2004 Annual Water Column Monitoring Report

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) has collected water quality data in Massachusetts and Cape Cod Bays for the Harbor and Outfall Monitoring (HOM) Program since 1992. This monitoring 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 and a low-frequency basis over an extended area throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay. The 2004 data represent the fourth full year of conditions since initiation of discharge from the bay outfall. This annual report evaluates the 2004 water column monitoring results, assesses spatial and temporal trends in the data, compares 2004 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 2004. The major features and differences from the baseline in 2004 include:

- Winter/spring 2004 was marked by extremely low air and water temperatures. Air temperatures in January 2004 were the lowest since 1893 resulting in very cold water temperatures.
- Early April was characterized by a 50-year storm event that resulted in over four inches of rain with concomitant increases in runoff and peak river flow both locally and regionally. The April storm event and resulting high flow conditions likely led to increased nutrient inputs to the system and contributed to the magnitude of the regional *Phaeocystis* bloom.
- The most significant biological event in 2004 was the major *Phaeocystis* bloom with extraordinarily high abundances observed throughout Massachusetts and Cape Cod Bays in April. The bloom was most prominent at Boston Harbor and coastal stations where *Phaeocystis* abundance was >10 million cells L^{-1}.
- Maximum nutrient concentrations were observed in February when the water column was well mixed and biological uptake of nutrients limited. In general, the nutrient concentrations during the two February surveys were higher than typically measured in the past likely due to meteorological and oceanographic conditions and lower biological utilization related to the lack of an early winter/spring diatom bloom in Massachusetts Bay.

- Productivity in 2004 generally followed patterns observed in prior years. Unlike many years, however, early February and fall peaks were not observed. Nearfield productivity rates reached annual maxima during the *Phaeocystis* bloom, but were on the lower end of the winter-spring bloom range observed during past years.
- In Boston Harbor, areal production increased in early April and continued to increase into June. The seasonal cycle observed in 2004 in the harbor was more similar to the pre-diversion trend than the post-diversion trend of winter/spring and fall peaks, but at the lower end of the range in magnitude previously observed.
- There was no indication of a fall bloom in 2004 in phytoplankton biomass, abundance, productivity or satellite data. It was the first year since monitoring began in 1992 not to exhibit indications of a fall bloom.
- Annual bottom water minimum DO levels measured in the nearfield in late September and in Stellwagen Basin in October were well above State Standards and considerably higher than levels typically measured during previous years.
- Zooplankton community abundance and taxa were similar to previous years. Zooplankton abundance was lower than typically observed over much of 2004. Low abundance in spring-summer appears to be correlated to the *Phaeocystis* bloom. Low abundance in the fall could be related to either bottom-up (no fall bloom) or top-down (ctenophore predation) controls.

The extraordinarily high abundances of *Phaeocystis* in the nearfield in March and April and the protracted duration of this bloom into May led to exceedances of both the winter/spring and summer *Phaeocystis* caution thresholds. The summer *Phaeocystis* threshold value, however, was exceeded as the spring *Phaeocystis* bloom was declining, but still present during the May survey. Data suggest that the *Phaeocystis* colonies observed in mid-May were remnants of a senescent bloom (chlorophyll:phaeophytin of 2:1 to 1:1 and colonies appeared to be senescent with ‘empty’ *Phaeocystis* cells, lower density of cells, and many fragmented/broken colonies). No *Phaeocystis* were observed in samples collected over the rest of the summer. The continued occurrence of spring *Phaeocystis* blooms in consecutive years (2000 to 2004) is a change from the pattern that had been observed during earlier baseline monitoring of these blooms occurring in single years in cycles of about 3 years. Although this was the fifth consecutive year that *Phaeocystis* has bloomed in the bays and the third year in which the summer threshold has been exceeded, it is not considered indicative of an impact associated with the outfall, but rather a change in the cycle of these events.

Changes in the nutrient regimes following diversion are unambiguous – NH_4 has dramatically decreased in Boston Harbor (~80%) 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 directly into changes in biomass, whether measured as chlorophyll, POC, or phytoplankton abundance although there has been a significant increase in winter/spring biomass at some nearfield and nearby stations. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with significant decreases in chlorophyll and POC and lower production, and results suggest that the seasonal pattern in productivity is changing from a eutrophic to a more normal temperate coastal pattern.

In May-July 2005, an extensive bloom of *Alexandrium fundyense* occurred along the coast of southern New England. *Alexandrium* is one of the nuisance algae of concern because it produces a toxin that can build up in shellfish to levels that can cause paralytic shellfish poisoning (PSP) in people. The bloom was exceptional in several ways: high toxin levels were measured farther south than ever before in New England; levels of toxicity in many locations were higher than previously observed at those stations; for some locations, toxicity above quarantine levels (levels high enough to close the shellfish beds) for the first time; and cell concentrations far exceeded those observed in the coastal waters of southern New England in the past.

MWRA participated in a region-wide collaborative monitoring effort intended to help understand the scale and duration and to evaluate the causes of this unprecedented red tide event. As of November 2005, preliminary indications are that an unusually large spring bloom occurred in the coastal waters of Maine, and this bloom moved south with stronger-than-usual coastal currents, a result of high spring runoff from large rivers in Maine. The bloom was transported into Massachusetts and Cape Cod bays and to waters south of the Cape by a pair of strong northeast storms in May. The data from this MWRA monitoring effort will not be further detailed in this report. The causes and effects of the bloom continue to be evaluated, and a more complete analysis will be presented in the 2005 annual report and an interpretive report focused on the 2005 Red Tide Event.

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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). A detailed description of the monitoring and its rationale is provided in the Effluent Outfall Monitoring Plan developed for the baseline period and the post discharge period Monitoring Plan (MWRA 1991 and 1997). A comprehensive review of the data in June 2003 led to revisions to the Ambient Monitoring Plan (MWRA 2004) that were first implemented in 2004. The changes to the water column monitoring program include reducing the number of nearfield surveys from 17 to 12 and reducing the number of nearfield stations from 21 to 7. These changes were based on both a qualitative and statistical examination of baseline and post-discharge data (MWRA 2003). The five surveys dropped were those previously conducted in May (WN0X5), July (WN0X8), August (WN0XA), November (WN0XG), and December (WN0XH). The 2004 data represent the first year of monitoring under the revised program and the fourth 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 2004 water column monitoring data have been reported in a series of survey reports, data reports, and semiannual interpretive reports (Libby *et al.* 2004a and 2005a). The purpose of this annual report is to present a compilation of the 2004 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 2004 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 2004 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?

Aesthetics

- Has the clarity and/or color of water around the outfall changed?
- Has the amount of floatable debris around the outfall changed?

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 2003 annual report (Libby *et al*. 2004b), this report focuses on addressing the 1991 monitoring questions. Those interested in an extensive presentation of all 2004 monitoring results are referred to Appendices A-D and the 2004 semiannual reports (Libby *et al.* 2004a and 2005a). 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 2004 monitoring data specifically presented in that section. The discussion includes an overview of the major findings from the 2004 water column data, integration and comparisons of baseline and post-discharge data, and comparisons of 2004 data against the established Contingency Plan (MWRA 2001) thresholds. The final section summarizes these discussions and presents the current understanding in respect to the monitoring questions (MWRA 1991).

2.0 2004 WATER COLUMN MONITORING PROGRAM

This section summarizes the 2004 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: 2004-2005 (Libby *et al*. 2005b). 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 2004 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 2004 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*. 2004a and 2005a). 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 2004 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 12 surveys that were conducted in 2004 (**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 34 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 (**Figure** 2-1). The nearfield stations, located in Massachusetts Bay in the vicinity of the outfall site, were sampled during each of the 12 surveys. The farfield stations, located throughout Boston Harbor, Massachusetts Bay, and Cape Cod Bay, were sampled during the seven combined farfield/nearfield surveys (note that the final combined survey was split between the October and November surveys WF04E and WF04F).

The seven 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** 2-1). 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** 2-1). Details on the sampling protocols can be found in the CW/QAPP (Libby *et al.* 2005b).

Table 2-1. Water quality surveys for 2004 (WF041-WF04F).

Survey[1]	Type of Survey	Survey Dates
WF041	Nearfield/Farfield	February 2-5
WF042	Nearfield/Farfield	February 23-25
WN043	Nearfield	March 23
WF044	Nearfield/Farfield	April 7-9
WN046	Nearfield	May 14
WF047	Nearfield/Farfield	June 14-17
WN049	Nearfield	July 20
WF04B	Nearfield/Farfield	August 17-19
WN04C	Nearfield	September 1
WN04D	Nearfield	September 27
WF04E	Nearfield/Farfield	October 18-19
WF04F[2]	Nearfield/Farfield	November 10-18

[1] Surveys WN045, WN048, WN04A, WN04G, and WN04H were dropped based on recommendations made by OMSAP (MWRA 2004).

[2] Weather delays postponed sampling at half of the farfield stations from WF04E until WF04F.

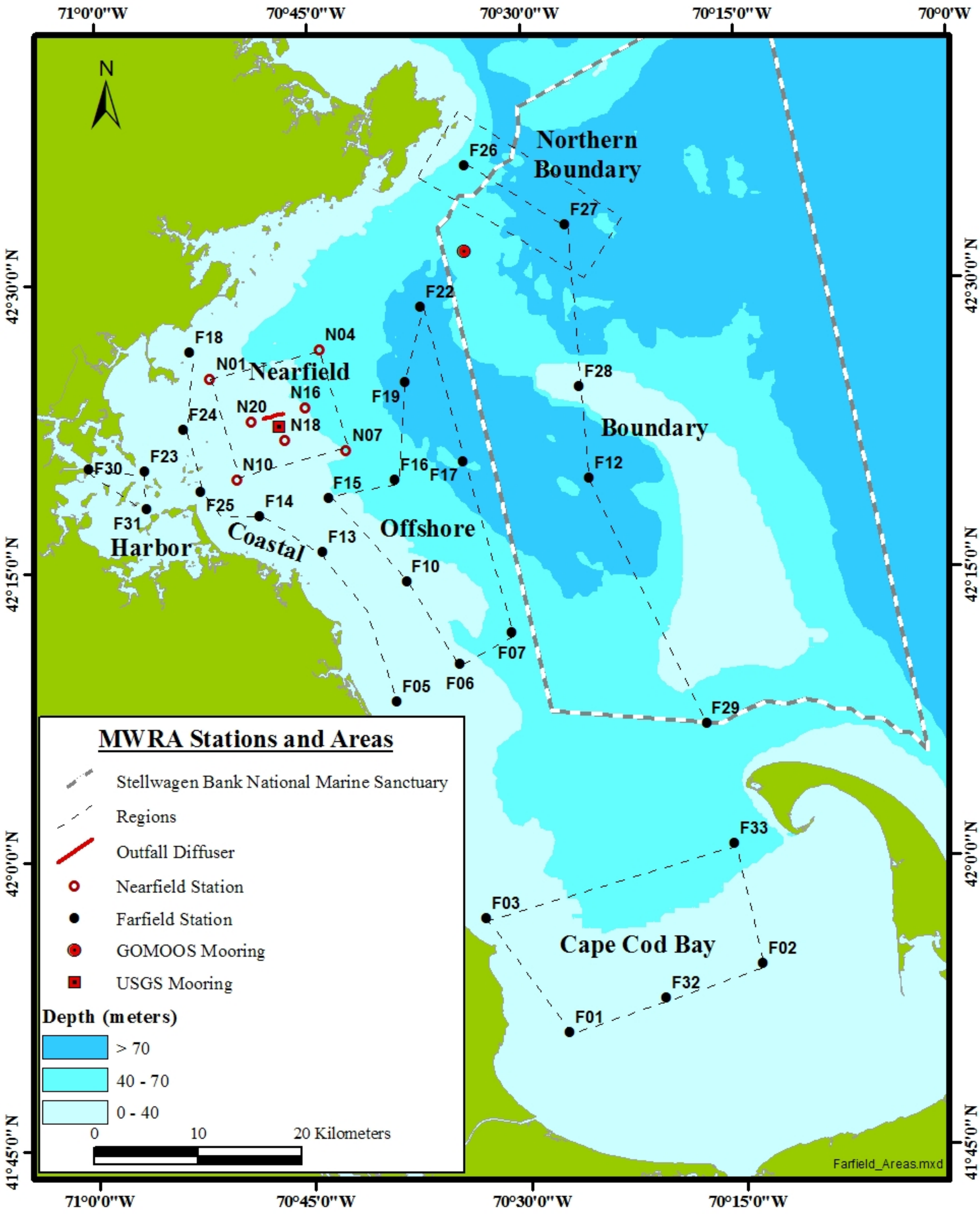


Figure 2-1. Locations of nearfield and farfield stations and regional station groupings, MWRA outfall, and USGS and GoMOOS moorings.

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, the timing of events over the cycle is 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.

Since the HOM program began in 1992, the ‘red tide’ organism, *Alexandrium fundyense*, has been 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 input of Gulf of Maine (GOM) waters to 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). This appears to have been the case in 2005 when meteorological conditions were such that an ongoing bloom of *Alexandrium* in the western GOM was transported into Massachusetts and Cape Cod Bays (Anderson *et al.* 2005).

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 2004 Results

The sequence of events described in Section 3.1 was generally evident in 2004 with some notable variations. Details on the physical, chemical and biological data collected in 2004 can be found in Appendices A-D and in the two semi annual reports (Libby *et al*. 2004a and 2005a). The major water quality features and differences from the baseline in 2004 are summarized below:

- The winter/spring of 2004 was marked by extremely low air and water temperatures. Air temperatures in January 2004 were the lowest observed since 1893 (NWS Logan) resulting in very cold water temperatures.
- Early April was characterized by a 50-year storm event that resulted in over four inches of rain with concomitant increases in runoff and peak river flow both locally and regionally. The April storm event and resulting high flow conditions likely led to increased nutrient inputs to the system and contributed to the magnitude of the regional *Phaeocystis pouchetii* bloom.
- The most significant biological event in 2004 was the major *Phaeocystis* bloom with extraordinarily high abundances observed throughout Massachusetts and Cape Cod Bays in April. The bloom was most prominent at Boston Harbor and coastal stations where *Phaeocystis* abundance was >10 million cells L^{-1} and the highest chlorophyll concentrations were measured.
- Considering the magnitude of the *Phaeocystis* bloom, peak chlorophyll concentrations were relatively low ($\leq 10\ \mu gL^{-1}$). SeaWiFS images show an abrupt decline in the chlorophyll signal associated with the *Phaeocystis* bloom by mid to late April.
- Maximum nutrient concentrations were observed in February when the water column was well mixed and biological uptake of nutrients limited. In general, the nutrient concentrations during the two February surveys were higher than typically measured in the past likely due to meteorological and oceanographic conditions and lower biological utilization related to the lack of an early winter/spring diatom bloom in Massachusetts Bay.
- Areal production in 2004 followed patterns typically observed in prior years. Unlike many years, an early February peak was not observed. A minor winter/spring diatom bloom was observed in Cape Cod Bay in February, but diatom abundance remained very low throughout Massachusetts Bay waters. Nearfield productivity rates reached annual maxima during the April bloom, but were on the lower end of the winter-spring bloom range observed during past years.
- In Boston Harbor, areal production increased in early April and continued to increase into June. The seasonal cycle observed in 2004 in the harbor was more similar to the pre-diversion trend than the post-diversion trend of winter/spring and fall peaks, but at the lower end of the range of magnitudes previously observed.
- Fall blooms have been a normal aspect of the seasonal biological cycle in Massachusetts Bay. However, the timing and magnitude of the bloom has been highly variable. In fall 2004, there was no indication in any of the phytoplankton biomass, abundance, productivity or satellite imagery data that a bloom occurred. It was the first year since monitoring began in 1992 not to exhibit indications of a fall bloom.

- In the nearfield, stratification had weakened by late September coincident with increased river flow (storms) and strong downwelling conditions. The breakdown of stratification appeared to have occurred in typical fashion supplying nutrients to the surface waters. Physical oceanographic or meteorological conditions may have played a role in the failure of a fall bloom in 2004.
- Annual bottom water minimum DO levels were measured in the nearfield in late September (7.55 mg L^{-1} and 80.4%) and had not increased much by October when the minimum DO levels were observed in Stellwagen Basin (7.72 mg L^{-1} and 80.4%). These DO levels are well above the threshold and State Standards and considerably higher than levels typically measured during previous years.
- Zooplankton community abundance and taxa were similar to previous years. Zooplankton abundance was lower than typically observed over much of 2004. Low abundance in spring-summer appears to be correlated to the *Phaeocystis* bloom. Low abundance in the fall could be related to either bottom-up (no fall bloom) or top-down (ctenophore predation) controls.

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 fundyense* 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}.

Dissolved oxygen concentrations were relatively high during the fall of 2004. Annual minimum in survey mean DO levels were measured in the nearfield in late September (7.55 mg L^{-1} and 80.4%) and in Stellwagen Basin in October (7.72 mg L^{-1} and 80.4%). These DO levels are well above the caution threshold and Massachusetts State Standards for Class SB waters. In comparison to previous years, the minimum concentrations are about 1 mg L^{-1} higher than typically observed in Massachusetts Bay (**Figure** 3-1). In addition to 2004, only in 1993 and 1996 has the annual nearfield DO minima not dropped below 80% (**Figure** 3-2). Stellwagen Basin DO %saturation levels remained above 80% during the June to October Threshold period, but did dip below 80% in November (78%) during the split farfield survey. These levels were among the higher minima that have been observed for this area since 1992.

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

Parameter	Time Period	Caution Level	Warning Level	Background	2004
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: 7.55 mg l^{-1} SW Basin: 7.72 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: 80.4% SW Basin: 80.4%
Bottom Water DO Rate of Decline (Nearfield)	Seasonal June-October	0.037 mg l^{-1} d^{-1}	0.049 mg l^{-1} d^{-1}	--	0.020 mg l^{-1} d^{-1}
Chlorophyll	Annual	118 mg m^{-2}	158 mg m^{-2}	--	69 mg m^{-2}
	Winter/spring	238 mg m^{-2}	--	--	101 mg m^{-2}
	Summer	93 mg m^{-2}	--	--	61 mg m^{-2}
	Autumn	212 mg m^{-2}	--	--	44 mg m^{-2}
Phaeocystis pouchetii	Winter/spring	2,020,000 cells l^{-1}	--	--	2,870,000 cells l^{-1}
	Summer	357 cells l^{-1}	--	--	164,400 cells l^{-1}
	Autumn	2,540 cells l^{-1}	--	--	None
Pseudo-nitzschia pungens	Winter/spring	21,000 cells l^{-1}	--	--	11 cells l^{-1}
	Summer	43,100 cells l^{-1}	--	--	3,375 cells l^{-1}
	Autumn	24,700 cells l^{-1}	--	--	660 cells l^{-1}
Alexandrium fundyense	Any nearfield sample	100 cells l^{-1}	--	--	5 cells l^{-1}

The nearfield mean areal chlorophyll for winter/spring 2004 was moderate (101 mg m^{-2}), but less than half the seasonal caution threshold of 238 mg m^{-2}. The extraordinarily high abundances of *Phaeocystis* did not manifest as correspondingly high chlorophyll biomass nor did the prolonged duration in the bloom lead to elevated seasonal mean values. The winter/spring mean areal chlorophyll in 2004 was comparable to those measured in 1992-1998 and 2001-2002 and well below those for 1999, 2000, and 2003 (**Table** 3-2). In 2004, no fall bloom was observed and nearfield chlorophyll values were near the baseline minimum in the early fall and remained below average near the end of the year. The summer and fall 2004 nearfield areal chlorophyll means were 61 and 44 mg m^{-2} respectively, which are approximately 66% and 20% of the caution threshold values. These seasonal values in combination with a relatively low winter/spring 2004 seasonal mean resulted in a low annual mean of 69 mg m^{-2}. The 2004 annual mean value is comparable to that measured in 2001, 2002 and 2003. All of the post discharge years' annual means have been below the caution threshold of 118 mg m^{-2} and well below the pre-transfer peak values measured in 1999 and 2000 (**Table** 3-2). Comparison of winter/spring and fall seasonal and annual mean areal chlorophyll indicates an apparent increase between baseline and post-discharge mean values (**Figure** 3-3). This increase is not significant, however, given the limited post-transfer dataset (n=4 or 5) and the high degree of interannual variability in the data. The wide range in seasonal and annual values is due primarily to the large blooms and associated chlorophyll levels in 1999 and 2000.

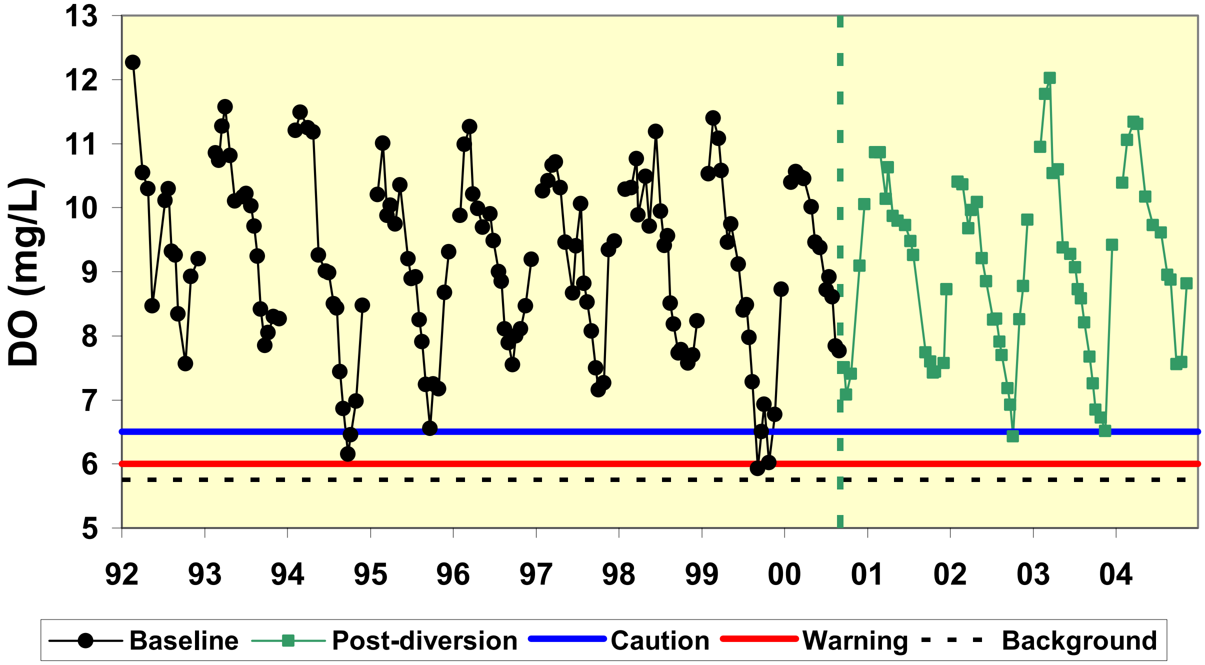
Table 3-2. Seasonal and annual mean areal chlorophyll (mg m^{-2}) in the nearfield.

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	180	57	170	126
2000	193	87	212	156
2001	70	45	87	67
2002	112	50	96	80
2003	178	45	87	99
2004	101	61	44	69
Caution Threshold	238	93	212	118
Baseline Mean*	82	51	90	67
Post Transfer Mean*	115	50	105	79

*Bay Outfall began discharging September 6, 2000. Data from 2000 are included in baseline for winter/spring and summer means, in post-transfer fall mean, and not used in annual mean comparison.

The extraordinarily high abundances of *Phaeocystis* in the nearfield in March and April and the protracted duration of the bloom into May led to exceedances of both the winter/spring and summer *Phaeocystis* caution thresholds (**Figure** 3-4). These 2004 seasonal means were also the highest winter/spring and summer values observed over the 1992 to 2004 monitoring period. The summer *Phaeocystis* threshold value was exceeded as the spring *Phaeocystis* bloom was declining, but still present during the May survey. Data suggest that the *Phaeocystis* colonies observed in mid-May were remnants of a senescent bloom (chlorophyll to phaeophytin ration of 2:1 to 1:1 and colonies appeared to be senescent with ‘empty’ *Phaeocystis* cells, lower density of cells, and many fragmented/broken colonies). No *Phaeocystis* were observed in samples collected over the rest of the summer. The continued occurrence of spring *Phaeocystis* blooms in consecutive years (2000 to 2004) is a change from the pattern that had been observed during earlier baseline monitoring of these blooms occurring in single years in cycles of about 3 years. Although this was the fifth consecutive year that *Phaeocystis* has bloomed in the bays and the third year in which the summer threshold has been exceeded, it is not considered indicative of an impact associated with the outfall, but rather a change in the cycle of these events. The factors contributing to the occurrence, magnitude and duration of *Phaeocystis* bloom is discussed in more detail in Section 3.4.7 and Appendix D. *Alexandrium* and *Pseudo-nitzschia* were observed intermittently, but at very low abundance.

(a) Nearfield



(b) Stellwagen Basin

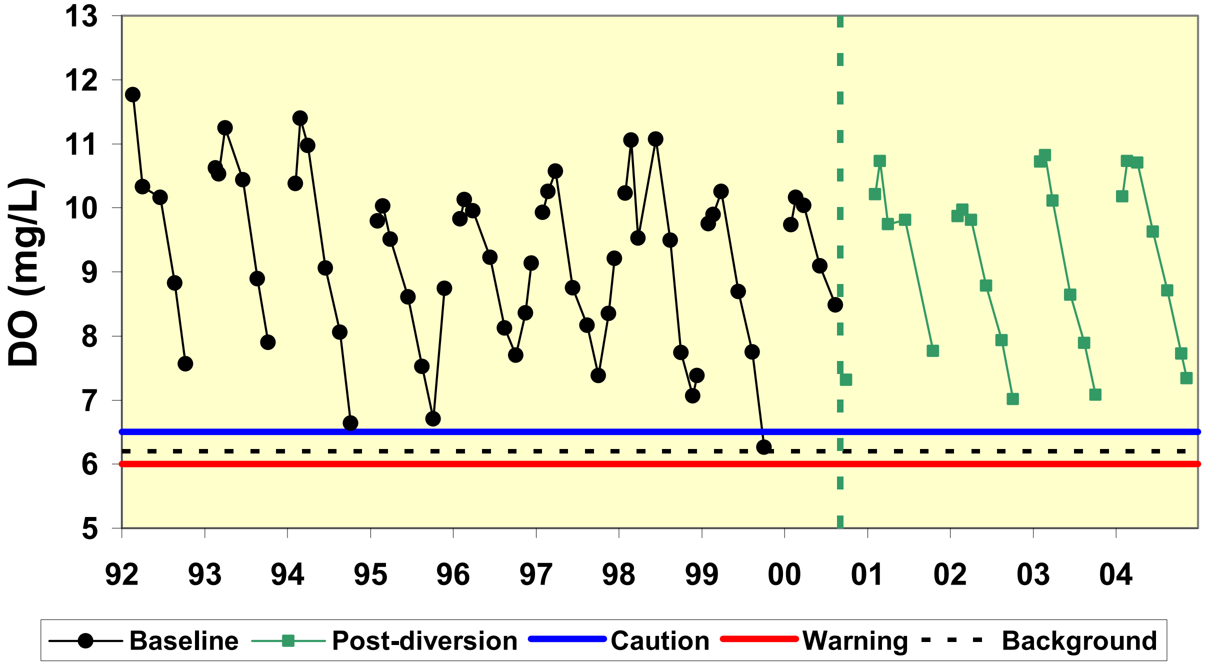
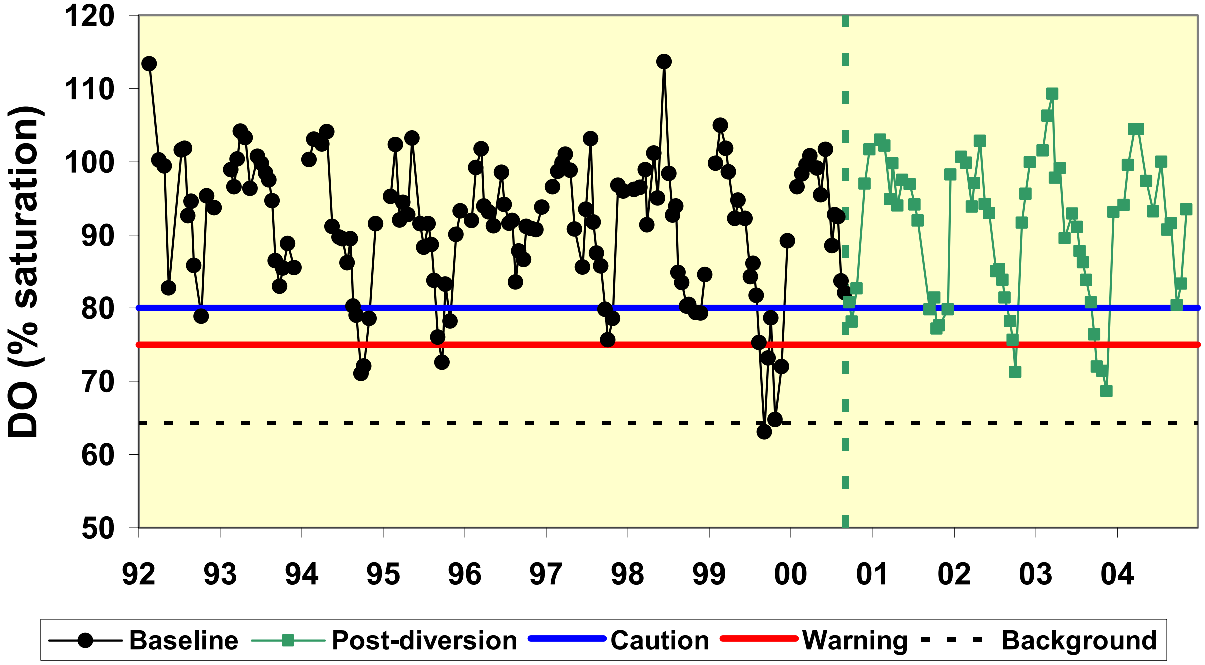


Figure 3-1. Survey mean bottom water dissolved oxygen concentration (mg L^{-1}) in the (a) nearfield and (b) Stellwagen Basin compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares. Stellwagen Basin data collected from stations F12, F17, F19, and F22.

(a) Nearfield



(b) Stellwagen Basin

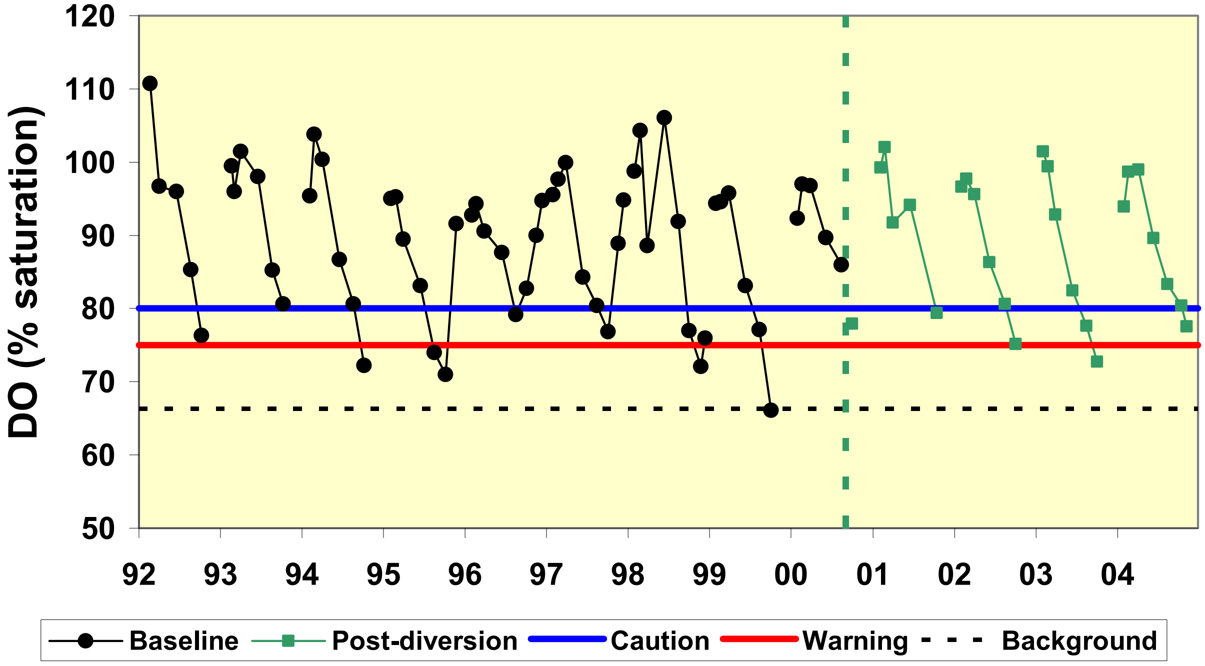


Figure 3-2. Survey mean bottom water dissolved oxygen percent saturation in the (a) nearfield and (b) Stellwagen Basin compared to contingency threshold levels. Baseline data in black circles and post diversion data in green squares. Stellwagen Basin data collected from stations F12, F17, F19, and F22.

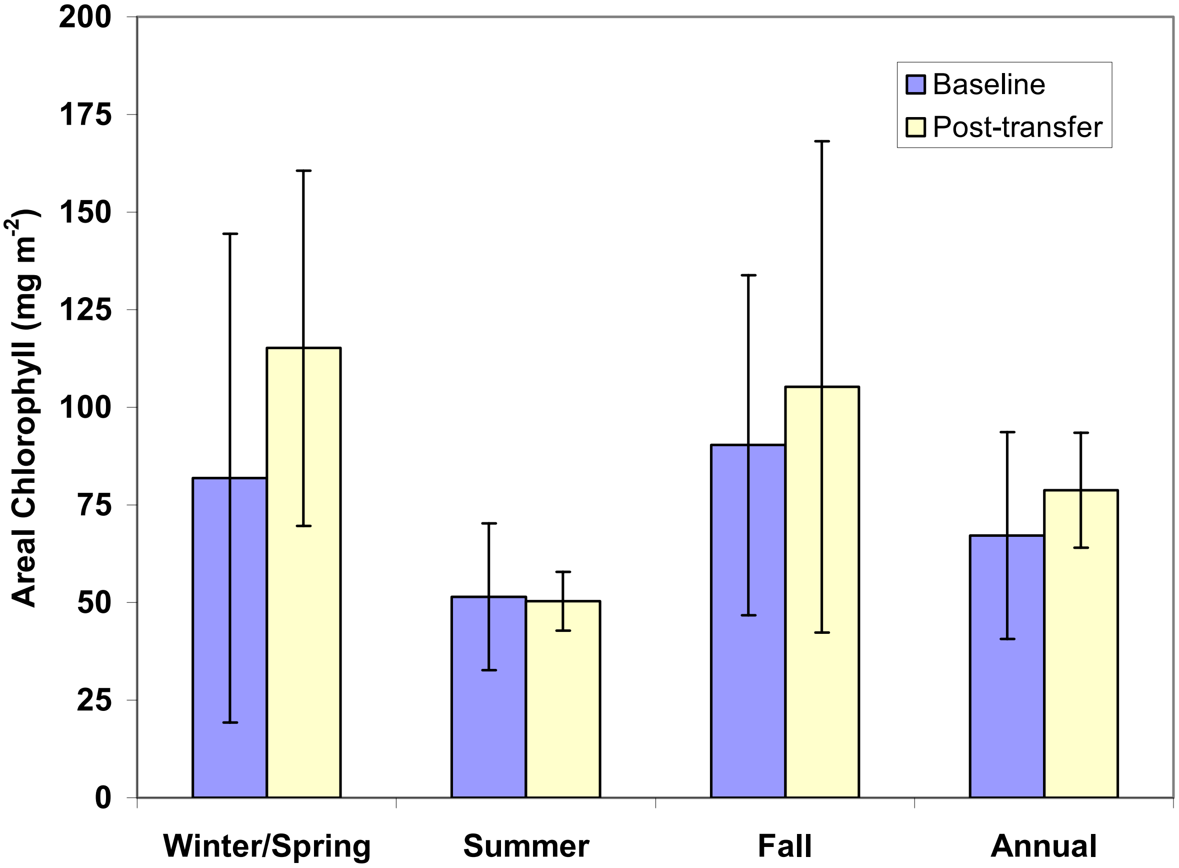


Figure 3-3. Comparison of baseline and post-transfer seasonal and annual mean areal chlorophyll (mg m^{-2}) in the nearfield. Error bars represent ±1 standard deviation. The effluent discharge was transferred to bay outfall in September 2000 – winter/spring and summer means for 2000 included in baseline, 2000 fall mean in post-transfer, and 2000 annual mean not used.

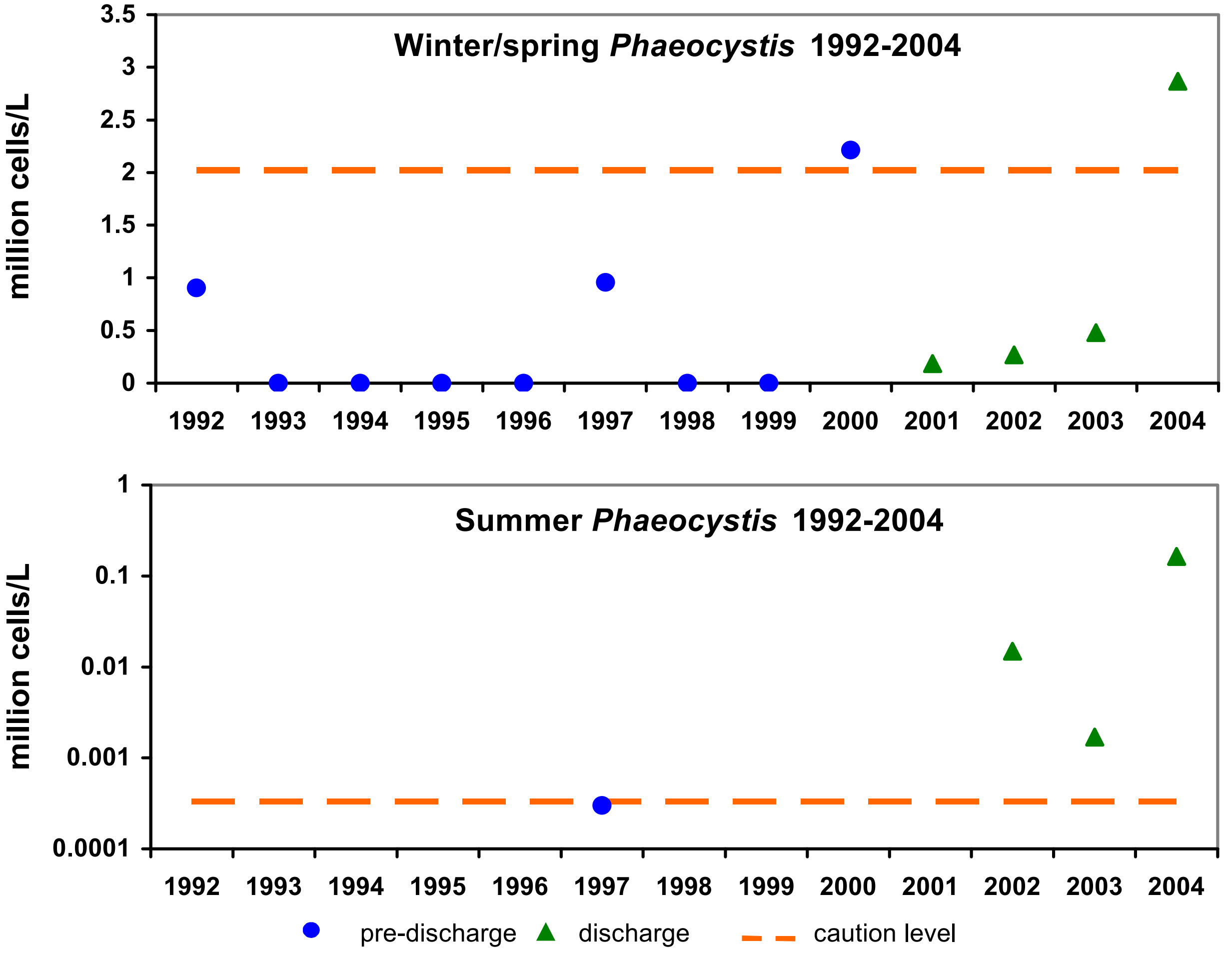


Figure 3-4. Winter/spring and summer seasonal mean nearfield *Phaeocystis* abundance (million cells L^{-1}) means versus threshold values for 1992 to 2004 (Note log-axis on summer plot).

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 plankton communities. These concerns were translated into the monitoring questions (MWRA 1991) that 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?*

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** 3-5). 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 input 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). 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 and from about April through October the water column is stratified and the effluent plume is trapped below the pycnocline. The extent of horizontal exchange has been examined by USGS researchers and indicates that there is 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 are observed in summer surface waters when the density gradient 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 open ports on 55 individual risers 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 (**Figure** 3-6). In addition to illustrating the vertical extent of the plume, the NH_4 distribution also highlights the variability in its horizontal distribution (both direction and extent). As discussed above, the predominant circulation pattern in Massachusetts Bay is counterclockwise, but currents are quite variable and highly dependent upon winds. The 2004 monitoring data continue to support these findings. For example, in June 2004, the plume appeared to extend from the nearfield towards Boston Harbor and coastal waters along the north shore (**Figure** 3-6). 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 10-20 km). Beyond 10 to 20 km, dilution reduces NH_4 concentrations to levels that approximate background variability. Recent results reported by USGS (Bothner and Butman 2005) compare modeling output versus monitoring data for baseline and post-diversion for both winter and summer conditions (**Figures** 3-7 and 3-8). It is clear that the model results that initially supported the diversion of the discharge to an offshore outfall have been corroborated by the monitoring results. More importantly, both sets of data indicate that the diversion has improved conditions in the harbor while affecting only a limited area restricted to within 10-20 km of the bay outfall as represented in these figures by the elevated "effluent" concentration.

Two other high “effluent” areas are depicted in plots of the post-transfer monitoring data just south of Cape Ann in **Figure** 3-7 and in Cape Cod Bay in **Figure** 3-8. These are due to NH_4 pools unrelated to the bay outfall. The winter data in **Figure** 3-7 likely depict the intrusion of nutrient rich coastal waters from the western Gulf of Maine into northern Massachusetts Bay. Several studies have reported the high nutrient (including NH_4) phenomenon in Cape Code Bay during the summer that results from locally high rates of remineralization (Jiang *et al.* 2006; Becker 1992). These pools of elevated “effluent”/NH_4 are clearly unrelated to the bay outfall and illustrate one of the drawbacks of using NH_4 as a tracer of the effluent plume.

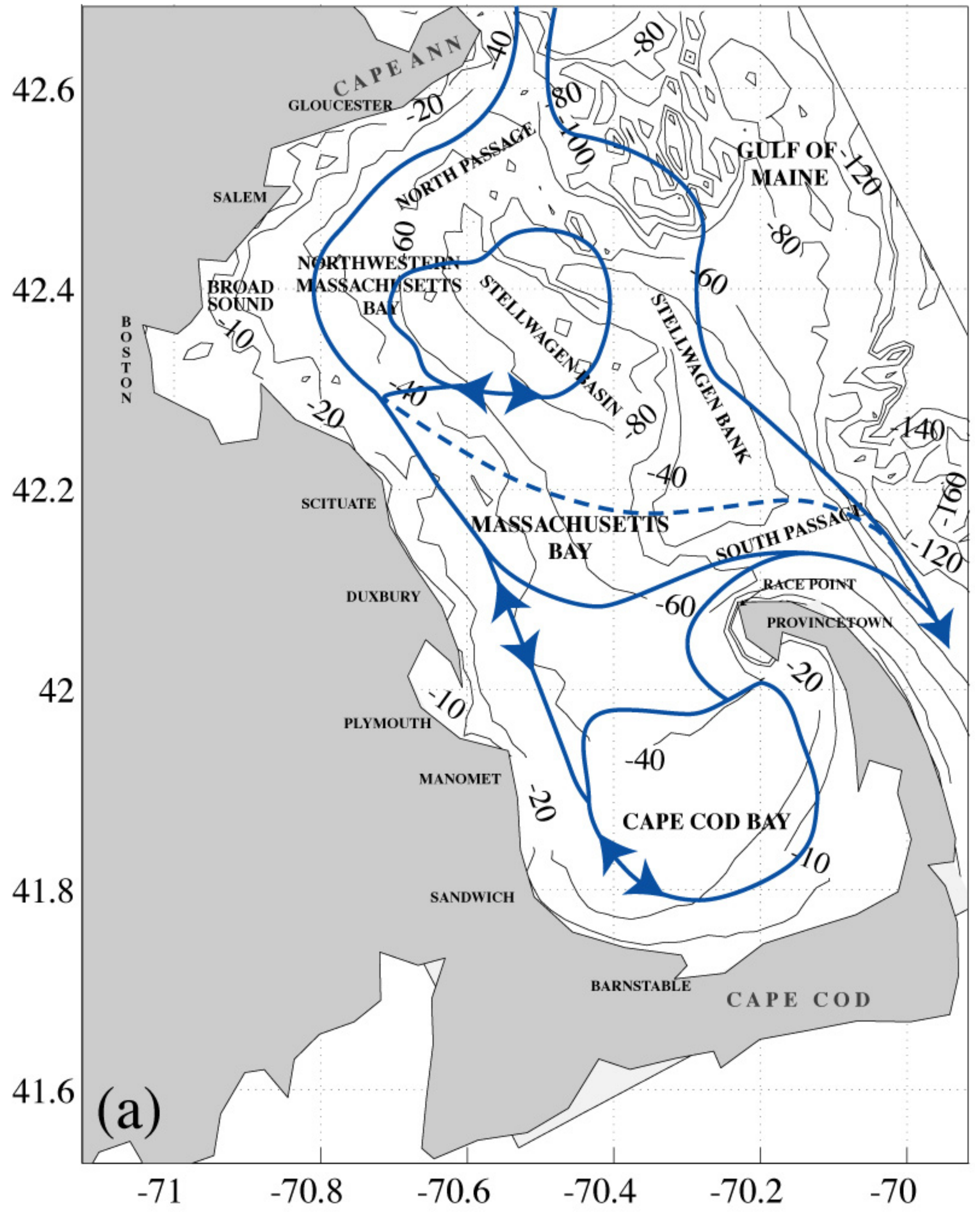
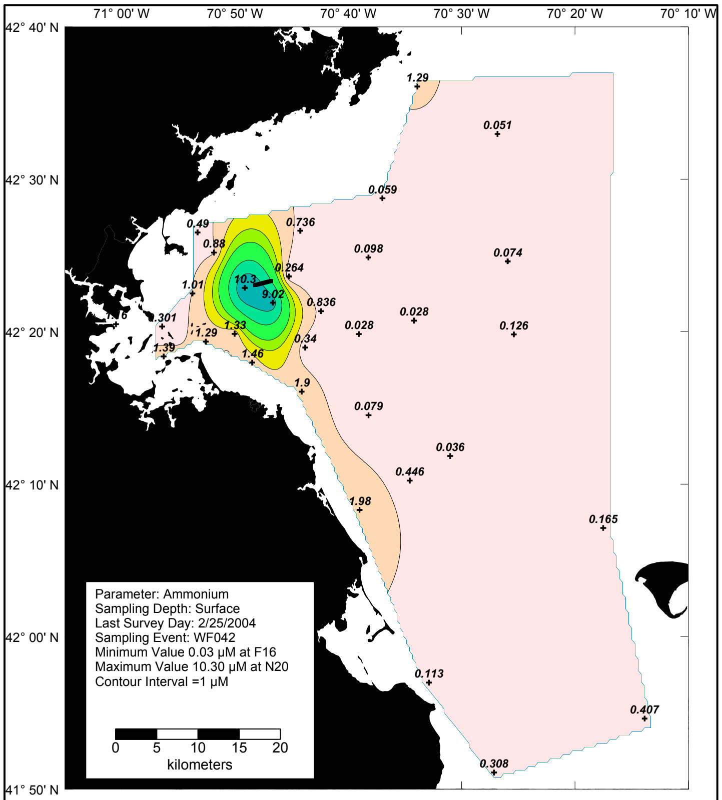


Figure 3-5. Summary of circulation within Massachusetts Bay (Lermusiaux 2001).

(a) February 2004



(b) June 2004

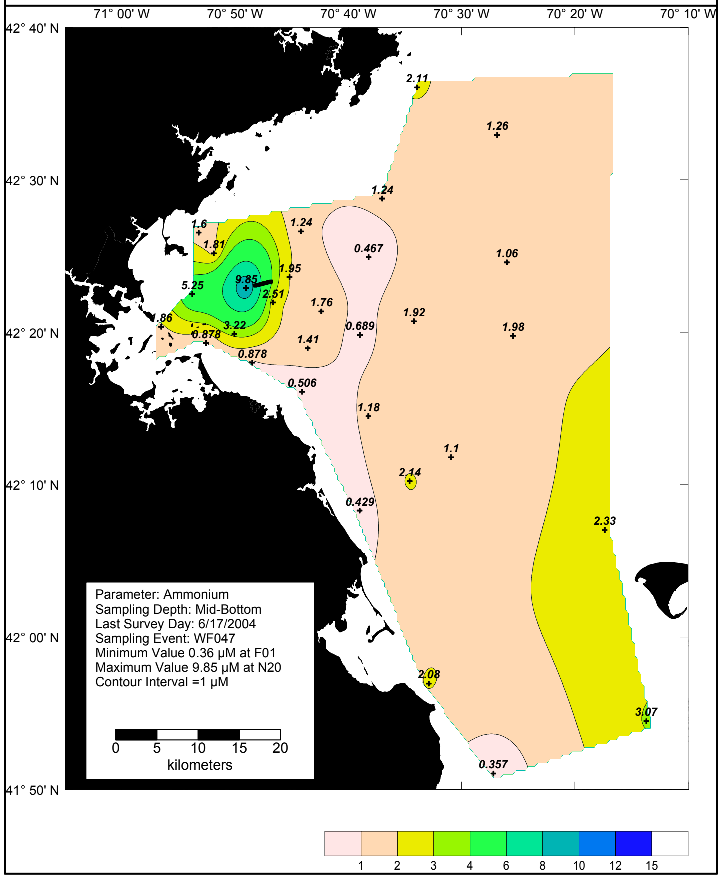
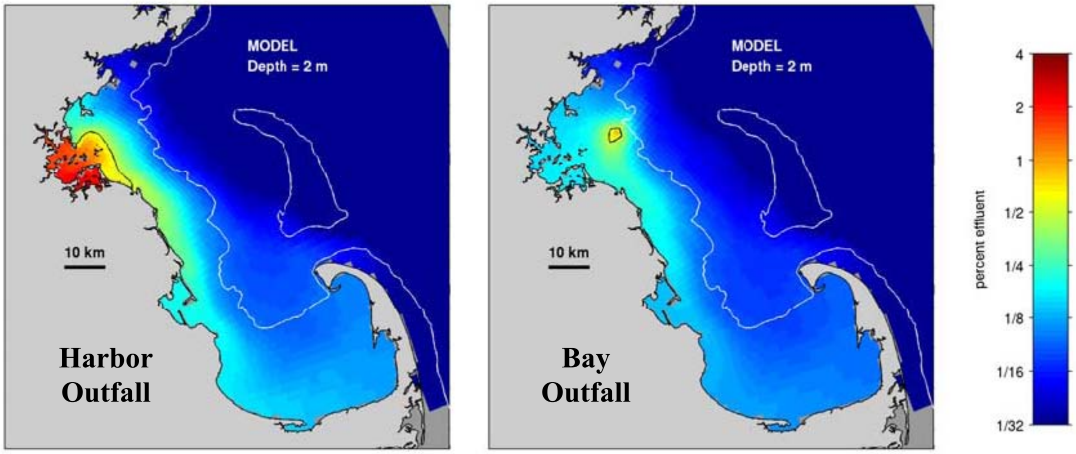


Figure 3-6. Contours of NH_4 concentrations (µM) in (a) surface waters February 2004 (WF042) and (b) at mid-depth June 2004 (WF047).

(a) Winter Model Results



(b) Winter Monitoring Data

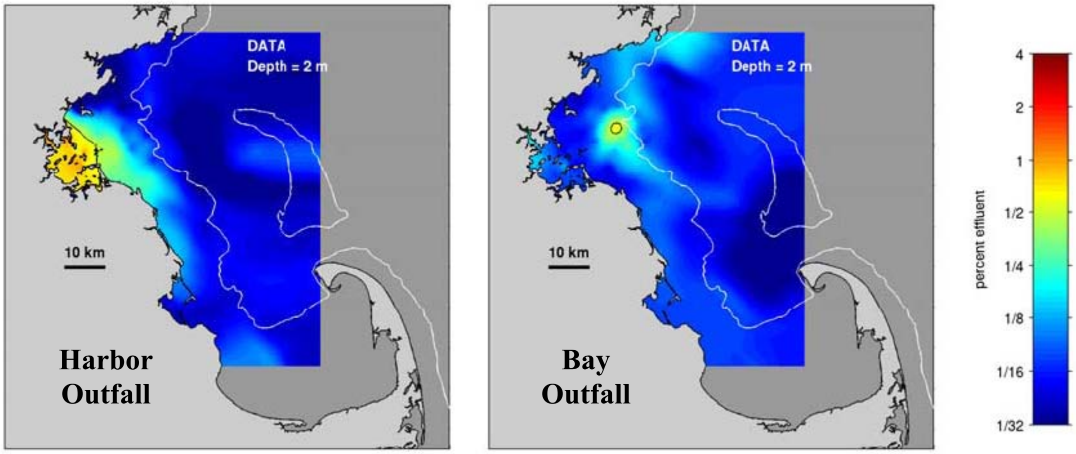
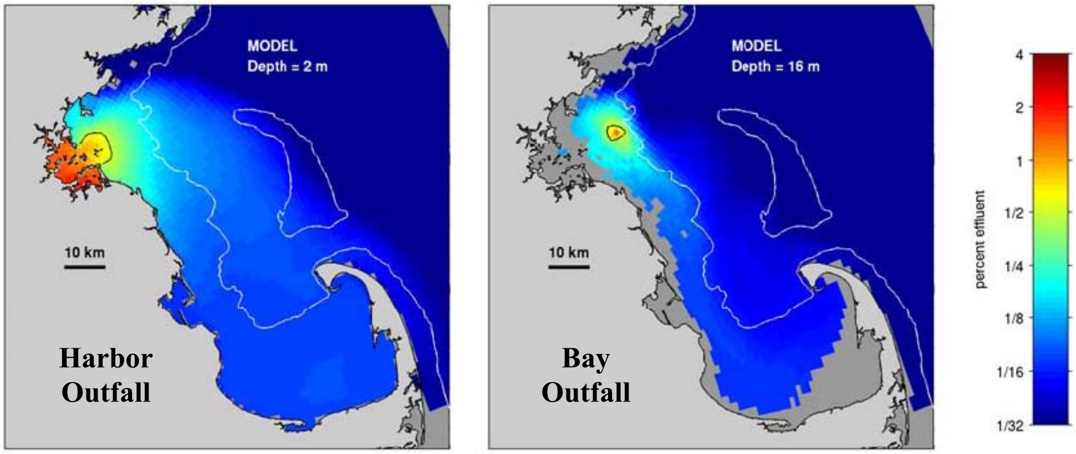


Figure 3-7. Comparisons of winter surface effluent concentrations for both harbor and offshore outfalls based on (a) model results and (b) monitoring data. (source Bothner and Butman 2005)

(a) Summer Model Results



(b) Summer Monitoring Data

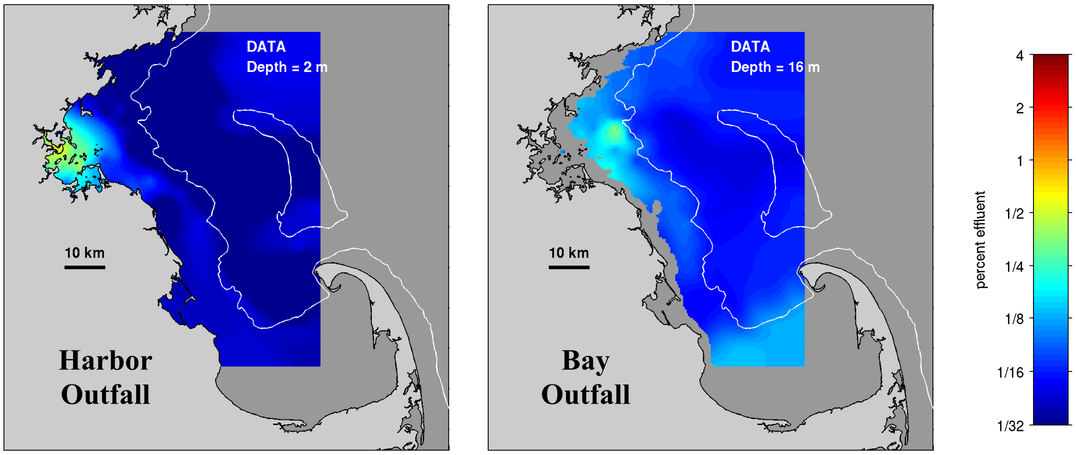


Figure 3-8. Comparisons of summer surface and mid-depth effluent concentrations for both harbor and offshore outfalls based on (a) model results and (b) monitoring data. (source Bothner and Butman 2005)

3.4.2 Aesthetics

→ *Has the clarity and/or color of water around the outfall changed?*
→ *Has the amount of floatable debris around the outfall changed?*

Field sampling personnel make visual observations when sampling in the nearfield. These observations are summarized in survey reports. In the summer stratified season, the outfall discharge is not visible at the surface. On very calm winter days, samplers sometimes see subtle circular areas of calmer water over each diffuser site. They do not see slicks, areas of excess algal growth, or sewage-related "floatables." Net tows during every survey in the outfall area were started in 1999 before the outfall came on-line. The contents of the net tows are photographed and identified.
During 2004, net tow observations were consistent with previous sampling years and did not find evidence of outfall related aesthetic concerns. The colonial pinnate diatom, *Thalassionema nitzschoides,* was observed on two surveys: the first occurring in late February and the second in mid May. *T. nitzschoides* is ubiquitous, but usually in low abundance. This species thrives in upwelling regimes and may be taking advantage of the artificial upwelling provided by the outfall. Additionally, small grease-like balls of material were observed during the majority of the net tows. This material was analyzed by MWRA in 2002 and was determined to consist of grease, unidentified algae and a variety of different bacteria. The bacteria were not types usually associated with sewage and secondary treatment. Collection of man-made debris in the tows did occur in small quantities during seventy-five percent of the surveys. Typical material collected was cellophane, fruit labels, plastic bags, cigarette filters and Styrofoam. This material is typical of land-runoff and had been seen in similar quantities prior to the diversion to the bay outfall.

3.4.3 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.

Post-transfer nearfield survey mean concentrations of NO_3, SiO_4 and PO_4 generally follow baseline trends and are comparable in magnitude to the levels observed over the baseline period with some minor exceptions. Nitrate and silicate concentrations tended to be higher than baseline values during September and October likely due to the lack of significant fall blooms since 2000 (**Figure** 3-9). In November and December, SiO_4 concentrations were lower than baseline due to the late fall diatom blooms observed in 2001 and 2003. Phosphate concentrations in the nearfield have increased with the transfer of the outfall offshore, but not to the same degree as that seen for NH_4 (**Figure** 3-10). There has been a significant increase in nearfield NH_4 concentrations since September 2000. This is evident throughout the year, but largest change is seen during the stratified summer months. In contrast to the trends observed in the nearfield, post-transfer NH_4 concentrations in Boston Harbor have been well below baseline levels (**Figure** 3-10). Phosphate levels in the harbor show a similar year-round decrease in mean concentrations since the transfer to the bay outfall. Nitrate and silicate, however, show a response in the harbor that is more closely tied to changes in productivity than in nutrient inputs. The concentrations of NO_3 and SiO_4 were below baseline means during the winter/spring and fall bloom periods (**Figure** 3-11) consistent with the indications that Boston Harbor is exhibiting more of a coastal production/bloom pattern now rather than the eutrophic summer peak in production that was observed during the baseline period.

The change in NH_4 concentrations is 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** 3-12a). 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 2004. Unlike these regions, little if any change in NH_4 concentrations was measured in offshore, boundary, and Cape Cod Bay waters from 1992 to 2004. The trends in annual mean concentration for other inorganic nutrients are more erratic as seen in the example of NO_3 (**Figure** 3-12b). 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. However, there does appear to be a trend of increasing NO_3 concentrations since the early 1990's. This is examined in more detail below in comparisons of baseline and post-transfer nutrient concentrations.

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 (see **Figure** 3-6 for example). The overall shift in NH_4 between baseline and post-transfer years is illustrated in contour plots depicting changes in seasonal mean concentrations across the entire survey area (**Figure** 3-13). The seasonal means are based on the MWRA threshold defined seasons of winter/spring (February-April), summer (May-August), and fall (September-December). The reduction in Boston Harbor and near-harbor coastal station NH_4 concentrations is consistent across each of the seasons as is the increase in NH_4 concentrations in the nearfield area.

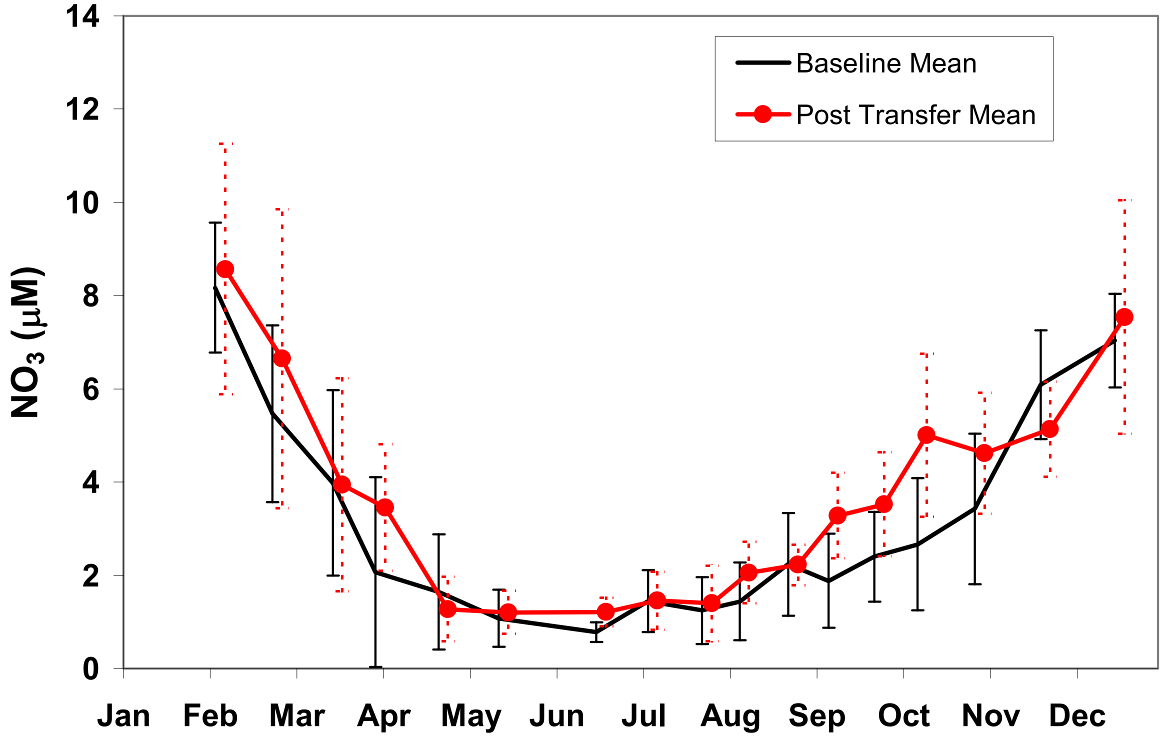
On an individual station basis, baseline to post-transfer differences in NH_4 concentrations were significant (based on t-tests with results of $p \leq 0.05$) for many of the stations in Boston Harbor and the nearfield (**Figure** 3-13). However, taken as a whole, these changes were only significant at a few stations after corrections were made to account for the multiple comparisons that were conducted. The Bonferroni correction takes into account the number of tests being compared and conservatively controls for Type I errors (falsely significant). All of the significant results discussed below are based on alpha = 0.05 with Bonferroni correction using the actual number of comparison tests. For example, there were 41 tests in the summer NH_4 difference plot. Applying the Bonferroni correction (0.05/41) means a $p \leq 0.0012$ would be significant.

When examined on a seasonal basis across stations and applying the Bonferroni correction, there were significant decreases in NH_4 concentrations at seven Boston Harbor water quality monitoring (BHWQM) stations (24, 77, 106, 124, 138, 140, and 141) and at HOM station F31 and an increase at HOM station N18 in the winter/spring. In the summer, only three harbor stations (BHWQM stations 77, 141, and 142) had significant decreases, while nearfield stations N16, N18 and N20 and coastal station F18 had significant increases. In the fall, all nine of the BHWQM stations showed significant decreases and the only significant increase was observed for HOM station N20.

There are several generalizations that can be made based on the results presented in **Figure** 3-13. First, it is clear that there has been a decrease in NH_4 concentrations in Boston Harbor. Nearly all of the comparisons show a decreasing trend in values and many of them are significant. Second, while there has been an increase in NH_4 concentrations at most of the nearfield stations and at the Broad Sound station F18 just to the northwest of the nearfield, the only significant increases have been at stations closest to the outfall (N16, N18 and N20) and in the summer at station F18. A significant increase in NO_3 was also observed at station F18 in the summer. This was the only significant change in NO_3 concentrations even though relatively large (> 1µM) changes were observed (**Figure** 3-14). Station F18 is located in an area susceptible to upwelling and these significant summertime increases in NH_4 and NO_3 are likely due to a combination of higher bottom water concentrations (outfall or ambient) and upwelling favorable conditions. Nitrate concentrations showed an increase at most nearfield stations during the fall. These increases in NO_3, however, were mirrored by increases throughout the bays (**Figure** 3-14) for example, fall NO_3 concentration at the Northern Boundary stations F26 and F27. Although the significant changes in NH_4 concentrations in the nearfield can be ascribed to the relocation of the outfall, the data suggest that this increase occurred on top of regional changes in nutrient concentrations. It is unknown whether the changes in regional nutrient concentrations are due to different loadings to the system (riverine, offshore Gulf of Maine surface or bottom waters, etc.) or to changes in seasonal biological patterns (i.e. fewer and less intense fall blooms).

Overall, 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.

(a) Nitrate



(b) Silicate

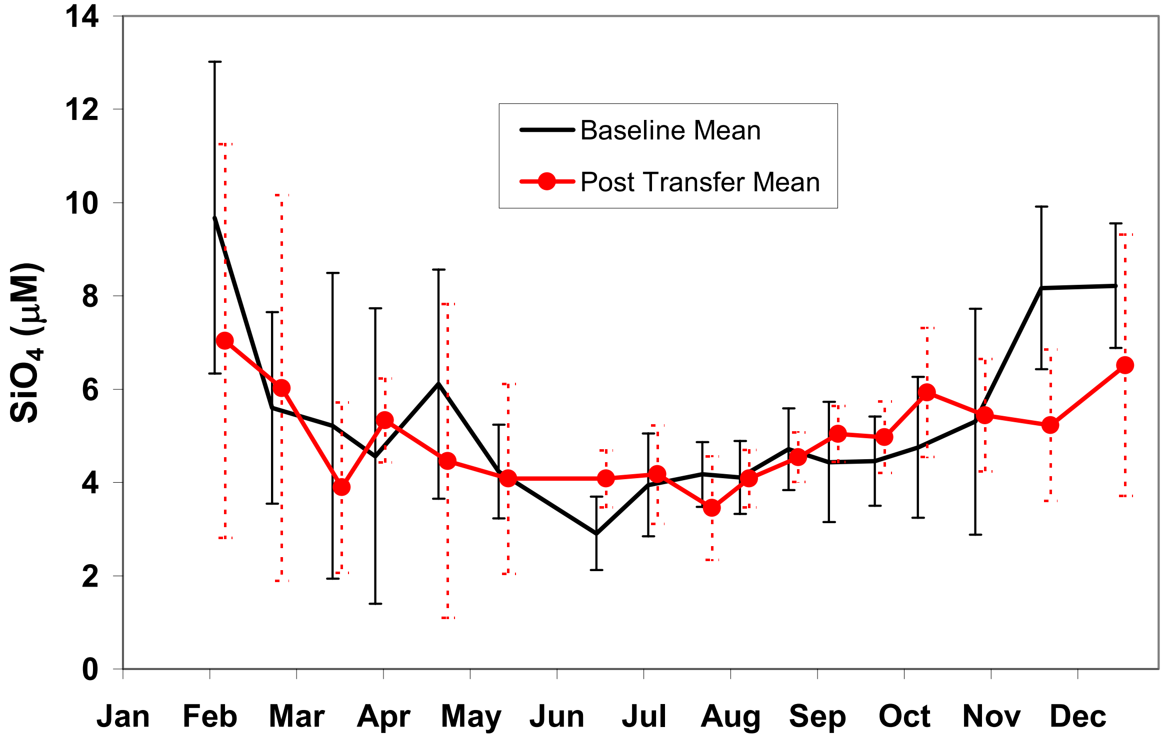
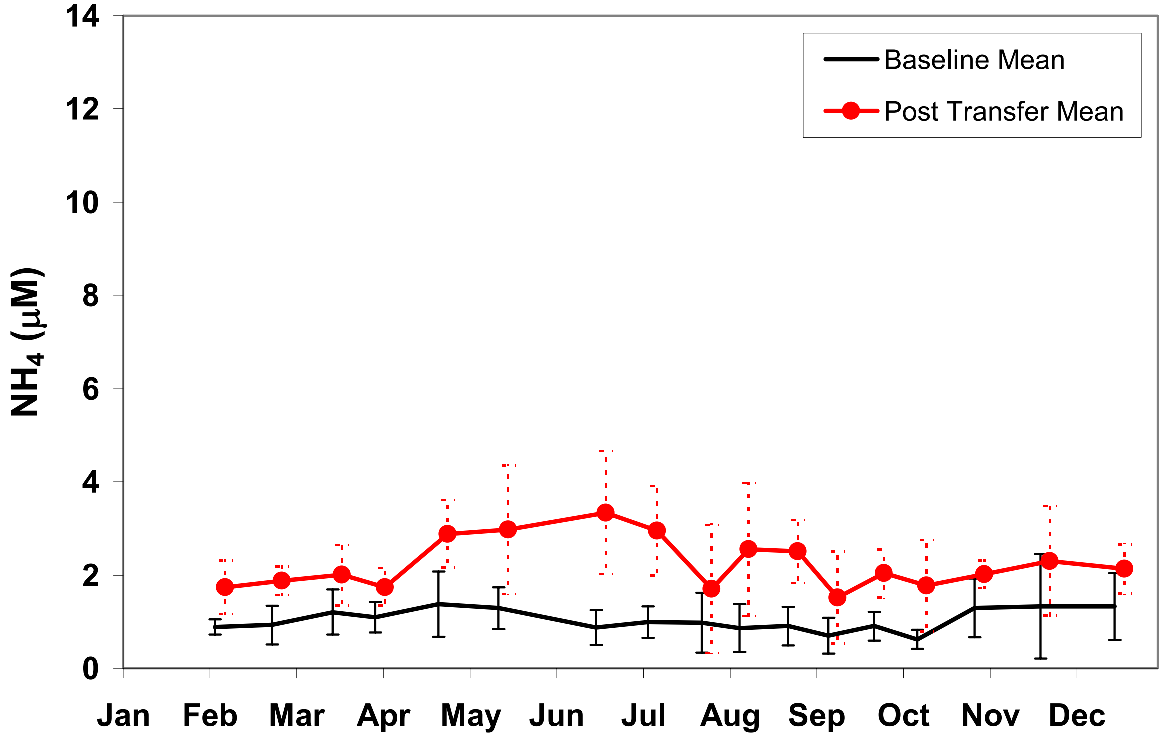


Figure 3-9. Time-series of baseline and post-transfer nearfield survey mean (a) NO_3 and (b) SiO_4 concentrations (µM). Error bars represent ±1 SD. Data collected from all depths and all stations.

(a) Nearfield NH_4



(b) Boston Harbor NH_4

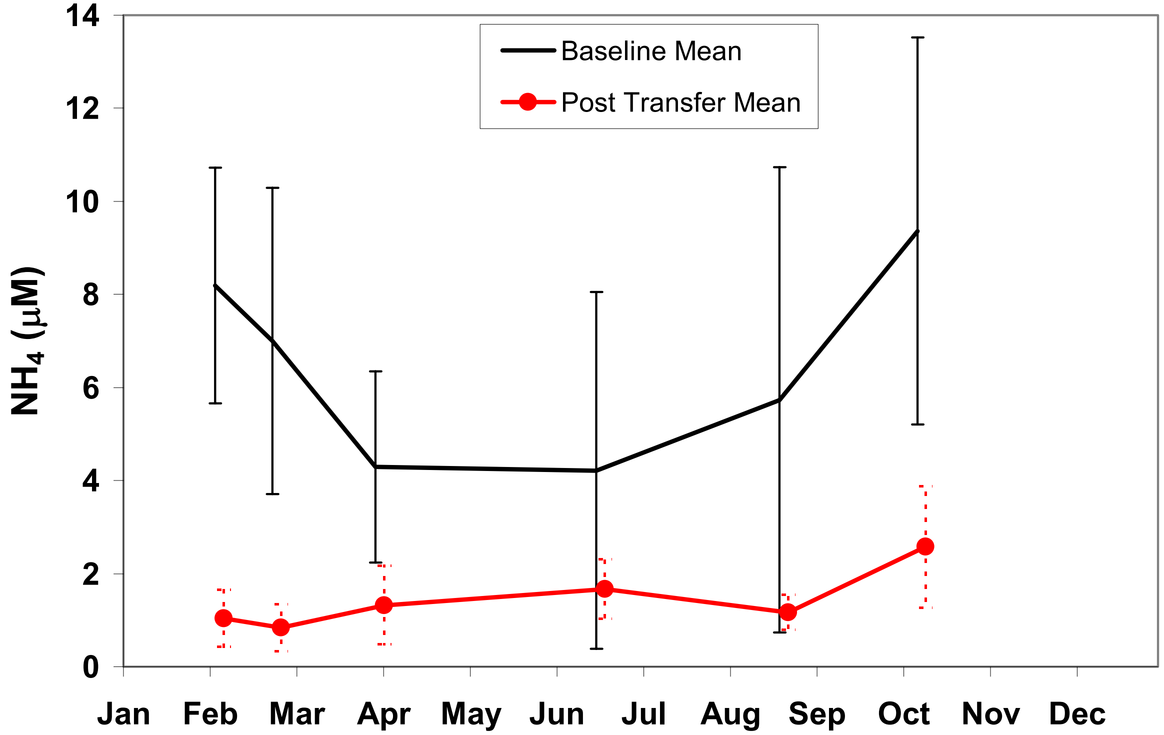
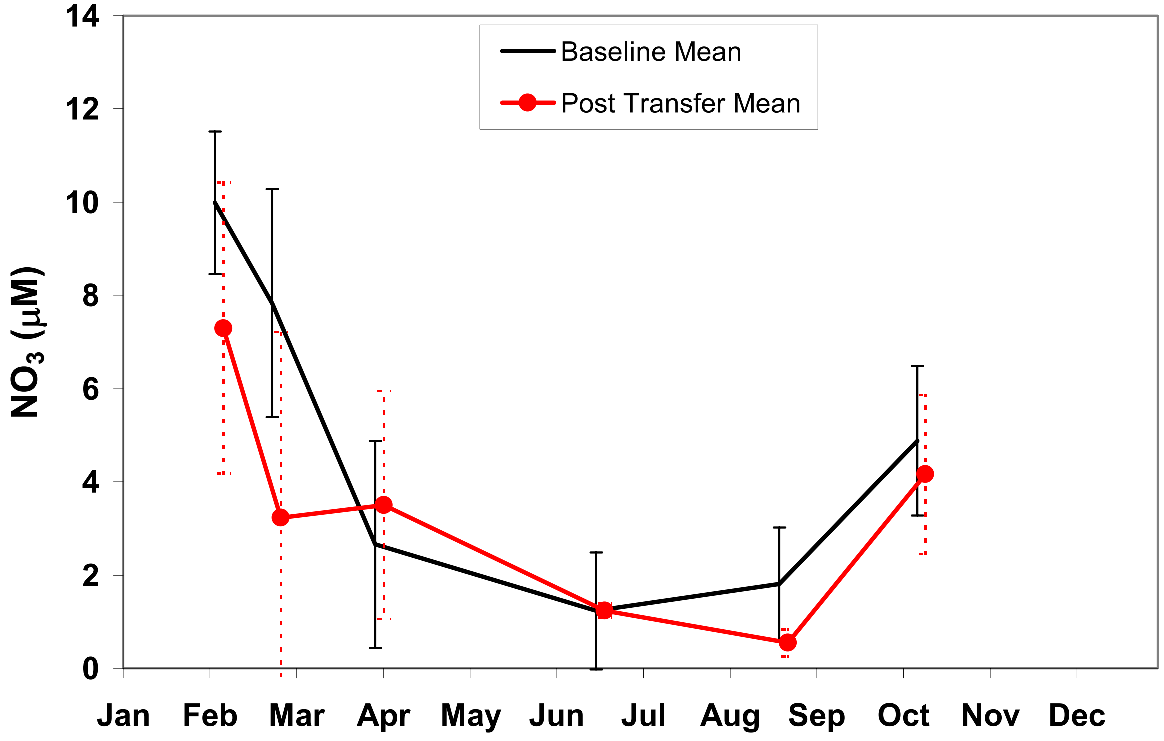


Figure 3-10. Time-series of baseline and post-transfer survey mean NH_4 concentrations (µM) in the (a) nearfield and (b) Boston Harbor. Error bars represent ±1 SD. Data collected from all depths and all stations.

(a) Nitrate



(b) Silicate

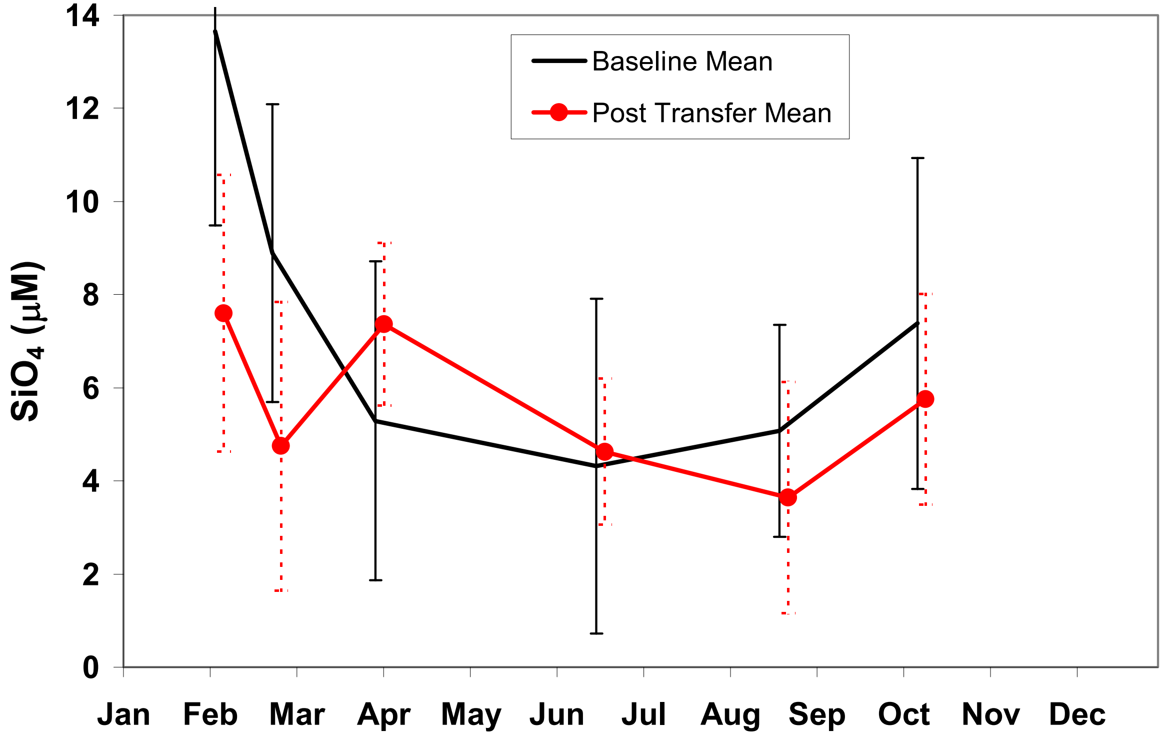
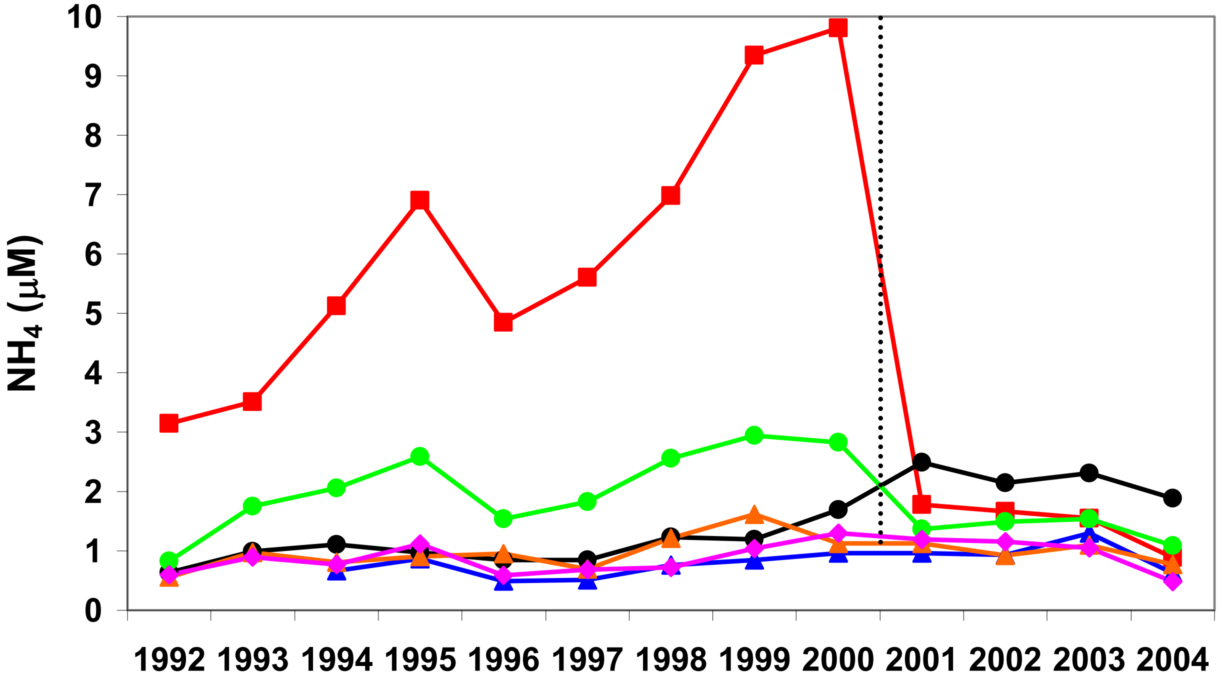


Figure 3-11. Time-series of baseline and post-transfer Boston Harbor survey mean (a) NO_3 and (b) SiO_4 concentrations (µM). Error bars represent ±1 SD. Data collected from all depths and all stations.

(a) Ammonium



(b) Nitrate

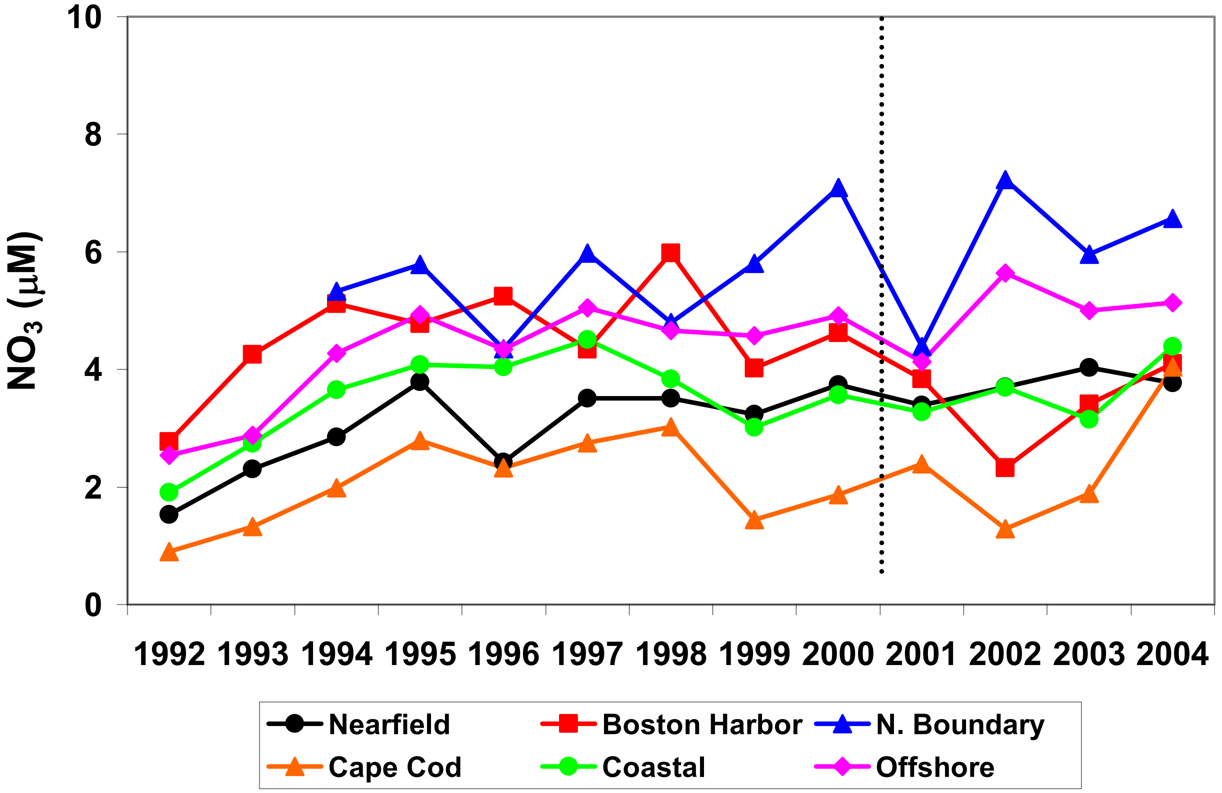


Figure 3-12. Annual mean (a) NH$_4$ and (b) NO$_3$ concentrations (µM) in Massachusetts and Cape Cod Bays. Mean of concentrations over depths, stations and surveys within each region.

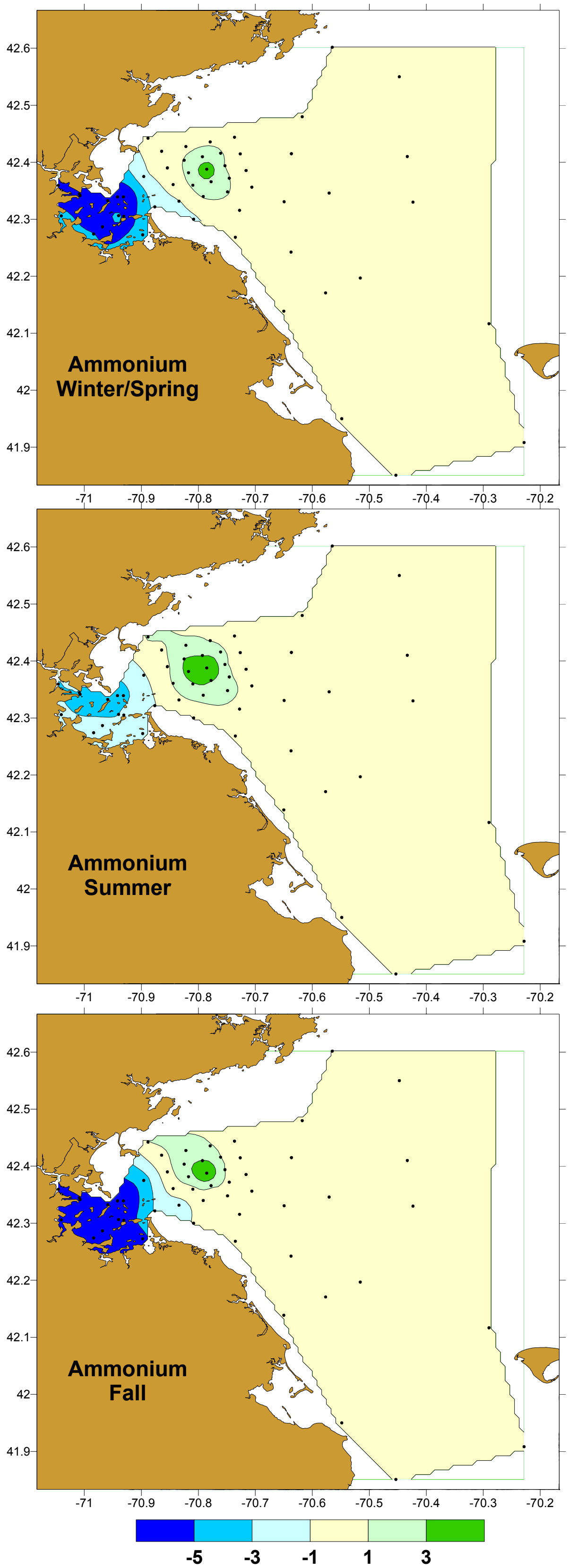


Figure 3-13. Change in seasonal NH_4 concentrations (µM) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

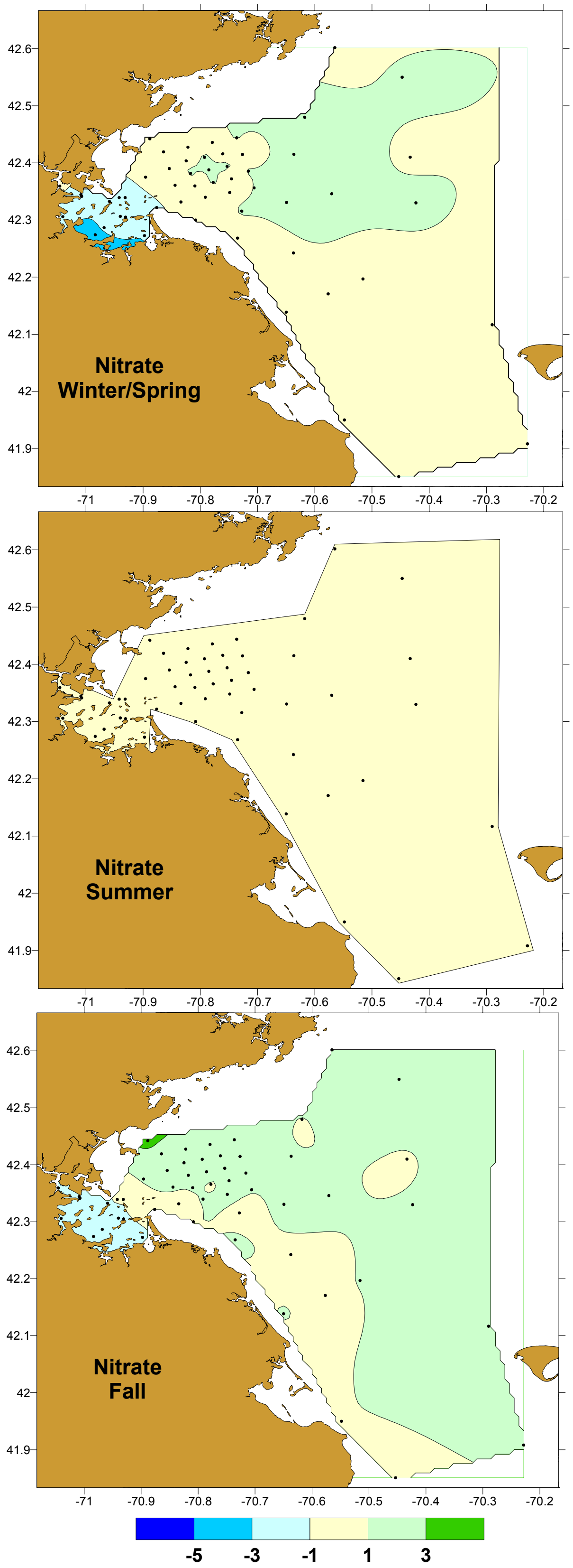


Figure 3-14. Change in seasonal NO_3 concentrations (µM) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

3.4.4 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** 3-15). The series of images shown in **Figure** 3-15 are from February to May 2004 and highlight the progression noted above – February Cape Cod Bay diatom bloom, March-April regional *Phaeocystis* bloom, and sharp decline of this bloom in late April. 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 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.

Post-transfer nearfield areal chlorophyll and POC concentrations were generally consistent with the baseline mean and seasonal patterns. The main deviations from the baseline were in early February, April and late fall (**Figure** 3-16). The higher post-transfer chlorophyll values in early February resulted from elevated production rates and early winter/spring blooms in 2001 and 2002. The consistent occurrence of March-April peaks in *Phaeocystis* led to elevated chlorophyll and POC concentrations in the nearfield during these months. Elevated chlorophyll and POC concentrations have been a relatively consistent feature of the post-transfer period from late October to December. The chlorophyll levels during the fall 2000 bloom were the highest measured during the monitoring program (~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. 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). Both survey mean areal chlorophyll and POC concentrations were high during the late October to December period in 2001, 2002 and 2003. In 2004, no fall bloom was observed and nearfield chlorophyll and POC values were below or at the baseline minimum from late September to November (see **Figure** B-18).

In Boston Harbor, there has been a clear increase in winter/spring chlorophyll and POC levels in 2001-2004 (**Figure** 3-17). February survey means for the post-transfer period are higher than the peak baseline means that had been observed during the summer surveys in June and August. From April to August, post-transfer survey mean areal chlorophyll levels have been well below the baseline mean and then increasing again in the fall to levels slightly higher than baseline (**Figure** 3-17a). POC concentrations in the harbor, like chlorophyll, increased in comparison to baseline in late February (**Figure** 3-17b). POC levels earlier in February and during the remainder of the year are relatively similar to the baseline means. The post-transfer survey mean POC concentrations in Boston Harbor, however, display a winter/spring and summer peak rather than increasing from February to April, remaining high all summer, and then decreasing in the fall as had been seen during the baseline period. The chlorophyll and POC data (along with production data presented in Section 3.4.6 and Appendix C) continue to 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.

A comparison of seasonal and annual mean areal chlorophyll in the nearfield shows that there has been an increase in winter/spring, fall, and annual mean levels since the bay outfall began discharging (see **Table** 3-2 and **Figure** 3-3). None of these changes in nearfield mean chlorophyll levels, however, is statistically significant. On a per station basis, baseline to post-transfer differences in areal fluorescence were significant (based on t-tests with results of $p \leq 0.05$) for only a limited set of stations in Boston Harbor (F23), coastal (F24 and F13), offshore (F06, F07 and F10), and boundary (F28) areas in the winter/spring. Taken as a whole and corrected for the multiple comparisons, as discussed previously, none of these changes were significant. This is a preliminary analysis and more powerful statistical tools will be used in future analyses to determine if statistically significant changes have indeed occurred.

In general, the winter/spring post-transfer period has been characterized by winter diatom (February) and an early spring *Phaeocystis* (March-April) blooms of varying intensities. These blooms have been regional in extent and thus the winter/spring increase shown in **Figure** 3-18 may be due to a natural cycle in blooms rather than any localized change. However, the fact that some of the lowest p values were calculated for the changes at stations just to the south of the nearfield (F13, F10, F06, and F07) is of interest given the locations and the relative mean flow during the winter/spring period. This will continue to be the focus of examination in the coming years.

The winter/spring increase in areal fluorescence was coincident with increases in POC concentrations throughout most of Massachusetts and Cape Cod Bays (**Figure** 3-19) though none of the increases were significant. POC concentrations in the harbor tended to decrease rather than increase during this season. Note, however, that the HOM data (stations F23, F30 and F31) increased while the MWRA BHWQM data (stations 24 to 142) decreased. This may be due to analytical differences or more likely due to the timing and frequency of sampling. Summertime areal fluorescence and POC levels tended to decrease throughout the monitoring area especially in Boston Harbor (**Figures** 3-18 and 3-19). In the fall, the areal fluorescence change pattern was more complicated with slight increases in the harbor, nearfield, offshore, and Cape Cod Bay and decreases in coastal and southern Massachusetts Bay waters. POC concentrations, however, consistently show a decrease throughout much of Boston Harbor, coastal and boundary areas. There was a slight increase in the nearfield and Cape Cod Bay.

In the nearfield, graphical comparisons of survey, seasonal, and annual mean chlorophyll and POC values suggest that there has not been a substantial change since the diversion of effluent. Seasonal and annual mean chlorophyll concentrations in the nearfield have increased, but not significantly. On an individual station basis, winter/spring chlorophyll levels have increased significantly at a number of stations throughout the region. The location of some of these stations in southern Massachusetts Bay is notable given the proclivity for transport to the south of the nearfield during the winter/spring period. In Boston Harbor, there has been both a change in the seasonal chlorophyll and POC patterns and in the magnitude of the values. 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 four 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 3.4.6.

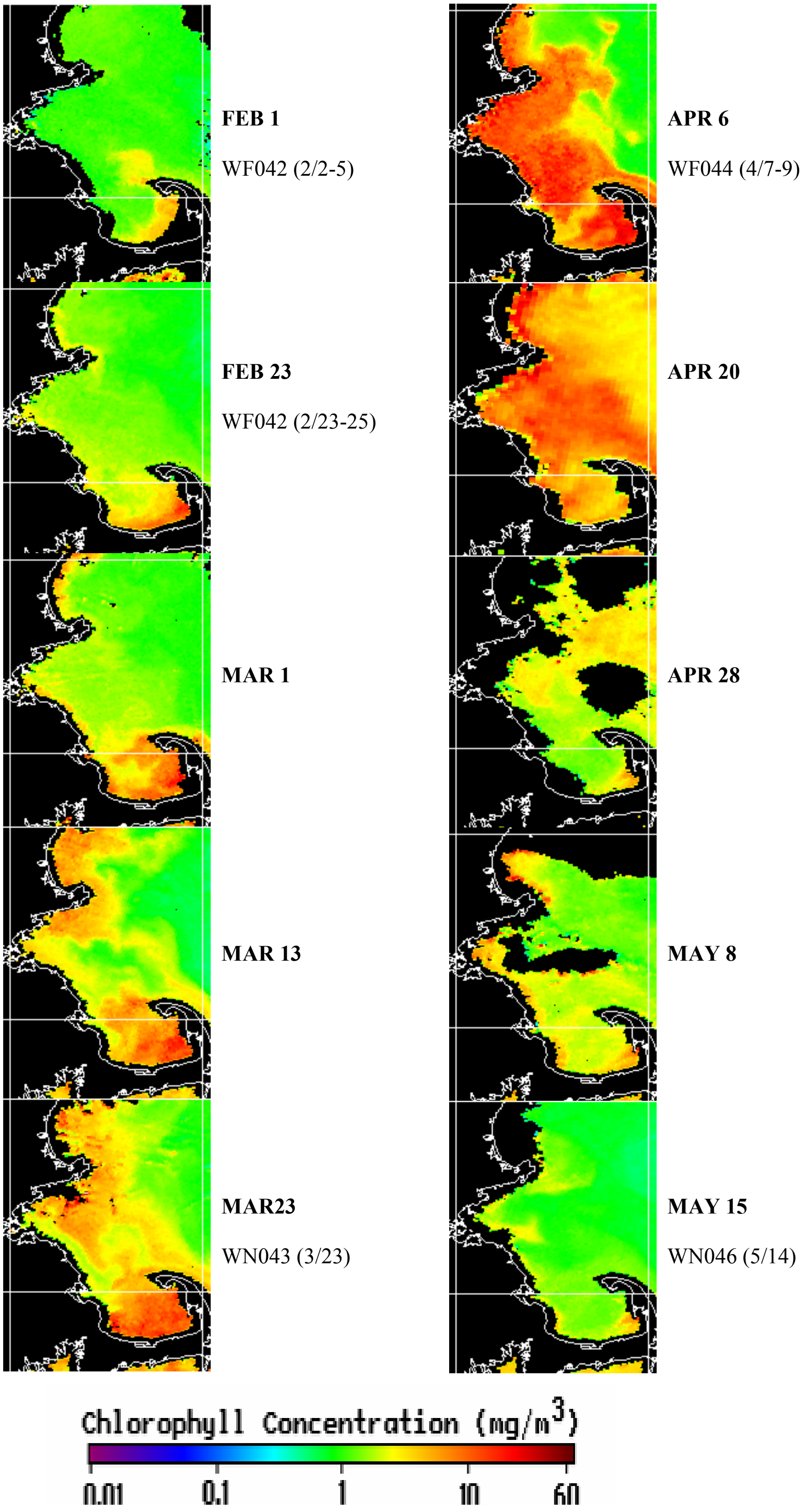
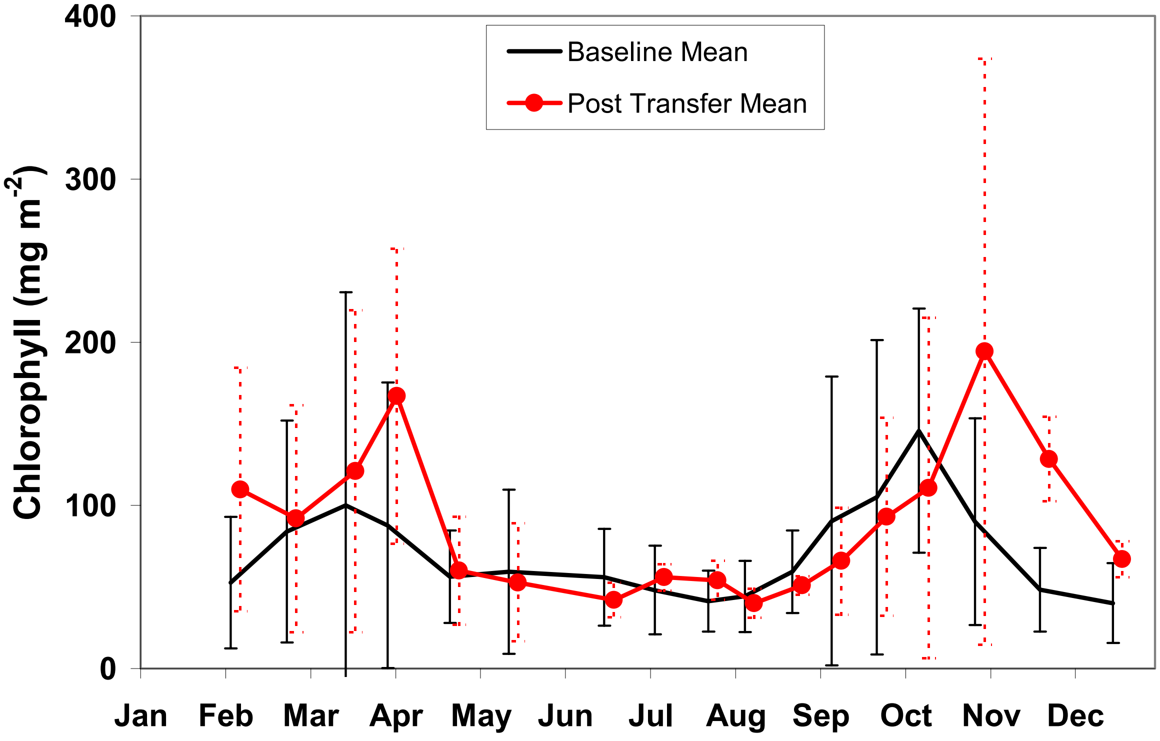


Figure 3-15. SeaWiFS chlorophyll *a* images for southwestern Gulf of Maine for February to May 2004.

(a) Areal Chlorophyll



(b) Particulate Organic Carbon

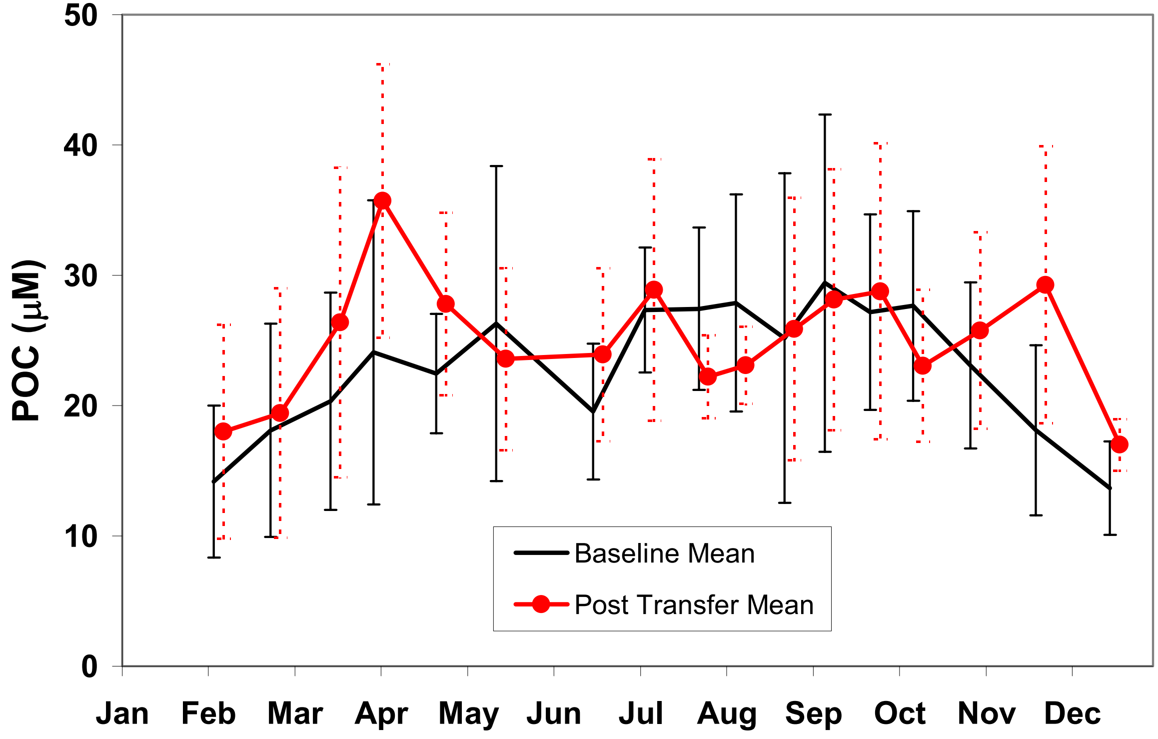
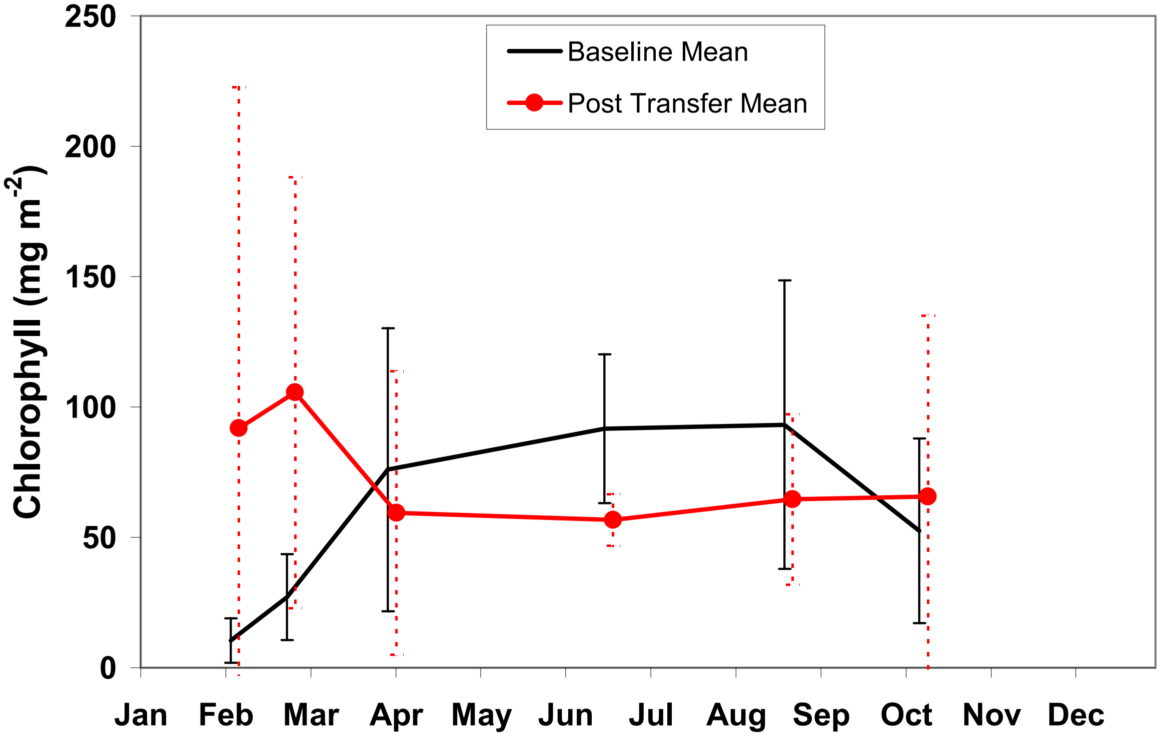


Figure 3-16. Time-series of baseline and post-transfer nearfield survey mean (a) areal chlorophyll (mg m^{-2}) and (b) POC concentration (µM). Error bars represent ±1 SD. Data collected from all depths and all nearfield stations.


(a) Areal Chlorophyll

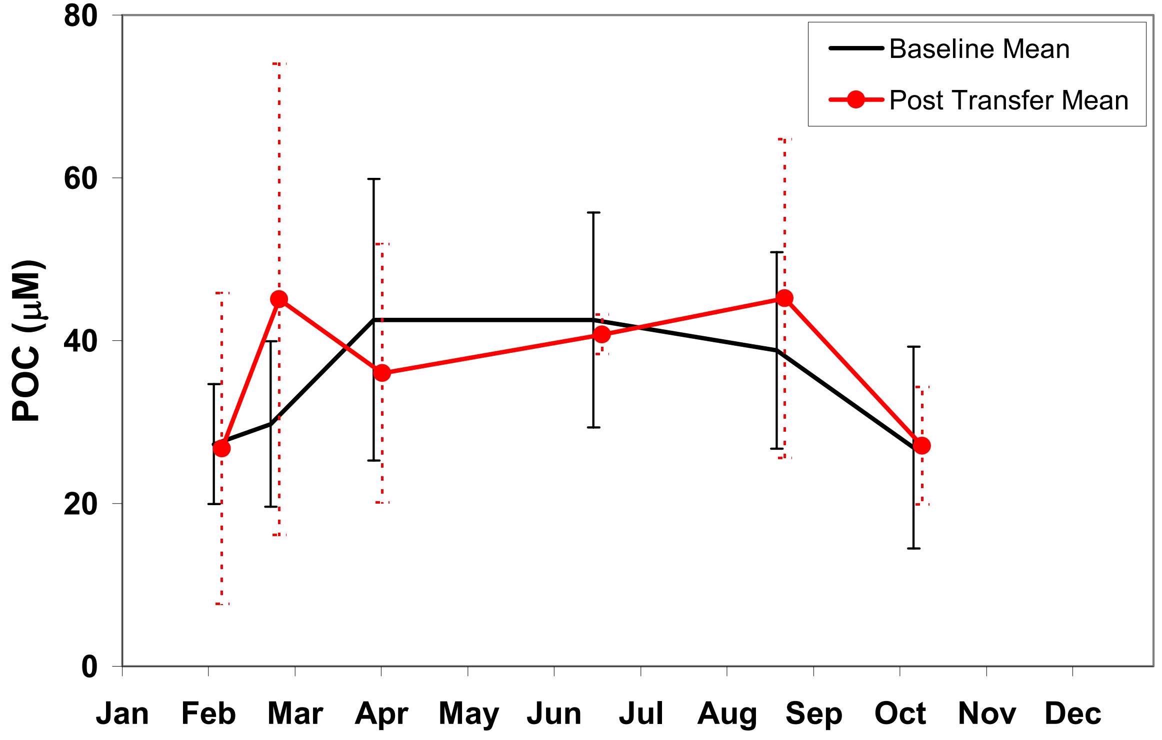

(b) POC

Figure 3-17. Time-series of baseline and post-transfer Boston Harbor survey mean (a) areal chlorophyll (mg m^{-2}) and (b) POC concentration (µM). Error bars represent ±1 SD. Data collected from all depths and all harbor stations.

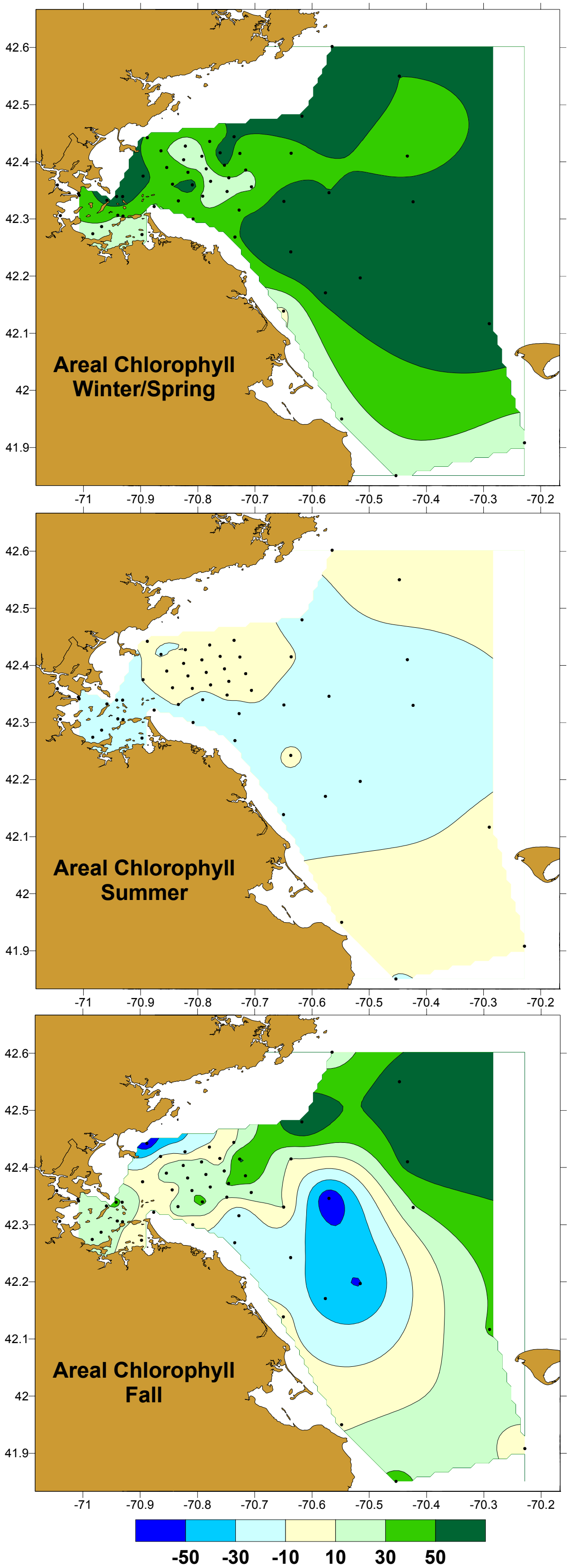


Figure 3-18. Change in seasonal areal chlorophyll (mg m^{-2}) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

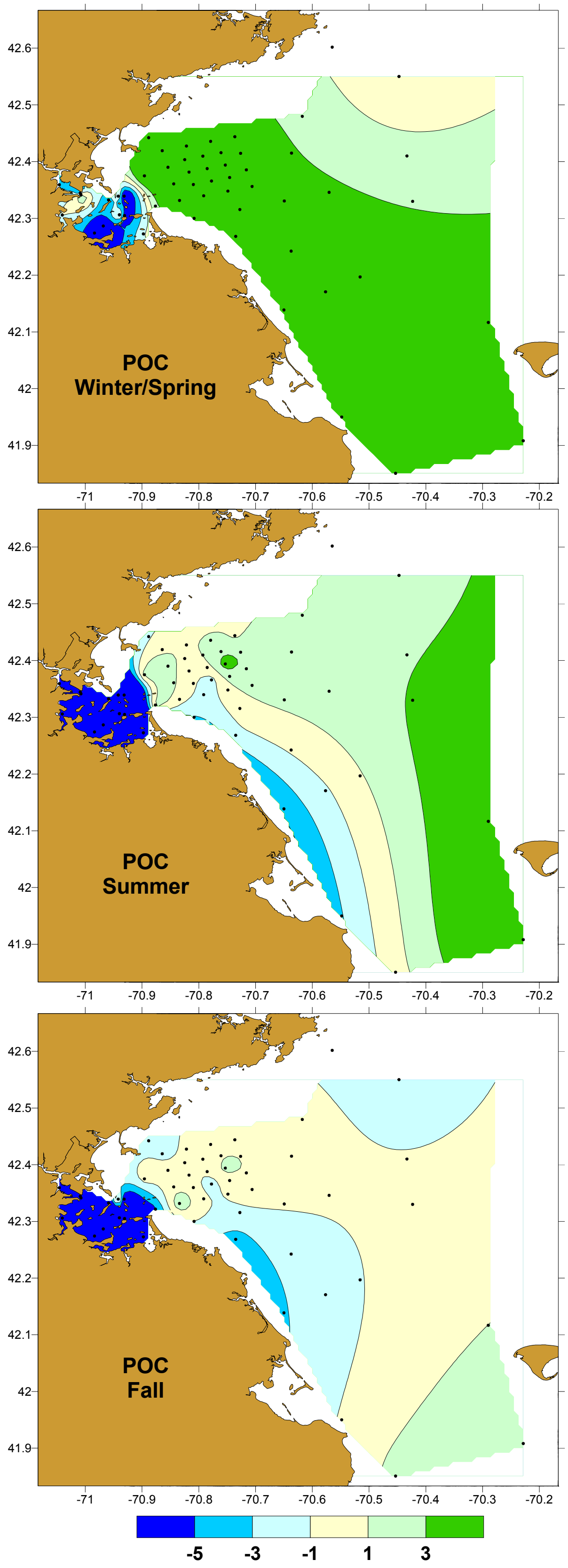


Figure 3-19. Change in seasonal POC concentrations (µM) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

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

The monitoring results have not measured 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. However, note that in 2004 DO levels did not go below 80% in the nearfield for the first time since 1996 and only the third time during the 1992-2004 period. The thresholds and state standards caveat the numerical standards by stating “unless background values are lower”. Thus, for regulatory purposes, current DO monitoring data are compared to background levels measured during baseline (see **Table** 3-1 and **Figures** 3-1 and 3-2) 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 (**Figure** 3-20). In fact, the 2004 DO levels were some of the highest observed during the 1992-2004 monitoring program (see **Figure** B-22).

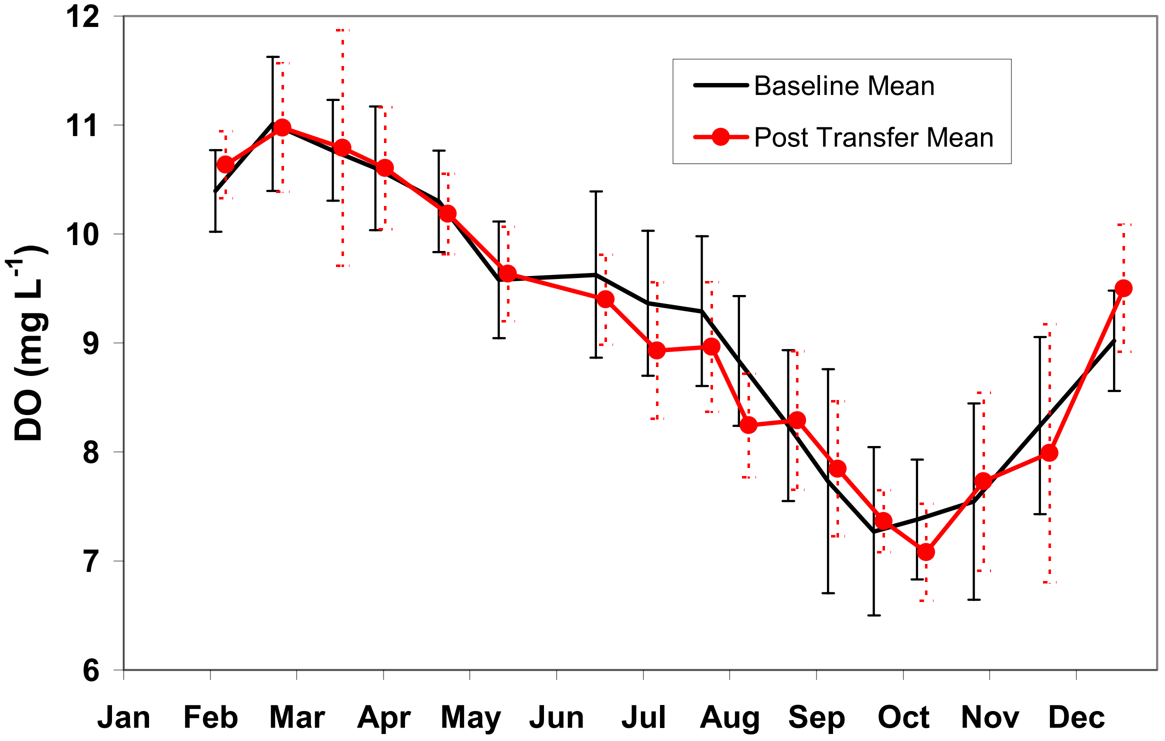
Bottom water DO levels in Massachusetts Bay exhibit a consistent seasonal pattern and invariably reach annual minimum concentrations in October/November (see **Figures** 3-1 and 3-2). Modeling and statistical analyses indicate that DO concentration and percent saturation at nearfield, Stellwagen Basin, 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, a statistical model was developed and used to examine the relative importance of physical oceanographic variables to bottom water DO concentrations. In 2004, the statistical model predicted a much lower nearfield minimum DO concentration given the forcing conditions than was actually observed (**Figure** 3-21). Its minimum value of 7.6 mg L^{-1} was much higher than average, but the forcing conditions should have produced average DO levels, as indicated by the regression model using bottom temperature and salinity. The model prediction for average DO conditions was based on average temperature conditions, but slightly higher than average early-season salinity, which is associated with lower DO conditions. The relatively high DO value, inconsistent with the regression model, indicates that some other factor in 2004 relieved the low oxygen condition.

The strong wind forcing that occurred in mid- to late September (see **Figure** A-4) may be the anomaly that relieved the low DO conditions. Although the influence of these events was not evident in the survey data, the Gulf of Maine Ocean Observing System (GoMOOS) mooring “A” at the entrance to Massachusetts Bay provides clear evidence of the water-column response (**Figure** 3-22). Waters were mixed to a 20-m depth during the storm in mid-September, as evidenced by the cooling of surface water and warming of 20-m water to the same temperature. The 50-m water did not change significantly, and the dissolved oxygen at the GoMOOS buoy continued to decrease until the complete overturn in late October (**Figure** 3-22). However, it appears that the nearfield is shallow enough that these mixing events caused ventilation of the bottom waters as shown for temperature at the USGS mooring to the south of the outfall (**Figure** 3-23; no DO sensor on this mooring deployment) and helped keep the DO from decreasing further.

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.

(a) DO Concentration



(b) DO %Saturation

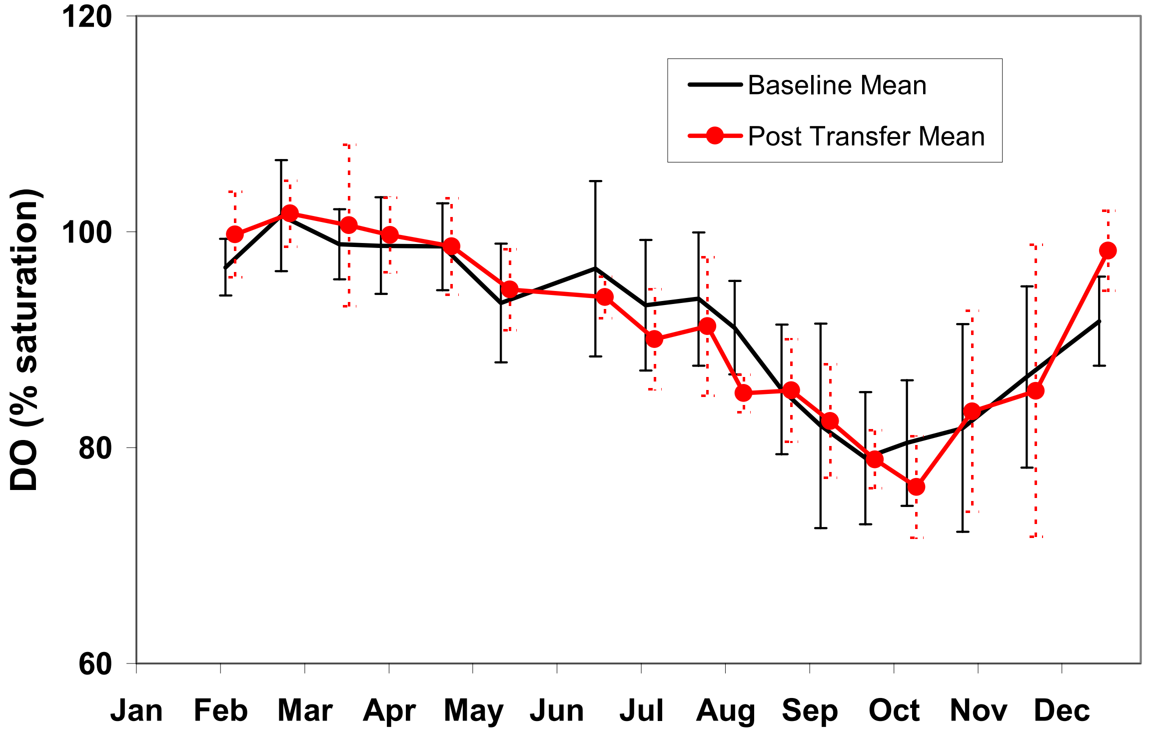


Figure 3-20. Time-series of baseline and post-transfer nearfield survey mean (a) DO concentration (mg L^{-1}) and (b) DO %saturation. Error bars represent ±1 SD. Data collected from all depths and all stations.

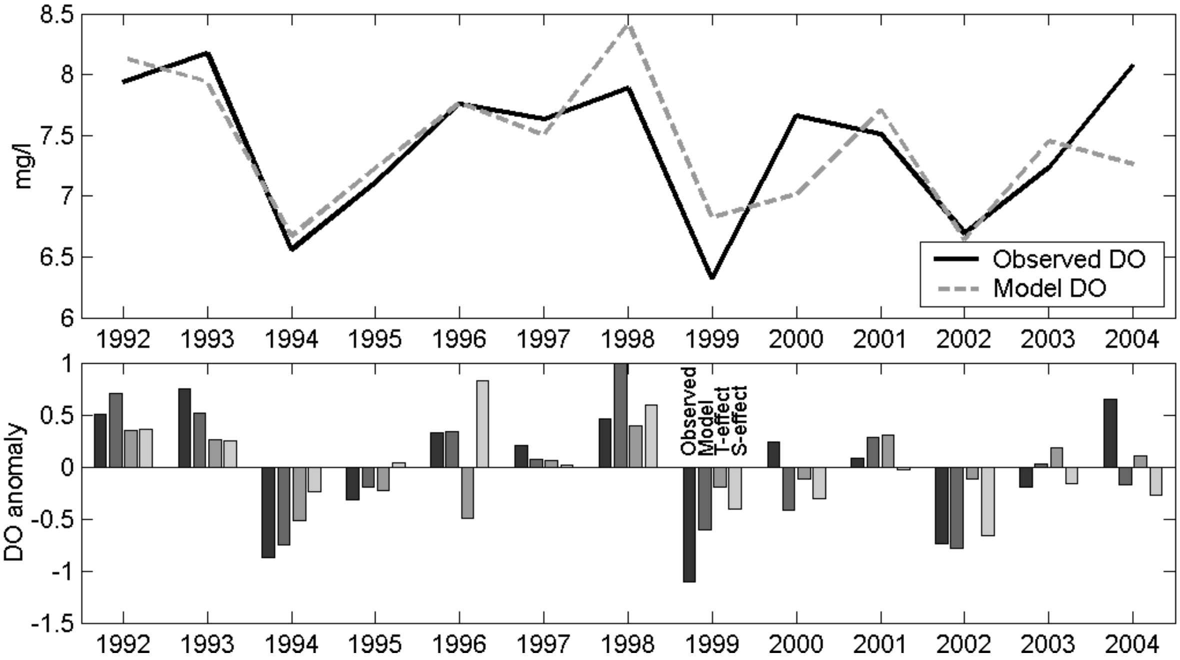


Figure 3-21. Upper panel: Average near-bottom dissolved oxygen during September-October, compared with linear regression model based on temperature and salinity variation. Lower panel: The bar plot shows the individual contributions due to temperature and salinity for each of the years. (Data are from nearfield stations N16, N18, and N20)

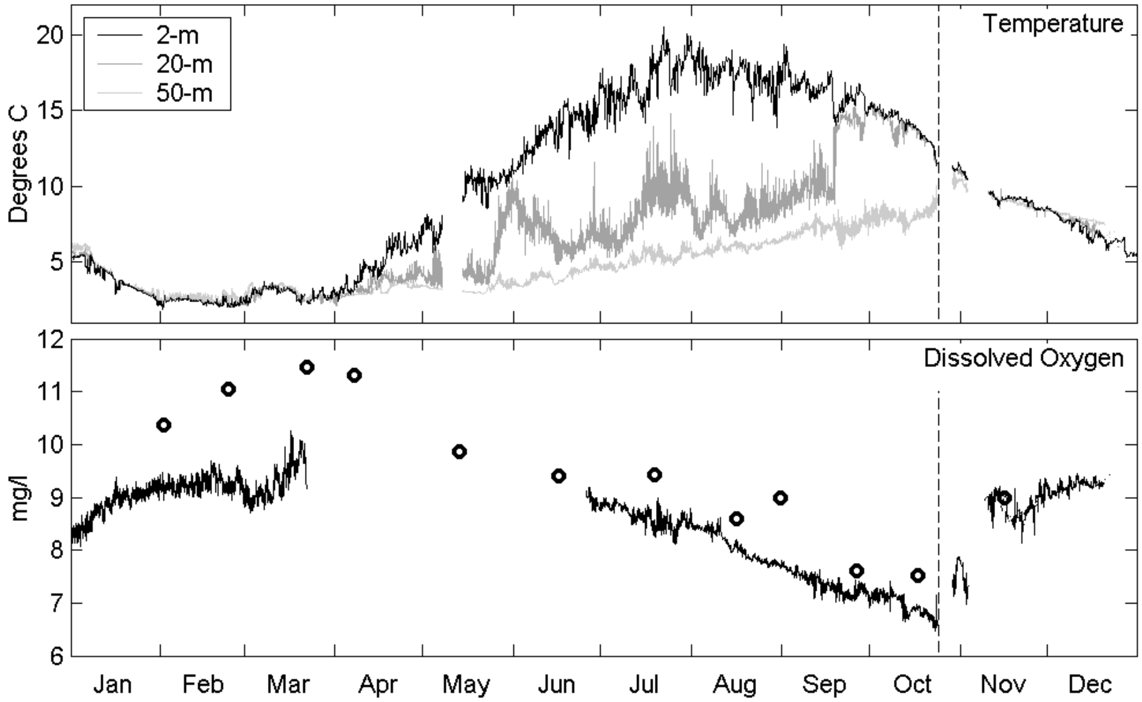


Figure 3-22. Data from the GOMOOS "A" mooring in Northeastern Massachusetts Bay. The upper panel shows temperature at 2, 20 and 50-m depth, and the lower panel shows dissolved oxygen at 50-m depth, with the nearfield DO measurements shown as "o" for comparison. The dashed line represents the turn-around of instruments on the mooring.

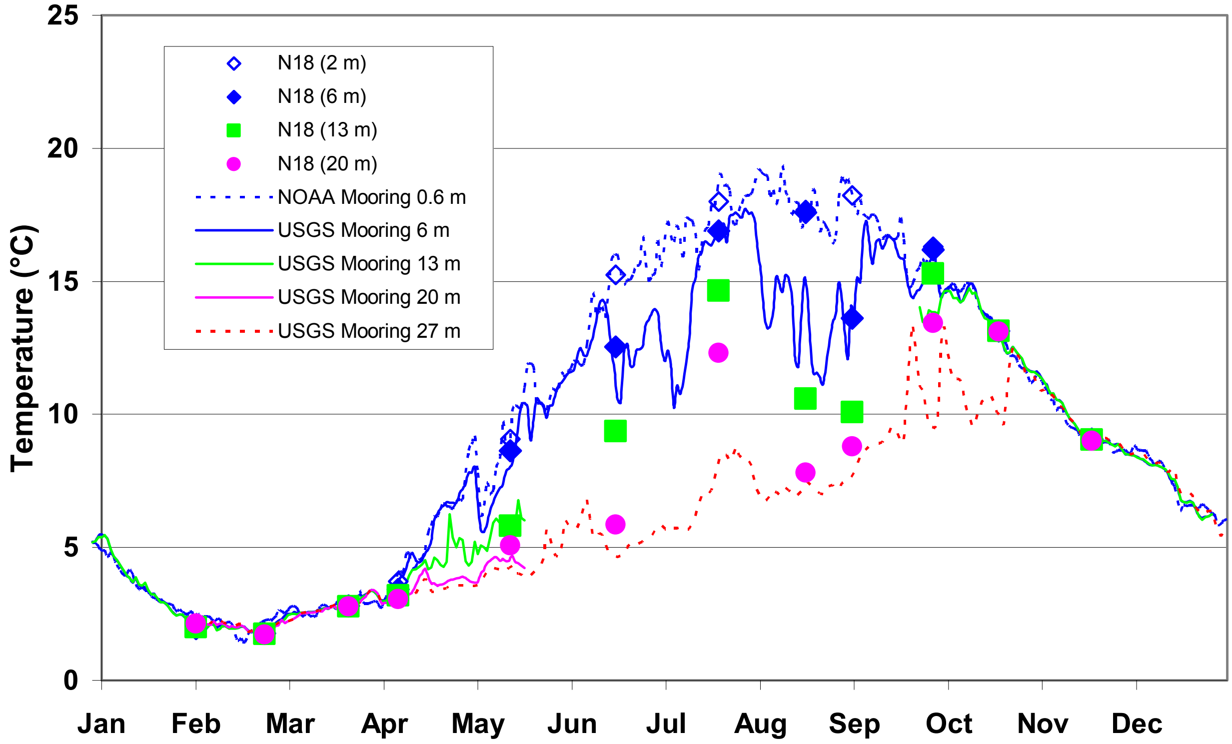


Figure 3-23. USGS LT-A mooring and NOAA 44013 buoy temperature data compared to station N18 results for 2004.

3.4.6 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 productivity 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.

Post-transfer 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** 3-24a). Timing of these events, however, is somewhat different from baseline years. An early onset of the winter/spring bloom was observed in February of both 2001 and 2002 resulting in the higher early February post-transfer production rate. As the *Phaeocystis* bloom has become a consistent event since 2000, the post-transfer productivity rate in April had nearly doubled from the baseline mean and is now the annual survey maximum in production in the nearfield. Summer production rates are comparable yet tended to be lower than those measured during the baseline period. However, in the fall the post-transfer trends were less defined than the dominant October peak seen during the baseline. In 2001-2004, there was a late summer/early fall peak (due primarily to the early fall bloom in 2002) and a late October-November peak (late fall blooms in 2001 and 2003). As noted earlier, there was no fall bloom in 2004 (see **Figure** C-2).

The post-transfer productivity data still suggest that Boston Harbor may be transitioning from a eutrophic pattern, but not to the extent that appeared in the data the first three years after diversion. Prior to transfer to the bay outfall, productivity in the harbor was characterized by increasing rates throughout the summer, followed by a fall decline (**Figure** 3-24b). The post-transfer harbor means suggest a pattern more typical of temperate waters with winter/spring peaks, lower summer rates, and possibly a late summer/fall peak. In 2004, the productivity pattern at station F23 differed somewhat from the pattern observed in 2001 – 2003 (see **Figure** C-2) with areal productivity similar to the observed baseline pattern. In 2004, unlike the previous year, no winter/spring bloom was evident in the harbor. Although no bloom was present, productivity in the harbor during late February 2004 was greater than the baseline mean for that time period and close to the late February baseline maximum. Also in 2004 there was no evidence of a fall bloom in the harbor or the nearfield results. In 2003, the presence of a spring bloom continued to suggest that the harbor station might be exhibiting a pattern of productivity similar to the nearfield stations, with the cause presumably the reduction in nutrients following the diversion of the outfall. The lack of a winter/spring bloom in the harbor in 2004 may have more to do with regional trends (no winter/spring bloom in the nearfield in 2004 until the Phaeocystis bloom in April) than a reversion to the baseline seasonal pattern. Overall, the decline in productivity observed at the station does indicate a shift to a less-enriched environment (**Figure** 3-24).

To further refine understanding of the changes in primary production, seasonal peak productivity during baseline and post-transfer years was compared (**Figure** 3-25). Examining the magnitude of seasonal blooms in the nearfield (average for stations N04 and N18) and harbor (station F23) indicates that the greatest effect of the outfall relocation is in seasonal productivity levels in Boston Harbor. The magnitude of the spring bloom in the harbor nearly tripled from a baseline mean of 623 mg C m^{-2} d^{-1} to 1720 mg C m^{-2} d^{-1} post-transfer. During the summer, the harbor showed the opposite pattern with a post-diversion mean of 1282 mg C m^{-2} d^{-1} compared to a baseline mean of 3754 mg C m^{-2} d^{-1}. Both the spring increase and summer decrease in production from baseline to post-transfer periods are significant

($P \leq 0.05$). In the fall, the values for the harbor followed a similar pattern to that seen in the summer with high baseline values (2951 mg C m^{-2} d^{-1}) and lower values post-diversion (1938 mg C m^{-2} d^{-1}). Over each of the seasons, there was little change in peak rates observed in the nearfield. Prior to the outfall relocation in 2000, the typical harbor pattern had low winter/spring production and high production in the summer which was maintained into the fall. After 2000, winter/spring production has increased while summer and fall production have decreased. Fall production has not decreased as much as the summer, however, leading to the appearance of a fall "bloom" in the harbor. In the nearfield, mean production values have increased slightly for spring and fall while decreasing somewhat in the summer but the changes are not statistically or biologically/ecologically significant.

Interannual variability in annual production can be quite substantial (**Table** 3-3), but the Boston Harbor rates were consistently about 30% to 130% higher than nearfield rates over the baseline period (except for 1998 when all rates were very low). Since diversion to the bay outfall, the harbor and nearfield station rates have become comparable (**Figure** 3-26). The changes in nearfield station annual production (+3% and -12% at N04 and N18, respectively) are not large nor are they significant. In Boston Harbor, however, the data indicate that there has been a nearly significant ($P=0.056$) reduction in annual production from baseline to post diversion rates of ~40%. Similar decreases are apparent in seasonal mean particulate organic carbon concentrations in the harbor (**Table** 3-3). 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 first three years after diversion to the bay outfall (Taylor 2004). All of these changes in production and biomass are coincident with a significant decrease in nutrient concentrations in the harbor. As discussed previously, there were significant increases in seasonal mean nutrient concentrations at many of the nearfield stations. However, this increase has not had any apparent effect on primary productivity or phytoplankton biomass concentrations in the nearfield area.

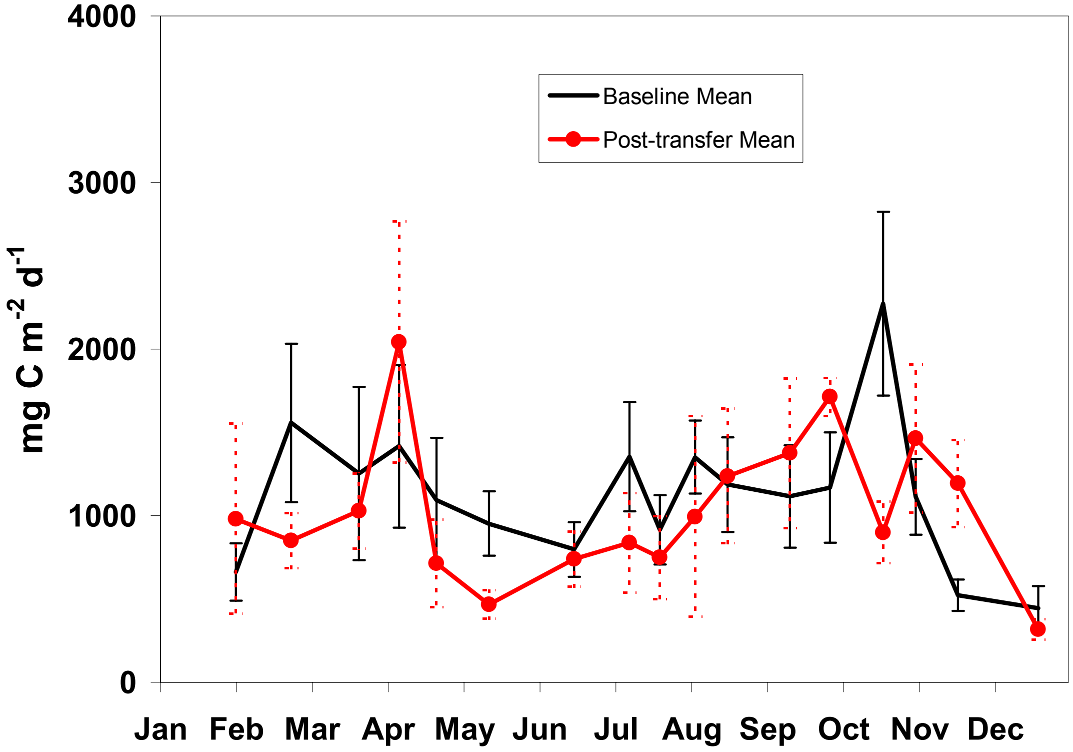
The apparent changes in pre- and post-transfer production in Boston Harbor suggest that the removal of the source of nutrients from the harbor is resulting in lower primary production rates and phytoplankton biomass concentrations (as chlorophyll and POC). In the nearfield, however, there is no clear change in production as a result of the transfer to the bay outfall. However, the interannual variability in these biological measurements and the limited amount of post-transfer data do not allow for definitive findings in the nearfield to date. The changes that have been observed in pre- and post-transfer production, biomass and nutrient utilization continue to be the focus of ongoing examination.

Table 3-3. Annual mean production (gC m^{-2} y^{-1}).

Year	N04	N16-18	F23
1995	390	544	763
1996	533	482	1087
1997	480	612	862
1998	191	213	224
1999	395	503	658
2000	511	664	494
2001	569	559	404
2002	532	607	587
2003	295	293	311
2004	247	207	332
Baseline Mean	398	471	719
Post-transfer Mean	411	417	408
Percent Change	+3%	-12%	-43%

*Bay Outfall began discharging September 6, 2000 – 2000 data not included for annual mean calculations.

(a) Nearfield Areal Production



(b) Boston Areal Production

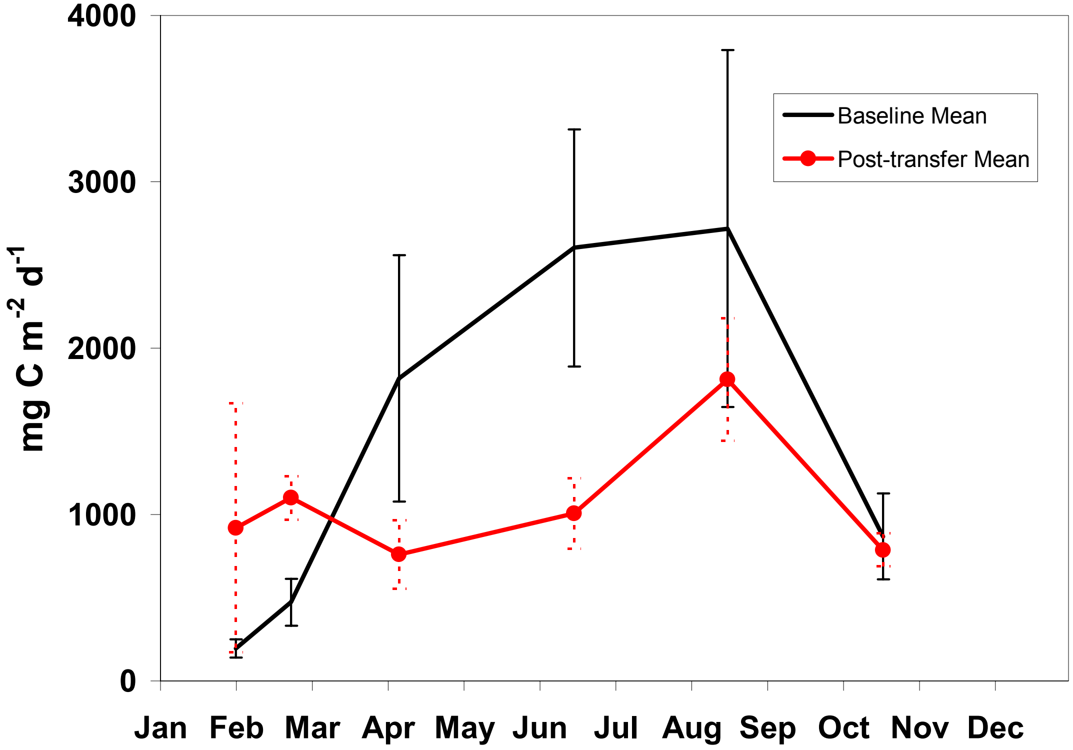
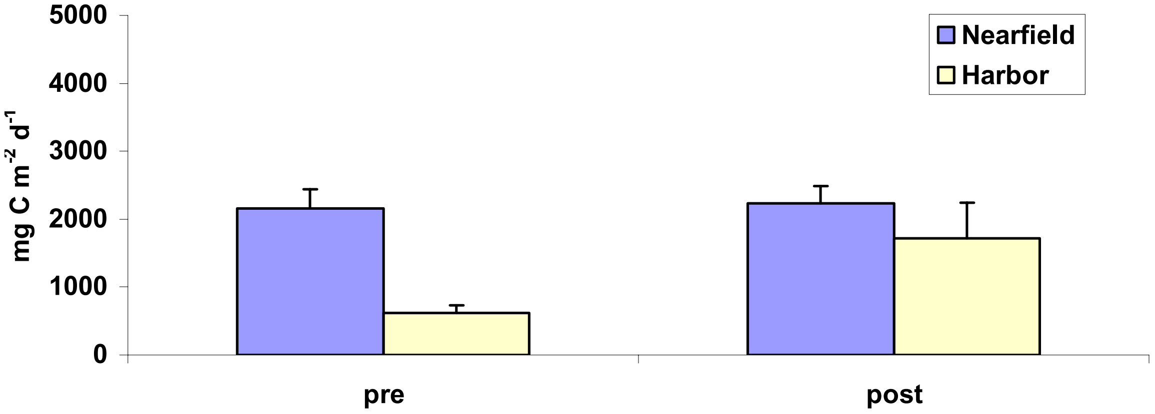
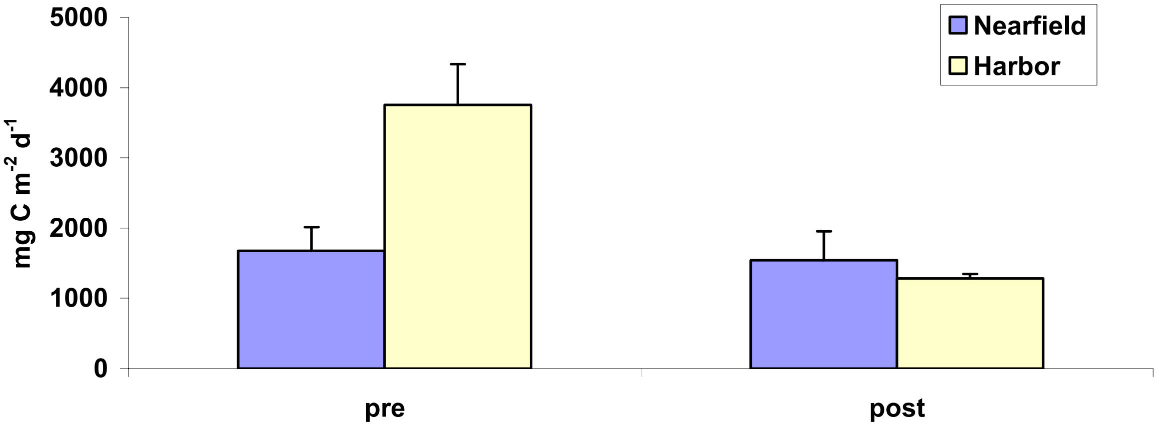


Figure 3-24. Time-series of baseline and post-transfer survey mean Areal Production (mg C m^{-2} d^{-1}) in the (a) nearfield and (b) Boston Harbor. Error bars represent ±1 SE. Data collected from all depths and all stations.

(a) Spring Peak Areal Productivity



(b) Summer Peak Areal Productivity



(c) Fall Peak Areal Productivity

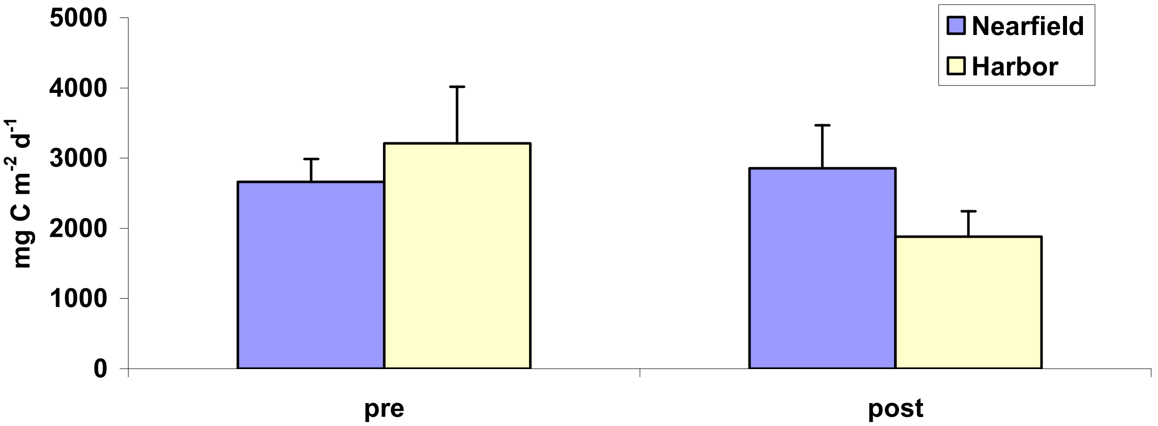


Figure 3-25. Spring, summer, and fall bloom peak production (mgC$m^{-2}d^{-1}$) at nearfield (N04 and N16/N18) and Boston Harbor (F23) stations. Pre vs. post outfall diversion – spring and summer 97-00 vs. 01-04 and fall 97-99 vs. 00-04.

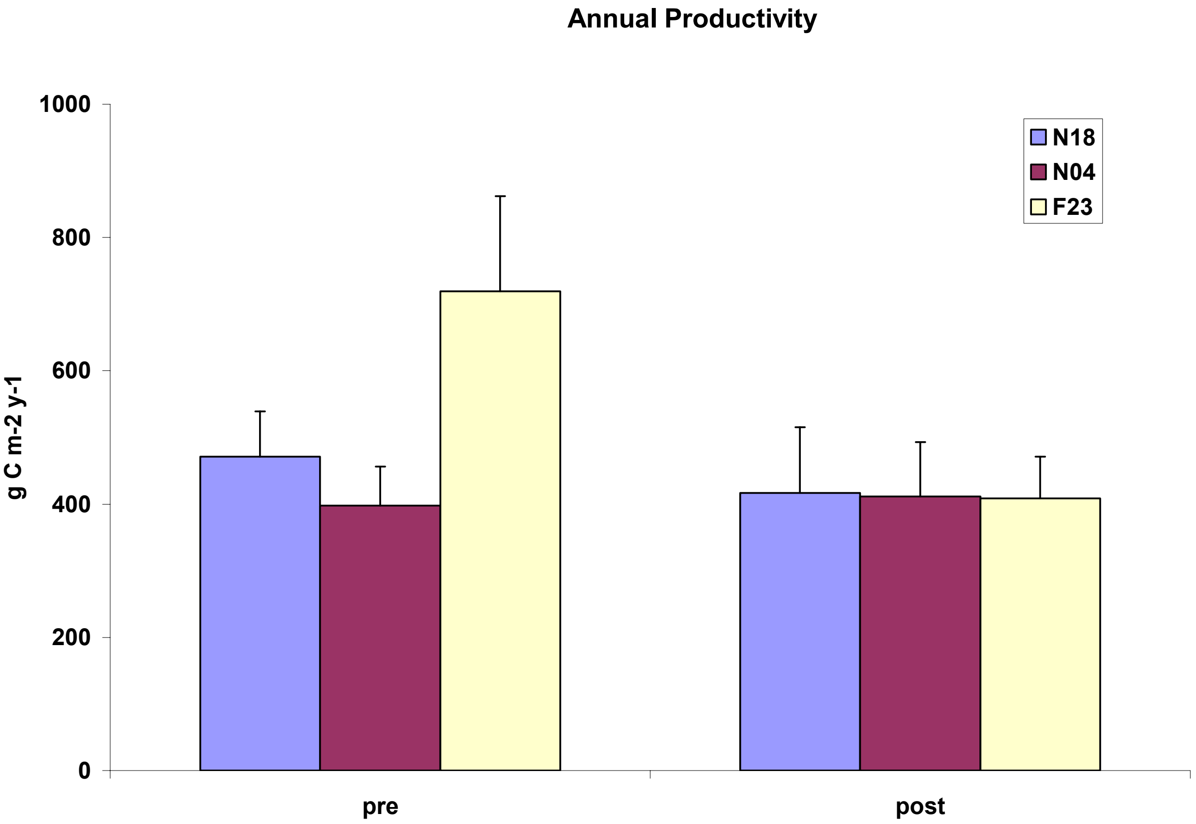


Figure 3-26. Annual potential production (gCm^{-2}yr^{-1}) for stations F23, N04 and N16/N18 pre (1995-1999) and post (2001-2004) outfall diversion (data from 2000 not included).

3.4.7 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) and Spring (March, April, May) – diatoms are usually abundant, including species of the genera *Chaetoceros* and *Thalassiosira*, with spring blooms of *Phaeocystis pouchetii* (mainly in April);
>
> Summer (June, July, August) – microflagellates are at peak abundance, with cryptomonads and the diatoms *Skeletonema costatum*, *Leptocylindrus danicus, Guinardia delicatula,* and various species of *Chaetoceros*;
>
> Fall (September through December) – diatoms are usually abundant, including *Asterionellopsis glacialis, Guinardia delicatula, Skeletonema costatum, Dactyliosolen fragilissimus, 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, and every year since 2000. The interannual variability associated with both magnitude and occurrence of phytoplankton blooms as represented by total phytoplankton abundance is comparable to seasonal variability (**Figure** 3-27). 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.

Post-diversion (2001-2004) phytoplankton assemblages were generally similar to those found during other baseline monitoring years. Nearfield total phytoplankton abundance tracks the trends observed during the baseline, with a few key differences as mentioned in the discussions of biomass and production. The nearfield peak for phytoplankton abundance has shifted from the fall to the spring bloom (**Figure** 3-28). The annual occurrence of the March-April *Phaeocystis* blooms since 2000 have led to nearly a doubling of survey mean total phytoplankton abundance during the March and early April surveys. In the fall, the lack of a bloom in 2004 along with relatively early (2002) or late (2001 and 2003) fall blooms in other years resulted in low abundances in early October when the baseline mean value was at its annual maximum. The late fall blooms in 2001 and 2003 also led to higher than baseline means in late October and November.

No major changes have been noted in the taxonomic composition of the phytoplankton community over the last thirteen 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*. 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 from 2000 to 2004. Although it is clear that the periodicity of spring *Phaeocystis* blooms has changed, the reason(s) for this change remain elusive. In addition to the apparent change in *Phaeocystis* trends, a few minor variations in phytoplankton abundance have been noted for various *Pseudo-nitzschia* and *Ceratium* species.

Phaeocystis:

Why *Phaeocystis* occurs in relatively high abundances in some years and not in others, however, is not well understood and continues to be a focus for the research community. Algal growth and abundance are influenced by many environmental factors including the availability of light, nutrients, water temperature, water movement, competition from other algal species for nutrients and light, and by grazing. It is possible that the large *Phaeocystis* bloom in 2004 was related to relatively high nutrient concentrations in the region, the extremely cold winter and spring and/or the precipitation pattern of little rain in February and March, followed by a wet April. A detailed discussion on this topic is included in Appendix D. A summary is provided here that focuses on the spatial extent and timing of the *Phaeocystis* blooms observed from 1992 to 2004 and provides some context as to what factors may be contributing to the occurrence, magnitude, and duration of the blooms.

Spatial Patterns

- → *Phaeocystis* blooms tend to occur throughout the Massachusetts and Cape Cod Bays region (**Figure** 3-29)
- → There is no consistent spatial pattern of abundance during these blooms, with high counts observed further offshore, in the nearfield, or closer in shore during different years.
- → *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 and coincident with the presence of *Phaeocystis* in waters from Buzzards Bay to the Gulf of Maine.

Temporal Trends

- → The timing of *Phaeocystis* blooms has been relatively consistent - typically first observed in March with peaks in late March or early April.
- → The duration of the bloom varies from year to year (see **Figure** D-9a), but there is no correlation between duration and magnitude of the blooms.
- → The only apparent change from pre- to post-transfer to the bay outfall is the extension of the bloom into May as suggested by the summer threshold exceedances in 2002, 2003 and 2004. *Phaeocystis* cells were also observed in May 1997 (the only large bloom observed during the baseline period).

Temperature Effect

→ 14 °C appears to be the physiological threshold for *P. pouchetii* growth (Jahnke and Baumann 1987) and is the maximum temperature at which *P. pouchetii* blooms in Massachusetts Bay (Hegarty and Villareal 1998).

→ The extended duration of *Phaeocystis* blooms in 1997 and 2002-2004 may be related to the presence of cooler waters (<14 °C) into June compared against temperatures in 2000 and 2001 when surface waters were <14 °C only into early May (see **Figure** D-9b).

Nutrient Effects

➢ **Silicate**

→ The "silicate-*Phaeocystis* hypothesis" postulates that diatoms outgrow *Phaeocystis* until silicate becomes limiting (Lancelot *et al*. 1987; Reid *et al*. 1990).

→ The larger *Phaeocystis* blooms in Massachusetts Bay have displayed this pattern in SiO_4 vs. DIN consistent with the silicate hypothesis (see **Figure** B-13).

→ *Phaeocystis* can also bloom when silicate is still high in the bays, contrary to the silicate hypothesis, but these 'blooms' have relatively low abundances (e.g. 1994).

➢ **N:Si Ratios**

→ During the transition from a winter/spring diatom bloom to a *Phaeocystis* bloom, SiO_4 concentrations decrease to the point where they either start to become limiting or the N:Si ratio becomes high enough that *Phaeocystis* can out-compete the diatoms for nitrogen.

→ A comparison of pre- and post-transfer winter/spring (February-May) surface DIN and NH_4 concentrations (**Figure** 3-30a) shows an increase in mean DIN from 4.2 to 5.9 µM and a doubling in mean NH_4 from 1 to 2 µM ($P<0.05$ for both).

→ The increase in DIN relative to SiO_4 has resulted in an increase in the N:Si ratio (**Figure** 3-30b) that suggests a higher proclivity for *Phaeocystis* dominated blooms, but given the regional nature of *Phaeocystis* blooms this is not likely to impact the occurrence of these blooms.

➢ **N_{ox}:N_{red} Ratios**

→ A difference in the ability to assimilate oxidized (NO_3, NO_2) and reduced (NH_4) forms of DIN also influences competition between diatoms and *Phaeocystis* (Peperzak *et al*. 1998).

→ In water having NH_4 concentrations above the 1-2 µM nitrate reductase limiting threshold, *Phaeocystis* is able to out-compete diatoms for the dominant form of DIN. In addition to drawing down SiO_4, the initial diatom bloom also draws down NO_3 and some NH_4. In situations where NH_4 supply rate is high, phytoplankton that can most rapidly utilize this NH_4 resource often bloom.

→ The N_{ox}:N_{red} has decreased 3.2 to1.6 from pre- to post-transfer (**Figure** 3-30b; $P<0.05$) as nearfield NH_4 concentrations have doubled.

→ *Phaeocystis* blooms have been observed to preferentially occur at lower N_{ox}:N_{red} than do diatom blooms (Tungaraza *et al*. 2003).

- Baseline - nearfield N_{ox}:N_{red} typically 6 in February, to 3 in late March and to 0.3 in May.
- Post-transfer - nearfield N_{ox}:N_{red} has seasonally fallen from 3 to 1.5 to 0.3 over the same period.

→ The increase in NH_4 and concomitant change in the ratio of N_{ox}:N_{red} could potentially alter competition for available DIN, favoring *Phaeocystis* over diatoms.

Ecological Effects

- → Ecological dynamics appear to change during years with a *Phaeocystis* bloom. There is a disconnect between bloom production rates and phytoplankton biomass and a decrease in zooplankton abundance with increasing phytoplankton biomass (**Figure** 3-31).
- → Colony formation by *Phaeocystis* tends to decrease vulnerability to grazing, at least temporarily (Hansen and Van Boekel 1991; Gasparini *et al*. 2000).
- → It has been suggested that *Phaeocystis* blooms might be noxious to certain animals (i.e. right whales) or that such blooms might be largely ungrazed by zooplankton. MWRA data are inconclusive as to bottom-up control during *Phaeocystis* blooms, but do suggest that there may be an impact on some species of copepods (see Section 3.4.8).

Pseudo-nitzschia:

Interannual comparisons of abundance of various taxa of *Pseudo-nitzschia* are complicated because the taxonomy of this genus has been changing during the period of the MWRA monitoring, and designations of various taxa presently in the database may not be comparable because different persons performed analyses. A close examination of the data, taxa naming conventions and changes in analytical personnel suggests that some of the changes seen in the *Pseudo-nitzschia* data may be real, while others are merely due to analytical modifications. The putative shift from *Pseudo-nitzschia* spp. to the *P. delicatissima* complex in winter is apparently a taxa naming issue, whereas the *P. pungens* to *P. delicatissima* complex shift in summer and fall is likely a combination of changing analysts and possibly a real shift. A more detailed discussion of this issue is presented in Appendix D.

Ceratium:

In 2004, nearfield abundance of dinoflagellates, in general, and *Ceratium*, in particular, were lower than the baseline mean and often below the baseline minimum (see **Figure** D-11). Similarly low *Ceratium* spp. abundances were observed in 2002 and 2003. The 2002 annual report suggested that the reduced *Ceratium* abundance might be due to a delay in the onset of spring stratification (Libby *et al*. 2003). The hypothesis that the establishment of a density gradient in the spring may favor *Ceratium* in competition with faster-growing diatom species. The speculated mechanism was that 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. A weak pycnocline in 2002 was partially attributed to dry conditions, with reduced stratification due to reduced freshwater runoff. In 2003, conditions were wet and increased precipitation and runoff led to salinity induced stratification in April. It was suggested that the stratification hypothesis may not explain the low *Ceratium* in 2003 (Libby *et al*. 2004b). Due to this discrepancy and the continued low abundance of *Ceratium* in 2004, a closer examination of the relation between stratification and *Ceratium* abundance in Massachusetts Bay was investigated through correlation analysis. A significant positive correlation was found between Massachusetts Bay stratification and *Ceratium* abundance (see **Table** D-1). The stratification-*Ceratium* correlation was strongest for the late spring to early summer period. The statistical linkage between stratification early in winter and *Ceratium* abundance later in the spring presumably reflects the *Ceratium* population's dependence on annual variation in the onset and persistence of stratification for achievement of population growth rates in excess of *in situ* loss process rates.

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 though there has been a shift in peak abundance to April when the *Phaeocystis* blooms tend to be at a maximum. The change in the frequency and duration of spring *Phaeocystis* blooms since 2000 appears to be related to regional factors and continues to be explored and will be examined in more detail in the 2005 Nutrient Issues Review.

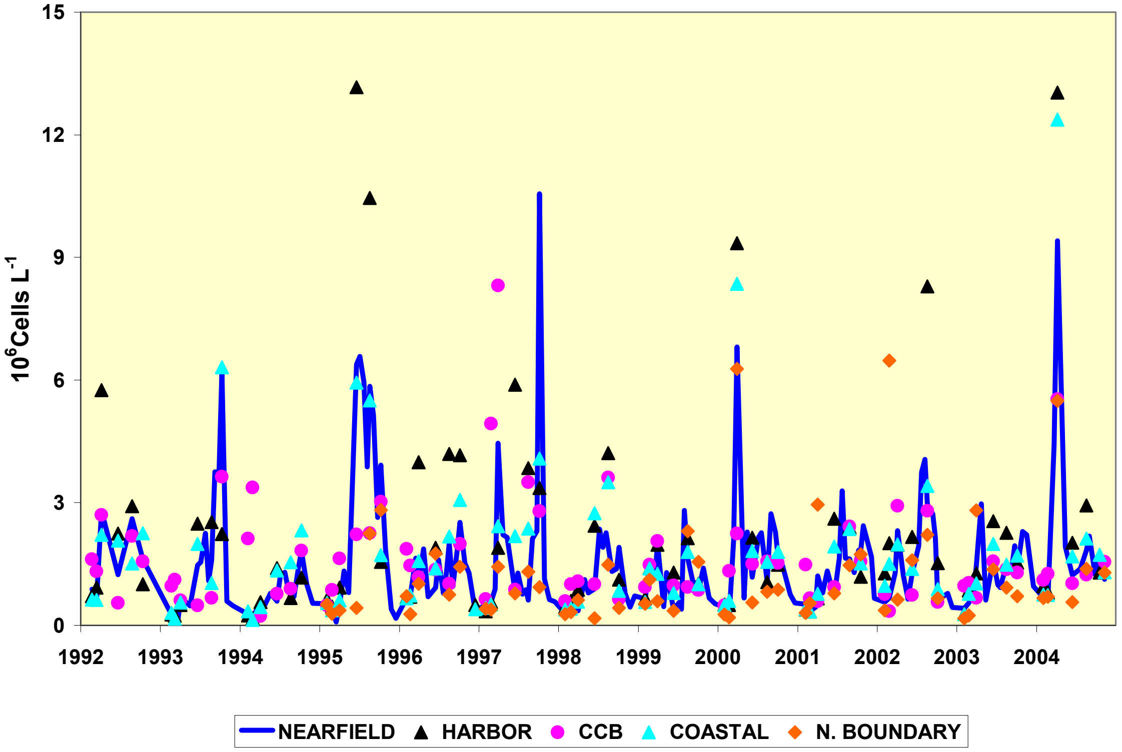


Figure 3-27. Total phytoplankton abundance by region, 1992-2004.

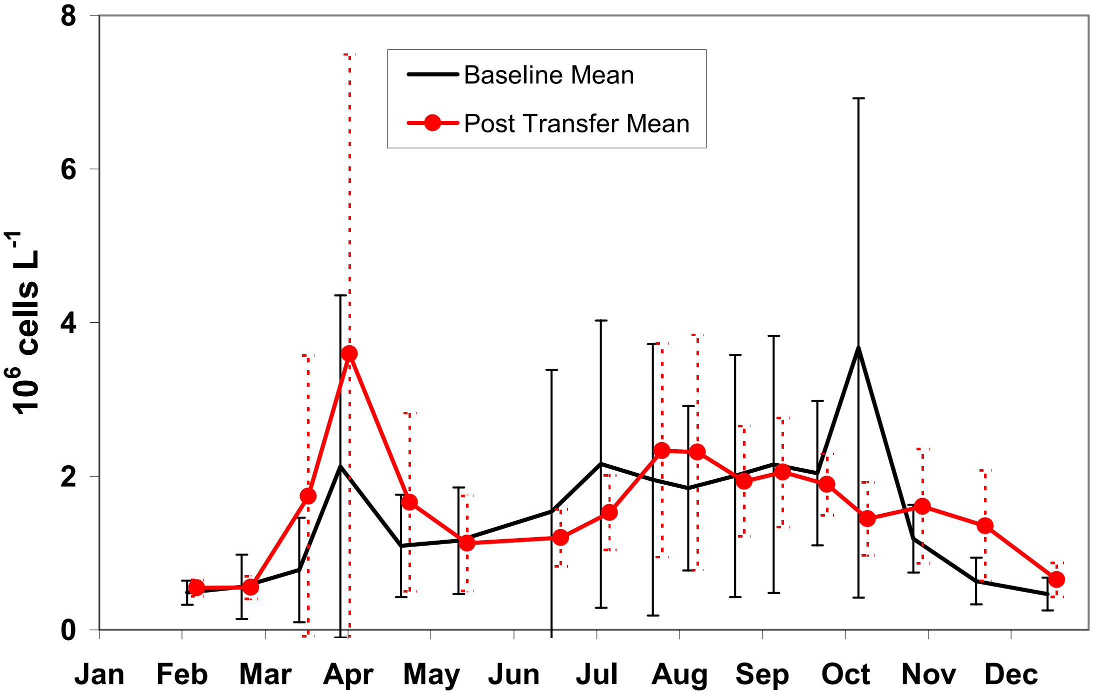


Figure 3-28. Time-series of baseline and post-transfer survey mean total phytoplankton abundance (million cells L^{-1}) in the nearfield. Error bars represent ±1 SD. Data collected from both surface and mid depths, and all nearfield stations sampled (fall 2000 data included in post-transfer).

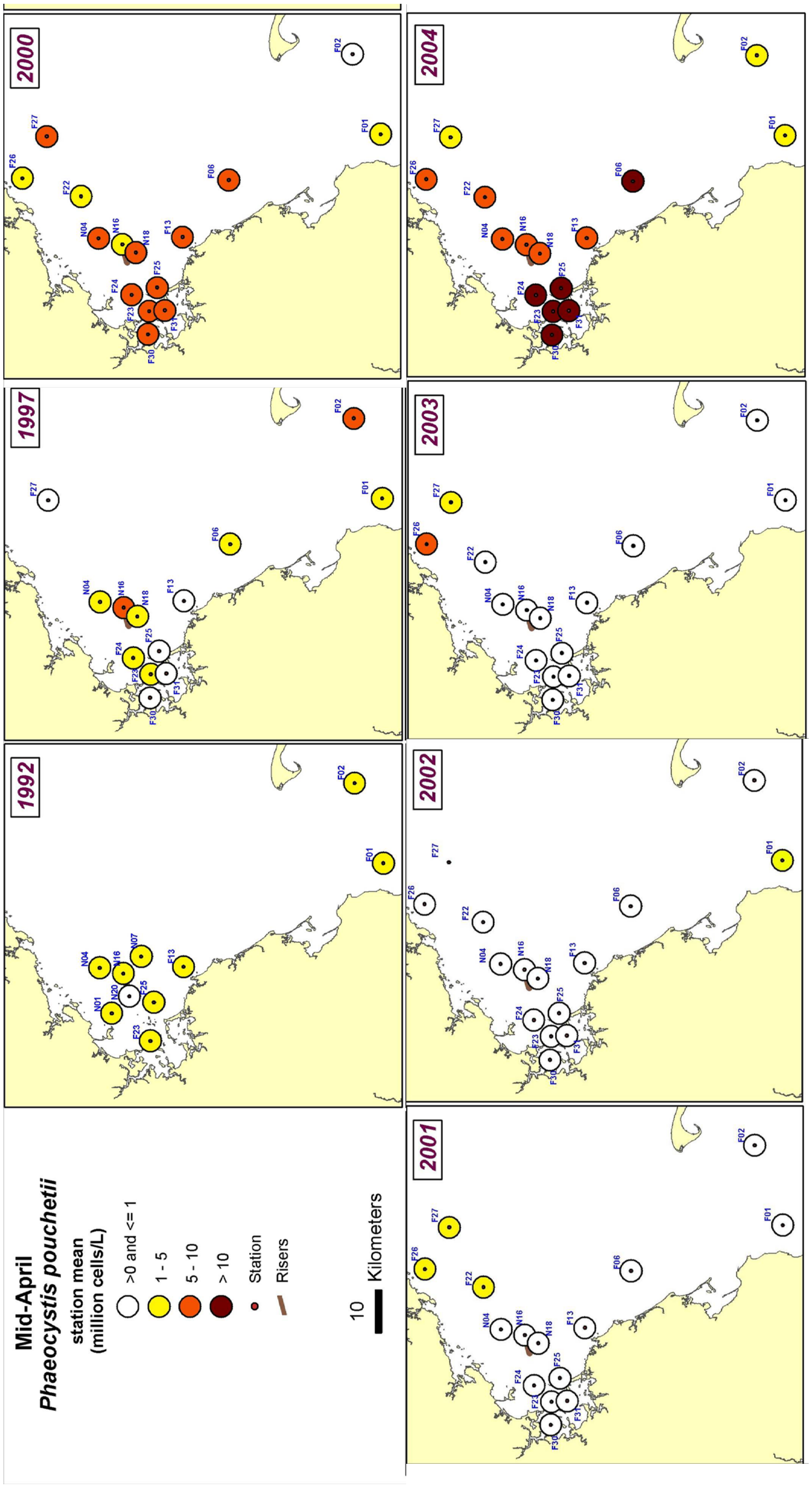
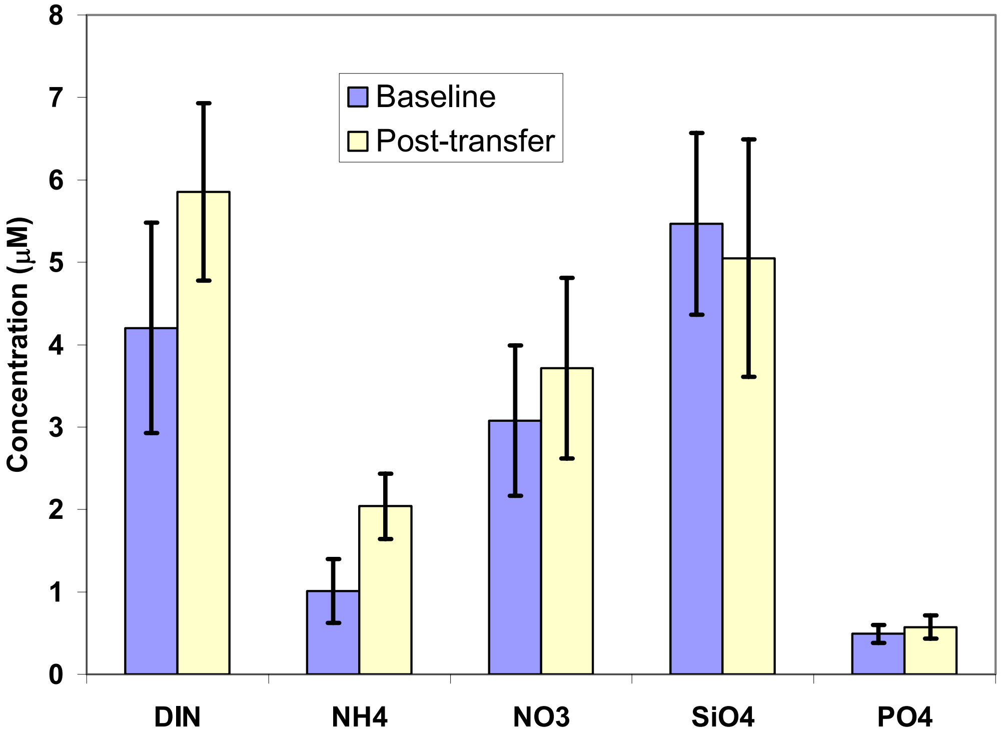


Figure 3-29. Spatial extent of the seven April blooms of *Phaeocystis*.

Each point represents a plankton sampling station. The number and location of stations sampled for plankton has changed over the course of the program.

(a) Nearfield Nutrients



(b) Nearfield Nutrient Ratios

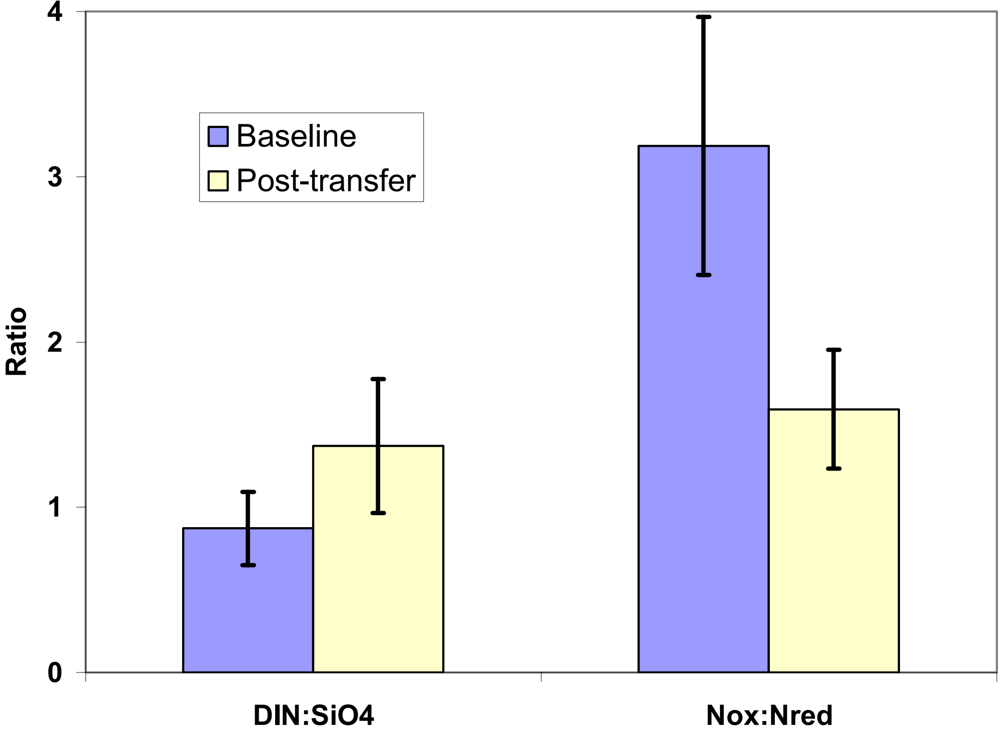
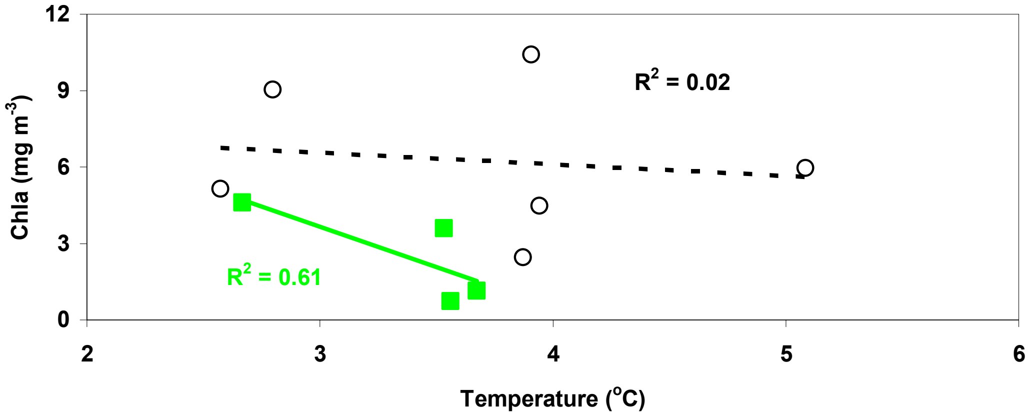
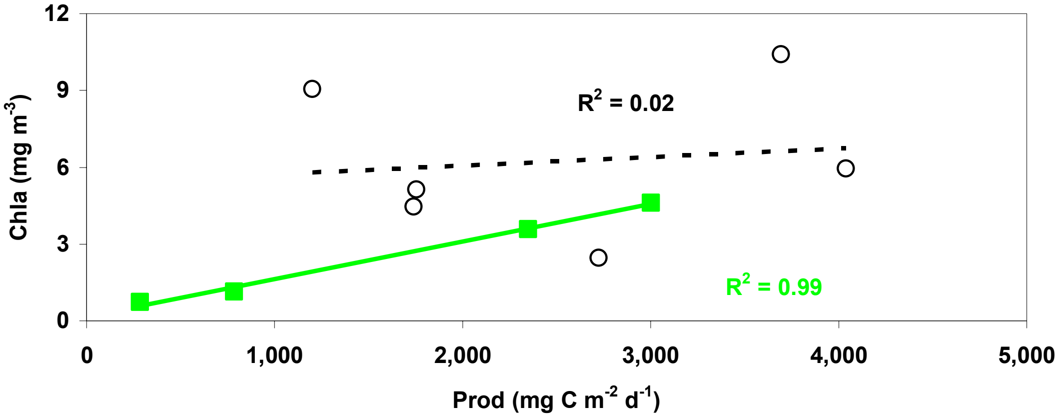


Figure 3-30. Winter/Spring Nearfield mean surface nutrient (a) concentrations (µM) and (b) ratios for baseline (1992-2000) and post-transfer (2001-2004) time periods.

(a) Peak Bloom Chla vs Mean Temperature



(b) Peak Bloom Chla vs Peak Bloom Production



(c) Peak Bloom Chla vs Mean Zooplankton Abundance

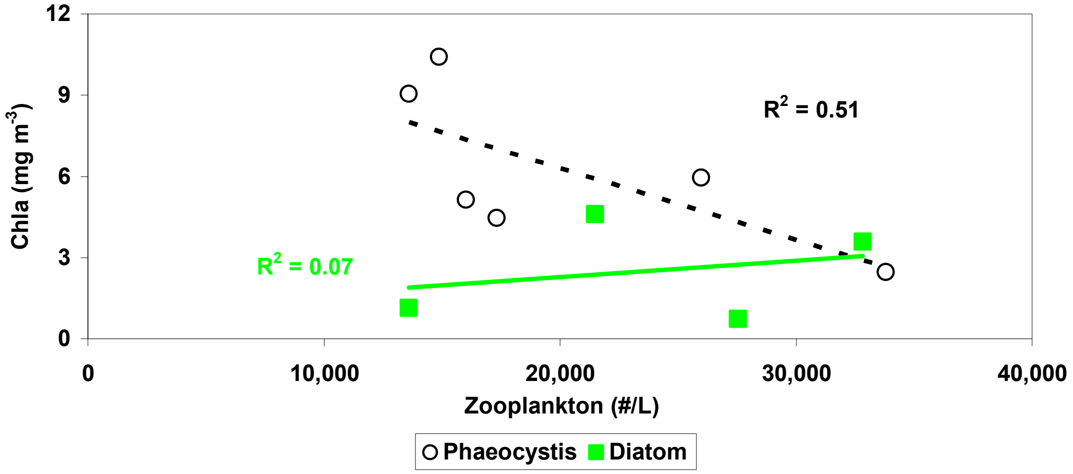


Figure 3-31. Spring bloom period (February to April) comparisons of peak bloom chlorophyll concentration vs. (a) mean temperature (Feb-Apr), (b) peak bloom production and (c) mean zooplankton (Feb-Apr) in the nearfield. Non-*Phaeocystis* year data (95, 96, 98 and 99) green squares and *Phaeocystis* year data (97, 00, 01, 02, 03 and 04) open circles.

3.4.8 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 and 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. Zooplankton abundance tends to follow a predictable temporal pattern, with abundance peaking in mid-summer and lower levels in spring and fall (**Figures** 3-32 and 3-33). The seasonal timing for individual species is, however, variable. Moreover, there is no clear seasonality in terms of dominant zooplankton taxa in the region. Total 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.

The monitoring questions were focused on detecting 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. It is, however, 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 or a top down impact via increased grazing by zooplankton predators. Both of these have been suggested for apparent decreases in zooplankton in the late spring/early summer and fall during the post-diversion period (**Figure** 3-33) and are discussed below. It is unclear at this time if the outfall has any direct or indirect role in these ecological relationships.

As discussed in Section 3.4.7, winter/spring ecological dynamics appear to be different depending on whether or not a *Phaeocystis* bloom occurs in the bays. Late spring and early summer nearfield zooplankton abundance means for 2001-2004 were low and well below the baseline values in June and July (**Figure** 3-33). The evaluation of the consecutive *Phaeocystis* blooms from 2000-2004 suggested that there is a negative relationship between the occurrence of these blooms and the abundance of zooplankton (**Figure** 3-31). *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 this is complicated by considerable documented variability, at least in the case of zooplankton grazing (Turner *et al.* 2002). Impacts of *Phaeocystis* blooms on zooplankton are 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* unpalatability to zooplankton.” Such speculation is complicated by observations that numerous various zooplankters appear to feed and survive well upon diets of *Phaeocystis*, but may have reduced fecundity (see Turner *et al*. 2002 and references therein). In general, observations of copepod abundance in April and May, the month of and after peak *Phaeocystis* abundance, during the bloom years from 2001 to 2004 are within the 1992-2000 baseline range but below the baseline mean (**Figure** 3-34a). The presence of relatively low copepod abundances during these surveys is offset by the fact that some copepod species, such as *Calanus finmarchicus*, were generally at the baseline mean in April and reached abundances well above the baseline in May (**Figure** 3-34b). To examine this in more detail, correlation analyses were undertaken to identify co-varying *Phaeocystis* and zooplankton patterns and 2-sample tests were carried out to identify differences in zooplankton abundance when *Phaeocystis* is present (+) or absent (-). The correlation analyses revealed seasonally varying taxon-specific patterns of *Phaeocystis* – zooplankton variation.

Examination of all data in monthly intervals revealed a positive correlation between *Phaeocystis* and *Calanus* abundance ($p<0.05$) in February. This correlation was strongly influenced by the elevated *Phaeocystis* and *Calanus* levels observed in late February of 2003, such that this correlation is not significant if the late February 2003 value is removed. *Calanus* was the only taxa having any positive correlation with *Phaeocystis* abundance, and it was highly dependent on elevated *Calanus* values observed in 2003. All other taxa had weak negative correlations with *Phaeocystis* abundance, with the strongest negative correlation observed later in the *Phaeocystis* season (i.e., April and May). For example when all data (*Phaeocystis* present and absent) were examined, *Oithona* abundance and total copepod abundance in April and May surveys were negatively correlated with *Phaeocystis* abundance, but not significantly ($p=0.05$ to 0.11). Looking at only April and May surveys when *Phaeocystis* was present, total copepod abundance was negatively correlated with *Phaeocystis* abundance ($p\leq0.05$; see **Figure** D-16). An exponential decay equation offers a better fit to the data ($p <0.001$), with total zooplankton abundance falling rapidly from near 9,000 animals m^{-3} when *Phaeocystis* abundance is low in April-May to <2,000 animals m^{-3} when *Phaeocystis* abundance exceeds 2 million cells l^{-1}. This regression is strongly dependent on the very high *Phaeocystis* abundances observed in April 2004.

The strong dependence of the correlative relationships described above on one or two observations during elevated *Phaeocystis* levels (i.e., >2 million cells l^{-1}) suggested the possibility of a square-wave or threshold response rather than a linear response of the zooplankton community to *Phaeocystis* abundance. To examine this, the nearfield data were divided into *Phaeocystis* present (+; >0 cells l^{-1}) or absent (-) and the corresponding abundance of various zooplankton taxa during these two conditions was compared using unpaired t-tests. As with regression analysis, the strongest *Phaeocystis* effect was seen in April and May. Mean April and May (combined) total zooplankton abundance when *Phaeocystis* was absent (16,030 animals m^{-3}) was about twice the abundance observed when *Phaeocystis* was present (7,406 animals m^{-3}). Most of the difference in total zooplankton abundance when *Phaeocystis* was present or absent appears to be due to the response of *Oithona*. *Oithona* abundance in March and April when *Phaeocystis* was absent was 6,156 animals m^{-3}, while *Oithona* abundance decreased by more than 50% when *Phaeocystis* was present to 2,846 animals m^{-3}. This difference is highly unlikely to have occurred by chance alone ($p = 0.0509$). Other groups examined (*Acartia*, *Calanus*, and nauplii) had no significant difference in abundance when *Phaeocystis* was present versus absent.

These analyses show that there is a mixed seasonally varying and taxon-specific response to *Phaeocystis* in Massachusetts Bay. The observed patterns of elevated *Calanus* early in the season (Feb-Mar) and reduced *Oithona* and total zooplankton abundance late in the season (April-May) in elevated *Phaeocystis* winter-spring years may reflect the influence of *in situ* processes such as differential growth and reproductive success that may be influenced by *Phaeocystis*. Alternatively, different oceanographic regimes (i.e., variable influence of nearshore vs. offshore water masses) having different fauna (*Calanus*-dominated vs. *Oithona* dominated) may be operative in and co-varying with *Phaeocystis* vs. non-*Phaeocystis* bloom years.

The other change in zooplankton abundance post diversion is the apparent decrease during the fall (**Figure** 3-33). This decrease appears to be in relation to late summer-fall ctenophore blooms. 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. Blooms of *Mnemiopsis leidyi* were not apparent from the beginning of sampling in 1992 until October 2000. Since 2000, this ctenophore has been present every fall, in varying degrees. The fall 2000 appearance of ctenophores was primarily in October, and primarily in Boston Harbor, whereas subsequent blooms in 2002, 2003, and 2004 may have occurred earlier in August and often persisted to November and over a larger area. 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 predation. Although zooplankton abundances declined drastically during these periods, community composition remained similar compared to the same season in previous years.

The reason for the increase in ctenophore abundance, however, is unknown, 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 low zooplankton abundance in fall 2004 was further complicated by the lack of a fall bloom. In previous years, decreased zooplankton grazing due to lower zooplankton abundance was often cited as a possible factor in the development of fall blooms. In 2004, it seems more likely that other physical oceanographic conditions influenced the fall bloom and the lack of a bloom provided less organic material for the zooplankton contributing to the low abundances.

The zooplankton community has not detectably changed in response to the outfall going on line. Although variability in zooplankton abundance has been observed, it appears to be related to regional ecological factors, rather than the outfall and effects of nutrient enrichment in the nearfield. The low abundance in spring and summer appears to be correlated to the occurrence of *Phaeocystis* blooms since 2000. However, some species (*Calanus*) exhibited a positive correlation with *Phaeocystis* abundance/presence. It is unknown whether this mechanism is due to bottom-up control of zooplankton during *Phaeocystis* blooms or physical and environmental factors that lead to the blooms and the apparent changes in the zooplankton community assemblage. The low zooplankton abundance in the fall could be related to either bottom-up (lack of fall bloom – no food) or top-down controls (continued presence of ctenophores). Process and rate studies would be necessary to examine the factors contributing to this interrelationship in more detail.

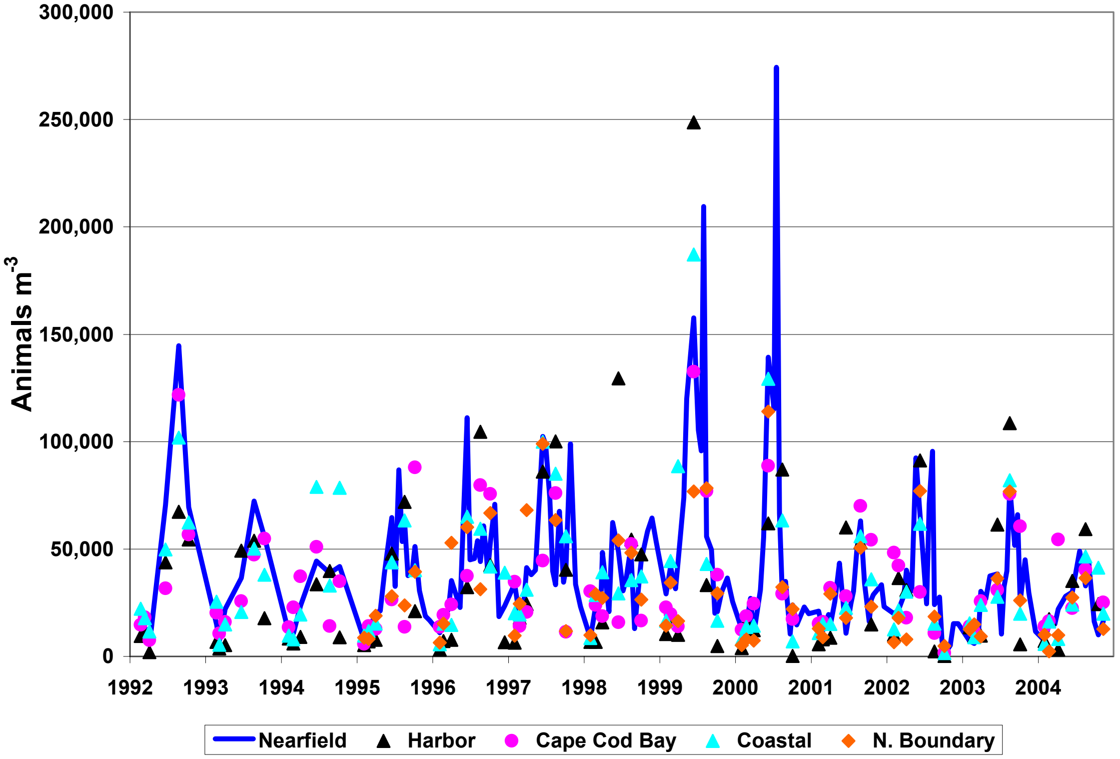


Figure 3-32. Total zooplankton abundance by region, 1992-2004.

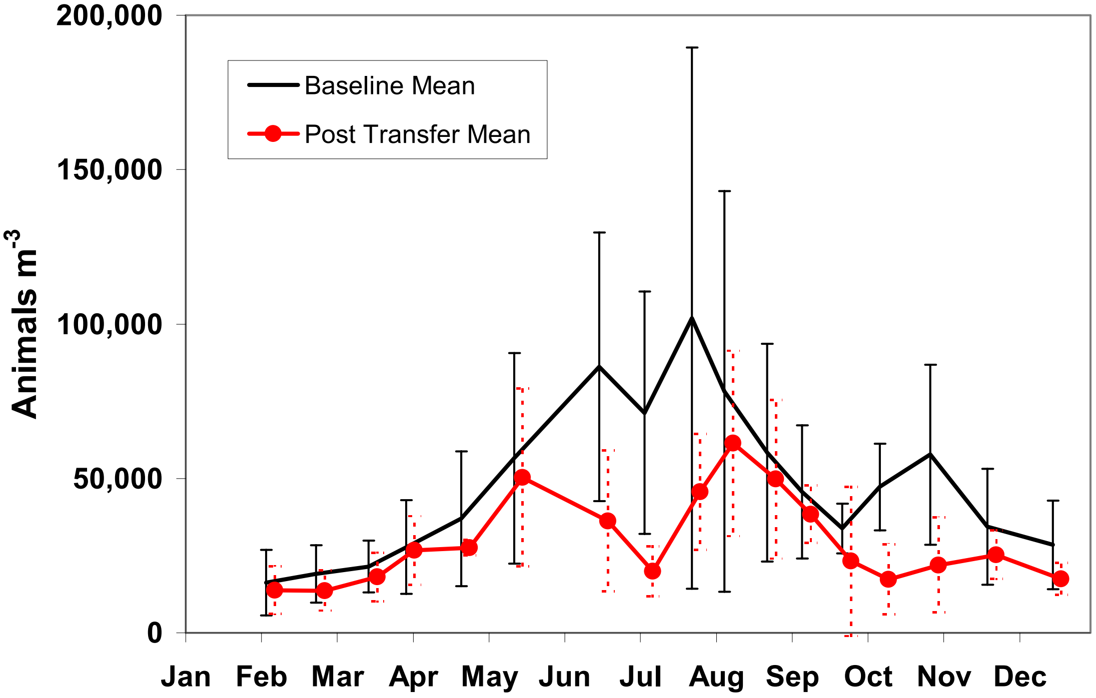
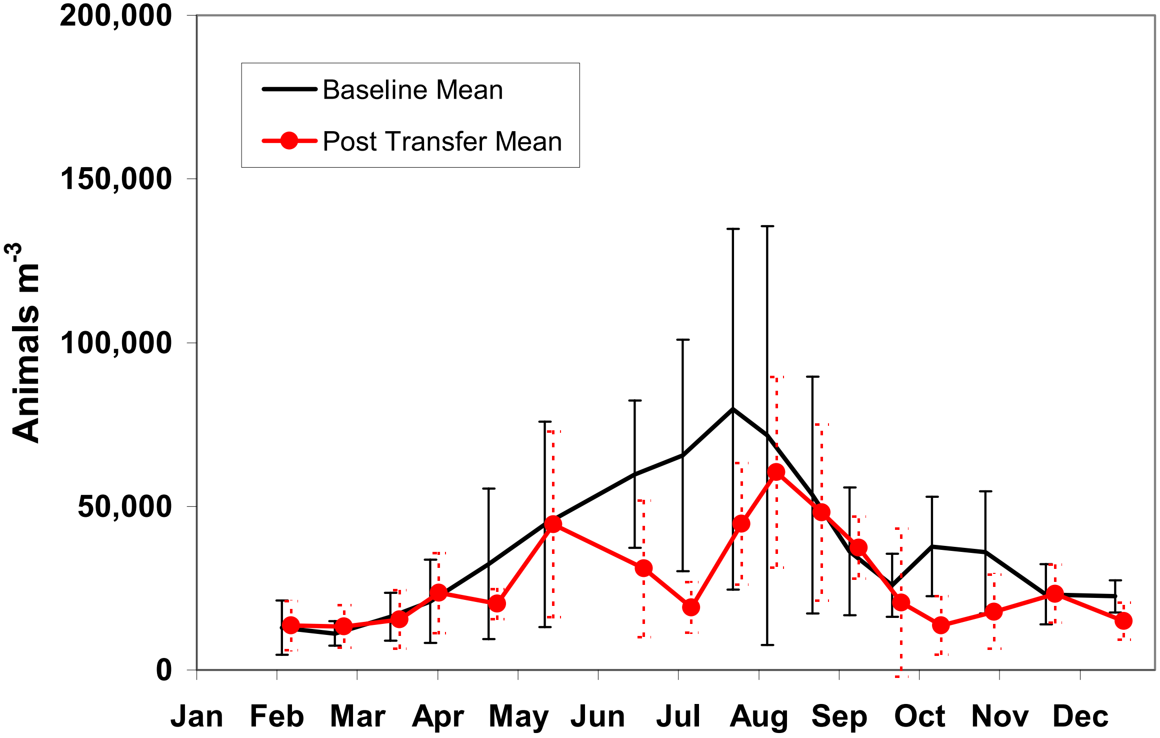


Figure 3-33. Time-series of baseline and post-transfer survey mean total zooplankton abundance (animals m^{-3}) in the nearfield. Error bars represent ±1 SD. Data collected from all nearfield stations sampled (fall 2000 data included in post-transfer).

(a) Total Copepods



(b) Total *Calanus*

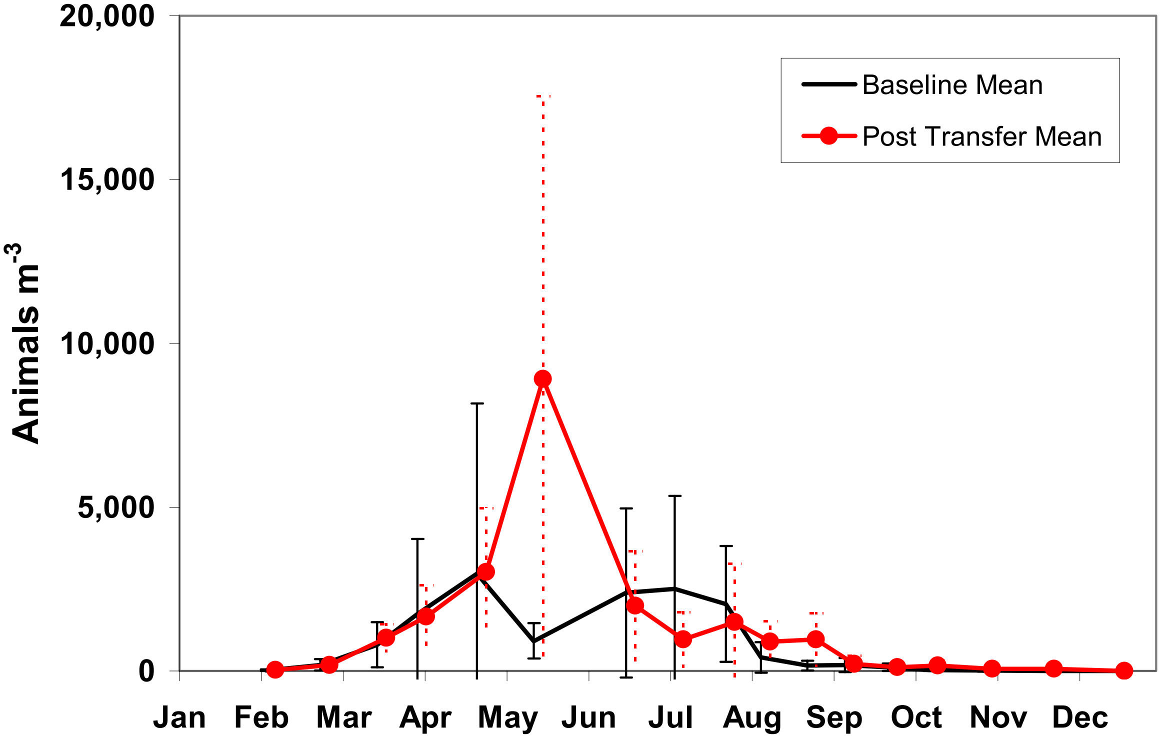


Figure 3-34. Time-series of baseline and post-transfer survey mean nearfield abundance (animals m^{-3}) of (a) total copepods and (b) total *Calanus*. Error bars represent ±1 SD. Data collected from all nearfield stations sampled (fall 2000 data included in post-transfer).

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. 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 plankton communities. A summary of the current understanding (→) and some of the remaining issues to be resolved and recommendations (➢) 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 (Note that MWRA is playing a proactive role in augmenting current mooring instrumentation and planning for potential replacement of the USGS mooring in 2006)

- ➢ Importance of coupling high resolution physical oceanographic data with survey data and potentially moored instrument data measuring chemical and biological parameters.
- ➢ Can new technologies (moorings, AUVs, etc.) augment or eventually replace ship-based surveys and provide additional insight into the remaining unresolved question listed below?

Aesthetics

- Has the clarity and/or color of water around the outfall changed?
- Has the amount of floatable debris around the outfall changed?

  - → No apparent changes in water clarity have been noted in the nearfield
  - → Anthropogenic debris continues to be collected in the net tows, but there has not been a noticeable change in the materials collected nor in the quantity of debris
  - → Increase in presence and abundance of *Thalassionema nitzschoides* in the tows. This phytoplankton species is ubiquitous, but usually at low abundance. Increase likely related to artificial physical conditions at the outfall site similar to upwelling regimes where this species thrives.
  - → Small grease-like balls of material have been observed during majority of the post-diversion net tows. This material consists of grease, unidentified algae and a variety of different bacteria. The bacteria were not types usually associated with sewage and secondary treatment.

  - ➢ The availability of baseline data on floatable debris is limited to 1999/2000 and is not quantitative. Thus, these monitoring questions cannot be definitively addressed. Although further sampling of debris in the vicinity of the outfall will serve to document appearance of any major change in floatable debris, the data to date have not shown a substantial increase in outfall related material and this aspect of the monitoring program could be dropped.

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, NO_3 and PO_4 in Boston Harbor.
  - → Dissolved inorganic nutrients (except SiO_4) have exhibited increases throughout Massachusetts and Cape Cod Bays at most stations. Significant increases in NH_4 were noted during each season in the nearfield and Broad Sound. Significant increases in NO_3 and PO_4 concentrations were also noted at nearfield and Broad Sound stations during the summer and fall.
  - → These increases are due to both the direct input of nutrients to the nearfield by the bay outfall and by an apparent regional increase in ambient concentrations (as evidenced by the significant increase in NO_3 at northern boundary stations F26 and F27).
  - → 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.

- ➢ Need to distinguish between localized and regional contributions to changes in nutrient concentrations.

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?

  - → 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), but not as quickly as first thought.
  - → Seasonal and annual mean chlorophyll levels have increased in the nearfield, but not significantly.
  - → Winter/spring phytoplankton biomass concentrations have increased post-diversion throughout most of the monitoring area. Likely due to the consistent occurrence of *Phaeocystis* blooms since 2000.
  - → Station specific increases in chlorophyll levels have been observed during the winter/spring period in the nearfield and nearby stations in the harbor (F23), coastal (F24 and F13), and offshore (F06, F07, and F10) areas.
  - → Major winter/spring and fall blooms consistently appear to be regional phenomena.

  - ➢ Given the high variability in phytoplankton biomass seasonally and interannually, additional, and perhaps more focused, monitoring will be required before the extent of the changes can be determined in the nearfield (significant increase vs. changes within the noise).
  - ➢ Although there is no clear indication that the winter/spring increases in biomass are related to the outfall, the location of the stations with significant increases is focused on the nearfield and vicinity – especially the nearby ‘downstream’ stations in southern Massachusetts Bay.
  - ➢ 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. Innovative approaches and new technologies may provide a mechanism to address these more subtle impacts.

- 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 significantly (~40%) in Boston Harbor on an annual basis though they appear to have increased during the winter/spring bloom.
  - → 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, but this change is not as pronounced as was indicated by the first few years of post-diversion data.
  - → There have been no clear changes in primary production in the nearfield.

  - ➢ 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 three 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, 2003 and 2004 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 *Phaeocystis* biomass increases.
  - → There have been no substantial blooms of other nuisance species (*Alexandrium*, *Pseudo-nitzschia*, etc.) since the outfall went online.
  - → Dramatic 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).
  - → Decreases in zooplankton abundance post-diversion have been noted and appear to be correlated with occurrence of *Phaeocystis* blooms in the spring and presence of ctenophores in the fall.

  - ➢ The occurrence and duration of the *Phaeocystis* blooms will continue to be the focus of study and will be examined in detail in the 2005 Nutrient Issues Review. The changes in these blooms 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. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with significant decreases in chlorophyll and POC, lower production, and an ongoing change in the seasonal productivity from a eutrophic to more normal temperate coastal pattern. Although the effluent plume is consistently observed in the nearfield, detectable levels are confined to an area within about 20 km of the outfall. There are no indications that the higher nearfield NH_4 concentrations have translated into significant changes in biomass, whether measured as chlorophyll, POC, or phytoplankton abundance, although there appear to have been increases in winter/spring and fall bloom biomass in the nearfield and subtle plankton community changes.

The MWRA HOM monitoring program may be at a nexus in which the focus of the program needs to be reevaluated. Substantial changes in the ecosystem have not resulted from the transfer of the effluent discharge from Boston Harbor to Massachusetts Bay. However, there have been a number of minor or more subtle changes that have been observed. To understand if and how the bay outfall may be contributing to these subtle changes will likely require a new measurement focus to address key ecological and biological process factors. However, given the lack of substantive adverse impact from the outfall relocation, it is unclear what agency(ies) has responsibility to support the necessary studies. Is it the MWRA's monitoring responsibility or a research oriented endeavor? It is anticipated the MWRA will revisit the monitoring program in 2006 and seek to modify the program based on continued gains in the understanding of the ecosystem and to meet current regulatory requirements. During this process, these responsibility issues will need to be addressed and a decision made as to whether it is necessary to augment or revise the current monitoring approach to examine and understand the observed subtle impacts or if the program should focus only on regulatory/permit criteria.

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LINK TO APPENDICES

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