2003 annual water column monitoring report

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Massachusetts Water Resources Authority
Environmental Quality Department
100 First Avenue
Charleston Navy Yard
Boston, MA 02129
(617) 242-6000

prepared by

Scott Libby[1]
Rocky Geyer[2]
Aimee Keller[3]
Jeff Turner[4]
David Borkman[4]
Candace Oviatt[3]

[1]Battelle
397 Washington Street
Duxbury, MA 02332

[2]Woods Hole Oceanographic Institute
Woods Hole, MA 02543

[3]University of Rhode Island
Narragansett, RI 02882

[4]University of Massachusetts Dartmouth
North Dartmouth, MA 02747

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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 supports the HOM Program mission to assess the environmental effects of the relocation of effluent discharge from Boston Harbor to Massachusetts Bay. Data from 1992 through September 5, 2000 established baseline water quality conditions and a means to detect significant departure from the baseline after the bay outfall became 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 2003 data represent the third full year of conditions since initiation of discharge from the bay outfall. This annual report evaluates the 2003 water column monitoring results, assesses spatial and temporal trends in the data, compares 2003 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).

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 (DO) 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 2003. The major features and differences from the baseline in 2003 include:

- A return to normal freshwater inflow from the drought conditions present in 2001-2002, colder than normal water temperatures in winter/spring period, upwelling-favorable winds that produced colder than average bottom water temperatures during the summer, and a delay in the breakdown in stratification until late November 2003.
- The winter/spring bloom of diatoms in February 2003 was most prominent in Cape Cod Bay, Boston Harbor, coastal and western nearfield waters. This was a departure from the trend in 2001 and 2002 when the diatom bloom apparently occurred or peaked prior to the early February survey.
- A spring *Phaeocystis pouchetii* bloom observed throughout Massachusetts and Cape Cod Bays was most pronounced in northern Massachusetts Bay. This bloom was present in the nearfield from February to May.
- These blooms led to a sharp decrease in nutrient concentrations and a high seasonal chlorophyll level in the nearfield that was one of the highest recorded during the monitoring program.

- Ammonium (NH_4) concentrations continue to be an excellent tracer of the effluent plume, albeit not a conservative one and elevated levels of NH_4 remain within ≤20 km of the bay outfall.
- A prolonged fall diatom bloom occurred from late September into December. Chlorophyll and POC concentrations were close to baseline maxima during the late fall bloom, but plankton and productivity rates were relatively low in comparison to previous fall blooms.
- Nearfield areal production followed patterns observed in prior years though lower peak rates were measured during the winter/spring and fall blooms.
- Productivity in Boston Harbor was lower than baseline levels and the apparent change in the seasonal productivity pattern from a eutrophic summer peak to a more temperate winter/spring bloom peak rates continued to be observed.
- Minimum DO levels were measured in November in the nearfield (6.5 mg l^{-1} and 69%).
- There were no harmful or nuisance phytoplankton blooms in Massachusetts and Cape Cod Bays in 2003, other than the spring *Phaeocystis* bloom.
- Zooplankton community abundance and taxa were similar to previous years.
- Comparison of winter-spring (February-April) nearfield abundances of *Calanus finmarchicus* copepodites and adults with the boreal winter index of the North Atlantic Oscillation yields a significant negative correlation suggesting that some components of marine plankton communities in Massachusetts Bay may be sensitive to variations in long-term climatic and oceanographic patterns.

The only exceedance of Contingency Plan thresholds for water quality parameters in 2003 was for the summer *Phaeocystis* threshold. The *Phaeocystis* bloom is becoming a more regular event in the bays with the fourth consecutive bloom (2000-2003). However, the spring *Phaeocystis* bloom in 2003 began earlier (February), and lasted longer (May) than most previous blooms which were typically April events. The 2003 *Phaeocystis* bloom abundance was well below threshold values for the winter/spring, but, as the bloom was still present in mid May (albeit in only one sample at 48,000 cells L^{-1}), the summer *Phaeocystis* threshold value was exceeded. This was not necessarily indicative of any problem or impact associated with the outfall, but was rather due to the duration of the bloom and the very low summer threshold value. The interannual variability in duration of the *Phaeocystis* bloom may in fact be related to water temperatures. Winter/spring chlorophyll levels and autumn *Pseudo-nitzschia pungens* abundance approached, but did not exceed thresholds values.

Changes in the nutrient regimes following diversion are unambiguous – NH_4 has dramatically decreased in Boston Harbor (-82%) and nearby coastal waters while increasing in the nearfield (~50%). 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 significant changes in biomass, whether measured as chlorophyll, POC, or phytoplankton abundance although there has been a slight increase in winter/spring and fall bloom production and biomass. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with significant decreases in chlorophyll and POC and lower production, and preliminary results indicate that the seasonal pattern in productivity may be changing from a eutrophic to a more normal temperate coastal pattern. Continued study is necessary before statistically significant change can be documented in the bays 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 objectives of the HOM Program are 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 2003 data represent the third 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 2003 water column monitoring data have been reported in a series of survey reports, data reports, and semiannual interpretive reports (Libby *et al.* 2003a and 2004). The purpose of this annual report is to present a compilation of the 2003 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 2003 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 to December 2003 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?
- Has 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?
- Has 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 (Appendix A), water quality parameters – nutrients, chlorophyll, and DO (Appendix B), primary production (Appendix C), and phytoplankton and zooplankton community composition (Appendix D). As with the 2002 annual report (Libby *et al*. 2003b), this report focuses on addressing the 1991 monitoring questions. Those interested in an extensive presentation of all 2003 monitoring results are referred to Appendices A-D and the 2003 semiannual reports (Libby *et al.* 2003a and 2004). A summary of the current understanding of the system is presented in Section 3 and serves as a basis for discussion of topics pertinent to the post discharge data in general and 2003 monitoring data specifically presented in that section. The discussion includes an overview of the major findings from the 2003 water column data, integration and comparisons of baseline and post-discharge data, and comparisons of 2003 data against the established Contingency Plan (MWRA 2001) thresholds. The final section summarizes these discussions and presents the current understanding with regards to addressing the monitoring questions (MWRA 1991).

2.0 2003 WATER COLUMN MONITORING PROGRAM

This section provides a summary of the 2003 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*. 2002a). 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 2003 water column surveys have been presented in quarterly data reports: nutrient (including calibration information, sensor and water chemistry data), plankton (phytoplankton and zooplankton), and productivity/respiration. The 2003 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*. 2003a and 2004). 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 2003 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 17 surveys that were conducted in 2003 (**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.* 2002a).

Table 2-1. Water quality surveys for 2003 (WF031-WN03H).

Survey #	Type of Survey	Survey Dates
WF031	Nearfield/Farfield	February 5-8
WF032	Nearfield/Farfield	February 26, March 1-4
WN033	Nearfield	March 20
WF034	Nearfield/Farfield	April 1-3, 7
WN035	Nearfield	April 23
WN036	Nearfield	May 15
WF037	Nearfield/Farfield	June 18-21
WN038	Nearfield	July 9
WN039	Nearfield	July 21
WN03A	Nearfield	August 4
WF03B	Nearfield/Farfield	August 18-21
WN03C	Nearfield	September 10
WN03D	Nearfield	September 25
WF03E	Nearfield/Farfield	October 6-9
WN03F	Nearfield	October 31
WN03G	Nearfield	November 18
WN03H	Nearfield	December 19

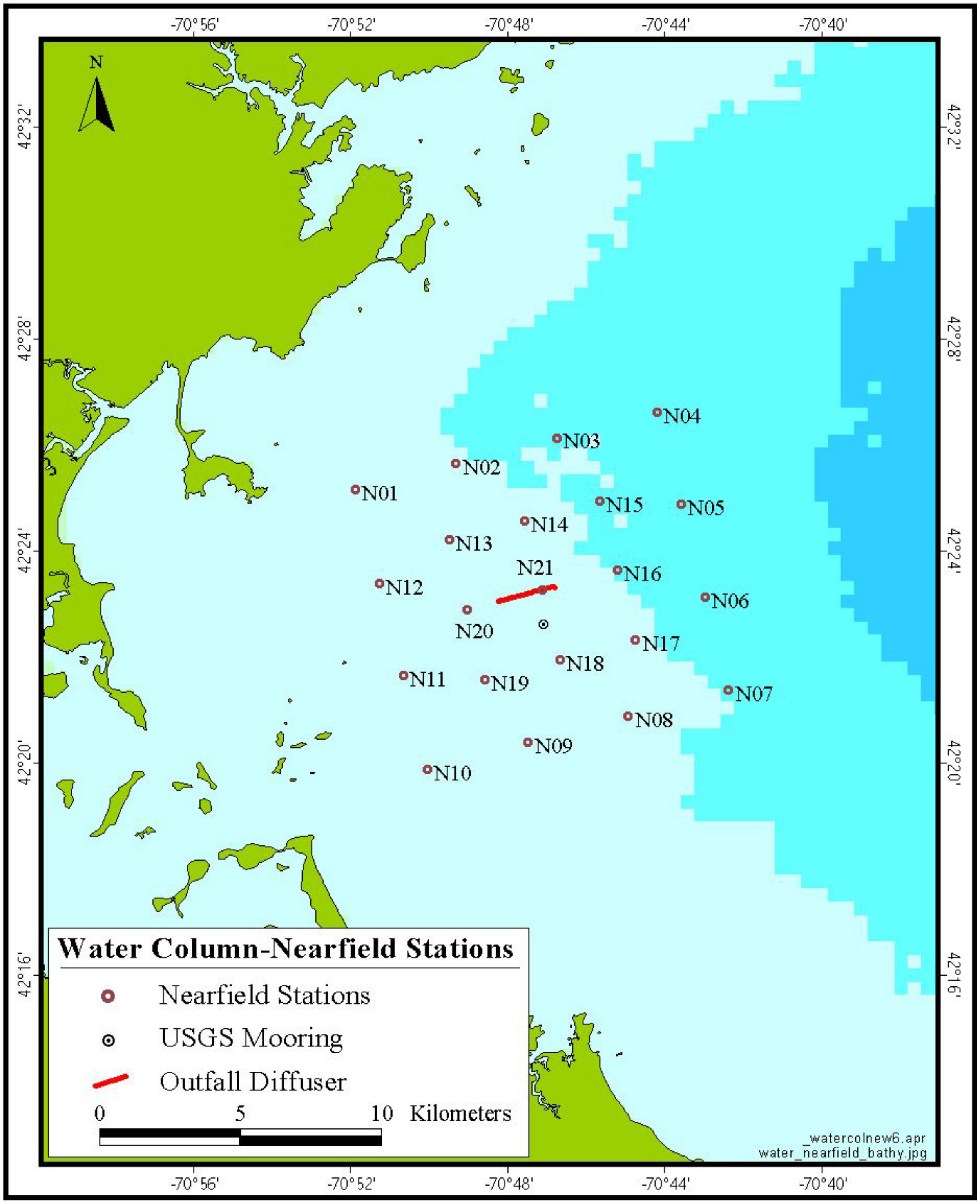

Figure 2-1. Locations of nearfield stations, MWRA offshore outfall, and USGS mooring.

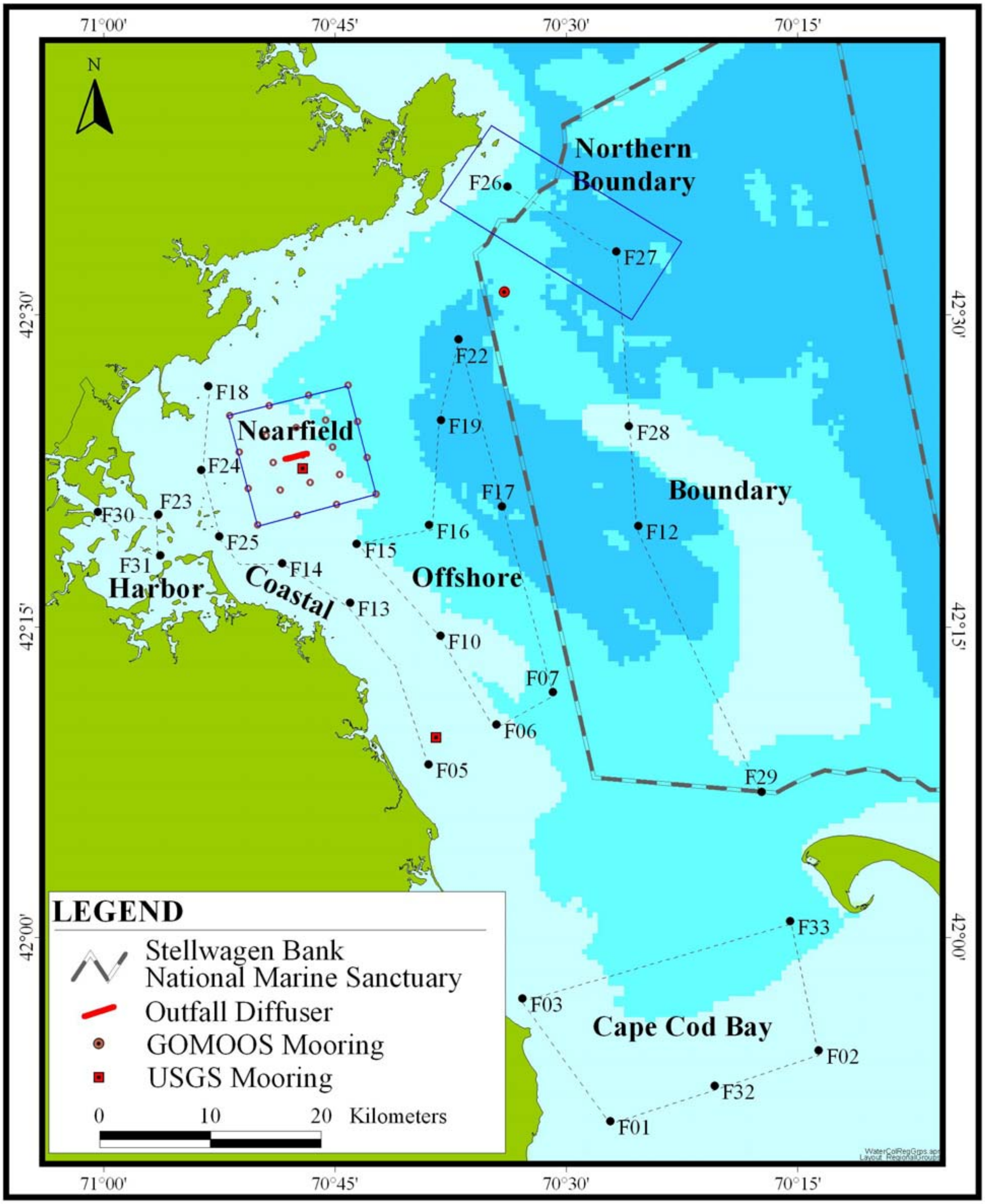

Figure 2-2. Locations of farfield stations and regional station groupings.

3.0 RESULTS AND DISCUSSION

3.1 Overview of System Trends and Characteristics

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 are the primary influences on the occurrence, timing and extent of water quality events in the bays. Although Massachusetts and Cape Cod Bays generally follow an annual cycle typical for temperate coastal waters (**Figure** 3-1), the timing of events over the cycle are influenced by regional meteorological and oceanographic conditions.

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, usually assorted species of *Thalassiosira* and *Chaetoceros*, 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 increases due to the decrease in surface water salinity associated with the spring freshet. The increase in 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, undergo senescence, and are 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 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 DO 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 DO in this region. Temperature also has a direct effect on DO levels by increasing rates of respiration.

In the fall, cooling surface waters and strong winds promote mixing of the water column. When stratification breaks down, oxygen is replenished in the bottom waters and nutrients are supplied to surface waters usually stimulating a fall phytoplankton bloom. The fall bloom is typically a mixed assemblage of diatoms including *Asterionellopsis glacialis, Rhizosolenia delicatula, Skeletonema costatum, Leptocylindrus minimus,* and *L. danicus*. Some of the largest blooms, however, have been species specific such as the *A. glacialis* bloom in September-October 1993. Typically, fall blooms end by early winter, when declining light levels limit photosynthesis. The lowest bottom water DO 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.

3.2 Synopsis of 2003 Results

This sequence of events described in Section 3.1 was generally evident in 2003 with some notable variations. Details on the physical, chemical and biological data collected in 2003 can be found in Appendices A-D and in the two semi annual reports (Libby *et al*. 2003a and 2004). The major water quality features and differences from the baseline in 2003 are summarized below:

- The most notable characteristics of the physical properties in 2003 were a return to normal freshwater inflow from the drought conditions present in 2001-2002, colder than normal water temperatures in winter/spring period, upwelling-favorable winds that produced colder than average bottom water temperatures during the summer, and a delay in the breakdown in stratification until late November 2003.
- A winter/spring bloom of diatoms was observed in February 2003 that was most prominent in Cape Cod Bay, Boston Harbor, coastal and western nearfield waters. This was a departure from the trend in 2001 and 2002 when the diatom bloom apparently occurred or peaked prior to the early February surveys.
- There was a bloom of *Phaeocystis pouchetii* in the spring throughout Massachusetts and Cape Cod Bays that was most pronounced in northern Massachusetts Bay. This is the fourth year in a row (2000-2003) for this feature, thus it appears that the *Phaeocystis* bloom is becoming a more regular event in the bays. The spring 2003 *Phaeocystis* bloom began earlier (February), and lasted longer (May) than most previous blooms which were typically April events.
- The occurrence of these two substantial blooms led to a sharp decrease in nutrient concentrations and a high seasonal chlorophyll mean in the nearfield that was one of the highest recorded during the monitoring program.
- The dramatic decrease in NH_4 in Boston Harbor and nearby coastal waters and increase within 20 km of the outfall in Massachusetts Bay continues to be the most obvious changes in the system post diversion. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with decreases in chlorophyll and POC, and a change in the seasonal productivity from a eutrophic to more normal temperate coastal pattern. In the nearfield, the higher NH_4 concentrations have not translated into a significant increase in biomass, whether measured as chlorophyll or POC.
- The fall diatom bloom occurred over a prolonged period from late September into December. Although the chlorophyll and POC concentrations were close to baseline maxima during the late fall bloom, plankton and productivity rates were relatively low in comparison to previous fall blooms.
- Areal production in Massachusetts Bay in 2003 followed the patterns observed in prior years, although at lower levels of production especially for the winter/spring and fall bloom peak rates. Productivity in the harbor in 2003 remained lower relative to baseline levels and continued to show the apparent change in the seasonal productivity pattern observed in 2001 and 2002.
- Annual minimum DO levels were measured in November in the nearfield (6.5 mg l^{-1} and 69%) rather than in October. DO levels were slightly higher in October (6.7 mg l^{-1} and 72%) with comparable minima observed throughout Massachusetts Bay. The DO minima in Stellwagen Basin were well above those in the nearfield and levels in both areas were above baseline background levels.

- The *Phaeocystis* bloom in 2003 was well below threshold values for the winter/spring. As in 2002, however, the bloom extended into May (albeit in only one sample at 48,000 cells l^{-1}) causing the summer *Phaeocystis* threshold value to be exceeded due to the duration of the bloom and the very low summer threshold value.
- There were no harmful or nuisance phytoplankton blooms in Massachusetts and Cape Cod Bays in 2003, other than the spring *Phaeocystis* bloom. The nuisance algae *Alexandrium* spp. was observed intermittently at abundances well below threshold values. The potentially-toxic diatoms of the genus *Pseudo-nitzschia* were routinely present in the summer and fall, and the nearfield autumn mean value for *P. pungens* approached the autumn threshold value.
- Zooplankton community abundance and taxa were similar to previous years
- Comparison of winter-spring (February-April) nearfield abundances of *Calanus finmarchicus* copepodites and adults with the boreal winter index of the North Atlantic Oscillation yields a significant negative correlation suggesting that some components of marine plankton communities in Massachusetts Bay may be sensitive to variations in long-term climatic and oceanographic patterns.

3.3 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 DO concentrations and percent saturation in bottom waters of the nearfield and Stellwagen Basin, rate of decline of DO from June to October, 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** 3-1). The DO values compared against thresholds are calculated based on the mean of bottom water values for surveys conducted from June to October. The seasonal rate of nearfield bottom water decline is calculated 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). The *Pseudo-nitzschia “pungens*” threshold designation can include both non-toxic *P. pungens* as well as the identical-appearing (at least with light microscopy) domoic-acid-producing species *P. multiseries* and since resolving the species identifications of these two species requires scanning electron microscopy all *P. pungens* and *Pseudo-nitzschia* unidentified beyond species were included in the threshold. For *Alexandrium* each individual sample value is compared against the threshold of 100 cells l^{-1}.

The nearfield minima DO concentration for June-October 2003 (6.72 mg l^{-1}) was well above the background and threshold values. While the nearfield DO percent saturation minimum of 71.4% was below the nominal warning threshold value, it was above the background value of 64.3%. The mean bottom water DO minima for Stellwagen Basin was higher than in the nearfield, but as in the nearfield the minima DO %saturation (72.8%) was below the nominal warning threshold value of 75%. As the nearfield and Stellwagen DO %saturation minima were above established background threshold values, there was no threshold exceedance for DO. In 2003, DO levels continued to decrease into November reaching minima of 6.5 mg l^{-1} and 69%. Although this survey was outside of the threshold period (June – October), the values were still above background threshold levels.

Table 3-1. Contingency plan threshold values for water column monitoring.

Parameter	Time Period	Caution Level	Warning Level	Background	2003
Bottom Water DO concentration	Survey Mean in June-October	<6.5 mg l^{-1} (unless background lower)	<6.0 mg l^{-1} (unless background lower)	Nearfield: 5.75 mg l^{-1} SW Basin: 6.2 mg l^{-1}	Nearfield: 6.72 mg l^{-1} SW Basin: 7.07 mg l^{-1}
Bottom Water DO %saturation	Survey Mean in June-October	<80% (unless background lower)	<75% (unless background lower)	Nearfield: 64.3% SW Basin: 66.3%	Nearfield: 71.4% SW Basin: 72.8%
Bottom Water DO Rate of Decline (Nearfield)	Seasonal June-October	0.037 mg l^{-1} d^{-1}	0.049 mg l^{-1} d^{-1}	--	0.021 mg l^{-1} d^{-1}
Chlorophyll	Annual	107 mg m^{-2}	143 mg m^{-2}	--	99 mg m^{-2}
	Winter/spring	182 mg m^{-2}	--	--	178 mg m^{-2}
	Summer	80 mg m^{-2}	--	--	45 mg m^{-2}
	Autumn	161 mg m^{-2}	--	--	87 mg m^{-2}
Phaeocystis pouchetii	Winter/spring	2,020,000 cells l^{-1}	--	--	482,000 cells l^{-1}
	Summer	334 cells l^{-1}	--	--	1,700 cells l^{-1}
	Autumn	2,370 cells l^{-1}	--	--	None
Pseudo-nitzschia pungens	Winter/spring	21,000 cells l^{-1}	--	--	232 cells l^{-1}
	Summer	38,000 cells l^{-1}	--	--	60 cells l^{-1}
	Autumn	24,600 cells l^{-1}	--	--	8,900 cells l^{-1}
Alexandrium tamarense	Any nearfield sample	100 cells l^{-1}	--	--	6.6 cells l^{-1}

Thus, the threshold and state standards were not exceeded as both of them include qualitative language that levels must be above 6.0 mg l^{-1} or 75% "unless background conditions are lower". A review of previous survey means (**Figures** 3-2 and 3-3) indicates that DO concentration has only dropped below 6 mg l^{-1} once during baseline (nearfield in 1999). Percent saturation levels, however, dropped below the caution threshold of 80% during all but two of the twelve 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% five of the twelve years in both the nearfield and Stellwagen Basin.

The nearfield mean areal chlorophyll for winter/spring 2003, 178 mg m^{-2}, is comparable to but below the seasonal caution threshold of 182 mg m^{-2}. This is the highest winter/spring value since the outfall went online. Although 2003 showed an increase from 2001 and 2002, it was comparable to the areal chlorophyll values seen winter/spring 1999 and 2000 (**Table** 3-2). In 1999 and 2000, the high winter/spring chlorophyll concentrations were coincident with a substantial region-wide winter/spring diatom (1999) or *Phaeocystis* (2000) bloom. Although 2003 lacked a single major regional winter/spring bloom, the combination of elevated chlorophyll concentrations over much of the water column during both the nearshore diatom bloom and the offshore *Phaeocystis* bloom resulted in relatively high chlorophyll concentrations in the nearfield from February through April. The 2003 winter/spring seasonal chlorophyll mean was the second highest value that has been observed during the monitoring program (**Table** 3-2).

Table 3-2. Seasonal and annual mean areal chlorophyll (mg m^{-2}) in the nearfield.

Year	Winter/ Spring	Summer	Fall	Annual
1992	60	60	84	67
1993	33	61	136	77
1994	71	55	90	71
1995	36	27	85	50
1996	90	28	46	53
1997	49	38	41	43
1998	25	52	70	52
1999	158	57	170	127
2000	193	87	212	156
2001	69	45	87	67
2002	112	50	100	82
2003	178	45	87	99
Baseline Mean*	79	51	90	67
Post Transfer Mean*	120	47	122	83

*Bay Outfall began discharging September 2000 – 2000 data included in baseline for winter/spring and summer means, in post-transfer fall mean, and not used in annual mean comparison.

In contrast to the high winter/spring values, summer and fall 2003 nearfield areal chlorophyll means were relatively low (45 and 87 mg m^{-2}, respectively) and approximately 50% of the caution threshold values. These low seasonal values in combination with the high winter/spring 2003 mean resulted in an annual areal chlorophyll mean of 99 mg m^{-2}. Although this value is considerably higher than the 2001 and 2002 annual means (67 and 82 mg m^{-2}, respectively), it is still below the caution threshold of 107 mg m^{-2} (**Table** 3-1). Comparison of winter/spring and fall seasonal mean areal chlorophyll indicates an apparent increase between baseline and post-discharge mean values (**Table** 3-2). This increase is not significant, however, given the limited post-transfer dataset (n=3 or 4) and the high degree of interannual variability in the data. Additional monitoring data will be needed before a definitive change can be distinguished or ruled out.

Although there was a substantial and prolonged *Phaeocystis* bloom from February to mid May 2003, the nearfield mean winter/spring abundance was only 25% of the threshold. The summer *Phaeocystis* threshold value, however, was exceeded as the spring *Phaeocystis* bloom was present at low and declining abundance in May. The continued presence of *Phaeocystis* in May, albeit only in one sample and at low abundance (48,400 cells l^{-1}), and the very low summer threshold value resulted in an exceedance. This exceedance was not considered indicative of an impact associated with the outfall and may be a consequence of extended periods of cooler temperatures in the bay (see Appendices A and D).

The dinoflagellate *Alexandrium tamarense* was recorded, but only in very low abundance (<10 cells l^{-1}). *Pseudo-nitzschia "pungens"* were observed during many of the July to December 2003 surveys. Abundance of *Pseudo-nitzschia* peaked during the early October survey with a nearfield mean value of 52,000 cells l^{-1}. The autumn mean abundance in 2003, however, was below the threshold value. Indications are that the abundances of *Pseudo-nitzschia* were relatively high throughout Massachusetts Bay and at stations sampled for the Stellwagen Bank National Marine Sanctuary (SBNMS) monitoring program in early October 2003 (Appendix D). The abundance of *Pseudo-nitzschia delicatissima*, however, tended to be even higher. This *Pseudo-nitzschia* species has also been shown to produce domoic acid (Pan *et al.* 2001, Amzil *et al.* 2001). The summer-autumn 2003 marine mammal die-off in Gulf of Maine and Georges Bank waters is likely linked to a *Pseudo-nitzschia* bloom because domoic acid was found in the tissue of at least one dead humpback whale (US Marine Mammal Commission

Meeting, October 2003). Thus, the elevated *Pseudo-nitzschia* (*P. pungens* and *P. delicatissima*) abundances that were recorded for the MWRA and SBNMS sampling area in October appears to have been part of a widespread bloom that may have contributed to vectorial intoxication of whales through diatom – zooplankton – fish – whale food chains.

3.4 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 DO 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 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. These questions are the focus of the data presentations and are directly addressed in the following subsections. The monitoring questions are presented along with a summary of findings.

3.4.1 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, seasonally dependent, 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 (**Figure** 3-4). 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. 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 do not 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. In late spring and summer, Cape Cod Bay becomes isolated from this circulation.

As the surface waters warm up in May and June, temperature stratification dominates over that due to the freshwater input. There is a strong and persistent pycnocline throughout most of Massachusetts and

Cape Cod bays in the summer that is occasionally punctuated by upwelling and storm mixing events. 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 waters generally remain stratified until late October, when surface cooling and wind stress cause the water column to become vertically mixed.

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 1991). A stormy early autumn can also lead to early fall turnover.

The importance of the inputs of Gulf of Maine water to Massachusetts and Cape Cod Bays cannot be overemphasized as research has shown it to be a major influence on circulation, water properties, and biology in the bays (Beardsley *et al.* 1997). 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 (HydroQual 2001)
- 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 MWRA 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 (**Figure** 3-5), while from about April through October the water column is stratified and the effluent plume is trapped below the pycnocline (**Figure** 3-6). The extent of horizontal exchange is illustrated by **Figure** 3-7, which presents a set of progressive vector diagrams from 2000 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

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[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.

essentially no mean flow at the outfall location; bottom currents of around 6 cm s^{-1} 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. The largest displacements in **Figure** 3-7 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).

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*. 2001). The effluent plume, as defined by the distribution of elevated NH_4 concentrations, surfaces when the water column is well mixed and remains trapped beneath the pycnocline during seasonal stratified conditions (**Figures** 3-5 and 3-6). In addition to illustrating the vertical extent of the plume, the NH_4 distribution has also highlighted the variability in its horizontal distribution (both direction and extent). 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*. 2002). 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 above, the predominant circulation pattern in Massachusetts Bay is counterclockwise, but currents are quite variable and highly dependent upon winds. The 2003 monitoring data continue to support these findings. For example, in June 2003, the plume appeared to extend from the nearfield into coastal waters along the north shore (**Figure** 3-8). 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 (within 20km).

3.4.2 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 Appendix B, 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). The spatial patterns in NH_4 concentrations in the harbor, nearfield and bays since the diversion in September 2000 consistently confirm this (**Figures** 3-8 and 3-9). This prediction has also been validated by an analysis of field data from the first year of bay outfall discharge that indicated 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 (**Figure** 3-10a). Concurrently, NH_4 concentrations followed a similar trend (increasing and then decreasing) 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 last full year before the bay outfall came online, the annual mean NH_4 levels have almost doubled in the nearfield. Harbor, coastal, and nearfield NH_4 concentrations have remained relatively stable since 2001. There has been little if any change in NH_4 concentrations measured in offshore, boundary, and Cape Cod Bay waters over the entire monitoring program (1992-2003). 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** 3-10b 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 (see **Figures** B-13 and B-14).

Clear changes in nearfield and farfield nutrient regimes have been measured and 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.

3.4.3 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 (POC) 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, which are typically regional in nature (i.e. southwestern Gulf of Maine). 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.

Within the bay system, spatial distributions of chlorophyll tend to be 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. During March/April, the input of fresher, buoyant surface waters from the Gulf of Maine is often conducive to phytoplankton blooms and is expressed in elevated levels of chlorophyll. It is difficult to determine whether the increase in chlorophyll results from the transport of phytoplankton into the bays or rather from the existence of physical and nutrient conditions conducive to increased production. In either case, the influence of the Gulf of Maine on chlorophyll biomass in waters entering Massachusetts Bay near Cape Ann is often apparent in satellite imagery (**Figure** 3-11). The use of these images allows examination of the distribution of surface chlorophyll both within and outside of the bays and highlights the regional nature of blooms in these waters. The major blooms observed in Massachusetts Bay since SeaWiFS images became available (October 1997) have all been regional in nature: that is, there has been a coincident regional expression of elevated chlorophyll values over much of the southwestern Gulf of Maine during each of the blooms.

Since September 2000, nearfield areal chlorophyll values were generally consistent with the baseline mean and seasonal pattern. The largest deviation was observed in the fall of 2000 soon after the bay outfall became operational. The chlorophyll levels during the fall 2000 bloom were the highest measured during the monitoring program (~500 mg m^{-2}; **Figure** 3-12a). 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** 3-12b). This is corroborated by plankton counts, which were elevated, but not exceedingly high. Coincident SeaWiFS imagery indicated that this bloom was part of a regional event encompassing most of the Gulf of Maine coastal waters and unrelated to the startup of the bay outfall (Libby *et al.* 2001).

Other minor deviations from baseline chlorophyll patterns have occurred during the winter/spring and fall blooms **(Figure** 3-12a). High values in early February of 2001 and 2002 coincided with elevated production rates and early winter/spring blooms. In 2003, the winter/spring diatom bloom combined with the prolonged *Phaeocystis* bloom (March-May) led to elevated chlorophyll and POC concentrations from February to April. In 2002, the fall bloom appeared early (August and September), but the highest chlorophyll levels occurred during a secondary fall bloom in November. In 2003, chlorophyll levels were at or above the baseline maxima in late October and November. The relatively high (150 - 200 mg m^{-2}) chlorophyll values observed during each of these late fall blooms were well below the maximum values observed during major winter/spring and fall blooms during the baseline. A comparison of seasonal and annual mean areal chlorophyll in the nearfield suggests that there has been an increase in winter/spring, fall, and annual mean levels since the bay outfall began discharging (**Table** 3-2 and **Figure** 3-13). None of these changes, however, is statistically significant.

Particulate organic carbon concentrations in 2001-2003 generally followed the baseline means and trends except for the high peaks during the 2003 *Phaeocystis* bloom and peaks corresponding to fall blooms during each of the post discharge years (**Figure** 3-12b). During all four 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 except in 2003 when production levels were slightly lower than typically observed (<2,500 mg C m^{-2} d^{-1}; see Appendix C).

In Boston Harbor, areal chlorophyll followed a similar trend to that in the nearfield (**Figure** 3-14a). 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 and late February 2003 areal chlorophyll concentrations were higher than any previous values measured in Boston Harbor. Harbor POC concentrations were relatively low in 2001, and similar to baseline trends (**Figure** 3-14b). In 2002 and 2003, elevated POC concentrations were coincident with high chlorophyll and productivity during the winter spring blooms. The chlorophyll and POC data (along with production data presented in Appendix C) 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 the winter/spring bloom.

In 2002, the HOM data suggested that the harbor may also be experiencing a change to fall blooms (Libby *et al*. 2003b). Chlorophyll data collected for the more highly resolved (spatially and temporally) MWRA Harbor Monitoring Program, however, while confirming that there were substantial chlorophyll blooms in Boston Harbor in February 2002 and 2003, also indicated that summertime chlorophyll levels peaked in July rather than August 2002 (Taylor 2003). Thus, although HOM data did not capture the summer peak, it was still present in 2002 and 2003, albeit at lower levels than during baseline monitoring. Taylor (2004) noted that although there was no significant change in annual chlorophyll levels pre- versus post-discharge, there was a significant ($P<0.001$) decrease in summer chlorophyll concentrations of 36%. The lack of a significant change in the annual means in the Harbor Monitoring data is a reflection of the increased levels of chlorophyll during the winter/spring and in the fall.

In the nearfield, graphical comparisons of survey, seasonal, and annual mean chlorophyll and POC values suggest that there has not been a significant change since the diversion of effluent. Seasonal and annual mean chlorophyll concentrations in the nearfield have increased, but not significantly. Annual mean chlorophyll values in Massachusetts and Cape Cod Bays did increase from 1997 to 2000, but have decreased to lower levels since then. 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 and 2003, 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, however, has not been observed in spatial and temporal means over the first three years of post-transfer monitoring. 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 3.4.5.

3.4.4 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 >90% 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 a detectable change in DO concentrations or percent saturation in the nearfield or Stellwagen Basin since the effluent was diverted to the bay outfall. Survey mean DO values in both the nearfield and Stellwagen Basin often reach minimum concentrations of <6.5 mg L^{-1} and have consistently gone below 80% saturation each fall during both the baseline and post-discharge monitoring periods. 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** 3-1 and **Figures** 3-2 and 3-3) none of which have been exceeded since the outfall came online. There have been no detectable 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 October/November (see **Figures** 3-2 and 3-3). Modeling and statistical analyses indicate that DO concentration and percent saturation at nearfield, Stellwagen Basin, and northern boundary stations are highly correlated (HydroQual 2001, Geyer *et al*. 2002). Regional processes and advection are the primary factors governing bottom water DO concentrations in Massachusetts Bay (Geyer *et al*. 2002).

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

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

where T' and S' are the near-bottom temperature and salinity anomalies (relative to the 11-year mean for Sept.-Oct., A=7.417 mg l^{-1}, B=0.204, and C=1.87). For this report, the model is used in a forecast mode using the regression based on data collected from 1992-2002 to see how well the result matches the measured DO concentration minimum in 2003. The statistical model predicted a slightly higher bottom water DO minimum than measured for an inner set of nearfield stations in 2003, but overall the modeled and measured DO minima have been very close since the outfall went online (**Figure** 3-15). The measured and modeled DO concentrations were also close to the 11-year mean, so there was little information to be garnered from the relative contributions of temperature and salinity. The result reaffirms the correlations between these parameters and bottom water DO concentrations. In 2003, the cold bottom water resulting from upwelling-favorable conditions produced a positive anomaly in DO, which was compensated by salty bottom water due to dry conditions in early 2003 and results in a negative anomaly in DO (**Figure** 3-15). The result was average near-bottom DO conditions for the fall of 2003. The 2003 data continue to indicate that there has been no statistical change in the DO conditions since the onset of the Outfall discharge.

The GoMOOS "A" mooring located to the south of Cape Ann and the USGS mooring located in the nearfield (see **Figure** 2-2) provide documentation of the inflow conditions into Massachusetts Bay from the Gulf of Maine and conditions in the nearfield Although incomplete due to sensor issues, the timeseries of moored data from 2003 is particularly interesting with respect to the variations in DO (**Figure** 3-16). At the GoMOOS mooring during the spring, the near-bottom (50-m) DO fluctuates significantly on timescales of several days, most notably with sharp dips in concentration. Similar fluctuations in temperature were observed in the bottom water at the USGS mooring. These fluctuations are not resolved by the coarse temporal sampling of shipboard data. The record for the summer and early fall at the GoMOOS mooring shows much less short-term variability in DO (as well as in temperature and salinity). The data also show the well-documented downward trend associated with the stratified period. The timeseries data indicate that the decreases in DO occur episodically, in a stepwise manner. The trend in decreasing DO is also apparent at the nearfield USGS mooring in late September. As stratification begins to breakdown in the nearfield (October/November), large variations in the mooring temperature and DO data occur that were not resolved in the shipboard data. Further analysis is required to examine the actual mechanisms responsible for the high-frequency fluctuations in DO during the spring and fall as well as the step-like decline during the summer. In particular, it will be useful to distinguish horizontal advection from vertical exchange and/or local biological processes.

Monitoring data show no change in DO 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. 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. As the GoMOOS and USGS data set extends in time and becomes more consistent, it provides the basis for in-depth analysis of the mechanisms influencing the variability of DO.

3.4.5 Productivity

→ *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 (**Figure** 3-17). 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, an early fall bloom in 2002, and a late fall bloom in 2003. Additionally, some differences in the magnitude of fall peak bloom productivity were noted. The spring bloom production has changed relatively little at nearfield stations N04 and N18 during the post-transfer period (9% and -3%, respectively). Fall bloom peak productivity rates, however, have increased by 19% at station N18, the station nearest the outfall, and by 40% at station N04 in comparison to baseline values (**Figure** 3-18).

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 temperature and inversely correlated with zooplankton abundance (Keller *et al.* 2001). As subsequent data were collected, this relationship broke down as the occurrence of *Phaeocystis* blooms began to be an annual event rather than the ~3 year cycle observed during the baseline. When the data are aggregated according to whether or not a *Phaeocystis* bloom occurred that year, a very strong inverse relationship between temperature and winter spring bloom biomass is apparent for the non-*Phaeocystis* years, but only a weak one for the *Phaeocystis* years (**Figure** 3-19). It has been hypothesized that this is due to the unpalatibiliity of *Phaeocystis* to zooplankton (Huntley *et al.* 1987), but others have indicated that it may have more to do with the lower nutritional value of a *Phaeocystis* diet and resulting poor fecundity of zooplankton (Turner *et al.* 2002). Regardless of cause, ecological dynamics appear to be different during years with a *Phaeocystis* bloom with a disconnect between bloom production rates and phytoplankton biomass and a decrease in zooplankton abundance with increasing phytoplankton biomass (**Figure** 3-20).

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 blooms in 2001 and 2003. 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 fall blooms.

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 winter/spring and possibly fall peaks and lower rates in summer (**Figure** 3-17). Prior to transfer to the bay outfall, productivity in the harbor was characterized by increasing rates throughout the summer, followed by a fall decline. The pattern observed at station F23 in the spring and summer of 2003 resembles the seasonal cycle observed at the nearfield stations. In 2003, the spring bloom dominated the seasonal cycle. In 2002, the spring and late summer peaks were equivalent in magnitude, while in 2001 the August peak dominated the annual cycle. Chlorophyll data collected by the MWRA Harbor Monitoring Program confirmed that there were substantial chlorophyll blooms in Boston Harbor in February 2002 and 2003 and their data also indicate that there has been a significant ($P<0.001$) decrease in summer chlorophyll concentrations of 36% (Taylor 2004). Taylor (2004) also notes that there has been a significant reduction in dissolved inorganic nitrogen (DIN, -59%) primarily due to a reduction in NH_4 (-82%) since the effluent discharge was transferred to the bay outfall. These substantial changes in nutrient availability in the harbor have contributed to the altered seasonal productivity cycle and chlorophyll trends that have been observed.

To further refine understanding of the changes in primary production, potential annual productivity during pre- and post-outfall years was compared (**Figure** 3-21). Although none of the changes in annual production were significant, the data indicate slightly higher (3-17%) post diversion mean production at the nearfield stations and lower (-40%) 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 productivity stations N04 and N18. In Boston Harbor, routine monitoring by MWRA shows decreases in annual mean chlorophyll (-20%) and POC (-28%; significant at $P<0.05$) levels in the three years after diversion to the bay outfall (Taylor 2004). 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 DIN utilized during the spring bloom. By comparing pre-bloom nutrient concentrations to post bloom concentrations in surface waters, an apparent decrease or delta value can be calculated to indicate relative biological utilization (**Figure** 3-22). At nearfield stations the change in delta DIN over the spring bloom period was ~7.8 µM prior to diversion to the bay outfall. After diversion, delta DIN increased to 11 µM at N18 and 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 1.75 µM at N04. **Figure** 3-23 indicates a positive relationship between the winter spring productivity peak and the change in surface nitrogen concentration over the bloom period. The availability of an additional source of DIN, namely the NH_4 rich effluent in the nearfield, could be fueling the apparent increase in production observed during the first three years of the bay outfall.

The apparent changes in pre and post transfer production in Boston Harbor and the nearfield suggest that the additional source of nutrients removed from and added to each of the areas may be having an impact on primary production and phytoplankton biomass (as chlorophyll and POC). Production rates have decreased in the harbor and increased in the nearfield though neither change is statistically significant. Coincident changes in biomass have also been observed. The variability in these biological measurements and the limited amount of post transfer data do not allow for definitive findings and the changes observed in pre and post transfer production, biomass and nutrient utilization continue to be the focus of ongoing examination.

3.4.6 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 ever changing environmental influences on the habitat (e.g. annual change in irradiance, temperature, nutrient, grazer abundance). A substantial change to one of these environmental influences, such as the transfer of the effluent discharge to the offshore environs, could conceivably have an impact on phytoplankton abundance and species composition. Accordingly, the monitoring questions address this potential impact as well as focusing on changes in the presence and magnitude of nuisance or noxious phytoplankton blooms.

Over the nearly nine years of baseline monitoring (1992-2000), a "normal" seasonal succession in the phytoplankton communities of Massachusetts and Cape Cod Bay has been observed. 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:

> Winter (primarily February) – diatoms abundant, including *Chaetoceros debilis, C. socialis, Thalassiosira nordenskioldii,* and *T. rotula;*
>
> Spring (March, April, May) – usually (except during *Phaeocystis* years) assorted species of *Thalassiosira, Chaetoceros*, as well as the dinoflagellate *Heterocapsa rotundatum,* and (especially nearshore) cryptomonads;
>
> Summer (June, July, August) – microflagellates are at peak abundance, with cryptomonads, *Skeletonema costatum* (especially nearshore), *Leptocylindrus danicus, Rhizosolenia delicatula, Ceratulina pelagica*, and various small-sized species of *Chaetoceros*;
>
> Fall (September through December) – diatoms are abundant, including *Asterionellopsis glacialis, Rhizosolenia delicatula, Skeletonema costatum, Leptocylindrus minimus, L. danicus*, as well as cryptomonads, and assorted gymnodinoid dinoflagellates.

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, 2002 and 2003. The interannual variability associated with both magnitude and occurrence of phytoplankton blooms is comparable to seasonal variability (**Figure** 3-24). 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.

The differences in the nearfield phytoplankton annual cycle, relative to baseline observations, were explored by hierarchical examination of the major components of the nearfield phytoplankton (see Appendix D). Post-diversion (2001-2003) assemblages were generally similar to those found during other baseline monitoring years. During each post-diversion year, nearfield total phytoplankton abundance was usually at or slightly below the baseline mean value (**Figure** 3-25). The primary exceptions were the April 2003 *Phaeocystis* bloom, the late summer/early fall diatom bloom in 2002, and the late fall blooms in 2001 and 2003.

No major changes have been noted in the taxonomic composition of the phytoplankton community over the last twelve years, but there have been several variations in the timing and magnitude of various events in the seasonal succession. The most pronounced variations have been associated with the spring blooms of *Phaeocystis* (**Figure** 3-26). The pattern of occurrence and duration of these blooms appears to be changing. After recording spring blooms in 1992, 1994 (farfield), and 1997, there were consecutive blooms in 2000, 2001, 2002, and 2003. Thus, the pattern has changed from spring *Phaeocystis* blooms occurring in three-year cycles to blooms occurring annually. It is tempting to speculate that the change in the pattern and duration of *Phaeocystis* blooms might be related to the outfall. However, these blooms occur throughout the Massachusetts and Cape Cod Bays region, and in 2003, highest concentrations of *Phaeocystis* were in the area offshore from Cape Ann, upstream from the outfall (see **Figure** 3-11). It has also been noted that *Phaeocystis* blooms are a regular component of the spring phytoplankton assemblage in north temperate coastal seas (Cadee and Hegeman 2002), including the Gulf of Maine (Bigelow 1926). Direct and anecdotal evidence indicates that the blooms observed in Massachusetts Bay are regional in nature and have been coincident with the presence of *Phaeocystis* in waters from Buzzard’s Bay to the western Gulf of Maine.

Internationally, long-term observations indicate that *Phaeocystis* populations respond to trends in eutrophication and, possibly, warming winter temperatures. In the Dutch Wadden Sea, the duration of *P. globosa* and/or *P. pouchetii* blooms (defined as >1,000 cells ml^{-1}) increased ~5-fold (from 20 to 100 days per year) between 1975 and 1990, and has since declined to ~70 bloom days per year, tracking long-term changes in ambient N and P levels (Cadee and Hegeman 2002). Cadee and Hegeman (2002) also found that *Phaeocystis* blooms began about 25 days earlier (blooms starting in mid-March) in 1995-2000 than they did in the 1970s (blooms beginning in mid-April), a change that was linked to warmer winter temperatures. In the MWRA monitoring program, the frequency and duration of *Phaeocystis* blooms has been variable, but an increase in bloom frequency and duration of the bloom period into May in recent years has been noted.

While the monitoring program does not observe plankton populations at the daily to weekly time scale needed to resolve subtle shifts in bloom timing or duration, an examination of the *Phaeocystis* trends in light of high frequency surface water temperature data from the Boston Buoy provides insight into one of the factors that may be contributing to the duration of the *Phaeocystis* blooms in Massachusetts Bay (see Appendix D). *Phaeocystis* has a thermal tolerance range of –2 to 14 °C (Jahnke and Baumann 1987) and a Massachusetts Bay *P. pouchetii* isolate has been shown not to grow in nutrient and light replete laboratory conditions at temperatures >14 °C (Hegarty and Villareal 1998). Thus 14 °C appears to be the physiological threshold for *P. pouchetii* growth, and is the maximum temperature at which one might expect to observe *P. pouchetii* blooms in Massachusetts Bay. An examination of temperature data from the Boston Buoy suggests that the extended duration of the *Phaeocystis* blooms in 2002 and 2003 are related to the presence of cooler waters (<14 °C) into early June when compared against temperatures in 2000 and 2001 when surface waters reached 14 °C in mid May and the duration of the *Phaeocystis* bloom was abbreviated. Although the correlation between surface temperatures and bloom duration was significant (P=0.034), the data set was limited to only four points.

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 change in the frequency and duration of spring *Phaeocystis* blooms since 2000 appears to be related to regional factors such as temperature and are a normal component of the plankton seasonality in the bays. The atypical timing of the fall blooms in 2001 and 2003 (late and prolonged) and 2002 (early) while interesting, appears to be associated with physical and biological factors unrelated to the outfall. In 2001 and 2003, 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 these blooms may have been further enhanced by the input of additional nutrients into the nearshore waters via the outfall or upwelling, which may have entrained both nutrient-rich bottom waters and the effluent plume into the upper water column, continues to be explored.

3.4.7 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 (**Figures** 3-27 and 3-28). 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 are sporadically abundant and pulses of meroplankton can be seasonally important. The monitoring questions were focused on substantial changes in the zooplankton community because small changes would not be discernable given the variability and patchiness of zooplankton. It was envisioned that monitoring this component of the ecosystem would provide insight into a variety of potential food chain changes. One such potential change, for example, was the development of a more harbor-like zooplankton community with increased presence of harbor taxa such as *Acartia tonsa*. The hypothesis was that the higher nutrient load to the harbor (and now to waters near the bay outfall) supported a phytoplankton community in high enough densities for *Acartia* to thrive (Paffenhofer and Stearns 1988). The "*Acartia* hypothesis", however, was flawed as it appears that their presence in the harbor is more a function of the salinity regimes found in enclosed or partially enclosed estuarine waters like Boston Harbor (Tester and Turner 1991) than the relative availability of food. Thus, it appears to be a more complicated question to address than originally thought as it is unlikely that changes in ambient nutrient concentrations in the nearfield will lead to substantial changes to the zooplankton community. Subtle changes to the zooplankton community are more plausible, but will also be much more difficult to detect. These changes would most likely be due to a bottom up impact via dramatic changes in the phytoplankton assemblage and this has not been the case thus far.

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. Total zooplankton abundance tends to follow a predictable temporal pattern, with abundance peaking in mid-summer and lower levels in spring and fall. There is, however, no clear seasonality in terms of dominant zooplankton taxa in the region. Zooplankton abundance 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* (most abundant in winter-spring), *Eurytemora herdmani*, *Tortanus discaudatus*, and *Centropages hamatus*. 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. The major difference between post-transfer, particularly 2002, and the baseline in terms of zooplankton abundance was the precipitous decline in zooplankton abundance in late summer and fall due to ctenophore (*Mnemiopsis leidyi*) predation. Although zooplankton abundances declined drastically during these periods, community composition has remained similar compared to the same season in previous years. The reason for the increase in ctenophore abundance, however, is not known, but may be related to the temperature affects of global warming (Sullivan *et al*. 2001). Long-term temperature records from Woods Hole, MA indicate that there has been a significant trend of increasing water temperatures from 1970 to 2002 at Woods Hole, MA (Nixon *et al*. 2004) that could be contributing to the trend in ctenophore abundance.

The zooplankton community has not detectably changed in response to the outfall going on line. Although variability in zooplankton abundance has been observed, it has resulted from the impact of ctenophores on the rest of the zooplankton community, rather than the outfall and effects of nutrient enrichment in the nearfield. There has been 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 events of 2000 and 2002. In addition, multivariate statistical analyses reveal no clear temporal or spatial changes in zooplankton communities attributable to the outfall (Kropp *et al.* 2003). 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.

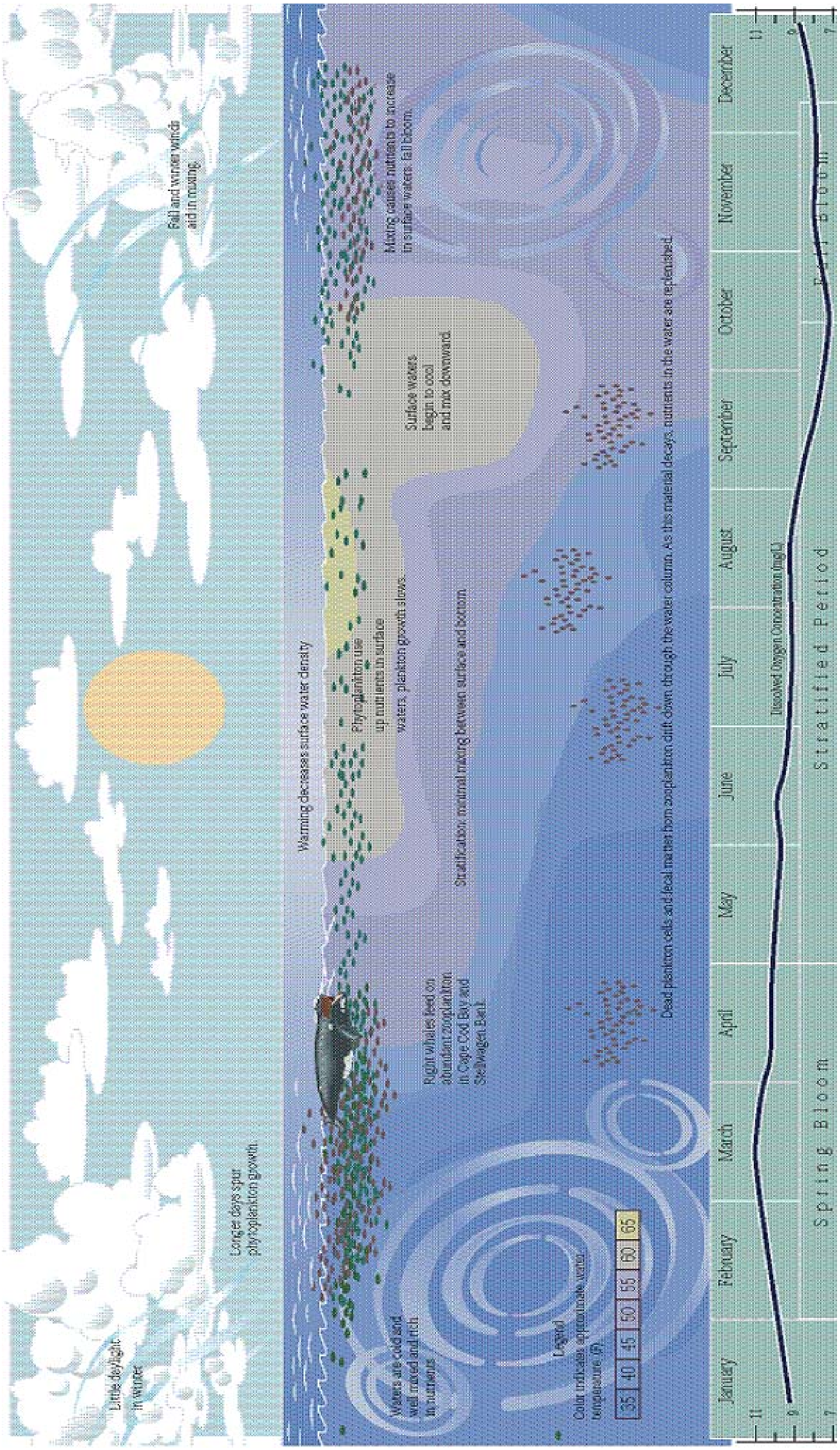
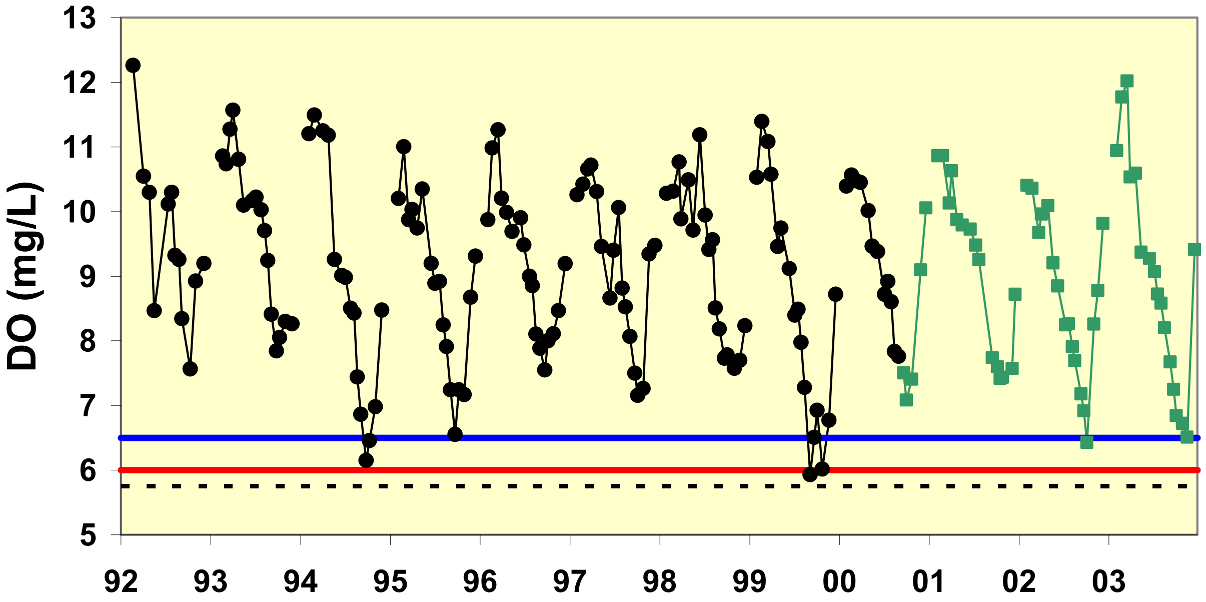


Figure 3-1. Seasonal cycle of coastal New England waters.

(a) DO concentration



(b) DO Percent Saturation

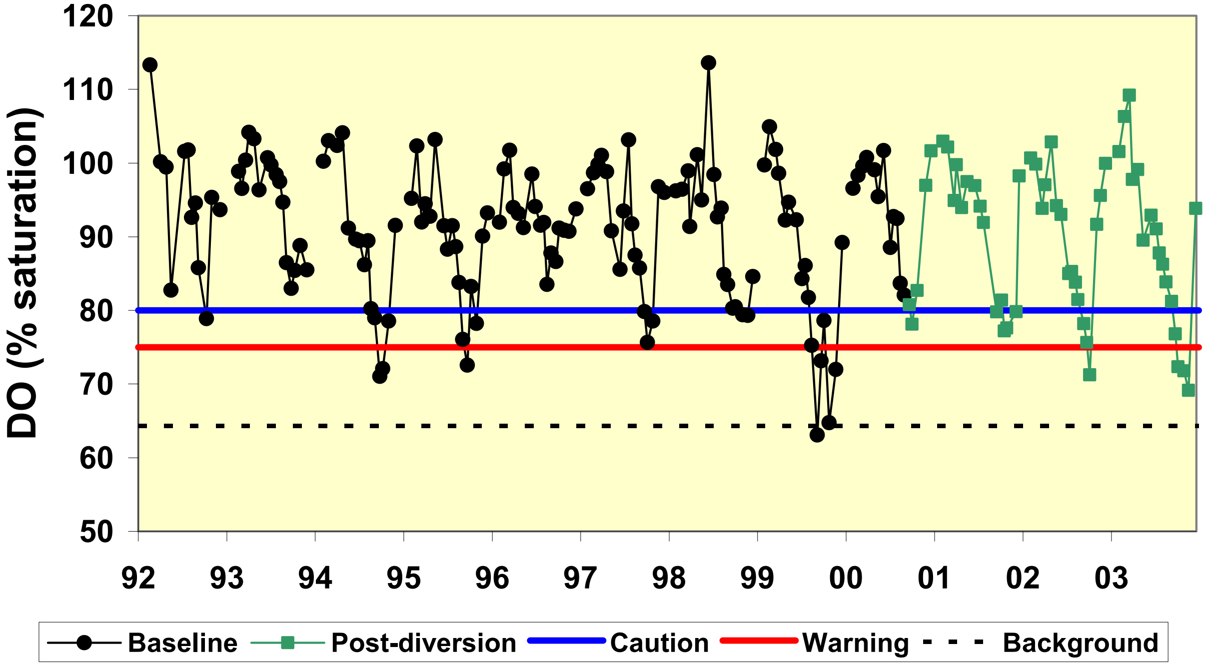
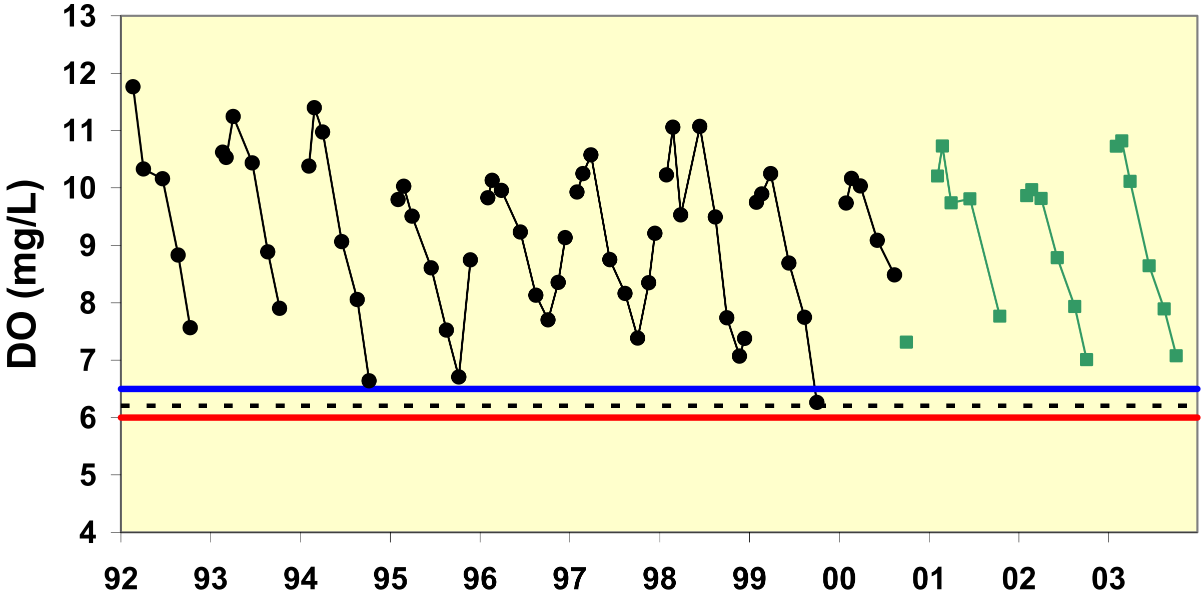


Figure 3-2. Survey mean bottom water dissolved oxygen (a) concentration and (b) percent saturation in the nearfield compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares.

(a) DO concentration



(b) DO Percent Saturation

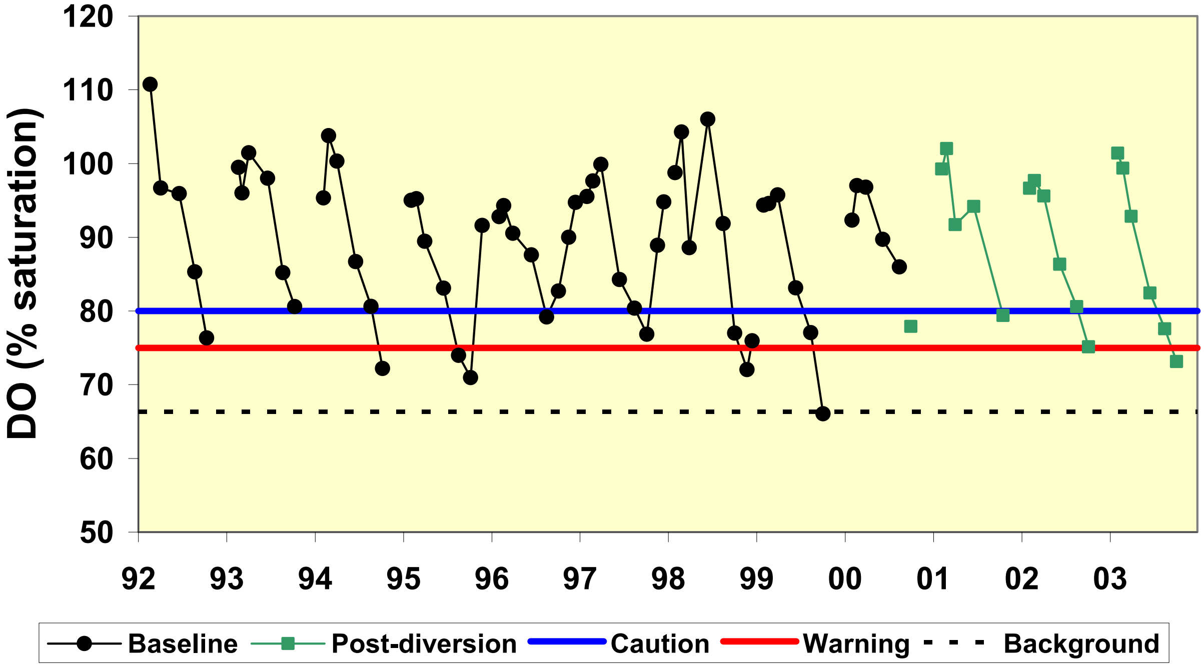


Figure 3-3. Survey mean bottom water dissolved oxygen (a) concentration and (b) percent saturation in Stellwagen Basin compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares. Data collected from stations F12, F17, F19, and F22.

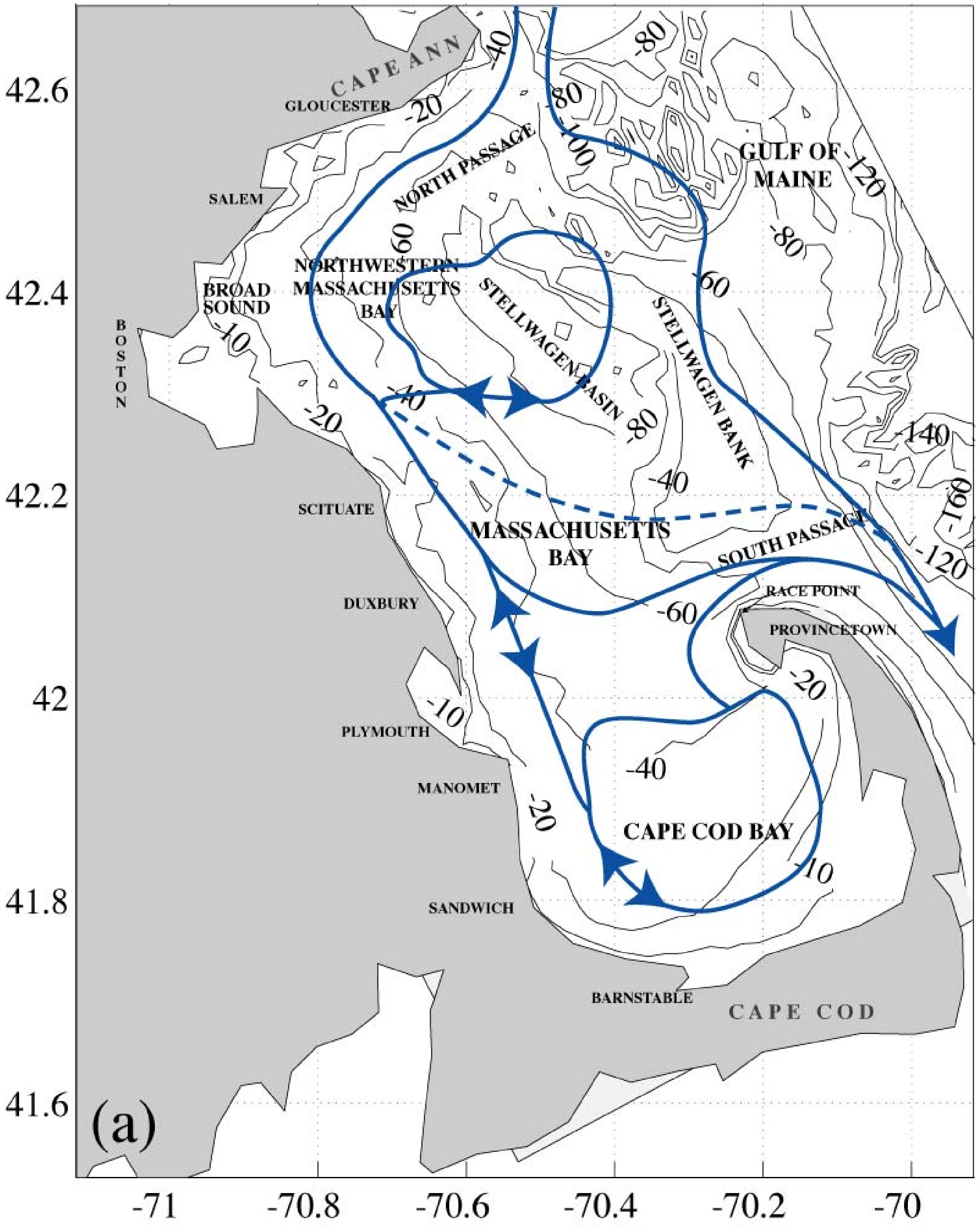


Figure 3-4. Summary of circulation within Massachusetts Bay (Lermusiaux 2001).

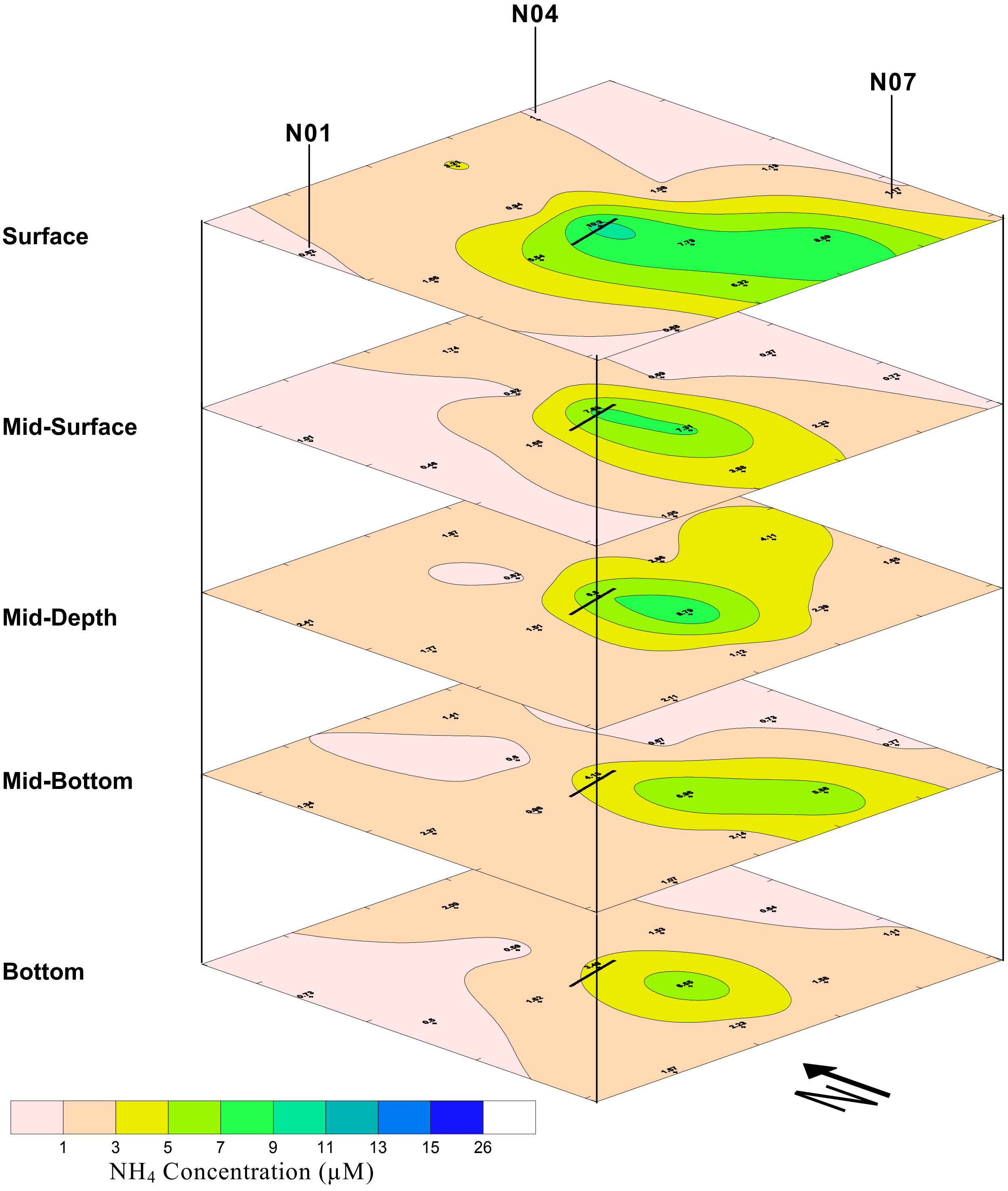


Figure 3-5. Ammonium concentrations at each of the five sampling depths for all nearfield stations during WF031 (early February).

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

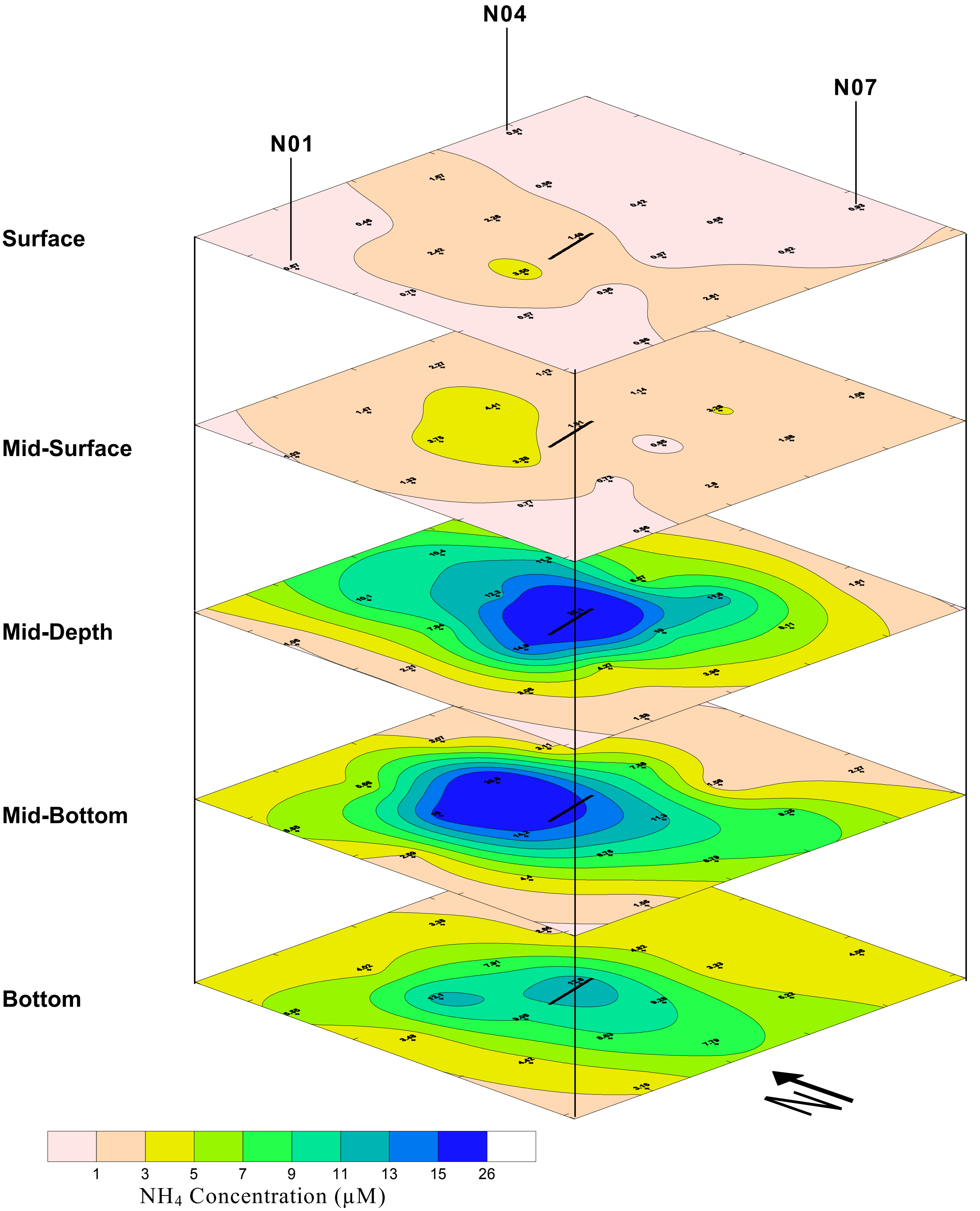
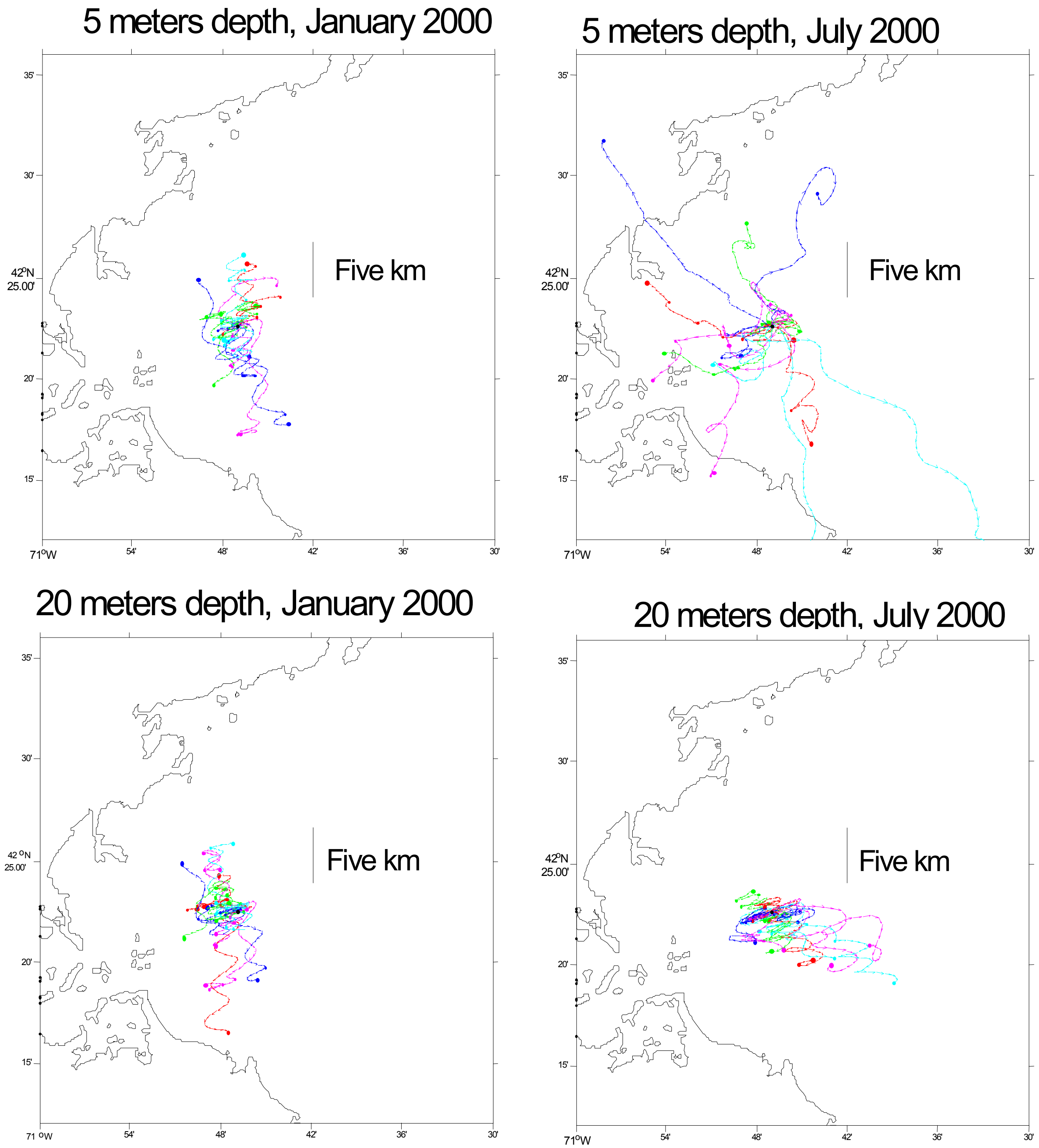


Figure 3-6. Ammonium concentrations at each of the five sampling depths for all nearfield stations during WN036 (mid May).

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


5 meters depth, January 2000

5 meters depth, July 2000

20 meters depth, January 2000

20 meters depth, July 2000

Figure 3-7. 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.

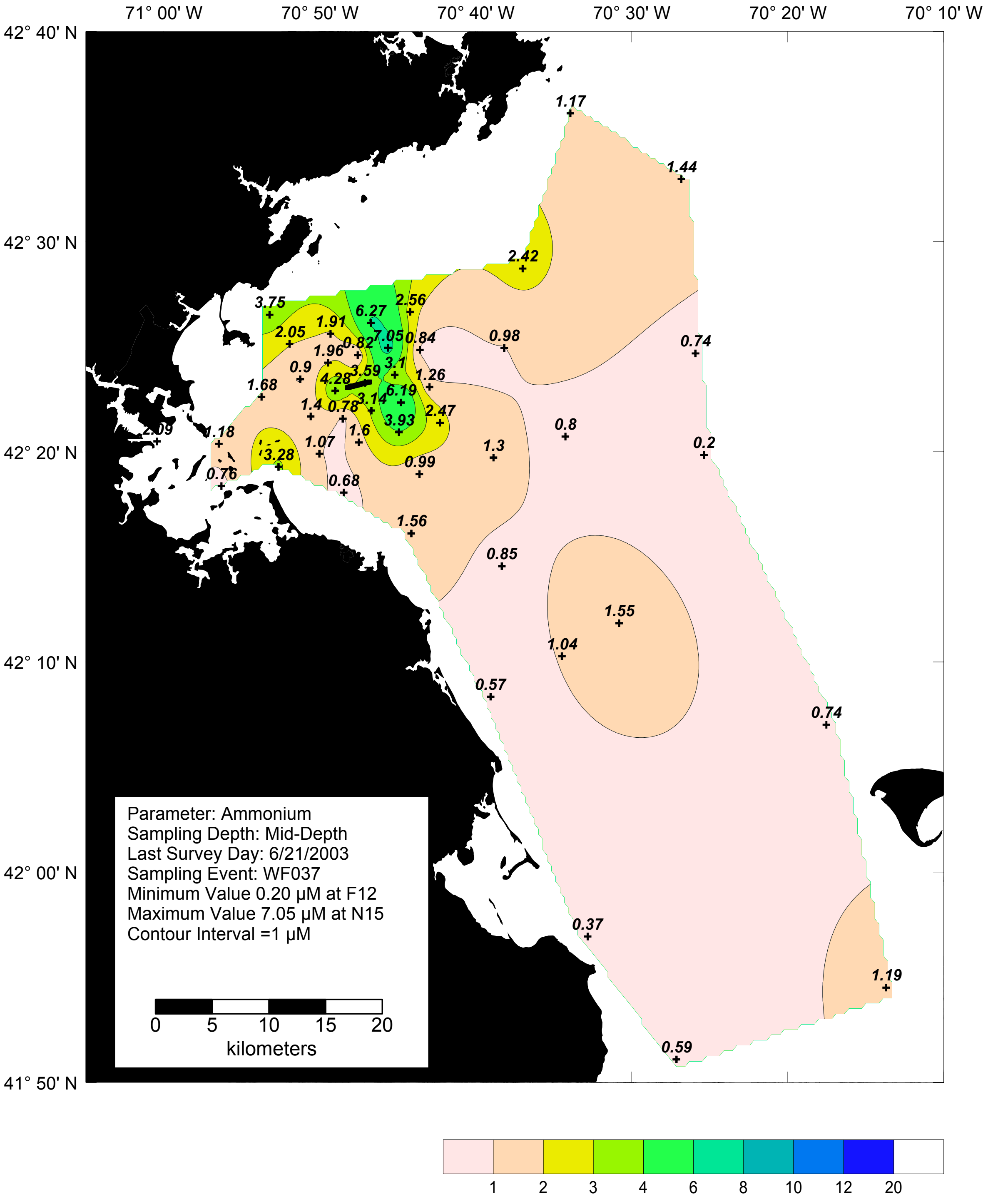
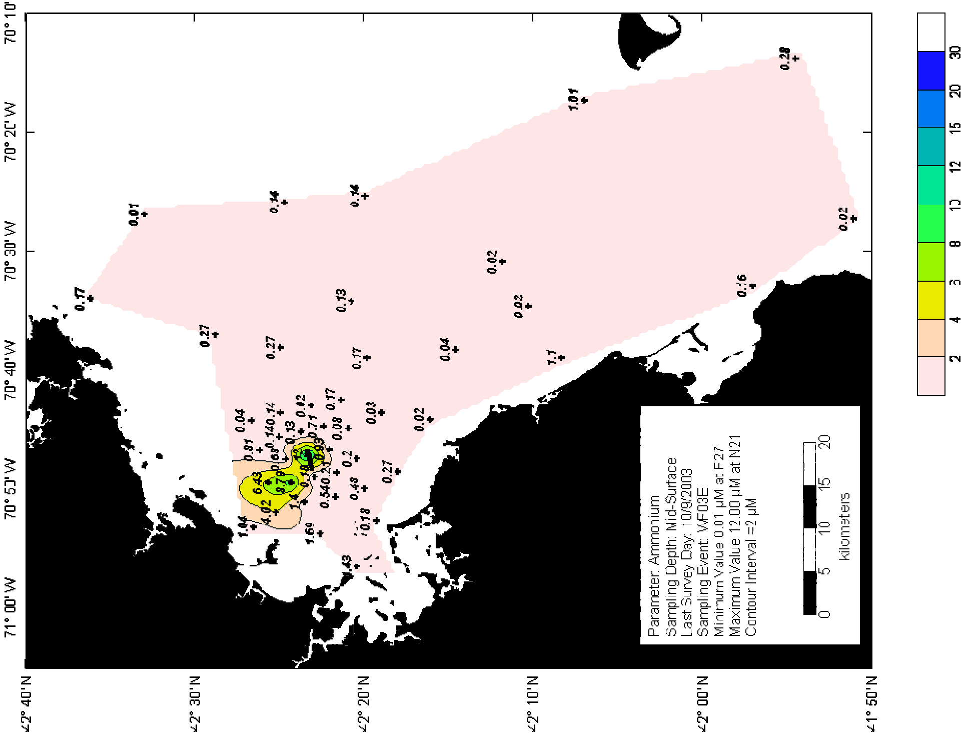


Figure 3-8. Mid-depth contour of NH_4 concentrations in June 2003.

(b) October 2003



(a) October 1999

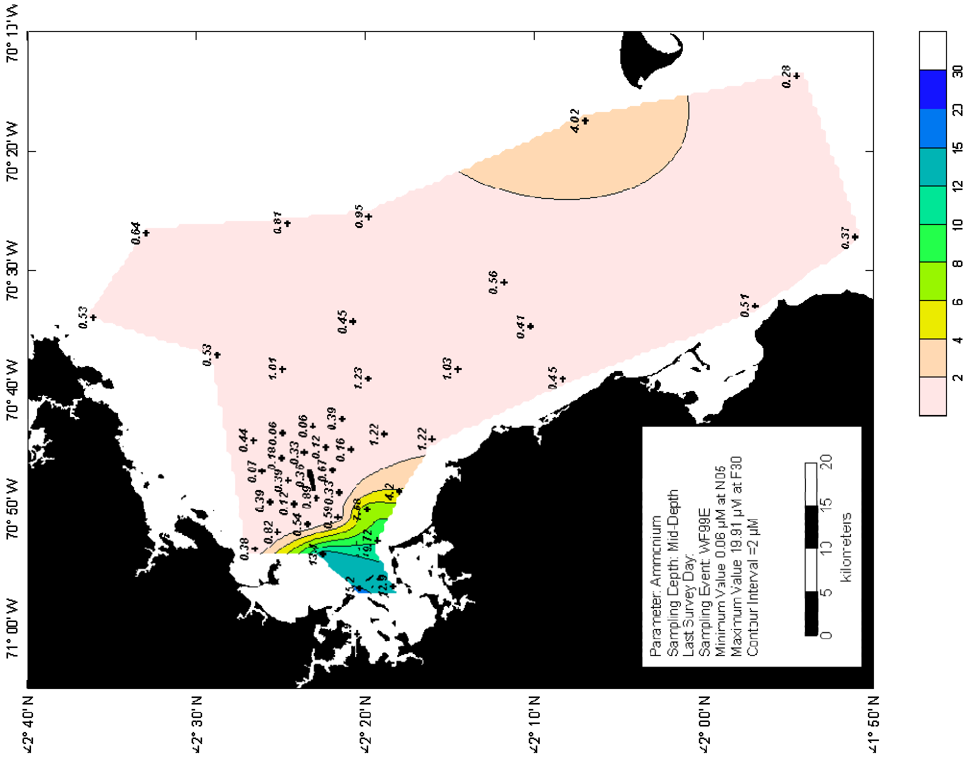
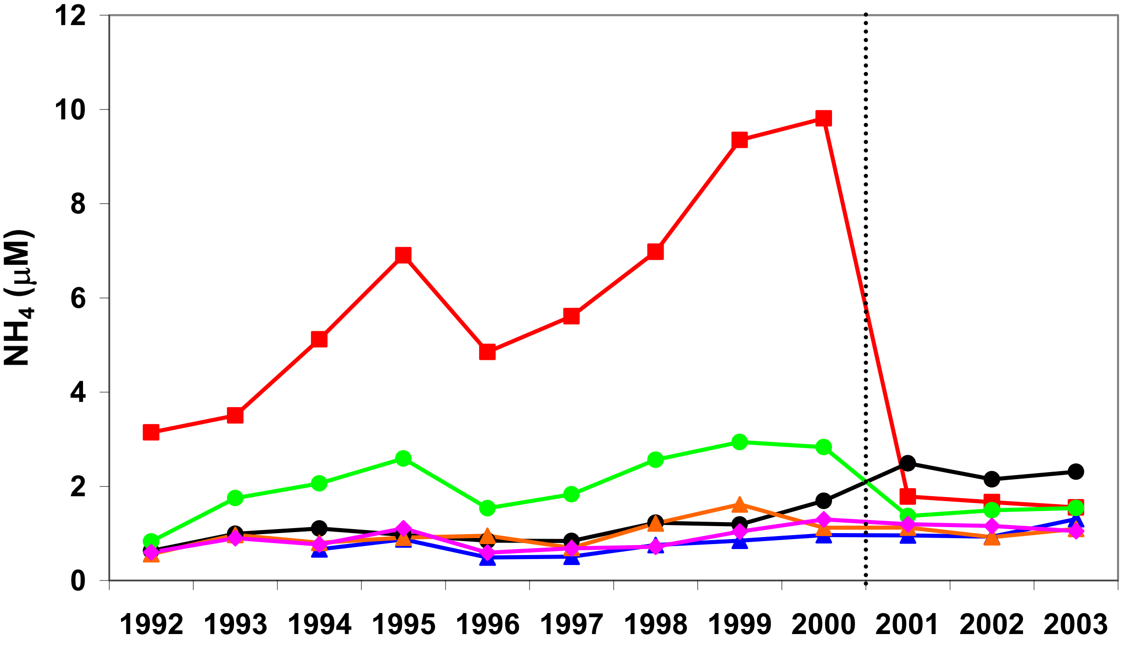


Figure 3-9. Mid-depth contour of NH_4 concentrations in (a) October 1999 and (b) October 2003.

(a) Ammonium



(b) Nitrate

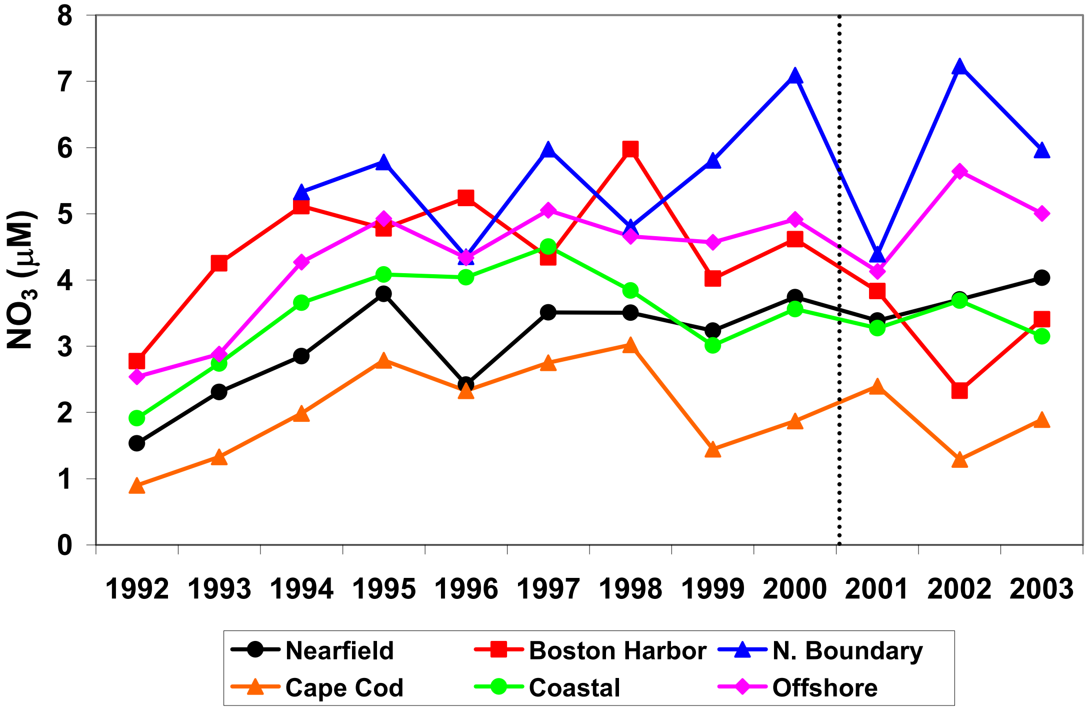


Figure 3-10. Annual mean (a) NH_4 and (b) NO_3 concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

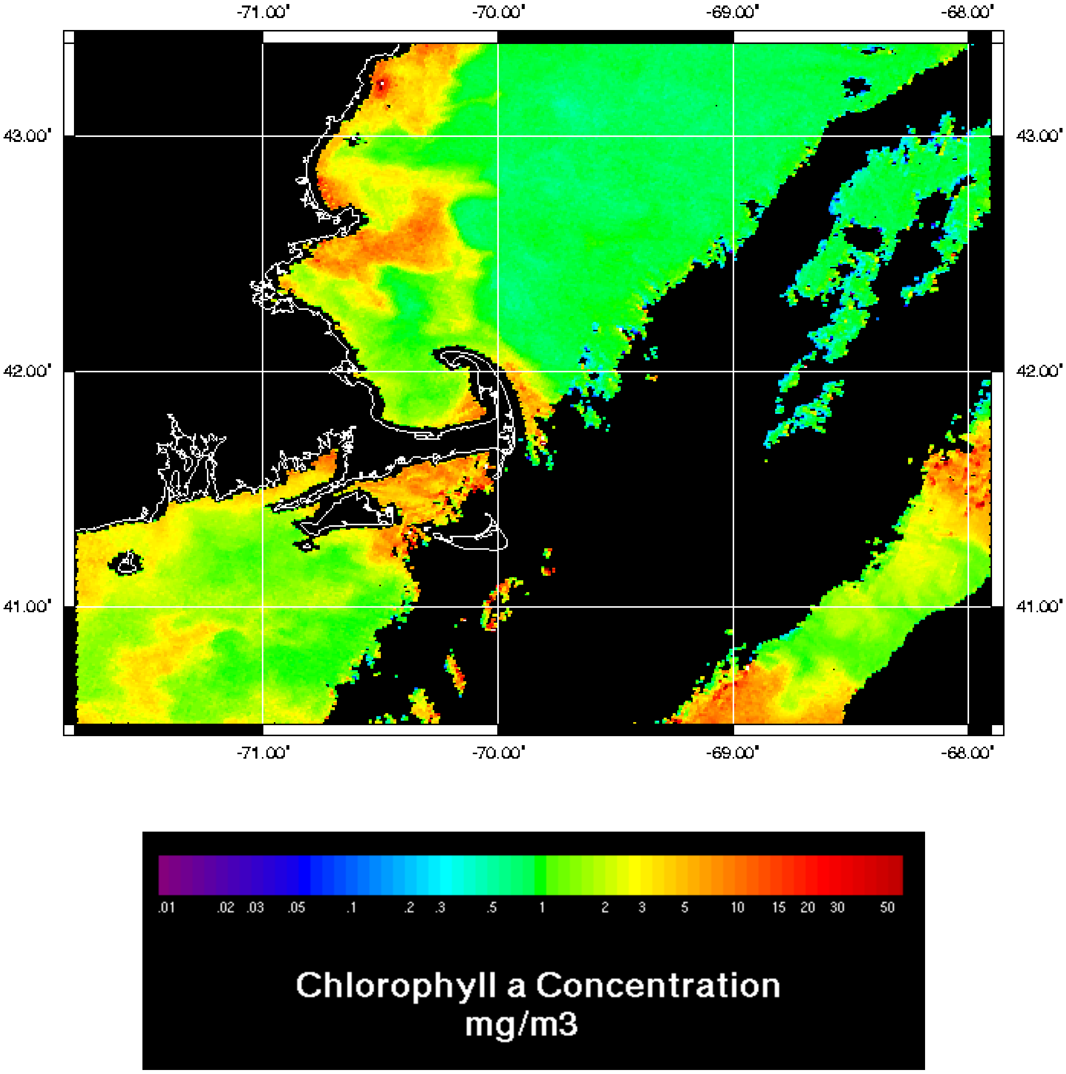
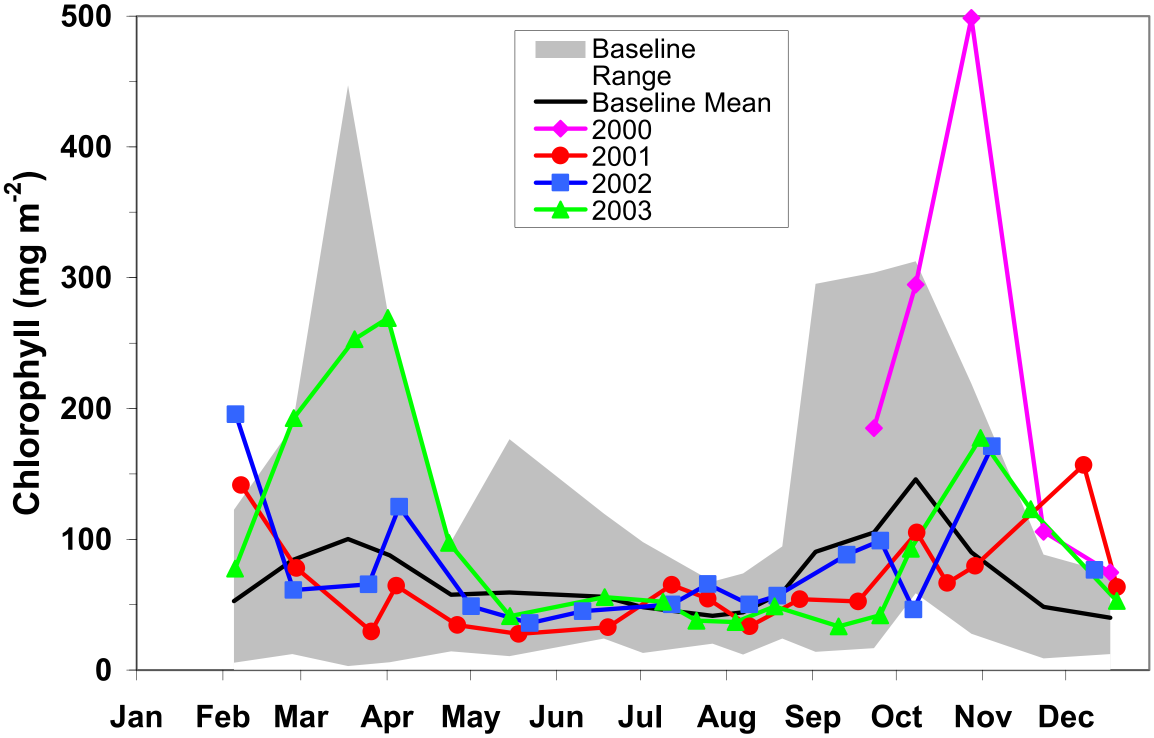


Figure 3-11. SeaWiFS chlorophyll *a* image for southwestern Gulf of Maine for March 27, 2003.

(a) Chlorophyll



(b) Particulate Organic Carbon

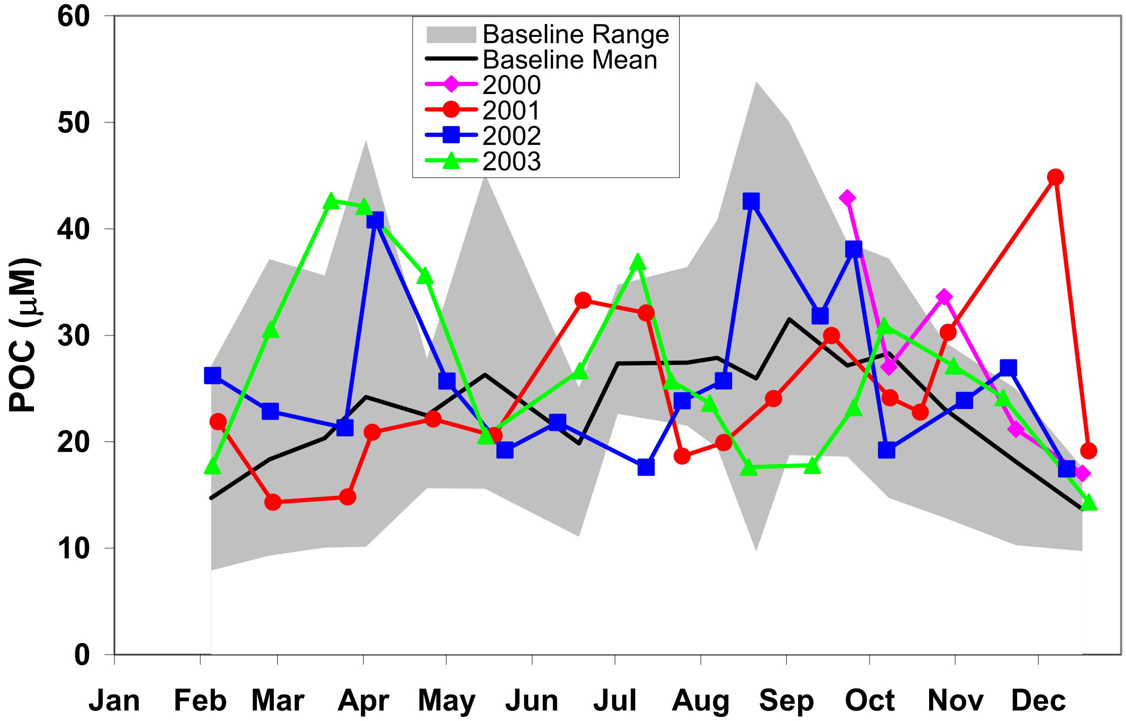


Figure 3-12. Time-series of survey mean (a) chlorophyll and (b) POC concentration in the nearfield post-diversion (fall 2000 to 2003) compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all nearfield stations.

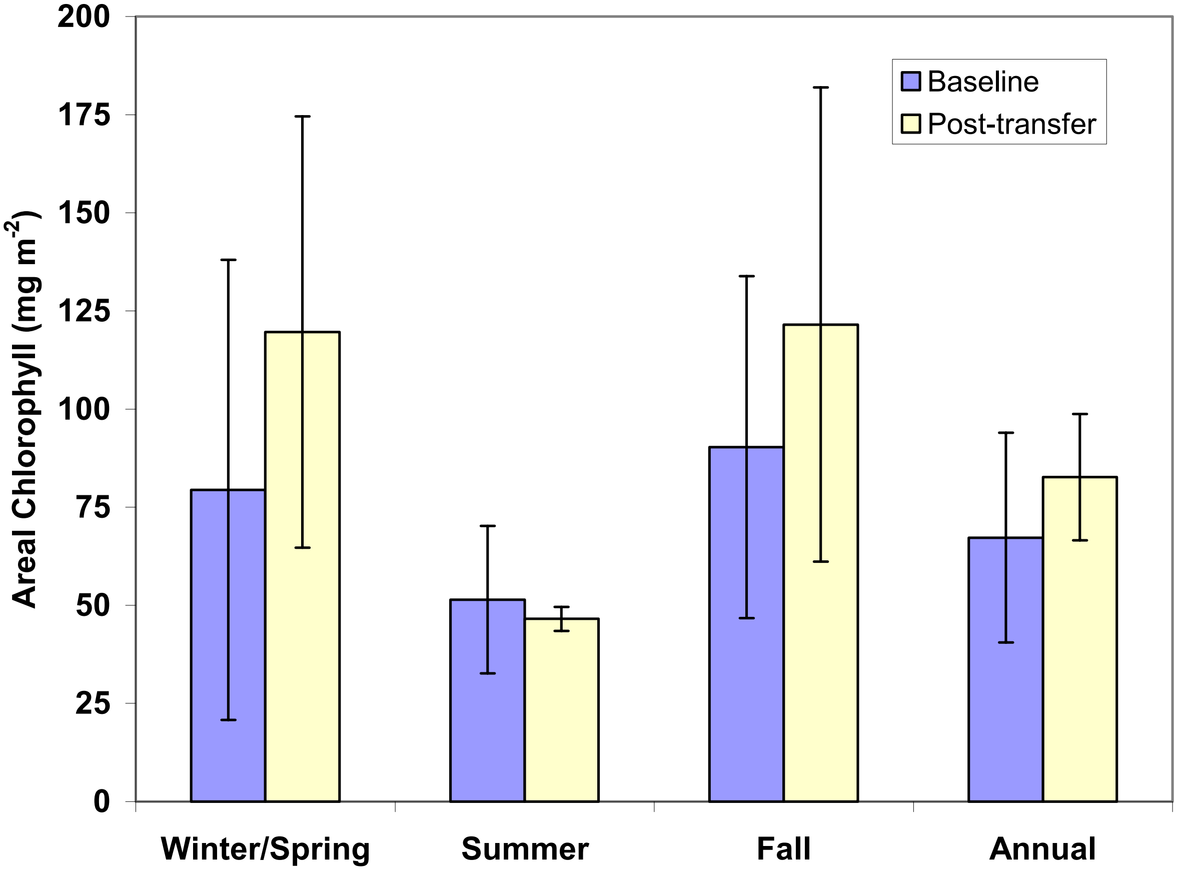
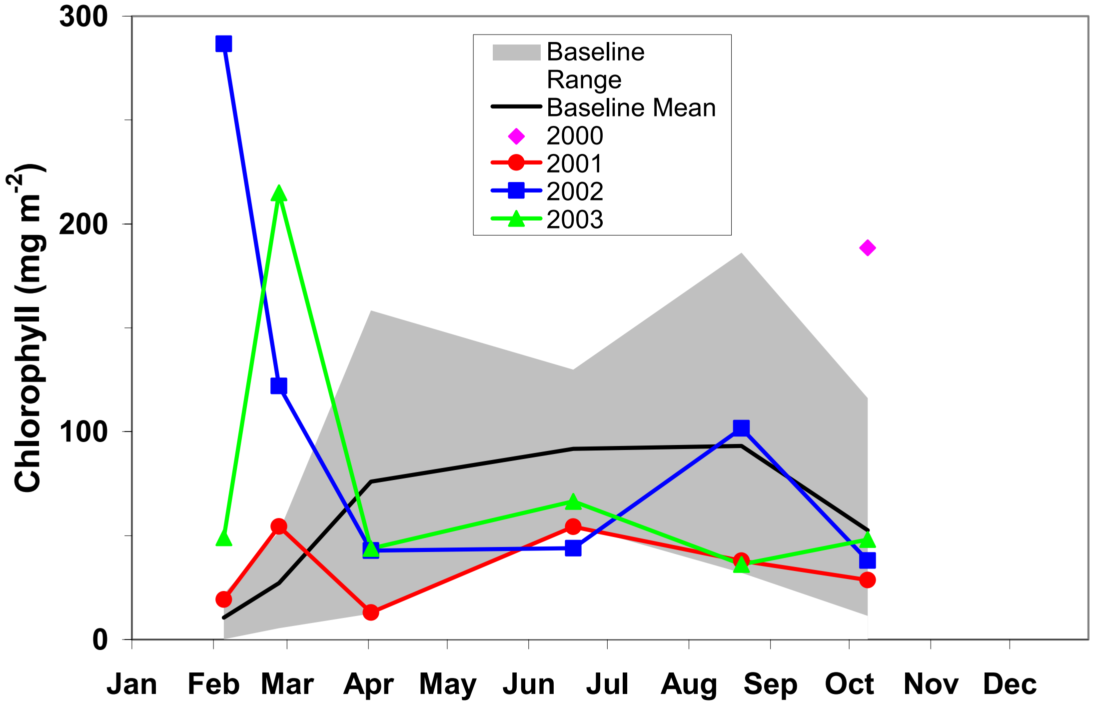


Figure 3-13. Comparison of baseline and post-transfer seasonal and annual mean areal chlorophyll in the nearfield. Error bars represent ±1 standard deviation. The effluent discharge was transferred to bay outfall in September 2000 – winter/spring and summer means for 2000 included in baseline, 2000 fall mean in post-transfer, and 2000 annual mean not used.

(a) Chlorophyll



(b) POC

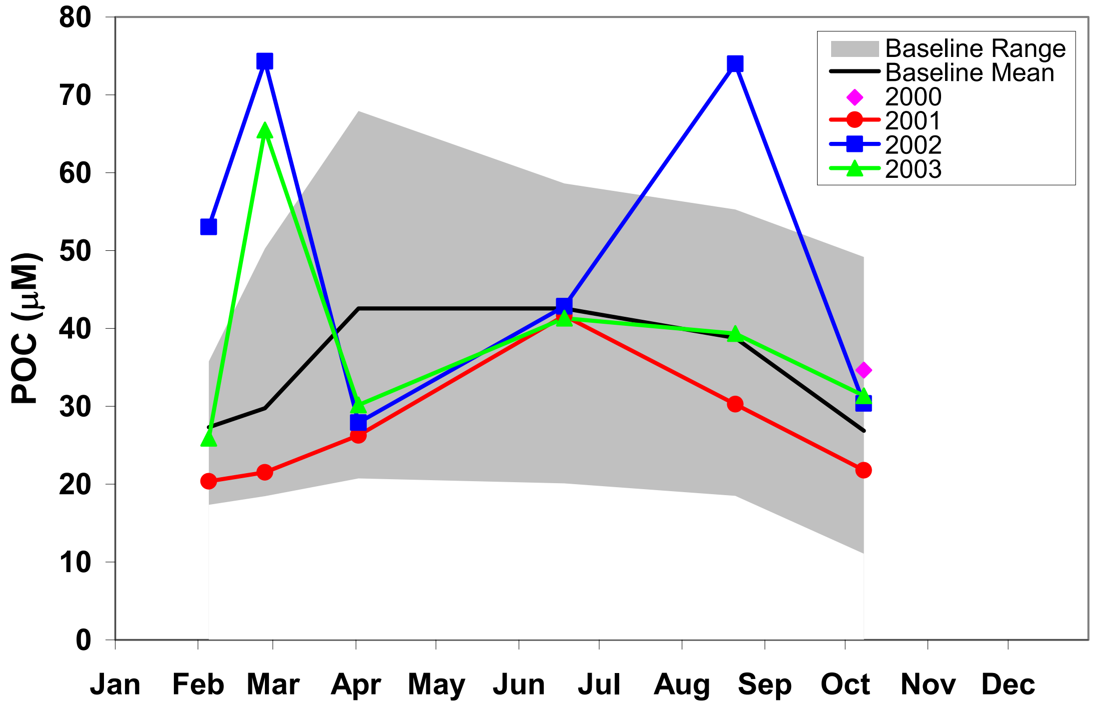


Figure 3-14. Time-series of survey mean (a) chlorophyll and (b) POC concentration in Boston Harbor post-diversion (fall 2000 to 2003) compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all harbor stations.

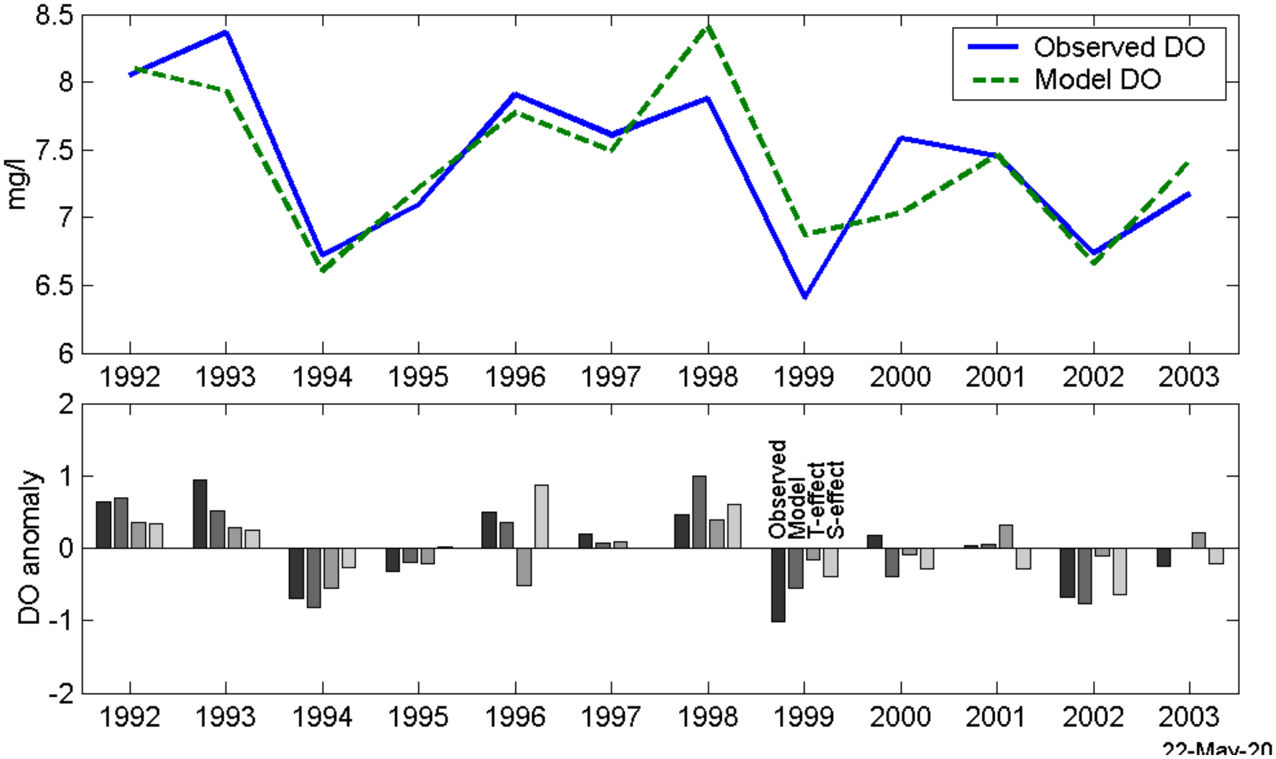
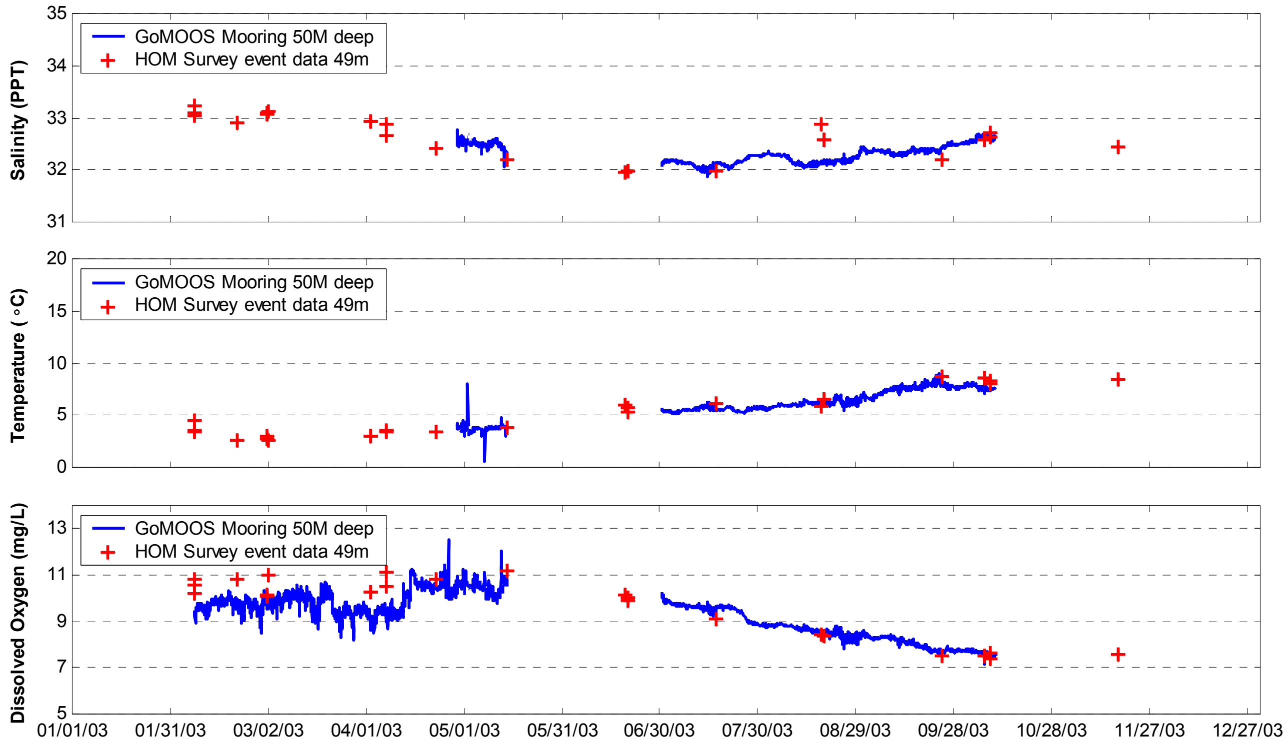


Figure 3-15. Upper panel: Average near-bottom dissolved oxygen during September-October surveys from nearfield stations N13, N14, N18, N19, N20, and N21, compared with linear regression model based on temperature and salinity variation. Lower panel: The bar plot shows the individual contributions due to temperature and salinity for each of the years.

(a) GoMOOS "A" Mooring - 50 m depth



(b) USGS Mooring - 32 m depth

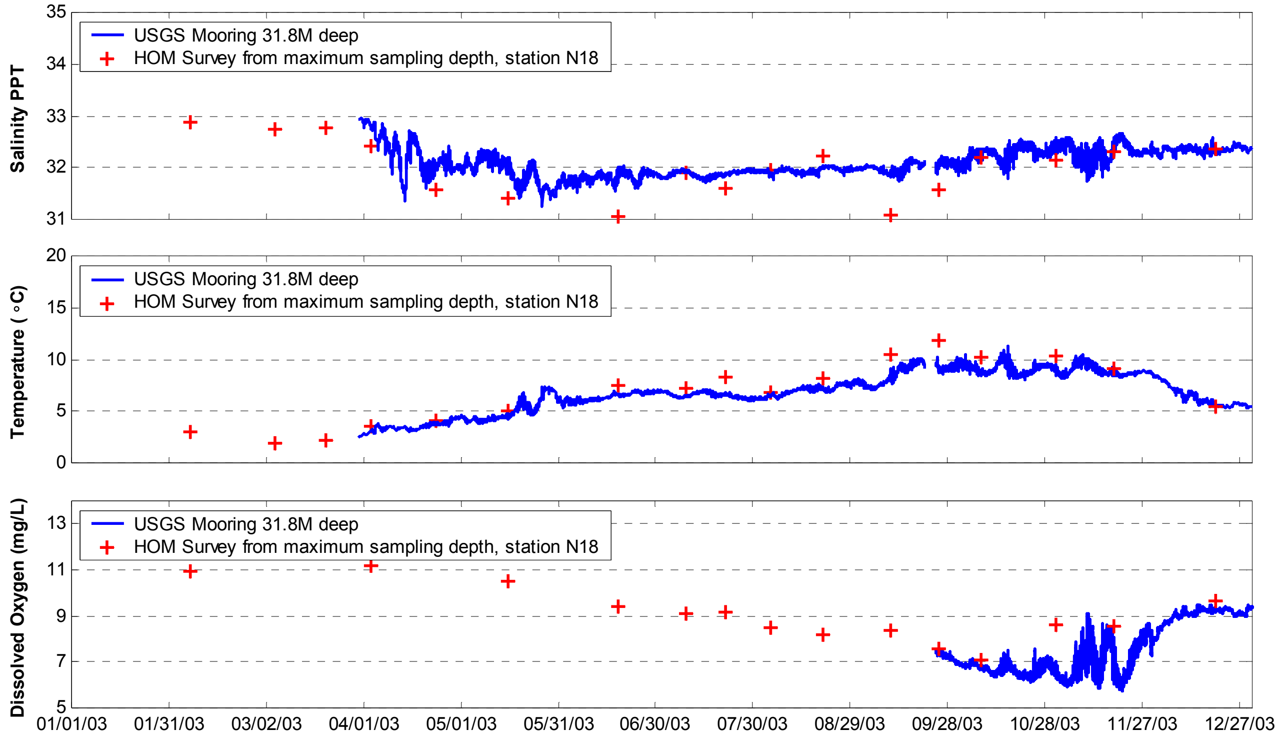
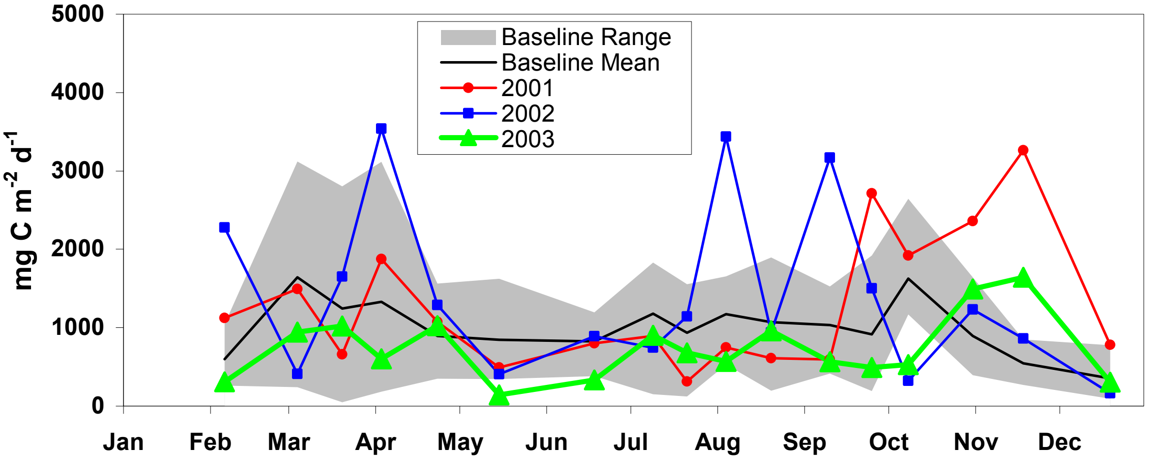
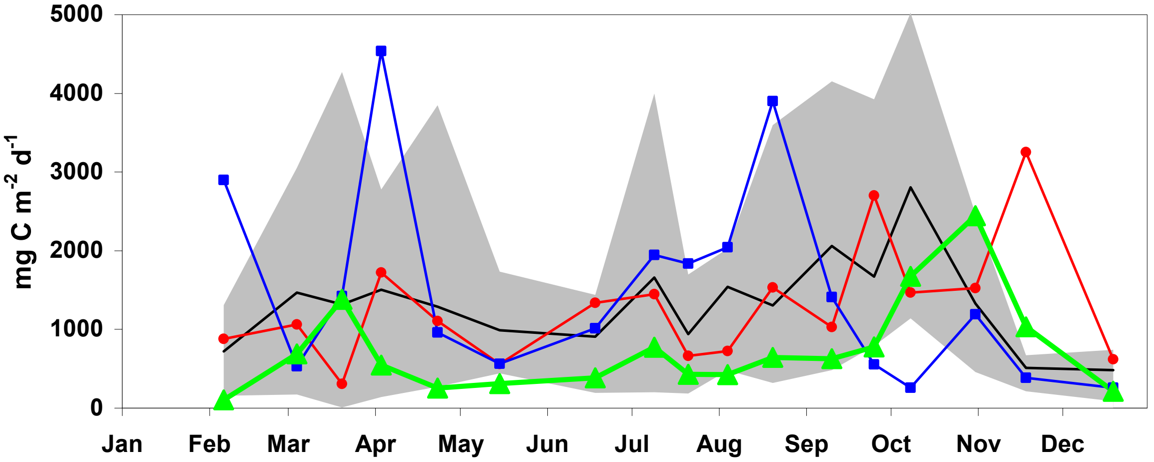


Figure 3-16. Comparison of near-bottom hourly data from (a) GoMOOS "A" and (b) USGS moorings to data from nearby MWRA monitoring stations (F22, F26, and F27; and N18, respectively).

(a) NO4



(b) N18



(c) F23

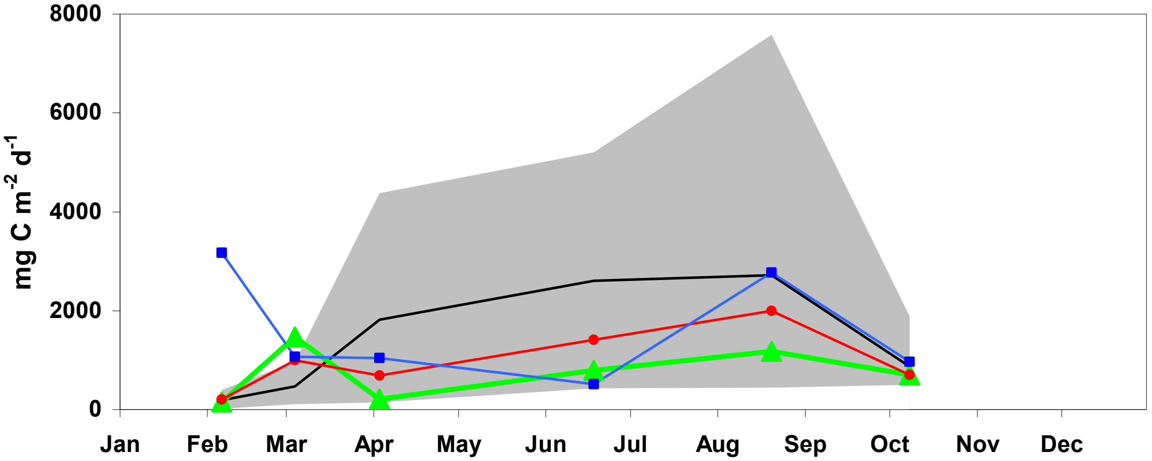


Figure 3-17. Time-series of areal production (mgCm^{-2}d^{-1}) at stations N04, N18 and F23 for 2001, 2002, and 2003 compared against baseline range and mean (1997 to September 2000).

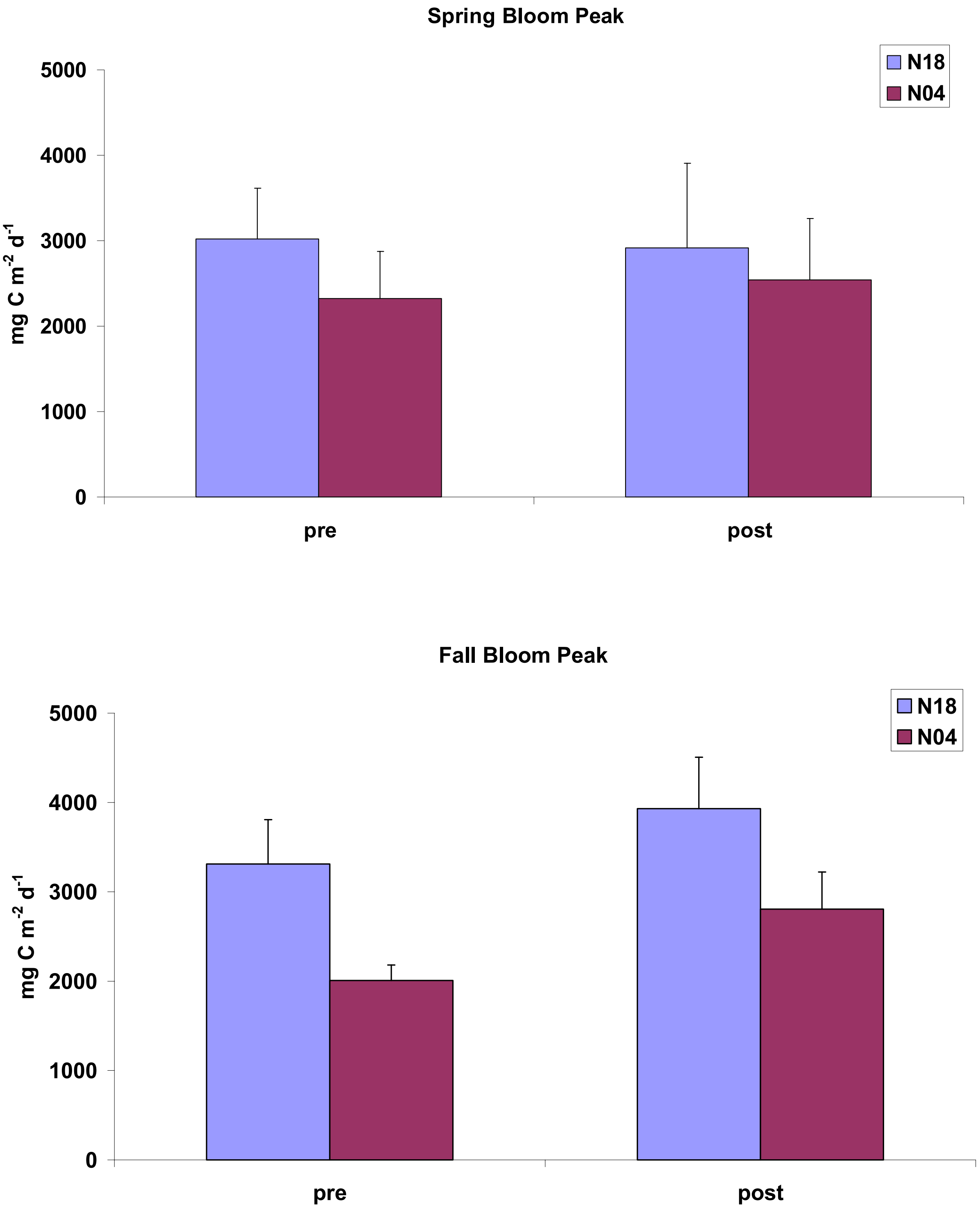


Figure 3-18. Spring and fall bloom peak production (mgCm^{-2}d^{-1}) at nearfield stations N04 and N16/N18. Pre vs. post outfall diversion - spring 97-00 vs. 01-03 and fall 97-99 vs. 00-03.

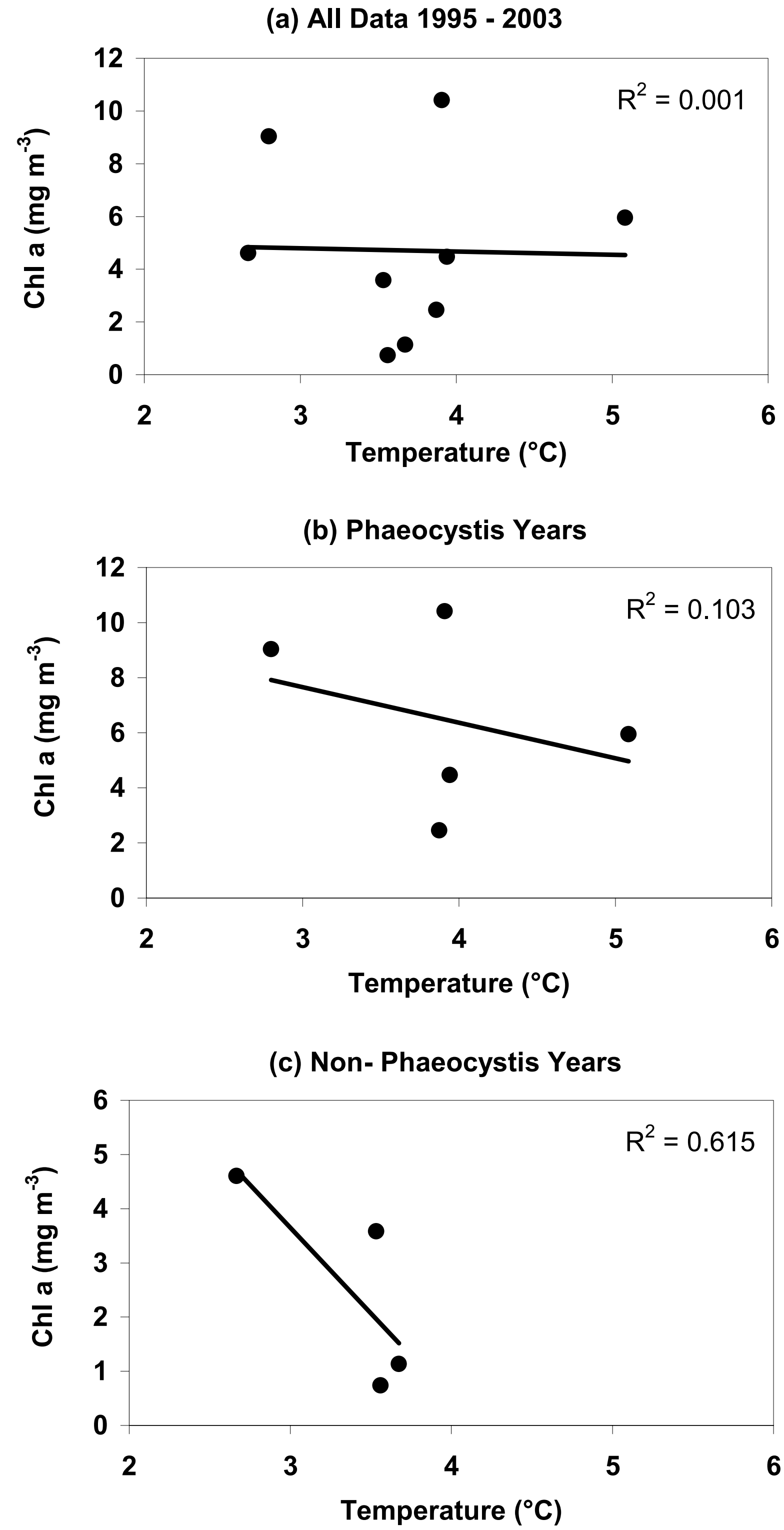
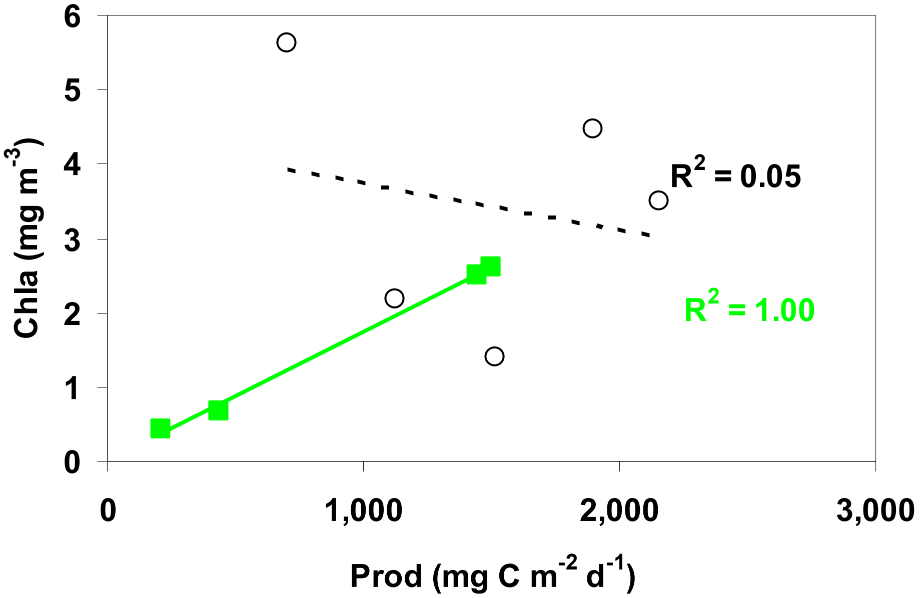


Figure 3-19. Nearfield peak chlorophyll vs. mean temperature during the February-April spring bloom surveys for 1995-2003.

(a) Bloom Chla vs Bloom Production



(b) Zooplankton Abundance vs Bloom Chla

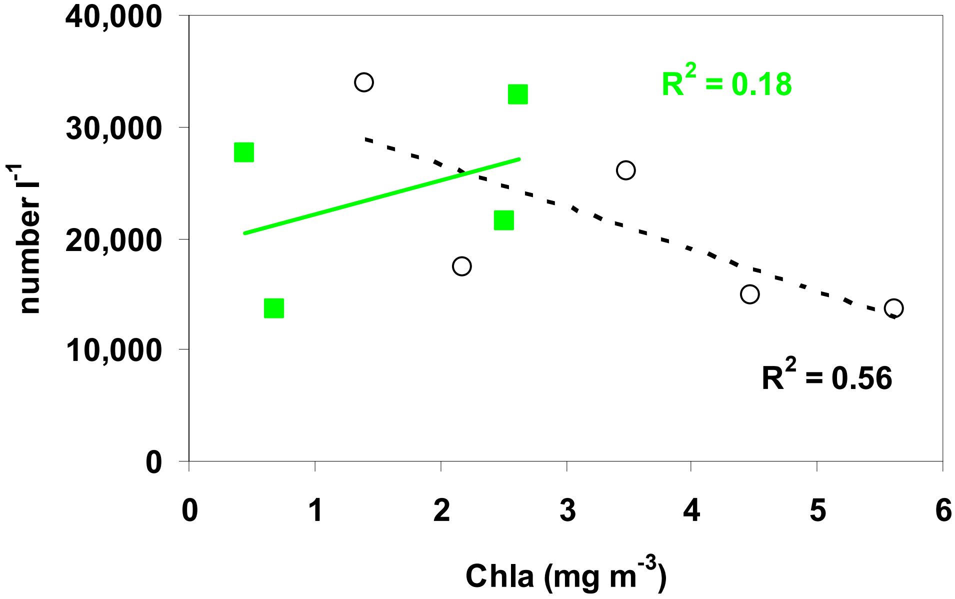


Figure 3-20. Spring bloom period (February to April) comparisons of nearfield average zooplankton, production and chlorophyll (stations N04 and N16/N18). Non-*Phaeocystis* year data (95, 96, 98 and 99) green squares and *Phaeocystis* year data (97, 00, 01, 02 and 03) open circles.

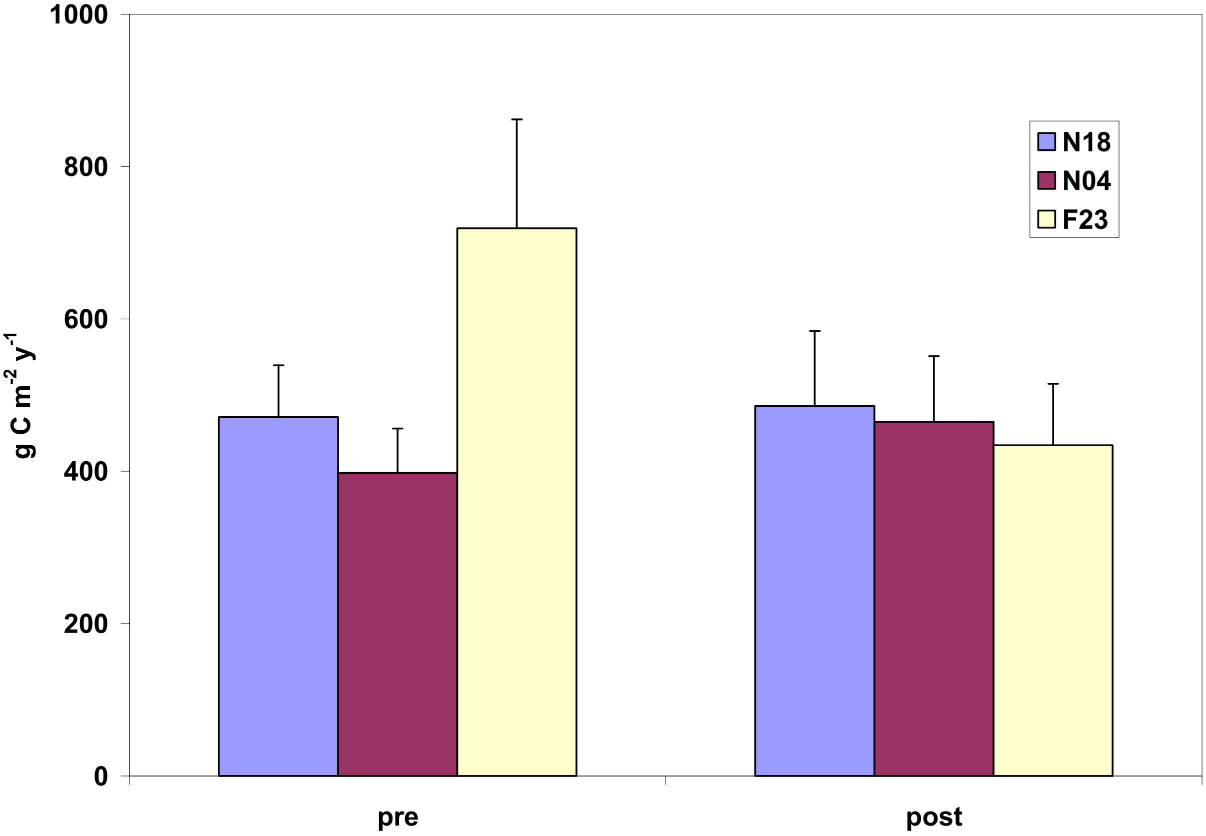


Figure 3-21. Annual potential production (gCm^{-2}yr^{-1}) for stations F23, N04 and N16/N18 pre (1997-1999) and post (2001-2003) outfall diversion.

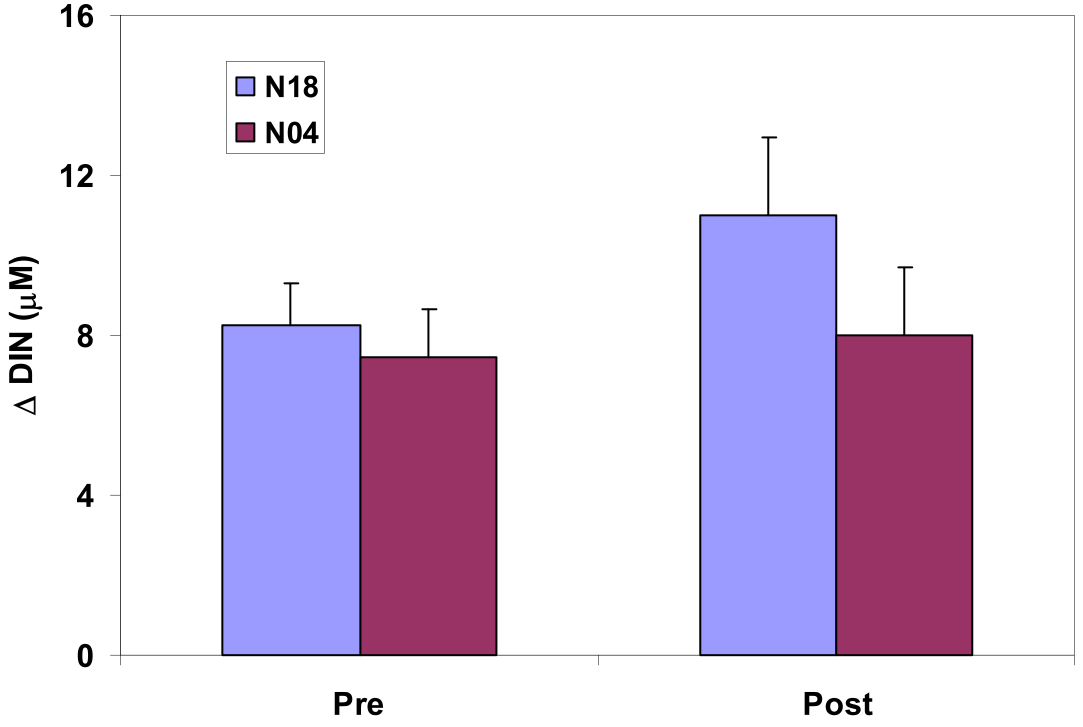


Figure 3-22. Change in mean water concentrations over spring bloom period of DIN for stations N04 and N16/N18 pre (1997-1999) and post (2001-2003) outfall diversion.

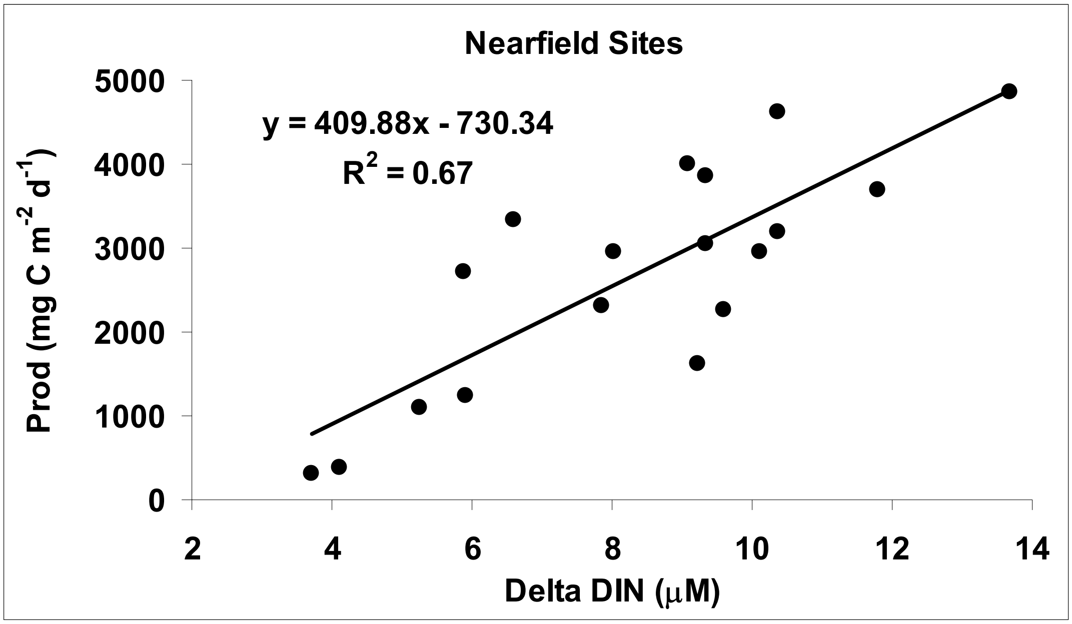


Figure 3-23. Delta DIN vs. peak production over the spring bloom period at stations N04 and N16/N18 from 1995-2003.

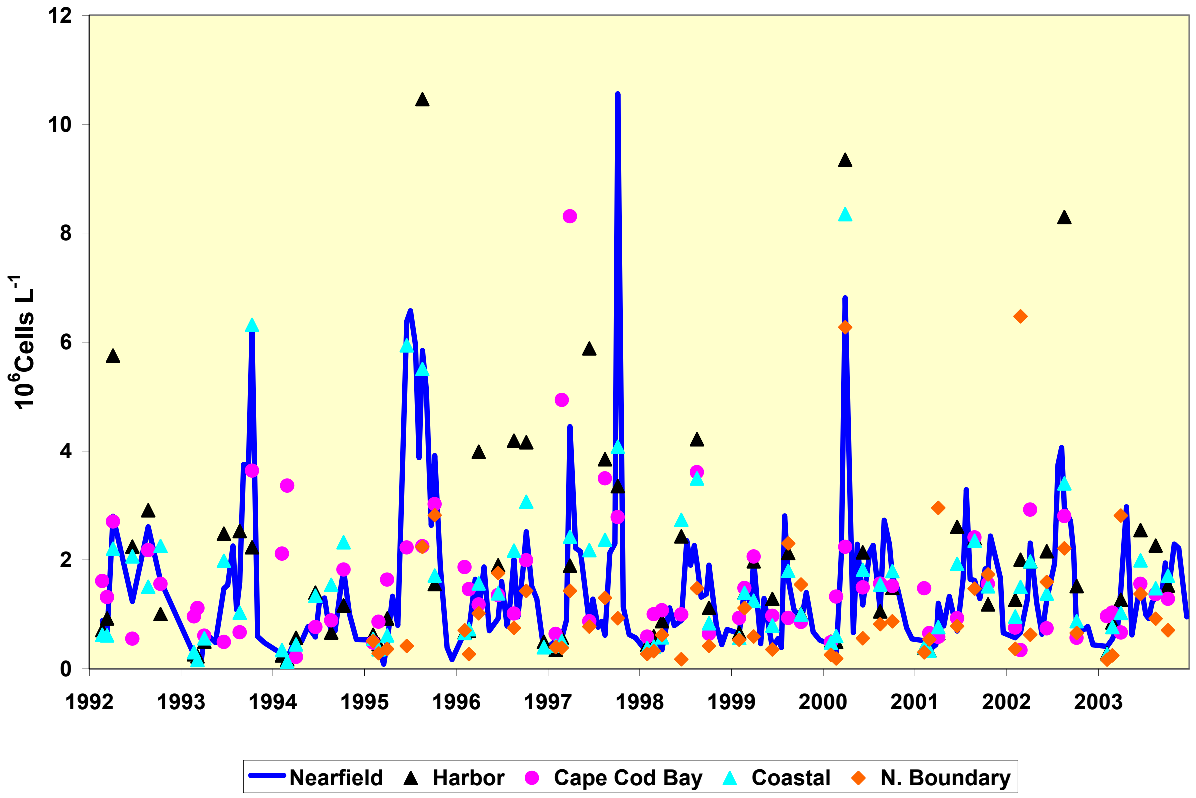


Figure 3-24. Total phytoplankton abundance by region, 1992-2003.

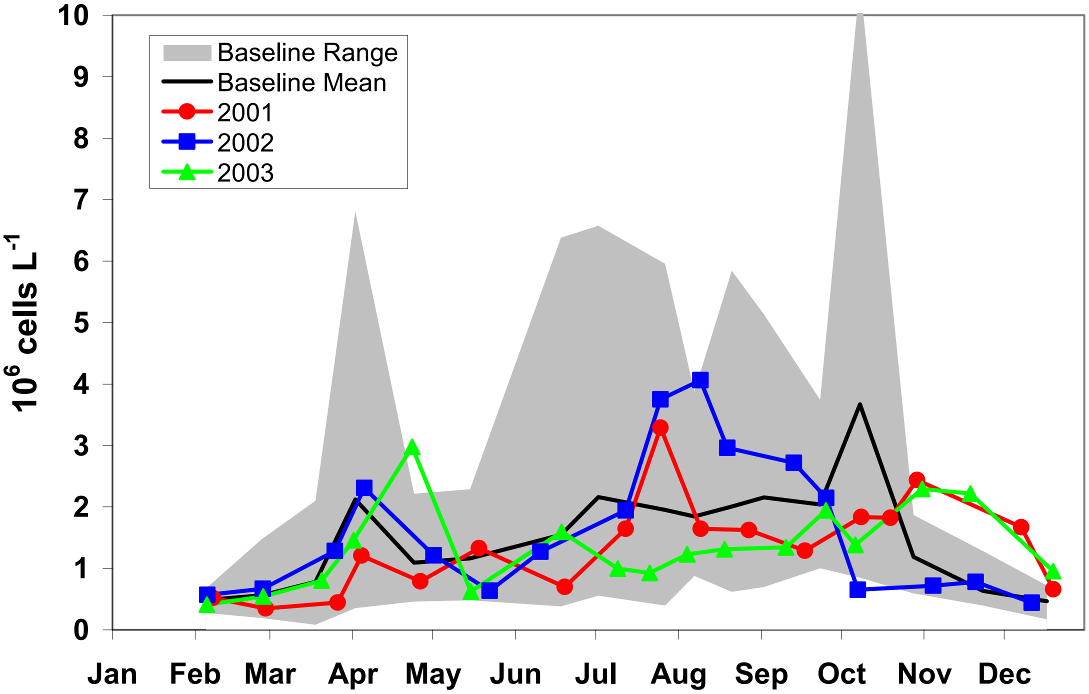


Figure 3-25. Time-series of survey mean total phytoplankton abundance in the nearfield in 2001-2003 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled (fall 2000 data not shown).

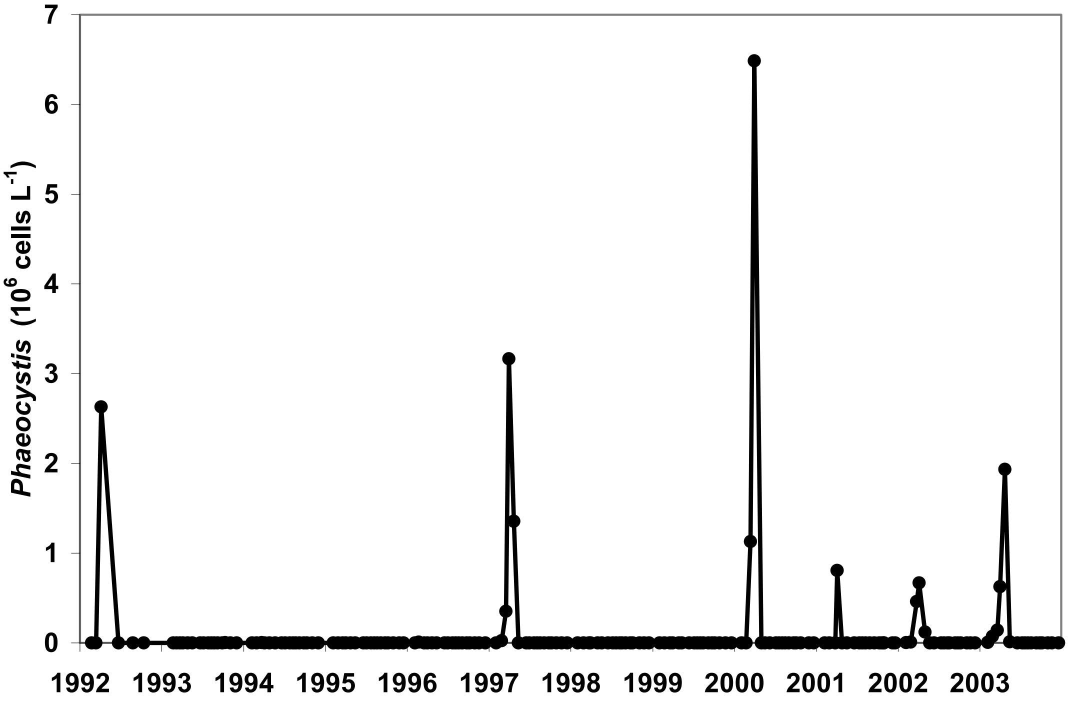


Figure 3-26. Time-series of average *Phaeocystis* abundance in the nearfield 1992-2003.

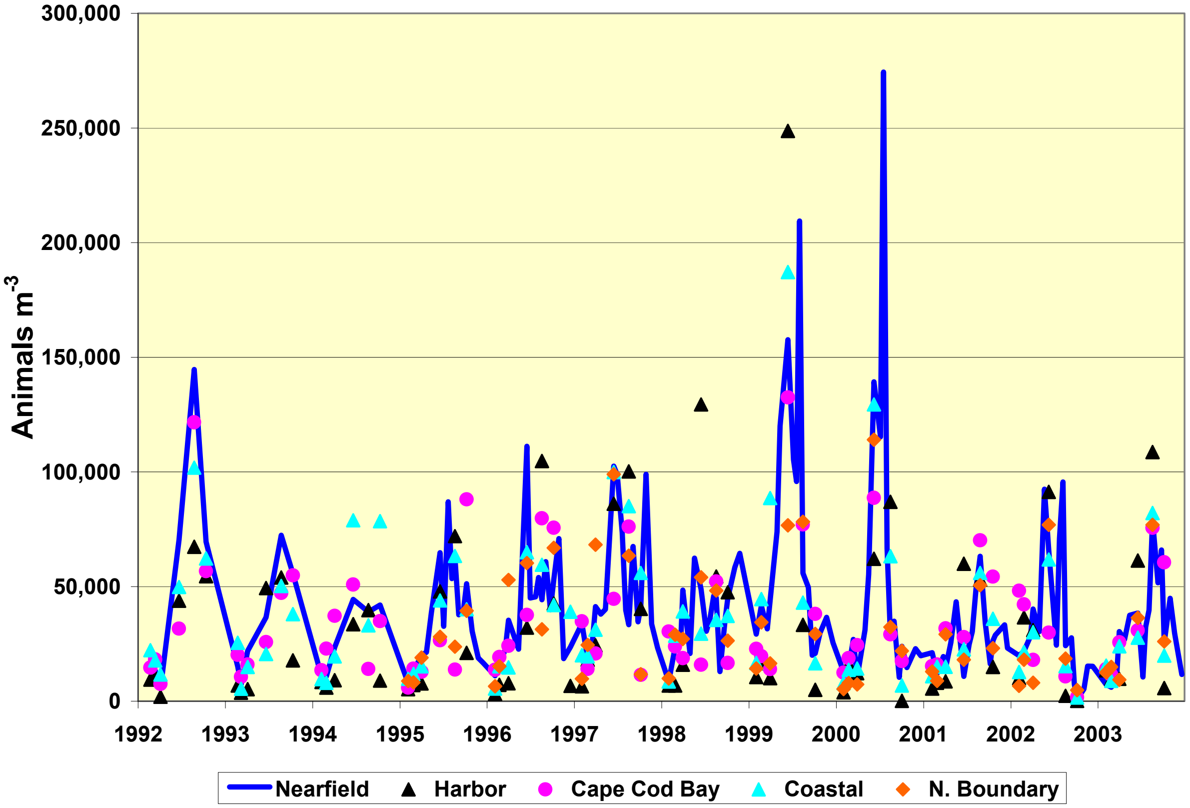


Figure 3-27. Total zooplankton abundance by region, 1992-2003.

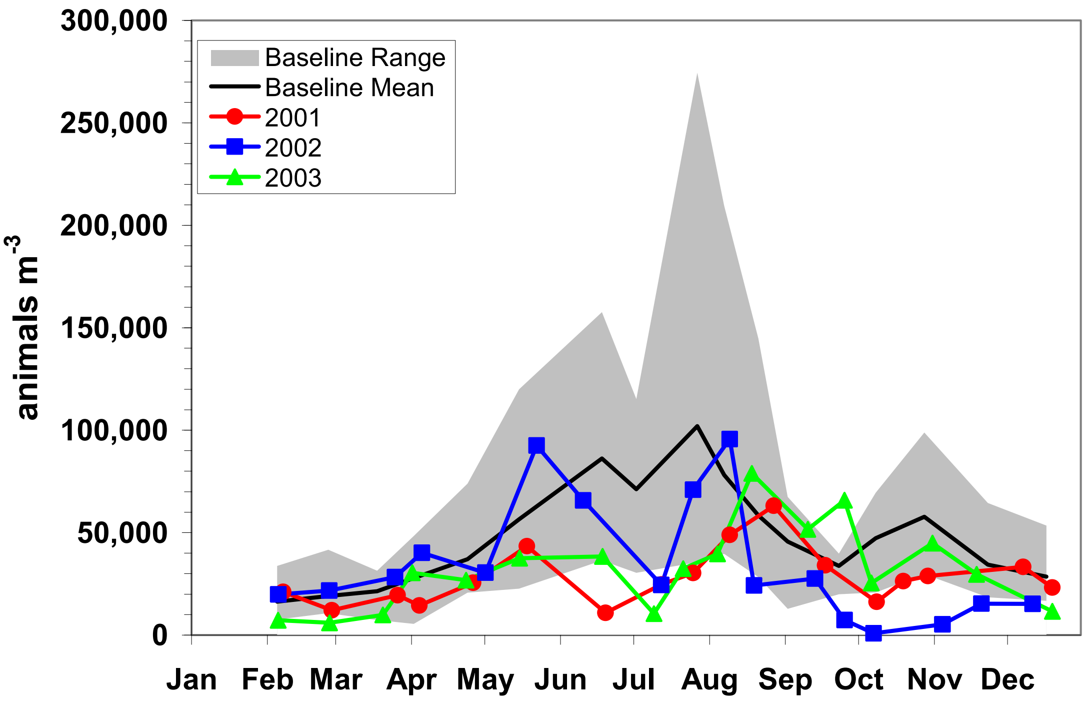


Figure 3-28. Time-series of survey mean total zooplankton abundance in the nearfield in 2001-2003 compared against the baseline range and mean. Data collected from all nearfield stations sampled (fall 2000 data not shown).

4.0 CONCLUSIONS

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, DO, 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.

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 DO 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 is more readily taken up by marine algae resulting in higher growth rates. 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. A summary of the current understanding (→) and some of the remaining issues to be resolved (➢) is included below.

Water Circulation

- What are the nearfield and farfield water circulation patterns?
  - → Circulation into and within Massachusetts and Cape Cod Bays is complex.
  - → The paradigm that circulation in the bays is counterclockwise was derived from the winter/spring circulation pattern, which is dominated by the freshet and meteorological conditions that entrain waters into the Massachusetts Bay from the western Maine coastal current. This leads to a predominantly counterclockwise current in the bays for this period, but not consistently over the year.
  - → Essentially no mean flow at the bay outfall location where bottom currents are ~6 cm s^{-1} and variable in direction.
  - → Long-term average, net velocity at the outfall location is small, but considerable random motion causes water parcels to be exchanged from the site to other parts of the bay.
  - → System is stratified from April to October.
  - → Effluent is rapidly diluted by oceanographic processes.
  - → Model and field results confirm that effluent plume generally confined to within 20 km of the bay outfall.

- ➢ Need to improve our understanding of the system with high resolution data sets such as those currently being collected at the GoMOOS and USGS moorings (e.g. exchange between Gulf of Maine and Massachusetts Bay, summer upwelling and mixing events, etc.)
- ➢ Importance of coupling high resolution physical oceanographic data with survey data and potentially moored instrument data measuring chemical and biological parameters.

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?

  - → There has been a significant decrease in NH_4 in Boston Harbor, small decrease in coastal waters and a substantial increase in the nearfield.
  - → Distribution (extent and direction) of the effluent plume in the nearfield is well characterized by NH_4 which is an excellent tracer albeit not a conservative one.
  - → Effluent plume, as measured during dye studies and characterized by NH_4 distribution during each survey, appears to be confined to within 20 km of the bay outfall.

  - ➢ Although clear changes have been observed, there is a need to continue to track the distribution of nutrients, but more importantly utilize new technologies to understand how the increase in nutrients might be impacting, or not, the biota in the nearfield and beyond – need for more highly resolved data both temporally and spatially (moored instruments, towed systems, etc.) to fully resolve the impact of NH_4 in particular on phytoplankton biomass.

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?

  - → Seasonal and annual mean chlorophyll levels have increased in the nearfield, but not significantly. The increase may have predated diversion to the bay outfall.
  - → Major winter/spring and fall blooms consistently appear to be regional phenomena.
  - → There has been a significant decrease in summer chlorophyll levels in Boston Harbor, but not on an annual basis due to the increased concentrations during the winter/spring bloom.
  - → A significant decrease in POC has been observed in Boston Harbor on a seasonal and annual basis.
  - → The harbor appears to be changing from a eutrophic to a more temperate coastal water pattern in phytoplankton biomass (dominated by winter/spring bloom rather than summer bloom as observed during the baseline period).

  - ➢ Given the high variability in phytoplankton biomass seasonally and interannually, additional monitoring will be required before the extent of the changes can be determined in the nearfield (significant increase vs. changes within the noise).
  - ➢ The current monitoring schema is designed to detect large changes in phytoplankton biomass due to the outfall, but more subtle changes that could explain the relative impact are missed – extension in the duration of blooms, localized increases in biomass (in summer, near the pycnocline), etc.

- 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?

  → Primary production rates have decreased (-40%) in Boston Harbor on an annual basis though they appear to have increased during the winter/spring bloom – neither of these changes is statistically significant.
  → Boston Harbor appears to be changing from a eutrophic system dominated by summer production to a more temperate coastal water system like the nearfield area that is dominated by winter/spring blooms.
  → Primary production in the nearfield has increased slightly for winter/spring and fall bloom peaks and on an annual basis. The changes have been much smaller than observed in the harbor and are not yet statistically significant.

  ➢ As is the case with the biomass data, the limited dataset precludes any final determination of impact or lack thereof – additional monitoring is needed and it may be fruitful to revisit the application of productivity models in order to leverage the large dataset available from other stations (light, biomass, etc. measured at many more than the 3 productivity stations).

- Has 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?
- Has 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?

  → Species composition of the plankton communities has remained relatively consistent in the taxa present and the variability in the abundance of these taxa from year to year. No dramatic changes have been evident and all changes are well within the envelope-of-variability established during baseline.
  → Unlike the increases that have been observed in seasonal and annual biomass and production in the nearfield, no such increases have been seen in phytoplankton abundance.
  → There has been an increase in the occurrence of *Phaeocystis* blooms from a 2-3 yr cycle during the baseline to annually since 2000 – the reasons for this change and the extended duration of the blooms in 2002 and 2003 are unknown, but it appears to be part of a regional trend possibly related to variability in water temperature and unrelated to the outfall.
  → Ecological dynamics appear to change relative to the occurrence of a spring *Phaeocystis* bloom such as a disconnect between bloom production rates and phytoplankton biomass and a decrease in zooplankton abundance as phytoplankton biomass increases.
  → There have been no substantial blooms of other nuisance species (*Alexandrium*, *Pseudo-nitzschia*, etc.) since the outfall went online.
  → The timing of the fall blooms in 2001 and 2003 suggests that these blooms are occurring later and are perhaps longer in duration. We speculate that the additional source of nutrients from the bay outfall may be contributing to this, though it appears that the main cause for these trends is a delay in the breakdown in stratification.
  → Changes in the zooplankton community have not been seen, nor, upon further examination of the presumptions on which the monitoring questions were based, are dramatic changes expected (subtle changes may occur, but will be much more difficult to both detect or attribute).

- ➢ The occurrence and duration of the *Phaeocystis* blooms will continue to be the focus of study as the changes that have occurred are coincident with the transfer to the bay outfall and will continue to have the potential to be associated with the outfall until a clearer explanation can be given.
- ➢ Evaluate data in light of long-term temperature data for the region and undertake comparative studies using data from other waterbodies in the greater Gulf of Maine system.
- ➢ Need for continued information of plankton community structure to assess subtle changes in the system – long-term impact?

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?
  - → No change in the relative level of DO minima in the nearfield or farfield or in the seasonal rate of decline from April-June to October when annual minima are typically measured.
  - → DO minima (concentration and percent saturation) in the nearfield and Stellwagen Basin are often below established numeric thresholds and standards, but this has consistently been the case since 1992.
  - → Modeling and statistical analyses indicate that there is a strong correlation between nearfield and farfield (boundary) bottom water DO, which suggests DO levels are controlled by large scale regional processes.
  - → Advection has been shown to be one of the primary factors governing bottom water DO concentrations (likely due to residence time rather than movement of higher or lower DO waters).
  - ➢ Data resolution on the scale of weeks or months is not conducive to understanding the shorter term variability – the availability of *in situ* DO sensors on the GoMOOS and USGS moorings should provide additional insight on short term changes and could serve as the basis for in-depth analysis of the mechanisms influencing the variability of DO (horizontal advection, vertical exchange or local biological processes).

In summary, the 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 significant changes in biomass, whether measured as chlorophyll, POC, or phytoplankton abundance. There appears to have been an increase in winter/spring and fall bloom production and biomass in the nearfield. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with significant decreases in chlorophyll and POC, lower production, and a change in the seasonal productivity from a eutrophic to more normal temperate coastal pattern. Continued monitoring is necessary before statistically significant change can be documented in the bays 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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APPENDIX A

Physical Characterization

A. PHYSICAL CHARACTERIZATION

A.1 Circulation and General Physical Properties

A.1.a 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** A-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.

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 1991). A stormy early autumn can also lead to early fall turnover.

A.1.b 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** A-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 waters of Massachusetts Bay are 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** A-2, 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 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** A-2 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).

A.2 Forcing conditions

A.2.a Freshwater run-off

The river discharge for the Merrimack and Charles Rivers since 1990 is tabulated in **Table** A-1 and is shown graphically in **Figure** A-3. The beginning of 2003 was slightly drier than average, representing the end of a drought that started in the fall of 2001. From April on, the flow conditions had returned to normal. The low flow of the Merrimack in the first part of the year produced slightly higher near-bottom salinities in the late summer than average, as will be noted below. The individual run-off events are evident in the annual timeseries plot, shown in **Figure** A-4. This timeseries is notable in the number of significant discharge events which occurred in November and December.

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[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.

Table A-1. Seasonal river discharge (m^3s^{-1}) summary for Charles and Merrimack Rivers (1990-2003).

Year	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Charles River Discharge				
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
2003	**13**	**17**	**5**	**10**
mean	14	12	3	8
Merrimack River Discharge				
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
2003	**235**	**384**	**82**	**366**
mean	278	343	90	214

A.2.b Wind Forcing

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. The upwelling index is shown in **Table** A-2 and **Figure** A-5. The year followed the typical pattern of variation, starting with downwelling favorable conditions, switching to upwelling during the summer, and going back to downwelling in the late fall. The upwelling conditions in July and August were stronger than average, comparable to the strong upwelling years of 1991-1993. This strong upwelling condition produced colder than average bottom water temperatures (see **Figure** A-7). Wind speeds were close to the mean for each of the seasons in 2003 (**Table** A-3).

Table A-2. Southerly (upwelling) wind stress estimated seasonally averaged stress in Pa*10^3 at the Boston Buoy.

Year	Jan.-Mar.	Apr.-Jun.	Jul.-Sep.	Oct.-Dec.
1990	-0.0	1.4	0.8	0.1
1991	-1.6	-0.2	1.0	-4.2
1992	-3.8	-0.4	1.0	-3.4
1993	-4.5	-0.0	1.3	-1.3
1994	-3.5	1.0	0.4	-1.7
1995	-0.1	0.0	-0.0	-0.9
1996	-2.8	0.5	-0.2	-1.3
1997	-0.1	-0.8	0.5	-2.2
1998	-4.3	-0.8	0.9	-0.5
1999	-2.1	-0.2	0.7	-0.9
2000	-3.3	0.0	-0.1	-2.6
2001	-4.6	-0.3	0.6	-0.1
2002	0.5	0.2	-0.3	-2.7
2003	**-2.2**	**-1.7**	**1.2**	**-1.4**
mean	-2.3	0.0	0.5	-1.7

Table A-3. Wind speed seasonally averaged speed in m s^{-1} at the Boston Buoy.

	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
2003	**7.5**	**4.8**	**4.0**	**7.1**
mean	7.3	5.3	4.7	7.0

A.2.c Air Temperature

Air temperature is only of significance to the water properties during the winter, when it sets the minimum water temperature. **Table** A-4 shows the wintertime air temperature for the period of the monitoring program. The winter of 2002-2003 was the second coldest of the period, only exceeded by 1993-1994. The timeseries of the air temperature at the outfall site is shown in **Figure** A-6. The cold wintertime temperatures are shown to be made up of a sequence of very cold air outbreaks in January and February. The temperatures remained cold for most of the spring, and they were normal for the rest of the year.

Table A-4. Winter air temperature, 1992-2003. 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
2002-2003	**-0.9**
mean	1.0

A.3 Physical Oceanographic Conditions

A.3.a Water Temperature

The continuous timeseries of near-surface water temperature in the nearfield for 2003 (**Figure** A-7) shows the influence of the cold winter and spring, with colder than average conditions until June. The large fluctuations during the summer are typical of that time period—they result from upwelling-downwelling fluctuations as well as short-lived wind-mixing events. **Figure** A-8 shows the near-surface and near-bottom data obtained through the entire monitoring program during the shipboard surveys. Conditions in 2003 are notable in the cold winter temperatures of both surface and bottom waters, and the colder than average bottom water temperatures in the fall. The former is due to the cold winter air temperatures, whereas the latter is due to the strong upwelling conditions during the summer.

A.3.b Salinity

The salinity data in 2003 showed a return to normal conditions following the drought of 2002 (**Figure** A-9). The salinity at the beginning of the year was the highest of the 12-year record, but the normal freshet of 2003 produced a significant drop in surface salinity, and the bottom salinity dropped back to normal values during the fall, when surface and bottom waters were mixed.

The salinity data as presented in **Figure** A-9 were subjected to a correction for the second half of the year, due to a calibration problem of the conductivity cell on the profiling instrument. The calibration error was first identified by a significant deviation from climatology at the end of the record. This led to a quantitative comparison between the shipboard salinity measurements and moored salinity measurements at various sites in Massachusetts Bay. The outcome of these comparisons yielded a correction factor for the salinity, of the following form:

$$\Delta S = -S_a - S_b(yd - 183)/183$$

where ΔS is the salinity correction, $S_a=0.7$ and $S_b=0.5$, and yd is the year day. The correction factor was applied from day 183 to 365, so the correction factor varied from –0.7 to –1.2. To test whether the corrected salinity is consistent with the observed climatology, a regression was performed between bottom salinity and variation of freshwater inflow from the Merrimack River, which previous analysis had revealed to be significantly correlated with a 6-month lag. Before applying the correction, the average near-bottom salinity at the outfall site for the fall of 2003 exceeded the regression curve by more than 1 psu. After the correction, the data were within 0.05 psu of the regression curve, i.e., the corrected values of salinity were consistent with the climatological variation with respect to freshwater inflow.

A.3.c Stratification

Stratification was higher during the summer of 2003 than any year since 1998 (**Figure** A-10). The strong stratification was due to larger differences between surface and bottom salinity than usual, as the system recovered from drought conditions. The bottom salinity has a longer response time than surface salinity, so there was a large differential during the spring and summer months, when the surface waters had returned to normal salinities.

A.3.d Dissolved Oxygen

The dissolved oxygen concentration showed a normal seasonal progression in 2003 (**Figure** A-11). The minimum DO was just below 7 mg/l, which is close to the average over the monitoring program. Regression analysis between DO, temperature and salinity was consistent with these measurements and indicated a minimum slightly above 7 mg/l occurring just before destratification. This level of DO concentration is consistent with the observed relationship with near-bottom temperature and salinity, as shown in **Figure** A-12. The cold bottom water resulting from upwelling-favorable conditions produced a positive anomaly in DO, but this was compensated by salty bottom water due to dry conditions in early 2003, which results in a negative anomaly in DO. The result was average near-bottom DO conditions for the fall of 2003. The 2003 data continue to indicate that there has been no statistical change in the DO conditions since the onset of the bay outfall discharge.

A.4 Summary of 2003 Physical Conditions

The two notable characteristics of the physical properties in 2003 were 1) a return to normal freshwater inflow, and 2) upwelling-favorable winds which produced colder than average bottom water temperatures. Because of the lag in the response of bottom-water salinity to changes in freshwater flow, the deep salinity remained high until the fall of 2003. The near-bottom dissolved oxygen at the outfall site was average in the fall of 2003, with compensating effects of cold bottom water and slightly elevated salinities. The dissolved oxygen data indicate that the values and variability at the outfall site are consistent with the observations prior to the initiation of the outfall, suggesting that there is no observable influence of the outfall on dissolved oxygen.

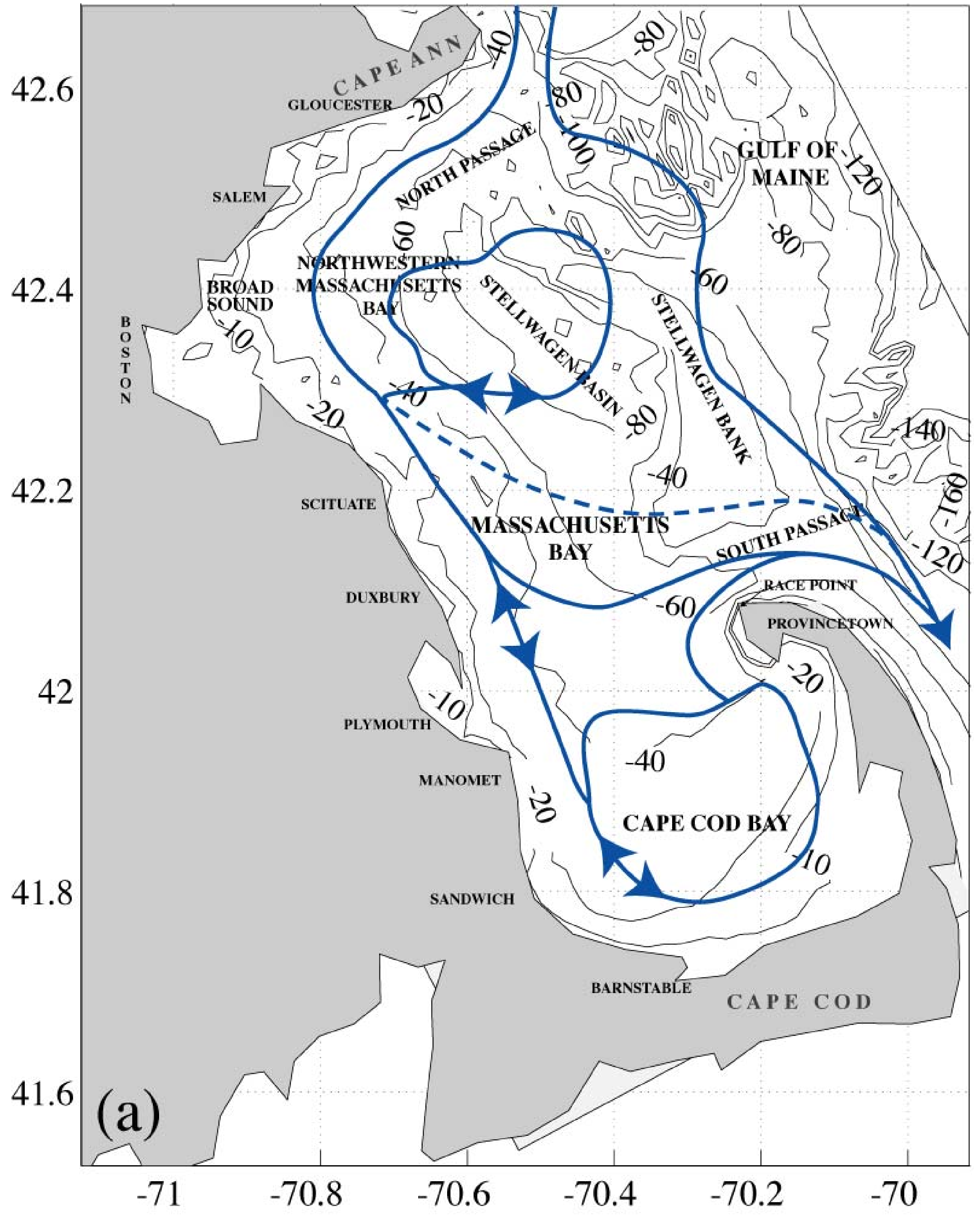
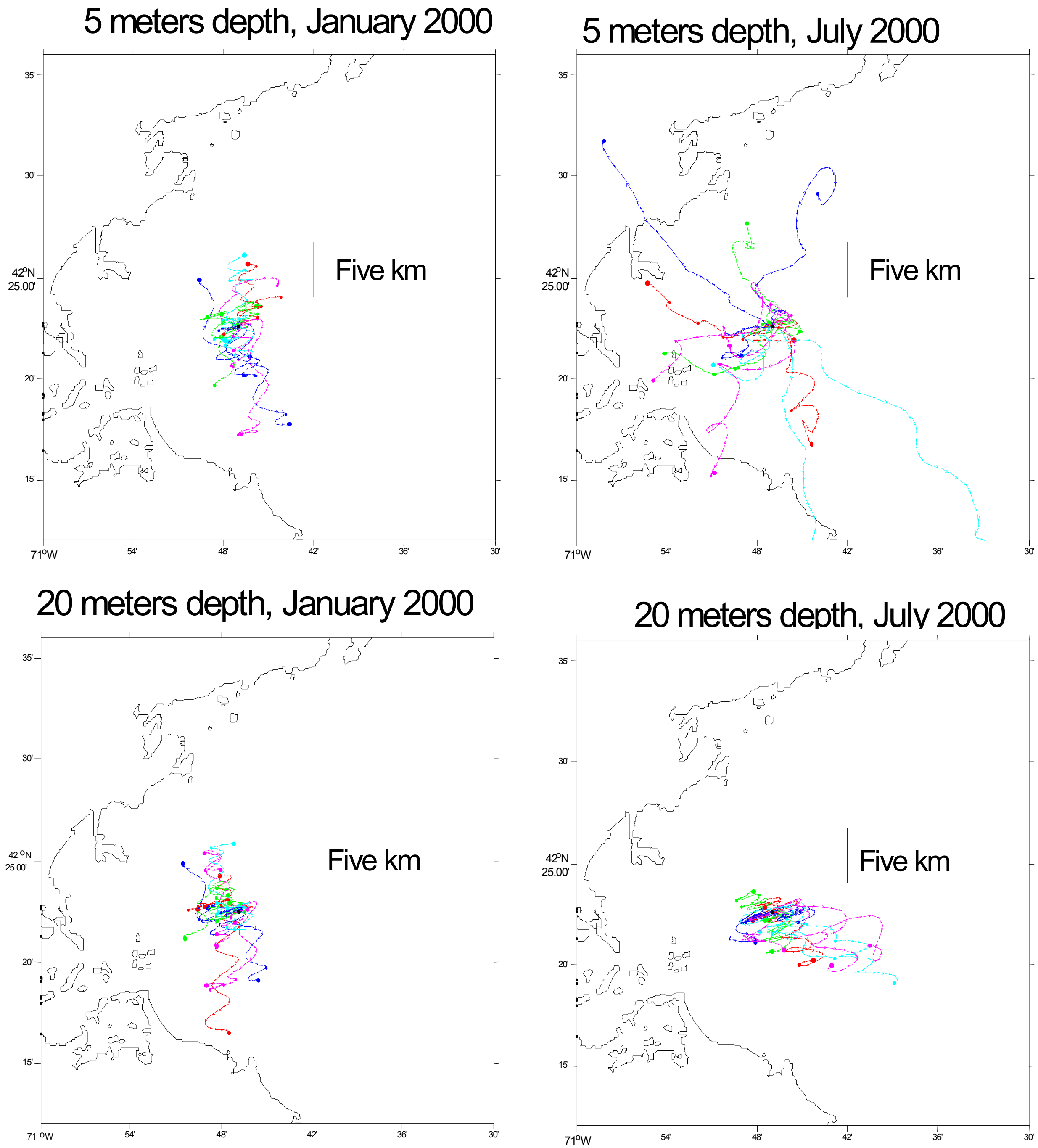


Figure A-1. Summary of circulation within Massachusetts Bay (Lermusiaux 2001).



5 meters depth, January 2000

5 meters depth, July 2000

20 meters depth, January 2000

20 meters depth, July 2000

Figure A-2. 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.) Each colored line represents a separate 24-hr vector. The Acoustic Doppler Current Profiler on the USGS mooring measured currents. Figures courtesy Soupy Alexander and Brad Butman, USGS.

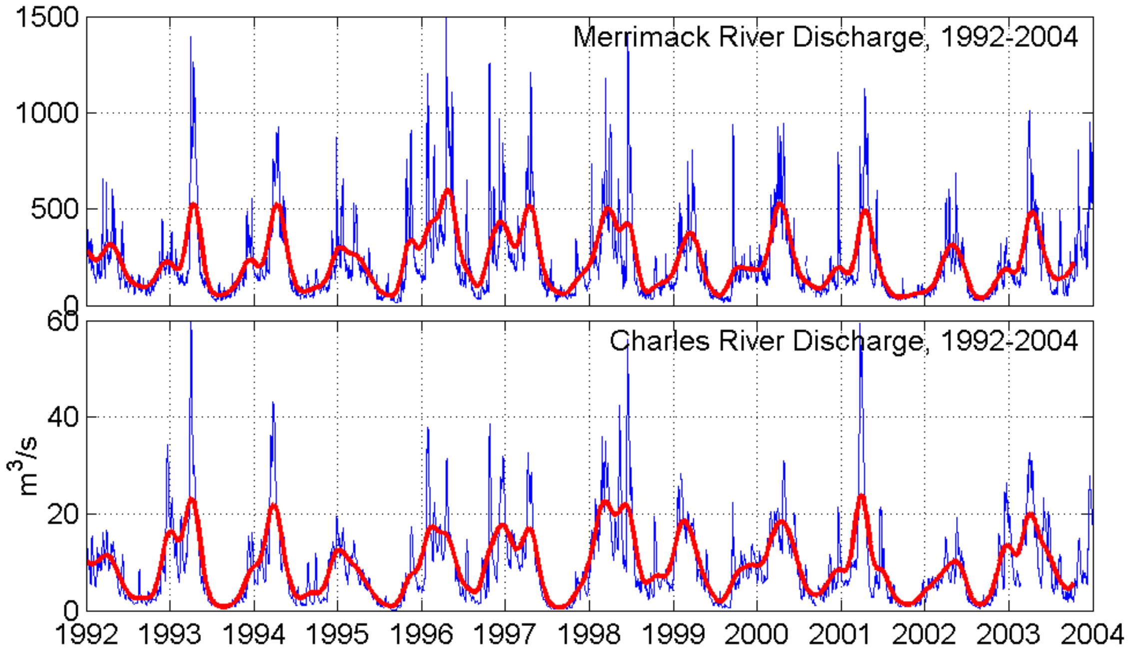


Figure A-3. River discharge at the Merrimack River (at Lowell) and the Charles River (at Waltham), from 1992 through 2003 (data from USGS). Thick red lines indicate three-month moving averages.

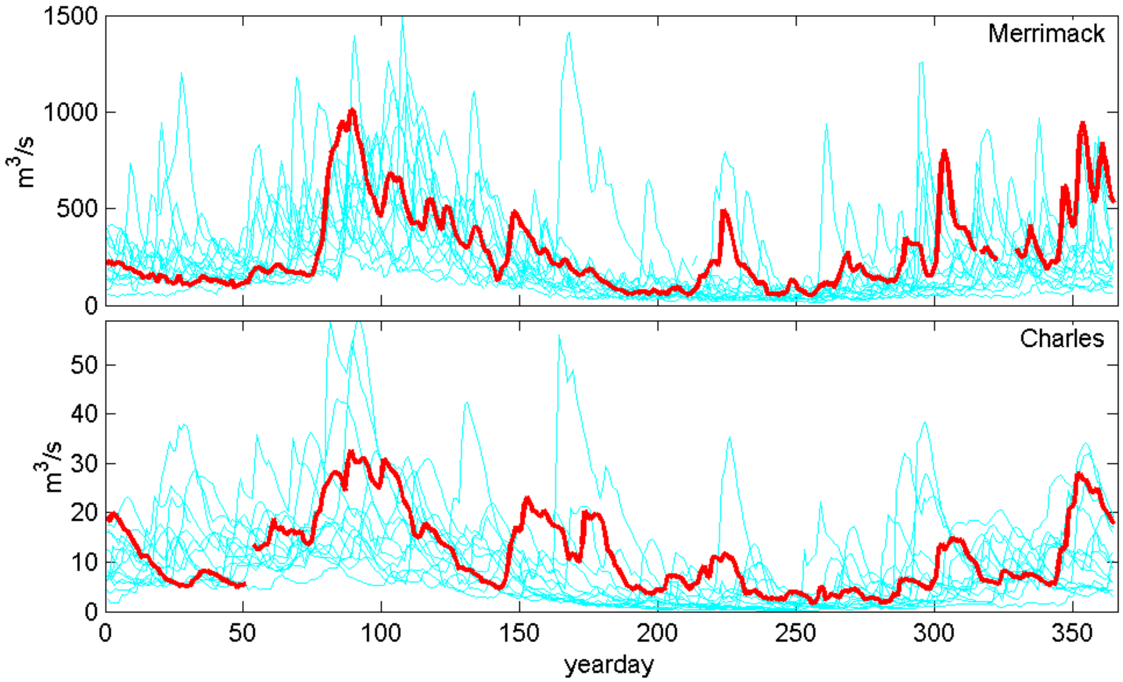


Figure A-4. Comparison of the 2003 discharge of the Charles and Merrimack Rivers (thick curves) with the observations of the past 12 years (thin lines).

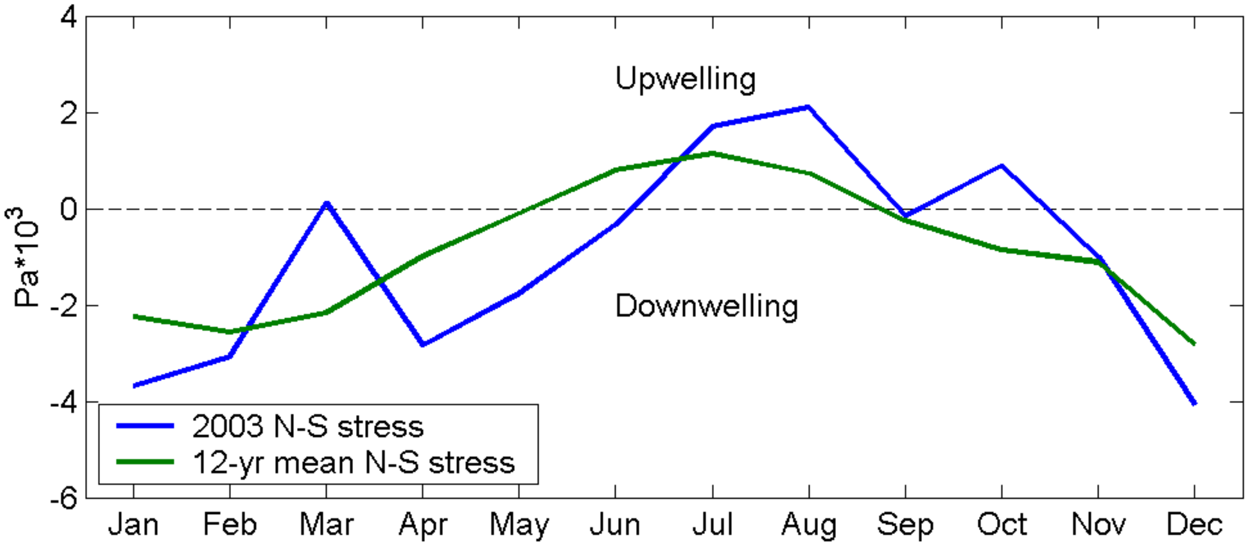


Figure A-5. Monthly average N-S wind stress at Boston Buoy for 2003 compared with 12-year average. Positive values indicate northward-directed, upwelling-favorable wind stress.

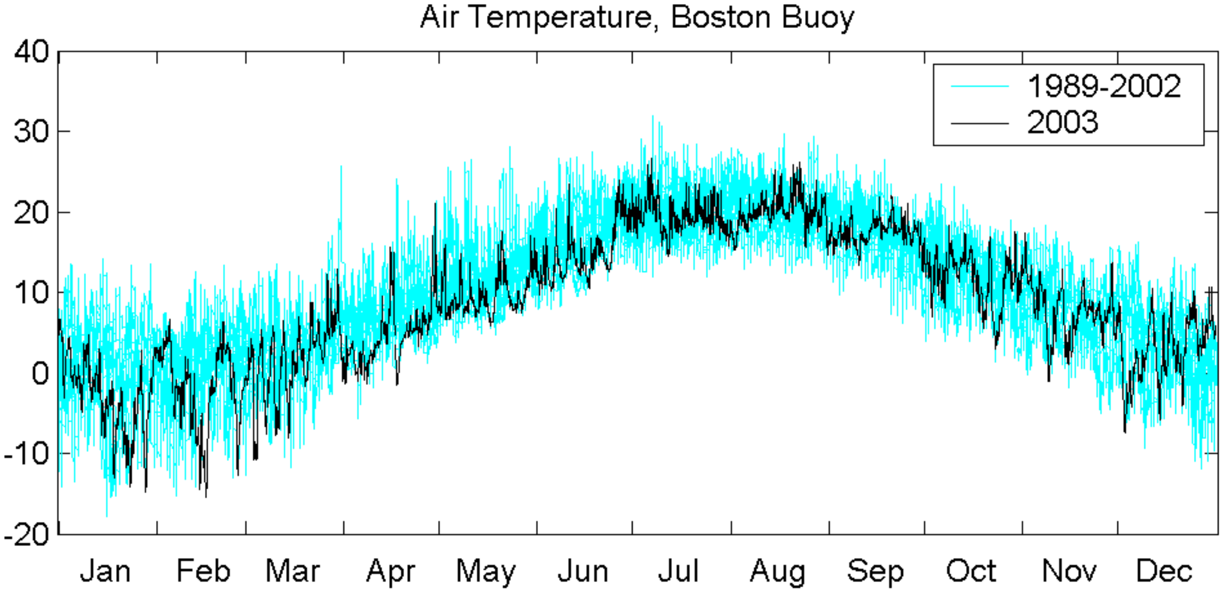


Figure A-6. Hourly air temperature (°C) for 2003 at the Boston Buoy (black) superimposed on the data from the previous 14 years (turquoise).

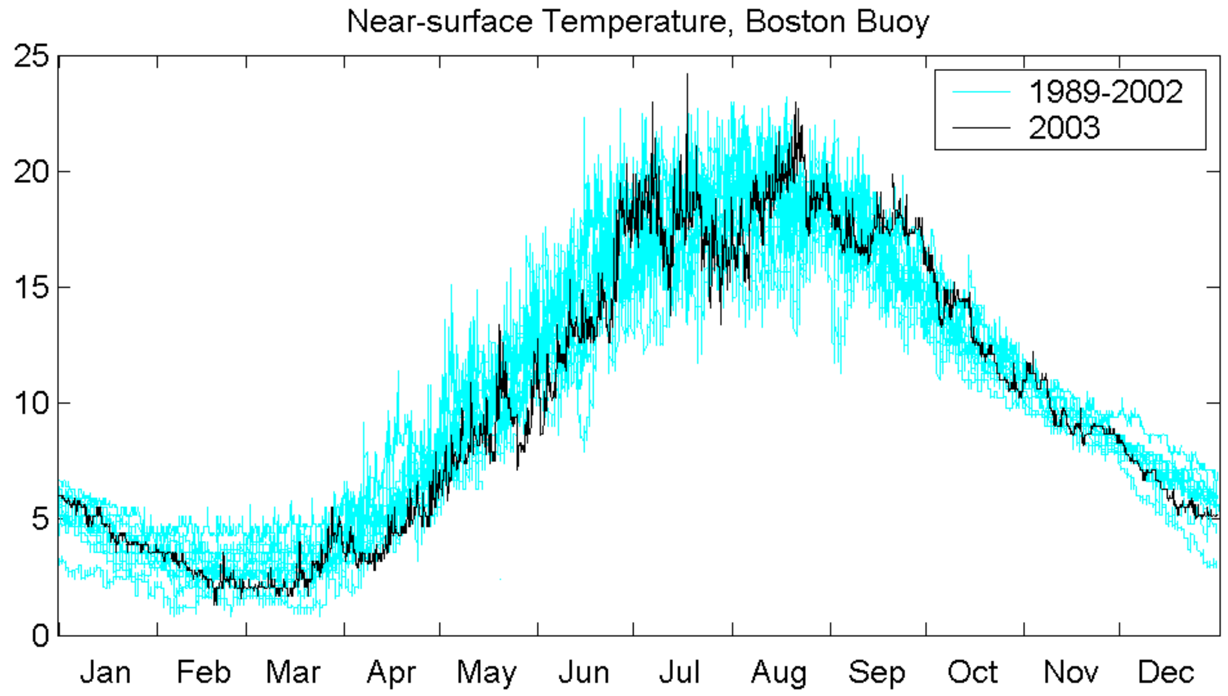


Figure A-7. Hourly near-surface temperature for 2003 at the Boston Buoy (black) superimposed on the data from the previous 14 years (turqouise).

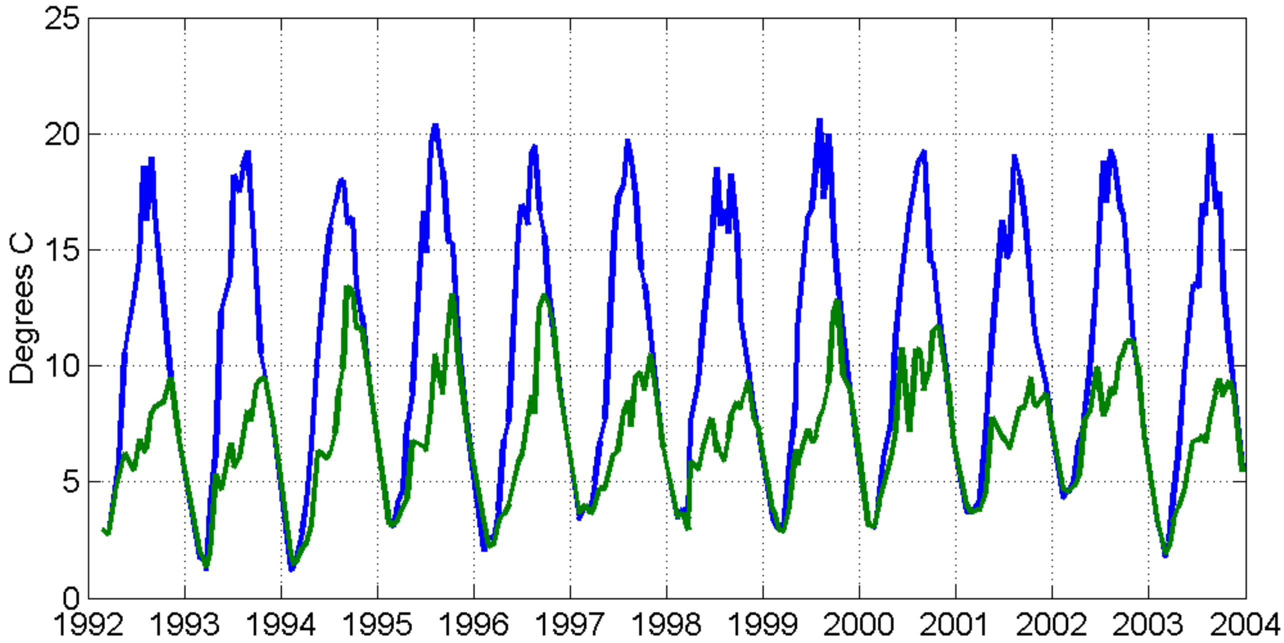


Figure A-8. Timeseries of near-surface (blue) and near-bottom (green) temperature in the vicinity of the outfall (averaging the data from nearfield stations N13, N14, N18, N19, N20 and N21).

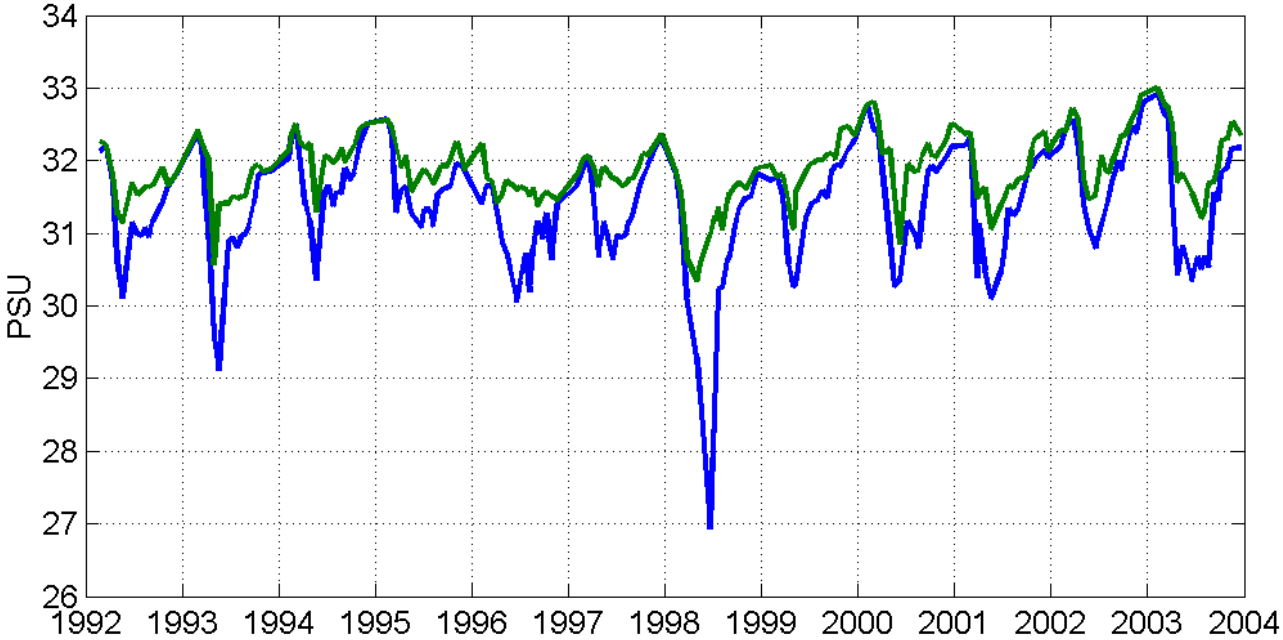


Figure A-9. Timeseries of near-surface (blue) and near-bottom (green) salinity in the vicinity of the outfall (same stations as Figure A-6).

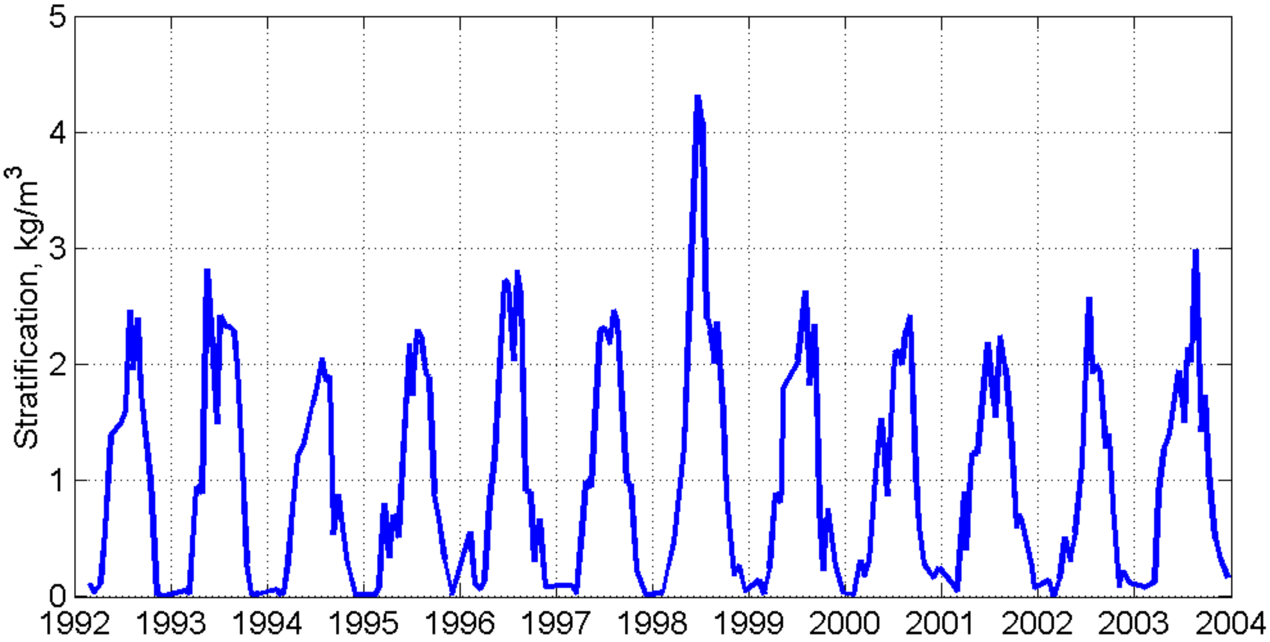


Figure A-10. Timeseries of stratification in the vicinity of the outfall (same stations as Figure A-6).

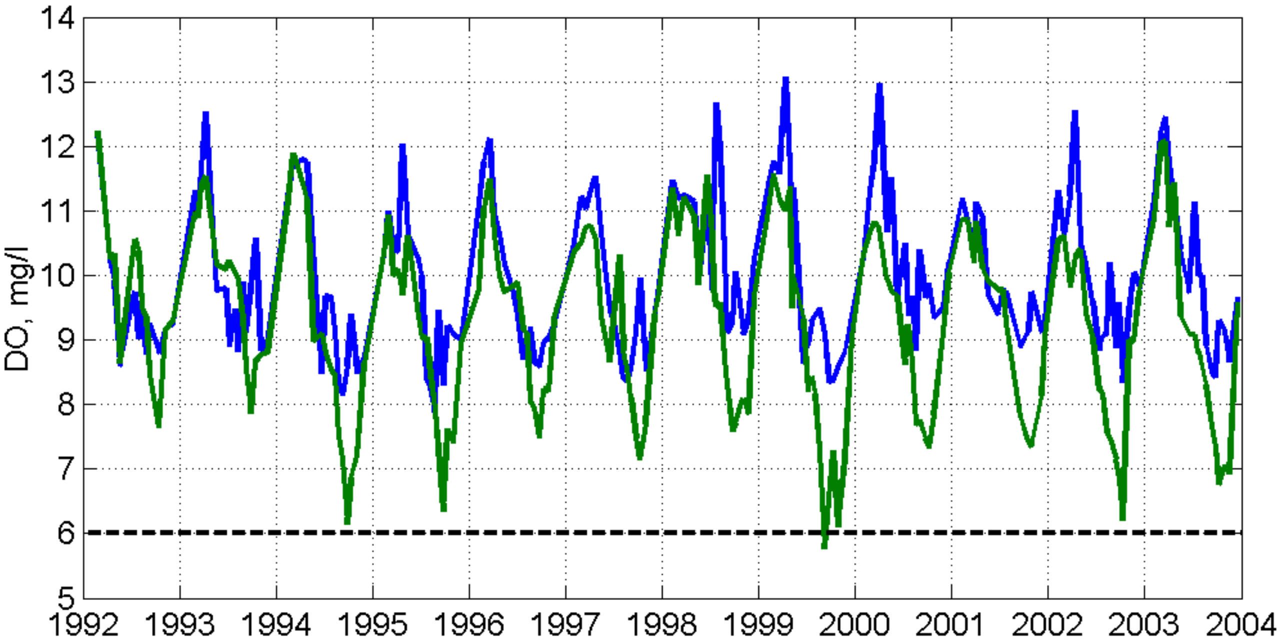


Figure A-11. Timeseries of near-surface (blue) and near-bottom (green) dissolved oxygen in the vicinity of the outfall (same stations as Figure A-6).

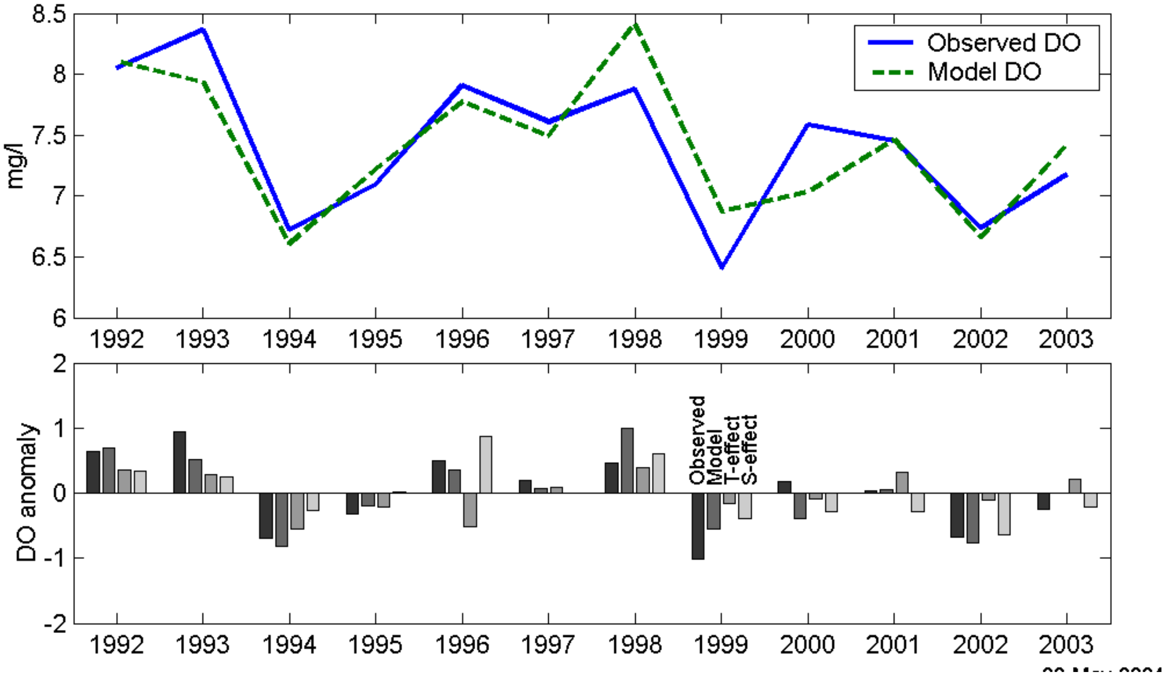


Figure A-12. Upper panel: Average near-bottom dissolved oxygen during September-October, compared with linear regression model based on temperature and salinity variation. Lower panel: The bar plot shows the individual contributions due to temperature and salinity for each of the years.

APPENDIX B

Water Quality

B. WATER QUALITY

This section presents a summary of 2003 water quality trends, based on information contained in the two semiannual reports (Libby *et al.* 2003b and 2004), and interannual comparisons of 2003 seasonal trends vs. 1992 to 2000 baseline and 2001 and 2002 results. In 2003, trends in water quality parameters: nutrients, phytoplankton biomass [chlorophyll and particulate organic carbon (POC)], and dissolved oxygen were generally consistent with those observed during previous years, although the timing and magnitude of events were different. Each section addresses issues in both the nearfield and the farfield.

B.1 Summary of 2003 Results

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. In recent years, the winter/spring diatom bloom has been typically followed by a bloom of *Phaeocystis pouchetii* in April. Late 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 2003. The major features and differences from the baseline in 2003 are discussed below.

Nutrients:

The nutrient data for 2003 generally followed the typical progress of seasonal events in Massachusetts and Cape Cod Bays. High nutrient concentrations were observed in early February when the water column was well mixed and biological uptake of nutrients was limited (**Figures** B-1 to B-3). Nutrient concentrations in Cape Cod Bay surface waters were low in comparison to Massachusetts Bay due to elevated diatom abundance in early February and remained relatively low throughout the report period. Massachusetts Bay surface water nutrient concentrations decreased from early February through April. The exception to this was for silicate which tended to increase from late February/early March to April coincident with a transition from a diatom dominated bloom in February to a *Phaeocystis* bloom in April (**Figure** B-3a). Nutrient concentrations in the surface waters were depleted throughout much of the nearfield region by mid March and throughout the entire study area by June.

Seasonal stratification throughout the summer led to persistent nutrient depleted conditions in the upper water column due to biological utilization. It also ultimately led to an increase in nutrient concentrations in bottom waters due to increased rates of respiration and remineralization of organic matter. In late fall, nutrient concentrations began to increase with the breakdown of stratification (**Figures** B-1 to B-3). The relatively late breakdown in stratification, however, delayed the development of typical fall nutrient conditions until later in the season. The weak stratification and moderate nutrient flux into surface waters likely supported the prolonged fall bloom.

Surprisingly high nutrient concentrations were observed in the nearfield bottom waters from September to December and throughout Cape Cod and Massachusetts Bay in October. Maximum bottom water concentrations for NO_3 and SiO_4 ranged from 10-15.5 µM and 12-17.3 µM, respectively. These elevated levels probably resulted from the prolonged stratification and perhaps from transport of deeper, offshore Gulf of Maine waters into the bays. By December, the water column was well mixed and nutrient concentrations were at typical winter levels.

Throughout 2003, ammonium continued to be an excellent tracer of the effluent plume in the nearfield (**Figure** B-4). During well-mixed conditions, a strong NH_4 effluent signal is observed above the outfall and reaches the surface, but once stratification sets up, the plume is trapped below the pycnocline. In addition to illustrating the vertical extent of the plume, the nutrient distributions continue to show that the plume is generally confined to within 20 km of the outfall and that the location of the plume is variable (**Figure** B-5).

Phytoplankton Biomass:

In 2003, there was a winter/spring bloom of diatoms in February that was most prominent in Cape Cod Bay, Boston Harbor, coastal and western nearfield waters (see **Figures** D-1 and D-2). Regional chlorophyll and POC maxima were observed in Cape Cod Bay, coastal and Boston Harbor waters in late February/early March during the diatom bloom (**Figure** B-6). Biomass concentrations were lower, but also increasing at the stations in the nearfield, offshore and boundary areas.

The prolonged bloom of *Phaeocystis* observed throughout Massachusetts and Cape Cod Bays from February to April was most pronounced in northern Massachusetts Bay. The highest chlorophyll concentrations (21 μgL^{-1}) of 2003 were recorded in the nearfield in April during the *Phaeocystis* bloom. Comparable chlorophyll levels (~18 μgL^{-1}) were also measured at station F26 during this bloom. SeaWiFS images for this time period suggest that these elevated chlorophyll values may have been due to, or enhanced by, entrainment of waters from the Gulf of Maine into northeastern Massachusetts Bay during the freshet (**Figure** B-7).

The occurrence of these two blooms led to high nearfield mean areal chlorophyll (178 mg m^{-2}) for winter/spring 2003, which is comparable to but below the seasonal caution threshold of 182 mg m^{-2}. This is the highest winter/spring value since the outfall went online. In contrast to the high chlorophyll concentrations, productivity was relatively low during the winter/spring period in comparison to past years (see **Appendix** C). Areal production in 2003 followed patterns typically observed with a distinct peak associated with the winter/spring phytoplankton bloom, but peak production values were lower than the range usually observed. Although 2003 lacked a major region-wide winter/spring bloom, elevated chlorophyll concentrations over much of the water column during both the nearshore diatom bloom and the offshore *Phaeocystis* bloom resulted in high areal chlorophyll levels in both the nearfield and farfield (**Figure** B-8).

Phytoplankton biomass was relatively low from June to September. Exceptions were observed in Boston Harbor and the nearfield. In the harbor, chlorophyll and POC concentrations remained elevated in comparison to other areas though well below the winter/spring bloom maxima (**Figure** B-6). In the nearfield, biomass concentrations were elevated in early July relative to the rest of the summer surveys. This increase in chlorophyll and POC was not coincident with any peak in production or total phytoplankton, though there was a sharp increase in dinoflagellate abundance during this survey (see **Figure** D-8). Otherwise phytoplankton biomass remained low and unlike 2002 there was no late summer/early fall bloom.

A distinct feature in fall 2003 was a mixed assemblage diatom bloom which lasted from late September into December. Even though it was prolonged, the relative magnitude of the bloom was minor in comparison to past fall blooms in terms of phytoplankton abundance (1-2.3 million cells L^{-1}) and productivity (<2500 mg C m^{-2} d^{-1}). Chlorophyll and POC concentrations peaked in October and were comparable to previous fall blooms, but the timing of the peak values was later than typically observed. SeaWiFS imagery and fluorescence data from the USGS mooring corroborate both the magnitude and the spatial and temporal extent of elevated chlorophyll concentrations from late September into December (**Figures** B-9 and B-10). By mid December, chlorophyll and POC concentrations had decreased to low winter levels.

Dissolved Oxygen:

DO concentrations in 2003 followed trends that have been observed consistently since 1992 and concentrations were relatively high early in the year and low in the late fall, but generally within the range of values observed previously. Bottom water DO levels are typically at a maximum in the winter, begin to decline following the establishment of stratification and the cessation of the winter/spring bloom, continue to 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. In 2003, the delay in the overturn of the water column led to the annual survey minima being measured in November.

In 2003, maximum bottom water DO concentrations (10.5 - 12.2 mgL^{-1}) occurred in February and March (**Figure** B-11a). By April, bottom water DO concentrations had decreased throughout Massachusetts Bay. Mean bottom water DO had decreased by 1.5 mgL^{-1} in the harbor, coastal and nearfield waters. This was likely related to the decline of the diatom bloom – lower production and potential for increased respiration. The offshore, boundary, and Cape Cod Bay showed only slight decreases (<0.3 mgL^{-1}) over this time period. Nearfield bottom water DO concentrations remained steady from early to late April, before declining by 1 mgL^{-1} in May. From April to June, bottom water DO concentrations decreased by 1-2 mgL^{-1}. The June mean bottom water DO concentrations have been used to establish setup conditions prior to the summer decline and have been a benchmark for interannual comparisons. In 2003, June DO concentrations were at typical levels and uniform across the survey area (9-9.5 mgL^{-1}).

There was a steady decline in nearfield DO concentrations from April through late November before increasing when the water column was mixed in December (**Figure** B-11a). In August, bottom water DO concentrations were relatively high throughout the bays at approximately 8 mg L^{-1}, only dropping below 7.5 mg L^{-1} in southeastern Cape Cod Bay. By October, bottom water DO concentrations had decreased by ~1 mg L^{-1} across all farfield regions to about 7 mg L^{-1}, with only Cape Cod Bay station F02 dropping below 6 mg L^{-1}. The delay in destratification in fall 2003 led to a prolonged decline in nearfield DO values into November. Nearfield mean bottom water DO concentrations and %saturation reached minima of 6.5 mgL^{-1} and 69% in November. These minima were relatively high considering the extended period of decline. The minimum sample DO value for 2003 of 5.67 mgL^{-1} was recorded in November. This was the only nearfield DO value <6 mgL^{-1} for the entire period. It was not until December, as stratification eventually broke down, that bottom and surface waters were well mixed and stable DO values were found throughout the water column (~9.5 mgL^{-1} and 95%).

The trend of decreasing DO in the bottom waters was also apparent in the DO %saturation data (**Figure** B-11b). As with DO concentration, DO % saturation decreased from February to October in each of the survey areas (till November in the nearfield), although there were some fluctuations. Bottom waters were generally saturated to supersaturated during the February surveys. DO %saturation increased from late February to April in Cape Cod Bay and there was a relatively large increase in DO %saturation from early February to mid March in the nearfield both coincident with increased phytoplankton abundance and production rates. The shallow harbor bottom waters remained above 100% saturation from February to August before decreasing to 85% saturation in October. The deep waters at the boundary stations were under saturated throughout 2003. As with DO concentration, DO %saturation minima were observed in October (in November in the nearfield).

Mean bottom water DO concentrations and %saturation in the nearfield reached minima of 6.5 mgL^{-1} and 69% in November. These minima were relatively high considering the extended period of decline. Dissolved oxygen concentration and %saturation threshold values are based on survey mean minima from June to October. In the nearfield, threshold comparison minima were reached in late October (6.72 $mg\ L^{-1}$ and 71.8%). The survey mean bottom water minima for Stellwagen Basin stations were higher than in the nearfield. Both the nearfield and Stellwagen DO concentration and %saturation minima were well above established background threshold values and there was no threshold exceedance for dissolved oxygen.

Given that there were two major winter/spring blooms in 2003 and chlorophyll, as an indicator of biomass, was high in comparison to past years, it might have been expected that DO concentrations and %saturation would have been lower throughout the bays especially given the delay in the overturn of the water column in the fall. These factors, however, were likely offset by a decrease in the residence time of bottom waters in the bay. The findings of Geyer *et al.* (2002) indicated that there is an inverse relationship between winter/spring salinity and bottom water DO concentrations. The underlying hypothesis is that during years with high runoff and low salinity waters there is higher flow through the system and less of a decrease in DO concentrations. The low salinities that were measured in winter/spring 2003 resulting from high runoff likely compensated for the elevated biomass (and assumed flux to sediments) and delay in mixing. The low bottom water temperatures that were measured in 2003 also factored into the higher DO concentrations as respiration rates were relatively low in these waters in 2003 (**Figure** B-12).

B.2 Interannual Comparisons

Nutrients:

The nutrient data for 2003 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.

Nearfield survey mean concentrations of NO_3, SiO_4, and PO_4 in 2001, 2002 and 2003 generally follow baseline trends and are comparable in magnitude to the levels observed over the baseline period (**Figures** B-13 and B-14). 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. In 2003, NO_3 concentrations were at the baseline maxima, but SiO_4 values were below the mean and decrease to a level comparable to the baseline minima in late February. The low concentrations were coincident with the winter/spring diatom blooms observed to varying extents during each of these years. In 2001 and 2002, the apparent winter/spring draw down of nutrients was not as steep as observed during previous winter/spring bloom years because the bloom had begun prior to the first survey during both of these years. In 2003, however, there was a very sharp decrease in NO_3, SiO_4, and PO_4 from early February to late February that was coincident with the development of the winter/spring diatom bloom. Nearfield NO_3 and PO_4 concentrations continued to decline into March while SiO_4 concentrations increased as production peaked during the *Phaeocystis* bloom. Nearfield SiO_4 concentrations continued to increase from late February till late April during this bloom as *Phaeocystis* does not utilize this nutrient.

Over the late spring and summer nutrient concentrations tended to be at or slightly above the baseline mean, but generally within the baseline range for NO_3, SiO_4, and PO_4 (**Figures** B-13 and B-14). In 2001 and 2002, nutrient concentrations in the fall and winter tended to be higher than baseline maxima in September and October and lower that the baseline minima in late October to December. 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. 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. In 2003, even though physical oceanographic conditions were similar to 2001 (prolonged period of weak stratification) and there was a prolonged fall bloom, NO_3 concentrations remained at or above baseline maxima from September to December. Nearfield concentrations of SiO_4 and PO_4 also remained at or above baseline mean values for this period.

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, 2002 and 2003 surveys (**Figure** B-14b). Two of the primary deviations from this were observed in 2003 when NH_4 concentrations were close to the baseline mean values during the March/April *Phaeocystis* bloom and during the prolonged fall bloom in October to December. In contrast to the trends observed in the nearfield, NH_4 concentrations in Boston Harbor were below or near baseline minima for the entire year (**Figure** B-15a). 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, 2002 and 2003 – well below the baseline minimum during the winter/spring blooms and generally near the baseline mean the remainder of the year (**Figure** B-15b).

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 (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 have consistently confirmed this.

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** B-16a). 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 have remained stable from 2001 to 2003. Unlike these regions, little if any change in NH_4 concentrations was measured in offshore, boundary, and Cape Cod Bay waters from 1992 to 2003. 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** B-16b for NO_3. Year to year variability in NO_3, SiO_4, and PO_4 has more to do with timing of sampling and occurrence of blooms than any clear trends in background levels.

Phytoplankton Biomass:

Trends in chlorophyll and POC in 2003 were comparable to those observed during previous years. 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. In 2003, the main highlights included the relatively high winter/spring chlorophyll levels associated with the two spring blooms (diatoms and *Phaeocystis*) and the prolonged fall bloom.

In 2001, 2002 and 2003, nearfield areal chlorophyll values were generally consistent with the baseline mean and seasonal pattern. The main deviations from the baseline were in early February (2001 and 2002) and late fall (**Figure** B-17a). High values in early February of 2001 and 2002 coincided with elevated production rates and early winter/spring blooms. In 2003, the winter/spring diatom bloom combined with the prolonged *Phaeocystis* bloom (March-May) led to elevated chlorophyll and POC concentrations from February to April. The highest survey mean areal chlorophyll value 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. In 2003, chlorophyll levels were at or above the baseline maxima in late October and November. The relatively high (150 - 200 mg m^{-2}) chlorophyll values observed during each of these late fall blooms 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** B-17b). 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, 2002 and 2003 generally followed the baseline means and trends except for the high peaks during the 2003 *Phaeocystis* bloom and peaks corresponding to fall blooms during each of the post discharge years. During all four 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 except in 2003 when production levels were slightly lower than typically observed (<2,500 mg C m^{-2} d^{-1}).

In Boston Harbor, 2001, 2002 and 2003 areal chlorophyll (**Figure** B-18a) 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 and late

February 2003 areal chlorophyll concentrations were higher than any previous values measured in Boston Harbor. Harbor POC concentrations were relatively low in 2001, and similar to baseline trends (**Figure** B-18b). In 2002 and 2003, however, elevated POC concentrations were coincident with high chlorophyll and productivity during the winter spring blooms. The chlorophyll and POC data (along with production data presented in Appendix C) 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 the winter/spring bloom.

In 2002, the HOM data suggested that the harbor may also be experiencing a change to fall blooms (Libby *et al*. 2003). Chlorophyll data collected for the more highly resolved (spatially and temporally) MWRA Harbor Monitoring Program, however, while confirming that there were substantial chlorophyll blooms in Boston Harbor in February 2002 and 2003, also indicated that summertime chlorophyll levels peaked in July rather than August 2002 (Taylor 2003). Thus, although HOM data did not capture the summer peak, it was still present in 2002 and 2003, albeit at lower levels than during baseline monitoring. Taylor (2004) noted that although there was no significant change in annual chlorophyll levels pre versus post discharge, there was a significant ($P<0.001$) decrease in summer chlorophyll concentrations of 36% The lack of a significant change in the annual means in the Harbor Monitoring data is a reflection of the increased levels of chlorophyll during the winter/spring and fall blooms.

Variations in the strength of the spring and fall blooms are the major factors affecting the annual average chlorophyll (**Figure** B-19). The highest annual mean values occur in 1999 and 2000 when major blooms were observed in both spring and fall. In 2003, the very high chlorophyll levels associated with the substantial *Phaeocystis* bloom at many of the offshore and boundary stations led to comparably high annual mean areal chlorophyll values for these areas. However, because annual mean POC concentrations in 1999 and 2000 and in the boundary and offshore areas in 2003 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 (**Figure** B-20). 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. In 2003, POC levels were generally lower than 2002, but the nearshore stations in Boston Harbor, coastal waters and Cape Cod Bay continued to have the highest concentrations of chlorophyll and POC as has been the case since 1992. The nearfield annual mean POC concentrations were relatively stable from 2001 to 2003 and comparable to baseline values.

Dissolved Oxygen:

DO concentrations in 2003 followed trends that have been observed consistently since 1992 and concentrations were relatively high given the substantial spring blooms and prolonged period of stratification in the fall. 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 program is 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 the 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.

Since the bay outfall came on line, there has been little change in the DO cycle in the nearfield and Stellwagen Basin (**Figures** B-21 and B-22). DO levels were close to the baseline mean in 2001 in both areas and below the mean during 2002. In 2003, the primary deviations in the nearfield data were in late February and early March when values were at or above the baseline maxima and November as weak stratification led to a delay in the DO minima that was below the baseline minima for late fall. In Stellwagen Basin, DO levels were at or above the baseline mean in February, but were below the mean (and below the minima in June) for the remainder of 2003 (**Figure** B-22). The bottom water minima in these areas in 2003 were comparable to 2002 levels, lower than minima observed in 2000 and 2001, but higher than the baseline minimum that was measured in 1999 (**Figures** B-23 and B-24). 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).

B.3 Water Quality Summary

Over the course of the HOM program, a general sequence of events in water quality 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 the events are variable. Water quality conditions in the bays in 2003 generally followed those observed previously. There was a winter/spring bloom of diatoms in February that was most prominent in Cape Cod Bay, Boston Harbor, coastal and western nearfield waters. A prolonged bloom of *Phaeocystis* was observed throughout Massachusetts and Cape Cod Bays from February to April that was most pronounced in northern Massachusetts Bay. The occurrence of these two substantial blooms led to a sharp decrease in nutrient concentrations and high chlorophyll levels in the nearfield that approached, but did not exceed threshold levels. In the fall, the water column remained weakly stratified through November and the fall bloom occurred over a prolonged period from late September into December. Although the chlorophyll and POC concentrations were close to baseline maxima during the late fall bloom, plankton and productivity rates were relatively low in comparison to previous fall blooms. The delay in the overturn of the water column contributed to low DO levels that were measured in November.

The main change in comparison to baseline continues to be that 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 appear to be confined to an area within 20 km of the outfall. The higher nearfield NH_4 concentrations have not translated into an obvious increase in biomass, whether measured as chlorophyll or POC. In Boston Harbor, a dramatic decrease in NH_4 has been concomitant with decreases in chlorophyll and POC, 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.

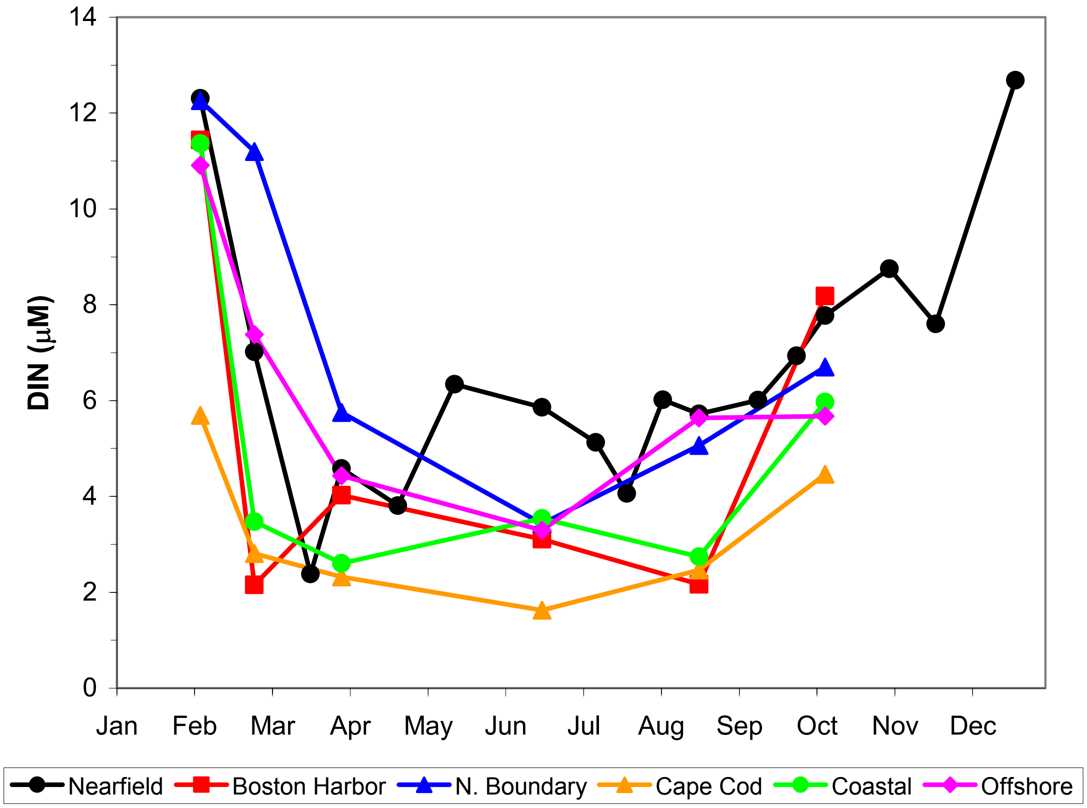
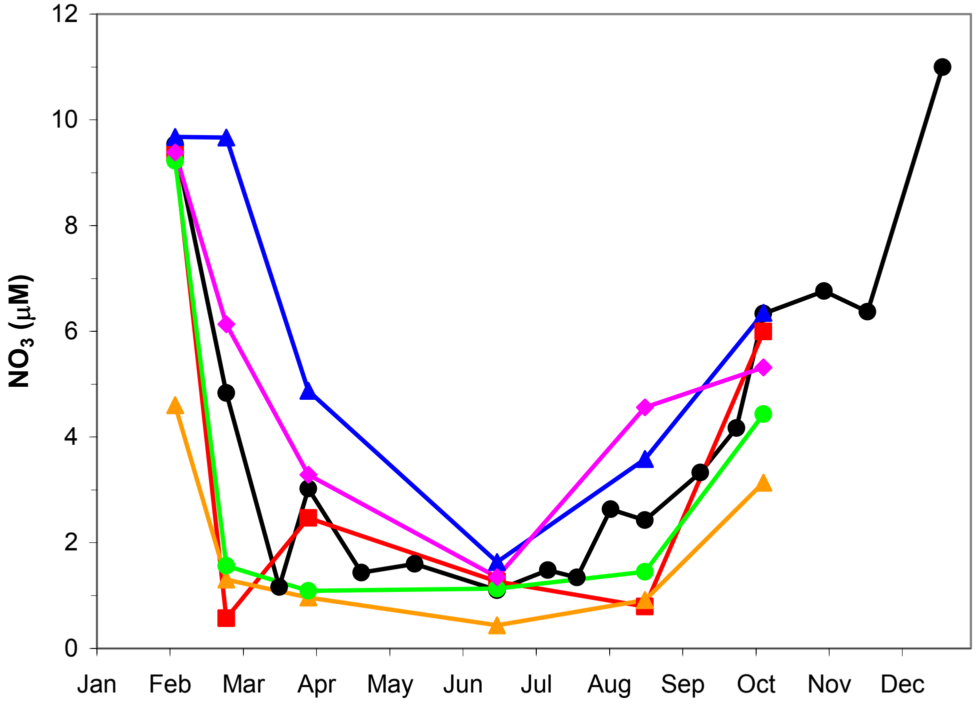


Figure B-1. Time-series of survey mean DIN concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region in 2003.

a) Nitrate



b) Ammonium

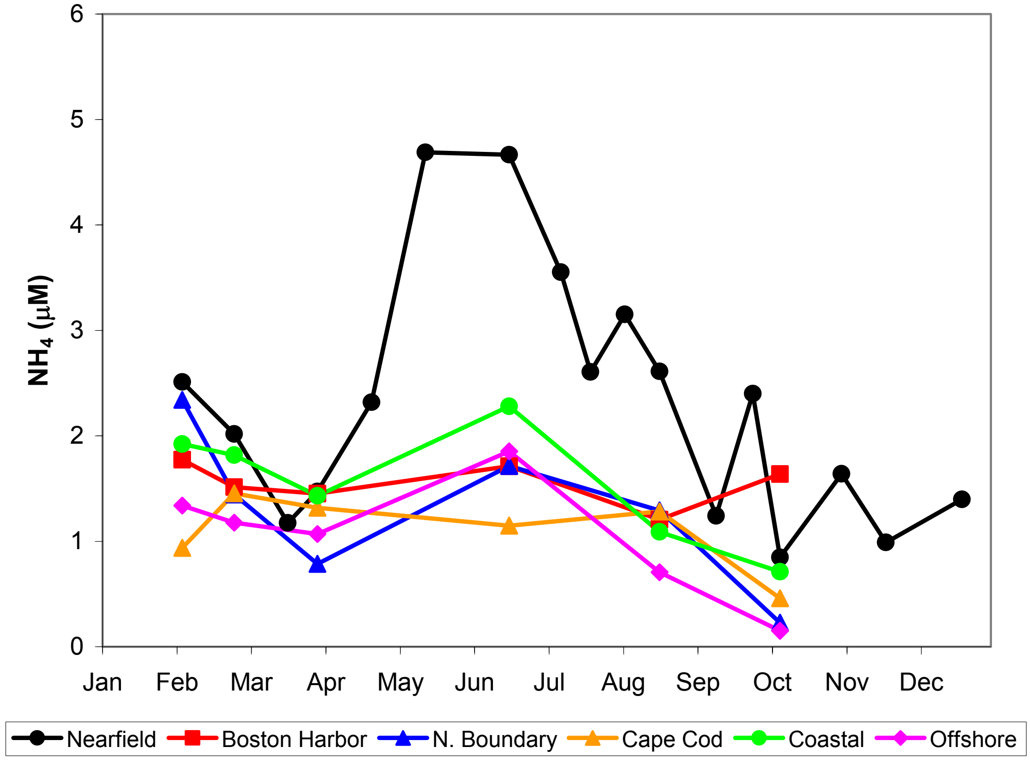
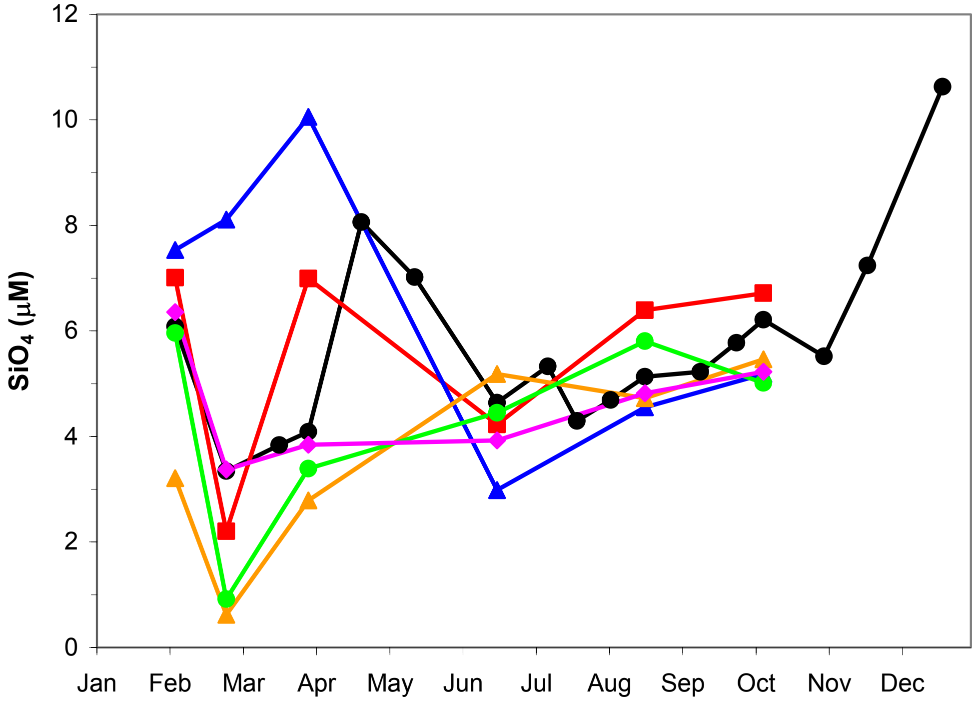


Figure B-2. Time-series of survey mean (a) NO_3 and (b) NH_4 concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region in 2003.

a) Silicate



b) Phosphate

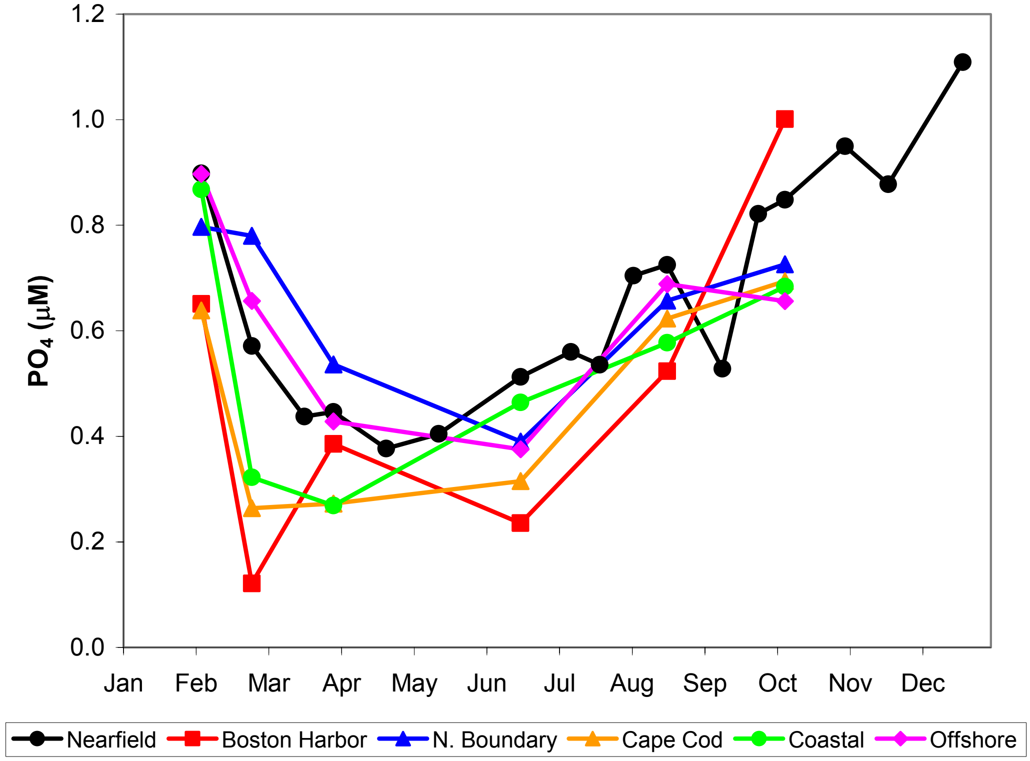


Figure B-3. Time-series of survey mean (a) SiO$_4$ and (b) PO$_4$ concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region in 2003.

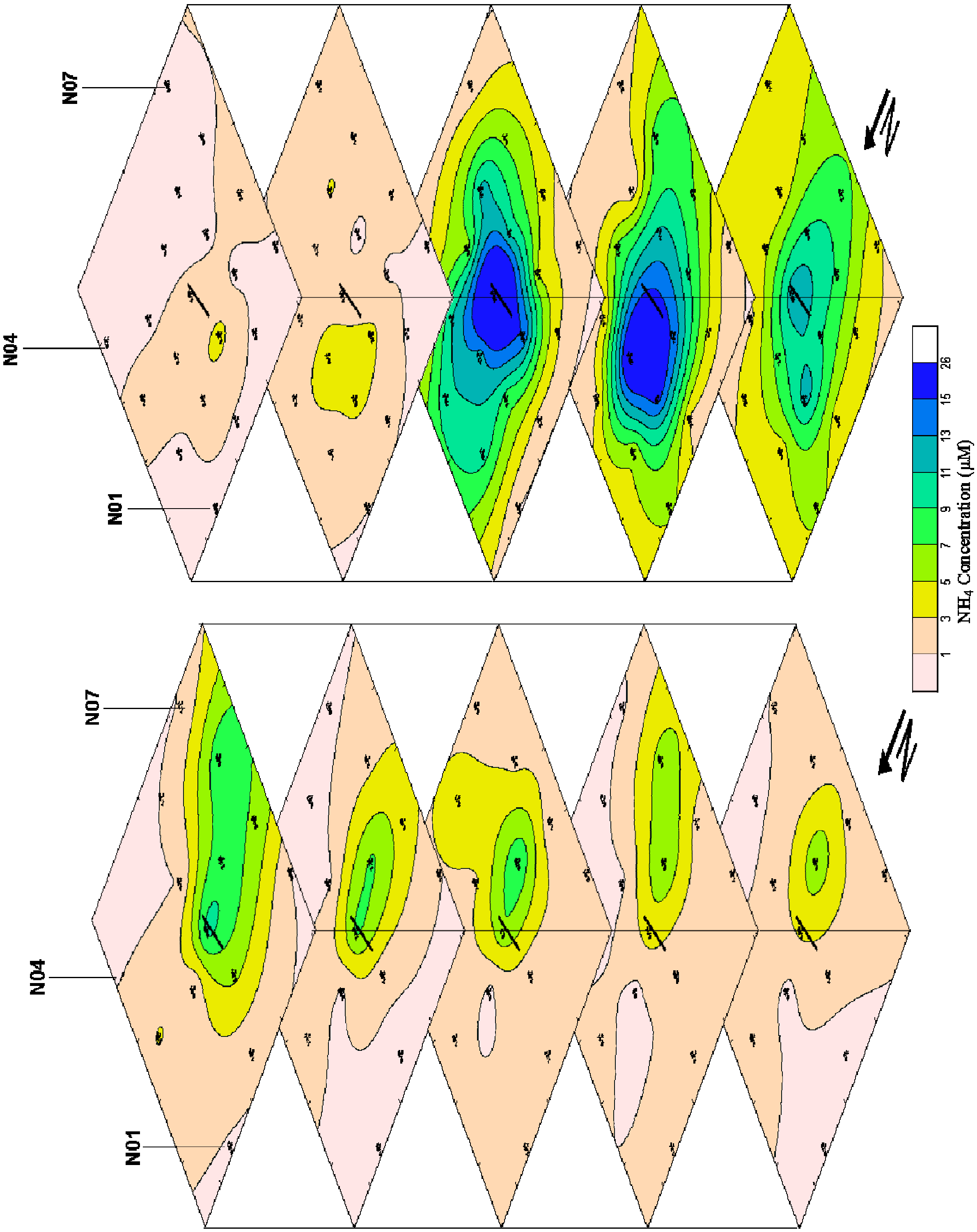


Figure B-4. Ammonium concentrations at each of the five sampling depths for all nearfield stations during WF031 and WN036.

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

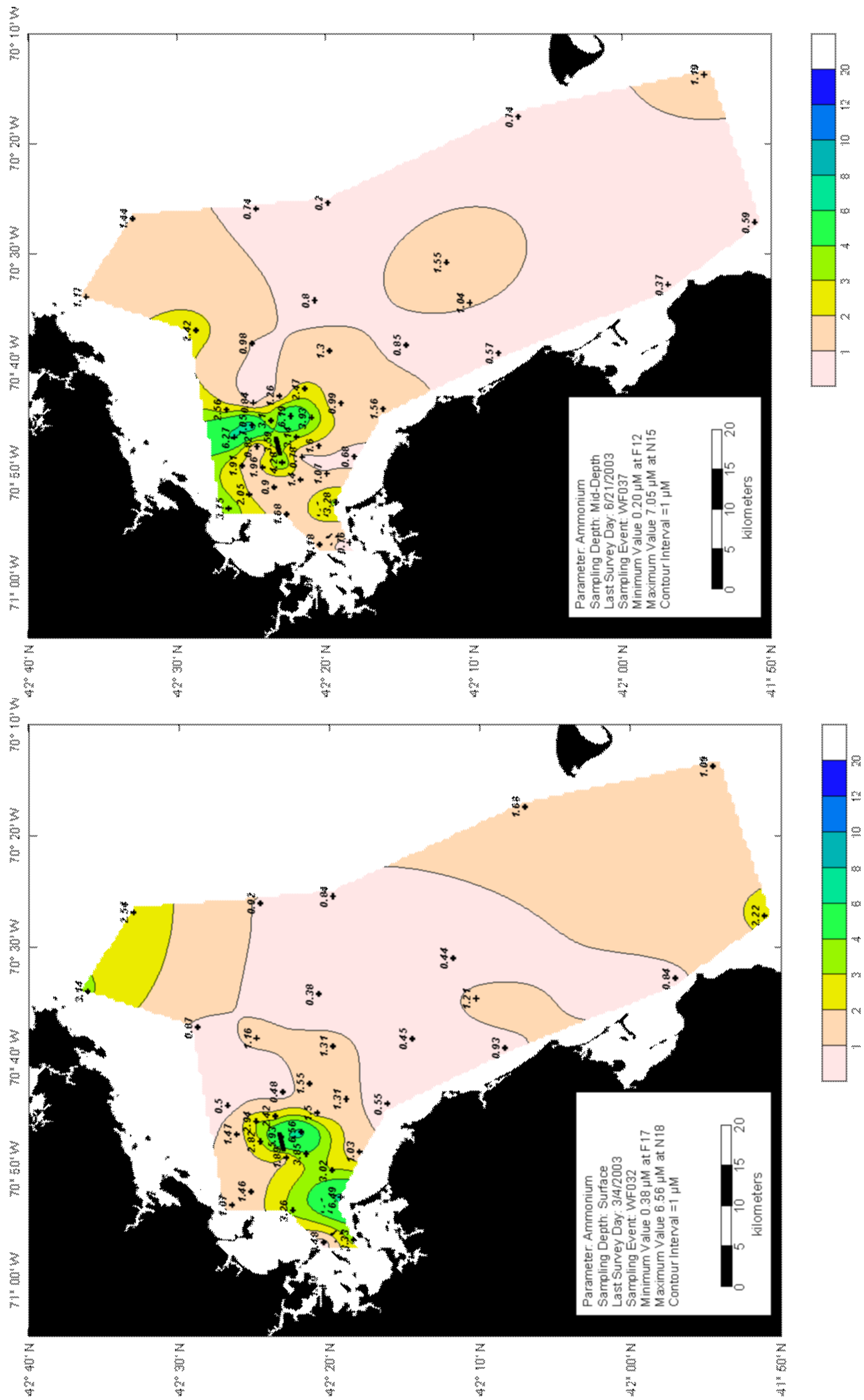
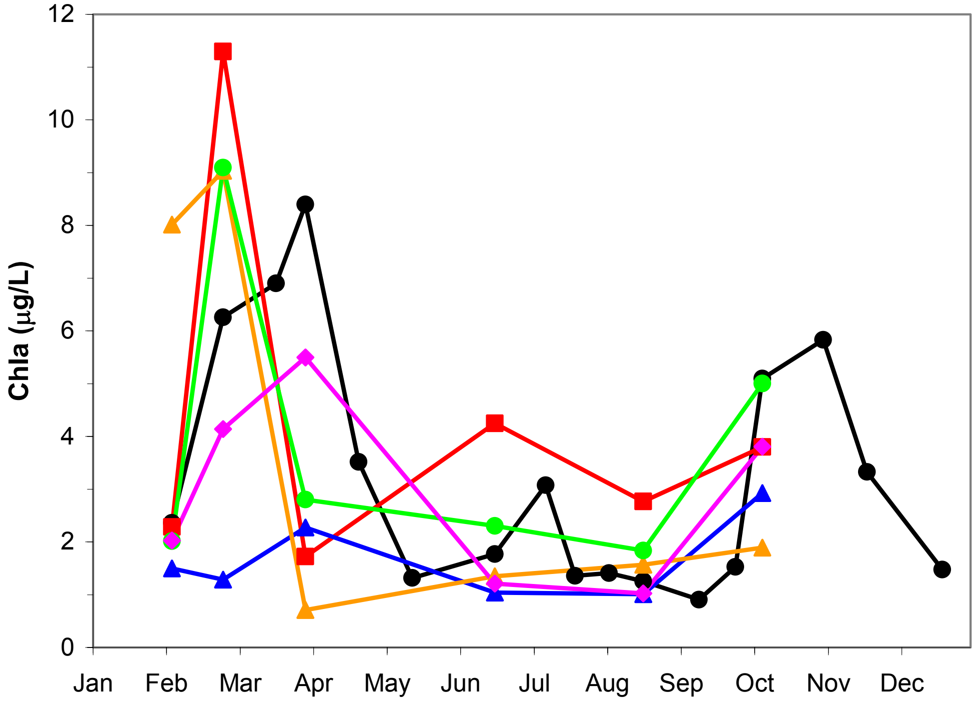


Figure B-5. Ammonium contour plots for farfield survey a) WF032 – surface (Feb/Mar 03) and b) WF037 – mid depth (Jun 03).

a) Chlorophyll



b) POC

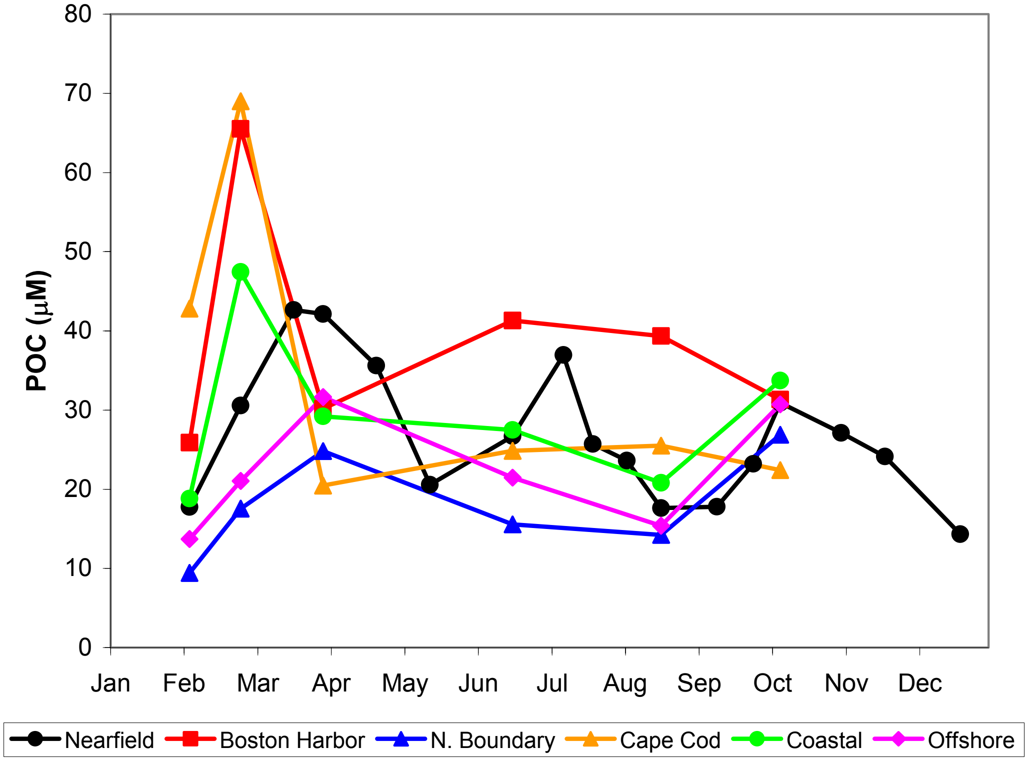


Figure B-6. Time-series of survey mean (a) chlorophyll (extracted) and (b) POC concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region in 2003.

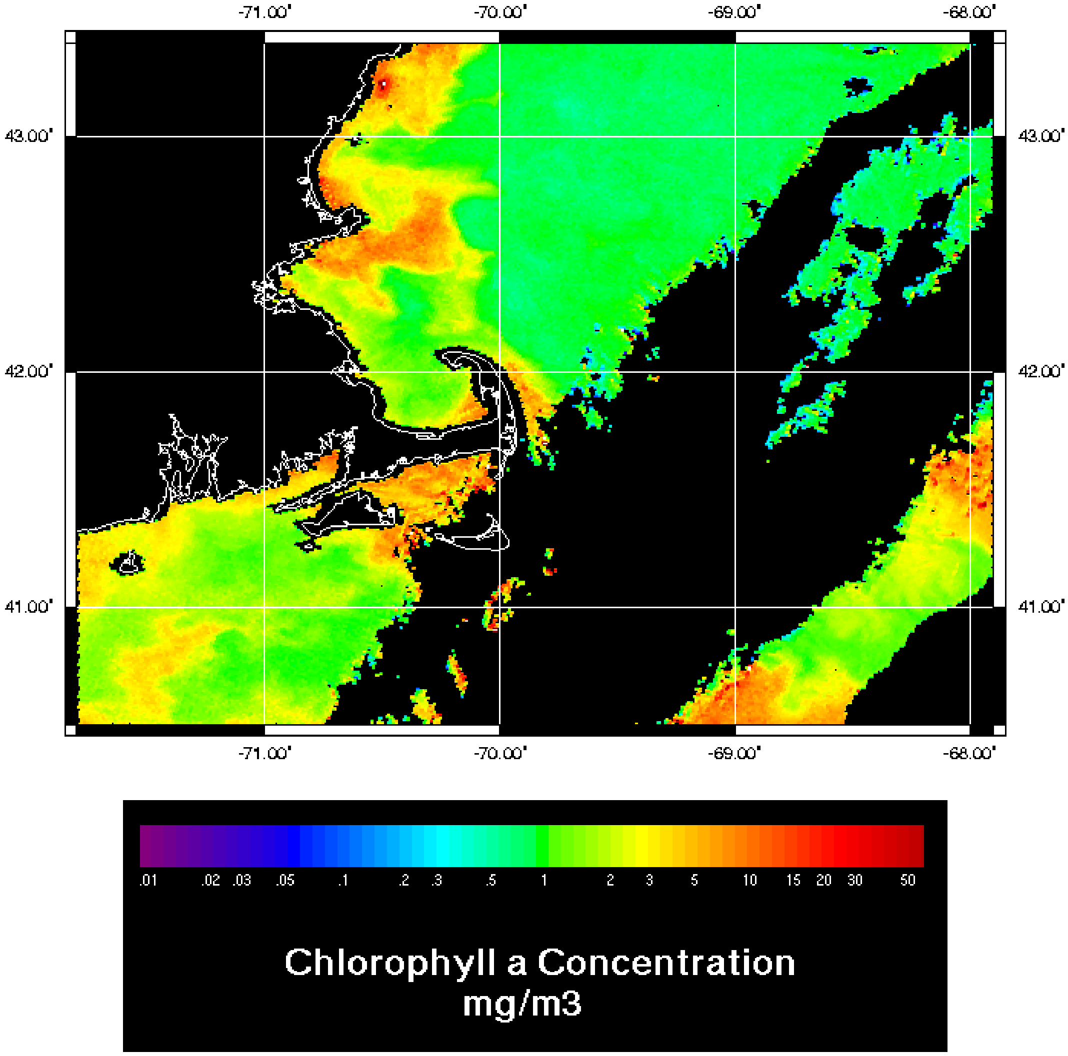


Figure B-7. SeaWiFS chlorophyll image for southwestern Gulf of Maine for March 27, 2003.

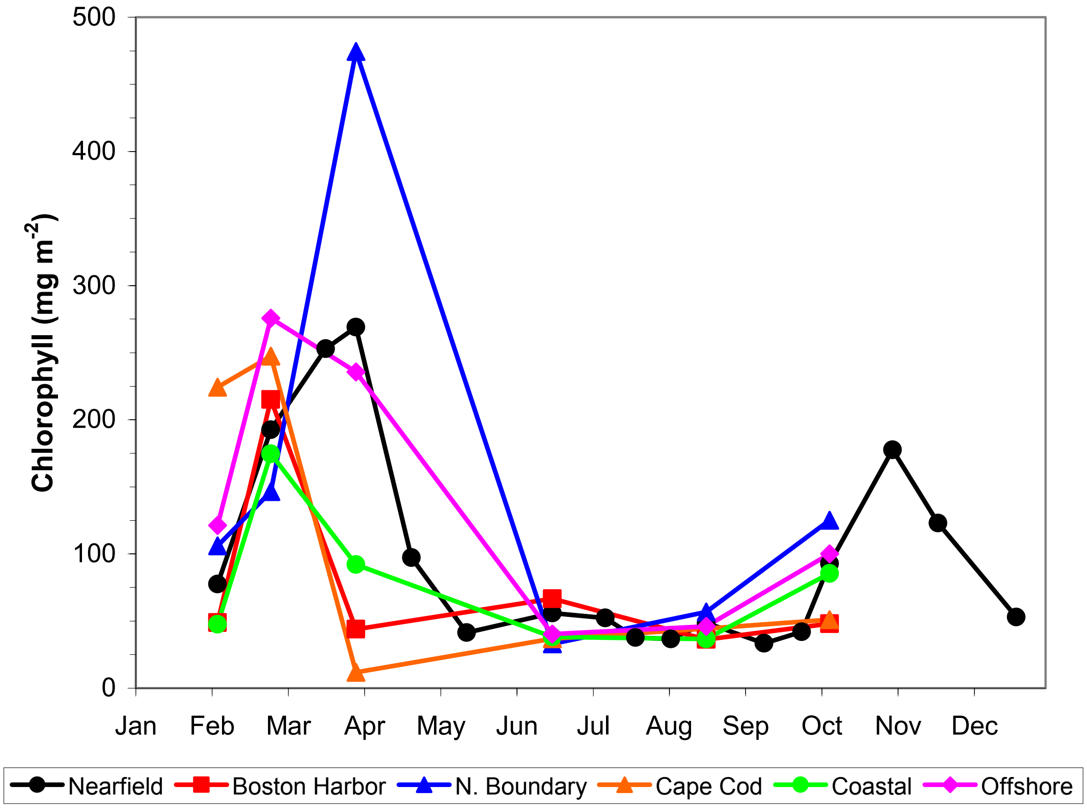


Figure B-8. Time-series of survey mean areal chlorophyll in Massachusetts and Cape Cod Bays. Mean of areal concentrations over stations within each region in 2003.

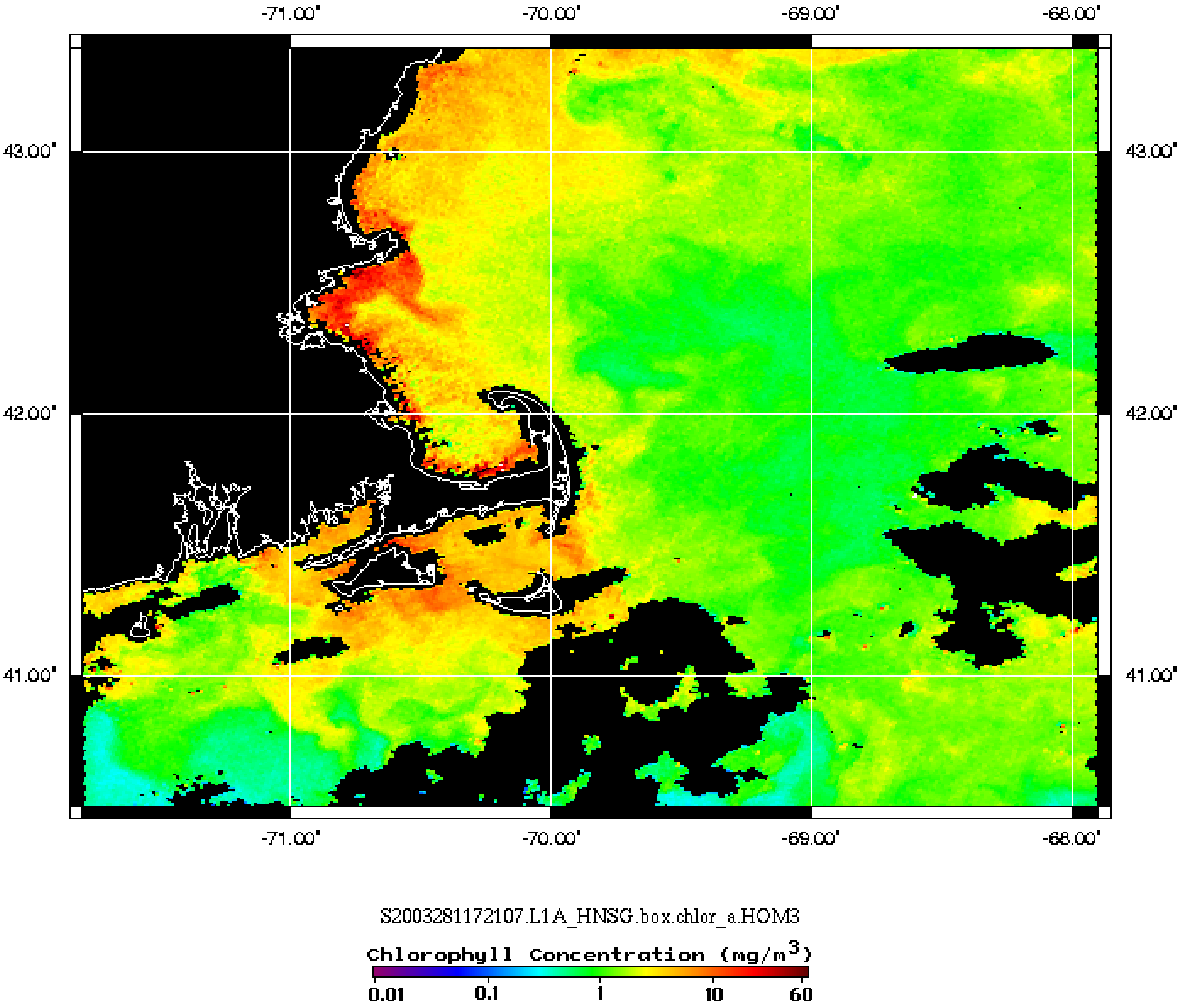


Figure B-9. SeaWiFS image for southwestern Gulf of Maine from October 8, 2003.

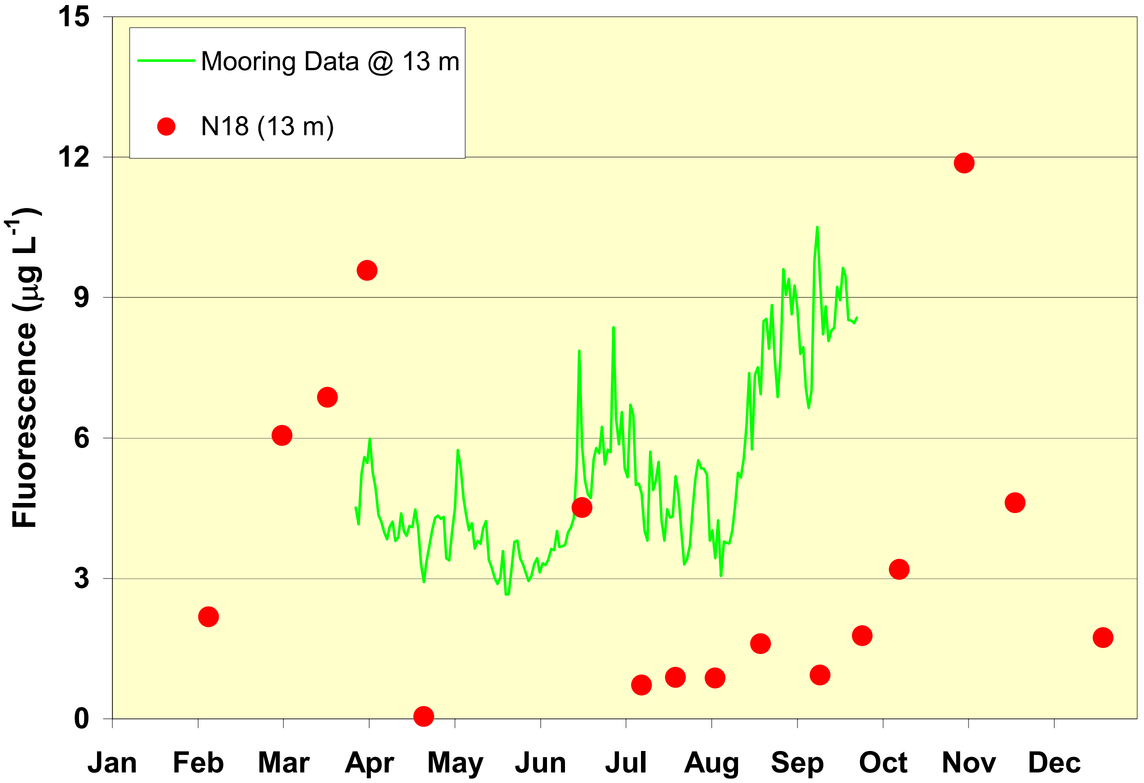
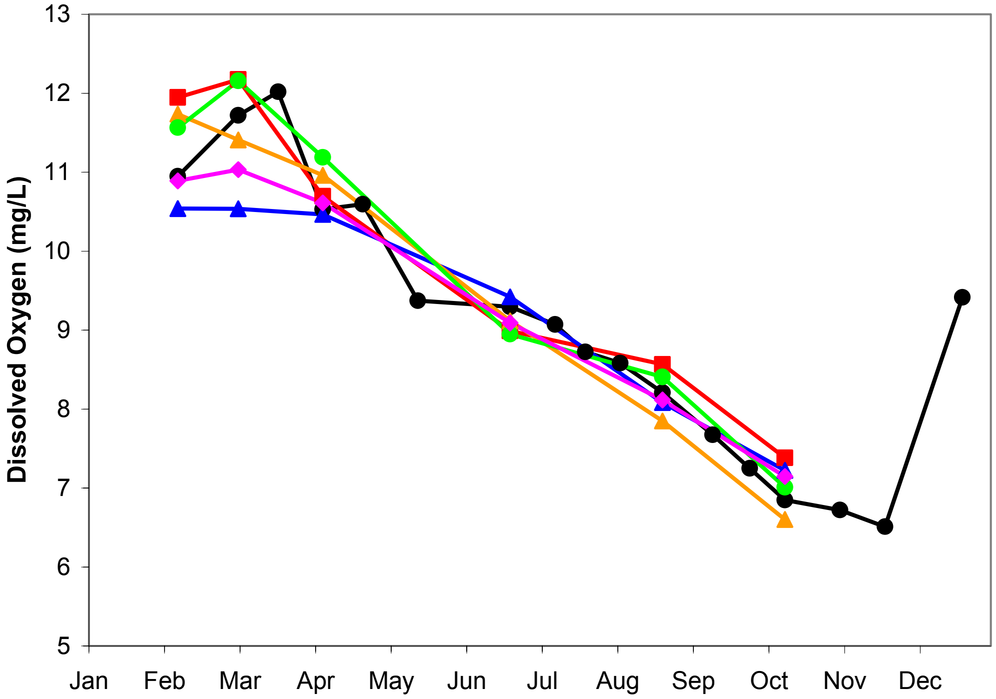


Figure B-10. MWRA and Battelle In Situ Wetstar fluorescence data – MWRA data acquired at ~13 m on USGS mooring and Battelle data acquired at 13 m at station N18. (Note that January to April 2003 and September 2003 to February 2004 data are not fit for use).

(a) DO Concentration



(b) DO Percent Saturation

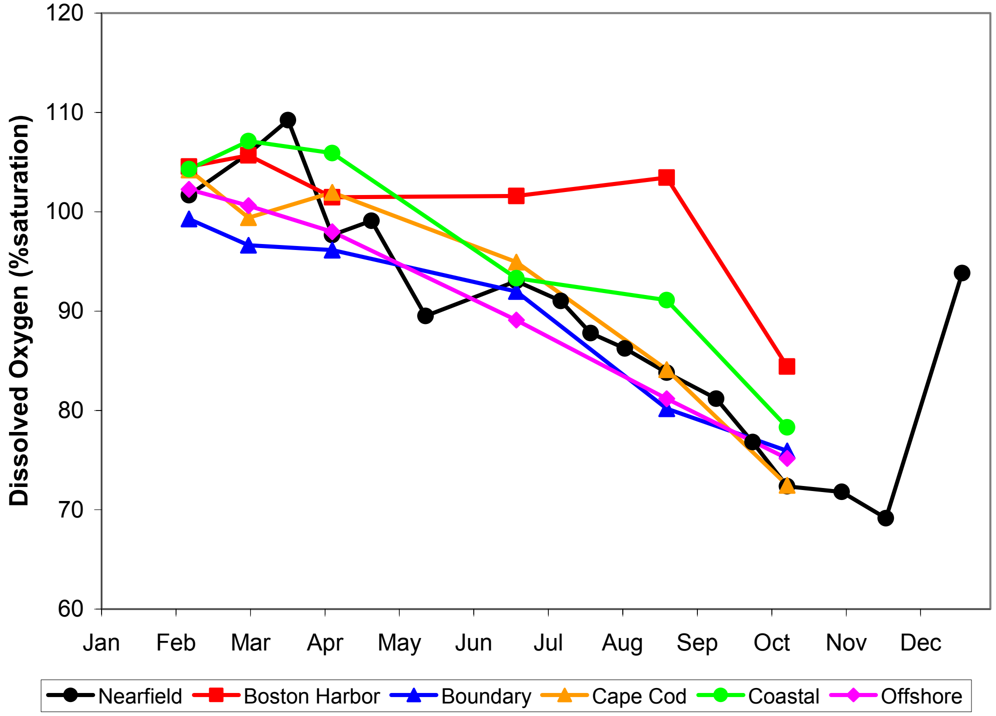
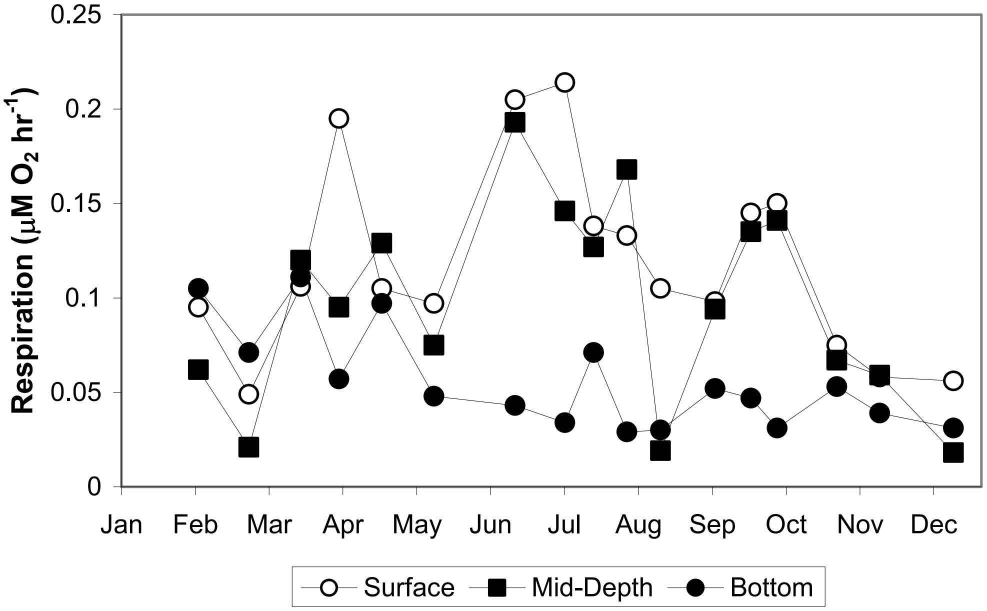


Figure B-11. Time-series of average bottom dissolved oxygen (a) concentration and (b) percent saturation in Massachusetts and Cape Cod Bays. Mean of values from all stations within each region in 2003.

(a) Station N18



(b) Station N04

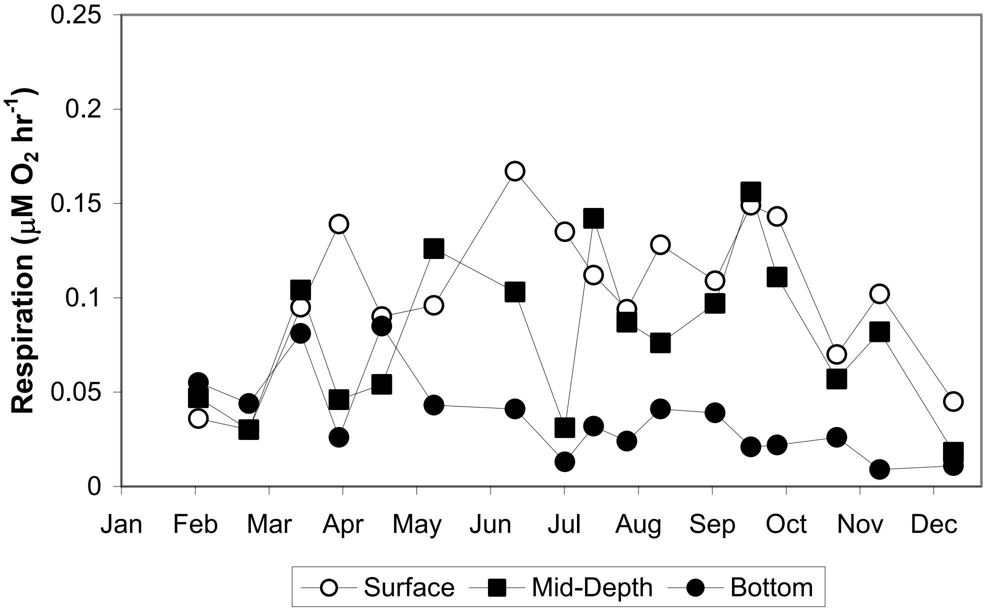
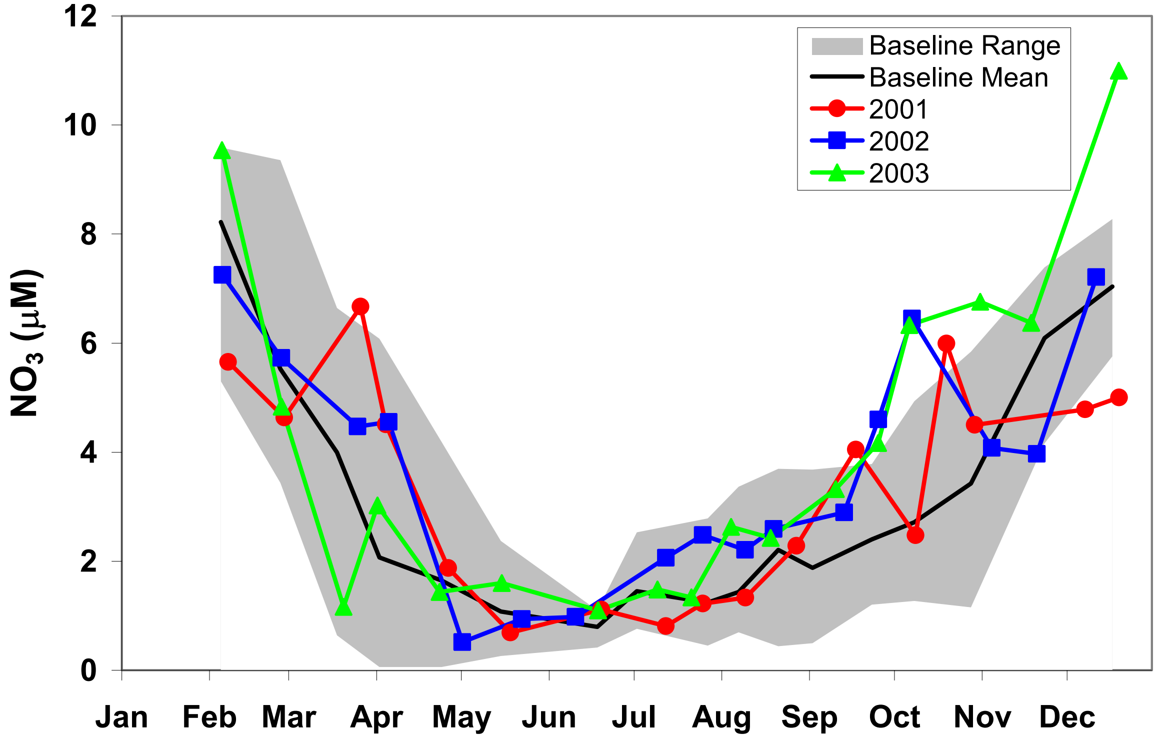


Figure B-12. Time series plots of respiration (μMO$_2$hr^{-1}) at nearfield stations N18 and N04 in 2003.

(a) Nitrate



(b) Silicate

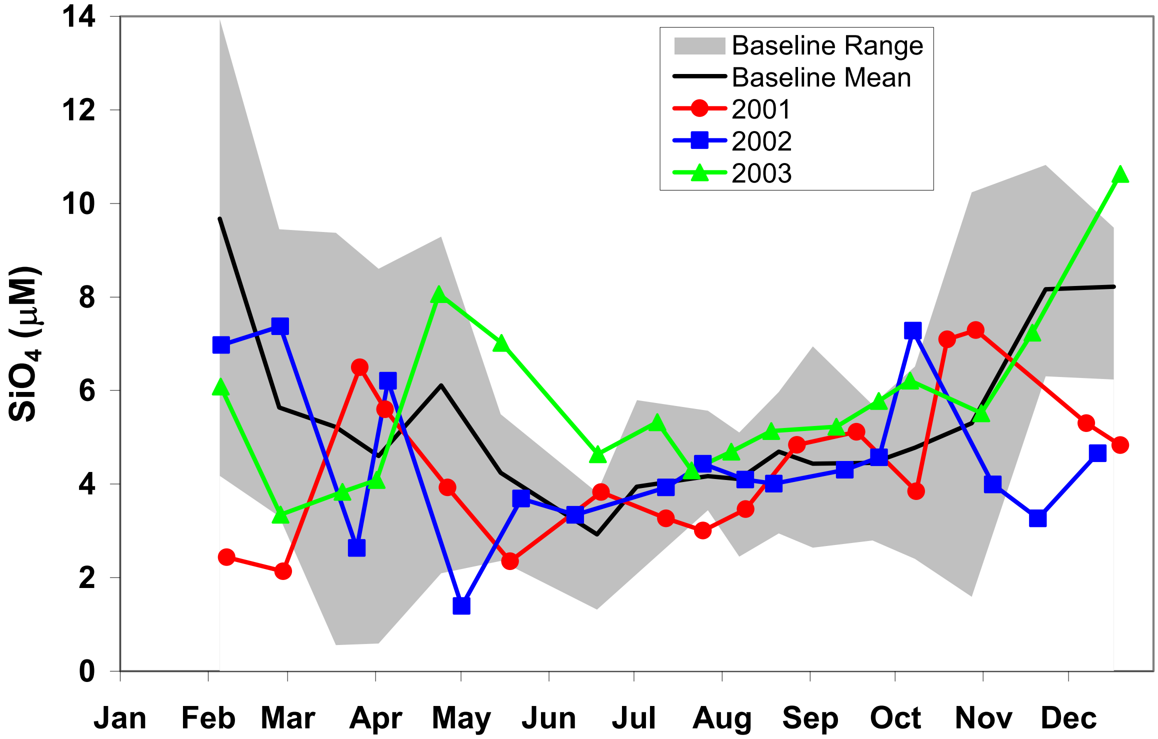
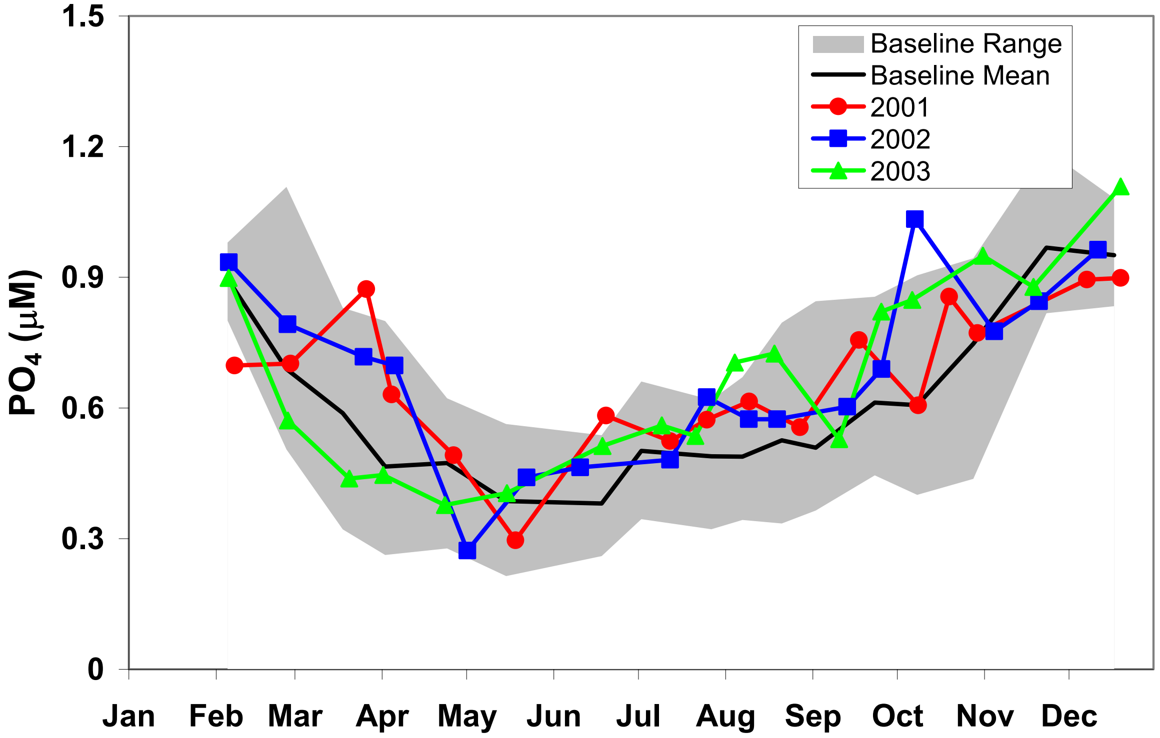


Figure B-13. Time-series of survey mean (a) NO_3 and (b) SiO_4 concentration in the nearfield in 2001, 2002 and 2003 compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all nearfield stations.

(a) Phosphate



(b) Ammonium

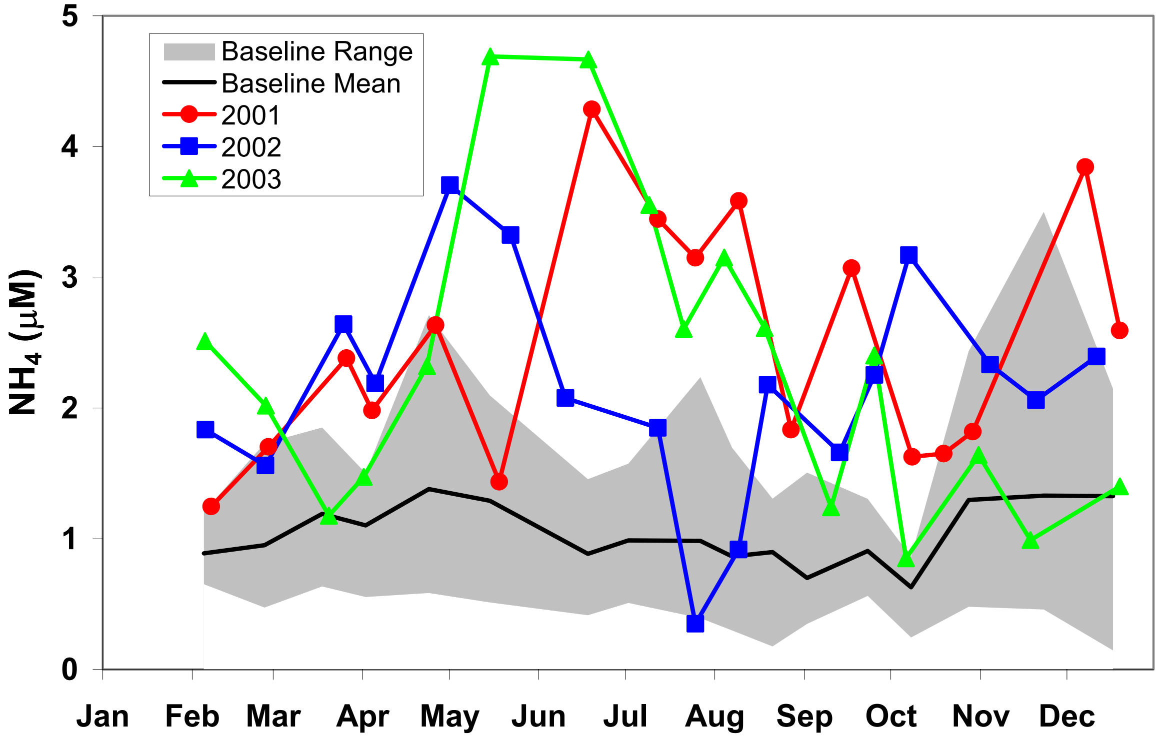
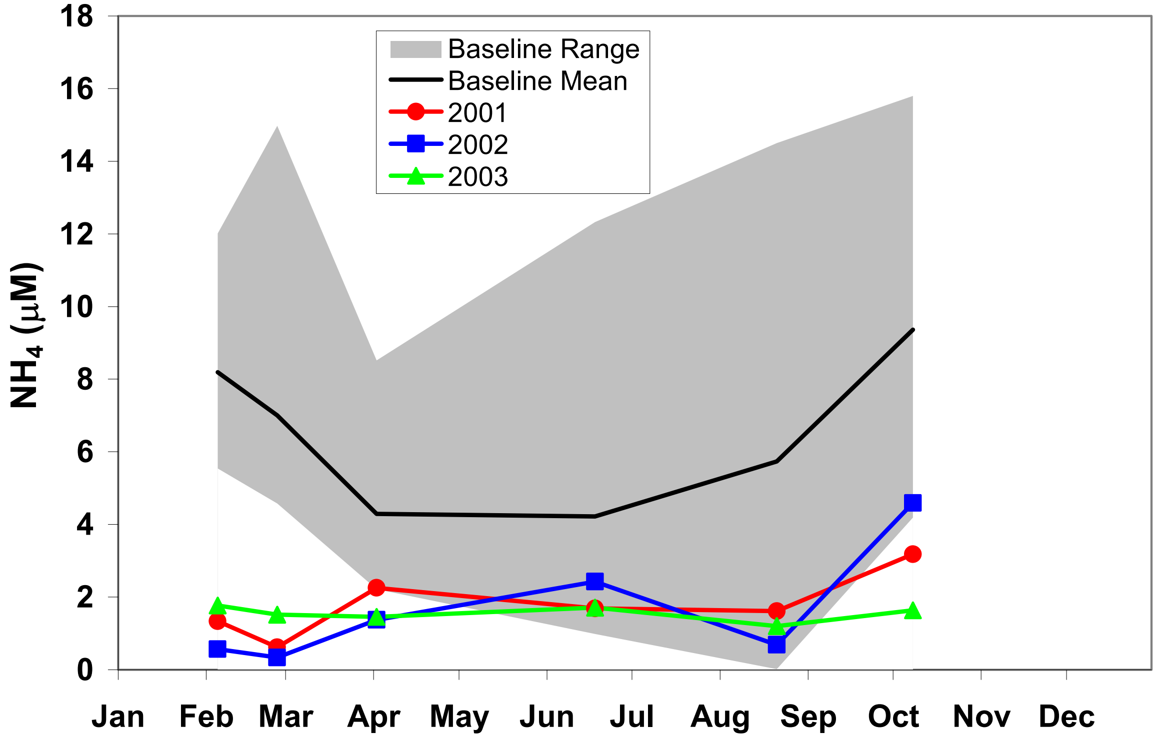


Figure B-14. Time-series of survey mean (a) PO_4 and (b) NH_4 concentration in the nearfield in 2001, 2002 and 2003 compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all nearfield stations.

(a) Ammonium



(b) Nitrate

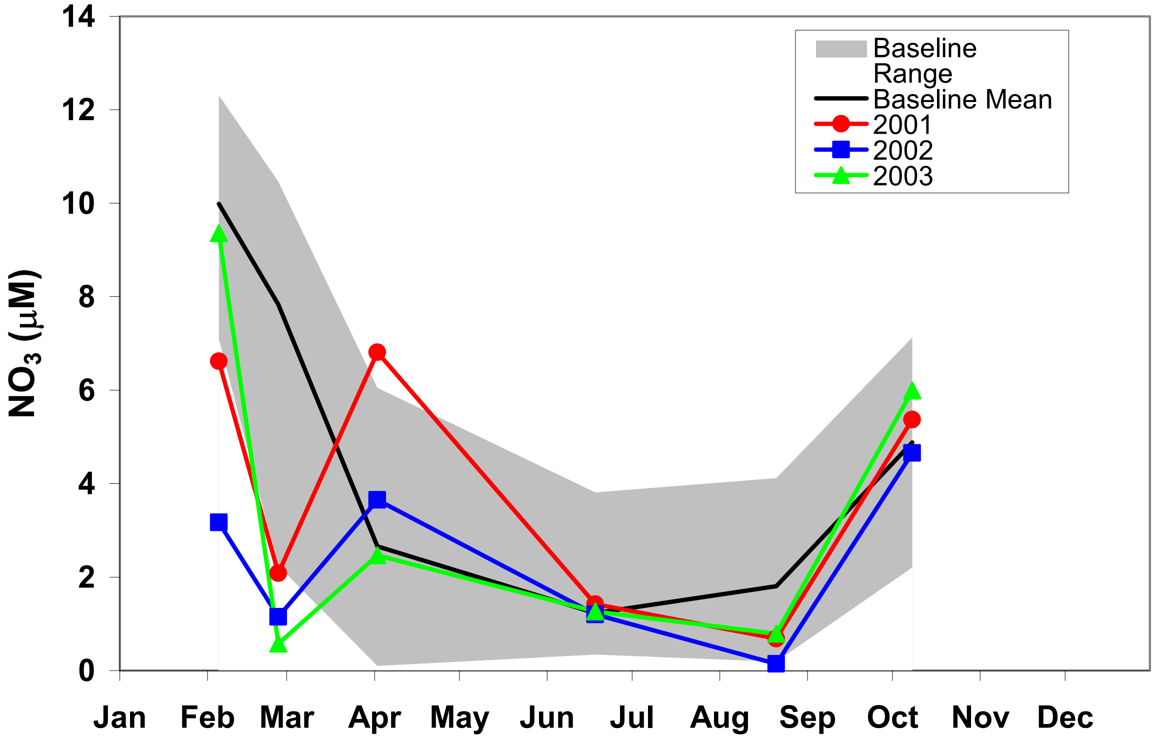
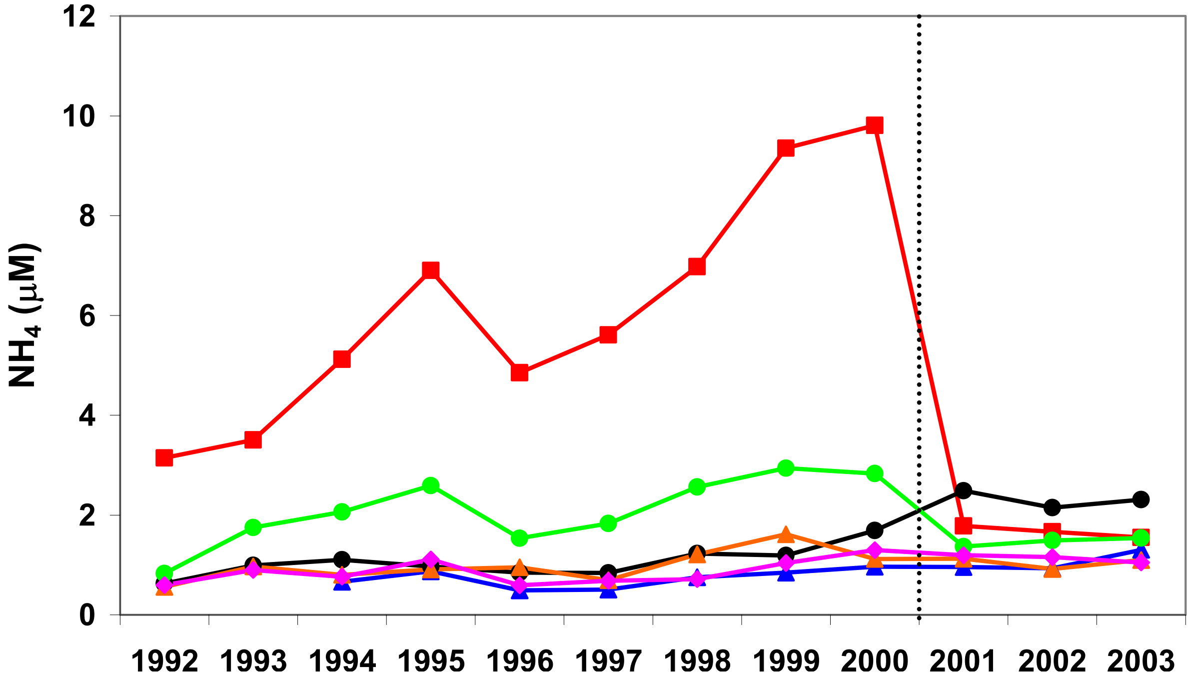


Figure B-15. Time-series of survey mean (a) NH$_4$ and (b) NO$_3$ concentration in Boston Harbor in 2001, 2002 and 2003 compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all harbor stations.

(a) Ammonium



(b) Nitrate

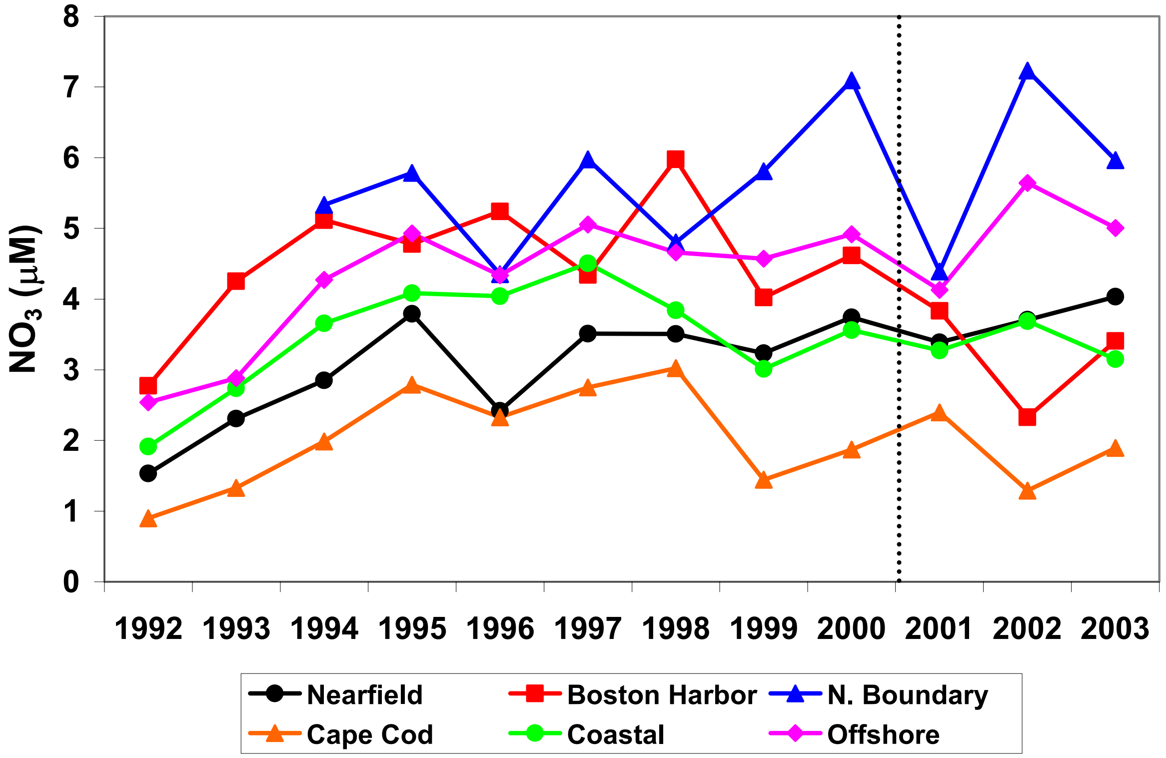
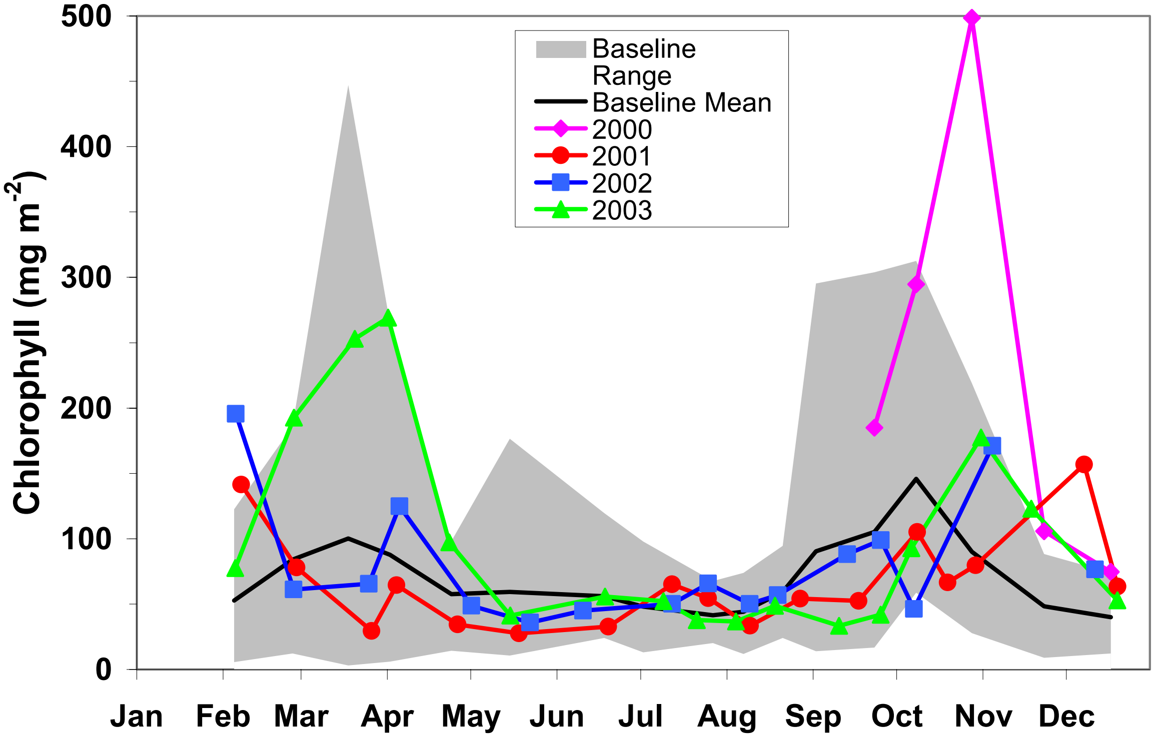


Figure B-16. Annual mean (a) NH_4 and (b) NO_3 concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

(a) Chlorophyll



(b) Particulate Organic Carbon

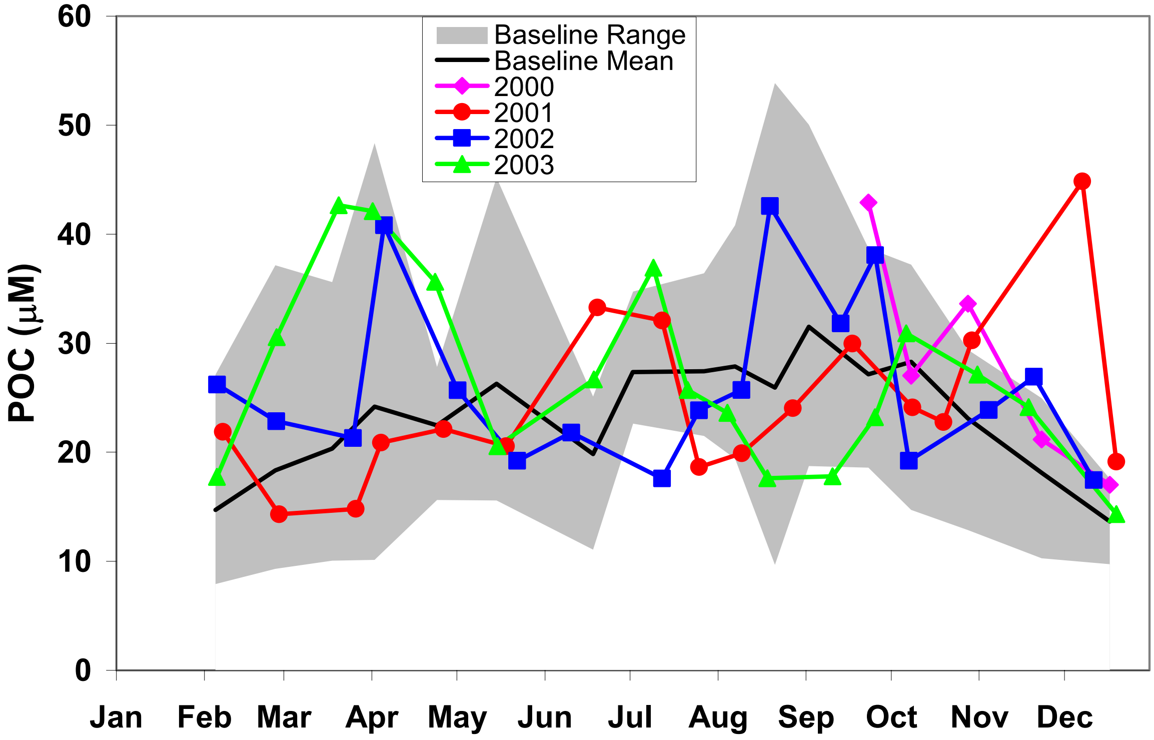
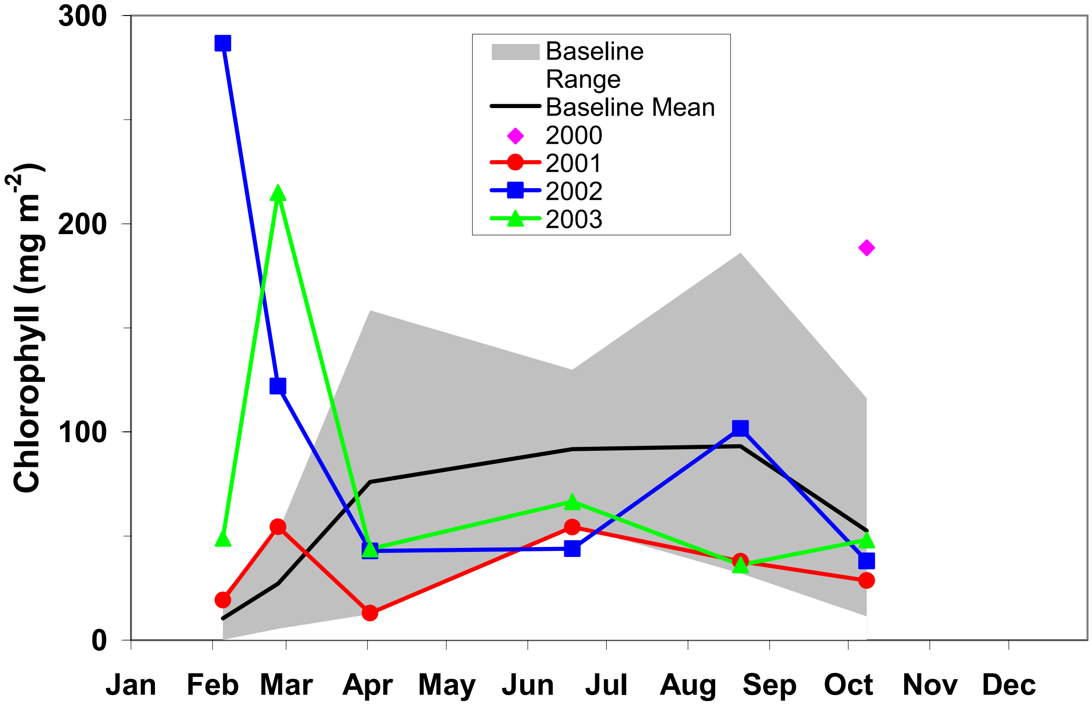


Figure B-17. Time-series of survey mean (a) chlorophyll and (b) POC concentration in the nearfield post-diversion (fall 2000 to 2003) compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all nearfield stations.

(a) Chlorophyll



(b) POC

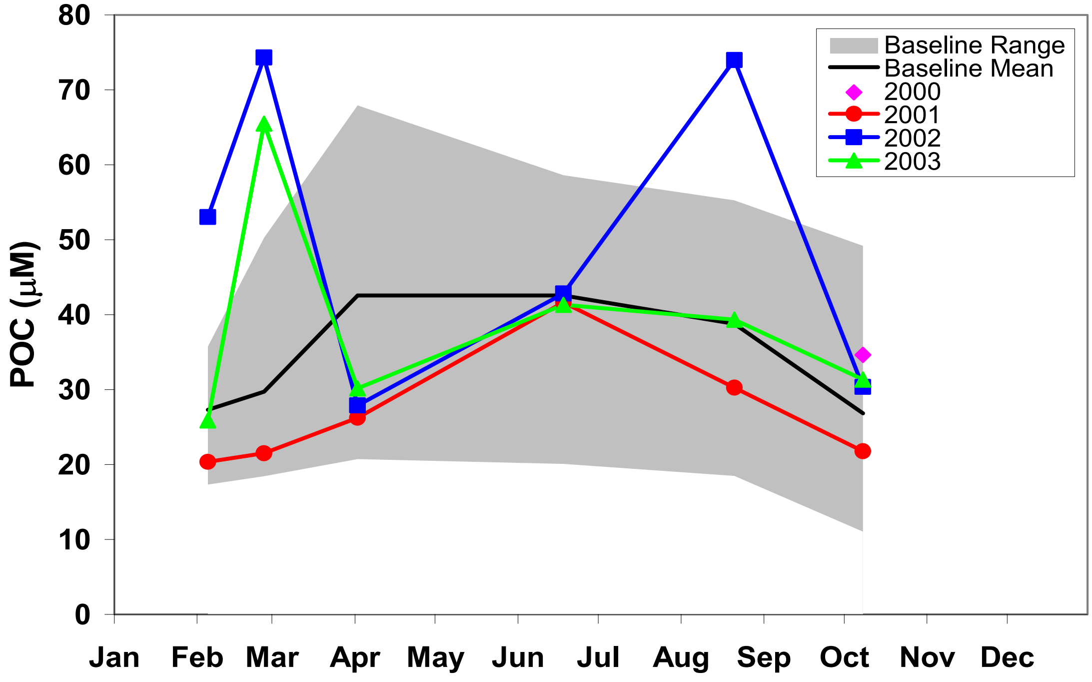
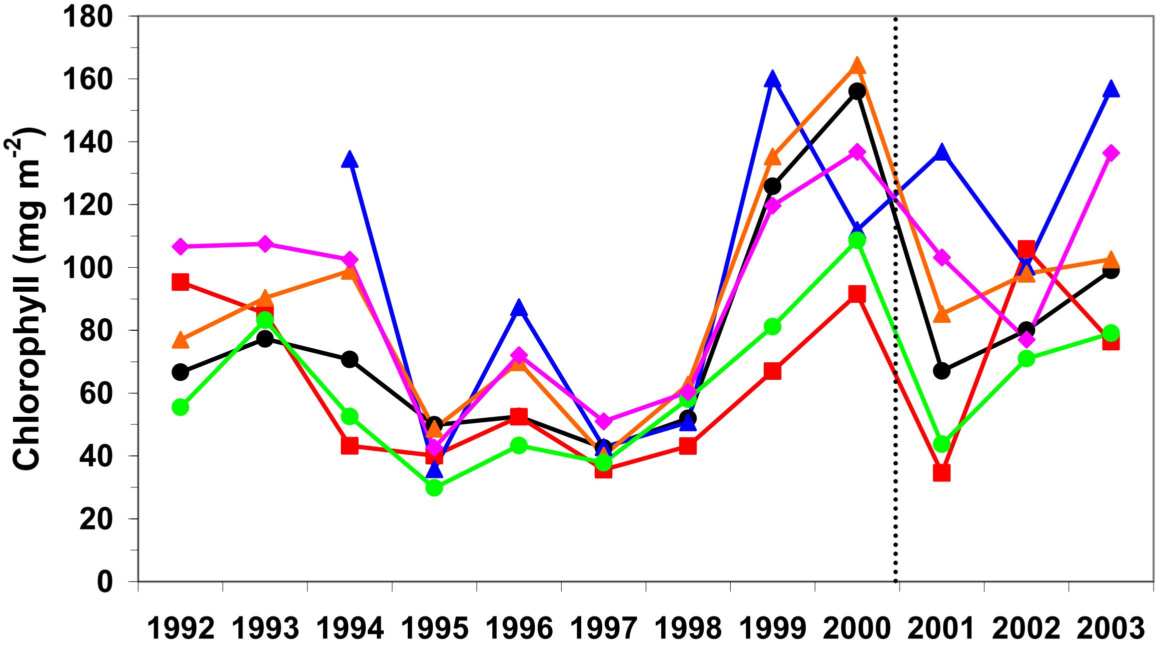


Figure B-18. Time-series of survey mean (a) chlorophyll and (b) POC concentration in Boston Harbor post-diversion (fall 2000 to 2003) compared against the baseline range and mean (1992-September 6, 2000). Data collected from all depths and all harbor stations.

(a) Annual Mean Areal Chlorophyll



(b) Annual Mean POC

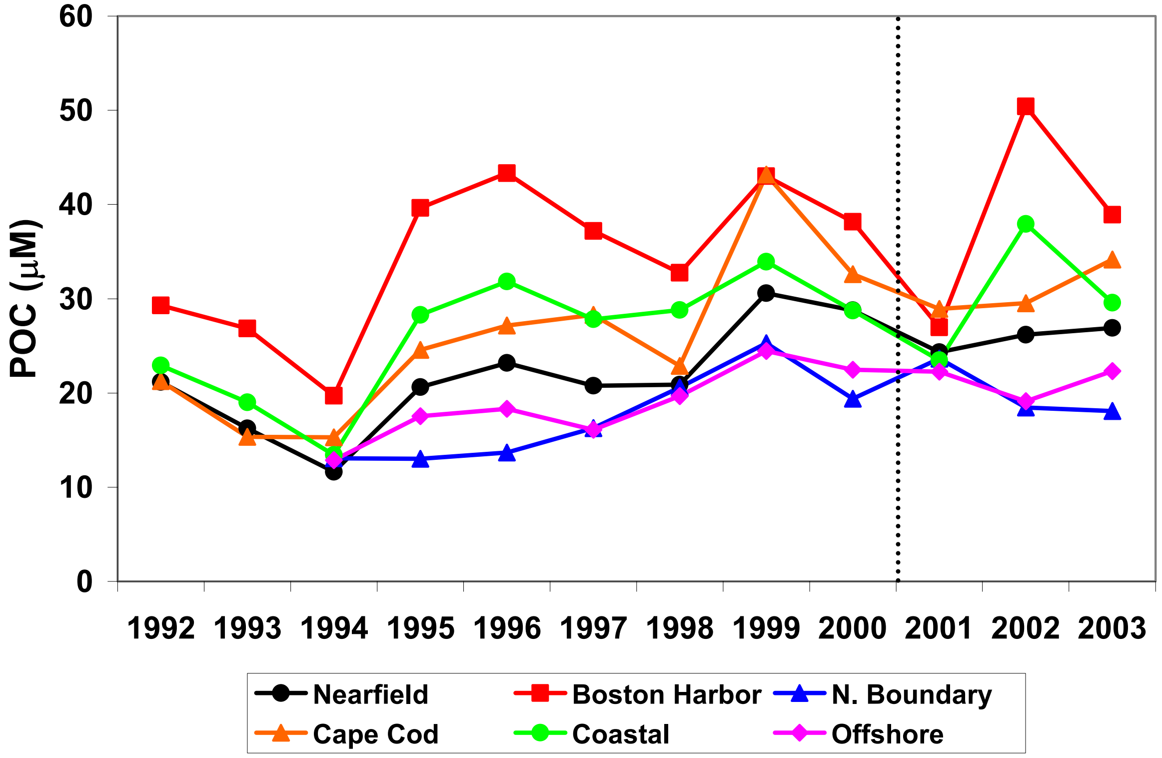


Figure B-19. Annual mean (a) areal chlorophyll and (b) POC concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

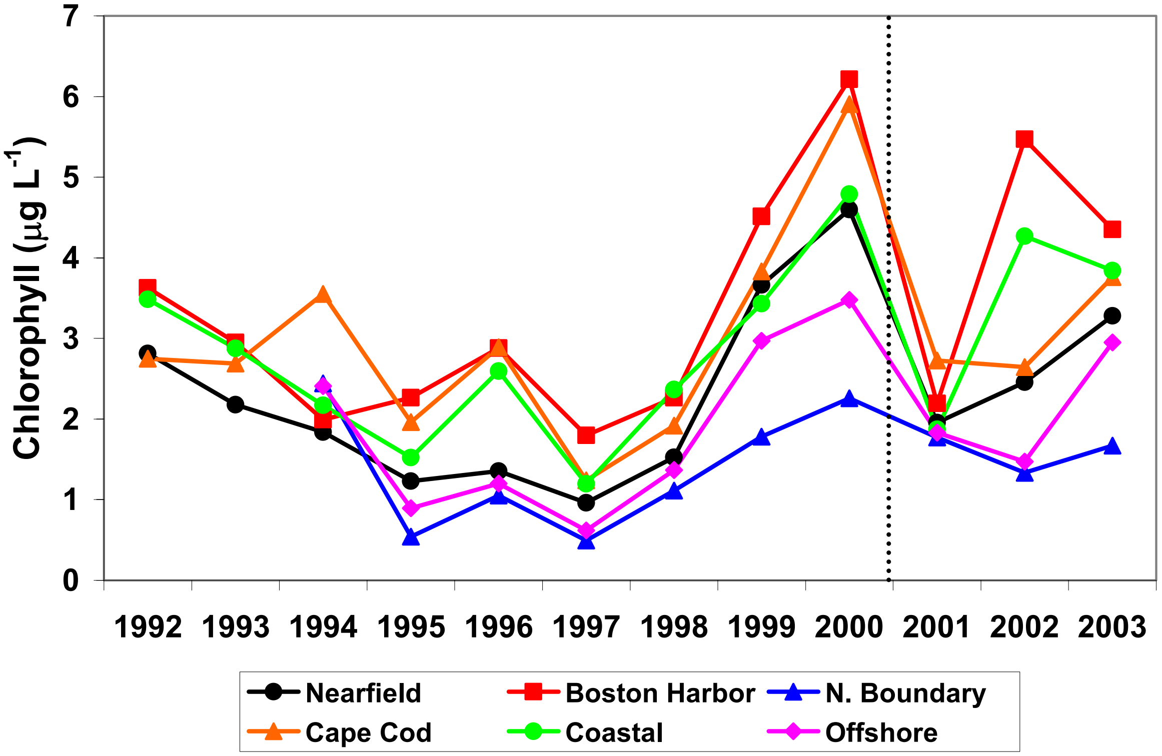
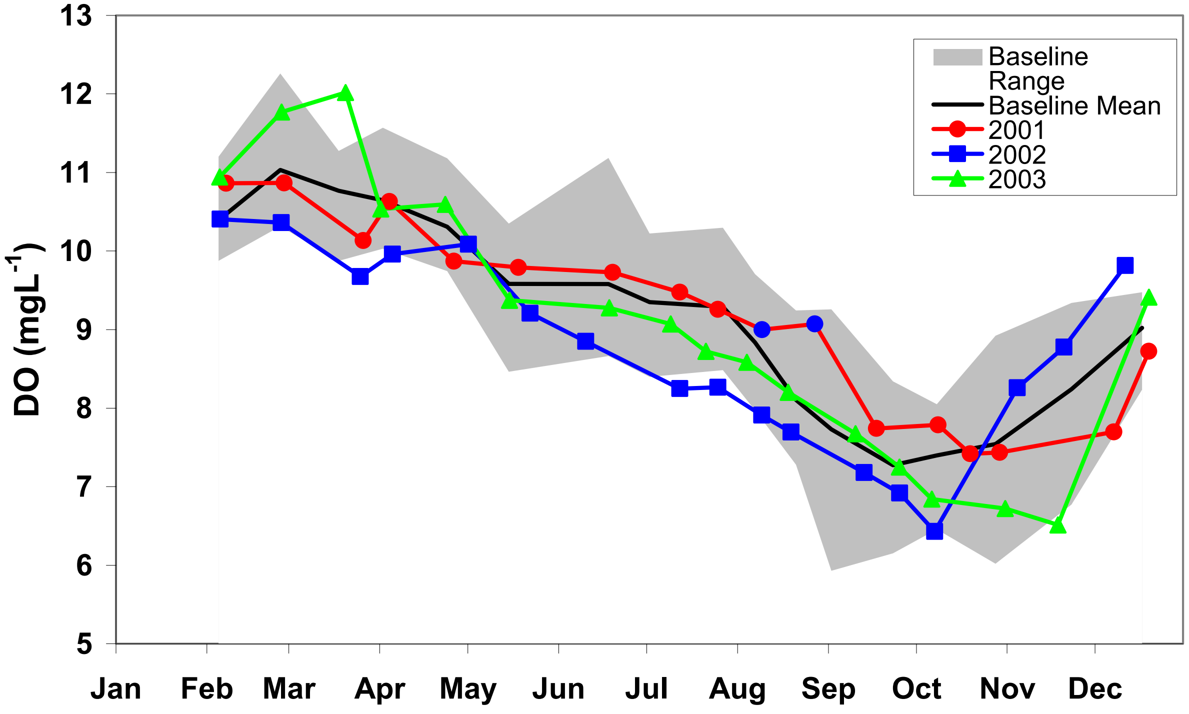


Figure B-20. Annual mean chlorophyll concentration in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

(a) DO Concentration



(b) DO Percent Saturation

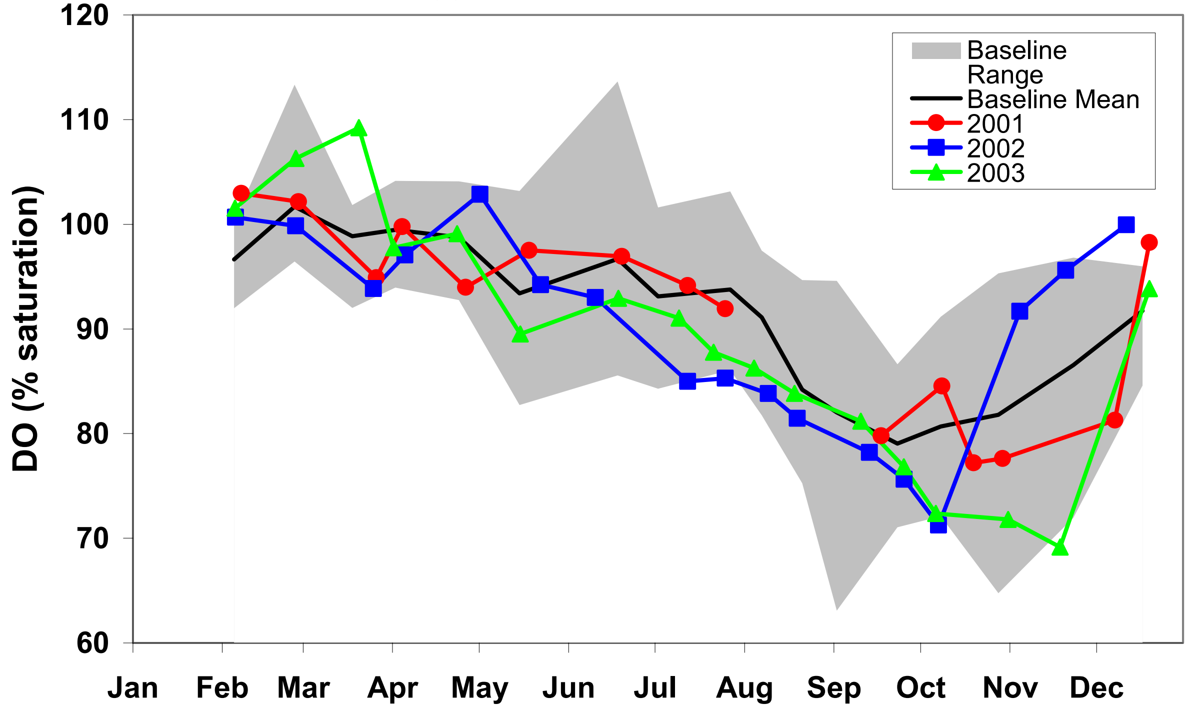
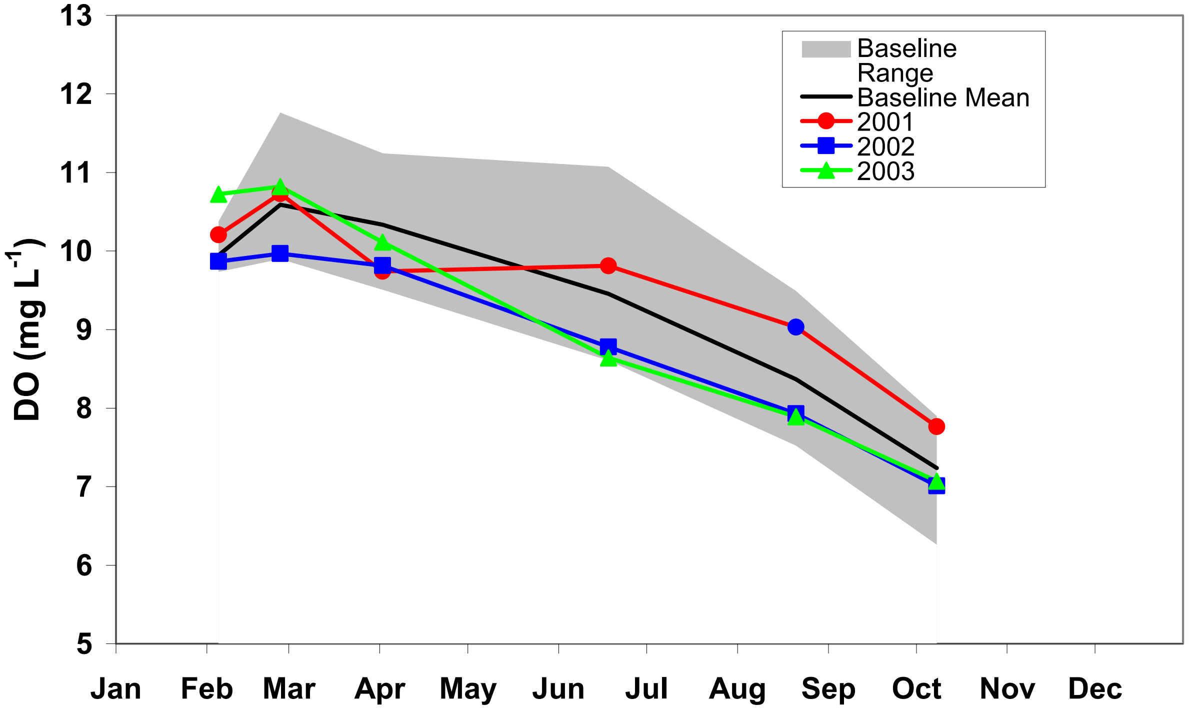


Figure B-21. Time-series of nearfield survey mean bottom water (a) DO concentrations and (b) DO %saturation in 2001, 2002 and 2003 compared against the baseline range and mean (1992-September 6, 2000). August 2001 data (blue dots) from Winkler titrations.

(a) DO Concentration



(b) DO Percent Saturation

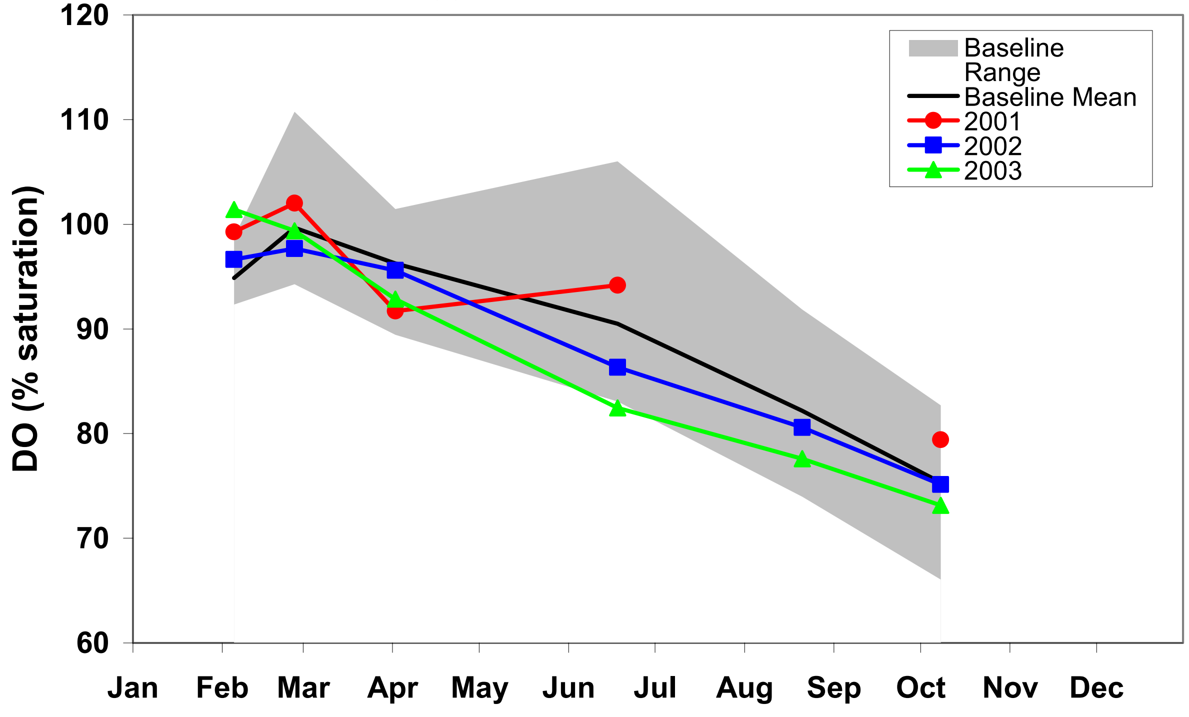
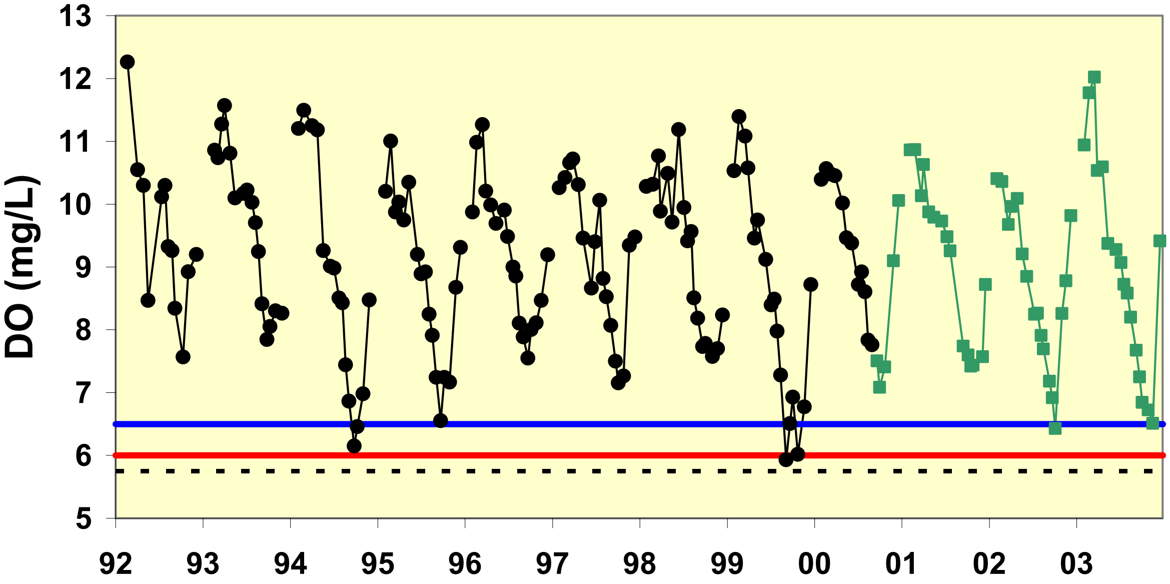


Figure B-22. Time-series of Stellwagen Basin survey mean bottom water (a) DO concentrations and (b) DO %saturation in 2001, 2002 and 2003 compared against the baseline range and mean (1992-September 6, 2000). August 2001 data (blue dot) from Winkler titrations. Data collected from stations F12, F17, F19, and F22.

(a) DO concentration



(b) DO Percent Saturation

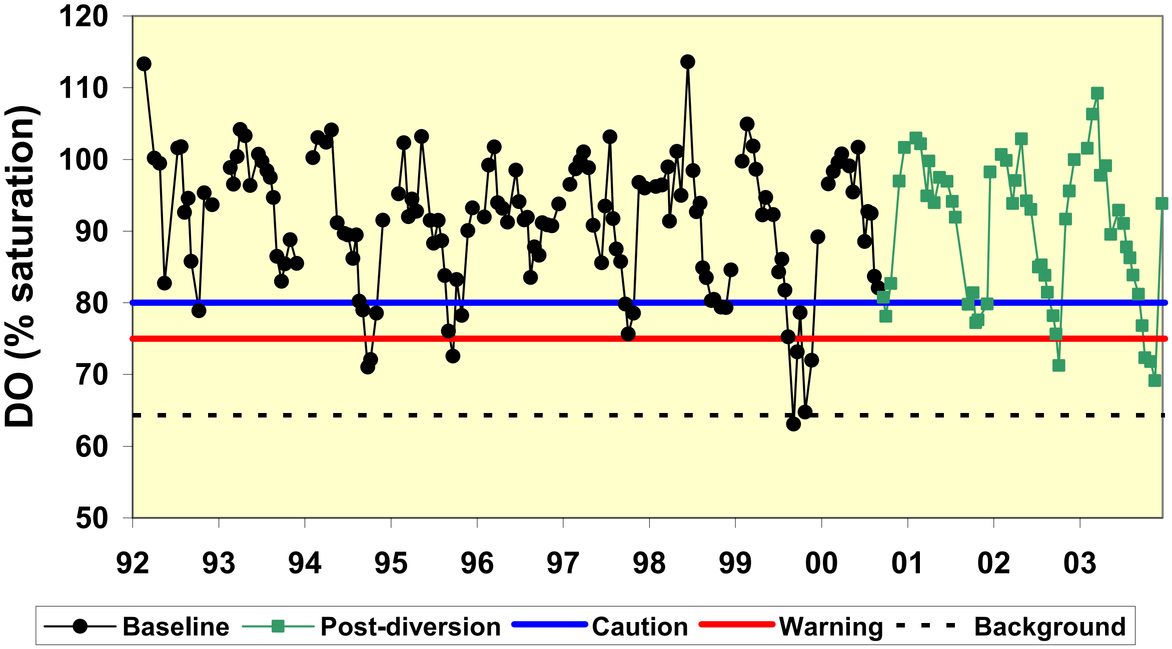
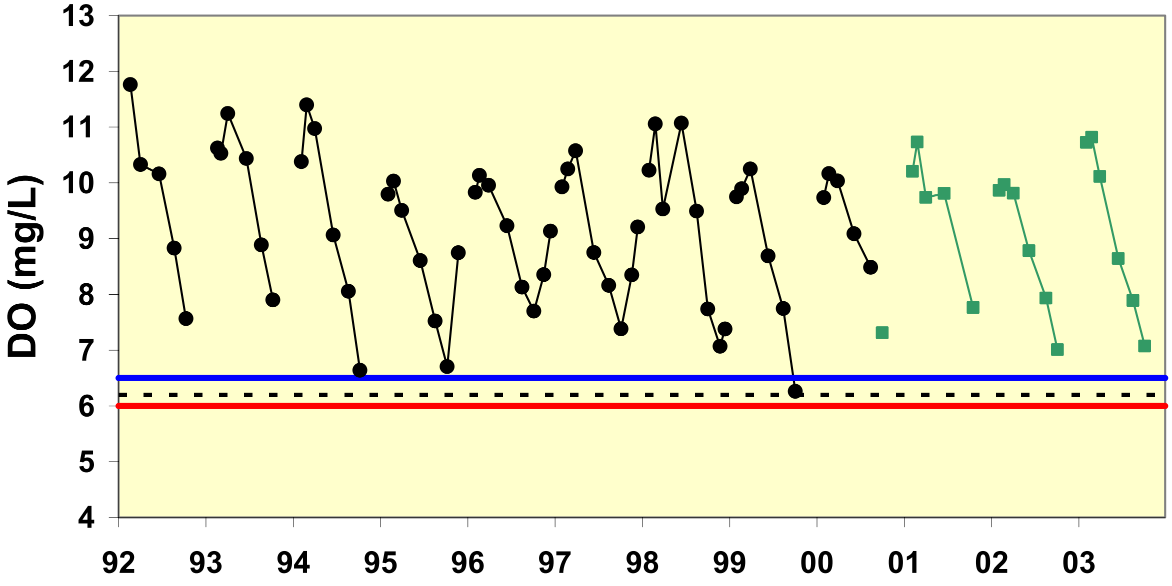


Figure B-23. Survey mean bottom water dissolved oxygen (a) concentration and (b) percent saturation in the nearfield compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares.

(a) DO concentration



(b) DO Percent Saturation

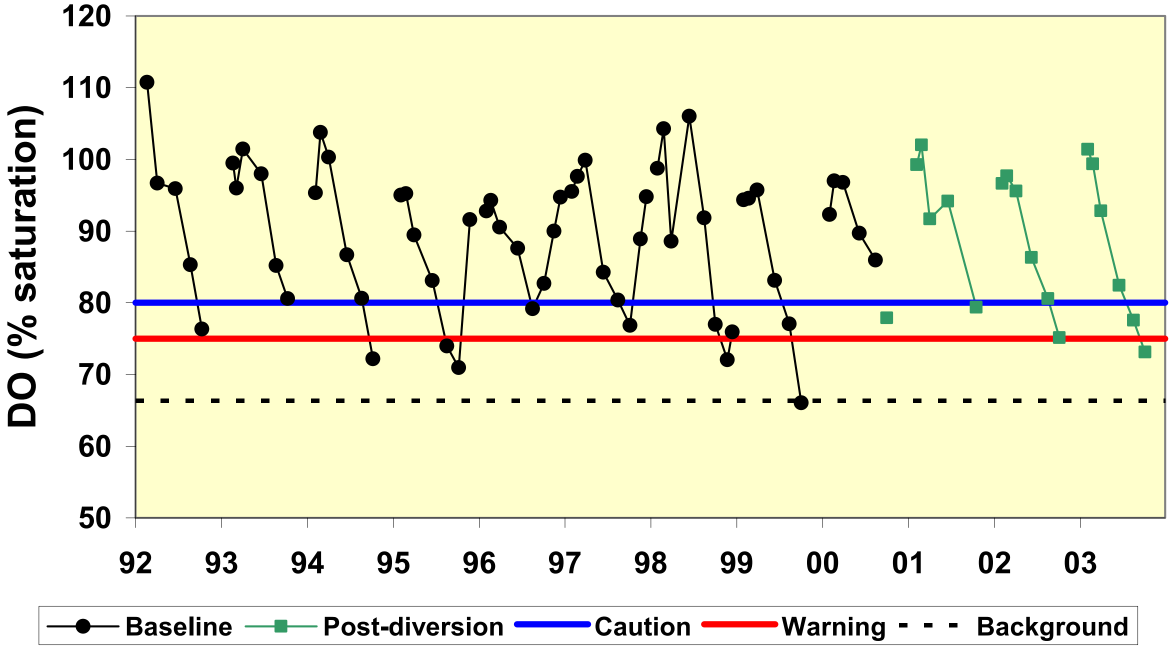


Figure B-24. Survey mean bottom water dissolved oxygen (a) concentration and (b) percent saturation in Stellwagen Basin compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares. Data collected from stations F12, F17, F19, and F22.

APPENDIX C

Productivity

C. PRODUCTIVITY

This section provides an overview of the trends and magnitude of primary productivity, as measured by ^{14}C methods, in Massachusetts Bay in 2003 with particular focus on the nearfield sites (station N04 and N18). The higher frequency sampling in the nearfield permits a more detailed examination of temporal trends and interannual differences in productivity in Massachusetts Bay relative to Boston Harbor. A detailed presentation of productivity data was undertaken in the two semi-annual reports for 2003 (Libby *et al*. 2003a and 2004). The current discussion focuses on the major themes described in the earlier reports. Additionally, we compare trends in productivity (seasonal, annual and bloom magnitude) for pre (1995 – 1999) and post (2001-2003) outfall periods and discuss Keller *et al*.'s (2001) warm winter – low bloom magnitude hypothesis utilizing additional data collected from 2000 – 2003. We also examine an alternate approach for calculating annual productivity and explore the interrelationships between productivity and other measured variables including nutrients, chlorophyll, dissolved oxygen and zooplankton abundance.

C.1 Summary of 2003 Productivity Results

C.1.a Nearfield Description

Areal production at the nearfield stations in 2003 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 – 2003. However, timing of events was somewhat different from earlier years, with a late onset of both the spring and fall blooms. Additionally, some differences in the magnitude of productivity were noted, with low bloom peaks during the spring and fall periods of elevated productivity particularly at station N04, relative to most years.

Potential and measured productivity were similar throughout much of the seasonal cycle in 2003, particularly during the later portion of the year (**Figure** C-1). The spring bloom in 2003 was underway by 20 March 2003 at both nearfield sites, as indicated by measured and potential areal productivity (**Figure** C-1). The initial productivity peaks in 2003 occurred simultaneously at both stations in late March but ultimately reached a higher level (1618 mg C m^{-2} d^{-1}) at station N18 compared with N04 (1230 mg C m^{-2} d^{-1}). The bloom period extended from late March through late April at station N04 but ended earlier at station N18. The decrease in potential productivity at both stations in May coincided with the decline in abundance of a *Phaeocystis* bloom, which peaked in the nearfield during April.

The duration of the spring bloom was similar to that observed in prior years. 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. In 2003, the onset of the bloom was observed in mid-March at both sites. The termination of the 2003 spring bloom occurred by mid-May, the typical timing observed in prior years. The onset of stratification and depletion of nitrogen in the surface waters coincided with the cessation of the spring bloom as in prior years.

Distinct winter-spring phytoplankton blooms were observed at both nearfield stations during the sampling period (**Figure** C-1). In general, nearfield stations are characterized by the occurrence of a winter-spring bloom. The winter-spring blooms observed at nearfield stations in 1995-2002 generally reached values of 2000 to 4500 mg C m^{-2} d^{-1}, with bimodal peaks often occurring in February – April concomitant with diatom and *Phaeocystis* blooms. The bloom in 2003 reached maximum values at the nearfield sites of ~1200-1600 mg C m^{-2} d^{-1} with peaks observed in late March/early April. Unlike many years, an early February peak was not observed. This was consistent with the lack of a centric diatom bloom. The winter-spring bloom peaks at both nearfield sites in 2003 were lower than values observed during the winter-spring period in recent years (1999 to 2002).

Potential areal production in the later half of 2003 at the nearfield stations varied somewhat from patterns typically observed in prior years. Potential productivity at station N04 was elevated relative to station N18 during the summer. During the early fall (September 25 to October 3, 2003) productivity was 2-3 times greater at station N18 relative to N04. By late fall, potential productivity was again greater at station N04 relative to N18. A bloom occurred during the mid summer (July) at both nearfield sites followed by a major increase in productivity in October, particularly at station N18. The typical October bloom present early in the month during 4 to 5 of the last 7 years was somewhat delayed in October 2003 and extended into November at station N04. The fall bloom peaks were lower in magnitude relative to peak fall bloom values observed during the post outfall period but similar to most values from 1995 to 1999, particularly at station N04. The fall blooms observed at nearfield stations in 1995-2001 generally reached values of 1600 to 5000 mg C m^{-2} d^{-1}, with blooms typically lasting 3-4 weeks. The fall bloom in 2003 reached peak values of 1700 to 2500 mg C m^{-2} d^{-1} in late October at station N18 and mid-November at station N04. From 1995-2000, the fall bloom peak has been consistently higher at station N18 compared with N04. In 2001 the peak fall productivity was similar at both sites while in 2002 peak late summer productivity was once again greater at N18. A similar trend was observed this year.

The fall peak in productivity in 2003 may be related to an increase in nutrient concentrations. The water column remained somewhat stratified later in 2003 relative to prior years and the delayed increase in surface nutrient concentrations may have fueled the delayed increase in productivity. As in most years, the increase in productivity followed the destratification of the water column. Zooplankton abundance in the nearfield region decreased during October, perhaps in response to the presence of ctenophores suggesting a link between the late occurrence of a bloom and decreased grazing via zooplankton.

C.1.b Boston Harbor Description

The productivity pattern at the Boston Harbor station F23 in 2003 differed somewhat from the pattern observed in 2001 – 2002 (**Figures** C-1 and C-2). Areal productivity at F23 peaked during the spring bloom period following the pattern observed in 2001 - 2002, however productivity was also elevated during the mid-summer and early fall. Productivity declined in October, however, the truncated sampling at F23 may not have captured the late October-mid-November period of peak fall productivity observed at the nearfield sites. As noted in 2001, the alterations in the seasonal productivity pattern in the harbor may be related to the diversion of treated effluent offshore. Prior to the outfall, productivity in the harbor was characterized by increasing rates throughout the summer, followed by a fall decline. The pattern observed at station F23 in the spring and summer of 2003 resembles the seasonal cycle observed at the nearfield stations. In 2003, the spring bloom dominated the seasonal cycle. In 2002, the spring and late summer peaks were equivalent in magnitude, while in 2001 the fall peak dominated the annual cycle. The altered seasonal productivity cycle may be tied to reduced nutrient availability in the Harbor in recent years during the summer-stratified period.

C.2 Interannual Comparisons

C.2.a Areal Productivity

To assess the potential effects of the September 2000 relocation of effluent discharge from Boston Harbor to Massachusetts Bay on areal productivity, we compared production measurements at the nearfield stations N04 and N18 and the Boston Harbor station F23 in 2003 to the baseline productivity data collected from February 1995 to August 2000 (**Figure** C-2). Areal production at the nearfield sites in 2003 was greater than the maximum recorded over the baseline period on two occasions during 2003 and less than the baseline minimum five times. The major deviation from the baseline data was the delay in the bloom peak during the fall period at both nearfield stations. In general, measured productivity during 2003 was lower than the baseline mean at both nearfield sites suggesting little change tied to increased nutrient availability related to the outfall.

At the Boston Harbor station, productivity in 2003 generally fell well below the baseline mean with the exception of the spring bloom period which was greater than the baseline maximum. The decrease in productivity in the harbor is most likely tied to decreased nutrient availability, as also suggested by the altered seasonal productivity pattern.

C.2.b Depth-Averaged Chlorophyll-Specific Production

The current and long-term results for chlorophyll-specific areal production at stations N04, N18 and F23 are presented in **Figure** C-3 in a similar fashion. However, the baseline period is shorter (1997 – 2000) since areal chlorophyll-specific productivity measurements were unavailable before 1997. For the nearfield sites, the chlorophyll-specific areal production in 2003 was generally below the baseline mean and frequently lower than the baseline minima. For the Boston Harbor station, the values were very close to the baseline minima throughout the winter-spring period and below the baseline mean for the remainder of the annual cycle.

Chlorophyll-specific areal productivity in 1997 was elevated compared to 1998 through 2001. For station N04, all of the points in the upper range of the baseline data in **Figure** C-3 are from 1997; for station N18, 15 of the 17 values in the upper range are from 1997. Differences in techniques (i.e. chlorophyll measurement and integration depth) between HOM2 and HOM3 most likely contributed to the high values observed in 1997. To assess the impact of the 1997 data on the baseline period, chlorophyll-specific productivity for station N04 was replotted without the 1997 data (**Figure** C-4). Throughout most of the annual cycle, chlorophyll-specific productivity now appears closer to the baseline mean, although occasionally still lower than the minima (as it also does for station N18, data not shown). The 2003 data, however, now exceed the baseline maxima on 3 occasions, suggesting that the shortened baseline period may not be useful for comparisons. Based on these findings, the differences in techniques between HOM2 and HOM3 need to be further examined before including the 1997 chlorophyll-specific production data in the baseline period.

C.2.c Bloom Magnitude

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. Spring peaks have changed relatively little at both nearfield sites during the post outfall period, however, fall bloom peaks have tended to increase in magnitude. During the spring at N18, the station nearest the outfall, primary productivity rates decreased from about 3000 to 2900 mg C m^{-2} d^{-1} (**Figure** C-5). At station N04 the rates increased from 2300 to 2500 mg C m^{-2} d^{-1}. During the fall, productivity peaks increased on average 600-800 mg C m^{-2} d^{-1} at the nearfield stations (**Figure** C-5). 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 – February through April. 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 (Libby *et al*. 2002). As data availability increased, however, the zooplankton vs. temperature relationship appeared less significant as shown in **Figure** C-6a. It was noted, however, that from 2000 to 2003 blooms of *Phaeocystis* 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 during non *Phaeocystis* years is highly correlated with warmer temperatures, but the relationship between phytoplankton biomass and temperature during *Phaeocystis* blooms is more variable (**Figure** C-6b and c).

There is a weak positive relationship between zooplankton abundance and production during the spring bloom (**Figure** C-7a). Zooplankton abundance, however, was positively correlated (weak) to mean bloom chlorophyll concentrations during non *Phaeocystis* years and negatively correlated (strong) during *Phaeocystis* years (**Figure** C-7b). This apparent disconnect between zooplankton correlations with bloom production and chlorophyll may have less to do with the initial hypothesis noting a temperature dependence on both phytoplankton biomass and zooplankton abundance (and by extension grazing) and more to do with the effect on zooplankton grazing during *Phaeocystis* blooms. The lack of a relationship between production rates and bloom chlorophyll also suggests that this is the case as even when production rates are low there is often a high amount of biomass present (i.e. not being grazed down; **Figure** C-7c). This is contrary to the near lockstep relationship between production and biomass during the non *Phaeocystis* years. For this report, all data from the first four nearfield surveys were included while previous analyses have looked at a variety of data groupings. The patterns generally hold true when individual stations are examined, but do change based on the time period selected (i.e. entire bloom period vs. specific surveys). These differences reflect the importance of spatial and temporal variation in bloom magnitude within the sampling region and winter/spring period. 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 pre-outfall period.

C.2.d 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. Here we compare an alternate approach to this method by assuming 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 results in a decrease in annual productivity; on occasion, increases occur if the initial or final samples were collected during bloom conditions (**Table** C-1).

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

	Stations					
Year	**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	521	532	542	607	556	587
2003	323	295	330	293	368	311

Figure C-8 compares potential annual productivity during pre and post outfall years utilizing both methods of calculation (note: 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 station N04 of about 50 g C m^{-2} y^{-1}, almost no change in N18 and a decrease at the mouth of Boston Harbor of about 325 g C m^{-2} y^{-1}. Utilizing the new approach the increase at the nearfield sites was 20 – 70 mg C m^{-2} d^{-1} and the decrease at Boston Harbor was about 300 g C m^{-2} y^{-1}.

Statistical analyses were performed to estimate significant differences pre and post diversion for annual and seasonal primary productivity estimations. No differences are significant as the sample set is limited to only three samples (2001 - 2003) for spring and annual comparisons and four years (2000-2003) of data for the fall comparisons. Although it was not significant, both calculation approaches indicate a decrease in annual production of ~40% in Boston Harbor.

C.2.e Interrelations between Production and Other Variables

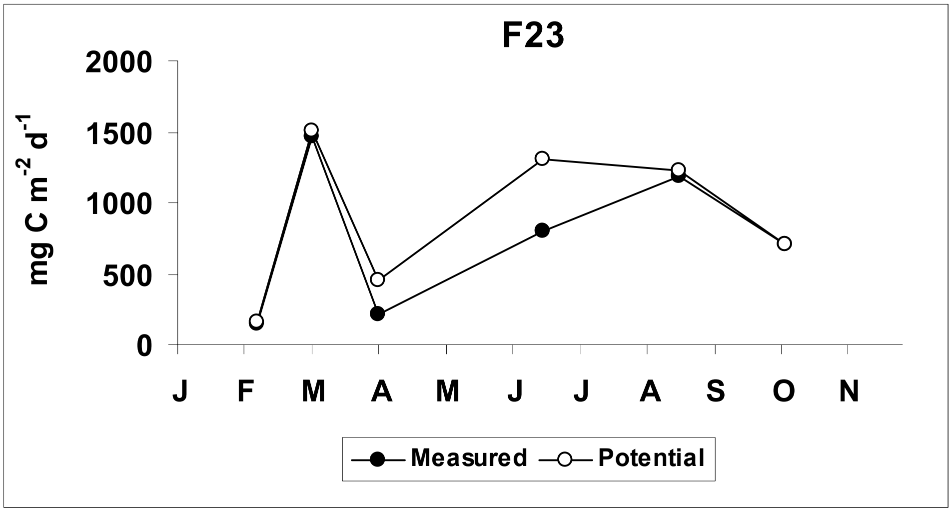
Although there were no significant differences between pre and post diversion production, the data do show higher post diversion mean production at the nearfield stations and lower mean production in Boston Harbor in comparison to the baseline values (**Figure** C-8). Similar changes are apparent in mean chlorophyll *a* and particulate organic carbon concentrations (**Figure** C-9). These changes are coincident with an increase in ammonium (NH_4) concentrations in the nearfield and a decrease in the harbor (**Figure** C-10).

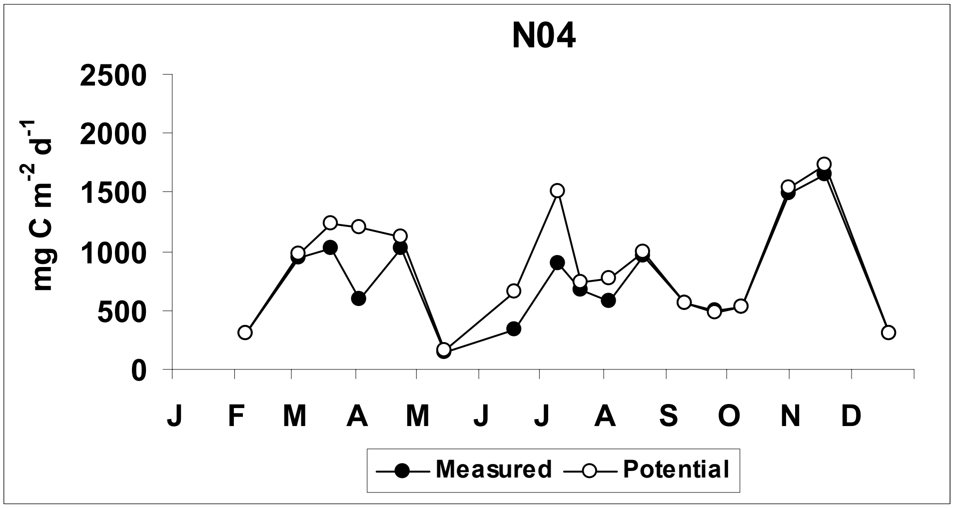
At the nearfield stations there is also an apparent increase in the amount of dissolved inorganic nitrogen (DIN) utilized during the spring bloom. By comparing pre-bloom nutrient concentrations to post bloom concentrations in surface waters, an apparent decrease or delta value can be calculated to indicate relative biological utilization (**Figure** C-11). At nearfield stations the change in delta DIN over the spring bloom period was ~7.5 µM prior to diversion to the bay outfall. After diversion, delta DIN increased to 10.8 µM at N18 and 8.0 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 1.75 µM at N04. **Figure** C-12 indicates a positive relationship between the winter spring productivity peak and the change in surface nitrogen concentration over the bloom period. The availability of an additional source of DIN namely the NH_4 rich effluent in the nearfield could be fueling the apparent increase in production observed during the first three 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.

In addition to the above relationships, correlations were examined between the magnitude of the winter/spring bloom and low oxygen in the bottom water the following spring/summer and between peak bloom production and biomass. These parameters were only weakly correlated. It has been suggested that regional physical factors play the dominant role in controlling bottom water dissolved oxygen in the nearfield (Geyer *et al.* 2002) and the disconnect between peak production and peak chlorophyll levels has been observed during both winter/spring and fall blooms in Massachusetts Bay (Libby *et al.* 2003b).

C.3 Summary

- Areal production at the nearfield stations in 2003 followed patterns observed in prior years, with the occurrence of both spring and fall blooms and variable summer productivity.
- Timing of events was somewhat different from earlier years, with a late onset of both the spring bloom and peak fall productivity.
- The major deviations from the baseline data in the nearfield region include the lower magnitudes of the seasonal blooms and the absence of a major bloom in October.
- At the Boston Harbor station, productivity in 2003 generally fell well below the baseline mean with the exception of the spring bloom period which exceeded the baseline maximum.
- Productivity in the harbor has decreased during the post outfall period with an apparent change in the seasonal productivity pattern.
- A comparison of potential annual productivity during pre and post outfall years indicates a slight increase in values at nearfield sites and a decrease at the mouth of Boston Harbor of about 40% (300 g Cm^{-2} y^{-1}). Productivity has increased during the spring and fall bloom peaks as well, but due to the small size of the data sets being compared none of these changes are significant.
- The NH_4 rich effluent in the nearfield could be fueling the apparent increase in production observed during the post-outfall period.





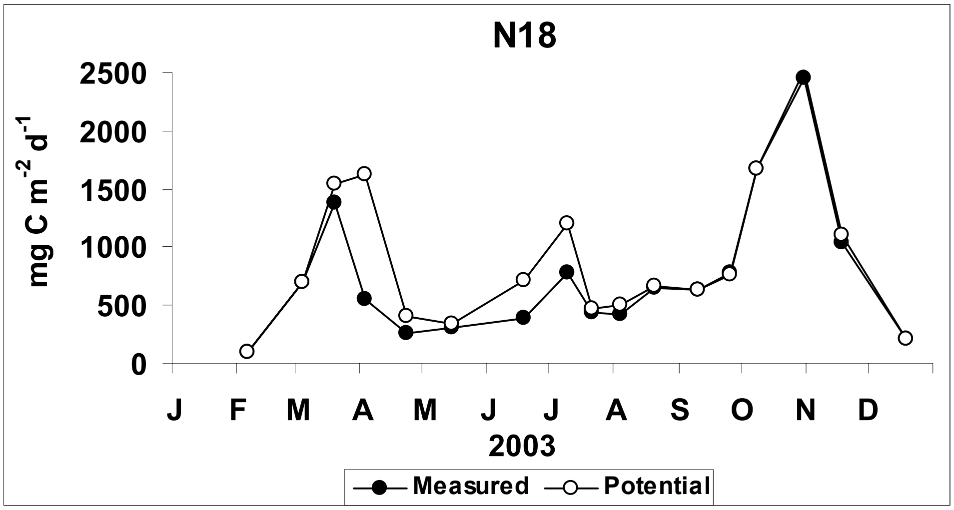
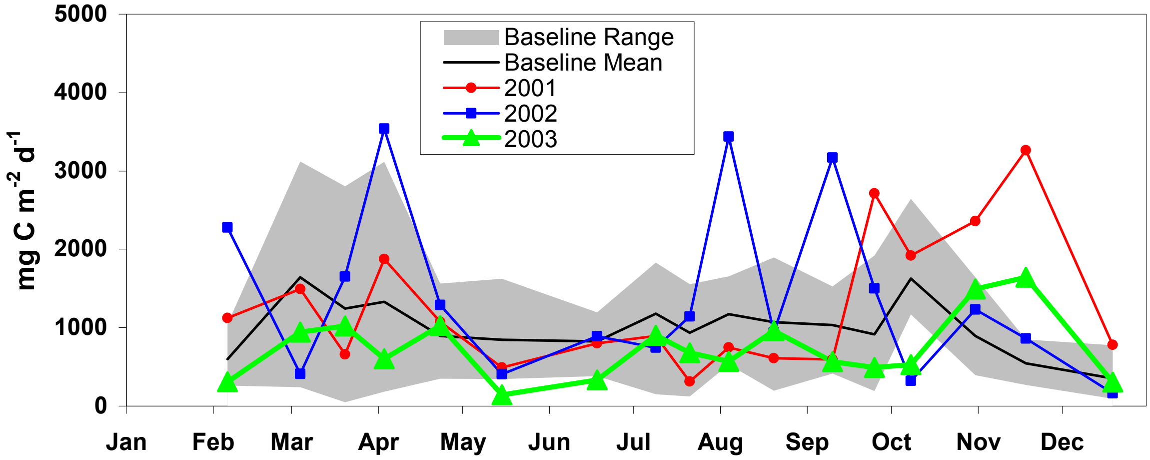
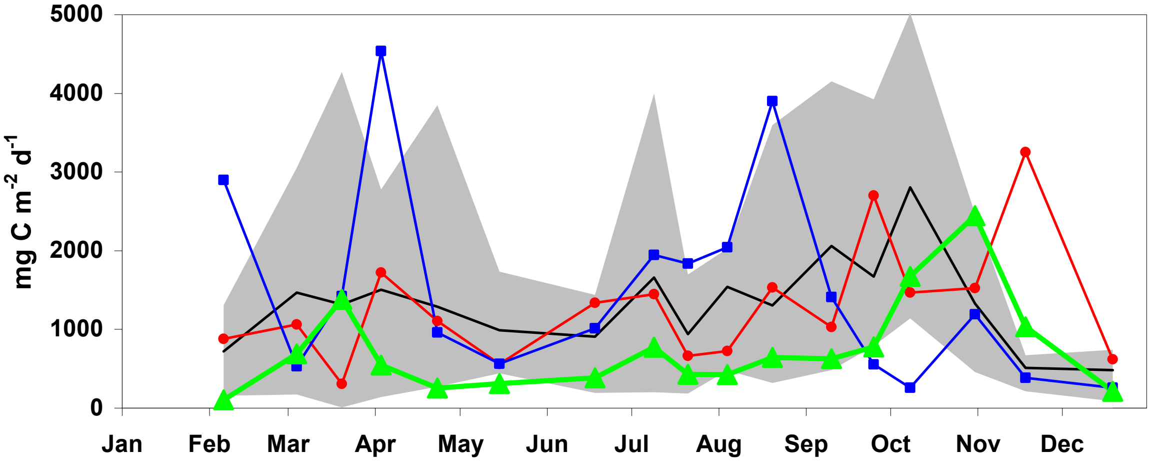


Figure C-1. Measured and potential areal production (mgCm^{-2}d^{-1}) in 2003 at stations F23, N04 and N18.

(a) NO4



(b) N18



(c) F23

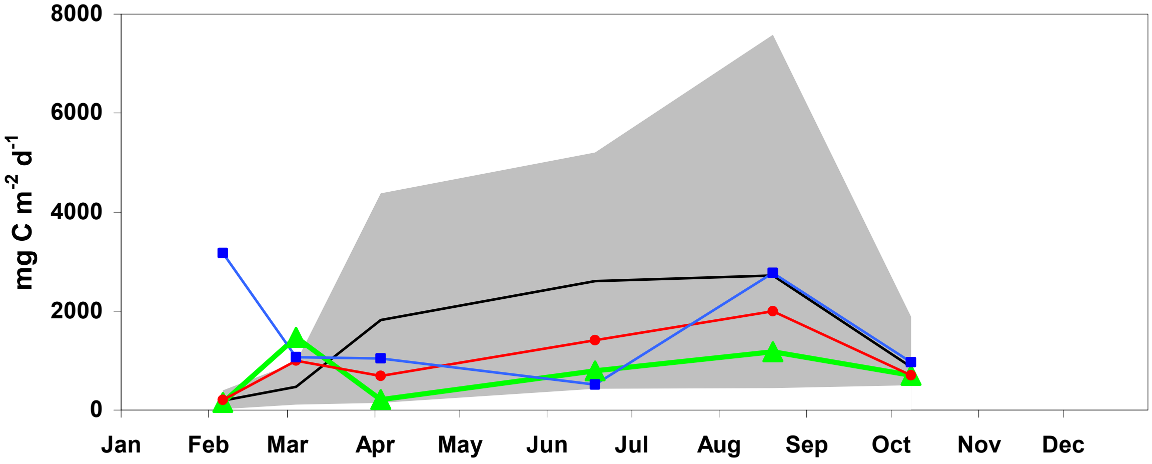
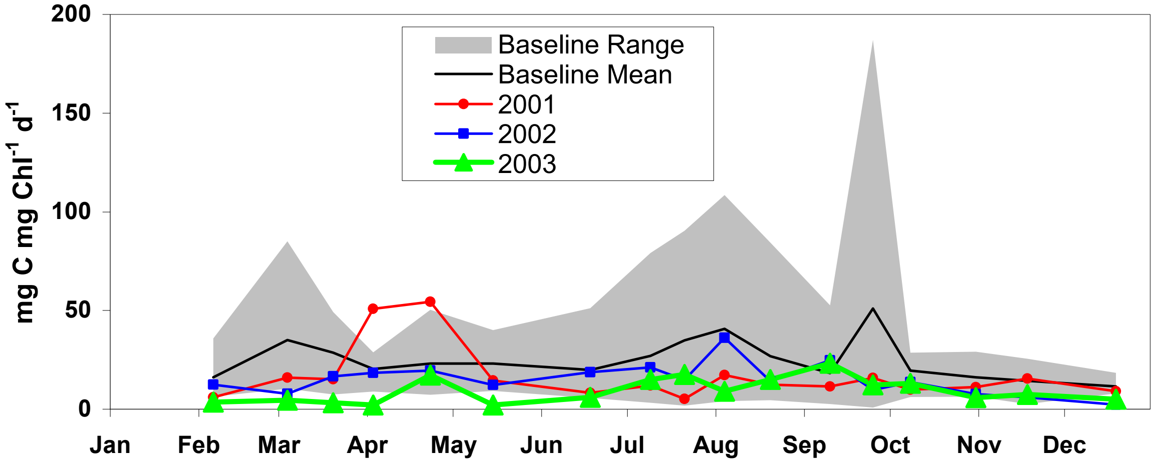
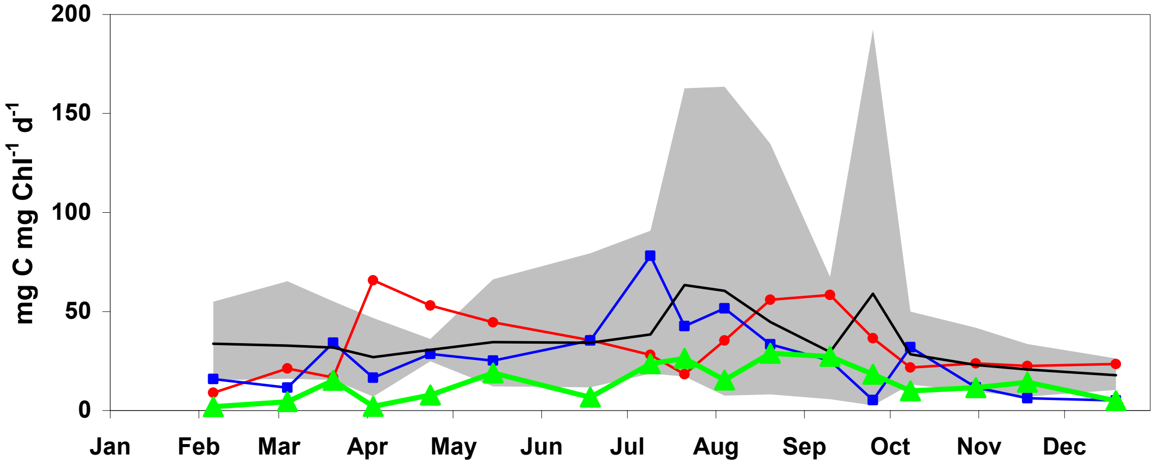


Figure C-2. Time-series of areal production (mgCm^{-2}d^{-1}) at stations N04, N18 and F23 for 2001, 2002, and 2003 compared against baseline range and mean (1997 to September 2000).

(a) N04



(b) N18



(c) F23

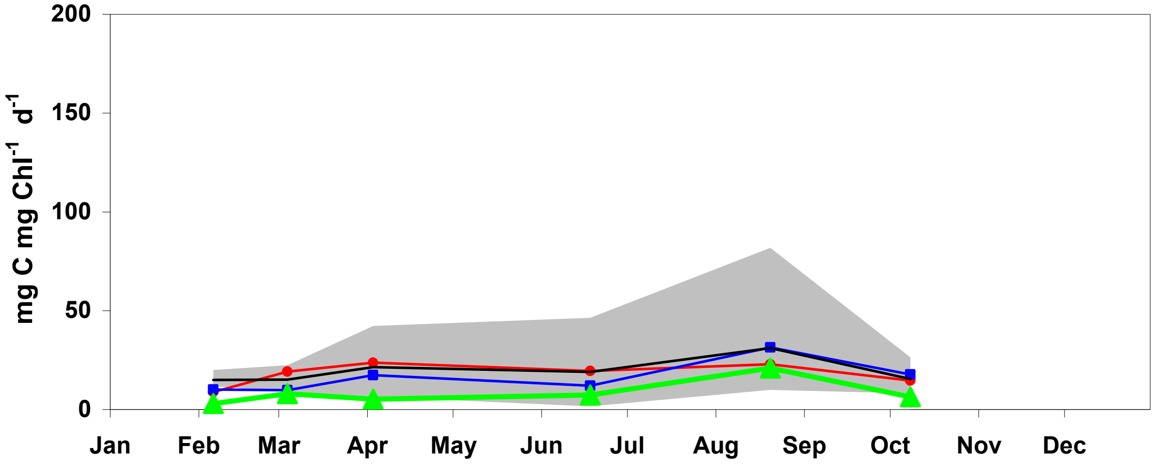


Figure C-3. Time-series of chlorophyll-specific areal production (mgCmgChl^{-1}d^{-1}) at stations N04, N18 and F23 for 2001, 2002, and 2003 compared against baseline range and mean (1997 to September 2000).

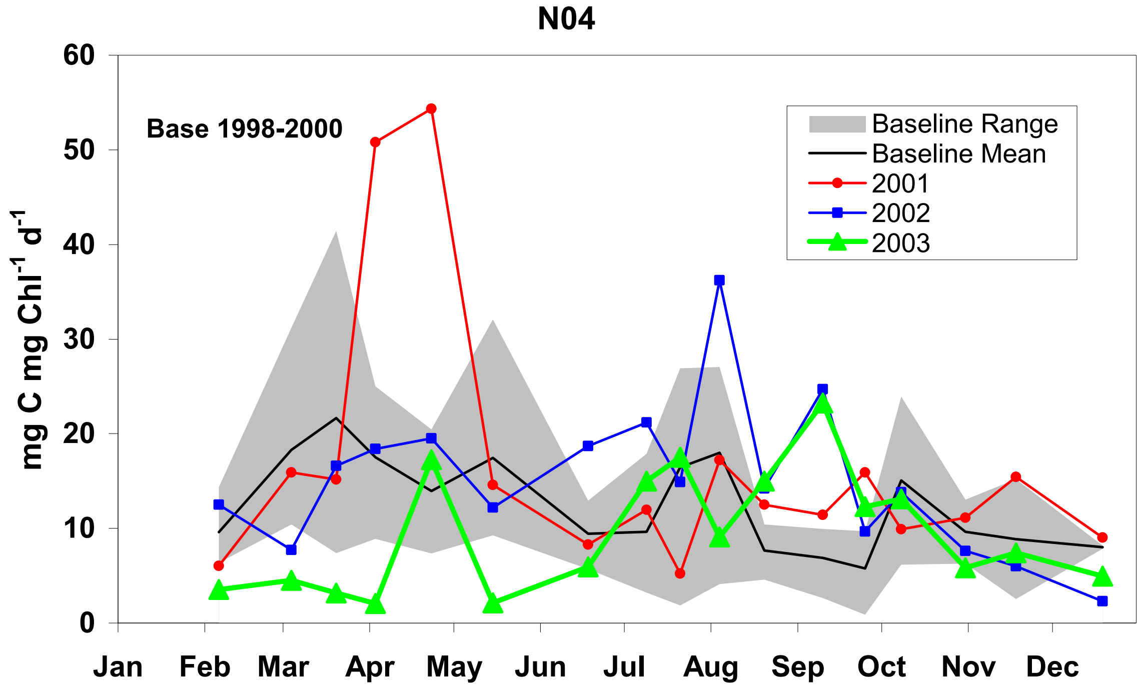
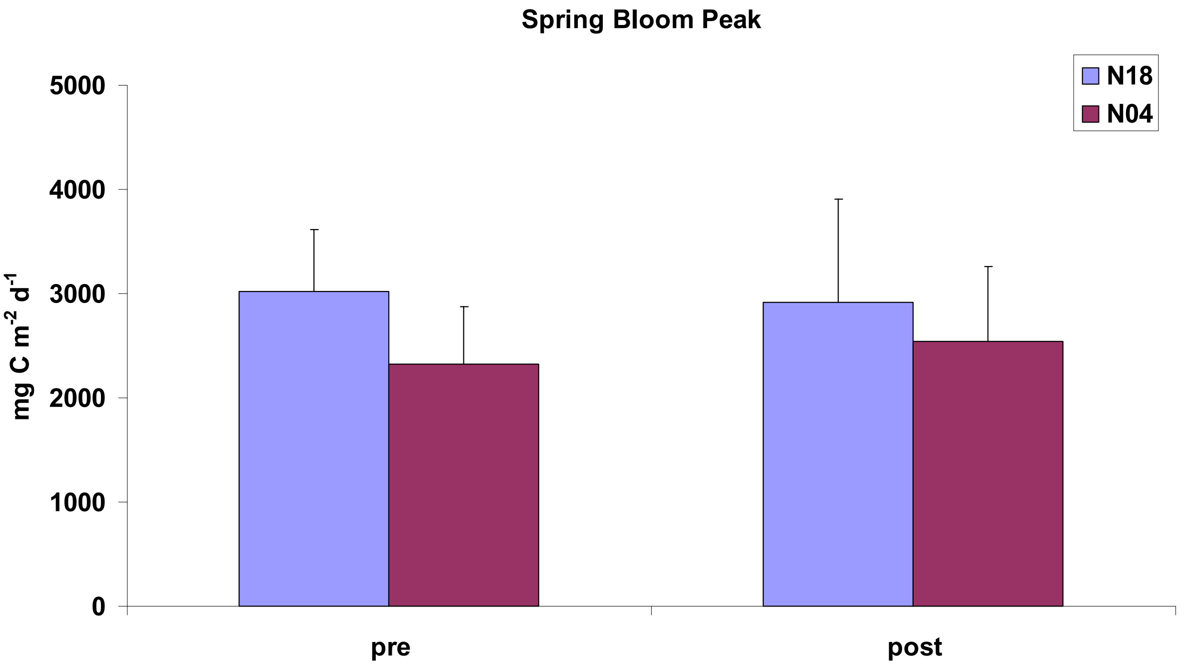


Figure C-4. Time-series of chlorophyll-specific areal production (mgCmgChl^{-1}d^{-1}) at station N04 in 2001, 2002 and 2003 compared against baseline range and mean using 1998-2000 data (no 1997).



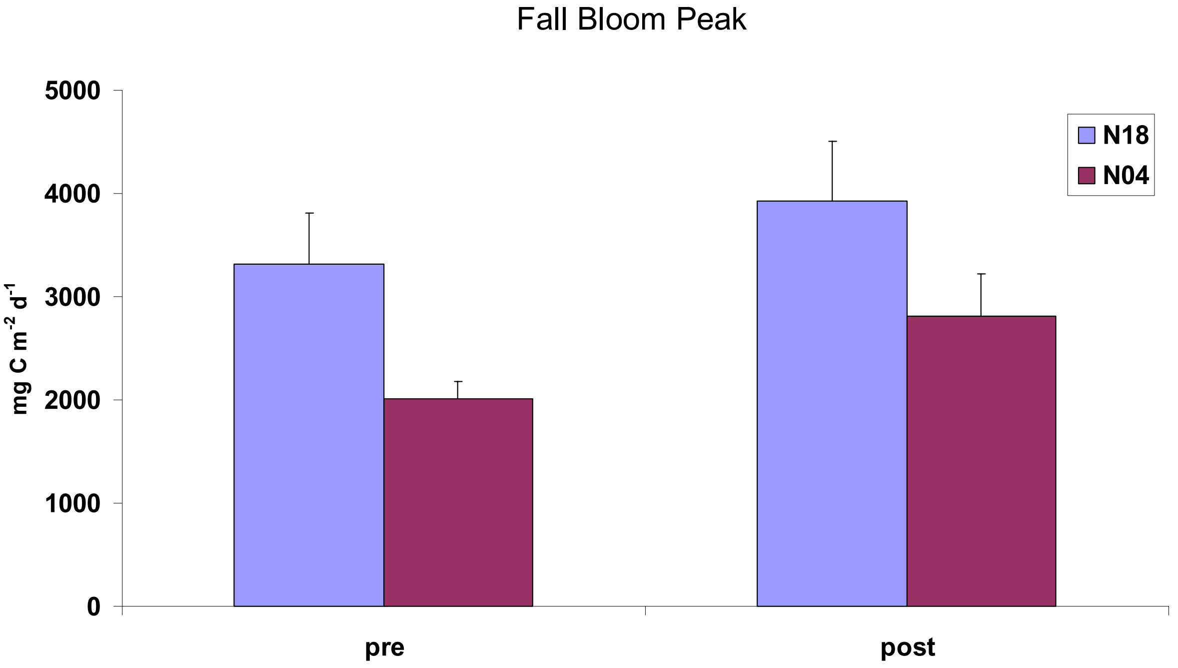
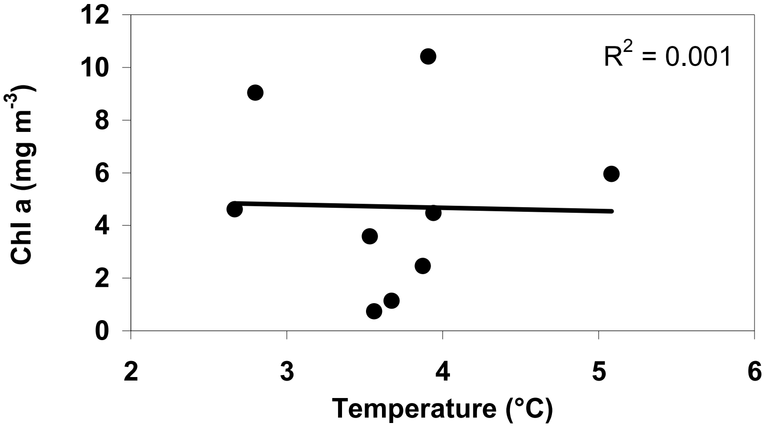
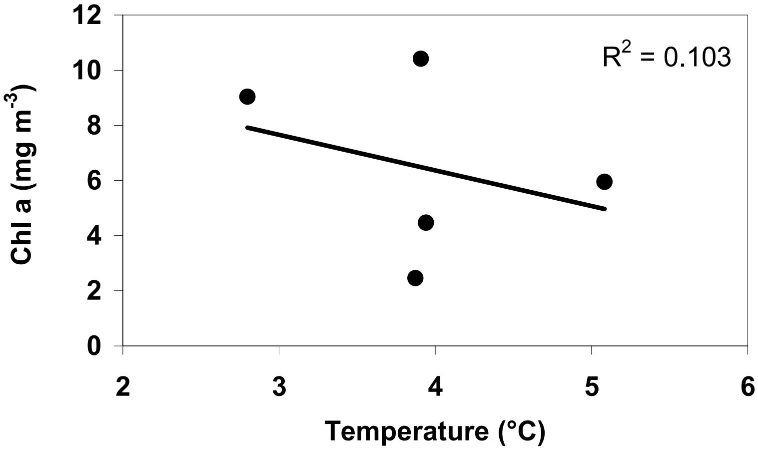


Figure C-5. Spring and fall bloom peak production (mgCm^{-2}d^{-1}) at nearfield stations N04 and N16/N18. Pre vs. post outfall diversion - spring 97-00 vs. 01-03 and fall 97-99 vs. 00-03.

(a) All Data 1995 - 2003



(b) Phaeocystis Years



(c) Non- Phaeocystis Years

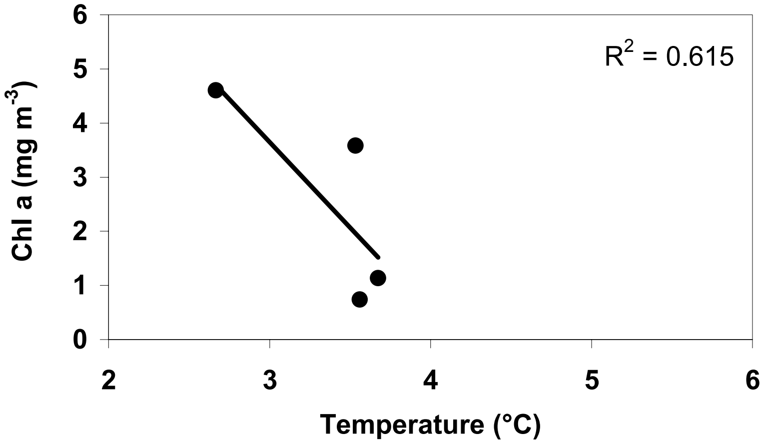
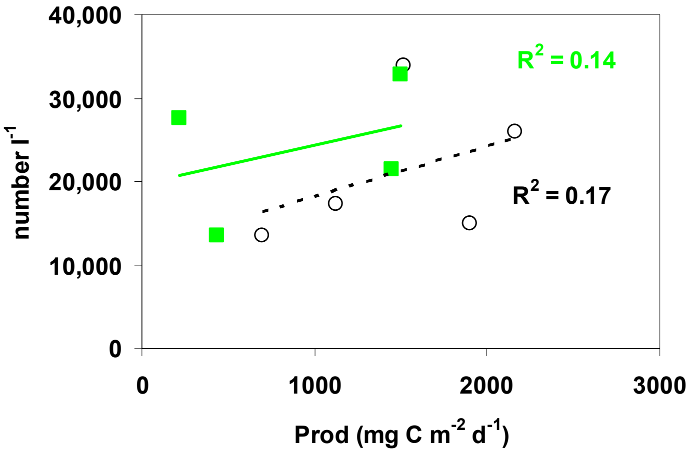
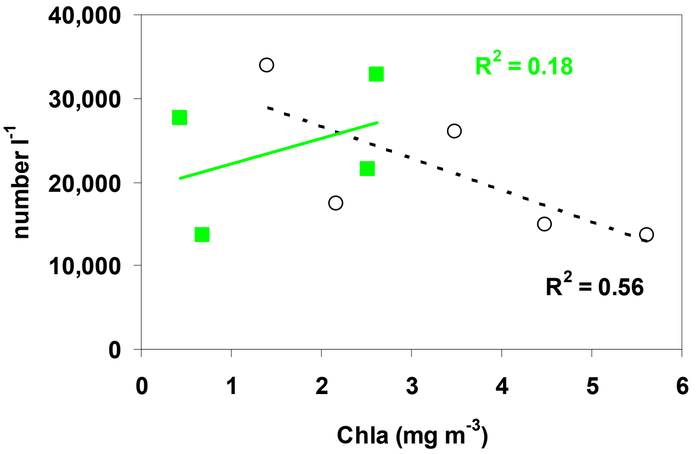


Figure C-6. Nearfield peak chlorophyll vs. mean temperature during the February to April spring bloom surveys for 1995-2003.

(a) Zooplankton Abundance vs Bloom Production



(b) Zooplankton Abundance vs Bloom Chla



(c) Bloom Chla vs Bloom Production

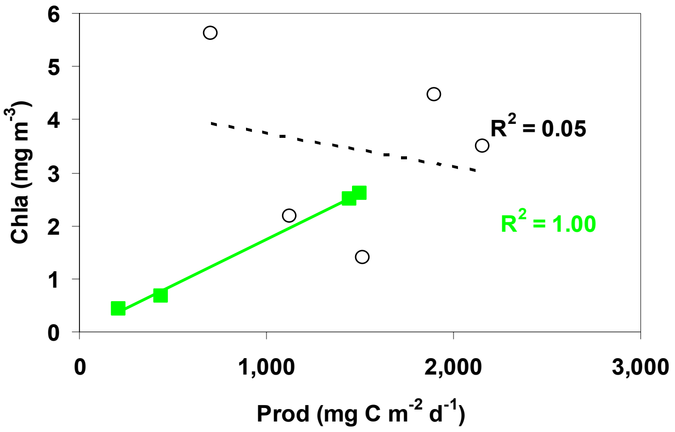
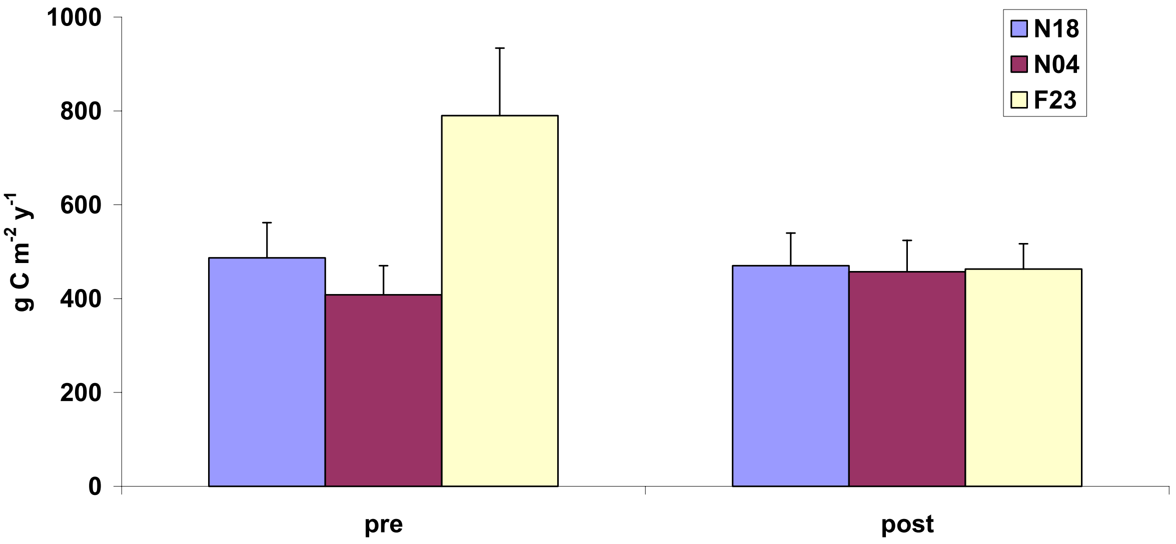


Figure C-7. Spring bloom period (February to April) comparisons of nearfield average zooplankton, production and chlorophyll (stations N04 and N16/N18). Non-*Phaeocystis* year data (95, 96, 98 and 99) green squares and *Phaeocystis* year data (97, 00, 01, 02 and 03) open circles.

(a) Potential Annual Productivity - Original



(b) Potential Annual Productivity - Alternative

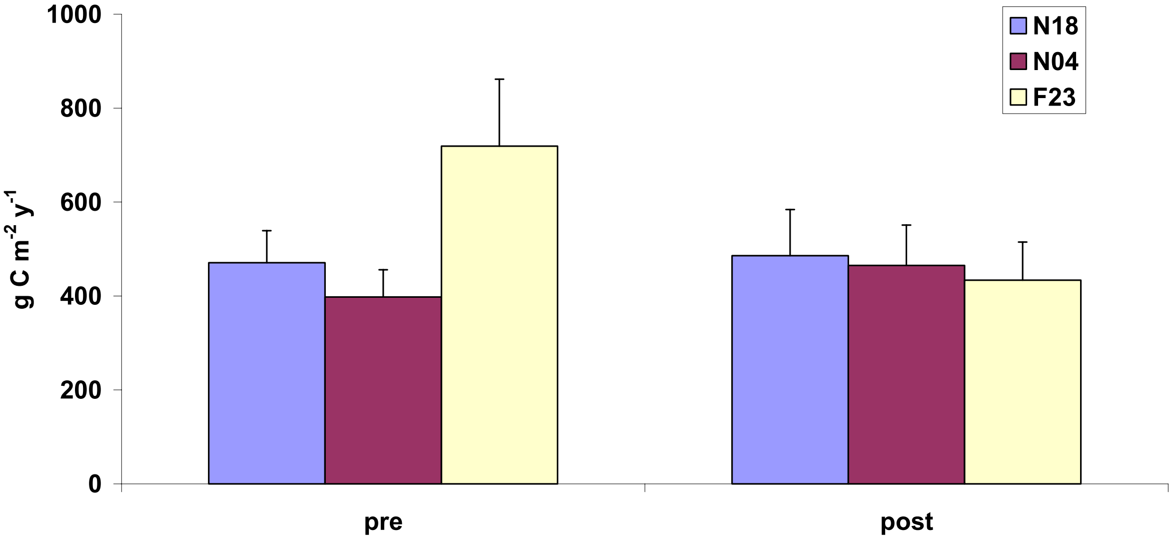


Figure C-8. Annual potential production (gCm^{-2}yr^{-1}) for stations F23, N04 and N16/N18 pre (1997-1999) and post (2001-2003) outfall diversion – (a) original calculation and (b) alternative approach.

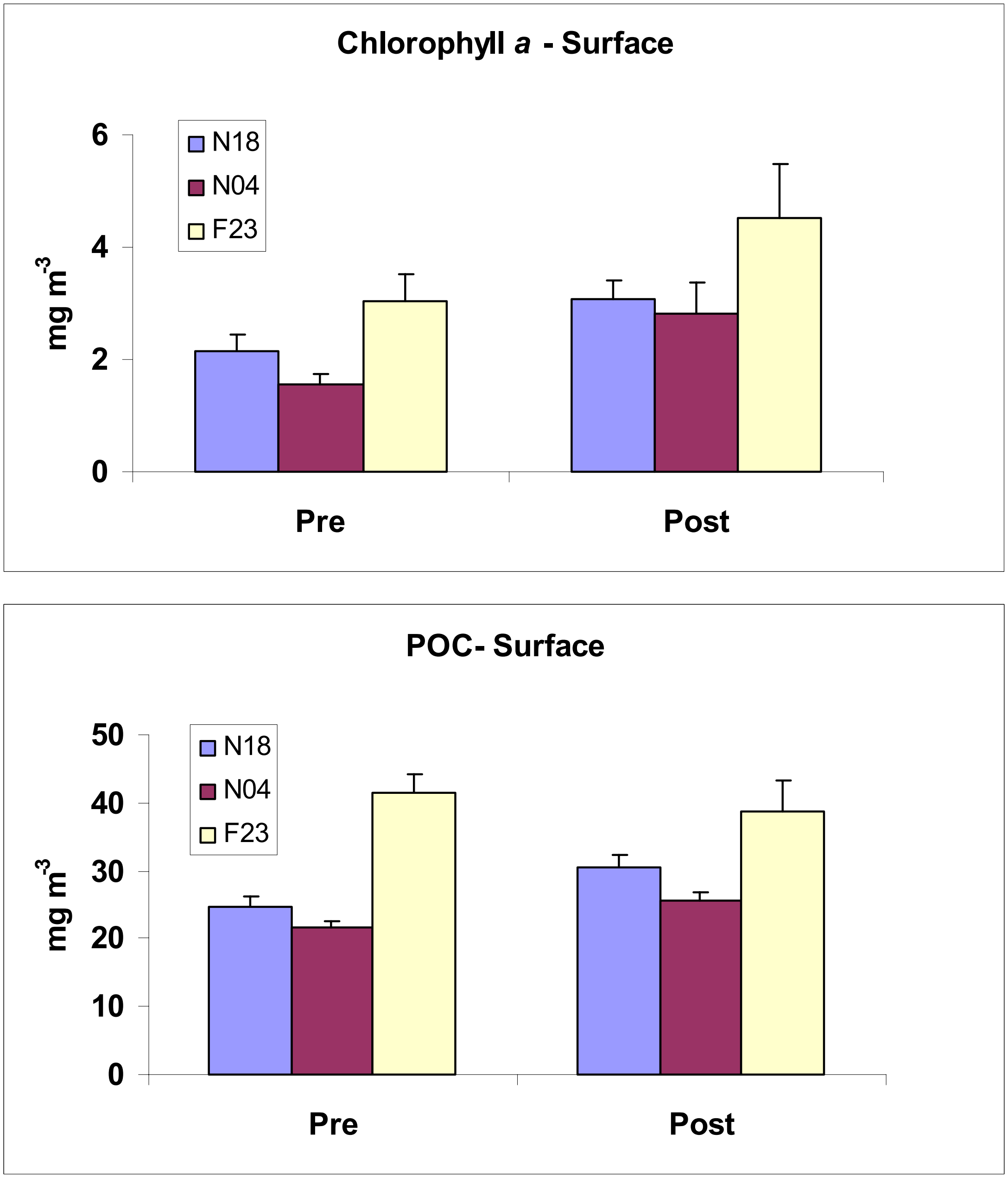


Figure C-9. Surface water concentrations of (a) chlorophyll and (b) POC for stations F23, N04 and N16/N18 pre (1997-1999) and post (2001-2003) outfall diversion.

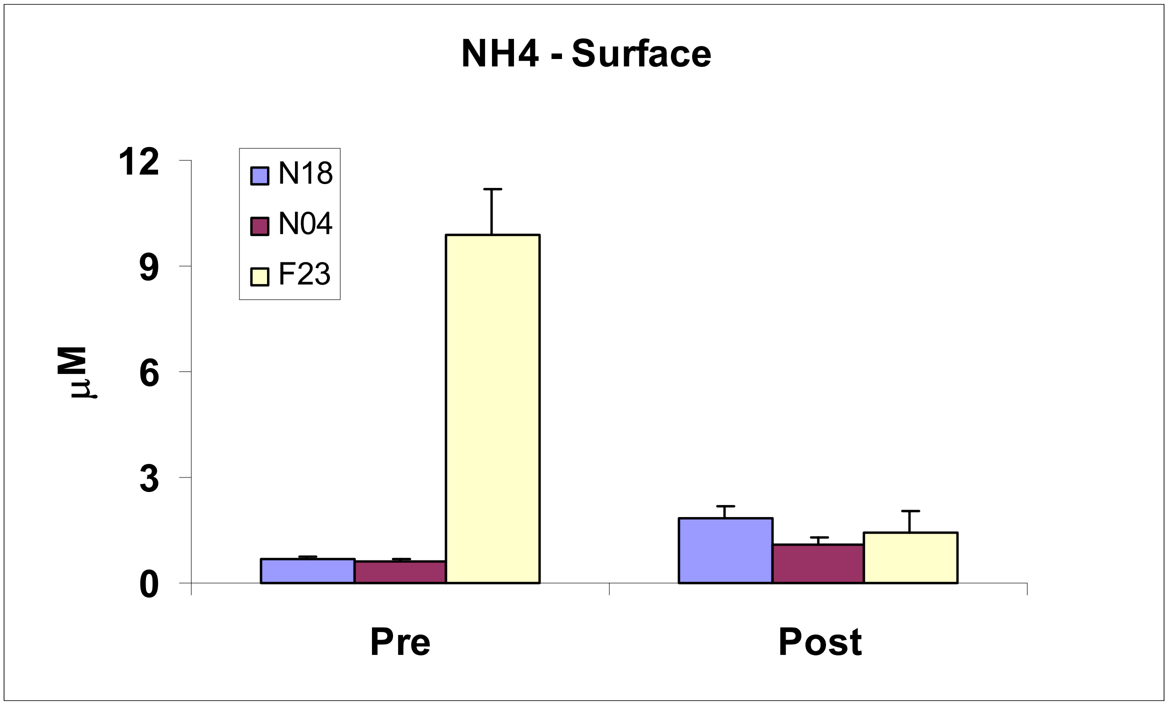


Figure C-10. Surface water concentrations of NH_4 at stations F23, N04 and N16/N18 pre (1997-1999) and post (2001-2003) outfall diversion.

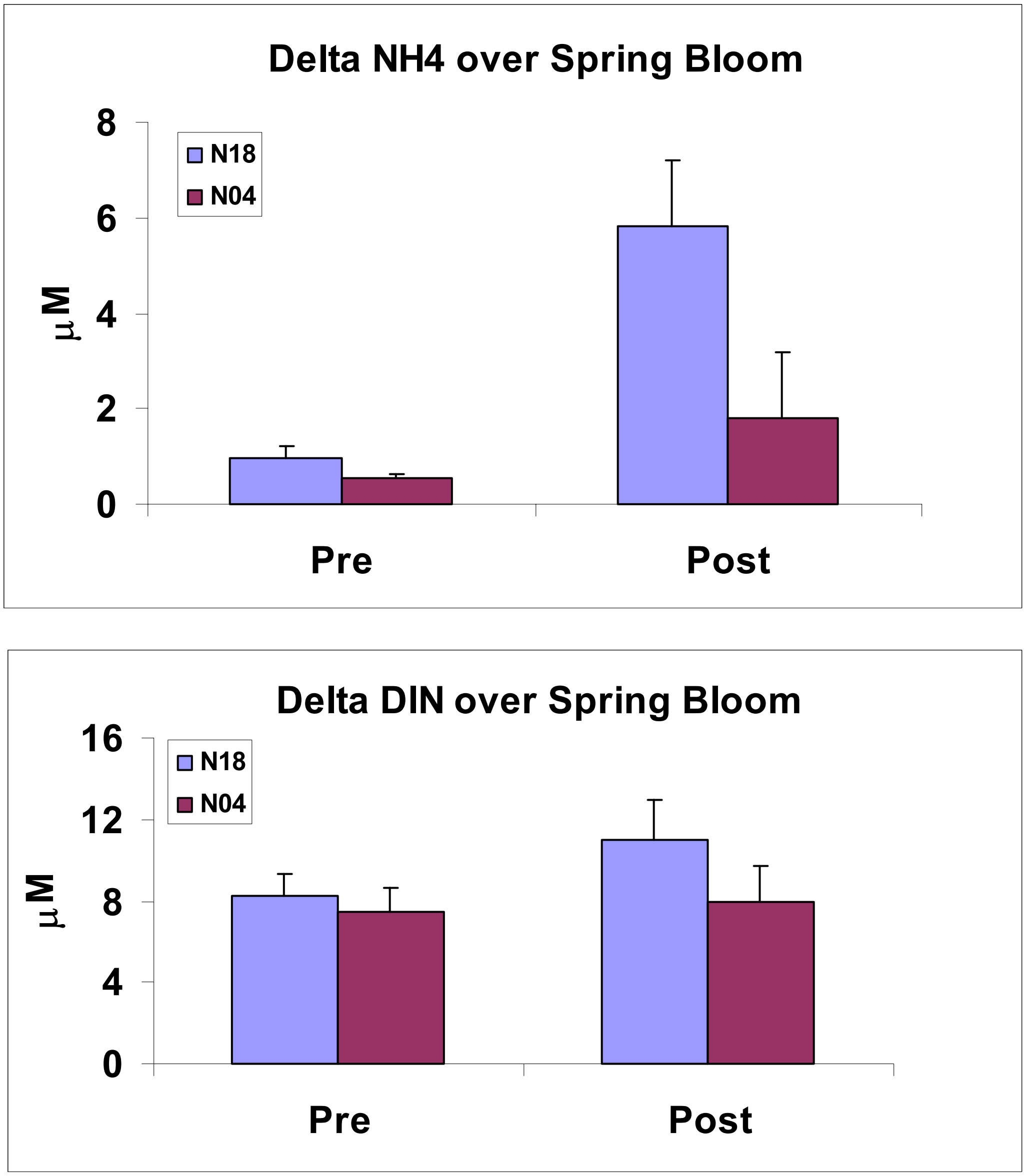


Figure C-11. Change in mean water concentrations over spring bloom period of (a) NH_4 and (b) DIN for stations N04 and N16/N18 pre (1997-1999) and post (2001-2003) outfall diversion.

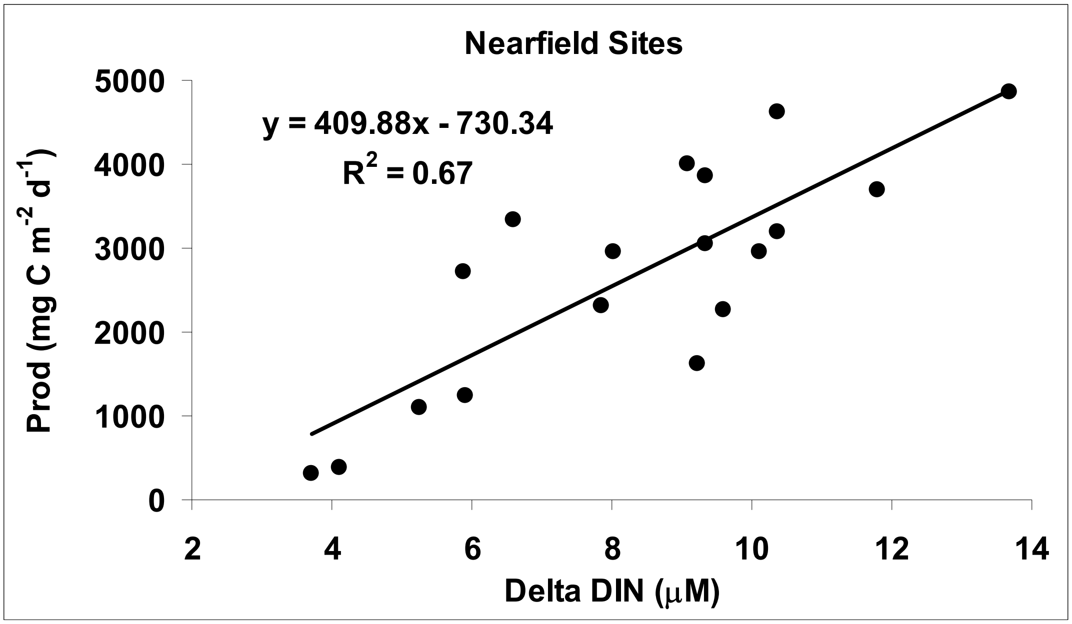


Figure C-12. Delta DIN vs. peak production over the spring bloom period at stations N04 and N16/N18 from 1995-2003.

APPENDIX D

Plankton

D. PLANKTON

In this section a summary of 2003 plankton trends is presented, based on information contained in the two semiannual reports, and interannual comparisons of 2003 seasonal trends vs. 1992 to 2000 baseline and 2001 and 2002 results. In 2003, trends in phytoplankton and zooplankton abundance, species composition and bloom cycles were generally consistent with those observed in previous years, although timing and magnitude of events were sometimes different. In addition to comparing 2003 to previous years, this appendix is structured in such a manner as to address the monitoring questions developed in the 1991 Monitoring Plan. Each section will address issues in both the nearfield and the farfield.

D.1 Summary of 2003 Results

Nearfield whole-water phytoplankton assemblages were dominated throughout most of the year by unidentified microflagellates, chrysomonads and several species of centric diatoms except during the prolonged winter-spring *Phaeocystis* bloom (**Figure** D-1). Assemblages during different periods were seasonally typical in terms of taxonomic composition.

The *Phaeocystis pouchetii* bloom in spring 2003 lasted longer (February-May) and was more abundant (up to 10.22×10^6 cells l^{-1}) than the blooms of this species during the same period in the previous two years (up to 3.13×10^6 cells l^{-1} in 2001, and up to 1.59×10^6 cells l^{-1} in 2002), but maximum levels were lower in 2003 than in 2000 (up to 12.26×10^6 cells l^{-1}). Most levels of *Phaeocystis* were $< 1.0 \times 10^6$ cells l^{-1} in February and March, and $1\text{-}2 \times 10^6$ cells l^{-1} in April. However, there were sporadic high values in April of 7.0×10^6 cells l^{-1} in a single sample from the nearfield and 10.22×10^6 cells l^{-1} at two boundary stations off Cape Ann. By May, *Phaeocystis* abundance had declined to $< 0.75 \times 10^6$ cells l^{-1} at most stations (**Figure** D-1). Unlike previous years with *Phaeocystis* generally blooming mainly in April, the 2003 bloom began in February and lasted through mid-May. The four consecutive *Phaeocystis* blooms (2000-2003) were a departure from the 3-year cycle for these blooms that had been observed during the baseline period, with single-year blooms in 1992, 1994, and 1997.

Centric diatom blooms occurred in Massachusetts Bay in February-March. Important nearfield taxa included *Stephanopyxis turris*, *Thalassiosira nordenskioldii*. At other locations in the farfield, important diatom taxa included *Guinardia delicatula*, *Eucampia zoodiacus*, *Skeletonema costatum*, *Stephanopyxis turris*, *Thalassiosira* spp, and *Thalassionema nitzschoides*. The highest spring abundances of diatoms were observed in Cape Cod Bay (**Figure** D-2). Important taxa in the spring Cape Cod Bay blooms included *Guinardia delicatula* and *Eucampia zoodiacus*.

Centric diatoms also bloomed in September-November, particularly in October. Important taxa during these fall diatom blooms included *Dactyliosolen fragilissimus* and *Skeletonema costatum* (late September, and early October) and *Leptocylindrus danicus* and *L. minimus* (late October and early November).

Dinoflagellates recorded for 20 µm-screened water samples were taxa typically recorded in previous years. Abundances of dinoflagellates of the genus *Ceratium* were somewhat lower than in many previous years.

There were no blooms of harmful or nuisance phytoplankton species in Massachusetts and Cape Cod Bays during 2003, other than the spring bloom of *Phaeocystis*. While the dinoflagellate *Alexandrium tamarense* or *Alexandrium* spp. (March-June, October) and diatoms of the genus *Pseudo-nitzschia pungens* and members of the *P. delicatissima* complex (June-December) were recorded, they were generally present in low abundance. The only nuisance algae caution threshold that was exceeded during this period was for the summer mean *Phaeocystis* abundance (3,500 cells l^{-1} vs. threshold of 334 cells l^{-1}). This was due to the continued presence of *Phaeocystis* in May, albeit only in one sample and at relatively low abundance (48,400 cells l^{-1}). This is discussed in more detail in Section D.2.a. Also of note, the nearfield autumn mean value for *P. pungens* (17.9 x 10^3 cells l^{-1}) approached the autumn threshold value (24.6 x 10^3 cells l^{-1}).

As has been typically observed, nearfield total zooplankton abundance generally increased from February through August, and declined from September through December (**Figure** D-3). Zooplankton assemblages were comprised of taxa recorded for the same time of year in previous years. Dominant taxa throughout the year included copepod nauplii, adults and copepodites of *Oithona similis*, *Pseudocalanus* spp., and sporadic pulses of various meroplankters such as bivalve veligers and barnacle nauplii. *Calanus finmarchicus* copepodites were abundant components of assemblages at some stations during the first half of the year. Ctenophores were sporadically present throughout July-October, with maximum occurrence in October.

There was high variability in zooplankton abundance between various stations within given surveys. The additional “winter zooplankton” samples in Cape Cod Bay during the first 3 farfield surveys aided considerably in capturing the considerable variability.

Data for *Calanus finmarchicus* for the winter period (February-April) strengthened the previously-established negative correlation between abundance of this copepod in Massachusetts Bay and the boreal winter North Atlantic Oscillation Index (December-March).

D.2 Interannual Comparisons

D.2.a Phytoplankton Community Composition

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:

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

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

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

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

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, 2002 and 2003. The interannual variability associated with both magnitude and occurrence of blooms as represented by total phytoplankton abundance is shown in **Figure** D-4. 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.

D.2.b Interannual Phytoplankton Comparisons

The differences in the 2003 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. Post-diversion (2001-2003) assemblages were generally similar to those found during other baseline monitoring years. During each post-diversion year, nearfield total phytoplankton abundance was usually at or slightly below the baseline mean value (**Figure** D-5). The primary exceptions were the April 2003 *Phaeocystis* bloom, the late summer/early fall diatom bloom in 2002, and the late fall blooms in 2001 and 2003.

The *Phaeocystis pouchetii* bloom in spring 2003 lasted longer (February-May) and was more abundant than the blooms of this species during the same period in the previous two years, but maximum levels were lower in 2003 than in 2000. Unlike previous years when *Phaeocystis* bloomed mainly in April, the 2003 bloom began in February and lasted through mid-May. The four consecutive years with *Phaeocystis* blooms (2000-2003) were a departure from the 3-year cycle for these blooms that had been observed during the baseline period, with nearfield blooms in 1994, 1997 and 2000 (**Figure** D-6).

The prolonged fall 2003 phytoplankton bloom lasted from September through December. This bloom was relatively minor in comparison to past blooms, and it occurred during a period of persistent nutrient depletion due to late breakdown in seasonal stratification. When nutrient levels began to increase with beginnings of seasonal overturn in late fall, persistent weak stratification and the late fall bloom kept surface nutrients at moderate levels until December, which likely supported the prolonged bloom. The bloom was a mixed assemblage of centric diatom species typically observed in Massachusetts Bay in the fall. In late September and early October, the assemblage was dominated by *Dactyliosolen fragilissimus* and *Skeletonema costatum*. By late October and into November, the dominant diatom species were *Leptocylindrus danicus* and *L. minimus*.

The fall bloom might also be related to reduced zooplankton grazing pressure, due to likely predation on herbivorous zooplankton such as copepods by ctenophores. However, such a link remains speculative, in view of zooplankton abundance in fall of 2003 being above the baseline range in September (**Figure** D-7). Nonetheless, the zooplankton abundances during the October survey were lower than typically observed, suggesting that increased grazing pressure by ctenophores may have both decreased zooplankton abundance and contributed to the occurrence of the fall bloom. The impact of ctenophore grazing, however, was not as apparent as observed in late summer/early fall 2002. Despite the presence of ctenophores throughout most of this period, zooplankton abundances in the second half of 2003 were higher than in 2002.

Phaeocystis:

Although there have not been major changes noted in the taxonomic composition of the phytoplankton community over the last twelve years, there have been several variations in the timing and magnitude of various events in the seasonal succession. The most pronounced variations have been associated with the spring blooms of *Phaeocystis pouchetii* (**Figure** D-6). Spring *Phaeocystis* blooms have been recorded for Massachusetts and Cape Cod Bays since the time of Bigelow (1926). Thus, these blooms are part of the normal seasonality of phytoplankton in the Gulf of Maine and numerous other locations throughout the world (see review by Turner *et al.* 2002). Direct and anecdotal evidence indicates that the blooms observed in Massachusetts Bay are regional in nature and are coincident with the presence of *Phaeocystis* in waters from Buzzard's Bay to the western Gulf of Maine.

Although *Phaeocystis* blooms are a normal component of the plankton seasonality in Massachusetts and Cape Cod Bays, the patterns of occurrence and magnitude of these blooms may be changing. After recording spring blooms in 1992, 1994, and 1997, with each bloom year interspersed with two consecutive years in which blooms were not recorded, there were four consecutive blooms in 2000, 2001, 2002, and 2003. At the time of this writing, there was also another major bloom in April 2004. Thus, the pattern has changed from spring *Phaeocystis* blooms occurring in three-year cycles to blooms occurring annually. Since the outfall went on line in September, 2000 it might be tempting to speculate that this change of pattern might be related to the outfall, were it not for the observation that spring *Phaeocystis* blooms occurred throughout the Massachusetts and Cape Cod Bays region, and in 2003, highest concentrations of *Phaeocystis* were in the area offshore from Cape Ann, upstream from the outfall (**Figure** D-1).

Further, although a *Phaeocystis* bloom was not recorded for spring of 1998 in the MWRA sampling area (**Figure** D-6), such a bloom was noted by the smell of acrylic acid in zooplankton samples during the ECOHAB sampling in April and May in Casco Bay, Maine. Also, during most of the spring *Phaeocystis* blooms in the MWRA sampling area, there have been indications (smell, zooplankton net clogging) of concurrent *Phaeocystis* blooms in Buzzards Bay, although most of the Buzzards Bay phytoplankton samples have not yet been analyzed. Thus, while the periodicity of spring *Phaeocystis* blooms has changed in Massachusetts and Cape Cod Bay, the reason(s) for this change remain elusive. Similarly, it is not clear why, unlike previous blooms which occurred primarily in late March and April, the 2002 and 2003 blooms began earlier, and lasted until early May, thereby causing exceedances of the "summer" *Phaeocystis* threshold by the presence of low abundances of this alga in early to mid-May in both years.

Long-term observations indicate that *Phaeocystis* populations respond to trends in eutrophication and, possibly, warming winter temperatures. In the Dutch Wadden Sea, the duration of *P. globosa* and/or *P. pouchetii* blooms (defined as >1,000 cells ml^{-1}) increased ~5-fold (from 20 to 100 days per year) between 1975 and 1990, and has since declined to ~70 bloom days per year, tracking long-term changes in ambient N and P levels (Cadee and Hegeman 2002). In this same long-term study, Cadee and Hegeman (2002) found that *Phaeocystis* blooms began about 25 days earlier (blooms starting in mid-March) in 1995-2000 than they did in the 1970s (blooms beginning in mid-April), a change linked to warmer winter temperatures. In the MWRA monitoring program, the frequency and duration of *Phaeocystis* blooms has been variable, with an increase in frequency and duration of the *Phaeocystis* bloom period into May in recent years. While the monitoring program does not observe plankton populations at the daily to weekly time scale needed to resolve subtle shifts in bloom timing or duration, some physical variables (temperature, at the Boston Buoy #440143) are monitored at high frequency, and interrogation of their long-term variation during 1992-2003 MWRA monitoring may yield insight on the observed variation in *Phaeocystis* bloom duration.

Phaeocystis pouchetii has a thermal tolerance range of –2 to 14 °C (Jahnke and Baumann 1987) and a Massachusetts Bay *P. pouchetii* isolate has been shown not to grow in nutrient and light replete laboratory conditions at temperatures >14 °C (Hegarty and Villareal 1998). Thus 14 °C appears to be the physiological threshold for *P. pouchetii* growth, and is the maximum temperature at which one might expect to observed *P. pouchetii* blooms in Massachusetts Bay. Water temperature at the

Boston Buoy (#44013, about 16 nm east of Boston) was examined to determine when the 14 °C temperature threshold was first reached in each year of MWRA monitoring. Data were available for all years between 1992 and 2003 except for 1995 and 1997. The first observed temperature reading of 14 °C or greater was recorded for each year. Seawater temperature at the Boston Buoy first reached 14 °C over a 39 day range between 1992 and 2003, occurring as early as 4 May (in 2001) in warm years and as late as 13 June (in 1993) during cold years (**Figure** D-8a). The mean date 14 °C was first observed was the 28th of May. Changes in phytoplankton monitoring frequency (i.e., nearfield plankton samples collected 6 vs. 17 times per year) prevent direct comparison of *Phaeocystis* bloom duration over the entire 1992 – 2003 period, but *Phaeocystis* tended to be present for longer periods during colder years having a longer period of <14 °C (**Figure** D-8b; **Table** D-1).

For example, during the past four years (2000-2003 inclusive), *Phaeocystis* was observed at station N04 over an 18 day interval (in 2000) and for only a single cruise (in 2001) when the 14 °C 'threshold' was reached on days 131 and 123 (early to mid May). In 2002 and 2003 *Phaeocystis* was present at station N04 for at least 82 (2002) and 73 (2003) days when 14 °C was not achieved until day 152 (2002) or 159 (2003) corresponding to early June. Annual variation in winter-spring water temperature and concomitant effects on related variables (nutrient, stratification, zooplankton grazing, etc.) may explain some of the observed variance in Massachusetts Bay *Phaeocystis* bloom duration. However the relatively low number of years having observations suitable for comparison (i.e. 1996 and later data having 17 samples per year sample frequency) and having available water temperature data (1997 data missing) results in a 'low n' problem of only seven years having data available for analysis. For these seven years, a Pearson correlation coefficient of +0.64 ($p = 0.1229$, $n = 7$ years) was found between day of 14 °C achievement and *Phaeocystis* duration. If the three years in which *Phaeocystis* was not observed (1996, 1998, 1999) are removed, the Pearson correlation coefficient increases to +0.97 ($p = 0.0340$, $n = 4$) indicative of a cold winter-spring water temperature – *Phaeocystis* relationship (**Figure** D-8c). However the 'low n' and the scatter of the points into short and long *Phaeocystis* duration years, while described by a linear relationship, may represent a non-linear relationship between cold years in which the water remains below 14 °C until early June (such as 2002, 2003) having long duration *Phaeocystis* presence and warmer years (like 2001, 2002) in which the water warms to >14 °C in early to mid May and *Phaeocystis* duration is shorter.

Table D-1. Date of first 14 °C water temperature achievement at the Boston Buoy and duration of *Phaeocystis pouchetii* presence at Station N04.

Year	Day of year 14 °C 1st observed	*Phaeocystis* bloom duration (days)
1992	157	1
1993	162	0
1994	159	1
1995	ND	ND
1996	142	0
1997	ND	54
1998	145	0
1999	147	0
2000	131	18
2001	123	1
2002	152	82
2003	159	73

ND = no data; 0 indicates *Phaeocystis* not observed;
1 indicates *Phaeocystis* observed in a single cruise.

Anecdotal accounts suggest that *Phaeocystis* blooms might be noxious or inimical to certain animals such as right whales, or that such blooms might be largely ungrazed by zooplankters, but such speculation is complicated by considerable documented variability, at least in the case of zooplankton grazing (reviewed by Turner *et al.* 2002). Impacts of *Phaeocystis* blooms on zooplankton are seductive in their speculative richness, but in reality, poorly understood. Perhaps because of its gelatinous and/or toxic nature, there has been the development of what Huntley *et al*. (1987) called the "legend of *Phaeocystis* unplalatability to zooplankton." Such speculation is complicated by observations that numerous various zooplankters appear to feed and survive well upon diets of *Phaeocystis* (see Turner *et al*. 2002 and references therein). Similarly, suggestions that *Phaeocystis* blooms in the nearfield region of Massachusetts Bay are associated with diminished zooplankton abundance are thwarted by observations that zooplankton abundance in April, the month of highest *Phaeocystis* abundance, during the bloom years of 2001, 2002, and 2003, is well within the 1992-2000 baseline range, which includes 6 of 9 years when *Phaeocystis* blooms did not occur.

Alexandrium:

Toxic dinoflagellates identified as *Alexandrium tamarense* (this species should probably now be referred to in the Gulf of Maine as *A. fundyense*, Don Anderson, personal communication) or cells of the genus *Alexandrium* that could not be positively identified to species were only sporadically recorded for the spring and summer at abundances of < 15.4 cells l^{-1}. Nearfield abundances were lower (<10 cells l^{-1}) and occurred only in the spring (**Figure** D-6).

Unlike most previous years, there were also fall occurrences of *Alexandrium* spp. in October 2003. *Alexandrium* spp. and *A. tamarense* were recorded only 9 and 2 times, respectively, in screened water samples in October, and only at farfield stations and at abundances of <10 cells l^{-1}, except for a single value of 19.4 cells l^{-1}, in Cape Cod Bay. All of these values were well below the threshold limit for *Alexandrium* in screened-water samples of 100 cells $l^{-1}$for any single nearfield sample. The low counts in October 2003 were recorded at the same time as a major *Alexandrium* red tide was occurring along the Maine coast that was extraordinary in both the timing and magnitude of the toxicity.

Pseudo-nitzschia:

Potentially-toxic diatoms of the genus *Pseudo-nitzschia* were recorded for many whole-water phytoplankton samples throughout 2003. However, during the first half of the year, these cells comprised >5% of cells counted in a given sample only during survey WF037 in June, when members of the genus comprised 70-143 x 10^3 cells l^{-1} at 4 stations. Although cells of the *P. pseudodelicatissima* complex were present in 68.5% of whole-water samples from July-December, at abundances of up to 204 x 10^3 cells l^{-1}, this species is not included in the threshold for *P. pungens* (which could also include the light-microscopically-indistinguishable, domoic-acid producing species *P. multiseries*). Nominal *P. pungens* were recorded for 28.3% of whole-water phytoplankton samples in July-December, at levels of up to 72 x 10^3 cells l^{-1}. Nearfield mean *P. pungens* abundance peaked at ~ 50 x 10^3 cells l^{-1} in late October (**Figure** D-6).

P. pungens were also observed on Stellwagen Bank during October 2003, with abundances ranging from 0-11,400 cells l^{-1} (mean of 1,600 cells l^{-1}) at the four SBNMS monitoring stations. As in at the MWRA stations, the abundance of *P. pseudodelicatissima* was much higher ranging from 0-56,700 cells l^{-1} (mean of 16,400 cells l^{-1}). This species is not included in the MWRA *Pseudo-nitzschia* threshold counts, but it is a known domoic acid producer (Pan *et al*. 2001, Amzil *et al*. 2001). The summer-autumn 2003 marine mammal die-off in Gulf of Maine and Georges Bank waters, which included at least 21 large whales as well as harbor seals, is likely linked to a *Pseudo-nitzschia* bloom because domoic acid, the toxin present in toxic *Pseudo-nitzschia* spp. (*P. multiseries* and

P. pseudodelicatissima), was found in the tissue of at least one dead humpback whale (US Marine Mammal Commission Meeting, October 2003).

The presence of multiple species of *Pseudo-nitzschia* in the MWRA monitoring region, difficulty in identifying Pseu*do-nitzschia* to species via light microscopy, the variable toxicity of Pseudo-nitzschia cells (Pan *et al*. 2001), the tendency for *Pseudo-nitzschia* populations to aggregate in thin layers that are easily overlooked by routine monitoring procedures (Rines *et al*. 2002) and the potential foodweb and human health consequences make *Pseudo-nitzschia* a difficult marine monitoring problem. Elevated *Pseudo-nitzschia* abundance on Stellwagen Bank in early October corroborates the regional nature of the autumn 2003 *Pseudo-nitzschia* bloom in Massachusetts and Cape Cod Bays. Thus, the *Pseudo-nitzschia* bloom that was recorded for the MWRA sampling area in October appears to have been much more widespread, possibly contributing to vectorial intoxication of whales through diatom – zooplankton – fish – whale food chains.

Ceratium:

In 2003, summer abundance of the dinoflagellates of combined species of the genus *Ceratium* were, with few exceptions, lower than the baseline mean for summer abundance (**Figure** D-9). Thus, 2003 was similar to the 2002 in terms of reduced *Ceratium* spp. abundance.

The 2002 annual report suggested that the reduced *Ceratium* abundance might be due to a delay in the onset of spring stratification and the relatively weak density gradient that might favor *Ceratium* in competition with faster-growing diatom species, because the vertical migratory capabilities of *Ceratium* might allow them to exploit solar radiation above, and nutrients below a pycnocline, when other competing phytoplankters could not. The weak pycnocline in 2002 was partially attributed to dry conditions, with reduced stratification due to reduced freshwater runoff. In fact, correlations between stratification and *Ceratium* abundance in Massachusetts Bay in April, June and September of 2002 (with a one-month lag) were significantly positive, and correlation coefficients between *Ceratium* abundance and the previous month's stratification alone explained approximately 50% of the variance in *Ceratium* abundance during the aforementioned months.

The explanation for reduced stratification contributing to low *Ceratium* abundance in 2002 cannot be invoked to explain low *Ceratium* abundance in 2003. Winter/spring air temperatures in 2003 were the coldest since 1977-78 and surface waters remained cold throughout much of the winter and spring. However, 2003 was a wet spring, and increased precipitation and runoff led to stratification due to low salinity at the surface that began in early April, and by the end of April the entire nearfield was stratified. The delay in vernal warming retarded the effects of the strong salinity gradient such that a strong pycnocline was not established in the nearfield until mid-May, but the pycnocline was strong throughout the bays by June. Despite the strong stratification, which persisted longer into the fall than normal, *Ceratium* abundance remained below the baseline range, throughout the June-early November period. Thus, the reduced stratification hypothesis suggested for the 2002 scenario does not appear to explain low *Ceratium* abundance under enhanced stratification in 2003.

D.2.c Zooplankton Communities

The variability in abundance and structure of the zooplankton community in 2003 in Massachusetts and Cape Cod Bays appears similar to patterns recorded since the beginning of sampling in 1992 (**Figures** D-7 and D-10). Assemblages have been dominated throughout by copepod nauplii, *Oithona similis*, and *Pseudocalanus* spp. copepodites, throughout the year, with subdominant appearances of other copepods such as *Calanus finmarchicus*, *Paracalanus parvus*, *Centropages typicus* and *C. hamatus*, and sporadic pulses of various meroplankters such as bivalve and gastropod veligers, barnacle nauplii, and polychaete larvae. Zooplankton abundance generally increased from February through mid- to late summer, and then progressively declined through the fall and into winter. The variability in total zooplankton abundance between stations within a given survey can be considerable, and the addition of two "winter" sampling stations in Cape Cod Bay adds to this generalization. In 2003, the 4 Cape Cod Bay stations had a variability of ±23.7% of the mean.

Winter-spring (February-April) nearfield abundances of *Calanus finmarchicus* copepodites and adults in 2003 strengthened the previously-established negative correlations of these copepods with the boreal winter index of the North Atlantic Oscillation (**Figure** D-11; Libby *et al*. 2003b). This suggests that some components of marine plankton communities may be sensitive to variations in long-term climatic and oceanographic patterns. The impact of such wide scale forcing factors on zooplankton in Massachusetts and Cape Cod Bays is just beginning to be examined and certainly seems 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.

The only substantial change over time in zooplankton patterns has been in relation to late summer-fall ctenophore blooms. Blooms of the ctenophore *Mnemiopsis leidyi* were not apparent from the beginning of sampling in 1992 until October 2000. Since then, this ctenophore has been present every fall, in varying degrees. Since no quantitative samples of this ctenophore have been taken by screening them out prior to preservation (except for a few samples in October 2003), and since this ctenophore disintegrates upon preservation in formalin, there is no way other than anecdotal to assess magnitude of ctenophore abundance or displacement volume. However, based upon the relative amounts of ctenophore "goop" in samples, 2000 was a much heavier year in terms of October ctenophore abundance, particularly in or near Boston Harbor, than in subsequent years. Such anecdotal observations, together with increased vigilance in regard to presence of ctenophores in the water during this and other sampling in contiguous waters, suggests that the fall 2000 appearance of ctenophores was primarily in October, and primarily in Boston Harbor, whereas subsequent blooms initiated earlier in August, and persisted to November in 2002 and 2003, and over a larger area. In order to better examine duration and magnitude of ctenophore blooms and their possible effects on reducing abundance of zooplankton and associated zooplankton grazing pressure on phytoplankton, quantitative screening and volume displacement measurements must be made on ctenophores in all samples where they are encountered.

The early summer nearfield zooplankton abundance means for 2001-2003 were all below the baseline minima (**Figure** D-7). Ctenophores were not recorded for the early summer periods in any of these years. Thus, the reason(s) for low post-baseline zooplankton abundance in early summer are unclear.

D.3 Plankton Summary

Patterns in plankton in 2003 were similar in many respects to those recorded for previous years. The phytoplankton was numerically dominated by microflagellates throughout most of the year, but with diatom blooms in winter-spring and fall. There was the now-typical bloom of *Phaeocystis pouchetii* in the spring. However, the spring *Phaeocystis* bloom in 2003 began earlier (February), and lasted longer (May) than most previous blooms which were typically April events. Dinoflagellate assemblages and abundances in 20 µm-screened samples were also similar to those of previous years, except that abundances of *Ceratium* spp. were somewhat lower than usual. There were no harmful or nuisance phytoplankton blooms in Massachusetts and Cape Cod Bays in 2003, other than the spring *Phaeocystis* bloom. However, *Alexandrium fundyense* was atypically present in low numbers in October, in addition to its normal late-spring appearance, also at low abundances. Potentially-toxic diatoms of the genus *Pseudo-nitzschia* were routinely present in the summer and fall, and the nearfield autumn mean value for *P. pungens* approached the autumn threshold value. Coincidentally, mortality of humpback whales offshore from Stellwagen Bank and on Georges Bank in October was associated with presence of domoic acid in dead whales, suggesting that the *Pseudo-nitzschia* bloom recorded in the MWRA sampling area was much more widespread.

Zooplankton community structure and abundance patterns were generally similar to previous years. Zooplankton abundance increased from winter through spring to summer, and declined through the fall. Zooplankton abundance was dominated by copepod nauplii, and adults and copepodites of *Oithona similis* and *Pseudocalanus* spp., with subdominant contributions by other copepods and sporadic pulses of meroplankters. Ctenophore predation likely contributed to the decline in abundances of other zooplankters from late summer through the fall. Comparison of winter-spring (February-April) nearfield abundances of *Calanus finmarchicus* copepodites and adults with the boreal winter index of the North Atlantic Oscillation yields a significant negative correlation suggesting that some components of marine plankton communities in Massachusetts Bay may be sensitive to variations in long-term climatic and oceanographic patterns.

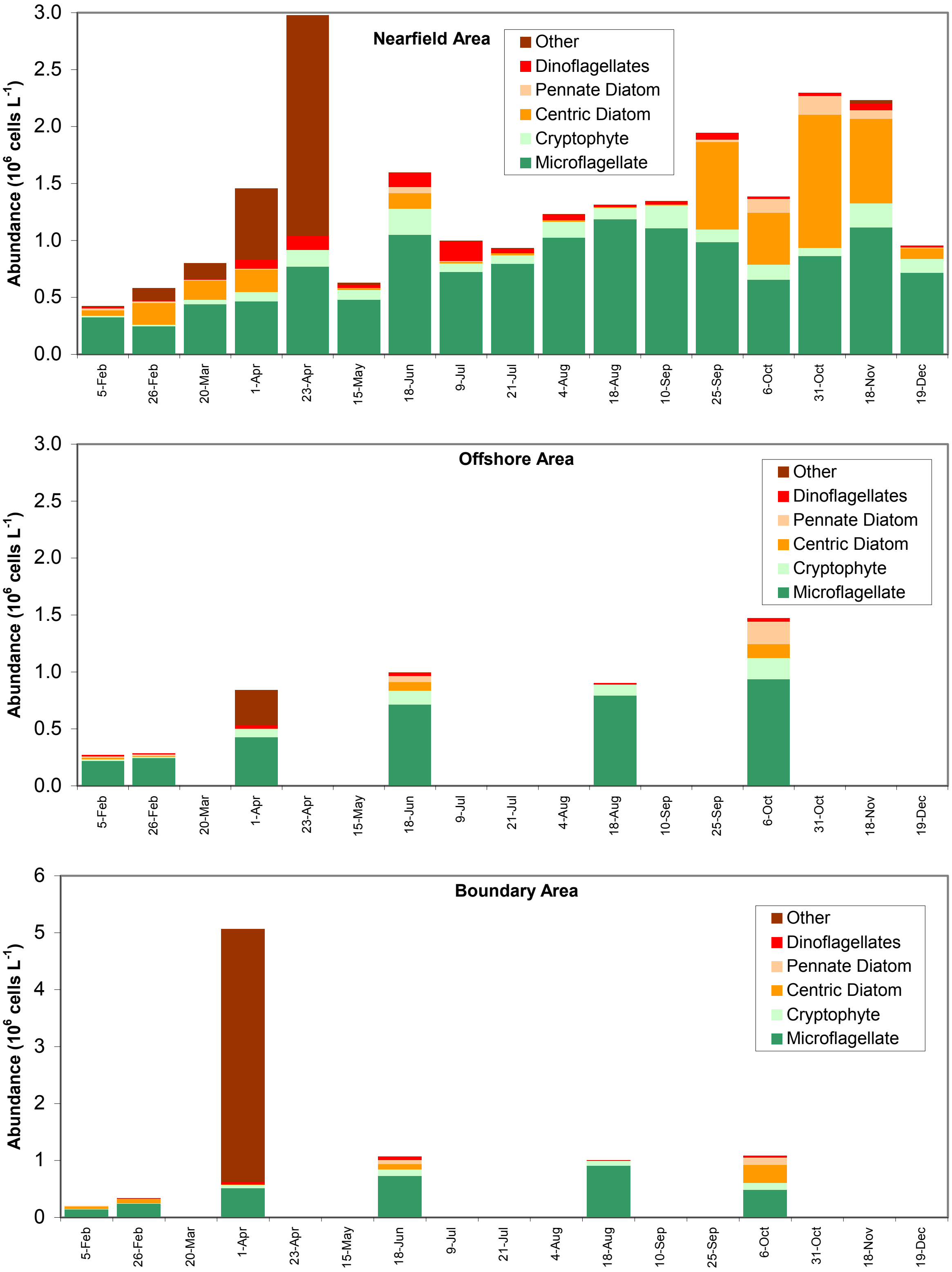


Figure D-1. Phytoplankton abundance by major taxonomic group by area for 2003. Note scale change for Boundary area data.

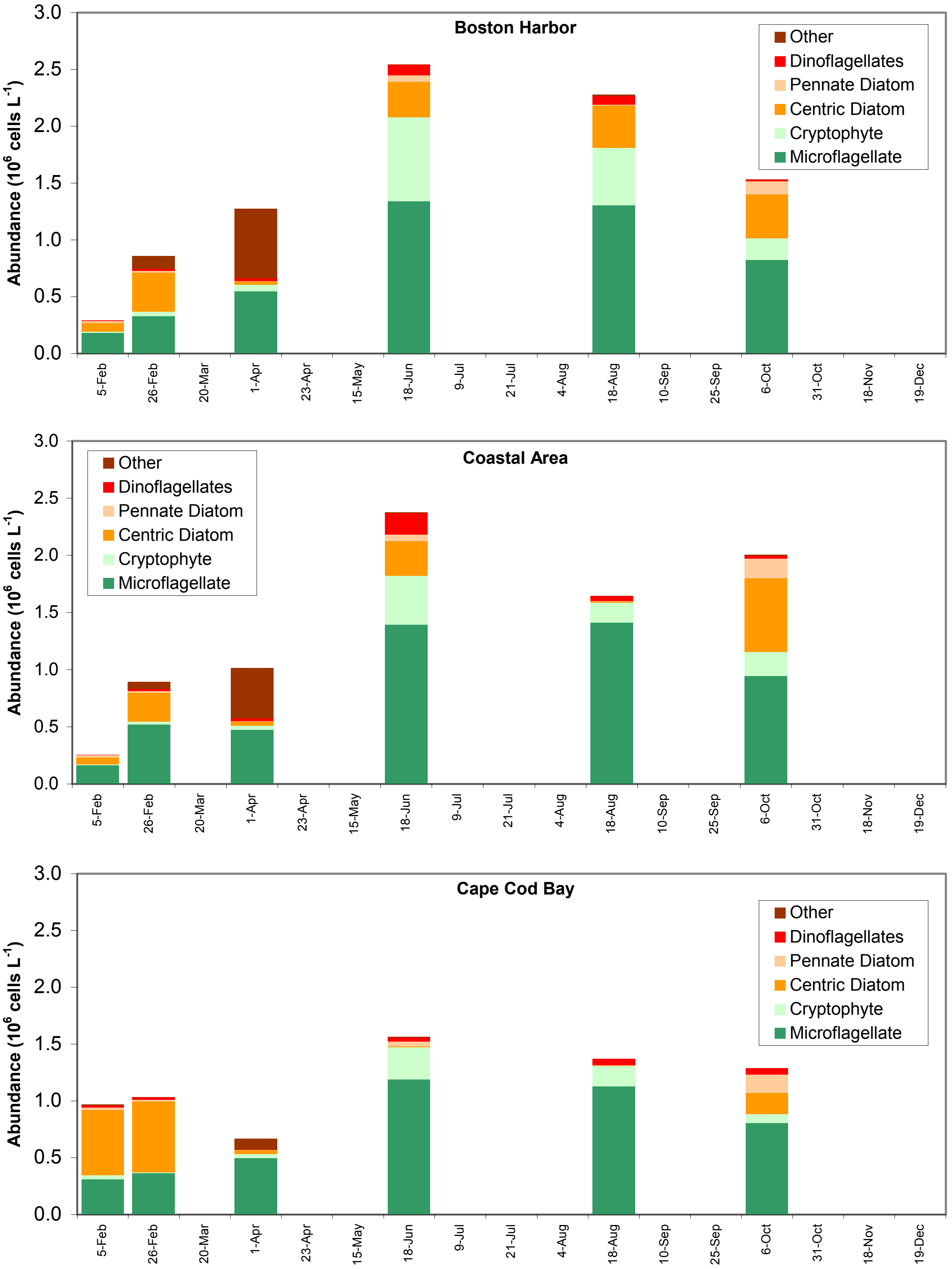


Figure D-2. Phytoplankton abundance by major taxonomic group by area for 2003.

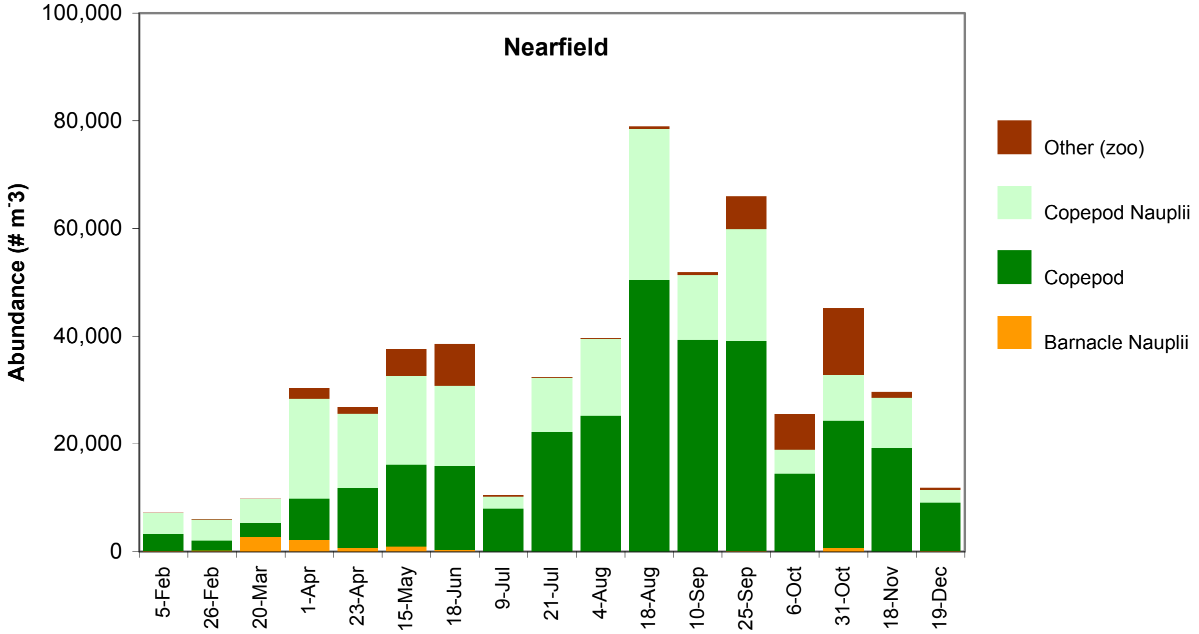


Figure D-3. Nearfield Zooplankton abundance by major taxonomic group for 2003.

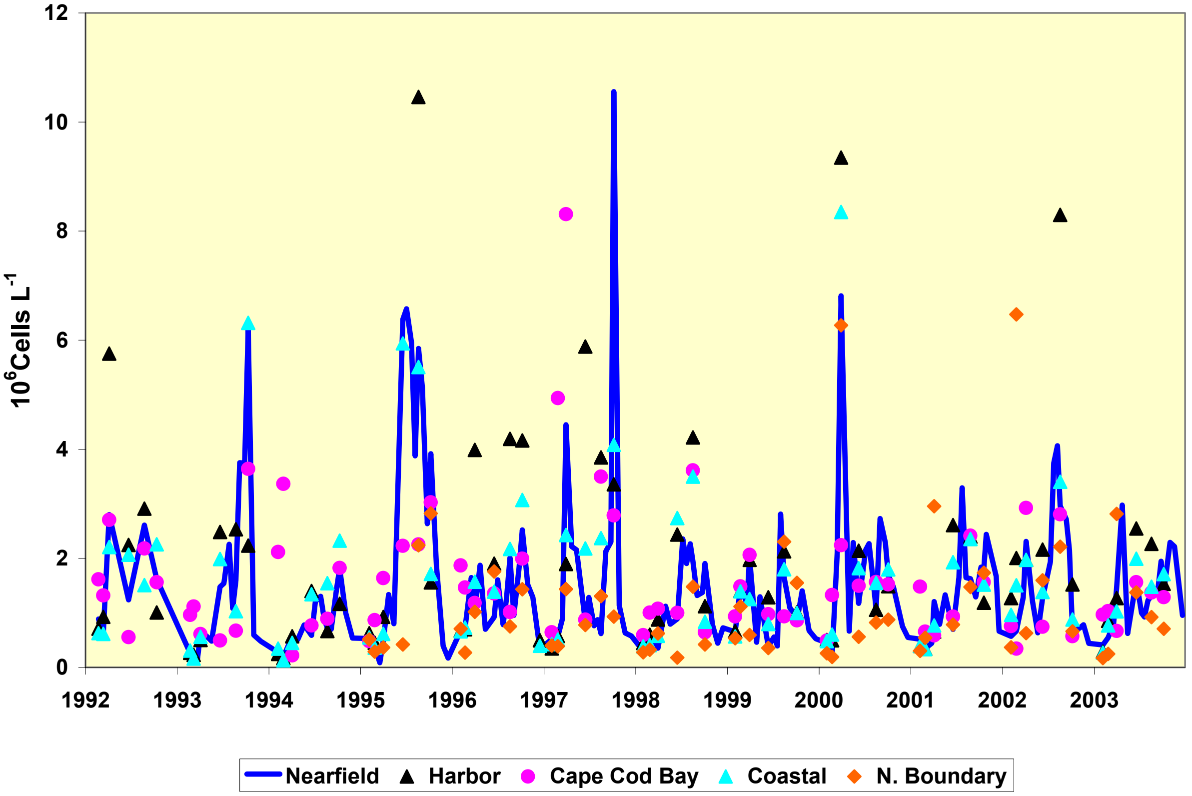
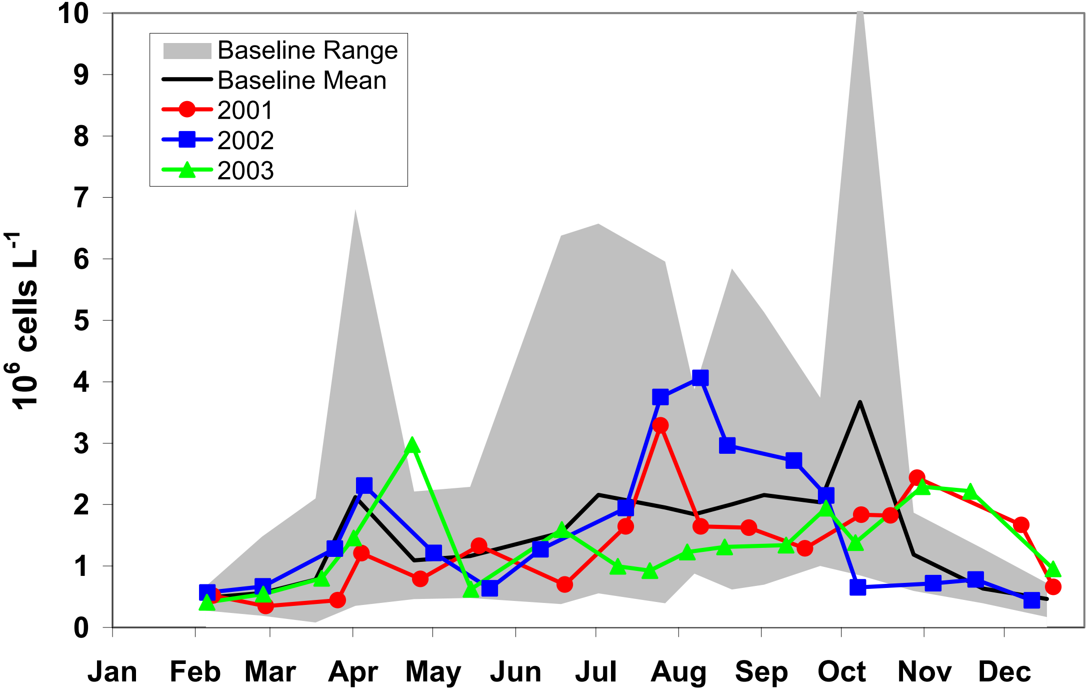


Figure D-4. Total phytoplankton abundance by region, 1992-2003.

(a) Total Phytoplankton



(b) Total Diatoms

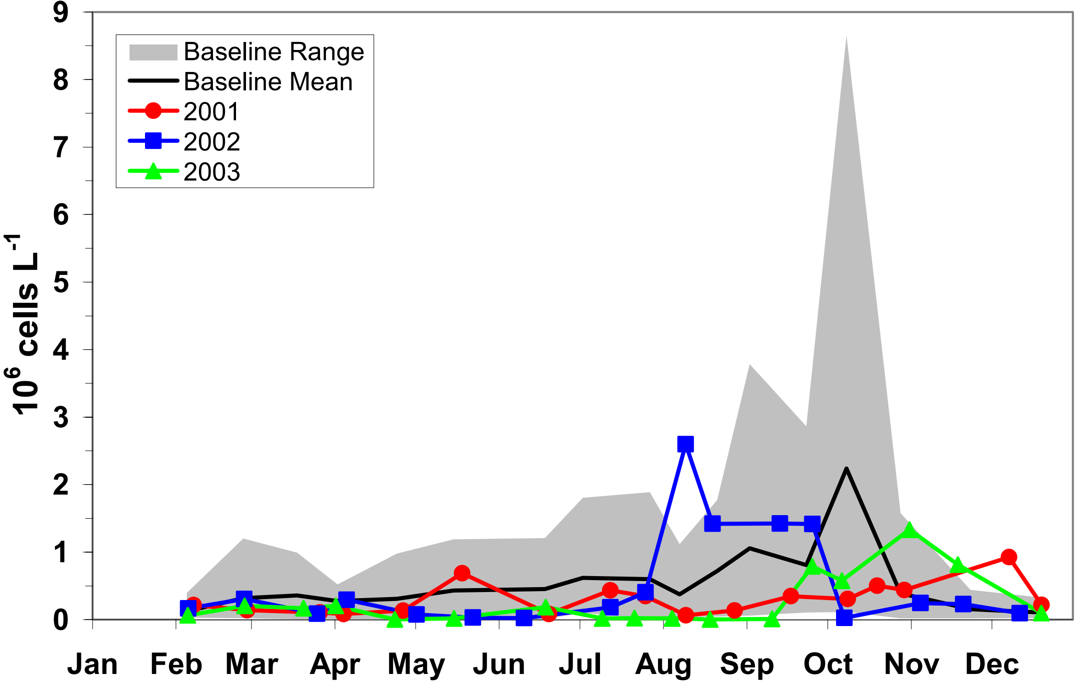
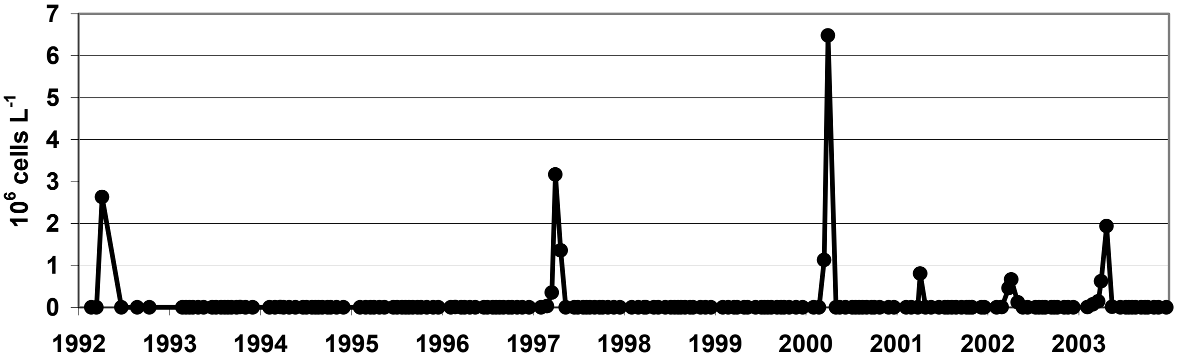
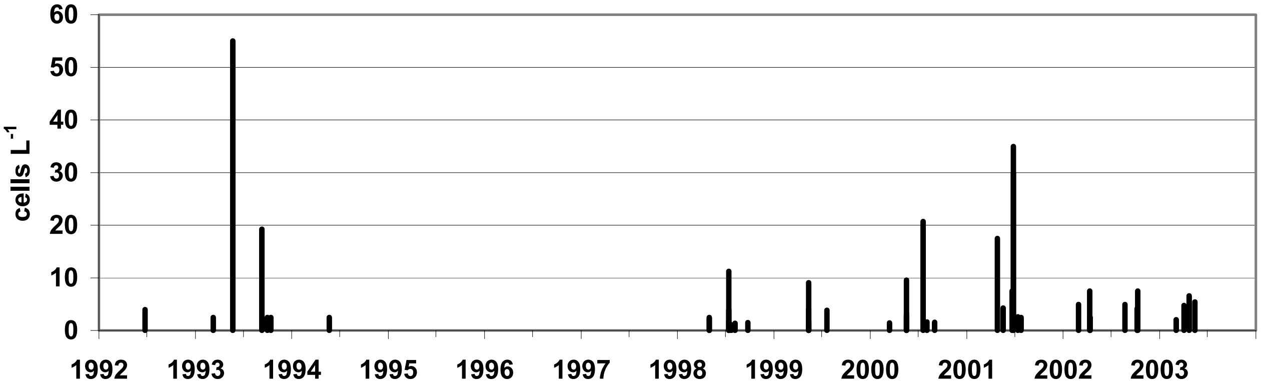


Figure D-5. Time-series of survey mean (a) total phytoplankton and (b) diatom abundance in the nearfield in 2001-2003 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled (fall 2000 data not shown).

(a) *Phaeocystis* - Nearfield



(b) *Alexandrium*: Non-Null Values - Nearfield



(c) *Pseudo-nitzschia* - Nearfield

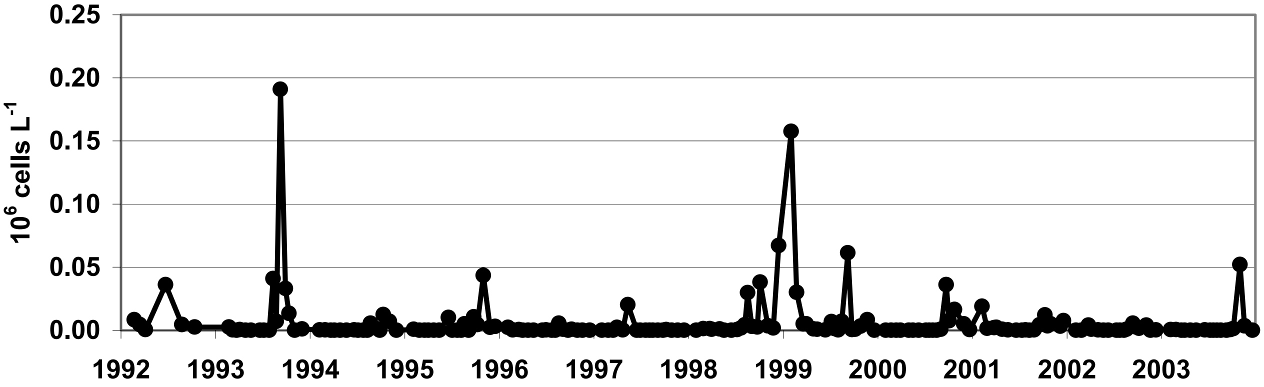


Figure D-6. Time-series of nuisance algae species in the nearfield (a) average *Phaeocystis* abundance, (b) non-null *Alexandrium* counts, and (c) average *Pseudo-nitzschia* abundance, 1992-2003.

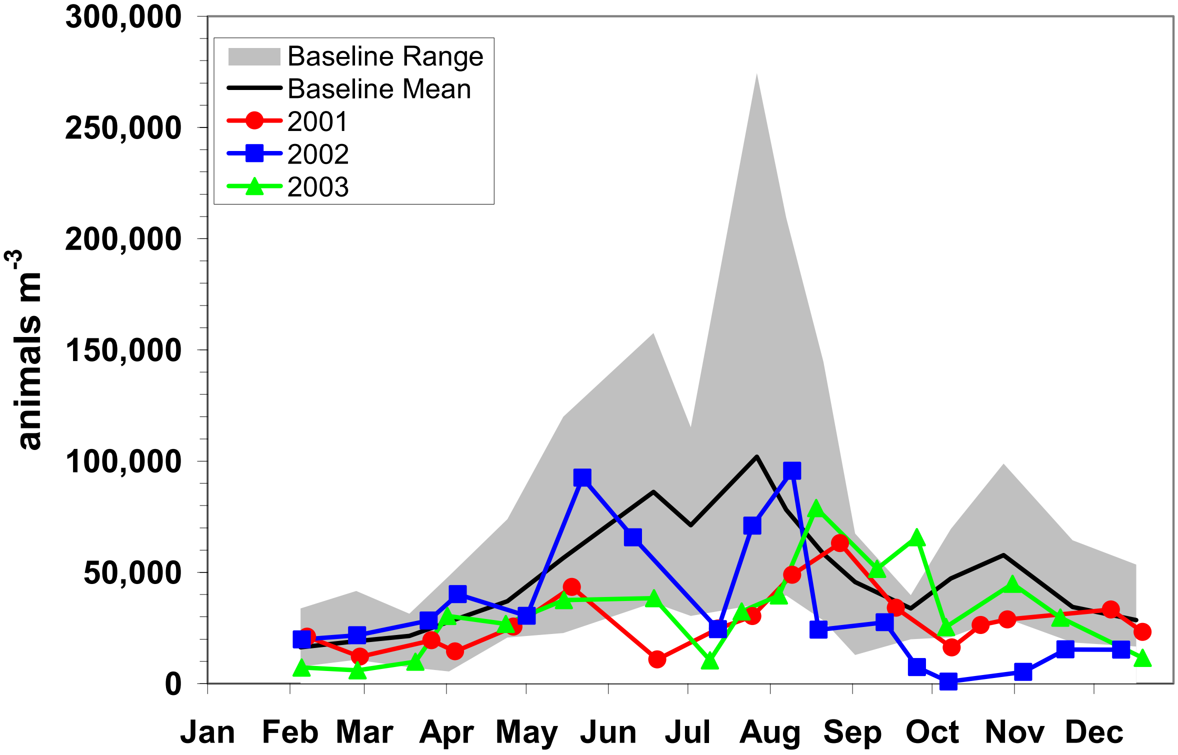
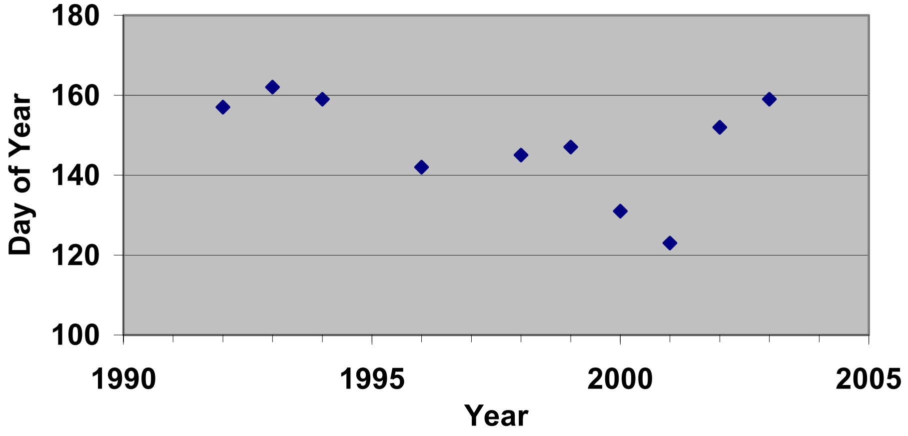
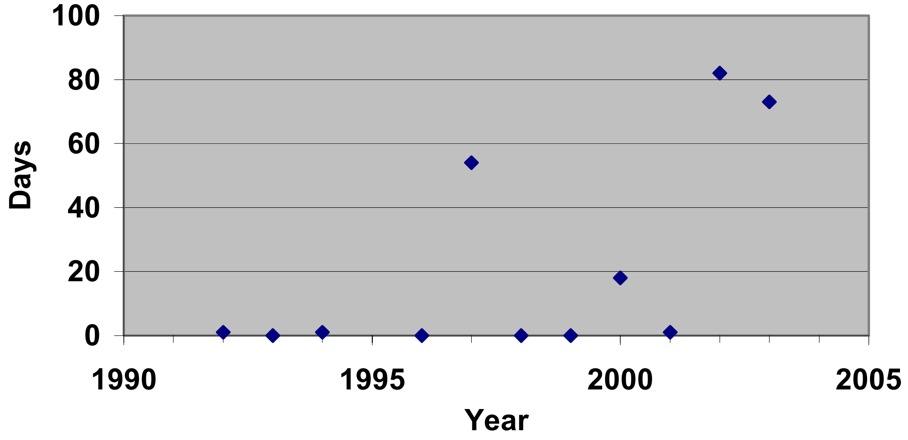


Figure D-7. Time-series of survey mean total zooplankton abundance in the nearfield in 2001-2003 compared against the baseline range and mean. Data collected from all nearfield stations sampled (fall 2000 data not shown).

(a) Day of Year 14C 1st Observed



(b) Phaeocystis bloom duration



(c) Duration vs. Day of Year

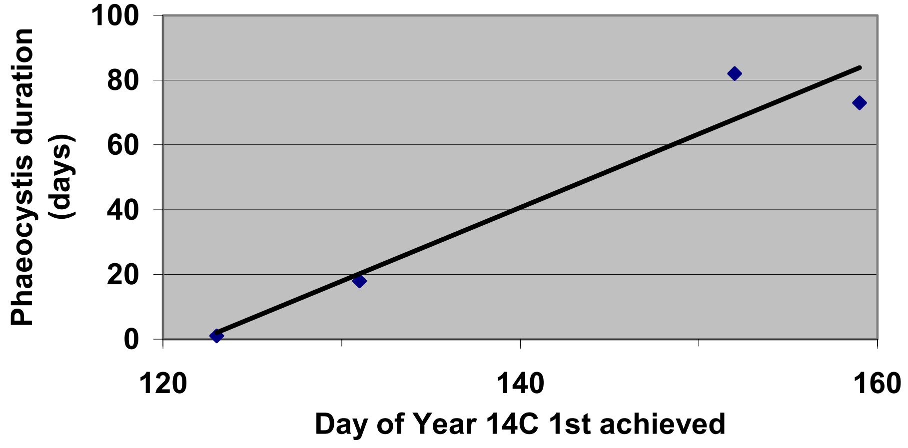
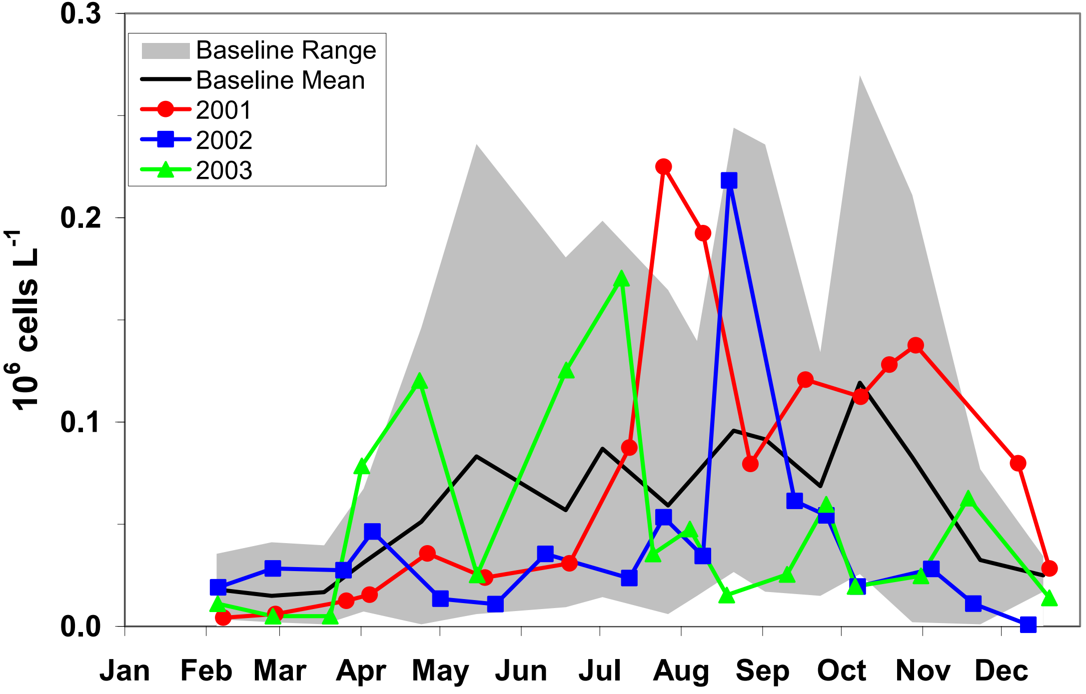


Figure D-8. Top panel: Day of the year that water temperature first attained 14 °C at the Boston Buoy in 1992-2003 (data missing for 1995 and 1997). Middle panel: Duration of *Phaeocystis* presence at station N04 in 1992-2003 (Duration determined as the difference between date of first and last appearance. A value of 1 indicates presence in a single sampling cruise. Data missing for 1995.) Bottom panel: Duration of *Phaeocystis* bloom vs. day of year 14 °C achieved for 2000-2003.

(a) Total Dinoflagellates



(b) Total *Ceratium*

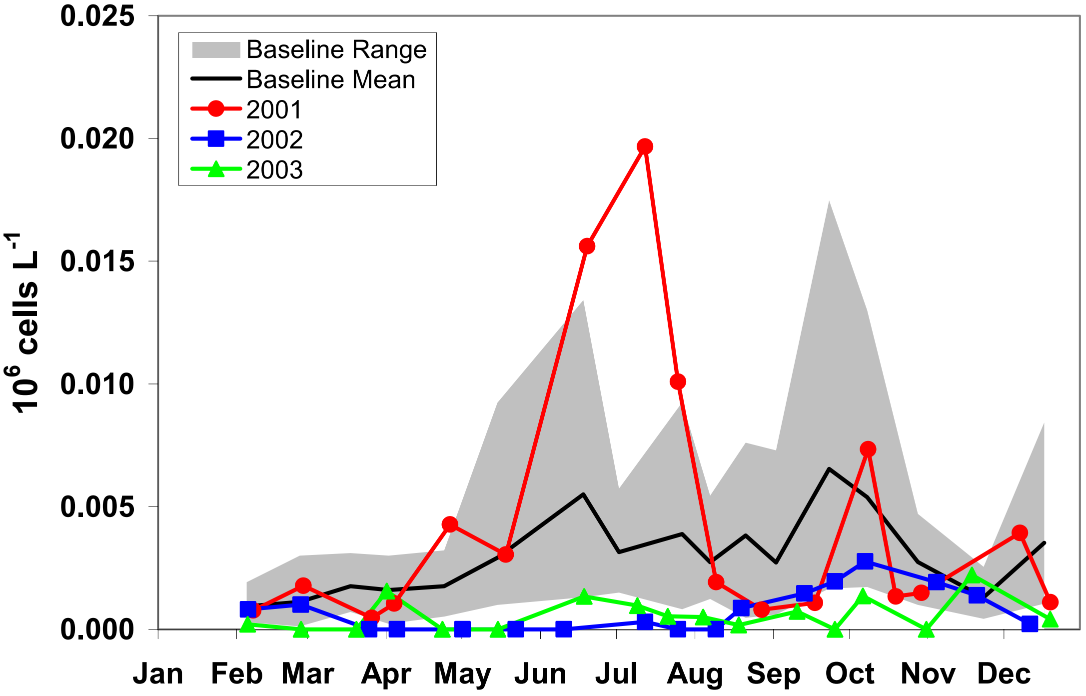


Figure D-9. Time-series of survey mean (a) total dinoflagellates and (b) *Ceratium* abundance in the nearfield in 2001-2003 compared against the baseline range and mean. Data collected from both surface and mid depths, and all nearfield stations sampled (fall 2000 data not shown).

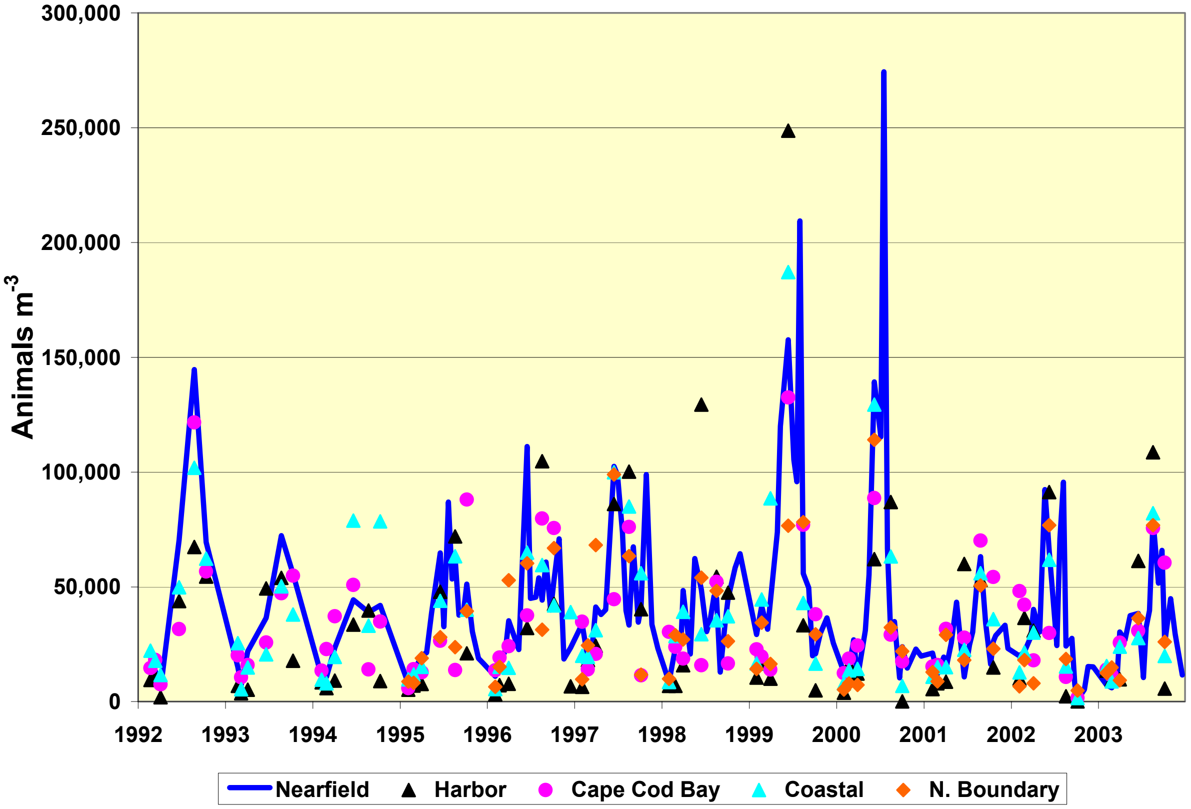
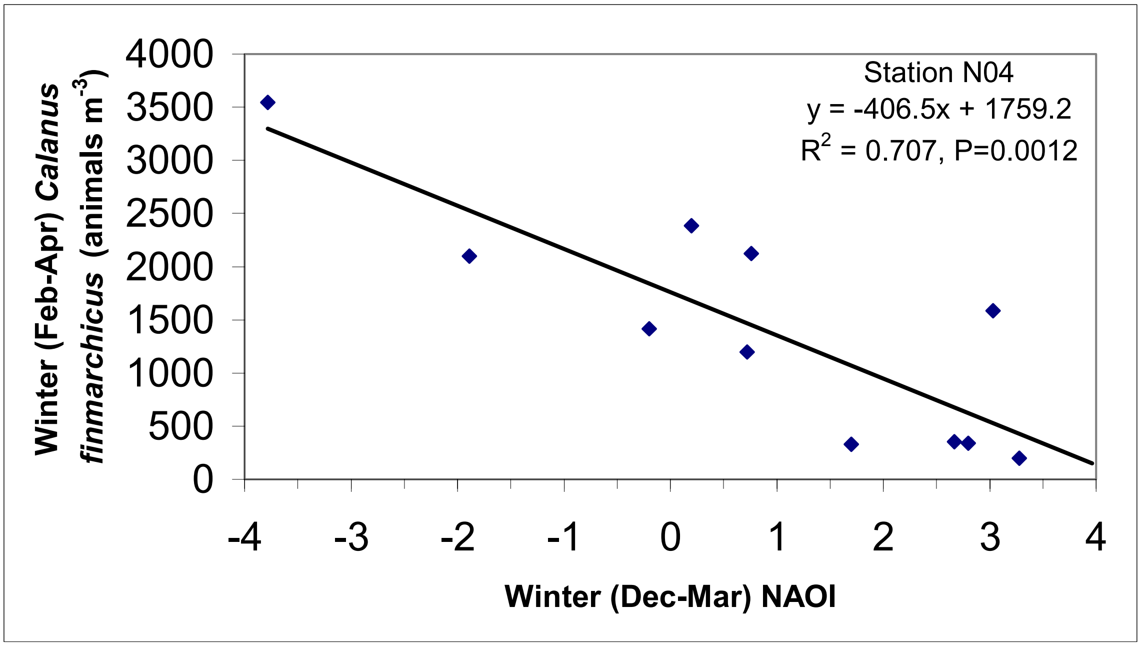


Figure D-10. Total zooplankton abundance by region, 1992-2003.



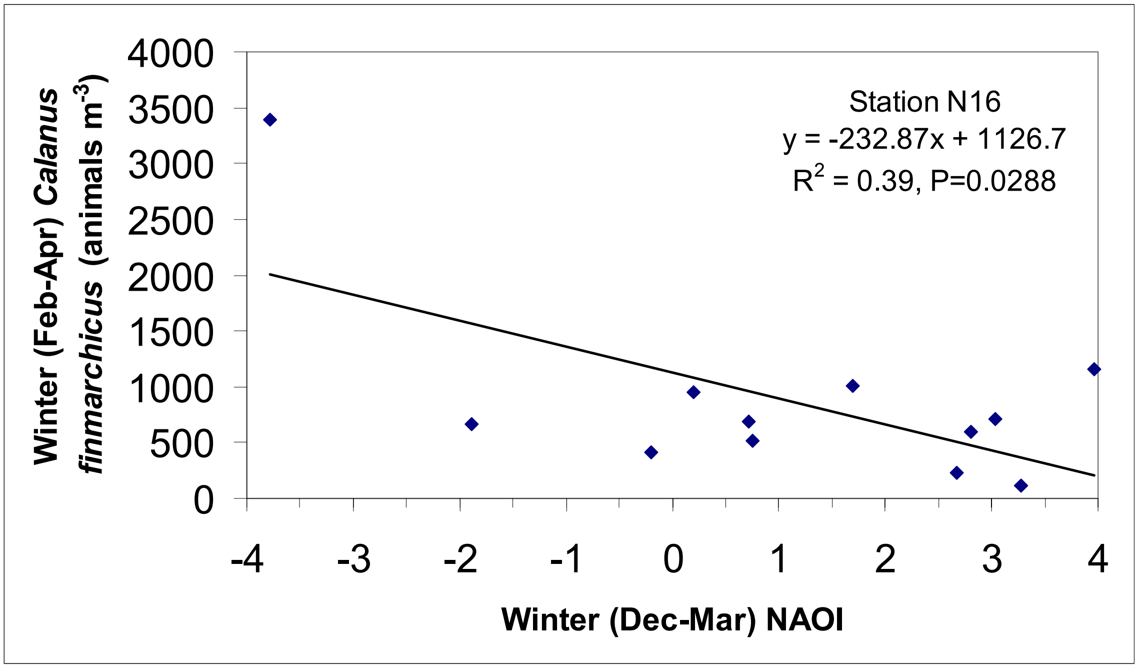


Figure D-11. Comparison of winter-spring nearfield abundances of *Calanus finmarchicus* (1992-2003) and the NAO index for winter (Dec-Mar) at nearfield stations N04 and N16.

Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
http://www.mwra.state.ma.us