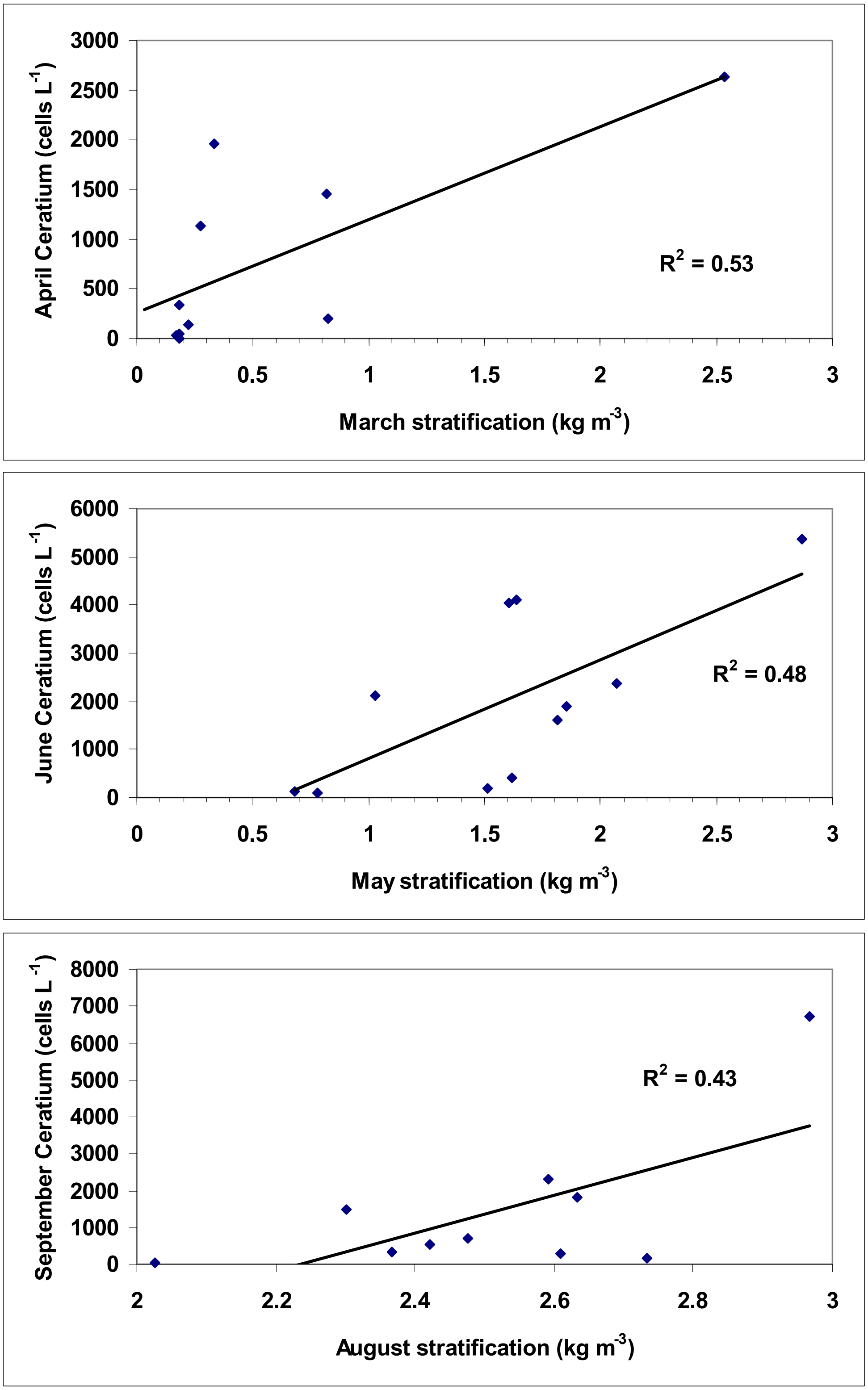


Figure 4-38. Significant (p=0.05) positive correlations between stratification and *Ceratium* abundance one month later for April (top panel), June (middle panel) and September (bottom panel).

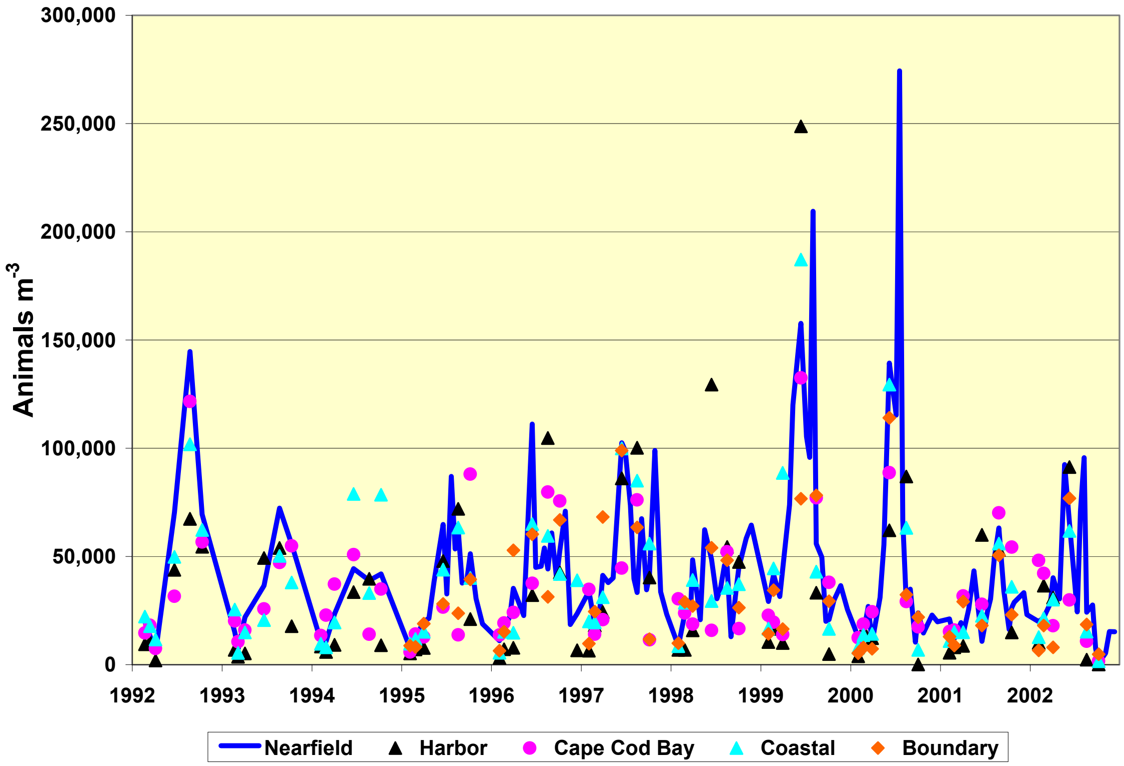


Figure 4-39. Total zooplankton abundance by region, 1992-2002.

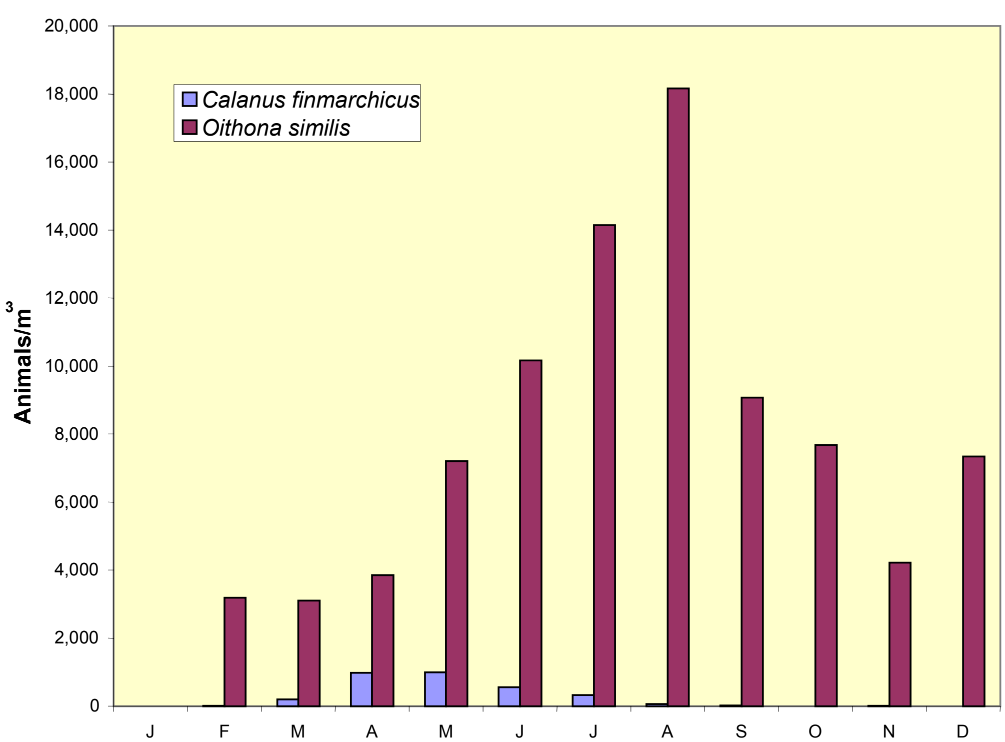


Figure 4-40. Nearfield monthly geometric means for *Calanus finmarchicus* and *Oithona similis*, 1992-2002.

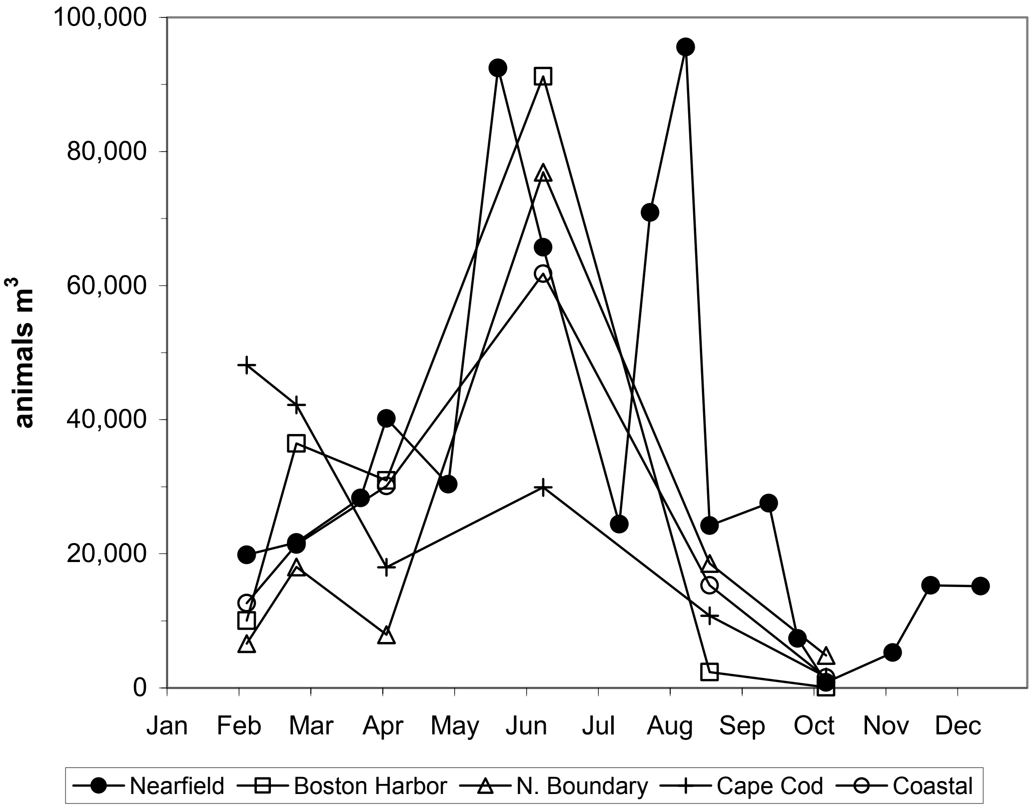


Figure 4-41. Time-series of total zooplankton abundance in Massachusetts and Cape Cod Bays. Mean of stations within each region.

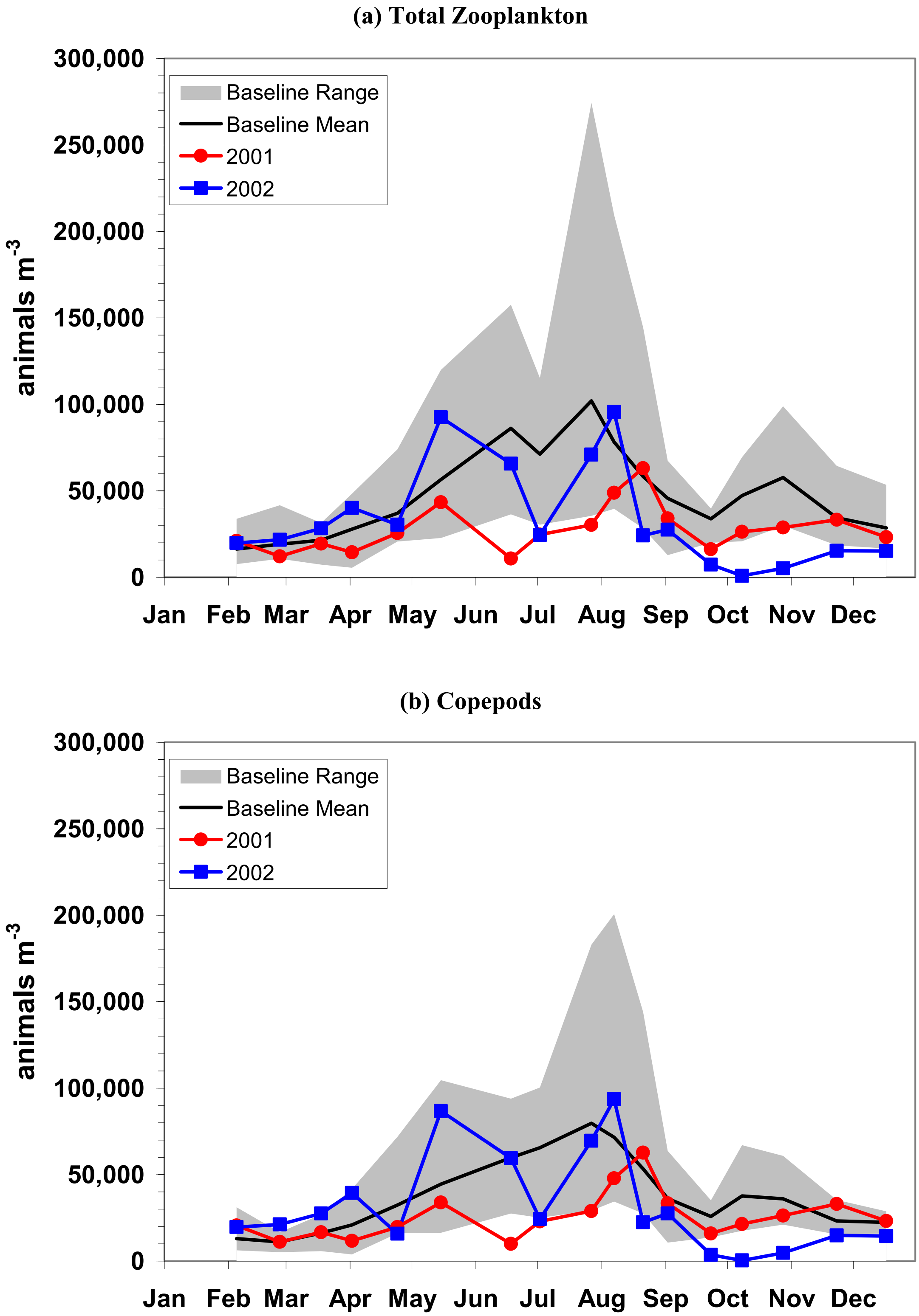
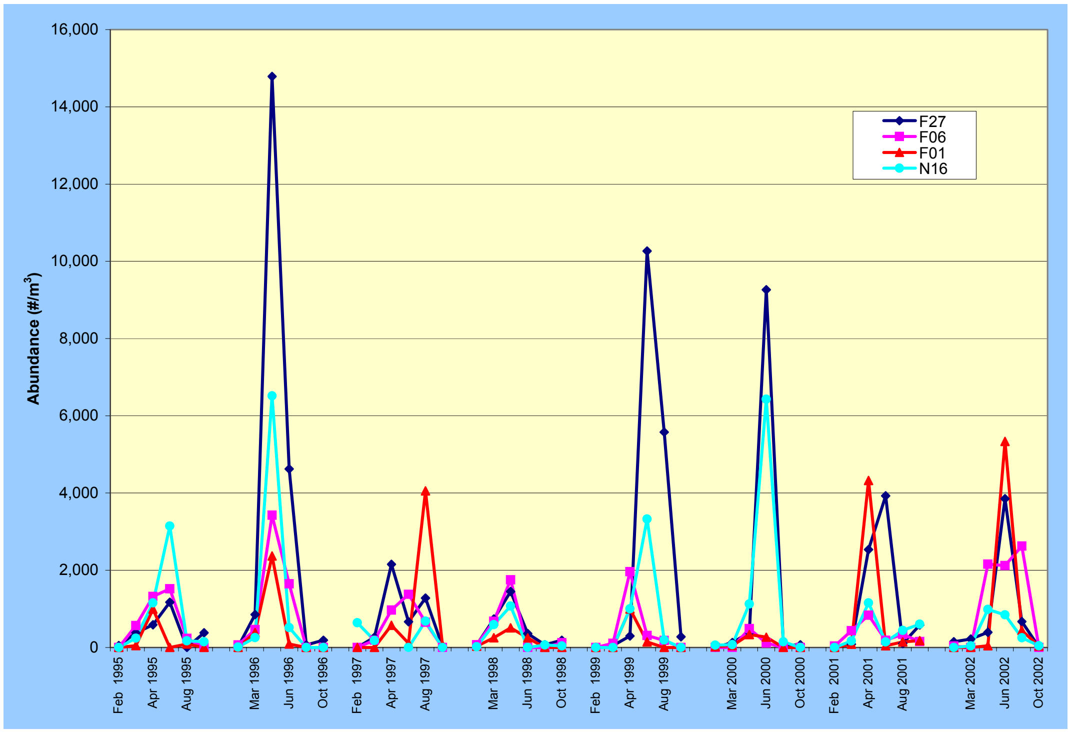


Figure 4-42. Time-series of survey mean (a) total zooplankton and (b) copepod abundance in the nearfield in 2001 and 2002 compared against the baseline range and mean. Data collected from all nearfield stations sampled.

(a) *Calanus Finmarchicus*



(b) *Oithona Similis*

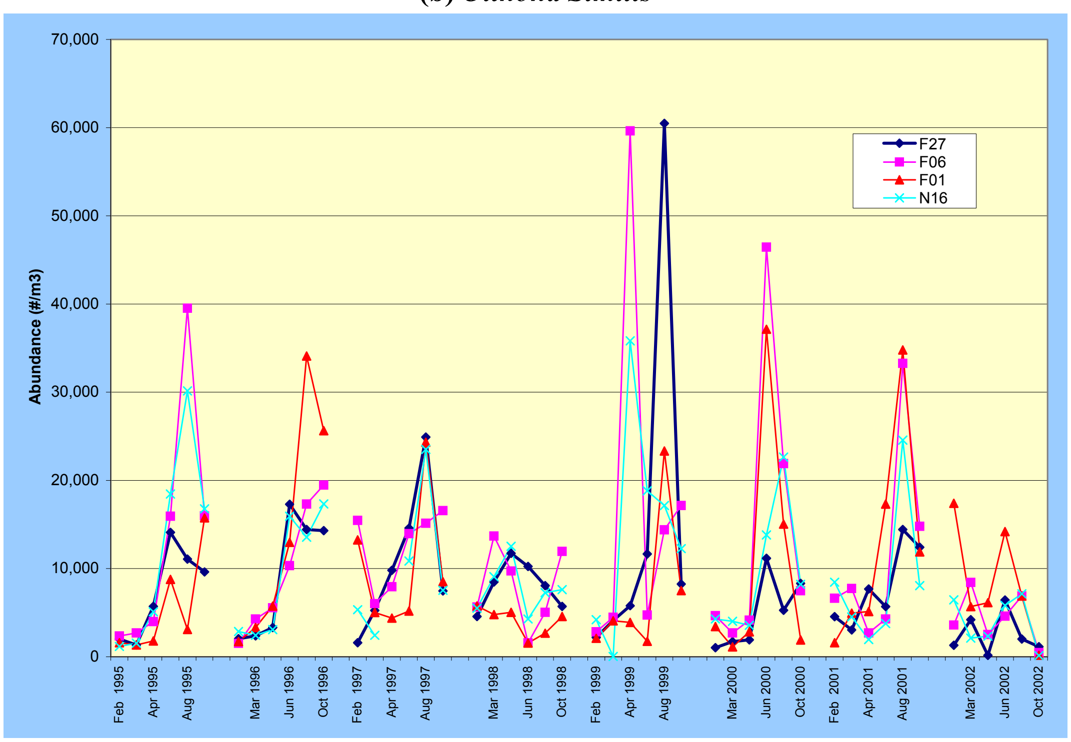


Figure 4-43. Plot of zooplankton abundance by survey for (a) *Calanus finmarchicus* and (b) *Oithona similis* at selected stations sampled on the 6 annual farfield surveys from 1995-2002.

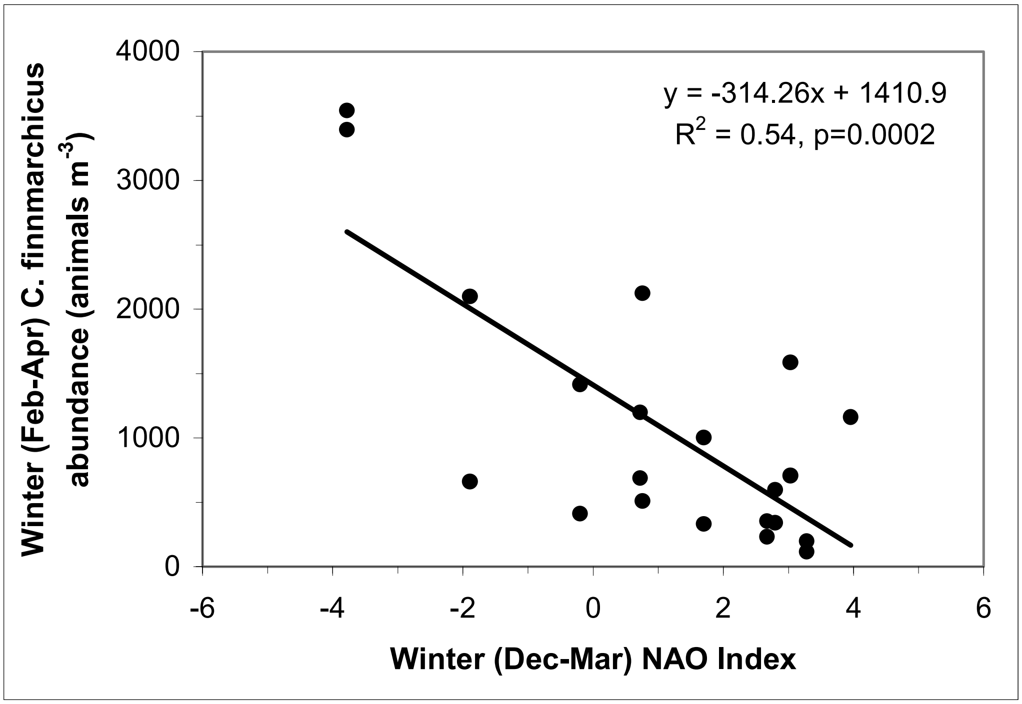


Figure 4-44. Comparison of winter-spring nearfield abundances of *Calanus finmarchicus* (1992-2002) and the NAO index for that winter.

5.0 SUMMARY OVERVIEW OF 2002

Over the course of the Harbor and Outfall Monitoring Program 1992-2002, 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.

This sequence has continued since the bay outfall became operational on September 6, 2000 and was generally evident in 2002. The major features and differences from baseline in 2002 include:

- Dry conditions in fall 2001 continued into 2002 and significantly impacted conditions in early 2002. Meteorological conditions led to a delay in the onset of stratification (June) and decreased the transport of Gulf of Maine waters into Massachusetts Bay in the spring.
- The winter/spring bloom started prior to the first survey in early February as indicated by the productivity, chlorophyll, and nutrient data. This is the second year in a row that the bloom was underway by early February and marks a departure from winter/spring bloom initiation in late February that had been observed during the 1995-2000 time period.
- The winter/spring bloom of centric diatoms (primarily *Skeletonema costatum*) observed in February 2002 was most prominent in the nearshore waters of Boston Harbor, coastal waters, and near Cape Ann.
- A minor *Phaeocystis pouchetii* bloom was observed throughout most of Massachusetts and Cape Cod Bays in April.
- These blooms did not deplete nutrient levels in the surface waters until June as the waters were only weakly stratified until this survey.
- The weak stratification in late spring and early summer also contributed to the relative scarcity of *Ceratium*, which usually increases in abundance as the water column becomes more stratified and their mobility gives them a competitive advantage over other phytoplankton.
- A substantial bloom was observed in August/September, which is earlier than usual for Massachusetts Bay.
- The early occurrence of the bloom may have been associated with the decimation of zooplankton populations by ctenophore (*Mnemiopsis leidyi*) predation.
- A late fall bloom was also observed, but only in the chlorophyll and production data as phytoplankton abundance did not increase.

- Annual minimum DO levels were measured in October in the nearfield (6.43 mgL^{-1} and 71.25%) with comparably low minima throughout Massachusetts Bay.
- Elevated NH_4 concentrations continued to be observed in the nearfield and serve as a tracer for the effluent plume.
- There has been a dramatic decrease in harbor NH_4 concentrations and a concomitant change in the seasonal productivity cycle from a eutrophic (summer peak) to more typical temperate coastal (winter/spring and fall peaks) pattern.

5.1 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 dissolved oxygen 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.

Parameter	Time Period	Caution Level	Warning Level	Background	2002
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	Nearfield - 6.43 mg/L Stellwagen - 7.01 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%	Nearfield - 71.3% Stellwagen - 75.1%
Chlorophyll	Annual	107 mg/m^2	143 mg/m^2	--	82 mg/m^2
	Winter/spring	182 mg/m^2	--	--	112 mg/m^2
	Summer	80 mg/m^2	--	--	50 mg/m^2
	Autumn	161 mg/m^2	--	--	100 mg/m^2
Phaeocystis pouchetii	Winter/spring	2,020,000 cells l^{-1}	--	--	268,000 cells l^{-1}
	Summer	334 cells l^{-1}	--	--	1,490 cells l^{-1}
	Autumn	2,370 cells l^{-1}	--	--	None
Pseudo-nitzschia pungens	Winter/spring	21,000 cells l^{-1}	--	--	900 cells l^{-1}
	Summer	38,000 cells l^{-1}	--	--	200 cells l^{-1}
	Autumn	24,600 cells l^{-1}	--	--	2,300 cells l^{-1}
Alexandrium tamarense	Any nearfield sample	100 cells l^{-1}	--	--	7.5 cells l^{-1}

The dissolved oxygen concentration and percent saturation survey mean minima for June – October of 2002 were below the caution (<6.5 mgL^{-1}) and warning (<75%) threshold in the nearfield and below the caution threshold for percent saturation (<80%) in Stellwagen Basin. All of these minima, however, were well above the background values. Thus, the threshold and state standards were not exceeded as both of include qualitative language that levels must be above 6.0 mgL^{-1} or 75% "unless background conditions are lower". A review of previous survey means (see **Figures** 4-20 and 4-21) indicates that DO concentration has only dropped below the 6 mgL^{-1} once during baseline (nearfield in 1999). Percent saturation levels, however, dropped below the caution threshold of 80% during all but two of the eleven monitoring years (1993 and 1996) in the nearfield and all but 1993 in Stellwagen Basin. Levels have been below the warning threshold and numerical state standard of 75% four of the eleven years in both the nearfield and Stellwagen Basin.

Even with the relatively large blooms in 2002, the nearfield mean areal chlorophyll values were all well below each seasonal and annual threshold. Although there was a minor *Phaeocystis* bloom in March and April, the nearfield mean abundance (268,000 cells L^{-1}) was well below the threshold (2,020,000 cells L^{-1}). The summer *Phaeocystis* threshold value, however, was exceeded as the spring *Phaeocystis* bloom was declining, but still present at low abundance on May 1, 2002. The timing of this survey and the very low summer threshold value resulted in an exceedance. However, this exceedance is not indicative of any problem or impact associated with the outfall. *Alexandrium* spp. and *Pseudo-nitzschia pungens* were observed intermittently and at abundances well below threshold values. The potentially toxic diatom *Pseudo-nitzschia pseudodelicatissima*, however, was present and frequently abundant throughout much of the area over this time period. This species is not currently included in the calculation of the *Pseudo-nitzschia "pungens"* threshold.

5.2 Monitoring Questions

The water column monitoring program focuses on the impact of MWRA effluent on the water quality of Massachusetts Bay with respect to nutrients and organic materials. The monitoring program looks extensively at possible effects of discharging nutrient-rich effluent into Massachusetts Bay, including eutrophication impacts such as nuisance algal blooms and hypoxia, and ecosystem impacts on planktonic communities.

When the outfall site was chosen and the outfall monitoring plan originally designed, MWRA expected to discharge primary treated effluent through the outfall for a number of years before full secondary treatment was available. As outfall completion was delayed, it became clear that effluent discharged in Massachusetts Bay would receive secondary treatment. Thus, the primary concerns shifted from effects of high-organic-material discharge on dissolved oxygen levels and on the benthic community to the effects of a nutrient-rich discharge into the bottom waters of the bay. Secondary sewage treatment effectively removes organic material, but removes only about 20% of the nitrogen. The biological treatment process also changes the nitrogen in the wastewater from primarily organic nitrogen to dissolved inorganic forms (i.e. NH_4), which may be more readily taken up by marine algae. Therefore, most of the concern in the water column about the new outfall is focused on the potential for eutrophication and for subtle ecosystem shifts in Massachusetts Bay, due to relocating the nutrient-rich discharge from the shallow, well-mixed, turbid waters of Boston Harbor to the deep, clear waters of Massachusetts Bay. These concerns were translated into the monitoring questions (MWRA 1991) that were listed in Section 1. They were the focus of the data presentations in Sections 3 and 4 and are directly addressed next. The monitoring questions are presented along with a summary of findings.

5.2.1 Water Circulation

→ *What are the nearfield and farfield water circulation patterns?*

Although often thought of as a system dominated by counterclockwise circulation, physical oceanographic data collected as part of this program in conjunction with researchers at USGS and WHOI indicates that circulation in Massachusetts and Cape Cod Bays is quite variable and subject to both local and regional forcing. On a regional scale, circulation in the bays is often affected by the larger pattern of water flow in the Gulf of Maine. The western Maine coastal current usually flows southwestward along the coast of Maine and New Hampshire and depending on prevailing oceanographic and metrological conditions may enter Massachusetts Bay south of Cape Ann. Optimal conditions for input usually occur during the spring when winds out of the northeast bring significant freshwater inflow from the gulf into the bays and transport generally follows the counterclockwise path along the coast to Cape Cod Bay. During the summer, winds are generally from the south which impedes surface water inflow, but are conducive to upwelling along the coast and entry of deep waters from the gulf into the bay.

The importance of the inputs of Gulf of Maine water cannot be overemphasized as research has shown it to be a major influence on water properties and biology in the bays, for example:

- HydroQual (2000) estimated that in 1992 the Gulf of Maine contributed 92% of the total nitrogen entering the bays, with MWRA effluent contributing 3% and other sources (mostly atmospheric) contributing 5%.
- Dissolved oxygen near the outfall is highly correlated with oxygen levels in deep water near the boundary.
- The relative magnitude of inputs from the Gulf of Maine may also influence bottom water DO by increasing or decreasing advection in the bays and in turn altering the residence time of bottom waters in the system (Geyer *et al*., 2002).
- Nuisance blooms such as *Alexandrium fundyense/tamarense* can be linked to the larger circulation in the Gulf of Maine – winds, currents and spring runoff during May can determine whether these blooms enter Massachusetts Bay or are transported out to sea (Anderson *et al.* 2002).

Massachusetts and Cape Cod Bays are clearly part of and influenced by the Gulf of Maine. Understanding this connection and taking it into account is critical in assessing the relative impact that the bay outfall may (or may not) have on water quality in Massachusetts and Cape Cod Bays.

The combination of the general circulation within Massachusetts Bay and local conditions and mixing determine the fate and transport of effluent discharged from the outfall. Vertical transport of the effluent plume is controlled by density gradients and horizontal transport determined by tides and wind-driven flow. In the winter, the water column is well mixed and the effluent plume reaches the surface, while from about April through October the water column is stratified and the effluent plume is trapped below the pycnocline. There is essentially no mean flow at the outfall location; bottom currents of around 6 cm/s are variable in direction (Butman *et al.*, 2002.) The primary temporal and spatial scales of variability near the outfall are those of the tides and of local weather patterns. The key point is that although the long-term average, net velocity is small at the outfall site, there is considerable "random" motion, which causes water parcels to be exchanged freely between the outfall site and other parts of the bay. Field results confirm much of this and demonstrate that the effluent is rapidly diluted by both hydraulics and oceanographic processes within 10 to 20 km of the outfall (Hunt *et al*., 2002; Mickelson *et al.*, 2002).

5.2.2 Nutrients

→ *Have nutrient concentrations changed in the water near the outfall?*

→ *Have nutrient concentrations changed in Massachusetts Bay or Cape Cod Bay and, if so, are they correlated with changes in the nearfield?*

Seasonal trends in nutrient concentrations are closely linked with both physical and biological factors and, as discussed in Section 4.2.1, have been observed year-in and year-out to varying degrees. The monitoring questions are focused on understanding whether or not the transfer of the MWRA effluent discharge from the harbor outfall to the bay outfall changes nutrient concentrations and, if so, where. As implemented, the transfer from the Boston Harbor into Massachusetts Bay did not create a new source of nutrients to the system, but rather it changed where the effluent is discharged both in location and water depth.

Model simulations predicted that when the effluent was transferred from Boston Harbor to Massachusetts Bay, effluent concentrations 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). Ammonium concentrations have proven to be an excellent tracer of the effluent plume both within and in close proximity to the nearfield (Libby *et al*., 2002c; Hunt *et al*. 2002). This prediction has been validated by field data that indicate that NH_4 concentrations have decreased significantly ($p<0.05$) in Boston Harbor and increased in the bay at only those stations within 20 km of the new outfall (Mickelson *et al*., 2002).

Even with the wide range of concentrations observed over the baseline, there have been a number of unambiguous changes in NH_4 concentrations associated with major MWRA upgrades to the wastewater treatment facilities. Annual mean NH_4 concentrations doubled from 1996 to 2000 in Boston Harbor as secondary treatment was phased in and dropped by 80% once the discharge was transferred to the bay outfall (see **Figure** 4-9a). Concurrently, NH_4 concentrations decreased at the coastal stations, which are strongly influenced by water quality conditions in Boston Harbor. In contrast, annual mean NH_4 concentrations in the nearfield increased as expected, but not as sharply as the harbor and coastal waters decreased. Compared to 1999, the annual mean NH_4 levels have almost doubled in the nearfield. There has been little if any change in NH_4 concentrations in offshore, boundary, and Cape Cod Bay waters from 1992 to 2002. In fact, annual mean NH_4 concentrations in Cape Cod Bay decreased from a maximum of 1.7 μM in 1999 to <1 μM in 2002.

Clear changes in nearfield and farfield nutrient regimes have been measured and they are consistent with model predictions. The effluent nutrient signature is clearly observed in the vicinity of the outfall, but is diluted to background levels over a few days and tens of kilometers. The impact of the changes in the nutrient regimes in both the harbor and nearfield are discussed in the following subsections.

5.2.3 Phytoplankton Biomass

→ *Has phytoplankton biomass changed and, if so, can changes be correlated with ambient water nutrient concentrations?*

→ *Has phytoplankton biomass changed in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?*

Trends in phytoplankton biomass as measured by chlorophyll and particulate organic carbon are tied to physical conditions, nutrient availability, and ecosystem dynamics. The seasonal phytoplankton biomass signal in Massachusetts and Cape Cod Bays is dominated by winter/spring and fall blooms.

Winter/spring phytoplankton blooms occur due to elevated growth related to increased light availability, nutrient replete conditions and seasonal stratification of the physical environment, prior to temperature-related increases in mortality due to grazing. Typically the timing of the fall bloom has been tied to decreased stratification and increased inputs of nutrients into the surface waters. The essence of the monitoring questions is that the changes in nearfield and farfield nutrient levels (increase in and near the nearfield and decrease in harbor and coastal waters) due to diversion could potentially change the seasonal trends and concentrations of phytoplankton biomass.

In the nearfield, graphical comparisons of survey and annual mean chlorophyll and POC values suggest that there has not been a substantial change since the diversion of effluent. Annual mean chlorophyll concentrations in Massachusetts and Cape Cod Bays did increase from 1997 to 2000, but decreased in 2001. Monitoring data and SeaWiFS imagery indicate the regional nature of chlorophyll blooms both within and outside of the bays. In Boston Harbor, there has been both a change in the seasonal chlorophyll and POC patterns and in the magnitude of the values. In 2001, and more so in 2002, the harbor has exhibited patterns in these parameters (and productivity) that are comparable to that observed in the nearfield and other temperate coastal waters. A clear relationship between changes in nutrients and chlorophyll levels has not been observed in spatial and temporal means. Data from the three productivity stations provides additional insight into the potential impact of additional nutrients in the nearfield and removal of a source of nutrients in Boston Harbor and is addressed in Section 5.2.5.

5.2.4 Dissolved Oxygen

→ *Has dissolved oxygen in the nearfield changed relative to baseline and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?*

→ *Has dissolved oxygen changed in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?*

→ *Does dissolved oxygen in the water column meet the State Water Quality Standard in the nearfield and farfield?*

Bottom water DO levels are typically at a maximum in the winter, decrease over the course of the summer during seasonal stratification, and reach annual minimum levels just prior to stratification breaking down in the fall – usually October. The monitoring questions were originally focused on the direct impact the primary treated effluent might have on DO levels. Since diversion, the Deer Island treatment plant has performed secondary treatment on at least 80% of the wastewater, and now processes >95% of the wastewater through secondary treatment. These improvements have shifted the focus from assessing whether or not the transfer of organically rich effluent (high BOD) could directly impact DO levels to understanding how the increase in nutrients might indirectly lead to changes in bottom water DO levels due to eutrophication processes.

The monitoring results have not measured change in DO concentrations or percent saturation in the nearfield or Stellwagen Basin since the effluent was diverted to the bay outfall. The numeric caution and warning levels were exceeded in 2001 and 2002 during periods of minimum DO levels, but this was consistently the case during the baseline period. The thresholds and state standards caveat the numerical standards by stating "unless background values are lower". Thus, for regulatory purposes, current DO monitoring data are compared to background levels measured during baseline (see **Table** 5-1) none of which have been exceeded since the outfall came online. There have not been any changes in DO levels or seasonal pattern after outfall start-up.

Bottom water DO levels in Massachusetts Bay exhibit a consistent seasonal pattern and invariably reach annual minimum concentrations in late September/October. Modeling and statistical analyses indicate that DO concentration and percent saturation at nearfield, Stellwagen Basin, and northern boundary stations are all correlated (HydroQual 2001 and Geyer *et al*. 2002). Regional processes and advection are the primary factors governing bottom water DO concentrations in Massachusetts Bay (Geyer *et al*. 2002).

Monitoring data show no change in dissolved oxygen concentrations (or percent saturation) in the nearfield or Stellwagen Basin since the effluent was diverted to the bay outfall. During periods of minimum DO, concentrations and percent saturation levels are often below established numeric thresholds and standards, but this is true for both the baseline and post diversion periods. Bottom water DO levels in Massachusetts Bay appear to be governed by large scale regional processes, and the impact of the diversion to the bay outfall on DO is expected to be minimal. Thus, even though some local changes in nutrient concentrations have occurred, concomitant changes in DO levels have not been observed.

5.2.5 Productivity

The productivity monitoring question has been slightly reworded to reflect the focus of the monitoring efforts at two stations in the nearfield and one at the mouth of Boston Harbor.

→ *Have production rates changed in the vicinity of the outfall or Boston Harbor and, if so, can these changes be correlated with changes in ambient water nutrient concentrations?*

Over the course of the monitoring program, general seasonal patterns have emerged for both the nearfield and Boston Harbor stations. The nearfield area is characterized by spring and fall blooms that often, but not always, occur and variable productivity during the summer. The harbor exhibited a more eutrophic seasonal pattern with a summer time peak in productivity. As the monitoring question suggests, changes in the nutrient regimes in the nearfield and harbor might be expected to have an effect on the seasonal trends, seasonal peaks, and overall magnitude of production.

Areal production at the nearfield stations has continued to follow the pattern observed during the baseline, with the occurrence of a spring and fall bloom and variable summer productivity. Timing of these events, however, is somewhat different from earlier years, with an early onset of the spring bloom in both 2001 and 2002, a delayed and prolonged fall bloom in 2001 (late September to November), and an early fall bloom in 2002 (August/September). Additionally, some differences in the magnitude of peak bloom productivity were noted, including elevated productivity during the spring and fall blooms at stations N18 and N04, relative to most years. In the spring, peak primary productivity rates increased by 20% at station N18, the station nearest the outfall, and by 40% at station N04 in comparison to baseline values. During the fall a similar pattern of increased productivity over baseline occurred for the two nearfield stations.

The productivity data suggest that Boston Harbor is transitioning from a eutrophic pattern with high summer rates to a pattern more typical of temperate waters with spring and possibly fall peaks and lower rates in summer. The altered seasonal productivity cycle appears to be related to reduced nutrient availability in the harbor during the summer-stratified period.

The timing and magnitude of the spring and fall blooms is a function of numerous ecological and physical factors. Evaluation of the relationships between these factors suggests that the magnitude of the winter spring bloom is correlated with the temperature and inversely correlated with zooplankton abundance (Keller *et al.,* 2001). The relationship is often obscured by the occurrence of *Phaeocystis* blooms, which may not be grazed by zooplankton either because of its size or phenolic content. The timing of the fall bloom is often associated with the breakdown in stratification and mixing of nutrients from bottom waters into the euphotic zone. A prolonged period of weak stratification and availability of nutrients likely contributed to the late, extended fall bloom in 2001. In 2002, the early appearance of the fall bloom may have been related to relaxation of zooplankton grazing pressure due to elevated ctenophore levels that decimated zooplankton abundance. The availability of an additional nutrient source in the nearfield could also be contributing to the changes in timing and magnitude of the winter/spring and fall blooms.

To further refine understanding of the changes in primary production, potential annual productivity during pre and post outfall years was compared utilizing two methods of calculation. Although none of the changes in annual production were significant, the data indicate higher post diversion mean production at the nearfield stations and lower mean production in Boston Harbor relative to the baseline values. Similar changes are apparent in mean chlorophyll *a* and particulate organic carbon concentrations at the nearfield stations. In Boston Harbor, routine monitoring by MWRA shows significant decreases in both chlorophyll and POC levels in the two years after diversion to the bay outfall (Taylor 2003). All of these changes are coincident with an increase in NH_4 concentrations in the nearfield and a decrease in the harbor.

At the nearfield stations there is also an apparent increase in the amount of dissolved inorganic nitrogen (DIN) utilized during the spring bloom. A significant and positive relationship between the winter spring productivity peak and the change in surface nitrogen concentration over the bloom period has been found to date. The availability of an additional source of DIN, namely the NH_4 rich effluent, in the nearfield is likely fueling the apparent increase in production observed during the first two years of the bay outfall. The changes observed in pre and post outfall production and nutrient utilization during the spring bloom are the focus of ongoing examination.

5.2.6 Phytoplankton

→ *Has phytoplankton species composition changed in the vicinity of the outfall and, if so, can these changes be correlated with ambient water nutrient concentrations?*

→ *Has phytoplankton species composition changed in Massachusetts Bay or Cape Cod Bay and, if so, can the changes be correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?*

→ *Has the abundance of nuisance or noxious phytoplankton species changed?*

Phytoplankton communities are mixtures of many species, with the abundance and composition of the community changing in response to each species' response to changing environmental influences on the habitat (e.g. annual change in irradiance, temperature, nutrient, grazer abundance). A "normal" seasonal succession in Massachusetts and Cape Cod Bay has been observed in the 1992-2000 baseline monitoring data. The interannual variability associated with both magnitude and occurrence of phytoplankton blooms is comparable to seasonal variability. Moreover, although such blooms may be intermittent, they tend to occur regionally and are usually observed throughout Massachusetts and Cape Cod Bay and beyond. The reasons that such species bloom in some years, but not others, remains unclear.

Trends in phytoplankton abundance and species composition since diversion have followed the patterns observed in prior years. There is no indication of an outfall effect on abundance or species composition of phytoplankton in the nearfield or regionally in the bays. Phytoplankton abundance in the winter/spring bloom has remained close to the baseline mean. Nearfield phytoplankton biomass and production have increased, though not significantly, and MWRA monitoring continues to explore how an increase may be related to increased nutrients in the nearfield. The atypical timing of the fall blooms in both 2001 (late) and 2002 (early) while interesting, appears to be associated with physical and biological factors unrelated to the outfall. In 2001, the water column remained stratified late into the fall resulting in a delay in the fall bloom until late October and November. In 2002, the fall diatom bloom occurred in August and September perhaps in response to ctenophore decimation of copepods and a decrease in grazing pressure. A hypothesis that the bloom may have been further enhanced by the input of additional nutrients into the nearshore waters via the outfall and/or upwelling, which may have entrained both nutrient-rich bottom waters and the effluent plume into the upper water column is being explored.

5.2.7 Zooplankton

→ *Has zooplankton species composition changed in the vicinity of the outfall and, if so, can these changes be correlated with ambient water nutrient concentrations?*

→ *Has zooplankton species composition changed in Massachusetts Bay or Cape Cod Bay and, if so, can the changes be correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?*

Zooplankton communities in Massachusetts and Cape Cod Bays are dominated by numerous species of copepods, all of which have widespread distributions in the Gulf of Maine, and some of which are found throughout the east coast of the United States. Total zooplankton abundance tends to follow a predictable temporal pattern, with abundance peaking in mid-summer and lower levels in spring and fall. The seasonal timing for individual species is variable. There is, however, no clear seasonality in terms of dominant zooplankton taxa in the region. Non-copepod zooplankton that are sporadically abundant and pulses of meroplankton can be seasonally important. Pulses of the ctenophore *Mnemiopsis leidyi* such as seen in summer and fall 2002 can result in substantial declines in the abundance of the rest of the zooplankton community, primarily through ctenophore predation on copepods and other zooplankton.

The zooplankton community has not detectably changed in response to the outfall going on line. The major difference between post-2000, particularly 2002, and most previous years in terms of zooplankton abundance was the precipitous decline in zooplankton abundance in late summer and fall due to ctenophore predation. Although abundances declined drastically during these periods, community composition was similar compared to the same season in previous years. Appreciable changes in zooplankton at the farfield stations have been observed, but they result from the impact of ctenophores on the rest of the zooplankton community, rather than the outfall and effects of nutrient enrichment in the nearfield.

These conclusions are supported by several lines of evidence, discussed in detail in Section 4.2.2. These include no long-lasting change in the abundance or composition of the zooplankton community. Any change since the outfall diversion is within the envelope-of-variability established during baseline. This includes the ctenophore event of 2002, which was preceded by a minor version of the same in 2000. In addition, multivariate statistical analyses reveal no clear temporal or spatial changes in zooplankton communities attributable to the outfall. However, results point to a possible link between the changes in zooplankton in Massachusetts Bay and climatic changes, such as the North Atlantic Oscillation, which affect much larger geographic areas than that covered by the MWRA sampling. There is even the possibility that changes in ctenophore abundance may relate to climate. Such questions are being explored further.

5.3 Summary

Much has been learned about the Massachusetts and Cape Cod Bays system over the course of the HOM program. Our understanding of the circulation and importance of the Gulf of Maine to both water properties and biology of the system has led to changes in the way we envision the bay outfall might impact (or not) the bays. No longer is the system viewed as a simple upstream to downstream conveyor belt, but rather one that has a weak and seasonal counterclockwise circulation pattern that is often obscured by tidal and local/regional wind forcing. The influence of the Gulf of Maine has been observed on circulation, nutrient loading, dissolved oxygen, and nuisance species in the bays. Improved understanding of these linkages remains critical for assessing the relative impact of the bay outfall on water quality in Massachusetts and Cape Cod Bays.

Changes in the nutrient regimes following diversion are unambiguous – NH_4 has dramatically decreased in Boston Harbor and nearby coastal waters while increasing in the nearfield. Although the effluent plume is consistently observed in the nearfield, detectable levels are confined to an area within 20 km of the outfall. The higher nearfield NH_4 concentrations have not translated into increased biomass, whether measured as chlorophyll, POC, or phytoplankton abundance. On a station specific basis, there has been an increase in winter/spring and fall bloom production and biomass in the nearfield. In Boston Harbor, a dramatic decrease in NH_4 has been concomitant with decreases in chlorophyll, POC, and production, and a change in the seasonal productivity from a eutrophic to more normal temperate coastal pattern. Further study is necessary before statistically significant change can be documented and conclusions drawn as to the impact, or lack thereof, that the transfer of discharge from the harbor to the bay outfall has on the Massachusetts and Cape Cod Bay system.

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