Water Column Monitoring in Massachusetts Bay: 1992-2006

Massachusetts Water Resources Authority

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Water Column Monitoring in Massachusetts Bay: 1992-2006

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) has collected ambient water quality data in Massachusetts and Cape Cod Bays since 1992 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 2006 data represent the sixth full year of conditions since initiation of discharge from the bay outfall. This annual report evaluates the 2006 water column monitoring results, assesses spatial and temporal patterns in the data, compares 2006 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 ambient monitoring program, a general sequence of water quality events has emerged from the data collected in Massachusetts and Cape Cod Bays. The patterns 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 to terminate the spring bloom. The summer is generally a period of strong stratification, depleted surface water nutrients, low biomass, and a relatively stable mixed-assemblage phytoplankton community. In the fall, stratification deteriorates and mixing 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. In winter, the combination of wind mixing and low light levels serve to inhibit primary production thus keeping biomass and phytoplankton abundance low until the following year's winter/spring bloom. This sequence has continued since the bay outfall became operational on September 6, 2000 and was generally evident in 2006.

For 2006, the major features and differences from the baseline include:

- 2006 was generally wetter than normal, most notably during May and June. Merrimack River flow was at near-record levels in mid-May and it was the highest it has been for the entire monitoring program (1992-2006). The May rain/river flow event caused severe flooding in NH and northeastern Massachusetts.
- The high river discharge and accompanying wind events during the spring were the most notable physical attributes in 2006. The occurrence of strong northeaster storms in April and early May produced lower salinities due to high river inputs to the coastal waters and higher stratification than usual.
- These meteorological and physical oceanographic conditions contributed to the occurrence of the most notable biological event in 2006 – a bloom of the toxic dinoflagellate *Alexandrium fundyense* in Massachusetts and Cape Cod Bays. The lack of persistent winds out of the north and northeast later in May and into June likely helped keep the 2006 bloom from reaching levels of abundance and toxicity seen in 2005.
- The 2006 *A. fundyense* bloom was not as severe as the unprecedented 2005 bloom, but was the second largest red tide episode in Massachusetts Bay since 1972. The bloom extended

from Maine to the waters off Massachusetts, and prompted shellfish closures from Maine south to the Marshfield/Duxbury line. This was not as extensive as in 2005 when closures occurred as far south as Martha's Vineyard.

- Typical concentrations of *A. fundyense* in most years are a few tens of cells L^{-1}, but in 2006, many samples had counts of >1,000 cells L^{-1}, with maximum counts in Massachusetts Bay of ~10,000 cells L^{-1}. Overall, levels were about 25% of those observed in 2005, but well above abundances seen in 1972-2004. Levels in the nearfield in 2006 easily exceeded the Contingency Plan threshold of 100 cells L^{-1}.
- A *Phaeocystis* bloom was observed for the seventh consecutive year. The bloom was observed from March to April with maximum abundances observed in April ($1\text{-}10 \times 10^6$ cells L^{-1}). There was a clear inshore to offshore increase in abundance with the highest abundances at stations F26 and F27 just south of Cape Ann. The phytoplankton and ancillary data suggest that the 2006 *Phaeocystis* bloom was transported into the bay from the Gulf of Maine.
- In May, *Phaeocystis* was observed in three samples collected in the nearfield (up to 220,000 cells L^{-1}), but it made up a relatively minor portion of the total phytoplankton community (0-16%). The presence of *Phaeocystis* in May nearfield samples resulted in an exceedance of the summer threshold. The May 2006 extended duration of the *Phaeocystis* bloom may have been related to the relatively cool water temperatures in May/June 2006. This is consistent with the inverse relationship between bloom duration and surface water temperatures observed in other years.
- Nutrient patterns generally followed typical seasonal progressions. The main exception was due to the strong summer upwelling conditions. July 2006 was one of the most strongly upwelling favorable periods of the monitoring program. This physical feature allowed nutrient replete waters to rise higher in the water column where light was not limiting phytoplankton production. This doming of bottom waters was evident in nearfield SiO_4, NO_3+NO_2 and NH_4 concentrations.
- High fluorescence levels were coincident with the elevated nutrient concentrations in July 2006. The upwelling of the nutrient rich waters fueled a moderately large summer diatom bloom dominated by *Dactyliosolen fragilissimus* in July. During the bloom, nearfield areal chlorophyll levels peaked at ~200 mg m^{-2} resulting in the summer chlorophyll threshold exceedance. POC concentrations reached maximum levels for 2006 with a nearfield mean of 63 μM.
- Satellite imagery suggests that scale of the July bloom was larger than the nearfield. Locally, in the nearfield, there may have been some additional stimulation of the bloom by the outfall in proportion to the contribution of the outfall to nutrient concentrations below the pycnocline (perhaps 10-50%). A large phytoplankton bloom can lead to lowered dissolved oxygen, but oxygen levels in water and sediment were normal in 2006 following the bloom.
- At nearfield stations and in the harbor, areal production for 2006 was less than the long-term average for almost all data points, except for the spring when productivity exceeded the baseline mean (stations N04 and N18). At the Boston Harbor station, productivity in 2006 generally fell well below the baseline mean with no spring bloom and a seasonal maximum in August.
- There has been a statistically significant decrease in post-transfer summer and annual primary production in the harbor. However, the apparent change in the seasonal productivity pattern seen in 2001-2003 from a high summer, eutrophic pattern to a pattern dominated by

spring and fall blooms like the waters of Massachusetts Bay was absent in 2006 as it has been since 2004. Overall, the decline in productivity measured at the harbor station indicates a shift to a less-enriched environment

- Only minor changes in seasonal and annual production have been observed in the nearfield between pre- and post-transfer periods. Mean production values have increased slightly for spring while decreasing somewhat in the summer, fall and annually, but none of these changes is statistically significant.
- Statistically significant increases were documented in phytoplankton biomass in surface waters during the spring bloom period at the nearfield stations. Biomass was significantly related to spring peak production. Significant differences were also observed in pre- and post-diversion nutrient concentrations (NH_4 and DIN) over the bloom period as well as in the reduction of these nutrients pre- and post-bloom. A variable but significant relationship exists between the peak spring productivity in the surface water and the change in surface nitrogen concentration over the bloom period.
- Total zooplankton abundance was lower than typically observed over the baseline during much of 2006. Zooplankton community structure and seasonal abundance patterns during 2006 were similar to previous years. As in past years, zooplankton abundance was dominated by copepod nauplii, and adults and copepodites of *Oithona similis* and *Pseudocalanus* spp., with subdominant contributions by other copepods and sporadic pulses of meroplankters.
- Dissolved oxygen levels were relatively low in the nearfield bottom waters from April to August (close to baseline minima). Reventilation in September prevented DO levels from falling well below threshold levels in fall 2006.
- The 2006 nearfield DO minima ranked in the lower half of values measured during the monitoring program. In Stellwagen Basin, DO levels reached the lowest levels for the post-discharge period. The Stellwagen Basin stations are deeper than the nearfield and likely less affected by the September reventilation conditions. The low 2006 DO minimum in Stellwagen Basin was the second lowest recorded by the MWRA program (1999 had the lowest value).

In addition to these 2006 events, there are other observations that continued to fit ongoing patterns of interests. For instance, the observed changes in the nutrient regimes following effluent diversion are unambiguous – NH_4 has dramatically decreased in Boston Harbor (by ~80%) and nearby coastal waters while increasing in the nearfield (by ~50%). The consistently elevated NH_4 signature in the plume is generally confined to an area within ~20 km of the outfall. The plume signature was not different than observed in prior years. Moreover, 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 in the nearfield and most of Massachusetts Bay. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with significant decreases in other nutrients (NO_3 and PO_4), chlorophyll, POC and lower production. These results are consistent with findings of other studies (Taylor 2006). However, significant changes in levels and temporal patterns have also occurred for other parameters throughout most areas of the bays. Many of these changes have been noted on both a station-by-station and grouped station basis. There are also regional patterns evident in the nutrient data such as an increase in fall NO_3 concentrations throughout Massachusetts and Cape Cod Bays.

Comparison of phytoplankton abundance levels prior to and after the September 2000 offshore outfall diversion indicated no significant changes in total phytoplankton. However, statistically significant changes in the abundance levels of some key phytoplankton functional groups were detected, with declines noted for total diatoms in most regions and declines in dinoflagellates in the coastal, nearfield and offshore regions. These pre-post diversion comparisons have likely identified long-term trends in some species that are only coincidental, not causal, with the offshore effluent diversion. For example, time series analysis showed that diatom abundance in the nearfield displayed cyclical behavior during 1992-2006 with relative peaks in 1994, 1998 and 2002 and a long-term decline since 1998. The diatom trend was negatively correlated with the long-term *Phaeocystis* trend suggesting some interaction between the long-term behavior of these components of the phytoplankton community during the winter-spring period. Multivariate analysis suggested that the phytoplankton flora of the MWRA monitoring area are spatially (within depth and the six regions examined) similar, with minor seasonal (winter vs. summer) differences and no dramatic long-term change in community structure evident. The statistical analyses also indicate that interpretation of 1992-2006 long-term changes in MWRA phytoplankton may be complicated by methodological differences in phytoplankton assessment during three distinct periods (1992-1994, 1995-1997, 1998-2006).

Pre-post September 2000 statistical comparisons and time series analyses of the main zooplankton groups suggest long term declines in total and many zooplankton species abundance. Total zooplankton, copepods and copepod nauplii have all declined since 2000, and *Oithona* spp. has declined since 1997. Only *Calanus finmarchicus* has displayed long-term increases with a 2- to 3-fold increase in Cape Cod Bay and the offshore region since 2000. The changes in zooplankton abundance could also be related to a variety of factors from physical hemispheric processes (i.e. NAO), to bottom-up control via *Phaeocystis* blooms in the spring (poor food source) or lack of substantial fall blooms (reduced food source), to top-down controls due to grazing by ctenophores or other predators. 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.

Although the significant changes in NH_4 concentrations in the nearfield can plausibly 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 (or other parameters) are due to different loadings to the system (riverine, offshore Gulf of Maine surface or bottom waters, etc.), changes in seasonal biological patterns (i.e. fewer and less intense fall blooms) or related to more circulation shifts related to larger scale processes (e.g. North Atlantic Oscillation).

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1.0 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) is conducting a long-term ambient monitoring program in Massachusetts and Cape Cod Bays. The objectives of the 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 monitoring plans developed for the baseline and post-transfer periods (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-transfer data (MWRA 2003). The five surveys dropped were those previously conducted in May (WN0X5), July (WN0X8), August (WN0XA), November (WN0XG), and December (WN0XH). The 2006 data represent the third year of monitoring under the revised program and the sixth 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	Secondary treatment begins to be phased in
July 9, 1998	Nut Island discharges ceased: south system flows transferred to Deer Island – almost all flows receive secondary treatment
September 6, 2000	New outfall diffuser system on-line
March 2001	Upgrade to secondary treatment completed
October 2004	Upgrades to secondary facilities (clarifiers, oxygen generation)
April 2005	Sludge line from Deer Island to Fore River completed and operational

The 2006 water column monitoring data have been reported in a series of survey reports and data reports. The purpose of this annual report is to compile the 2006 results in the context of the seasonal patterns and the annual cycle of ecological events in Massachusetts and Cape Cod Bays. The data are 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 major seasonal patterns on a regional scale and allows for a more thorough characterization of patterns in the nearfield area.

The 2006 data are also compared to previous baseline monitoring data to characterize patterns or departure from patterns that may be related to discharge from the bay outfall. The post-diversion data from September 6, 2000 to November 2006 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. 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?

A detailed examination of 2006 results and interannual patterns in physical, chemical and biological parameters is presented in the appendices: 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). The report includes an overview of the major findings from the 2006 water column data, comparisons of 2006 data against the established Contingency Plan (MWRA 2001) thresholds, the *A. fundyense* bloom of 2006, and integration and comparisons of baseline and post-transfer data including a statistical analysis of baseline to post-transfer changes. The final section summarizes these discussions and presents an overview of the current understanding of the system.

2.0 2006 WATER COLUMN MONITORING PROGRAM

This section summarizes the design of the 2006 ambient water quality monitoring 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: 2006-2007 (Libby *et al*. 2006c). Details on any deviations from the methods outlined in the CW/QAPP have been provided in individual survey 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 2006 water column surveys have been submitted to MWRA and subsequently reported in data reports. Additional data pertaining to the *A. fundyense* bloom were obtained from MWRA *Alexandrium* Rapid Response surveys (ARRS), Boston Harbor Water Quality Monitoring surveys (BHWQM; Rex and Taylor 2000), Woods Hole Oceanographic Institute (WHOI) cruises, and Center for Coastal Studies (CCS) surveys. Shellfish toxicity data were obtained from the Massachusetts Division of Marine Fisheries (MA DMF).

2.2 2006 Water Column Monitoring Program Overview

This annual report summarizes and evaluates water column monitoring results from the 12 water column surveys conducted in 2006 (**Table** 2-1). The water column parameters measured and presented in this report are listed in **Table** 2-2. 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 seven nearfield stations were sampled during each of the 12 surveys and are located in a grid pattern covering an area of approximately 110 km^2 centered on the MWRA bay outfall (**Figure** 2-1). The 27 farfield stations were sampled during the six combined farfield/nearfield surveys and 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 Gulf of Maine Ocean Observing System (GoMOOS) and USGS moorings (not operating in 2006) are also shown in **Figure** 2-1.

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.* 2006c).

The data are also grouped by season for comparisons of biological and nutrient data and also for calculation of chlorophyll and nuisance algae Contingency Plan thresholds. 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. Note that for the interannual comparisons including the intervention regression analysis in Section 4.2, December data are not used as those surveys were dropped from the ambient water quality monitoring program in 2004.

An additional 16 surveys were conducted in Massachusetts and Cape Cod Bays by MWRA and other research groups in response to the 2006 *Alexandrium* bloom (**Table** 2-1). Sampling procedures, station locations and preliminary results are provided in the ARRS survey report and on the internet (WHOI[1]). Samples were collected for *Alexandrium* probe analysis during all 16 of these surveys and during surveys WN066 and WF067, which were modified to focus on the bloom.

Table 2-1. Water quality surveys for 2006. Regular ambient monitoring surveys in bold and nearfield day of combined surveys is underlined.

Survey	Type of Survey	Survey Dates
WF061	**Nearfield/Farfield**	**February 10-11, 13**
WF062	**Nearfield/Farfield**	**February 28, March 1-2**
WN063	**Nearfield**	**March 22**
WF064	**Nearfield/Farfield**	**April 11-12, 14**
TI171	WHOI	April 11-12
TI177	WHOI	April 25-26
TI180	WHOI	May 11
WN066	**Nearfield**	**May 17**
BH1	BHWQM	May 17
TI181	WHOI	May 17-18
AF061	ARRS	May 24
TI184	WHOI	May 24-25
TI185	WHOI	May 31, June 1
AF062	ARRS	June 1
AF063	ARRS	June 6
CCS1	CCS	June 7
OC425 Leg1	WHOI	June 7-8
AF064	ARRS	June 13
OC425 Leg2	WHOI	June 15-16
CCS2	CCS	June 16
WF067	**Nearfield/Farfield**	**June 19, 20, 21**
TI191	WHOI	June 29-30
WN069	**Nearfield**	**July 19**
WF06B	**Nearfield/Farfield**	**August 21, 22, 23, 24**
WN06C	**Nearfield**	**September 5**
WN06D	**Nearfield**	**October 3**
WF06E	**Nearfield/Farfield**	**October 23-24, 27, 31**
WN06F	**Nearfield**	**November 18**

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[1] http://science.whoi.edu/users/olga/alex_surveys_2006/WHOI_Alexandrium_Surveys_2006.html

Table 2-2. Water column measurements.

Measurement Type	*In Situ* Parameter	Laboratory Analysis
Physical Characterization	temperature, salinity, dissolved oxygen	dissolved oxygen (DO)
Nutrients	colored dissolved organic matter (CDOM)	dissolved inorganic nitrogen (DIN = NH_4 + NO_3 + NO_2) ammonium (NH_4) nitrate (NO_3) nitrite (NO_2) phosphate (PO_4) silicate ($SiO_{4)}$
Phytoplankton Biomass	fluorescence	chlorophyll particulate organic carbon (POC)
Productivity		primary productivity
Plankton Community Structure		taxonomy and abundance of phytoplankton taxonomy and abundance of zooplankton.

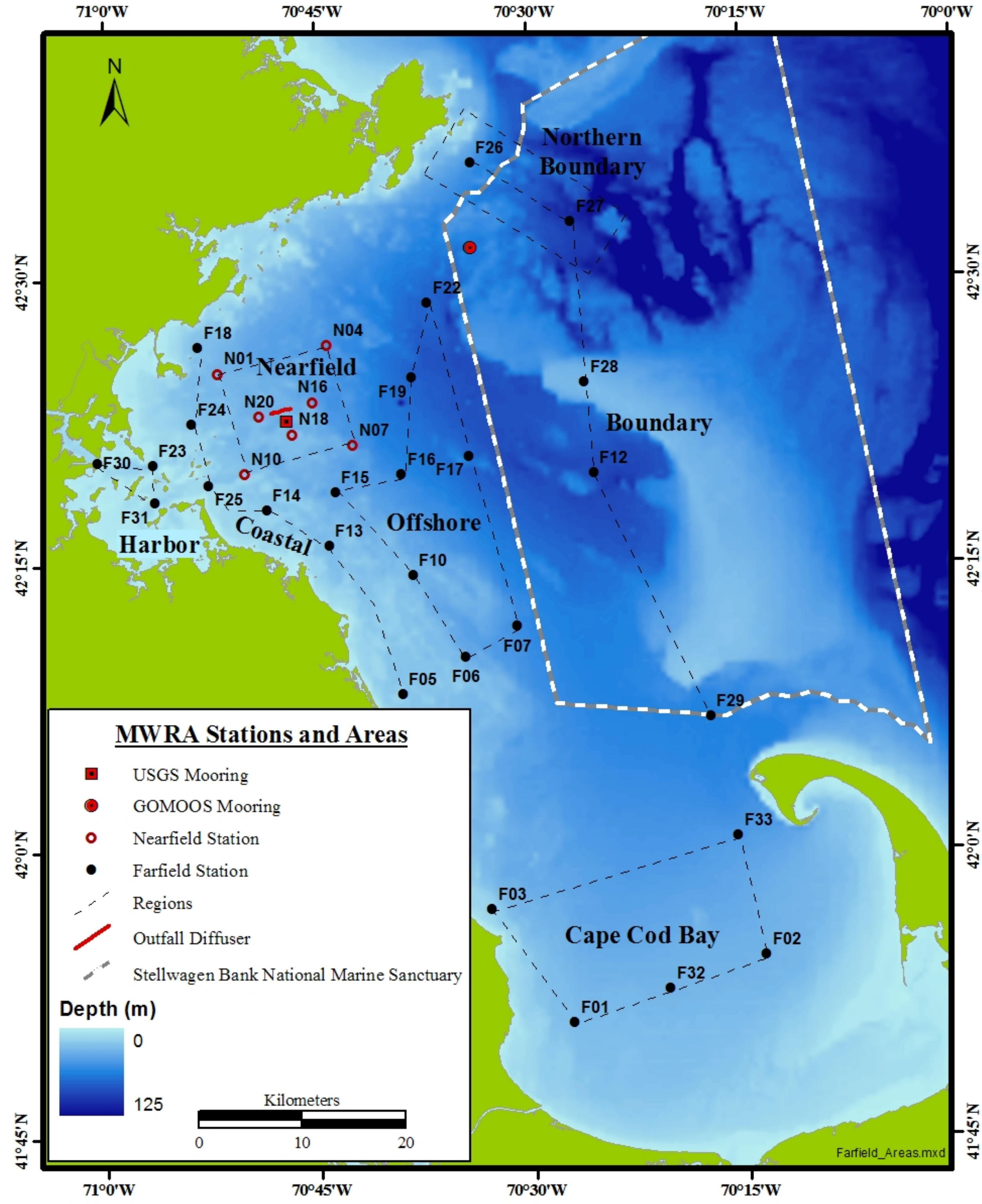


Figure 2-1. Locations of nearfield and farfield stations and regional station groupings, MWRA outfall, and USGS and GoMOOS moorings.

3.0 2006 MONITORING RESULTS AND DISCUSSION

The major water quality features and differences from the baseline in 2006 are summarized in this section. Details on the physical, chemical and biological data collected in 2006 can be found in Appendices A-D. Overall, water quality conditions in 2006 were quite similar to those observed in 2005 with very stormy springs (high winds and record precipitation/river flow) and spring blooms of the nuisance species *Phaeocystis* and red tide species *Alexandrium*. In 2006, a few differences were noted compared to previous post-diversion years with an atypical July diatom bloom and a relatively substantial fall diatom bloom observed in the nearfield in early October. The July bloom resulted in high chlorophyll levels that contributed to a summer chlorophyll threshold exceedance. Bottom water dissolved oxygen was relatively low in 2006 compared to previous years, but reventilation events in September ameliorated conditions and prevented bottom water DO levels from exceeding contingency plan thresholds.

3.1 Physical Characterization

River discharge influences salinity, stratification, and strength of the coastal circulation. 2006 was a wet year, like 2005, with near-record discharge on the Merrimack River (May 15, 2006; **Figure** 3-1) and it was the largest spring discharge on the Merrimack for the entire measurement period. The Charles River was wetter than normal, but not to the extreme extent of the Merrimack River. Although the flood of May 15 was devastating to the riparian towns in the lower Merrimack Valley, it only had a minor influence on currents in Massachusetts Bay, unlike the major event in 2005. This is apparently related to the timing of the winds relative to the freshwater inflow.

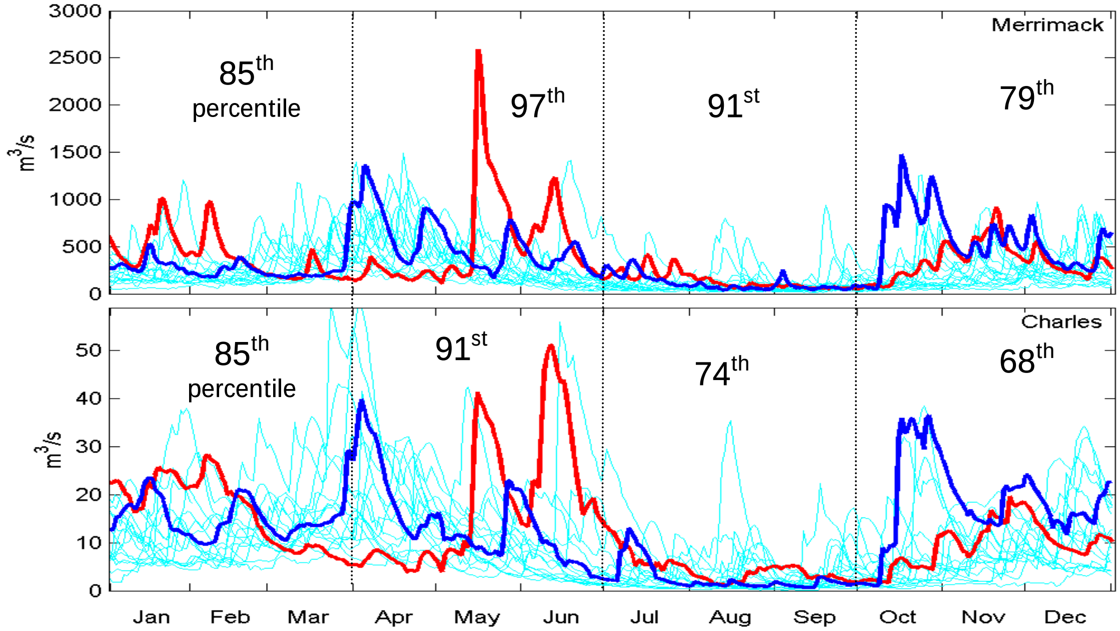


Figure 3-1. Comparison of the 2006 discharge of the Merrimack and Charles Rivers (red curve) with the observations of the past 16 years (2005 in bold dark blue and rest in light blue lines).

The most important aspect of the wind forcing in Massachusetts Bay is the average north-south component of wind stress, which determines the preponderance of upwelling or downwelling conditions. May is normally a transitional period between winter downwelling and summer upwelling favorable conditions, and so the net north-south wind stress is typically close to zero. In 2006, there was strong downwelling during the month of May, although not as strong as 2005 (**Figure** 3-2). The spring downwelling was associated with several late-season northeaster storms. As in 2005, they influenced the inflow from the Gulf of Maine importing fresh water and potentially harmful algal blooms from the Gulf of Maine (Anderson *et al.* 2005a).

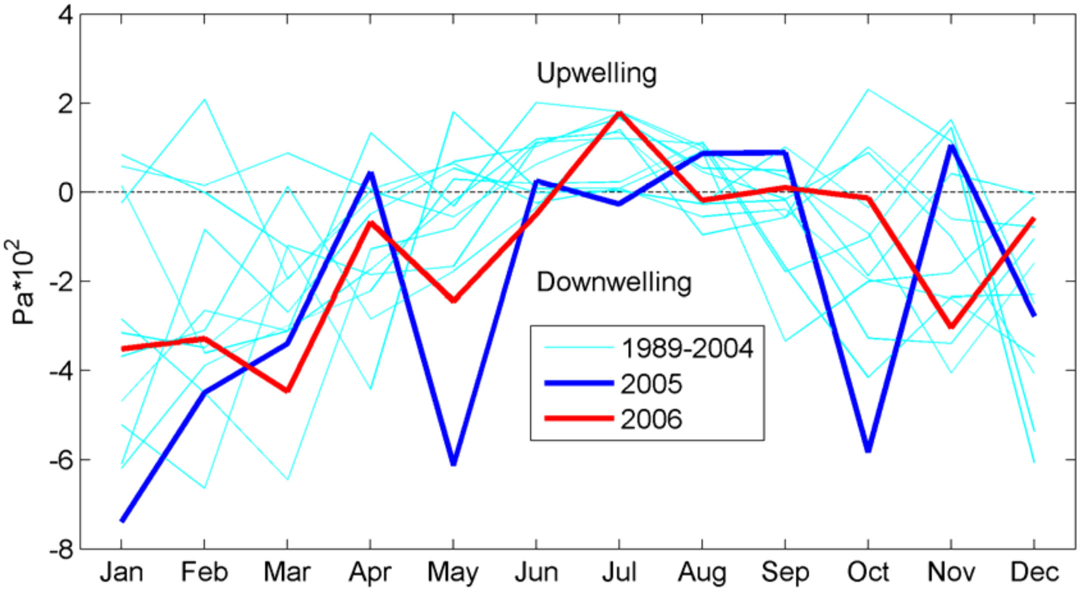


Figure 3-2. Monthly average N-S wind stress at Boston Buoy for 2005 (blue) and 2006 (red) compared with the previous 11 years of observations (1994-2004; light blue). Positive values indicate northward-directed, upwelling-favorable wind stress.

The oceanographic response of Massachusetts Bay to the anomalous wind forcing in May is evident in salinity, temperature and current data. In both 2005 and 2006, the salinities were significantly lower than average, due to the high river discharge levels. The 2006 conditions differed from 2005 in that the salinity anomaly was mostly confined to the surface waters, whereas it showed up strongly in both bottom and surface waters in 2005. This difference is probably related to the timing of freshwater flow events relative to the timing of northeaster storms. During 2005, one major wind event occurred around May 23 in combination with a peak in river outflow, and there was deep mixing of the fresh water (Libby *et al.* 2006b). In 2006, the very large discharge event around May 15 occurred with nearly easterly winds (**Figure** 3-3), which did not result in large currents at GoMOOS-A. This is probably because the winds were more perpendicular than parallel to the coast, so the Merrimack River plume was not being accelerated down-coast by the winds during that event. Thus, the particular conditions that caused the deep mixing in 2005 did not occur in conjunction with the strong river outflow in 2006.

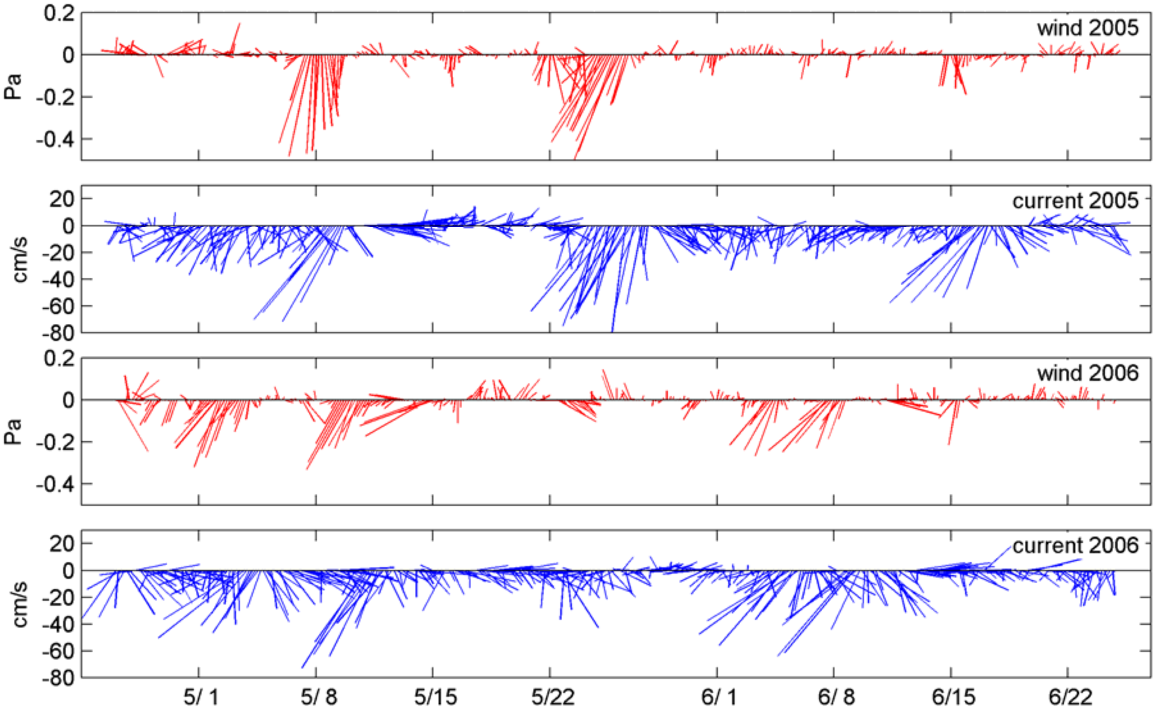


Figure 3-3. North-South wind stress (at the Boston Buoy) and near-surface currents at the GOMOOS-A buoy during May and June of 2005 and 2006.

The low surface salinity during the spring caused stronger than average stratification in May and June 2006, as shown in **Figure** 3-4. The stratification was approximately 50% stronger than normal during May and June 2006, due to the increased freshwater inflow. The stratification was weaker than normal during July and August, likely due to the prevalence of upwelling conditions in July (**Figure** 3-2).

The upwelling favorable wind conditions in July 2006 pushed surface waters offshore and deeper, cooler waters rose to the surface as shown in satellite imagery of sea surface temperature (SST, **Figure** 3-5). The SST image for July 14, 2006 shows lower temperatures in coastal waters near Cape Ann, in western Massachusetts Bay, and just north of Cape Cod Bay. **Figure** 3-5b shows that those temperatures averaged over an 8-day period were cool compared to normal for this time of year suggesting that at least over the period of the climatology used (1985-present) that upwelling is not as consistent an event as suggested by our analysis of monthly mean wind data. Although upwelling favorable conditions have occurred over most months of the monitoring program, they typically dominate during the summer months from June to August with July having the most consistently upwelling favorable conditions (**Figure** 3-2). Relatively strong upwelling conditions (>1 Pa$\times10^2$) have been observed in July during 8 of the 13 years since 1994. Five of these occurred during the baseline period (1994, 1995, 1996, 1998, and 1999) and three since the bay outfall became operational (2001, 2003, and 2006). An examination of the wind data at higher resolution may provide a better indication of the frequency of upwelling conducive wind events in western Massachusetts Bay. In addition to bringing cooler waters to the surface, the upwelling also provided an additional nutrient supply to the euphotic zone to support the summer diatom bloom that was observed (see Section 3.2).

Stratification in the nearfield decreased from early September to late October due to the seasonal increase in vertical mixing. In late October, the farfield survey (WF06E) was interrupted by a series of storms. The mixing associated with the storms resulted in a sharp decrease in stratification (**Figure** 3-4;

station N16 was sampled on October 27th and 31st and the two points in this figure for late October are indicative of the change in nearfield stratification over the course of these 4 days) and an increase in bottom water DO (**Figure** 3-6; nearfield stations sampled on October 31st after the storm events).

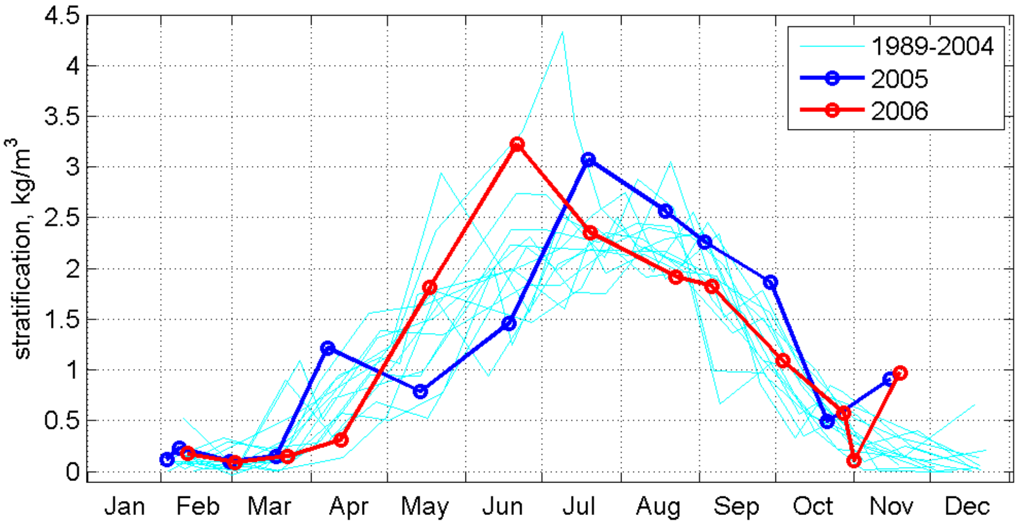


Figure 3-4. Stratification near the outfall site (mean of nearfield stations N16, N18 and N20) for 2005 (blue) and 2006 (red) compared with the previous 13 years of observations (1992-2004; light blue).

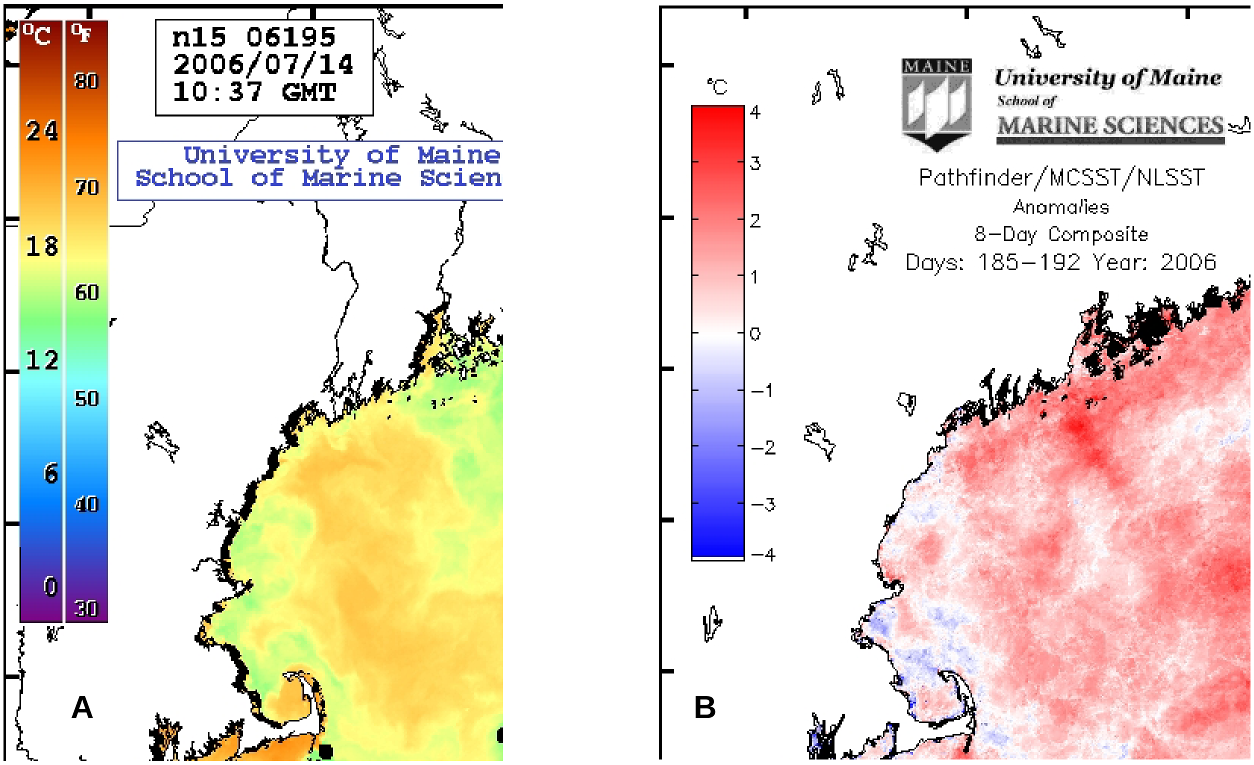


Figure 3-5. A. Sea surface temperature (SST) for July 14, 2006. B. SST 8-day composite anomaly for July 4-11, 2006. (Images obtained from http://wavy.umeoce.maine.edu/)

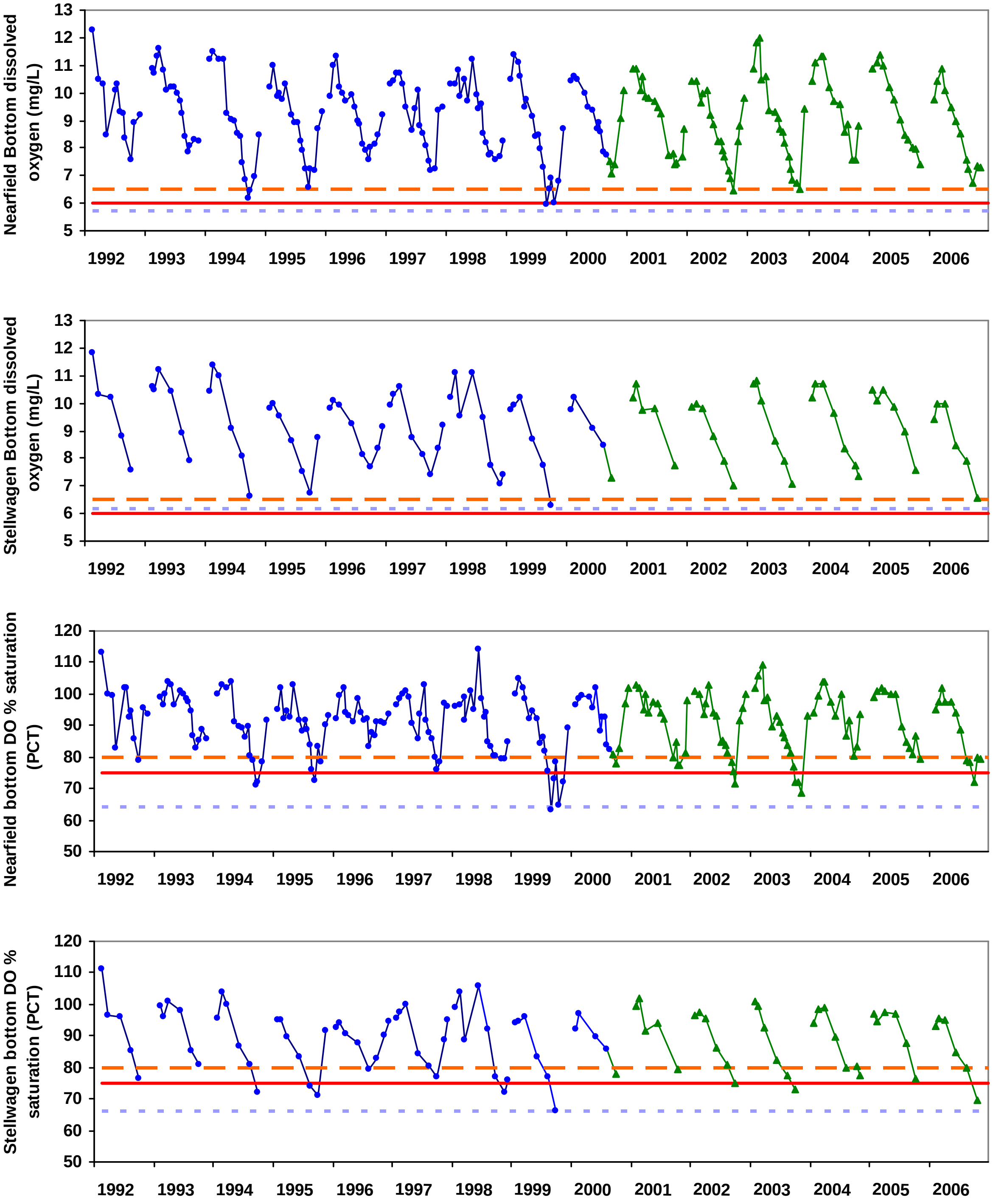


Figure 3-6. Survey mean bottom water dissolved oxygen concentration (mg L^{-1}) and percent saturation in the nearfield and Stellwagen Basin (as labeled) compared to contingency threshold levels (Caution level = orange hyphen line, warning level = solid red line, and background = blue dotted line). Baseline data in blue circles and post-transfer data in green triangles. Data for Stellwagen Basin collected from stations F12, F17, F19, and F22.

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

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2006
Bottom Water DO concentration	Survey Mean in June-October	<6.5 mg L^{-1} (unless background lower)	<6.0 mg L^{-1} (unless background lower)	Nearfield: 5.75 mg L^{-1} SW Basin: 6.2 mg L^{-1}	Nearfield: 6.76 mg L^{-1} SW Basin: 6.56 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: 72.1% SW Basin: 69.5%
Bottom Water DO Rate of Decline (Nearfield)	Seasonal June-October	0.037 mg L^{-1} d^{-1}	0.049 mg L^{-1} d^{-1}	0.024 mg L^{-1} d^{-1}	0.015 mg L^{-1} d^{-1}
Chlorophyll	Annual	118 mg m^{-2}	158 mg m^{-2}	79 mg m^{-2}	104 mg m^{-2}
	Winter/spring	238 mg m^{-2}	--	62 mg m^{-2}	129 mg m^{-2}
	Summer	93 mg m^{-2}	--	51 mg m^{-2}	*97 mg m^{-2}
	Autumn	212 mg m^{-2}	--	97 mg m^{-2}	94 mg m^{-2}
Phaeocystis pouchetii	Winter/spring	2,020,000 cells L^{-1}	--	468,000 cells L^{-1}	383,000 cells L^{-1}
	Summer	357 cells L^{-1}	--	72 cells L^{-1}	18,000 cells L^{-1}
	Autumn	2,540 cells L^{-1}	--	317 cells L^{-1}	Absent
Pseudo-nitzschia pungens	Winter/spring	21,000 cells L^{-1}	--	6,200 cells L^{-1}	Absent
	Summer	43,100 cells L^{-1}	--	14,600 cells L^{-1}	Absent
	Autumn	24,700 cells L^{-1}	--	9,940 cells L^{-1}	222 cells L^{-1}
Alexandrium fundyense	Any nearfield sample	100 cells L^{-1}	--	Baseline Maximum = 163 cells L^{-1}	5,667 cells L^{-1}

* The summer average chlorophyll value of 97 mg m^{-2} listed in this table was based on chlorophyll calibrated improperly. The error was discovered after MWRA released a notification of exceedance. Using the correct values, the summer average is 89 mg m^{-2}; although this is below the threshold of 93 mg m^{-2}, it is not very different and is still unusually high, so MWRA will continue to treat this as an exceedance. Chart and tables in the remainder of this report uses the correctly-calibrated chlorophyll and the corresponding summer average of 89 mg m^{-2}.

Since the bay outfall came on line, there has been little change in the annual DO cycle in the nearfield and Stellwagen Basin and 2006 was no exception (**Figure** 3-6). Unlike the previous two years, however, when bottom water minima in the nearfield were among the highest seen over the monitoring program, bottom water DO levels in the nearfield were relatively low in 2006. DO concentrations in the nearfield did not go below the 6.5 mg L^{-1} warning threshold, but the annual minimum was the sixth lowest for the program (after 1999, 1994, 2002, 2003, and 1995; **Figure** 3-6). DO %saturation values in the nearfield dropped below the 80% caution threshold in August, reached a minimum of 72.1% in early October, and remained below or near 80% for the remainder of the fall. Likewise in Stellwagen Basin, DO concentration minima remained just above the caution level of 6.5 mg L^{-1}, but reached a DO %saturation minimum of 69.5%, which is below the 75% warning threshold (**Figure** 3-6**; Table** 3-1). The deeper, cooler waters in Stellwagen Basin were likely not reventilated in September to the same extent as the shallower nearfield bottom waters and achieved lower DO levels. The DO %saturation minimum in Stellwagen Basin was the second lowest observed during the monitoring program (66% in 1999).

In addition to DO bottom water levels, there are contingency plan thresholds (MWRA 2001) for annual and seasonal chlorophyll levels in the nearfield and various nuisance algae (*Phaeocystis pouchetii*, *Pseudo-nitzschia pungens* and *Alexandrium fundyense* in the nearfield; **Table** 3-1). 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. In 2006, there were exceedances of the summer chlorophyll, the summer *Phaeocystis*, and the *Alexandrium* thresholds – each of these are discussed within the context of the overall summary of 2006 results in the text that follows.

3.2 Nutrients and Phytoplankton Biomass

The nutrient data for 2006 generally followed the typical progression of seasonal events in Massachusetts and Cape Cod Bays. The seasonal patterns in nutrient concentrations are closely linked with both physical and biological factors. Physical mixing or stratification combined with biological utilization and remineralization act to increase or decrease the concentrations of nutrients over the course of each year. Nutrient concentrations are high in the winter when consumption is low and mixing is thorough; concentrations decrease in the surface waters during the winter/spring bloom due to consumption by phytoplankton, while the onset of stratification cuts off the supply of nutrients from deeper waters; as stratification strengthens nutrients are generally depleted in surface waters and increase at depth in the summer; nutrients then return to elevated levels in the surface waters following the fall bloom and mixing of the water column. These cycles have been observed year-in and year-out to varying degrees (e.g. Libby *et al.* 2006b). Details on the nutrient levels and patterns are provided in Appendix B and summarized in this section.

Consistent with the above scenario, the highest nutrient concentrations were observed in early February when the water column was well mixed and biological uptake of nutrients was limited (**Figure** 3-7). The lowest nutrient concentrations at that time were observed in Cape Cod Bay, where an early winter/spring bloom of the diatom *Guinardia delicatula* was observed. By late February, NO_3 and SiO_4 were more consistent across the geographic regions as winter storm induced mixing continued and apparent rates of biological nutrient utilization changed. Areas with more moderate concentrations (coastal, offshore, boundary) showed little change from earlier in the month. The nearfield and Boston Harbor areas which were slightly elevated in early February showed declines in nutrient concentrations and became more similar to the other areas by late in the month. The opposite was true in Cape Cod Bay, where concentration increased slightly, but remained lower than the other regions. Overall, the late February nutrient values were fairly high compared to previous years.

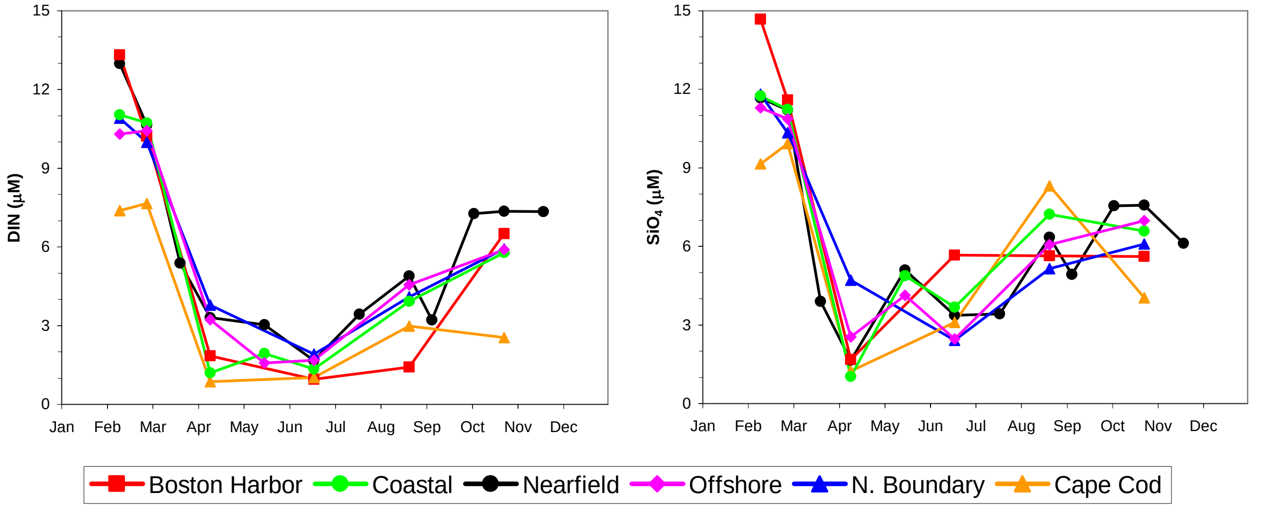
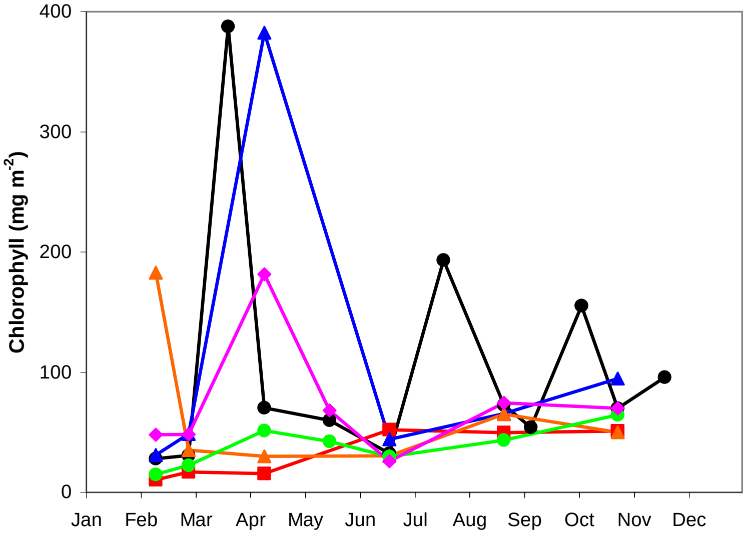


Figure 3-7. Time-series of survey mean DIN and SiO$_4$ concentrations in Massachusetts and Cape Cod Bays. Mean of concentrations over depths and stations within each region in 2006.

This changed rapidly as the winter/spring diatom bloom consumed PO_4, NO_3, and SiO_4 through March and into April. Based on nutrient and plankton data from the March nearfield survey and satellite imagery it appears that the peak of the winter/spring diatom bloom occurred in March in Massachusetts Bay. The March nearfield-only survey nutrient data shows substantial decline in all nutrients, including SiO_4 (**Figure** 3-7), and the plankton data shows that species of the diatom *Thalassiosira* dominated the community. Chlorophyll was elevated in many of the survey regions in April especially in the offshore and boundary areas (**Figure** 3-8a), but the highest survey mean areal chlorophyll level (388 mg m^{-2}) was measured during the March nearfield survey. A similar pattern was observed for particulate organic carbon (POC) concentrations with high POC in the offshore and boundary areas, while a winter/spring POC peak was observed in March for the nearfield (**Figure** 3-8b).

(a) Areal Chlorophyll



(b) POC

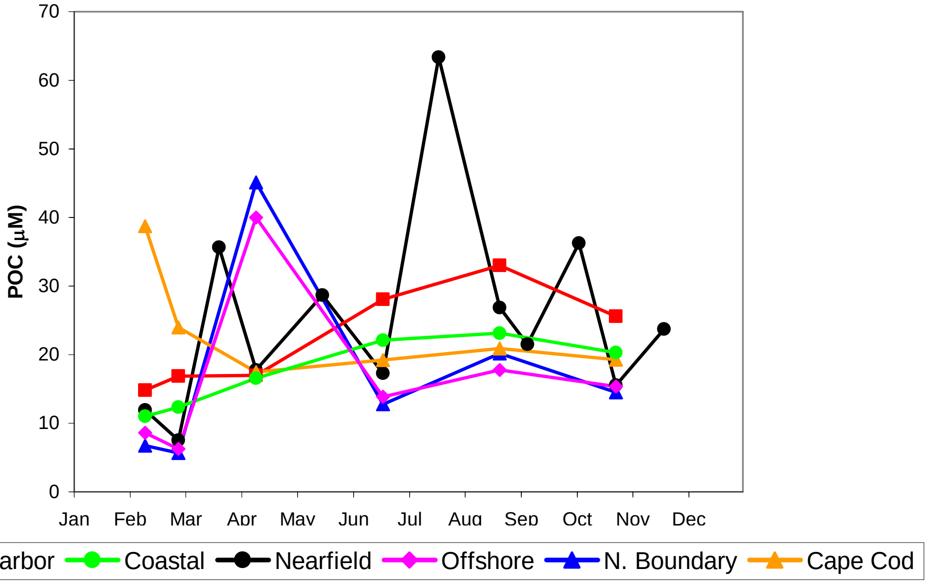


Figure 3-8. Time-series of survey mean (a) areal chlorophyll (mg m^{-2}) and (b) POC (µM) in Massachusetts and Cape Cod Bays. Mean of over (all depths for POC) all stations within each region in 2006.

This March *Thalassiosira* bloom likely drew down nutrients throughout much of the area, and by mid April nutrient-depleted conditions were observed over much of the bay. There was a general trend of nutrient concentrations increasing further away from the coast with the highest level observed at the northern boundary stations (**Figure** 3-7). The nutrient trends seen during this survey do not inversely correlate with the phytoplankton counts observed for the same period. The April (WF064) phytoplankton counts showed a large scale bloom of the nuisance species *Phaeocystis pouchetii* throughout boundary and offshore regions, and to a lesser extent in the nearfield. Very low plankton counts were seen in the harbor, coastal, and Cape Cod Bay regions. It might be expected that plankton abundance would be negatively correlated with nutrient concentrations (due to utilization); however, the opposite was true. The elevated *Phaeocystis* counts in the offshore and northern boundary stations in early April likely represented the western edge of an emergent offshore bloom that was entering the bay (**Figure** 3-9), while the inshore waters had lower nutrient concentrations due to the March diatom bloom.

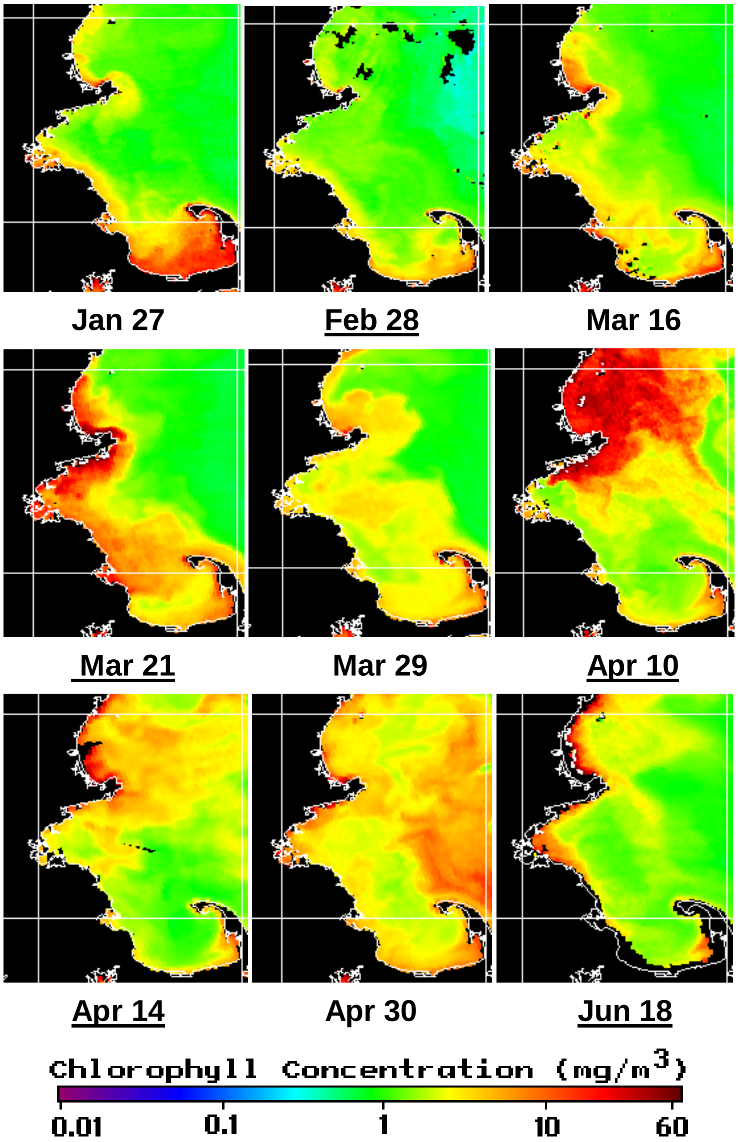


Figure 3-9. Selected MODIS chlorophyll images for southwestern Gulf of Maine for January through June, 2006. Dates coincident with surveys are underlined.

A few pieces of evidence suggest that there was a shift in the bloom community structure from mid March to mid April. First, as mentioned above, the mid March nearfield plankton data shows moderate diatom counts with virtually no *Phaeocystis.* Secondly, during the April survey SiO_4 was reduced to <2 µM in areas where very few phytoplankton were observed, and <5 µM in the regions dominated by *Phaeocystis*. Silicate is a required nutrient for diatoms but is not utilized by *Phaeocystis*, so the SiO_4 draw-down suggests that at least some portion of the bloom seen in the satellite imagery was related to diatoms. From the beginning of the year through April, both SiO_4 and DIN declined in a 1:1 relationship suggesting a diatom dominance of nutrient uptake (**Figure** 3-10). There was a substantial rebound in SiO_4 before May 17 as increased coastal runoff resupplied nutrients to the bay, while *Phaeocystis* continued to utilize DIN and the lack of diatoms during this bloom halted the draw down of SiO_4. The *Phaeocystis* bloom is discussed in more detail in Section 3.4.

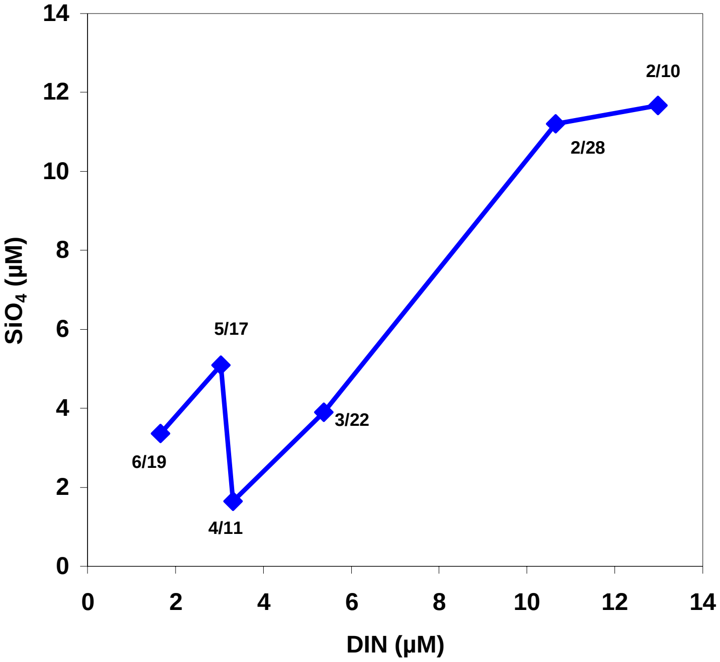


Figure 3-10. Nearfield mean SiO_4 and DIN concentrations from February through June 2006 (dates shown next to data points).

There were limited changes in nutrient concentration from mid April to mid May, as levels had already become quite low during the April phytoplankton bloom. Slight declines were generally seen in the nearfield and offshore areas, while slight increases were seen at coastal stations. These increases were likely due to high levels of coastal runoff. As discussed in Section 3.1.1, May was an exceptionally wet month, with some of the highest river flows in the historical record. Silicate showed a fairly strong rebound in all regions as a result of this runoff and decreased utilization following the crash of the diatom bloom (**Figure** 3-7). The mid-May nearfield survey was coupled with additional sampling for *Alexandrium* along the south shore which provided *in situ* water column and nutrient data for these regions. An additional four *Alexandrium* Rapid Response Surveys (ARRS) were also conducted on a weekly basis between the mid-May nearfield and mid-June farfield surveys. Surface water nutrient levels remained depleted in Massachusetts Bay for the most part (minor harbor signal) from May through June. The most noticeable signal was elevated SiO_4 concentrations associated with freshwater inputs from the Gulf of Maine and Boston Harbor during the ARRS survey on June 13th (**Figure** 3-11), conducted 2-3 days after the peak river flows measured earlier in June (see **Figure** 3-1). The fresher water also had higher relative concentrations of colored dissolved organic matter (CDOM). The CDOM *in situ* data are calibrated against a quinine sulfate dehydrate standard, but not against field samples and are considered here only as a relative comparison across the bay (*i.e.* cannot be compared to CDOM data from other monitoring/research programs). High CDOM to the northeast and along the coastal waters were coincident with the low salinity surface water and are indicative of riverine inputs. This riverine CDOM has been noted as possibly effecting blooms of *Alexandrium* (Anderson *et al.* 2005a). The 2006 *Alexandrium* bloom is discussed in more detail in Section 3.4.

By the June farfield survey, nutrient concentrations were generally depleted in the surface waters throughout the entire study area. The exception was SiO_4, mentioned above, which had increased in May from the very low levels seen following the spring diatom bloom. Coastal runoff during a notably wet June also contributed to the higher SiO_4 levels observed during in mid June (**Figure** 3-11).

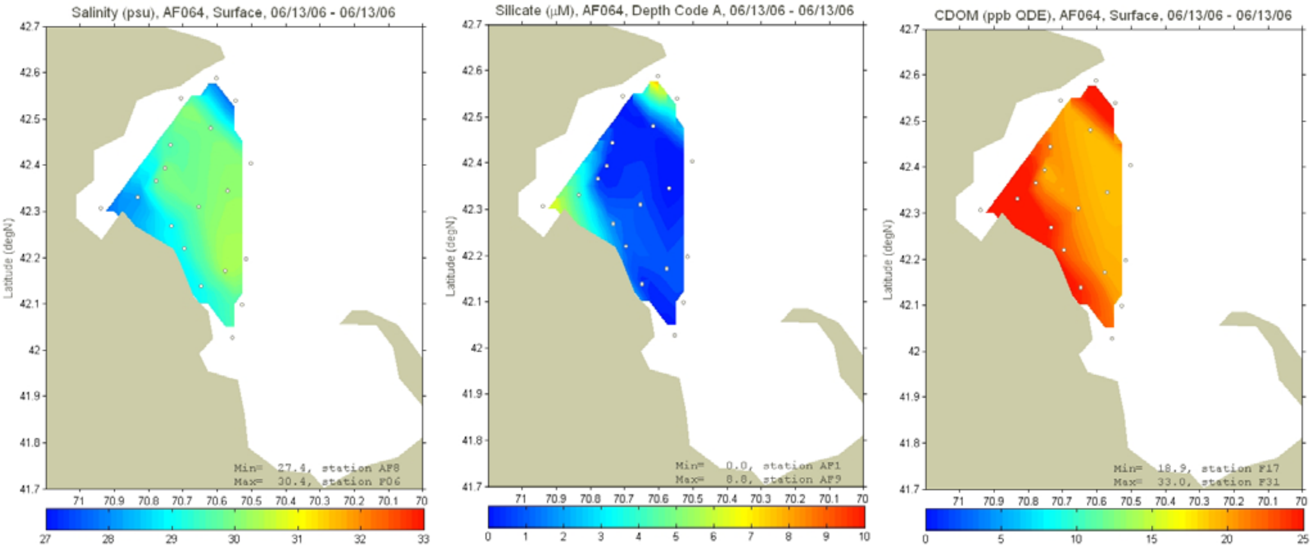


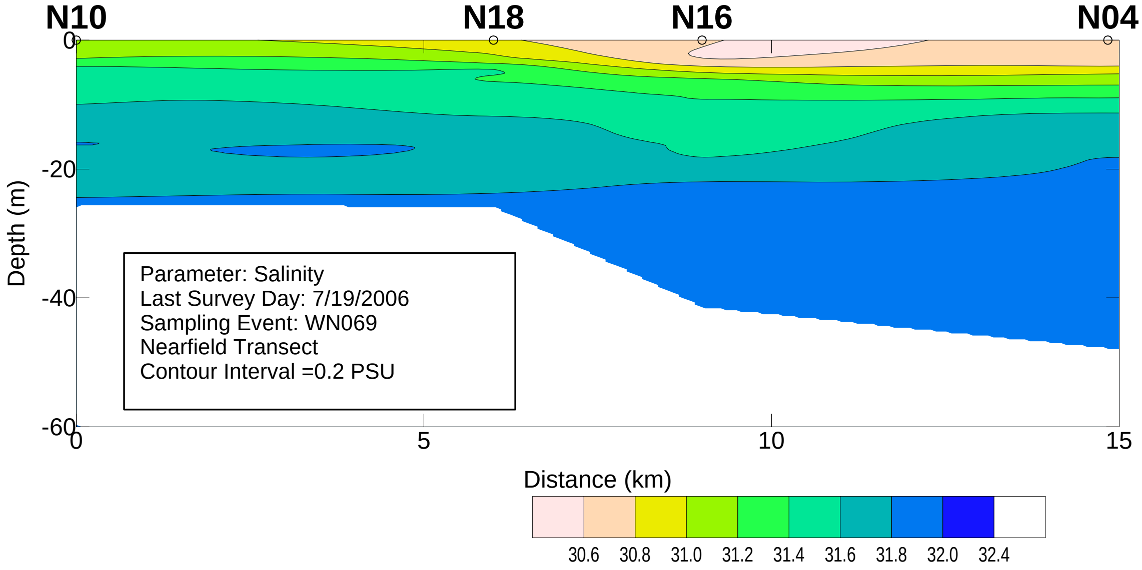
Figure 3-11. Surface water salinity (PSU), SiO_4 concentration (µM) and CDOM (relative ppb quinine sulfate dihydrate equivalents (QSDE)) in Massachusetts Bay during AF064 survey June 13, 2006.

Seasonal stratification typically leads to persistent nutrient-depleted conditions in the upper water column due to biological utilization and minimal mixing in the summer. In July 2006, although thermal stratification was present (driven by warm surface waters) and surface water nutrients were generally depleted, it appears that persistent, upwelling favorable winds in the weeks leading up to the July survey provided nutrients to the surface layer or euphotic zone. As discussed in Section 3.1.1, July 2006 was one of the most strongly upwelling favorable periods of the monitoring program. This physical feature allowed more saline (**Figure** 3-12) and nutrient replete (**Figure** 3-13) bottom waters to rise higher in the water column where light limitation no longer inhibited phytoplankton production. This doming of bottom waters seems to be occurring along this transect at station N18 with elevated SiO_4, NO_3+NO_2 and NH_4 concentrations present at 8-12 m depths, but elevated concentrations were present at about 10-m over the entire transect (**Figure** 3-13). In general across the nearfield area, there was a noticeable upwelling signal in a gradient from inshore (strongest) to offshore (weakest).

A look at *in situ* fluorescence along this same transect shows that the highest fluorescence levels were coincident with the elevated nutrient concentrations at station N18 as well as at other nearfield stations at about 12-15-m depth (**Figure** 3-12). The effect of upwelling on the July bloom was also evident in SeaWiFS chlorophyll data showing elevated chlorophyll levels (**Figure** 3-14) coincident with the cooler surface waters shown in **Figure** 3-5. Anomaly plots for SeaWiFS chlorophyll show elevated chlorophyll levels in the area of Boston Harbor and western Massachusetts Bay, including the nearfield for July 4-11, and along coastal waters from New Hampshire through Massachusetts Bay south to Cape Cod during July 12-19 (**Figure** 3-14).

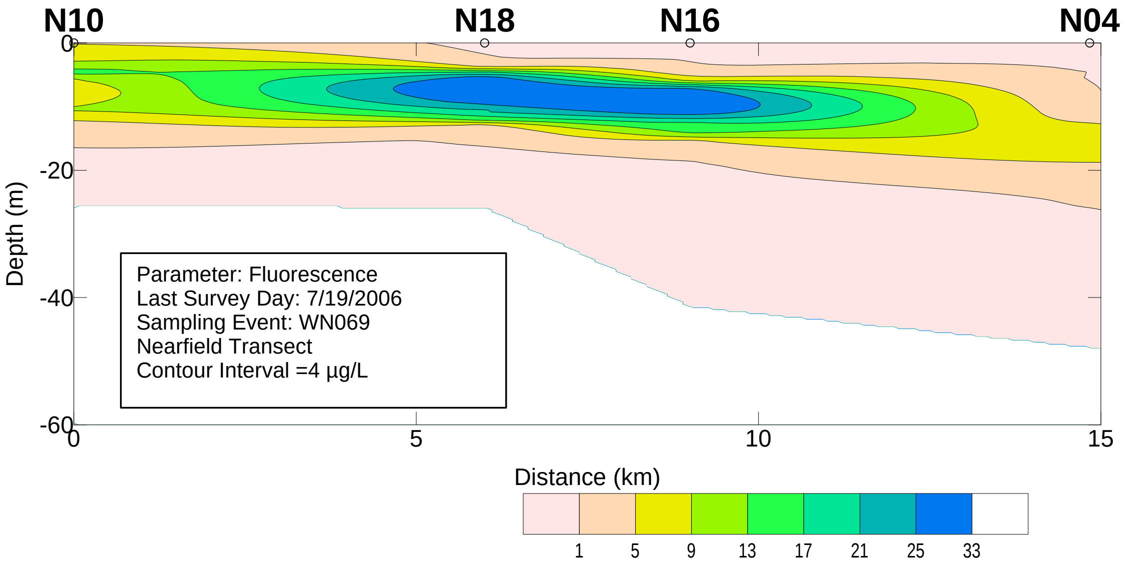
The upwelling of the nutrient rich (ambient and outfall origin) waters fueled the moderately large summer diatom bloom that was observed in mid July 2006. During the bloom, nearfield chlorophyll levels reached the second highest survey mean for 2006 at ~ 200 mg m^{-2} and POC concentrations reached maximum levels for 2006 with a nearfield mean of 63 µM (**Figure** 3-8). The diatom bloom abundance reached levels >2 million cells L^{-1} dominated by *Dactyliosolen fragilissimus*.

(a) Salinity



Parameter: Salinity
Last Survey Day: 7/19/2006
Sampling Event: WN069
Nearfield Transect
Contour Interval =0.2 PSU

(b) Fluorescence



Parameter: Fluorescence
Last Survey Day: 7/19/2006
Sampling Event: WN069
Nearfield Transect
Contour Interval =4 µg/L

Figure 3-12. Transect across the nearfield from station N10 to station N04 showing (a) salinity (PSU) and (b) *in situ* fluorescence (µg L^{-1}) during survey WN069 (July 19, 2006)

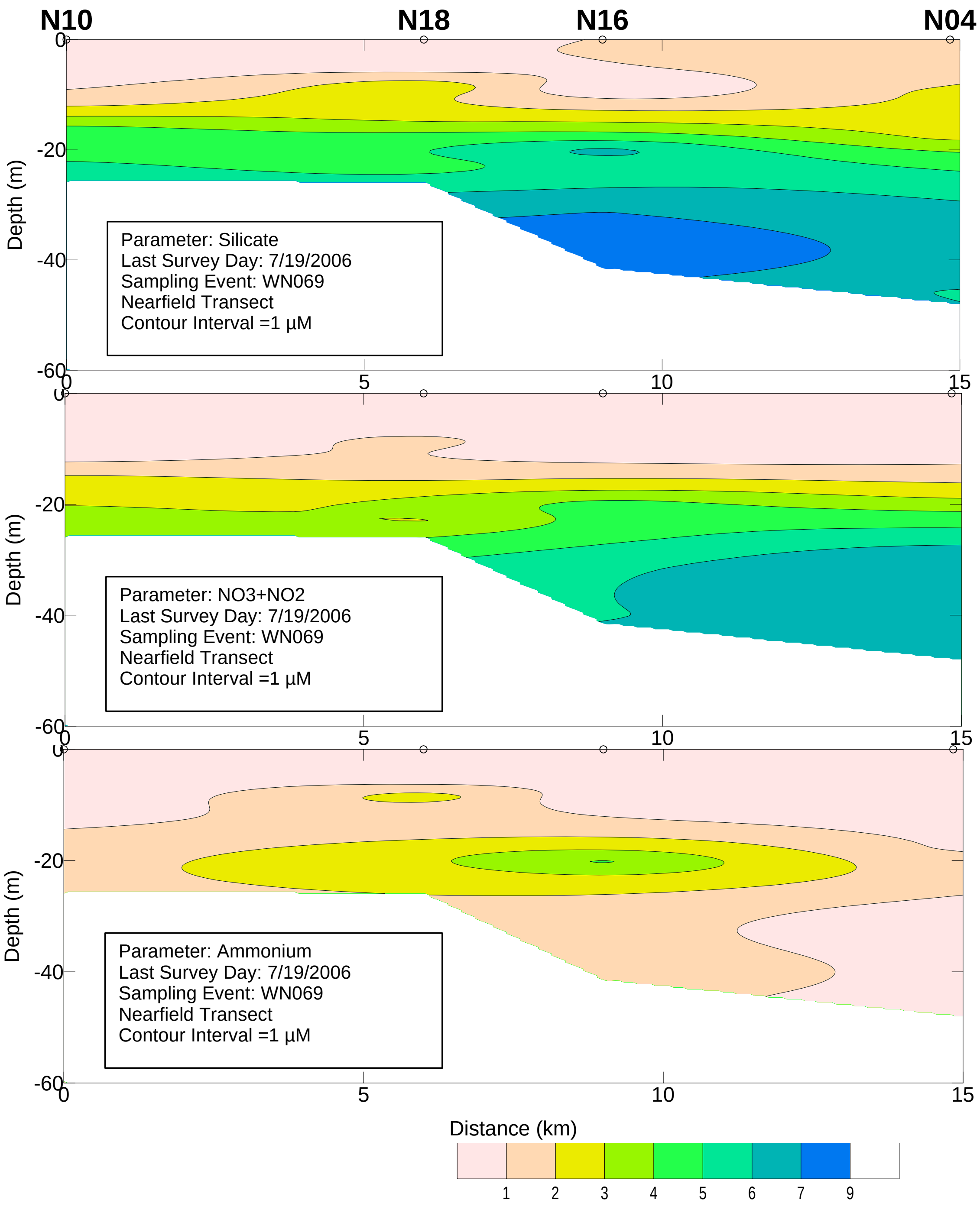


Figure 3-13. Transects across the nearfield from station N10 to station N04 showing SiO_4, NO_3+NO_2, and NH_4 concentrations (µM) during survey WN069 (July 19, 2006)

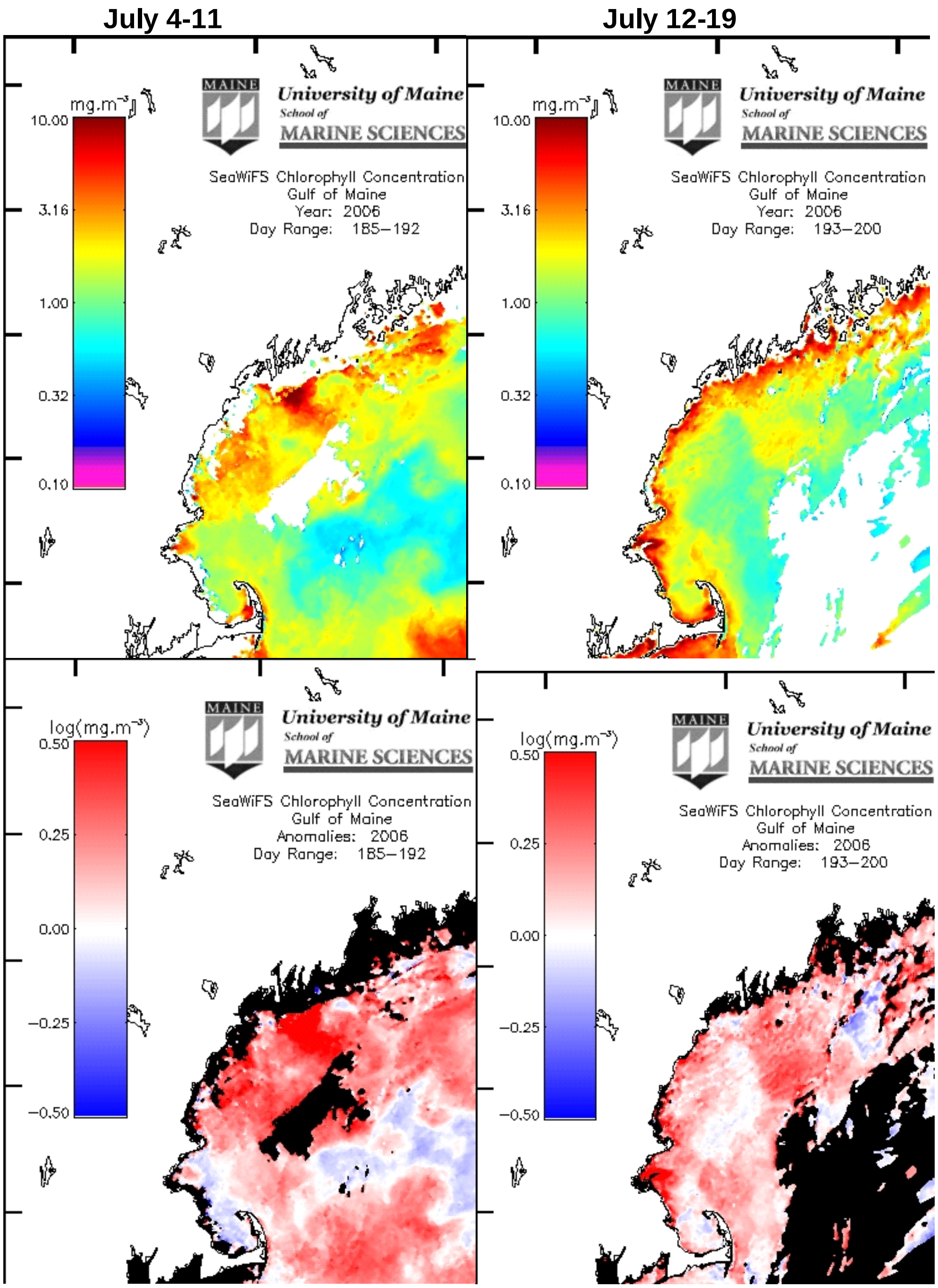
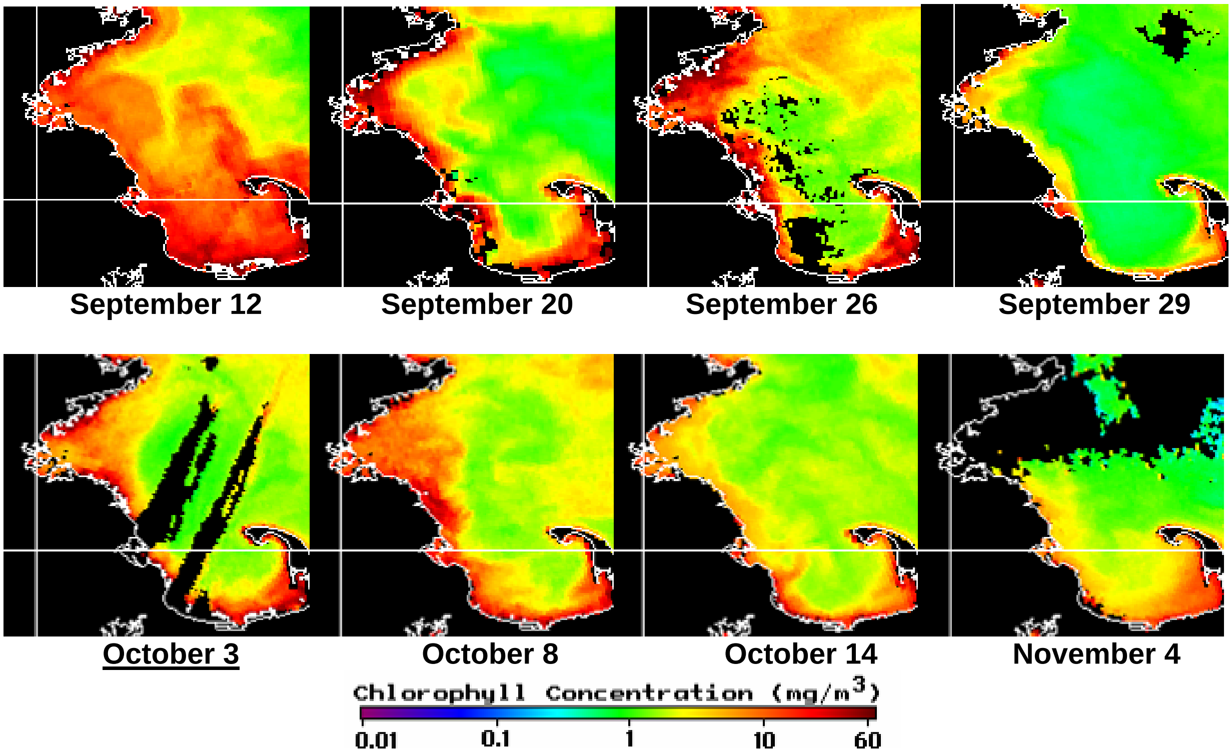


Figure 3-14. SeaWiFS 8-day composite (top) and 8-day anomalies (bottom) for July 4-11 (left) and July 12-19 (right) 2006. (Images obtained from http://wavy.umeoce.maine.edu/)

Surface nutrients remained low during the mid August farfield survey and early September nearfield survey, while total water column nutrient concentrations continued to increase (see **Figure** 3-7). A dip in all nutrient concentrations was seen during the September survey. Chlorophyll data, phytoplankton counts, and satellite imagery do not suggest that this decline in nutrient concentration was related to biological activity. It is likely then, that physical factors such as the reventilation events discussed in Section 3.1.1 may have be responsible for this impact on the average nutrient concentration in the water column. There was a large increase in nutrient concentrations from early September to early October even though there was only a small decrease in stratification (**Figure** 3-4). The nutrient concentration increases were seen in the nearfield by early October and throughout most other regions by the late October farfield survey (**Figure** 3-7). The exception was Cape Cod Bay which showed a decline in nutrient concentrations in the fall.

Satellite imagery from September and October suggest that two significant fall blooms may have occurred throughout Massachusetts and Cape Cod Bays (**Figure** 3-15). The chlorophyll levels were quite high throughout the bay during the September bloom, which occurred after the early September nearfield survey (September 5th) and prior to the October nearfield survey (October 3rd). Phytoplankton data from the early October nearfield survey indicates that the phytoplankton community was again dominated by *Dactyliosolen fragilissimus* during the fall 2006 bloom as it had been in July. It appears that the timing of the late October farfield survey came just after the end of this bay-wide bloom, which tailed off later in Cape Cod Bay than in other areas (**Figure** 3-15).


September 12 September 20 September 26 September 29

October 3 October 8 October 14 November 4

Figure 3-15. Selected MODIS chlorophyll images for southwestern Gulf of Maine for September to early November, 2006. Date coincident with nearfield survey is underlined. The September nearfield survey was conducted on 9/5 and the October farfield survey on 10/23-24, 27 and 31.

As discussed above, 2006 was marked by the occurrence of multiple diatom blooms and a *Phaeocystis* bloom in the nearfield. Nearfield seasonal and annual mean areal chlorophyll levels are compared against the Contingency Plan threshold values each year (**Table** 3-1). The nearfield mean areal chlorophyll for winter/spring 2006 was relatively high (129 mg m^{-2}), but well below the seasonal caution threshold of 238 mg m^{-2}. The occurrence of the March diatom bloom and the April *Phaeocystis* bloom contributed to the elevated seasonal mean values. The winter/spring mean areal chlorophyll in 2006 was slightly lower than the previous year, but still higher than those measured in 1992-1998, 2001-2002 and 2004 (**Table** 3-2). The winter/spring levels in 1999, 2000, and 2003 stand out as the highest of the monitoring program. The summer 2006 nearfield areal chlorophyll triggered a caution threshold exceedance (**Table** 3-1) and was greater than any summer mean measured during the program (**Table** 3-2). The nearfield summer mean in 2006 was driven by the very high chlorophyll levels observed in July (~200 mg m^{-2}) during an atypical summer bloom of the diatom *Dactyliosolen fragilissimus*. One of the primary factors contributing to the bloom was the upwelling favorable conditions in July 2006 bringing nutrients into the euphotic zone. Nearfield fall mean chlorophyll was close to the post-transfer mean value, but still the third highest of the post-transfer period. The fall mean was much higher than the last two years when fall blooms were not observed.

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**
2005	**133**	**63**	**43**	**80**
2006	**129**	**89**	**94**	**104**
Caution Threshold	238	93	212	118
Baseline Mean*	82	51	90	67
Post-transfer Mean*	**129**	**59**	**95**	**83**

*Bay Outfall began discharging September 6, 2000. Post-transfer data are in bold and shaded. 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.

As a result of sampling during multiple blooms, the 2006 annual mean areal chlorophyll value of 104 mg m^{-2} was the highest measured during the post-transfer years (**Table** 3-2). All of the post-transfer years' annual means have been well below the caution threshold of 118 mg m^{-2}. The 2006 annual mean approaches the threshold level, but is well below the peak annual values measured in 1999 and 2000 (**Table** 3-2). A comparison of seasonal and annual areal chlorophyll pre- and post-transfer shows an apparent increase for each of the periods (**Figure** 3-16). The largest differences are for winter/spring and annual comparisons. The post-transfer winter/spring mean is 57% higher than the baseline mean, but this increase is not quite statistically significant (T-test; P=0.10) due to the limited dataset and the high degree of interannual variability in the data. The annual areal chlorophyll also shows an apparent increase between baseline and post-diversion mean values (**Table** 3-2; **Figure** 3-16), which is also not statistically significant (P=0.11). The wide range in seasonal and annual values is primarily due to the large blooms and associated chlorophyll levels in 1999 and 2000.

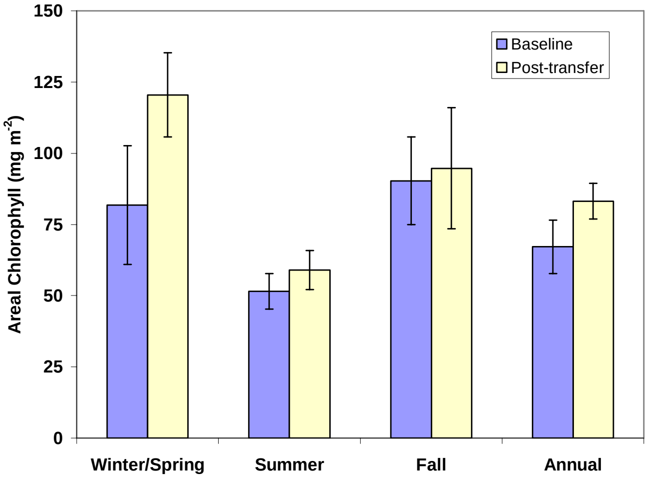


Figure 3-16. Comparison of baseline and post-transfer seasonal and annual mean areal chlorophyll (mg m^{-2}) in the nearfield. Error bars represent ±1 SE.

3.3 Productivity

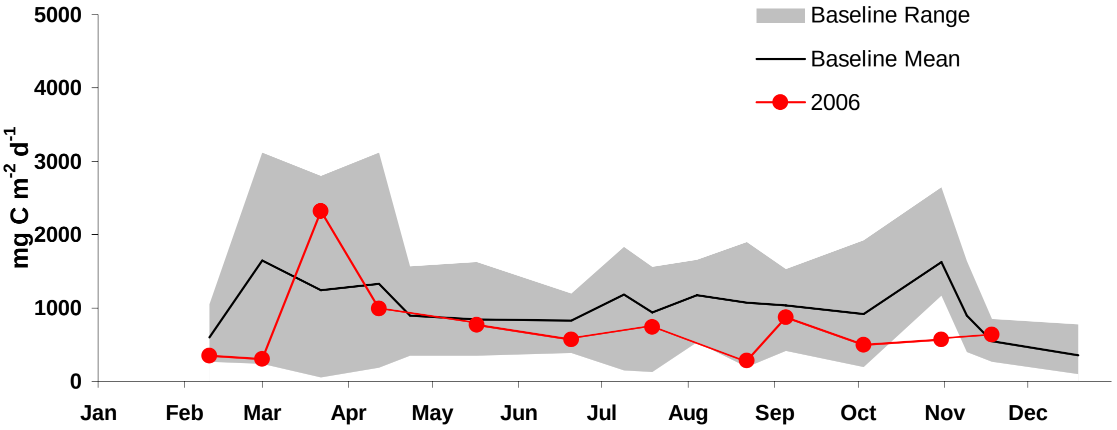
In 2006, the patterns of productivity seen at both the nearfield and Boston Harbor stations were somewhat different from the long-term patterns (1995 – 2002), but similar to the values seen in recent years (2003 -2005). The latter years tended to show reduced annual productivity at all three sites, the occurrence of a higher magnitude spring bloom at station N04 relative to N18, and the low magnitude of the fall bloom peaks at the nearfield stations. There is also an apparent disconnect between productivity rates and identification of a July 2006 phytoplankton bloom based on chlorophyll concentration and phytoplankton abundance.

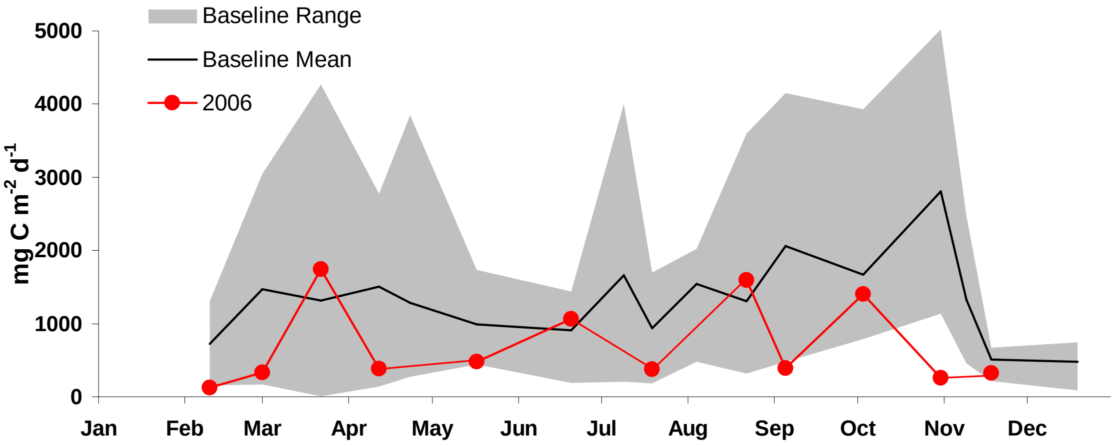
The timing of areal production at the nearfield stations in 2006 was similar between the two stations but the magnitude differed somewhat from the baseline mean (**Figure** 3-17). In 2006, the spring bloom peaked during March, somewhat later than the February peak observed in 2005, but similar to most years. The spring bloom peak magnitude in March was higher at station N04 (2,321 mg C m^{-2} d^{-1}) than at N18 (1,745 mg C m^{-2} d^{-1}) and was coincident with the survey mean chlorophyll maximum for the nearfield and an identified bloom of the diatom *Thalassiosira* spp. At both sites the bloom occurred during a single sampling period followed by a decline in productivity in April, when the *Phaeocystis* bloom was observed in the nearfield. April productivity was just under 1000 mg C m^{-2} d^{-1} at station N04 and much lower at station N18 (381 mg C m^{-2} d^{-1}). The trends in productivity from March to April are similar to those seen for chlorophyll, which decreased from an annual survey mean maximum in the nearfield in March (388 mg m^{-2}) to <20% of that value (70 mg m^{-2}) in April (see **Figure** 3-8) even though total phytoplankton abundance increased from 1.4 to 2.0 million cells L^{-1}. This change in phytoplankton abundance overlaid a change in dominant species from diatoms (0.5 million cells L^{-1}) to *Phaeocystis* (1.4 million cells L^{-1}). The change in both productivity and biomass from March to April may have been related to physiological differences in the bloom species and timing of sampling during the individual bloom (i.e. early, peak, post bloom). As noted in Section 3.2, the nearfield appeared to be west of the core of the April *Phaeocystis* bloom (abundance 10% of maximum counts measured at Station F27) and the cells may not have been growing rapidly in the lower nutrient waters of Massachusetts Bay.

The magnitude of the springtime peaks at both stations was higher than the baseline average (**Figure** 3-17). The spring bloom magnitude at N04 (2,321 mg C m^{-2} d^{-1}) was greater than at N18 (1,745 mg C m^{-2} d^{-1}), which is similar to the pattern seen in 2001, 2004 and 2005, but a pattern observed only once prior to diversion (**Figure** 3-18). The winter-spring bloom peaks at both nearfield sites in 2006 were similar to values observed during the winter-spring period from 1999 - 2002. The 2003 -2005 period was characterized by low magnitude winter spring blooms.

Primary production in 2006 was also calculated for the bays from SeaWiFS products using a primary productivity model from Hyde *et al.* (2007a). The Massachusetts Bay model was derived from the Vertically Generalized Productivity Model (VGPM) (Behrenfeld and Falkowski, 1997) and includes regionally tuned parameters for chlorophyll *a* (Hyde *et al.* 2007b), euphotic depth (Z_{eu}) and maximum chlorophyll specific carbon fixation rate (P^{b}_{max}) (Hyde *et al.* 2007a). Monthly composites of the model output revealed that in January and February, there was a bloom in Cape Cod Bay (**Figure** 3-19), which is corroborated by the phytoplankton biomass and abundance data. Production increased throughout Massachusetts Bay in March and peaked near Cape Ann in April (**Figure** 3-19) as suggested by the high biomass concentrations at the boundary and offshore stations (see **Figure** 3-8). These model results suggest that although nearfield productivity peaked during the March survey, baywide production likely peaked in April during the *Phaeocystis* bloom.

In general, patterns observed at the nearfield sites throughout the rest of the summer were consistent with those observed from 1995 – 2005 as both nearfield stations were characterized by variable productivity during the summer (**Figure** 3-17). Interestingly, there was no peak in productivity associated with the July bloom noted in phytoplankton biomass (chlorophyll and POC; see **Figure** 3-8) and abundance. Images developed by University of Maine Orono suggest that the July bloom was evident throughout the bays and western Gulf of Maine as elevated chlorophyll concentrations in July (see **Figure** 3-14). Likewise, the VGMB model results show elevated production in the bays during July (**Figure** 3-19). The large, atypical summer bloom of the diatom *Dactyliosolen fragilissimus* had abundances of 1 million cells L^{-1} in the surface waters at station N04 and 6 million and 4 million cells L^{-1} in the surface and chl*a*-max samples, respectively, at station N18. Oddly, even with this disparity in cell abundance, productivity, although low at both stations, was nearly twice as high at N04 (741 mg C m^{-2} d^{-1}) compared to N18 (374 mg C m^{-2} d^{-1}). Although there is no clear indication of why there was such a disconnect between productivity and phytoplankton biomass and abundance data, the depth of the chlorophyll peak around 8-12 m and relatively high light extinction at station N18 may explain the low production values seen at station N18 during this bloom.


(a) N04


(b) N18

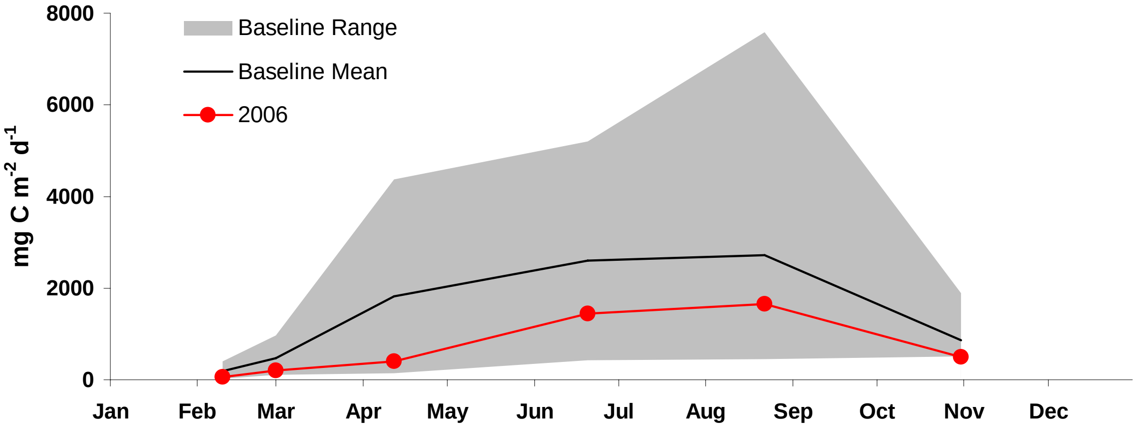

(c) F23

Figure 3-17. Time-series of areal production (mgCm^{-2}d^{-1}) at stations N04, N18 and F23 for 2006 compared against baseline range and mean (1997 to September 2000). Note the nearfield station baseline mean and range are shown for 17 surveys vs. 12 in 2006.

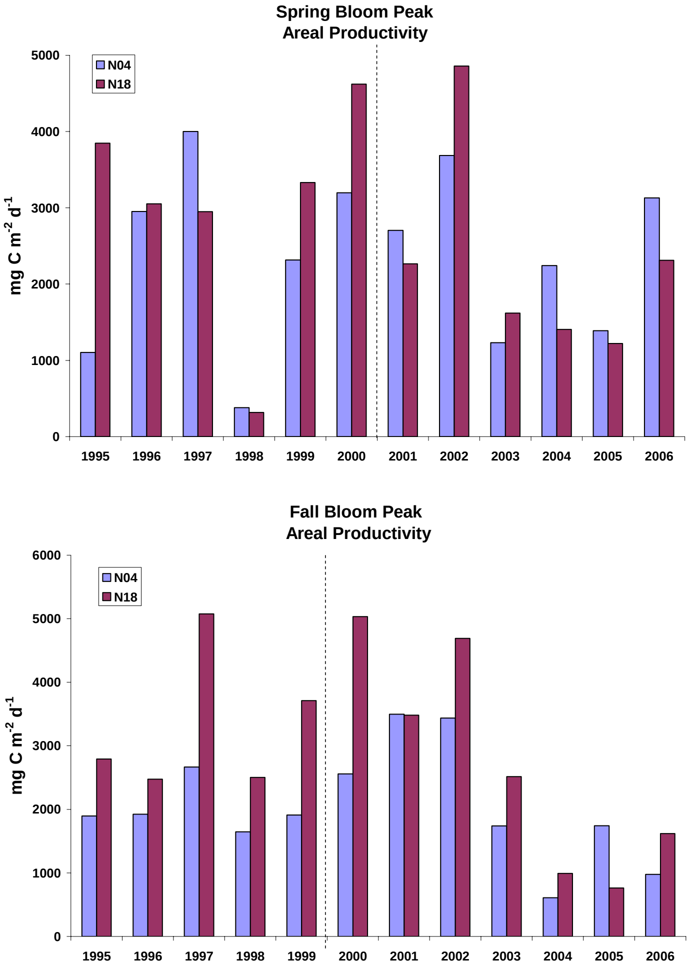


Figure 3-18. Spring and fall bloom peak potential areal productivity (mgCm^{-2}d^{-1}) at nearfield stations N04 and N16/N18.

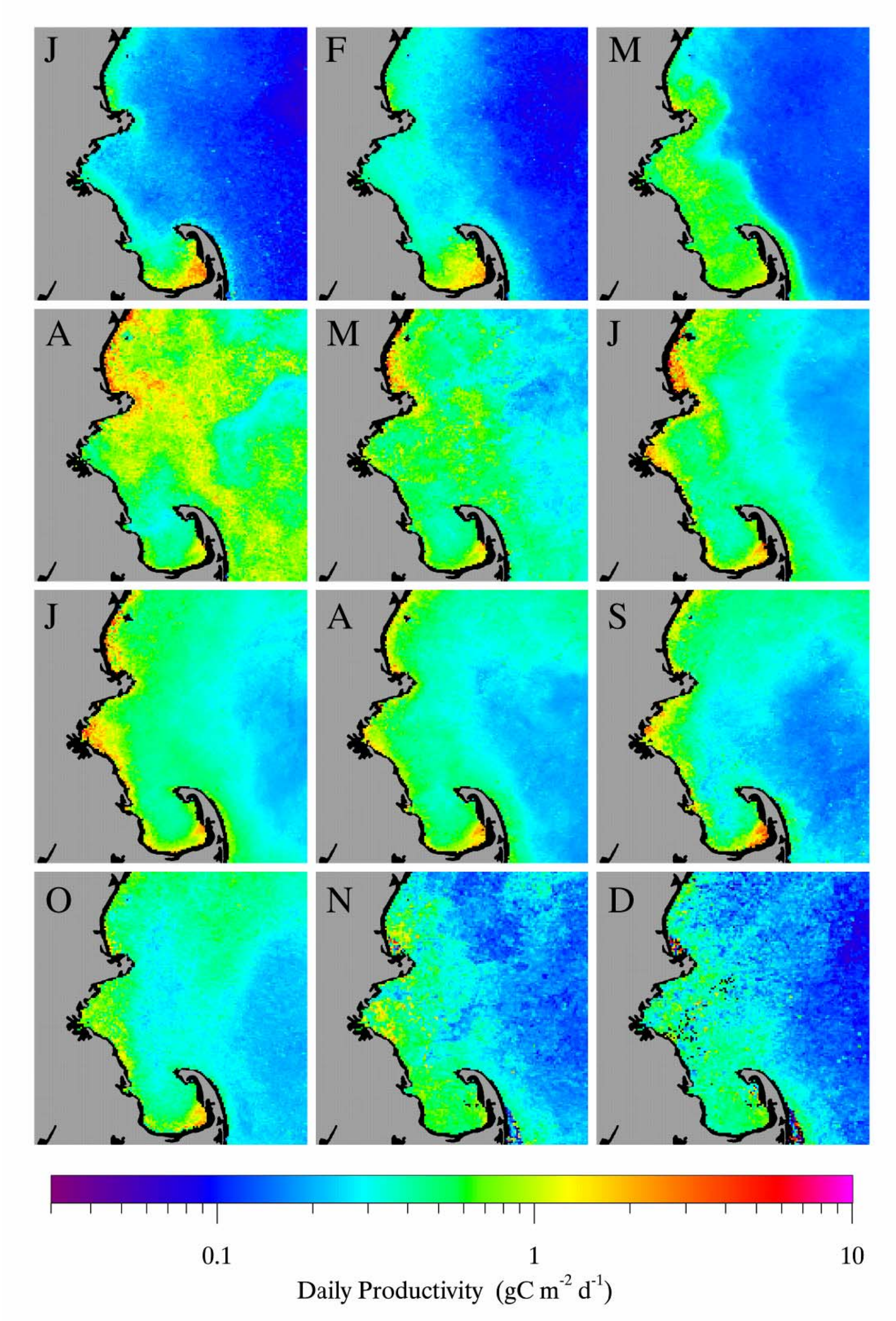


Figure 3-19. Monthly composite of daily productivity (g C m^{-2} d^{-1}) calculated using the VGMB model (Hyde *et al.* 2007a).

The magnitude of productivity was low (<900 mg C m^{-2} d^{-1}) from May to November at station N04, while two peaks in productivity were noted at station N18 in August (1,600 mg C m^{-2} d^{-1}) and early October (1,400 mg C m^{-2} d^{-1}; **Figure** 3-17). The August peak at station N18 was not coincident with any trends in phytoplankton biomass or abundance. The early October peak was coincident with peaks in chlorophyll and POC biomass measurements and with a diatom bloom again dominated by *Dactyliosolen fragilissimus* with elevated abundances of *Skeletonema costatum* (see Section 3.4) The magnitude of the fall bloom at N18 was relatively low and similar to 2004 and 2005, but higher than the peak observed at N04 (**Figure** 3-18). The monthly composite results for October from the VGMB model do not show very high productivity (**Figure** 3-19), but this may be due to averaging over the month and the short duration of the bloom as evidenced by low productivity in the nearfield by late October (**Figure** 3-17).

The productivity pattern at the Boston Harbor station (F23) in 2006 differed somewhat from the patterns observed in 2001 – 2005 (**Figure** 3-17). At the harbor station (F23), areal productivity increased over the spring period, peaked in the late summer and declined in the fall. The pattern is similar to that observed prior to the outfall diversion. No evidence of a spring bloom was seen in the farfield in 2006 which is consistent with the pattern observed in pre-outfall years. The maximum production seen at F23 was 1,658 mg C m^{-2} d^{-1} and occurred in late-August. Although the annual pattern in 2006 followed that seen during the baseline period, production values were low relative to the long-term mean throughout the annual cycle (**Figure** 3-17). In 2001-2003, the presence of spring blooms suggested 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. In 2004-2006, no spring bloom was evident at the harbor station and the annual maximum in productivity occurred during June or August similar to the baseline period. It does not seem likely that the harbor station is rapidly shifting to the nearfield pattern, but the overall decline in productivity seen at the Boston Harbor station does indicate a shift to a less-enriched environment.

3.4 Plankton Community Structure

3.4.1 Phytoplankton

In 2006, most trends in phytoplankton abundance, species composition and bloom cycles were generally consistent with those observed in previous years, although timing and magnitude of events were sometimes different. The main stories in 2006 relative to previous years were multiple diatom blooms (winter/spring, summer and fall), a relatively minor *Phaeocystis* bloom, and an *Alexandrium* red tide bloom which was high compared to levels prior to 2004, but much lower than that of 2005. Each of these events is discussed below and more details on the 2006 phytoplankton data are presented in Appendix D.

3.4.1.1 Winter/Spring Diatom and *Phaeocystis* Blooms

In February, there was a bloom of the diatom *Guinardia delicatula* in Cape Cod Bay. In early February, there were >1.2 x 10^6 cells L^{-1} of this diatom at both depths sampled at station F02, comprising 55-61% of cells counted (**Figure** 3-20). In late February, abundances had declined to 0.4 – 0.6 x 10^6 cells L^{-1}, but still comprised 28-46% of cells counted. Interestingly, this diatom, which was overwhelmingly dominant at station F02, either was not recorded, or comprised <5% of cells counted at all other stations in Massachusetts or Cape Cod Bays. A separate winter/spring diatom bloom was observed in the nearfield in March. This bloom was less intense and was dominated by *Thalassiosira* spp. (*T. rotula*, *T. nordenskioldii*, and *Thalassiosira* sp.). Abundances of these taxa were <0.3 x 10^6 cells L^{-1}, but comprised 7-23% of cells recorded in the nearfield samples. Although the abundances were not high, productivity and chlorophyll reached annual survey mean maxima for 2006 during the March diatom bloom. From March to April, there was an increase in total phytoplankton abundance from 1.4 to 2.0 million cells L^{-1} in the nearfield that was driven by a switch in dominant species from diatoms (0.5 million cells L^{-1}) to *Phaeocystis* (1.4 million cells L^{-1}). Trends in productivity and phytoplankton biomass (chlorophyll and POC) from March to April were opposite with these parameters all decreasing from peaks in March to relatively low values in April.

As discussed in Section 3.2, it appears that the peak of the diatom bloom may have occurred in late March, between the surveys, and that the low chlorophyll values and low phytoplankton abundances seen in Cape Cod Bay, Boston Harbor and coastal waters in April represent a post-diatom/pre-*Phaeocystis* bloom condition in these areas. The relative trend of increasing *Phaeocystis* abundance from inshore (barely present in the harbor and coastal waters) to a maximum of >10 million cells L^{-1} at boundary station F27 suggests that the *Phaeocystis* bloom entered the bay from the Gulf of Maine (**Figure** 3-20 and Appendix D). Fluorescence data from the GoMOOS mooring shows increasing fluorescence starting around March 21 and peaking at concentrations >30 µg L^{-1} (uncalibrated) from March 25 to April 10 (**Figure** 3-21a). The rapid increase in chlorophyll fluorescence in late March was coincident with an interval of time when currents were out of the north and northeast (influx of cells from Gulf of Maine) and peaked when both winds and currents were weaker and less consistent (*in situ* growth;
Figure 3-21b). Fluorescence at the buoy dropped sharply after April 10 and was back to <5 µg L^{-1} by April 20 after survey WF064. The GoMOOS buoy is located at the northeastern edge of the MWRA farfield study area near station F22 and is representative of the conditions in the northern boundary area.

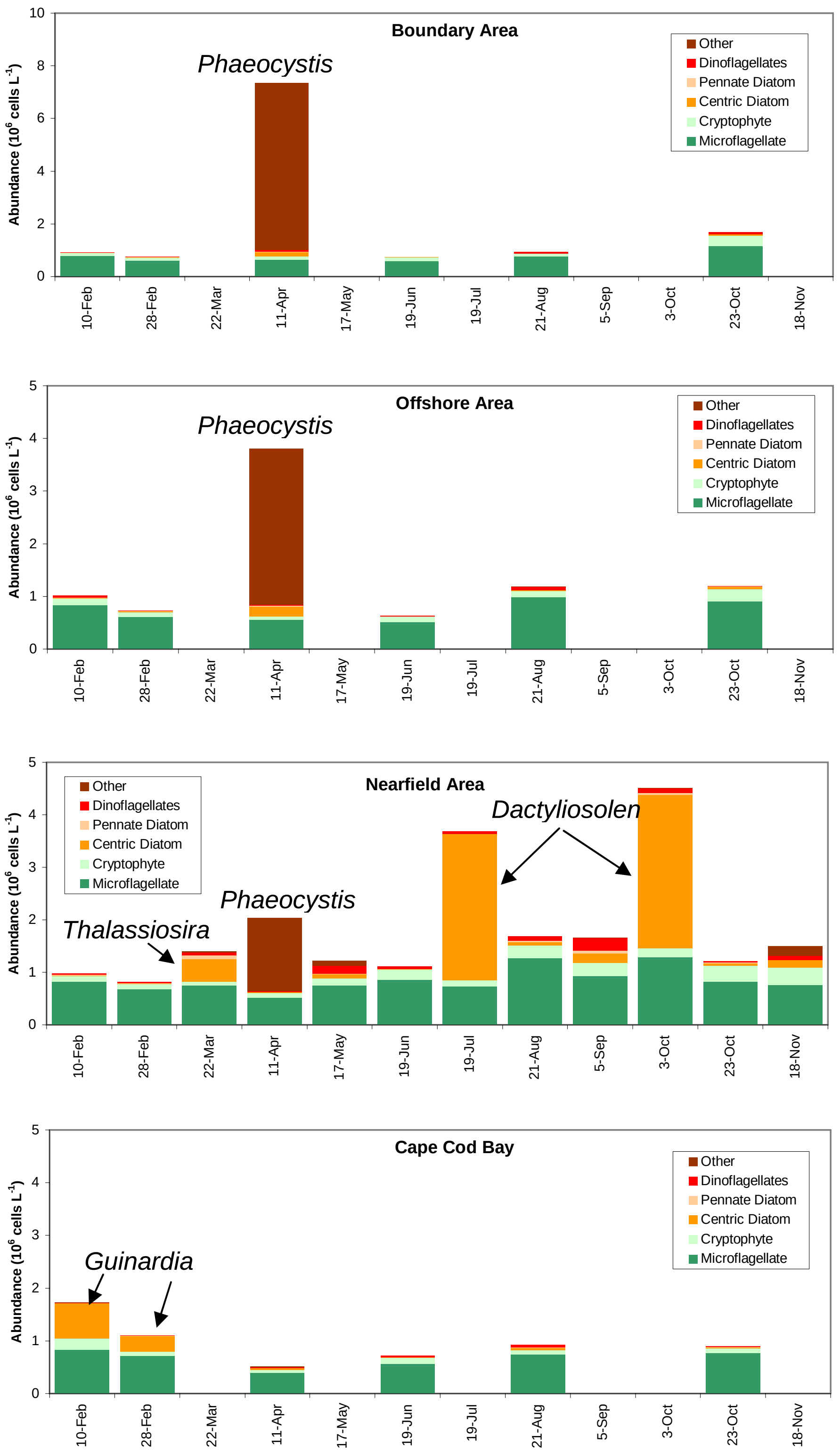
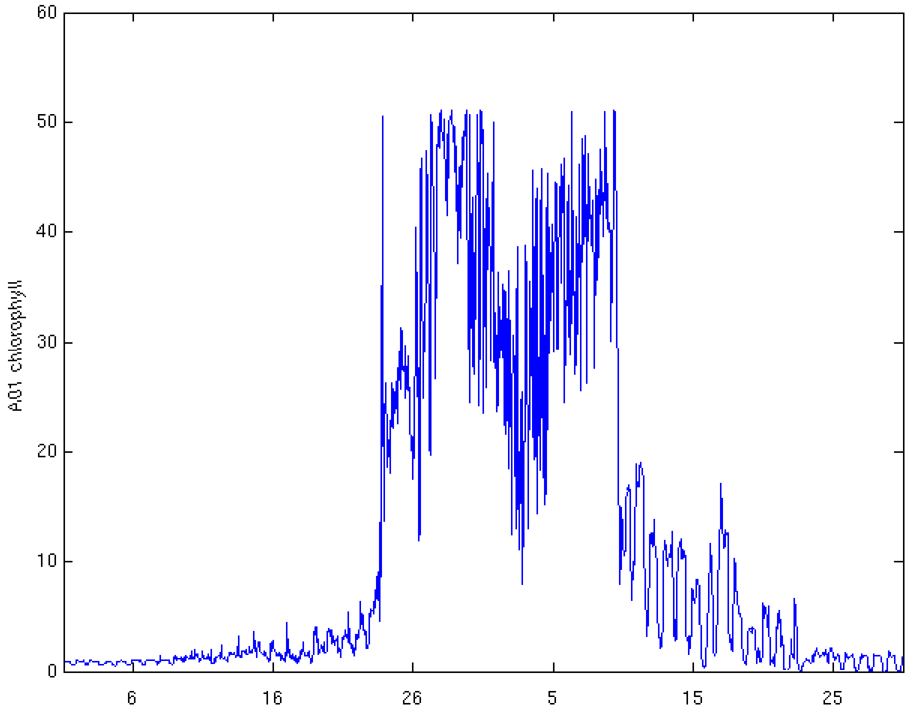


Figure 3-20. Phytoplankton abundance by major taxonomic group in northern boundary, offshore, nearfield and Cape Cod Bay areas for 2006. Note scale for boundary area is double.

(a) Chlorophyll Fluorescence



(b) Low-pass filtered Wind Stress and Ocean Currents

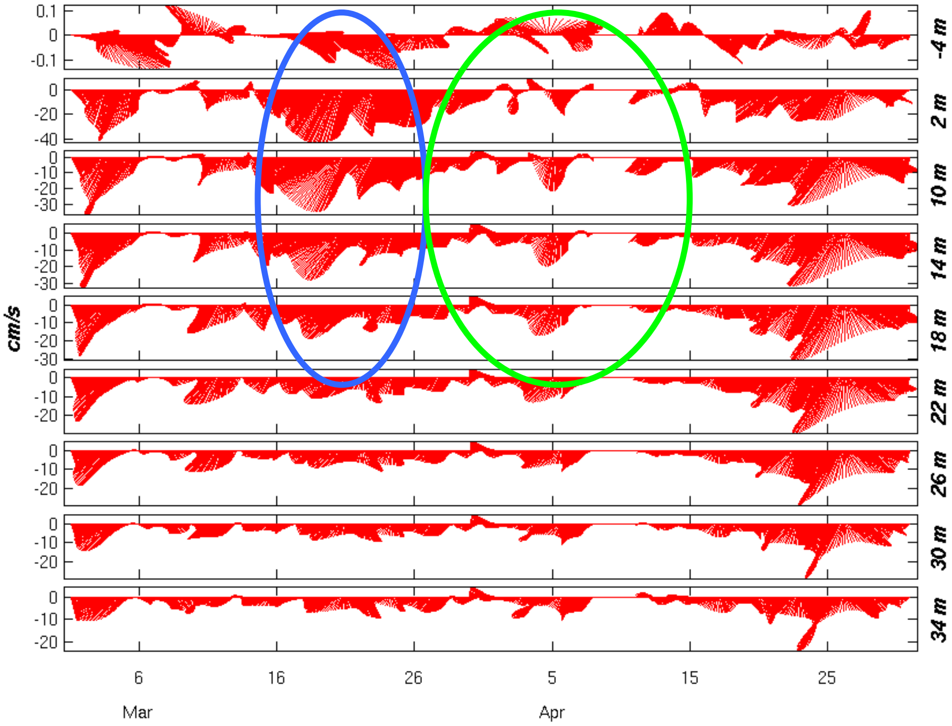


Figure 3-21. GoMOOS buoy A data on (a) chlorophyll fluorescence and (b) wind stress and ocean currents for March and April 2006 (low-pass filtered to remove tidal currents). Blue circle = period of strong N and NE winds and currents and Green circle = weak and inconsistent winds/currents. GoMOOS buoy A01 plot (a) generated online and plot (b) provided by Physical Oceanography Group, University of Maine (http://gyre.umeoce.maine.edu/gomoos.php).

The chlorophyll distribution seen in the satellite imagery as well as data from the GoMOOS A buoy support the notion that there was a late March to mid-April bloom in chlorophyll in northeastern Massachusetts Bay that was likely due to inputs to the bay from the Western Gulf of Maine. The satellite data indicates that elevated levels of chlorophyll persisted in the nearshore waters of the bays through April (**Figure** 3-9) and, given the continued presence of *Phaeocystis* in the nearfield on the May 17 survey, suggests that the 2006 *Phaeocystis* bloom entered the bay in late March and persisted through mid-May. The 2006 *Phaeocystis* bloom had ended by May, but samples collected from stations N04 and N18 during the May survey contained *Phaeocystis* (up to 220,000 cells L^{-1}), which made up a relatively minor portion of the total phytoplankton community (0-16%). Nevertheless, the presence of *Phaeocystis* in May nearfield samples resulted in an exceedance of the summer *Phaeocystis* threshold (**Table** 3-1). The May 2006 extended duration of the *Phaeocystis* bloom may have been related to the relatively cool water temperatures in May/June 2006 and the relationship continued to fit the pattern noted by Libby *et al*. (2006d) for bloom duration and surface water temperature (**Figure** 3-23).

Although there have not been any major changes in the taxonomic composition of the phytoplankton community over the last 15 years, there have been several variations in the timing and magnitude of various events in the seasonal succession. The most pronounced variations have been associated with the spring blooms of *Phaeocystis pouchetii* (**Figure** 3-22). After recording spring *Phaeocystis* blooms in 1992, 1994 (farfield), and 1997, there have been blooms during consecutive years from 2000 to 2006. Thus, the pattern has changed from spring *Phaeocystis* blooms occurring at ~3-year intervals to blooms occurring annually. Although it is clear that the periodicity of spring *Phaeocystis* blooms has changed, the reason(s) for this change remain elusive. Similarly, it is not clear why, unlike previous blooms which occurred primarily in late March and April, some of the blooms since 2002 began earlier, and lasted until early May, thereby causing exceedances of the “summer” *Phaeocystis* threshold by the presence of low abundances of this alga in May.

As observed during the previous blooms, the 2006 bloom was a regional event with elevated abundances measured throughout the bays. It has been noted that *Phaeocystis* blooms are a regular component of the spring phytoplankton assemblage in north temperate coastal seas (Schoemann *et al.* 2005), including the Gulf of Maine (Bigelow 1924). Direct as well as anecdotal evidence indicates that the blooms observed in Massachusetts Bay are regional in nature and have been coincident with the presence of *Phaeocystis* in waters from Buzzards Bay to the western Gulf of Maine (Libby *et al.* 2006d). There is no obvious spatial association with MWRA’s outfall—*Phaeocystis* has consistently been at least as, or more abundant far to the north and south of the outfall. Why *Phaeocystis* occurs in relatively high abundances in some years and not in others is not well understood and continues to be the focus of researchers. 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. A detailed evaluation of *Phaeocystis* blooms in Massachusetts Bay is presented in the 2005 Nutrient Issues Review (Libby *et al.* 2006d).

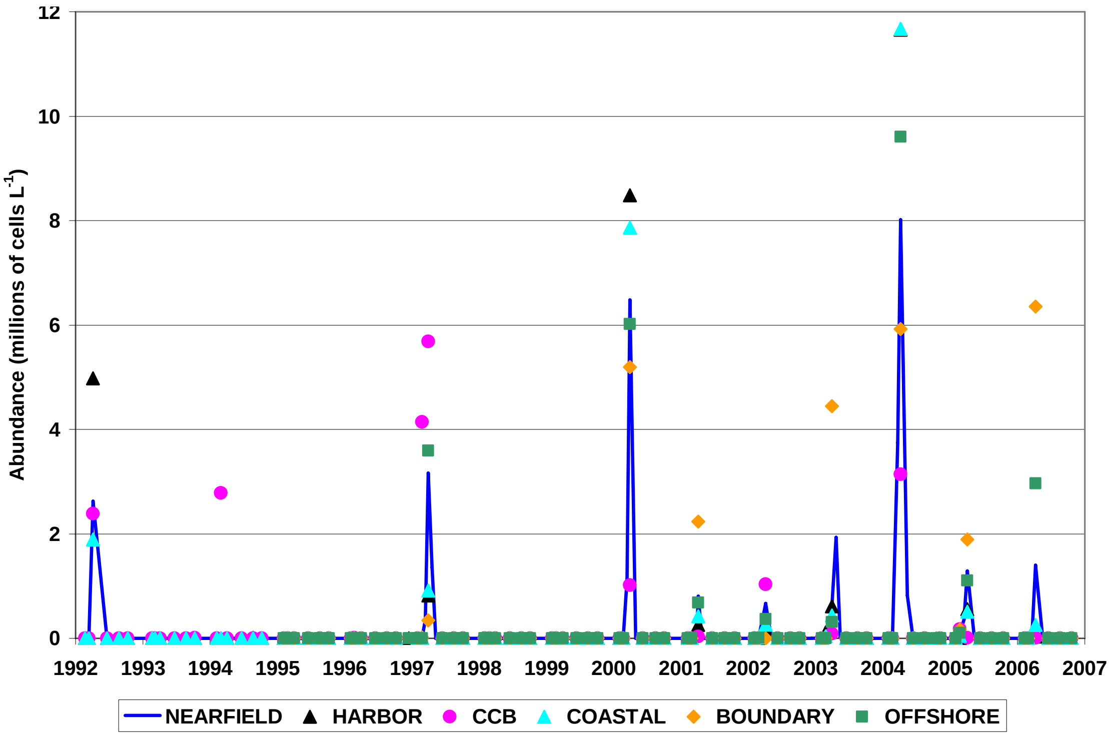


Figure 3-22. Time series of survey mean *Phaeocystis* abundance by area (1992-2006).

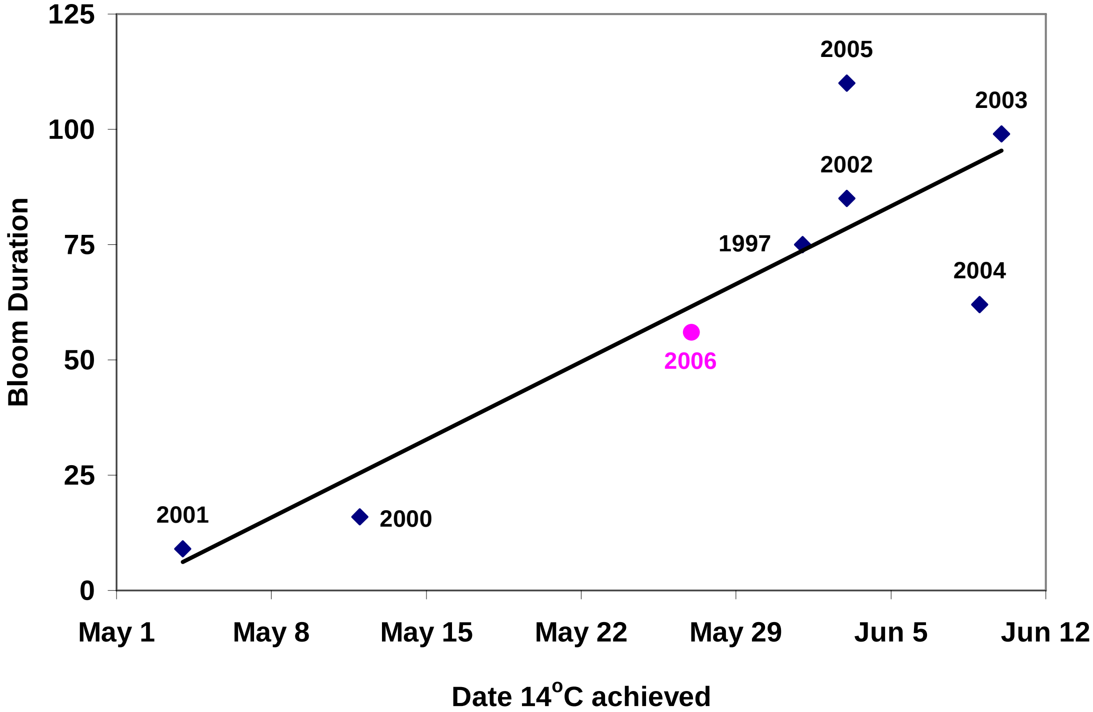


Figure 3-23. *Phaeocystis* bloom duration related to first date of 14°C at the NOAA 44013 Buoy 2000-2006. Linear regression r^2=0.77, n=8, P=0.004.

3.4.1.2 *Alexandrium* Bloom

The 2006 Gulf of Maine *Alexandrium* bloom was significant in size, and extended into Massachusetts Bay, but cell abundances and paralytic shellfish poisoning (PSP) toxicity were not as extensive or high as in 2005. Cell abundances in the bay in 2006 were well above those observed during the MWRA program from 1992 thru 2004, but about 25% of the maximum counts seen in 2005 (**Figure** 3-24). The 2006 *Alexandrium* bloom also resulted in the second highest (2005 was the highest) PSP toxicity measured in Massachusetts from 1972-2006 (**Figure** 3-25). The high PSP toxicity resulted in shellfish closures along the entire coast of Maine, NH and south to the Marshfield/Duxbury line in Massachusetts (**Figure** 3-26). Although these closures were far reaching, they were not as extensive nor as long in duration as those endured during the 2005 bloom, which closed nearly all of the Massachusetts coastline from May to July.

In 2006, *Alexandrium* counts from the screened water samples collected during regular MWRA water column surveys were relatively low with a maximum of 346 cells L^{-1} in May for the surface water at station N18. The highest nearfield count observed using the *Alexandrium fundyense*-specific DNA probe analysis was in the surface water at station N20 (5,667 cells L^{-1}). Both of these samples were collected during the mid-May nearfield survey (WN066) and are well above the caution threshold of 100 cells L^{-1} (**Figure** 3-24, **Table** 3-1). Note that both *A. tamarense* and *A. fundyense* occur in the Gulf of Maine and are considered to be varieties of the same species that cannot be distinguished from each other during routine monitoring analysis (Anderson *et al.* 1994; Scholin *et al.* 1995). For the purpose of this report, *Alexandrium* and *A. fundyense* are grouped together and both names are used interchangeably to refer to these saxitoxin-producing forms.

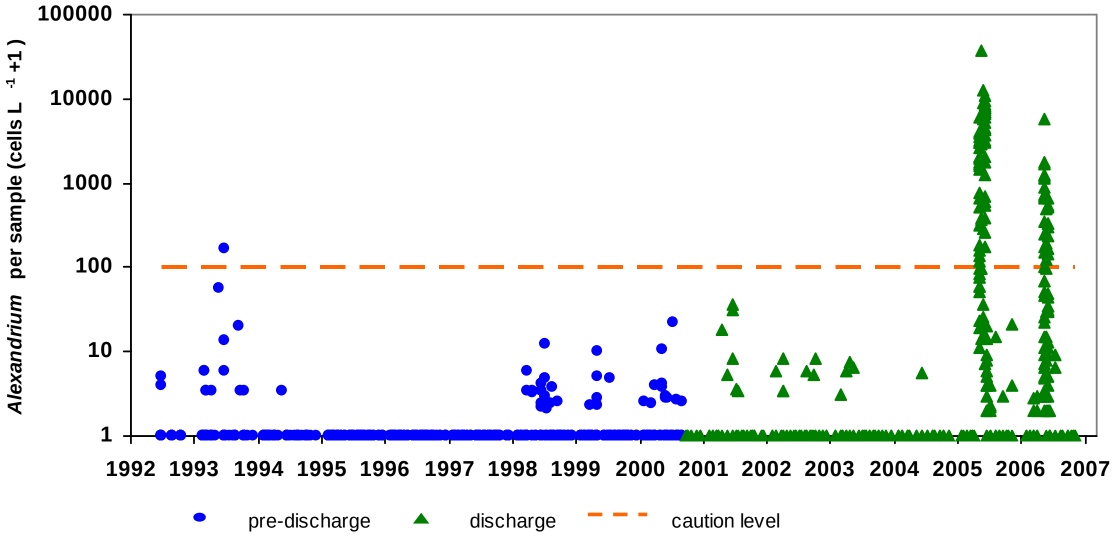


Figure 3-24. Nearfield *Alexandrium fundyense* abundance (cells L^{-1}) for individual samples for 1992 to 2006. Data from 20-µm screened water and DNA-probe analyses. Contingency Plan threshold value shown as dotted line. (Note log-axis and showing values +1).

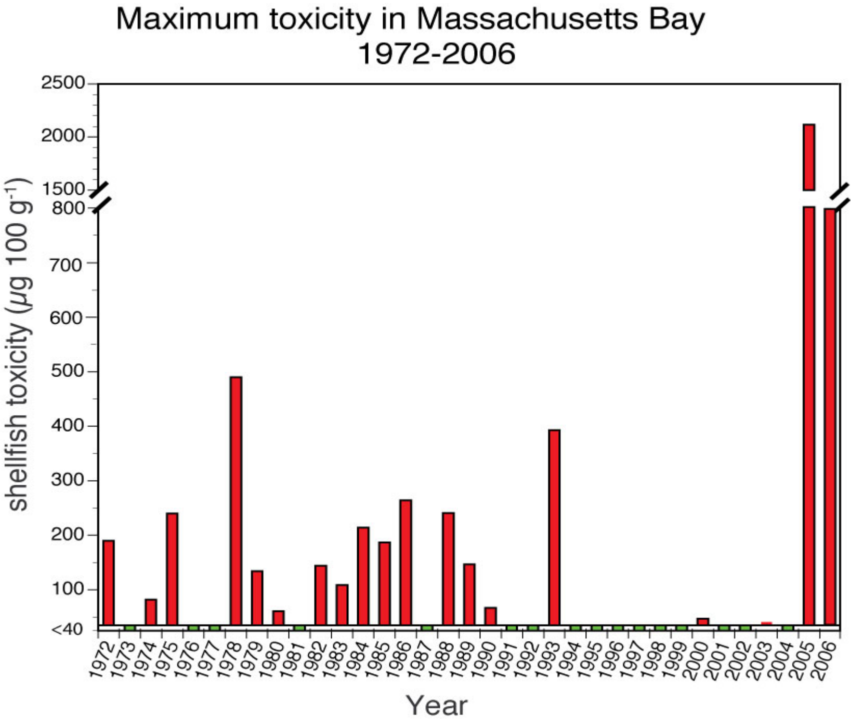


Figure 3-25. Maximum PSP toxicity measured within Massachusetts Bay from 1972 to 2006. (Source: data compiled by D. Anderson from Massachusetts Division of Marine Fisheries).

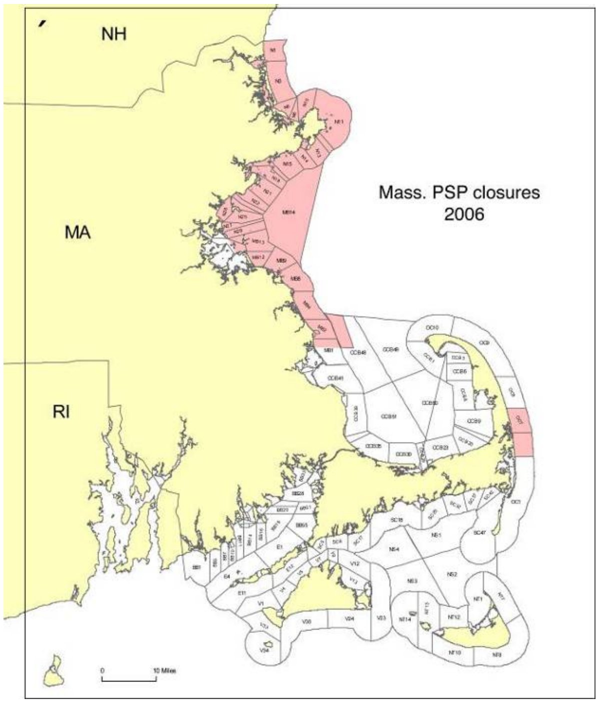


Figure 3-26. Shellfish closures along the Massachusetts coastline due to detection of PSP toxins during the 2006 *A. fundyense* bloom. Note that the closed area along the outer Cape Cod is the Nauset Marsh system, which has self-seeding, *in situ* blooms that occur independently of the regional, coastal blooms of this species. (Source: Massachusetts Division of Marine Fisheries).

A conceptual model developed during the Ecology of Harmful Algal Blooms (ECOHAB) - Gulf of Maine program explains many aspects of the blooms of *A. fundyense* (Anderson *et al.* 2005b; McGillicuddy *et al*. 2005; **Figure** 3-27). The model is built on a basic understanding of the regional circulation in the GOM. A key feature of GOM circulation is the Maine Coastal Current System (MCC), described by Lynch *et al*. (1997) as a composite of seven legs or segments with multiple branch points. The branch point of most interest for our evaluation is near Cape Ann, where Western MCC (WMCC) water can enter the Massachusetts/Cape Cod Bay system or it can predominantly bypass the bay, with water traveling along the eastern flank of Stellwagen Bank. 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. Also at the foundation of the model are cyst "seedbeds" in the sediments of the Bay of Fundy and the western Gulf of Maine south of the mouth of the Penobscot River (Anderson *et al.* 2005b). These serve as the inoculum for *A. fundyense* blooms in both the Eastern MCC and WMCC, respectively. Thus, the *A. fundyense* populations that cause PSP problems in the western Gulf, including Massachusetts Bay, have two possible origins. One is from cells delivered to the WMCC from the EMCC (Anderson 1997; Townsend *et al*. 2001; Keafer *et al.* 2005; Luerssen *et al*. 2005), and the other is from the germination of cysts from the large seedbed located offshore of Penobscot and Casco Bays (Anderson *et al*. 2005b).

When waters of the WMCC enter the bay, *A. fundyense* cells that are in the current enter as well. Timing is important, as transport events can obviously bring water without cells, if none are present in the WMCC near Cape Ann at that time. Likewise, the WMCC can have many cells in it, but few will enter the bay if the winds are not favorable when those cells are passing near the northern entrance to the bay. The residence time of water within the bay can be several weeks or longer (Geyer *et al*. 1992), so the introduced population can increase in abundance, causing toxin to accumulate in shellfish along the transport and growth pathway. Failure of the coastal current and its associated planktonic "pulses" of cells to enter the bay can result in years with little or no toxicity within the bay, even though PSP scores may be high in western Maine and New Hampshire. Because of the dynamic nature of this Cape Ann branch point, *A. fundyense* blooms and associated outbreaks of PSP within Massachusetts Bay are more sporadic than those in southwestern Maine, occurring every few years during the 1970s, '80s, and early 90s rather than annually (Franks and Anderson 1992). Since 1993, virtually no toxicity had been observed within the bay until the 2005 bloom.

Mathematical modeling conducted by WHOI scientists has evaluated the relative importance of three factors hypothesized to be the most important (river flow, winds and cyst abundance) to the development of *Alexandrium* blooms in general and the 2005 bloom in particular. The model sensitivity analyses suggest that the high abundance of cysts in the western GOM sediments in 2004 was the dominant factor underlying the 2005 bloom in the GOM (Anderson *et al.* 2007; Anderson *et al*. in prep; He *et al*. in prep). Wind forcing was also important, as episodic bursts of northeast winds caused onshore advection and concentration of offshore populations. These downwelling-favorable winds also accelerated the along-coast flow, resulting in transport of high cell concentrations into Massachusetts Bay. The model simulations suggest that even without the 2005 storms and wind patterns (i.e., with winds like those in 2004, a non-bloom year) a major bloom would likely have occurred in Massachusetts Bay, although later in the season. Anomalously high river runoff in 2005 resulted in stronger buoyant plumes/currents, which then transported more nutrients to the Western GOM as indicated by *in situ* nutrient measurements. While affecting cell abundance in Massachusetts Bay, these buoyant plumes were confined to the coast and had limited impact on the broad, gulf-wide bloom distribution. Nutrient sensitivity tests were also conducted and indicated that there was little impact on the gulf-wide bloom (Anderson *et al*. 2007). Overall, the model sensitivity results indicate that 2004 cyst abundance is the predominant factor in the 2005 bloom.

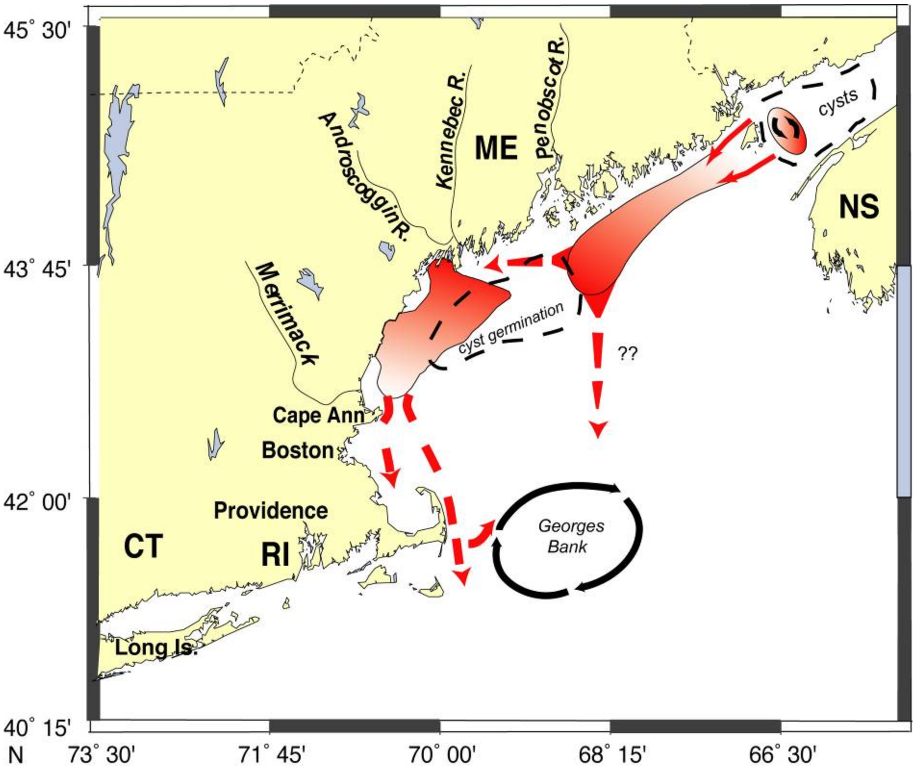


Figure 3-27. Conceptual model of *A. fundyense* bloom dynamics in the Gulf of Maine. Red dashed arrows represent episodic transport pathways. Cyst accumulation zones or seedbeds are outlined with black dashed lines. Red color denotes the extent of bloom development in a given area. (From Anderson *et al*. 2005b).

WHOI researchers conducted a cyst survey in fall 2005 that showed cyst abundances in a similar distribution, but at abundances of about 50% the 2004 levels (Anderson *et al.* in prep). Thus, expectations were that there would be another large, regional *Alexandrium* bloom in 2006.

The conditions that had been implicated as contributing to the 2005 *A. fundyense* bloom were also observed in 2006:

1. Abundant rainfall potentially provided micro- and macro-nutrients, increased stratification, and augmented alongshore transport.
2. Northeaster storms occurred when cells were abundant and in locations where the wind-driven surface currents advected them into Massachusetts Bay.
3. High abundance of cysts in western GOM sediments, documented in a fall 2005 survey, provided a large inoculum from which a major bloom could develop.

The 2006 bloom was indeed substantial and eventually extended from the Bay of Fundy to Cape Cod, and out to Georges Bank. Below is a chronology of its development, but please note that at the time of writing, the MWRA and WHOI datasets for 2006 have not been merged as had been done with the 2005 data (Anderson *et al*. 2007); thus the contour maps showing MWRA or WHOI data are on different scales, and MWRA plotted log+1 abundance. Furthermore, note that the counts reported for the WHOI surveys in this report are “live counts” made using traditional microscopic techniques while onboard the survey vessel at sea – their data on the probe counts of preserved samples from these surveys was not yet available. These live counts are comparable to those made using the fluorescent DNA-probe method

(Anderson *et al*. 2005d; Keafer *et al*. 2005), except that the probe method can distinguish *A. fundyense* definitively and the traditional microscopic technique may include other species of *Alexandrium* (*i.e. A. ostenfeldii*).

In April 2006, *Alexandrium* was first observed in the bays during WHOI surveys aboard the *R/V Tioga* (TI171 and TI177; **Figure** 3-28) and during the regular MWRA farfield survey (WF064). Typical concentrations of *Alexandrium* in the MWRA sampling area in most years are < 100 cells L^{-1} and in early and mid-April 2006 all WHOI and MWRA samples in the bays had counts of < 40 cells L^{-1}. *Alexandrium* abundance was highest at a station to the north of Cape Ann during the late April *R/V Tioga* survey reaching 145 cells L^{-1} (**Figure** 3-28). This cell count and the PSP closures in western Maine (May 2) and elevated NH PSP levels caused MWRA to consider implementing the *Alexandrium* Rapid Response Survey (ARRS) plan (Libby 2006).

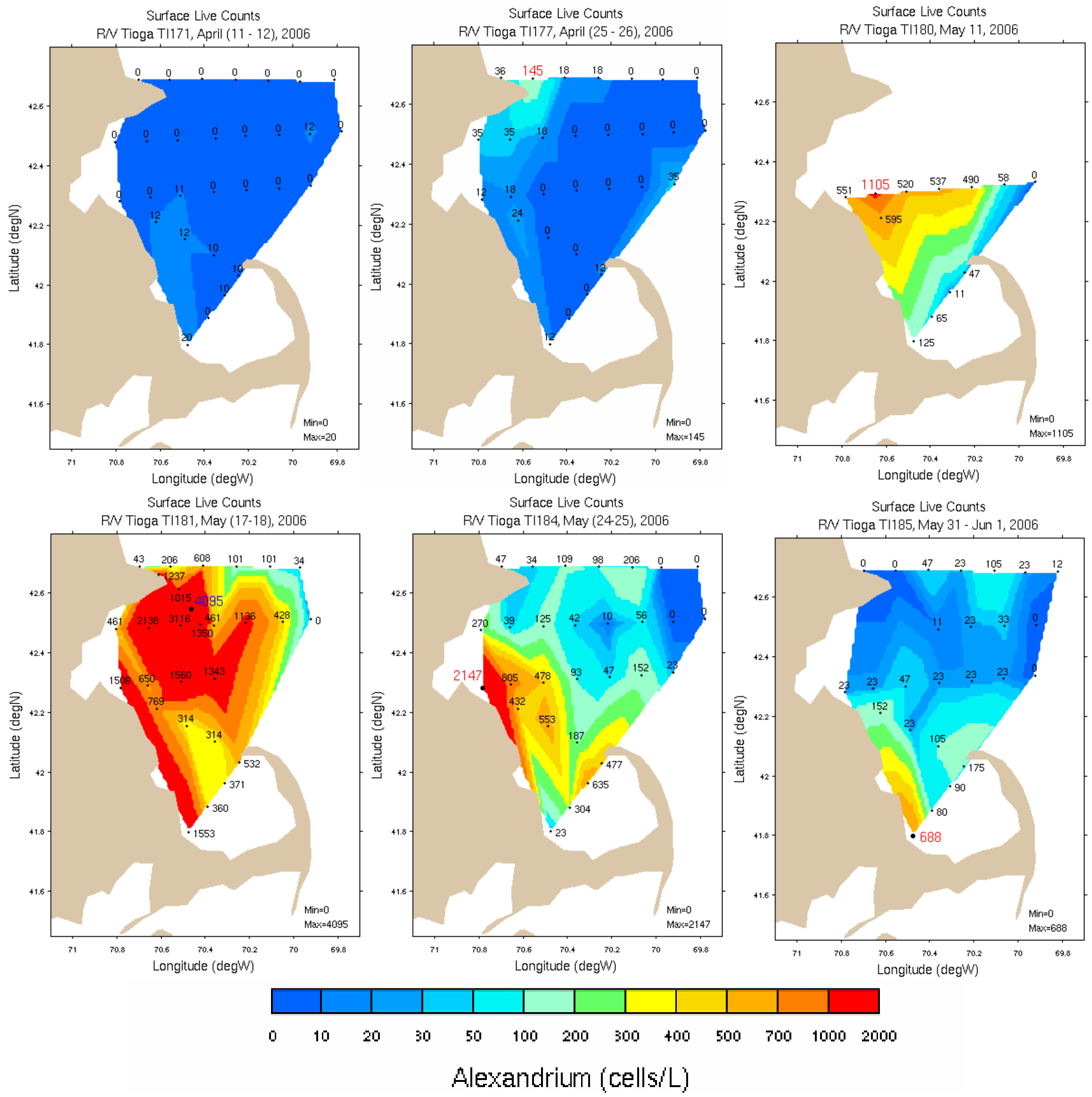


Figure 3-28. Surface water live counts of *Alexandrium* during WHOI *R/V Tioga* surveys from April to June 2006. Data and figures from Anderson, McGillicuddy, and Keafer unpublished data from http://science.whoi.edu/users/olga/alex_surveys_2006/WHOI_Alexandrium_Surveys_2006.html.

The *R/V Tioga* survey on May 11 was not able to be completed due to high winds and seas, but high *Alexandrium* counts (>500 cells L^{-1}) were observed in Massachusetts Bay with the maximum count of 1,105 cells L^{-1} measured in surface waters off of Cohasset to the south of the nearfield area (**Figure** 3-28). These results triggered the ARRS monitoring plan for 2006 and the nearfield survey (WN066) scheduled for May 17 was modified to collect *Alexandrium* probe samples at the nearfield stations and six additional stations along the South Shore. High *Alexandrium* abundances (≥ 692 cells L^{-1}) were measured in the surface water at all 13 stations sampled with a maximum of 8,418 cells L^{-1} at station F13 (**Figure** 3-29). This station is located off of Cohasset and is in the same general area as the maximum count from the *R/V Tioga* survey (TI180) nearly a week earlier. Another *R/V Tioga* survey (TI181) was conducted coincident with WN066 on May 17-18 that collected samples over a broader spatial extent in the bays, east of Stellwagen Bank and north of Cape Ann (**Figure** 3-28). Surface live counts of >1,000 cells L^{-1} were found off of Sandwich in Cape Cod Bay and throughout most of Massachusetts Bay. The highest abundance (4,095 cells L^{-1}) was seen in northeastern Massachusetts Bay south of Cape Ann. These two surveys (WN066 and TI181) in mid May captured the peak of the 2006 *Alexandrium* bloom in the bays as subsequent surveys showed a bloom with generally lower counts and less extensive spatial coverage across Massachusetts and Cape Cod Bays.

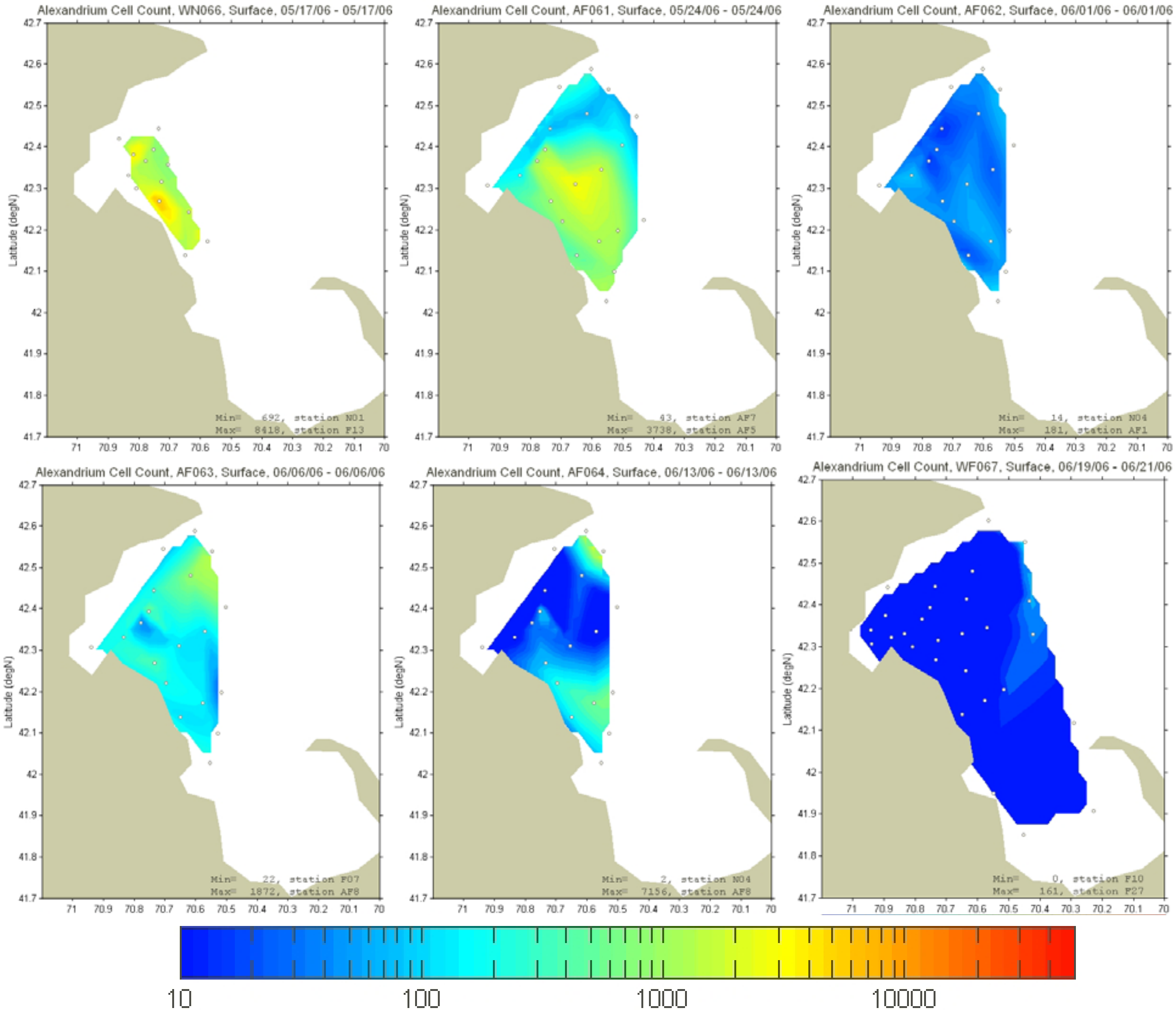


Figure 3-29. Surface water *Alexandrium* abundance (DNA probe, cells L^{-1}) during each of the MWRA surveys from May through June.

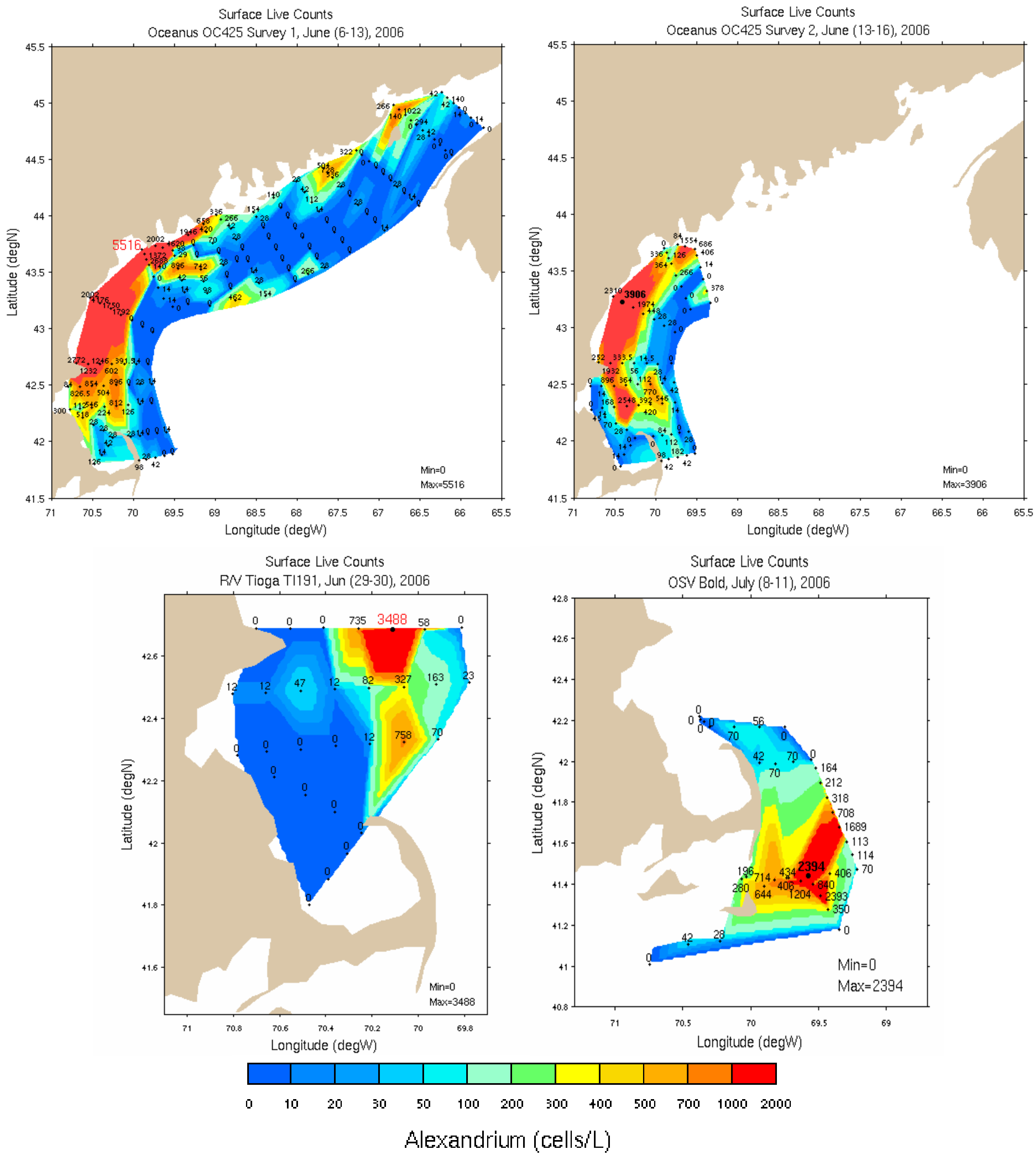


Figure 3-30. Surface water live counts of *Alexandrium* during WHOI *R/V Oceanus*, *R/V Tioga* and *OSV Bold* surveys from June and July 2006. Data and figures from Anderson, McGillicuddy, and Keafer unpublished data.

In hindsight, it is clear that although the 2006 *Alexandrium* bloom in Massachusetts Bay faltered after mid-May, it was on track to being a substantial bloom: the abundances observed during the May 17-18 surveys were much higher than any pre-2005 measurements and were even comparable to the values seen in May 9-17, 2005 (Anderson *et al.* 2007). Given these high counts, a repeat of the unprecedented 2005 bloom and associated PSP levels was expected. Fortunately, meteorological conditions did not continue to mimic those of 2005. Although there had been strong northeaster storms in late April/early May that likely transported the bloom into Massachusetts Bay and a subsequent northeaster on May 10-12, the winds for the rest of May to mid-June were weak and inconsistent. These conditions were neither conducive for cell inputs from the GOM to the bays nor for downwelling and buildup of waters along the coasts as in 2005 (Anderson *et al*. 2005a). By May 24, *Alexandrium* counts had decreased, especially in northeastern and eastern Massachusetts Bay (<200 cells L^{-1}; **Figure** 3-28 and **Figure** 3-29). During these surveys, the highest abundances were found at station AF5 south east of the nearfield (3,738 cells L^{-1}) during the MWRA survey AF061 (May 24) and just to the north of Cohasset (2,147 cells L^{-1}) on survey TI184.

The lull in winds combined with increasing stratification and low surface water nutrient levels likely contributed to the drop in *Alexandrium* abundance by May 31-June 1. Maximum surface water NH_4, NO_3 and PO_4 concentrations during the AF062 survey (June 1) were all ≤ 0.3 µM. The surface water *Alexandrium* abundance peaked at only 181 cells L^{-1} at station AF1 off of Plymouth Harbor (**Figure** 3-29). Similar counts were seen during the TI185 survey (May 31-June 1), but there was a higher maximum (688 cells L^{-1}) observed further to the south near the Sandwich end of the Cape Cod Canal (**Figure** 3-28). *Alexandrium* counts were higher for the AF062 10 and 20-m depth samples (up to 825 cells L^{-1}, data not shown) presumably due to the availability of nutrients deeper in the water column. By June 6-8, *Alexandrium* abundances had increased over most of the bay, but peak counts (>1,000 cells L^{-1}) were found in northeastern Massachusetts Bay during both Leg1 of the *Oceanus* survey (**Figure** 3-30) and survey AF063. Higher abundances were found further north off of Casco Bay, ME (>5,000 cells L^{-1}) during the *Oceanus* survey and on the southward Leg 2 of this survey the main part of the bloom remained north and offshore of Massachusetts Bay. A similar pattern was observed during the coincident AF064 survey (June 13) with the maximum *Alexandrium* abundance (>7,156 cells L^{-1}) seen at station AF8 south of Cape Ann. The only other sample with *Alexandrium* abundance >1,000 cells L^{-1} was at nearby station AF9 also in the surface waters. This survey was conducted after a substantial rainfall/river flow event (see **Figure** 3-1) that was evident in the bays as a riverine signal of lower salinity near Boston Harbor and in northeastern Massachusetts Bay (see **Figure** 3-11). The riverine plume was also rich in macro-nutrients and micro-nutrients as evidenced by relatively high SiO_4 and CDOM concentrations, respectively. This riverine CDOM has been noted as possibly effecting blooms of *Alexandrium* (Anderson *et al.* 2005a) by providing micronutrients including essential trace metals and organic materials that are important growth factors for *Alexandrium* (Prakash and Rashid 1968; Wells *et al.* 1991; Gagnon *et al*., 2005).

On June 19-21, *Alexandrium* abundance had decreased sharply ≤70 cells L^{-1} (mostly <10 cells L^{-1}) throughout the bays at all depths, except at station F27 south east of Cape Ann where surface and 10-m counts were 161 and 765 cells L^{-1}, respectively. By the end of June, surface counts in the bay were <50 cells L^{-1} and the bloom was clearly an offshore population (**Figure** 3-30). A subsequent survey in July found that the bloom had remained offshore to the southeast of Cape Cod and no cells were observed in eastern Massachusetts Bay.

Overall, the 2006 *Alexandrium* bloom was significant, but still substantially shorter and smaller in Massachusetts and Cape Cod Bays than the bloom in 2005. The 2006 bloom lasted about four weeks (mid May to mid June) with counts of 1,000 to 10,000 cells L^{-1} observed in the bays. By mid-June, these higher abundances were primarily observed in northeastern Massachusetts Bay. In comparison, the 2005 bloom was present in the bays for nearly 2 months with abundances as high as 40,000 cells L^{-1}

(Anderson *et al.* 2005a; Anderson *et al.* 2007). The maximum cell counts observed in Massachusetts Bay at the height of the 2006 bloom were only 25% of those observed at the peak of the 2005 bloom. Additionally, shellfish closures triggered by the 2006 bloom were modest compared to 2005. Closures in Massachusetts Bay extended no further south than the Marshfield/Duxbury line (**Figure** 3-26), whereas the 2005 bloom closed all of Massachusetts and Cape Cod Bays, and extended as far south as Nantucket. Nonetheless, the 2006 bloom would have been a major event if not for the unprecedented *Alexandrium* bloom in 2005 as cell counts and toxicity were second only to the levels observed the previous year and were well above historical levels (**Figure** 3-24 and **Figure** 3-25).

One reason for a less intense bloom in the bays in 2006 may be due to the difference in meteorological conditions in late May and early June as noted above. As observed in 2005, 2006 was notable with respect to the frequency of northeaster storms during the late spring months. Plots of the wind forcing and near-surface current response at the GoMOOS-A buoy (see **Figure** 3-3) indicate the strong southeastward currents during the events in both 2005 and 2006. One important difference between the two years is in the duration of the wind events and timing of the northeaster storms and the high river flow events. The winds and resulting currents were stronger and of longer duration in 2005 compared to 2006 (**Figure** 3-3). Also during 2005, the late May northeaster storm occurred in combination with a peak in river outflow, and there was deep mixing of the fresh water and a strong near coastal expression of the current (Libby *et al*. 2006b). In 2006, the very large discharge event around May 15 occurred with nearly easterly winds (**Figure** 3-3), which did not result in large currents at GoMOOS-A. This is probably because the winds were more perpendicular than parallel to the coast, so the Merrimack River plume was not accelerated down-coast by the winds during the 2006 event and, therefore, not into Massachusetts Bay. The winds and associated currents continued to be weak and inconsistent from mid-May to mid-June, transporting cells within the bay to offshore waters, and keeping the main portion of the *Alexandrium* bloom offshore in June.

An important observation from the 2006 *A. fundyense* bloom is that the cells that were observed within Massachusetts Bay were predominantly advected into the bay. This is the pattern that has been observed for many years (Anderson 1997), but the large cell concentrations observed within the bay during the 2005 bloom led to the conjecture that abundant cysts would be formed within the bay that would overwinter, and then initiate an *in situ* bloom in 2006. The early season WHOI sampling was designed to detect such a bloom, but as seen in **Figures** 3-26 to 3-28, advection from the north appears to be the dominant inoculation mechanism. This is consistent with the extremely low cyst abundances measured in Massachusetts Bay sediments in a cyst survey conducted in the fall of 2005 (D.M. Anderson, unpublished data). It is not known why the cysts were so sparse in the bay following the 2005 event, but this might reflect a termination of the bloom due to grazing, a lack of suitable conditions to induce encystment (thin, high concentration layers of cells, nutrient limitation), or the transport out of the bay once sexuality was induced may have been too rapid to retain cysts.

The main objective of the ARRS monitoring effort is to evaluate what, if any, impact the bay outfall has on *Alexandrium* blooms in Massachusetts Bay. Based on the plume advection hypothesis (Anderson *et al*. 2005c) and historical DMF PSP data, it was hypothesized that two patterns that might be suggestive of an outfall effect would be if South Shore shellfish became more toxic or *Alexandrium* abundances were higher than toxicity or cell abundance on the North Shore, or became toxic first. During the 2005 red tide event, this was in fact observed, as the highest cell counts, and early and persistent toxicity were observed along the South Shore near Plymouth and Sandwich. In-depth examination of the data and model analyses were not able to find any significant link between the outfall and these regional patterns in cell abundance and toxicity for the 2005 bloom, but local effects could not be ruled out (Anderson *et al.* 2007). Thus, it is unclear if such a linkage can be made based on the monitoring data. One reason may be that the *a priori* hypotheses were in error as physical oceanographic conditions during the 2005 bloom are able to explain much of the patterns observed. The intense northeaster storms not only transported water into the bays from the Gulf of Maine, but also rapidly pushed waters along the shore and to the south (Anderson *et al.* 2005a; Anderson *et al.* 2007). As a result, there is no need to invoke a nutrient stimulation or enhancement of growth to account for high cell concentrations and toxicity along the South Shore in 2005. The *a priori* hypothesis may indeed be suggestive and consistent with an outfall effect, but it is by no means indicative of a causative impact.

Nor is an outfall effect evident in the 2006 data. The early 2006 PSP toxicity pattern was similar to early 2005 with toxicity first noted in Maine and New Hampshire. In Massachusetts, PSP toxicity was first observed on the North Shore, then on the South Shore, but unlike 2005 the highest levels of PSP toxicity were found on the North Shore (~750 µg). Levels remained elevated on North Shore long after PSP toxicity was no longer measurable along the South Shore. These trends fit the historical patterns, but not the *a priori* hypotheses of an outfall effect. The only data that are suggestive of a possible outfall exacerbation of the 2006 bloom were the high toxicity levels (>180 µg saxitoxin per 100 g) recorded over a 2-week period in Cohasset. These levels were higher than MA DMF stations further to the south and to the north in Massachusetts Bay. The reasons remain unclear and may be undeterminable, although modeling approaches may help us to better understand the dynamic of these blooms. The *A. fundyense* population dynamics model (McGillicuddy *et al.* 2005) has certainly been a useful tool in examining the 2005 *Alexandrium* bloom (Anderson *et al.* 2007; Anderson *et al.* in prep; He *et al.* in prep). The extensive dataset on the 2006 bloom provides another opportunity to examine *Alexandrium* bloom dynamics and possible linkages with outfall nutrients via the proven modeling approaches. Different initial conditions (cysts), winds, currents and nutrient/*Alexandrium* distributions were observed in 2006 compared to 2005. The 2006 bloom exhibited PSP toxicity patterns similar those observed in the years prior to the 2005 event (though much higher levels). Further analysis of the differences between the 2005 and 2006 blooms – forcing factors, magnitude/duration, and PSP toxicity patterns – should provide additional insight into *Alexandrium* bloom dynamics in the Gulf of Maine and Massachusetts Bay.

3.4.1.3 Summer and Fall Diatom Blooms

In 2006, there were two blooms of the diatom *Dactyliosolen fragilissimus*; one in July and the other in early October (**Figure** 3-20). Both of these blooms were observed during nearfield surveys so the extent of the blooms is not completely known. The high chlorophyll levels (second highest survey mean for 2006 - **Figure** 3-8) associated with the July bloom elevated the mean summer 2006 chlorophyll level above the MWRA summer chlorophyll caution threshold (**Table** 3-1). The high chlorophyll concentrations during the early October bloom contributed to a relatively high fall mean chlorophyll concentration especially in comparison to the last few years when no substantial fall blooms have been observed (**Table** 3-2).

In July, *Dactyliosolen fragilissimus* was present in the nearfield at abundances of 1.29 to 5.86 x 10^6 cells L^{-1} and comprised 60-90% of cells counted from three of the four whole water phytoplankton samples collected. There were no *D. fragilissimus* in the mid-depth sample at station N04. The maximum abundance was in the surface water sample at station N18. The July 2006 *D. fragilissima* bloom led to a survey mean total diatom abundance well above the baseline range (**Figure** 3-31). The regional extent of the bloom as indicated by composite SeaWiFS images produced by University of Maine Orono suggest that the July bloom may have occurred throughout coastal waters in Massachusetts and Cape Cod Bays as well as the western Gulf of Maine (see **Figure** 3-14).

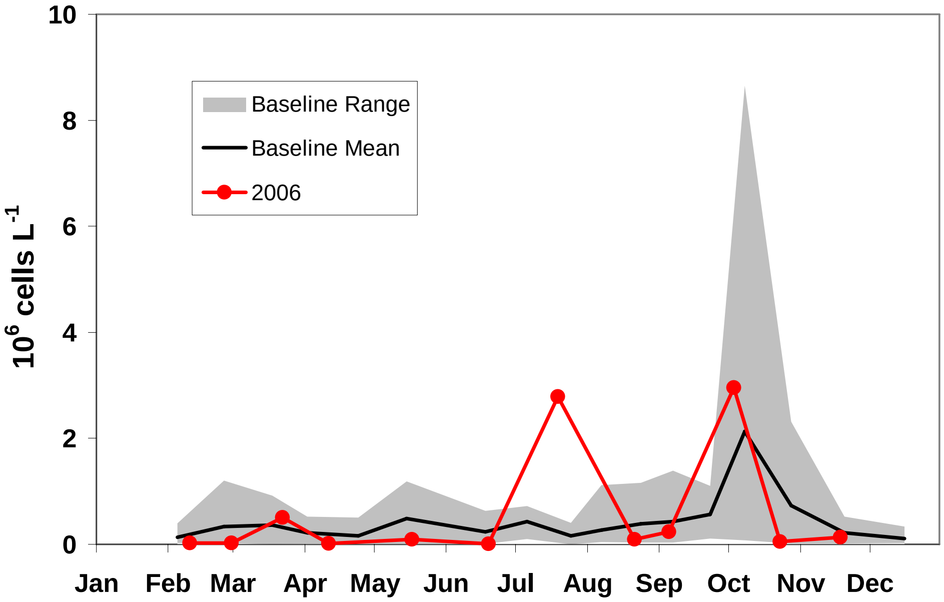


Figure 3-31. Time-series of survey mean total diatom abundance (10^6 cells L^{-1}) in the nearfield in 2006 compared against the baseline range and mean. Note the nearfield survey baseline mean and range are shown for 17 surveys vs. 12 in 2006. Data from stations N04, N16 and N18 only.

The July *D. fragilissimus* abundance peak was corroborated by a summer peak in areal chlorophyll levels and the annual maximum survey mean POC concentrations for the nearfield (**Figure** 3-8). Interestingly, a peak in productivity was not associated with the bloom (**Figure** 3-17). Production at station N04 was nearly double that at N18 even though phytoplankton abundance was only ~20% of the station N18 values. Although there is no clear reason for this disconnect between productivity and phytoplankton data, the depth of the subsurface chlorophyll maximum and relatively high light extinction at station N18 may explain the low production values seen at this station. The primary factor contributing to the occurrence of the bloom is the strong upwelling condition in July 2006 (see Section 3.1.1). This physical feature allowed nutrient replete waters to rise higher in the water column (**Figure** 3-13) where light limitation no longer inhibited phytoplankton production. Elevated nutrient concentrations were observed at 8-12 m depths and the highest in *situ* fluorescence values were coincident with the elevated nutrient concentrations near the pycnocline (**Figure** 3-12). It appears that the upwelling of the nutrient rich (ambient and outfall origin) waters fueled the moderately large summer *D. fragilissimus* bloom observed in mid July 2006.

In October, this same species was observed at bloom abundances at both depths at both nearfield stations sampled (1.40-2.44 x 10^6 cells L^{-1}), comprising 33-53% of cells counted. Another centric diatom, *Skeletonema costatum*, also made up a substantial portion of the surface N04 and mid-depth N18 sample with abundances of 1.3 and 1.4 x 10^6 cells L^{-1}, respectively. This early October mixed assemblage diatom bloom was on average comparable to the July bloom and elevated October total diatom abundance to near the high end of the baseline range (**Figure** 3-31). The early October bloom was coincident with peaks in chlorophyll and POC biomass measurements and a peak in production at station N18 though production was relatively low at station N04. Overall, even though the diatom abundance was relatively high in comparison to previous years, the magnitude of productivity at stations N04 and N18 during the fall bloom was relatively low and similar to 2004 and 2005 (**Figure** 3-18) – years when no fall bloom was evident in the production, biomass or phytoplankton data. MODIS satellite imagery for October 2006 suggests that the fall bloom observed in the nearfield occurred throughout Massachusetts and Cape Cod Bays (**Figure** 3-15). The satellite imagery shows a decline in Massachusetts Bay chlorophyll concentrations prior to the late October farfield survey.

3.4.2 Zooplankton

The variability in abundance and structure of the zooplankton community in 2006 in Massachusetts and Cape Cod Bays appear similar to patterns recorded since the beginning of sampling in 1992 (see Appendix D). Assemblages have been dominated throughout by copepod nauplii, *Oithona similis*, and *Pseudocalanus* spp. copepodites, throughout the year, with subdominant appearances of other copepods such as *Calanus finmarchicus*, *Paracalanus parvus*, *Centropages typicus* and *C. hamatus*, and sporadic pulses of various meroplankters such as bivalve and gastropod veligers, barnacle nauplii, and polychaete larvae. Zooplankton abundance generally increased from February through mid- to late summer, and then progressively declined through the fall and into winter.

Comparison of baseline and post-transfer zooplankton abundance and total copepod abundance in the nearfield suggests that there has been a decrease in abundance 1992-2000 to 2001-2006 (**Figure** 3-32). In 2006, nearfield means for total zooplankton and total copepods were at or below the baseline minima for all but the September survey. This has generally been the case during the post-transfer period with low values for copepod adults/copepodites and nauplii. *Oithona similis*, consistently the most abundant of the copepod taxa in the bays, has shown the most dramatic decrease for the February to August time period. The post-transfer decrease in total copepods has not been found only in the nearfield. This decrease is also apparent at stations in the boundary and offshore locations (**Figure** 3-33). However, not all copepod taxa have exhibited this decrease. *Calanus finmarchicus*, a relatively large zooplankter, has been present in the nearfield at abundances approximating the baseline mean during most of the year with a large increase in abundances being observed in May (**Figure** 3-34). Also, *Calanus finmarchicus* has shown post-transfer mean levels that approximate or exceed baseline means for the boundary, Cape Cod Bay and offshore regions (**Figure** 3-34).

It is unclear why zooplankton abundances have been lower in recent years than previously. This is explored using statistical approaches in the next section to discern whether or not these trends are significant. It may be that the apparent post-transfer decreases in total zooplankton abundance and copepod abundance at various locations throughout the survey area are driven by a few anomalously high values such as for the nearfield in 1999 and 2000 that are skewing the mean values (Appendix D).

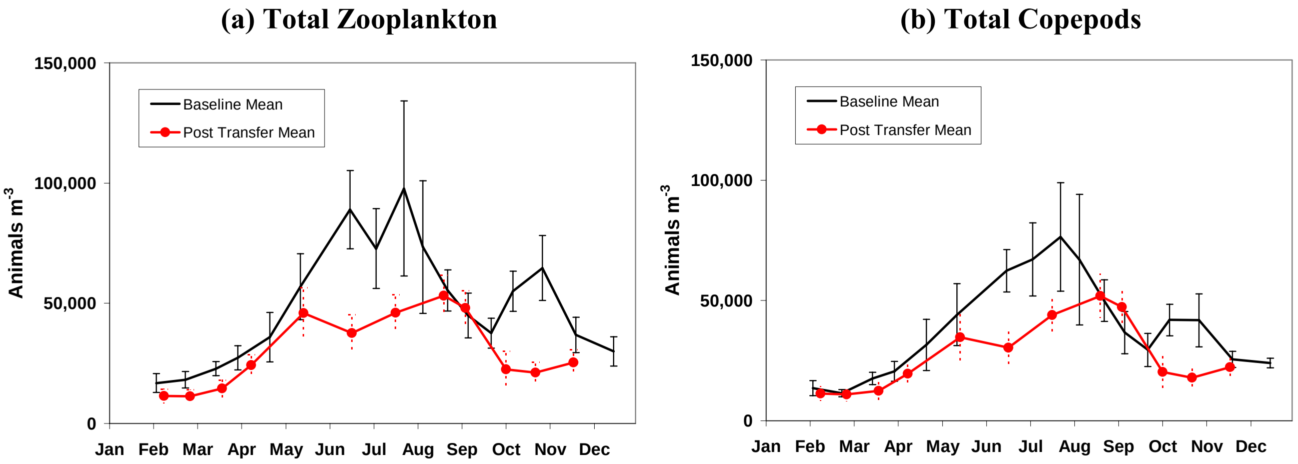
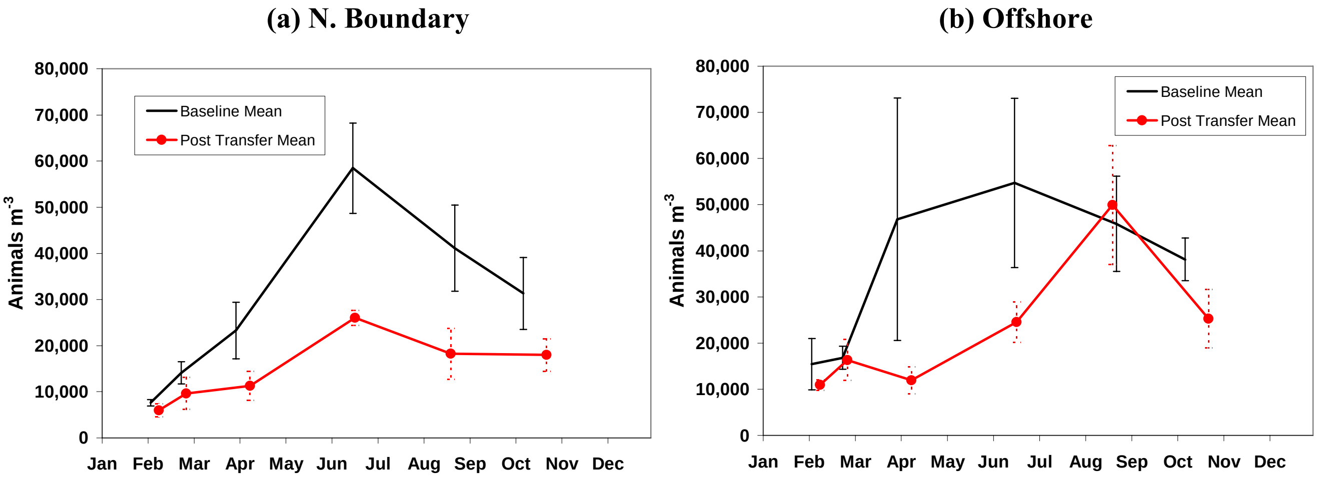
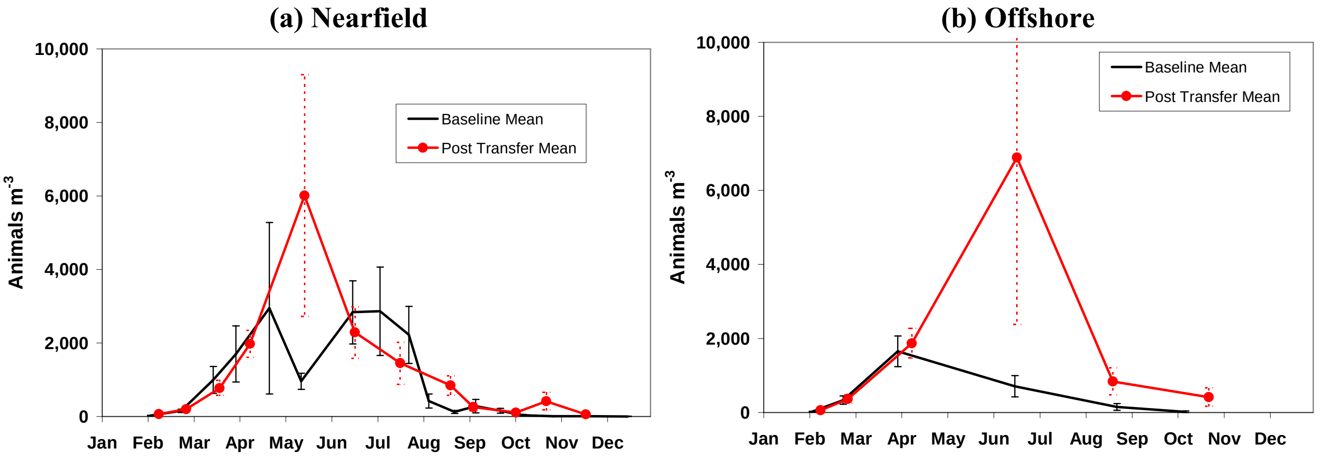


Figure 3-32. Time-series of survey mean (a) total zooplankton and (b) total copepod abundance in the nearfield during baseline (black) and post transfer (red) periods. Error bars represent ± SE. Note the nearfield survey baseline and post-transfer means are shown for 17 and 12 surveys, respectively and data are from stations N04, N16 and N18 only.

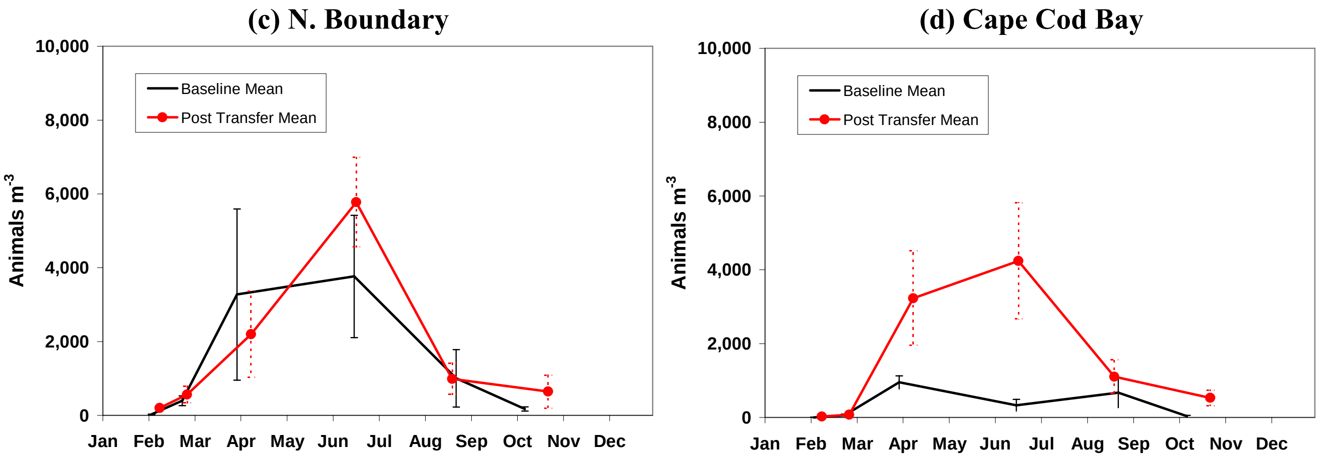

(a) N. Boundary

(b) Offshore

Figure 3-33. Time-series of survey mean total copepod abundance in the (a) northern boundary and (b) offshore areas during baseline (black) and post transfer (red). Error bars represent ± SE.


(a) Nearfield

(b) Offshore


(c) N. Boundary

(d) Cape Cod Bay

Figure 3-34. Time-series of survey mean *Calanus* abundance in the (a) nearfield, (b) offshore, (c) northern boundary and (d) Cape Cod Bay areas during baseline (black) and post transfer (red). Error bars represent ± SE.

4.0 INTERANNUAL COMPARISONS

Over the course of the ambient water quality monitoring program, general temporal and spatial patterns in water quality characteristics have emerged from the data collected in Massachusetts and Cape Cod Bays. The patterns 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 strongly influenced by regional meteorological and oceanographic conditions.

4.1 Physical Characterization

Massachusetts and Cape Cod Bays are subject to the combined influence of atmospheric forcing (wind stress, heat flux, and precipitation), river inflows (both direct and remote), and boundary forcing of tidal flows, storm surges, and currents of the Gulf of Maine—in particular the Western Maine Coastal Current (WMCC) (Brooks 1985; Brown and Irish 1992; Geyer *et al.* 2004). Temperature variations are mainly due to surface heating and cooling, following the seasonal cycle of air temperature. Salinity is mainly influenced by the river inflows, particularly the Merrimack and the Charles Rivers. The water properties in Massachusetts Bay are also influenced by the conditions in the Gulf of Maine—in fact it is instructive to think of Massachusetts Bay as a small "arm" of the Gulf of Maine rather than a distinct water body. This is illustrated in particular by the dissolved oxygen variations in Massachusetts Bay, which very closely track the variations in dissolved oxygen of the adjacent waters of the Gulf of Maine (Geyer *et al.* 2002).

Figure 4-1 shows a comparison of the GoMOOS-A 50-m DO data to the nearfield near-bottom observations for the July-December period for 2002 through 2006. The notable feature of the comparison is that the offshore waters show a very similar decrease in DO to the nearfield—a nearly constant decrease of approximately 1 mg L^{-1} per month. The interannual variations are mainly due to differences in the initial DO levels and the time of reventilation, when the DO level increases sharply. There are slight year-to-year differences in the slope of the nearfield DO to the GoMOOS data; for example in 2002, the nearfield decreased more rapidly than offshore, whereas in 2006 the nearfield showed a lower rate of decrease than offshore. The most likely explanation for a lower rate of decrease, as in 2006, is that there was some reventilation in the shallower waters of the nearfield (in September or October) that did not penetrate to 50-m depth measured at the GoMOOS-A buoy. The higher nearfield rates during other years may be associated with warmer water or possibly with higher consumption rates closer to shore.

The GoMOOS time series illustrate that the reventilation is a sudden process, occurring when fall cooling (due typically to a frontal passage) causes the overlying water to reach the density of the near-bottom water (see the next section for more information about destratification). The temporal resolution of the nearfield surveys was not adequate to determine whether the timing of reventilation was significantly earlier in the nearfield—it would be expected to be somewhat earlier due to the shallower water. These data confirm the observation noted by Geyer *et al*. (2002) and reported in previous water column reports (e.g. Libby *et al.* 2005a and 2005b) that the dissolved oxygen variation is mostly associated with regional variability rather than local variations associated with the conditions at the outfall. There are slight variations at the outfall from the regional patterns, but the interannual variations are mostly associated with the regional signal.

Currents within Massachusetts Bay are generally on the order of 10 cm/s (or 8 km/day) (Butman 1975), with stronger currents near the mouth, particularly in the vicinity of Race Point to the south and Cape Ann to the north. There is a general counter-clockwise circulation in Massachusetts Bay (Geyer *et al.*

1992), although the mean flow becomes weak in western Massachusetts Bay, and most of the flow there is due to tidal and fluctuating, wind-forced motions. The predominant wind-forced motions are upwelling and downwelling currents. Upwelling is caused by southerly winds, most typically during summer months. The surface currents are directed offshore due to the Coriolis effect acting on the wind-induced motions (Ekman transport; Csanady 1982). This causes the warm surface waters to be advected offshore and replaced by cooler waters that have upwelled from below the thermocline. Downwelling is the other important type of wind-forced motions. It is most strongly driven by northeasterly winds, as it sets up an along-coast flow between Cape Ann and Boston. During the spring, northeasterly winds may advect low-salinity water from the GMCC (Butman 1975), enhancing the circulation in Massachusetts Bay and potentially advecting harmful algal blooms into the bay (Anderson *et al*. 2005a). Downwelling is also associated with strong vertical mixing. Both upwelling and downwelling may contribute to increased productivity by bringing nutrients into the surface layer, either by advection (in the case of upwelling) or mixing (in the case of downwelling).

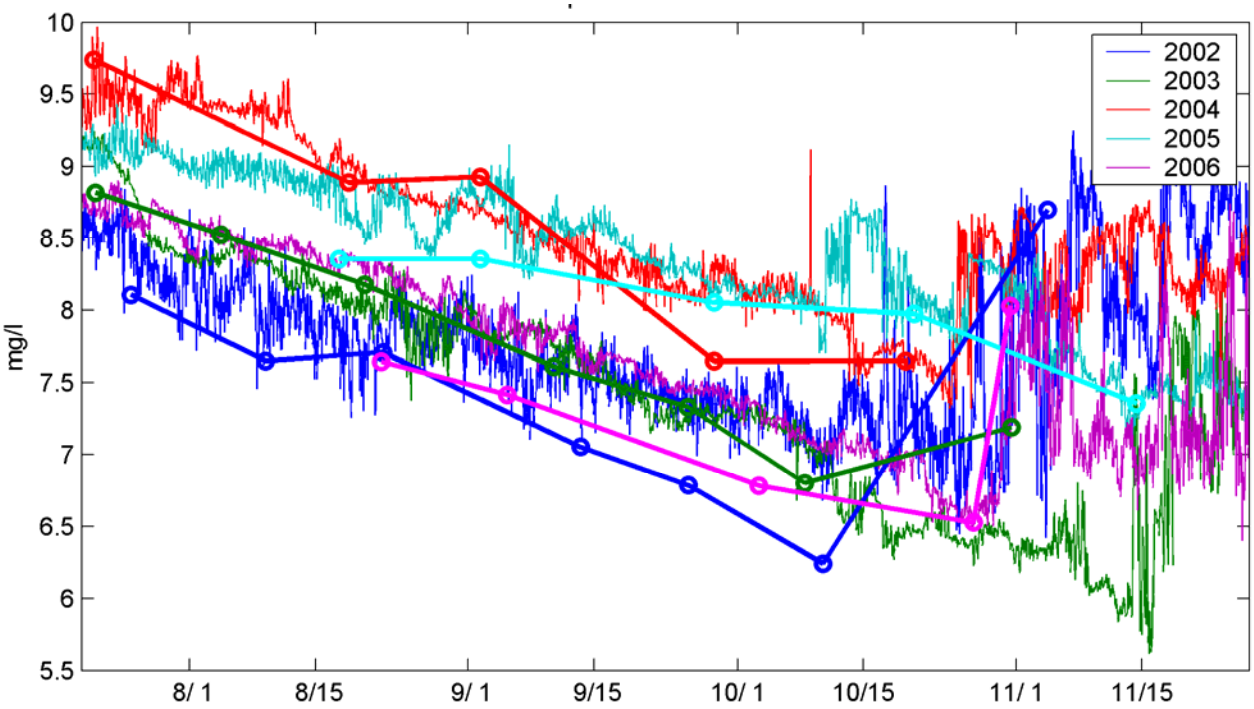


Figure 4-1. Timeseries of dissolved oxygen measured at the GoMOOS-A buoy, 50-m depth (thin, jagged continuous lines), compared with the nearfield, near-bottom DO (average of stations N16, N18 and N20), for the July-December period from 2002 to 2006. The GoMOOS data were adjusted based on the farfield station F22 to remove sensor offsets and drift (typically 1-2 mg/l errors).

The fate of effluent from the outfall depends on the stratification conditions and the regional current pattern. Stratification persists from May through October—this causes the trapping of the outfall plume below the pycnocline. During the unstratified winter months, the outfall plume mixes through the whole water column, with roughly twice the initial dilution as during the stratified months. The transport and dispersion of the effluent away from the outfall occurs due to a complex combination of tidal, wind-driven and density-driven motions. The dispersion is relatively rapid, rendering the effluent signal indistinguishable from ambient water within 10-15 km from the outfall site. No particular conditions have been identified that would significantly increase the residence time of the effluent during the unstratified period. Thus, the main importance of the physical forcing is to affect the physical and biological environment of the receiving waters. This section briefly examines the interannual patterns of key water quality parameters (nutrients, biomass and productivity) and provides statistical analyses of the pre- vs. post-diversion changes in these parameters as well as examining the more subtle changes observed in plankton community structure.

4.2 Nutrients

Seasonal patterns in nutrient concentrations are closely linked with both physical and biological factors and 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 and when. As implemented, the transfer from the Boston Harbor into Massachusetts Bay did not create a new source of nutrients to the system; rather it changed where the effluent is discharged both in location and water depth.

Annual reports have dealt with and examined the changes in nutrients since the bay outfall came on line by looking at changes in survey means by area, annual means by area, pre and post differences by station and season. Some of these comparisons are presented in Appendix B. In this section, we revisit the overall trends in annual mean nutrient concentrations across areas and then examine these trends at the seasonal level for seven key parameters (NH_4, NO_3, SiO_4, PO_4, areal fluorescence, chlorophyll and POC). In the 2005 annual report, a series of T-tests and intervention tests using a regression model approach were run to examine the pre- to post-diversion differences on a seasonal basis both for individual stations and groups of stations. The results of the regression analyses on individual stations showed that the percentage of significant slopes was great enough to indicate that regression-based tests are more appropriate than t-tests (which assumes a slope of zero) for assessing change (Libby *et al.* 2006b). Therefore, only the regression model approach was employed. However, instead of testing whether pre- and post-diversion intercepts and slopes differed, the analyses for 2006 examined the differences between estimated averages for the two time periods based on the regression models developed for each parameter, season, and location.

The regression methodology employed assumes that temporal parameter trends follow a linear model before and after outfall diversion and identifies cases where the linear temporal trend after diversion is significantly different than the linear temporal trend before diversion. The regression model analyses were performed for all individual stations and for pre-determined geographical station groupings (a modification of existing MWRA area groupings as shown in **Figure** 2-1) to increase power of change detection. The stations included in each grouping are as follows:

- Boston Harbor – F23, F30, F31 and Boston Harbor water quality monitoring (BHWQM) stations 24, 77, 106, 124, 138, 139, 140,141 and 142
- Cape Cod Bay – F01, F02 and F03
- Coastal – F14, F18, F24 and F25
- Nearfield – N01, N04, N07, N10, N16, N18 and N20
- MB north – F22, F26 and F27
- MB offshore – F12, F17, F19 and F28
- MB south – F05, F06, F07, F10, F13, F15 and F16.

The same sets of statistical tests and analyses performed for the 2005 report were repeated for the 2006 analyses. Shapiro-Wilk tests for normality were calculated for each individual station by season and parameter. The P-values were graphed and tested against a uniform (0,1) distribution with a Kolmogorov-Smirnov test for each season-parameter pair. Species for which the P-values associated with the log-transformed data more closely matched a uniform (0,1) distribution were flagged as needing log transformation. For each chemical, a one-way ANOVA model with a site effect was performed and the residuals graphed and tested for normality. Outcomes of the two evaluations of normality indicated that four parameters appear to be more normally distributed in log10-transformed space than in the non-transformed space: areal fluorescence, chlorophyll, NH_4, and POC. The remainder of the evaluation for these four parameters was performed on the log10 transformed values.

For each station grouping, the data was divided into pre- and post-intervention datasets. Each set of data was then modeled in a simple linear regression. The P-values from these regression analyses that tested whether the slope parameter was significantly different from zero were tested against a uniform (0,1) distribution with a Kolmogorov-Smirnov test. The results for the Kolmogorov-Smirnov test of uniformity showed that there were significant slope effects for simple linear regressions pre- and post-diversion. When analyzing individual stations, 83% of baseline slopes and 50% of post-diversion slopes were significantly different than zero. Similarly, 71% and 63% of baseline and post-diversion slopes were significant when grouping the stations. Although, it is expected that 5% of these slopes would be statistically significant by chance, the percentage of significant slopes was great enough to indicate that, as was found in 2005, regression-based tests are more appropriate than t-tests for assessing change. Therefore, a regression model was employed to test whether the intercept and slope of pre-diversion parameter values differed from the intercept and slope of post-diversion parameter values.

Levine's test was used to test for homogeneity of variance in residuals from the pre and post-diversion regressions. As observed in 2005, the results indicated that it was not appropriate to assume homogeneity of variance when performing the regression analyses and the following model, assuming non-homogeneous variances, was applied using SAS PROC MIXED (Little *et al*. 2006):

$$Y_i = (1 - I_{Post})(\beta_{0,\mathrm{Pre}} + \beta_{1,\mathrm{Pre}} \cdot time) + I_{Post}(\beta_{0,Post} + \beta_{1,Post} \cdot time) + \varepsilon_i$$

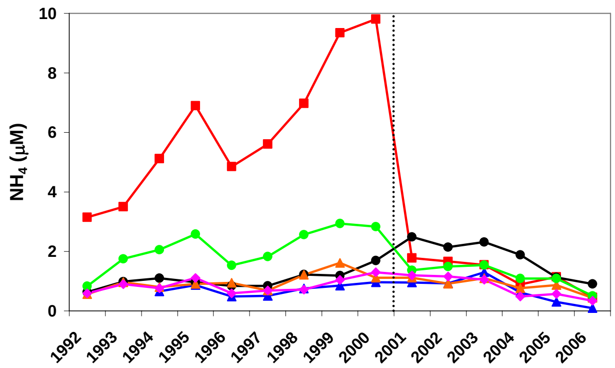
where I_{Post} is an indicator variable that is equal to zero for pre-diversion data and one for post-diversion data. A two degree of freedom test that contrasts $\beta_{0,Pre}$ with $\beta_{0,Post}$ and $\beta_{1,Pre}$ with $\beta_{1,Post}$ was performed to determine whether or not parameter status and trends prior to diversion differed from status (intercepts) and trends (slopes) after diversion on a station by station and grouped station basis.

A regression model was developed for each combination of species, stations and seasons. By providing information about group (pre-diversion or post-diversion) and average dates, average concentration and associated standard error were estimated from the model. The pre- and post-diversion estimates were tested for equality. The null hypothesis was that there is no difference between pre- and post-diversion. P-value is the probability to see a difference equal to or more extreme than observed difference given the null hypothesis is true. A small P-value indicates it is unlikely to get the observed difference given the null hypothesis is true and we reject the null hypothesis. By using the regression model to perform this test, the test is more powerful than a standard t-test, since the t-test would have an inflated variance estimate that incorrectly includes variability due to trends in the variance estimate. The regression model estimates do not suffer from this and take into account temporal variability in both the estimated average and standard error.

Multiple comparison corrections have not been made for these analyses; rather the findings and discussion rely on a weight of evidence in ascribing significant change. In this analysis when the number of significant results is substantially higher than 5% of the tests, the difference is deemed significant relative to the intervention. Additionally, if the tests with $P \leq 0.05$ are spatially grouped, it provides more certainty that those tests are significant. The statistical results are provided in context of the graphical characterization of the data and pre- vs. post-diversion changes.

The most obvious and expected change in nutrient concentrations that was associated with the diversion to the bay outfall was the increase in NH_4 concentrations in the nearfield and decrease in Boston Harbor and nearby coastal waters. This has been borne out since the bay outfall came online with a definable effluent plume often observed by its NH_4 signature in the nearfield – up to the surface during well-mixed conditions and confined below the pycnocline during periods of stratification. The change in NH_4 has also been found in annual mean concentration data for these areas. For example, the annual mean NH_4 concentration in Boston Harbor dropped sharply from 2000 to 2001 (**Figure** 4-2a). A similar sharp decrease was also measured 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, however, the last full year before the bay outfall came online, annual mean NH_4 levels in the nearfield increased and had almost doubled several years after the relocation. This gradual transition may in fact reflect the period when the discharge, high in NH_4, was located at the harbor mouth, and the signature reached into the bay near the present outfall.

(a) Annual NH_4



(b) Annual NO_3

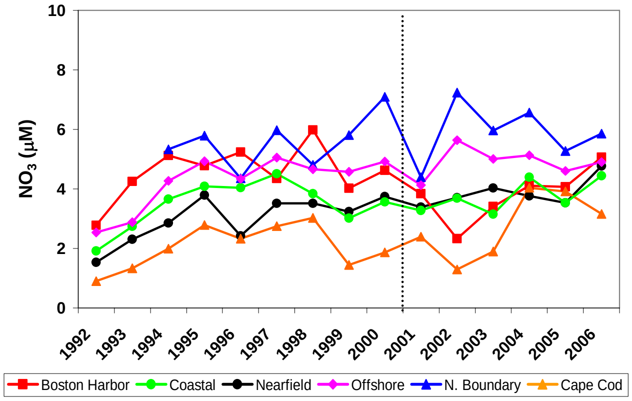


Figure 4-2. Time-series of annual mean (a) NH_4 and (a) NO_3 concentrations (µM) by area. Data collected from all depths and all stations.

Levels in the nearfield in 2005 and 2006, however, decreased from previous years to levels comparable to baseline values. This may be due to the stormy winter/spring during each of those years that likely increased dilution of the plume NH_4 signal in the nearfield. It had been suggested that the decrease from 2003-2006 may be an artifact associated with the sampling re-design of the nearfield that was instituted in 2004 (reductions of 21 to 7 stations and 17 to 12 surveys). An examination of the data using only results from the 7 stations and 12 surveys currently sampled showed nearly identical patterns (slightly lower annual mean concentrations in 1999 and 2000). The sampling re-design is not the reason for declining NH_4 concentrations from 2003 to 2006 in the nearfield. As presented in **Figure** 4-2, this pattern was also detected in each of the other areas of the bays. Overall, NH_4 levels in offshore, boundary, and Cape Cod Bay waters have remained steady since 1992 suggesting no change at these farfield areas since the transfer to the bay outfall.

The patterns in annual mean concentrations of other inorganic nutrients are more erratic as seen in the example of NO_3 (**Figure** 4-2b). 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 patterns in background levels. However, there does appear to be a pattern of increasing NO_3 concentrations since the early 1990's except in Boston Harbor. The largest change has been seen in the nearfield and offshore Massachusetts Bay and Cape Cod Bay waters.

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, Hunt *et al.* 1999). 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 (Libby *et al.* 2006a). 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** 4-3). 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.

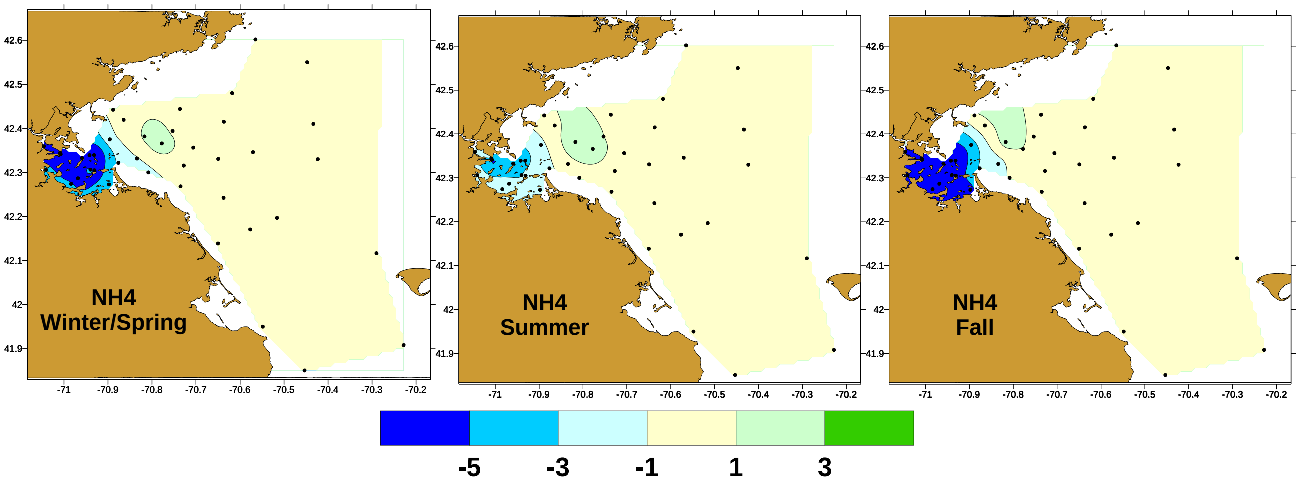


Figure 4-3. Change in seasonal NH_4 concentrations (µM) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

When analyzed on a station by station basis over all three seasons there were significant changes in the pre- vs. post-diversion regression based averages for 45% (55 of 123) station/season combinations of NH_4 data. In Boston Harbor, all of the 36 station/season combinations showed a significant change (decrease) in seasonal mean NH_4 concentrations (all P-values were <0.01 and 29 of 36 were <0.0001). At the four coastal stations, 5 of 12 combinations showed significant changes. Most of the changes were decreases in winter/spring mean NH_4 concentrations (stations F14, F24 and F25), but at station F18 there was a significant increase in the summer. About half of the 21 station/season combinations in the nearfield had significant changes (increases for all but station N10) from pre to post-diversion. NH_4 concentrations decreased at station N10 during both the winter/spring and fall by more than 1 µM (**Figure** 4-3) and these decreases were statistically significant. This station has historically exhibited patterns in water quality parameters consistent with harbor and coastal areas and is influenced by tidal flow from the inshore waters. Significant increases in NH_4 seasonal mean concentrations in the nearfield were restricted to the 3 stations closets to the bay outfall (stations N16, N18 and N20). Except for station N16 fall, all of the increases in seasonal mean NH_4 at these three stations were significant (P-values from 0.04 to ≤ 0.0001).

To increase the statistical power to detect change, the stations were grouped geographically, as detailed above, and analyzed with the regression model analysis. The results of this analysis are presented in **Table** 4-1. Not surprisingly, the results for Boston Harbor show significant ($P<0.0001$) decreases in NH_4 concentrations during all three seasons. Significant decreases were also noted in the coastal region (winter/spring and fall) and throughout most of Massachusetts Bay (all MB regions, but not the nearfield) during the winter/spring. Nearfield values increased pre- to post-diversion during each season, but only the summer average was significantly higher than the pre-diversion NH_4 level (**Table** 4-1).

Table 4-1. Results of testing whether estimated pre- and post-diversion averages (as estimated using the regression models) are significantly different. The change in averages pre- to post-diversion and the associated P-value are listed by parameter, season, and station group.

Parameter	Station	Winter-Spring		Summer		Fall	
		Change	P-value	Change	P-value	Change	P-value
Areal Fluorescence	Boston Harbor	22.93	0.0279*	-24.02	0.0008*	5.31	0.5624
	Cape Cod Bay	8.52	0.6277	2.99	0.5754	-22.53	0.1143
	Coastal	29.81	0.0008*	-9.53	0.0617	-20.47	0.2331
	MB North	85.48	0.0003*	5.51	0.4796	-35.19	0.3514
	MB Offshore	45.50	0.0041*	-2.74	0.7327	-22.73	0.1981
	MB South	44.46	<0.0001*	-7.52	0.0893	-58.70	<0.0001*
	Nearfield	50.07	<0.0001*	6.00	0.0903	-11.20	0.1646
CHLA	Boston Harbor	1.23	<0.0001*	-2.17	<0.0001*	0.16	0.4217
	Cape Cod Bay	0.37	0.5415	-0.35	0.1478	-0.48	0.4790
	Coastal	0.94	0.1455	-0.33	0.4154	0.46	0.5703
	MB North	0.31	0.5767	0.32	0.2250	-0.43	0.2491
	MB South	1.60	0.0003*	-0.56	0.0639	-1.15	0.0845
	Nearfield	1.57	<0.0001*	0.21	0.1482	0.16	0.6017
NH_4	Boston Harbor	-5.21	<0.0001*	-2.32	<0.0001*	-7.12	<0.0001*
	Cape Cod Bay	-0.17	0.1227	-0.04	0.8124	-0.01	0.9537
	Coastal	-1.20	<0.0001*	0.01	0.9631	-0.90	0.0460*
	MB North	-0.29	0.0073*	0.06	0.6224	-0.11	0.1933
	MB Offshore	-0.32	<0.0001*	-0.03	0.7960	-0.08	0.1723
	MB South	-0.32	0.0004*	0.10	0.2236	0.07	0.4035
	Nearfield	0.26	0.0524	0.78	<0.0001*	0.23	0.0909
NO_3	Boston Harbor	-1.51	0.0002*	-0.42	0.0171*	-0.96	0.0002*
	Cape Cod Bay	0.49	0.4506	0.38	0.2016	1.01	0.0019*
	Coastal	-0.12	0.7101	0.42	0.0040*	1.34	0.0151*
	MB North	1.02	0.0634	-0.06	0.8722	1.36	0.0099*
	MB Offshore	1.06	0.0010*	-0.08	0.8143	0.76	0.1863
	MB South	0.64	0.0092*	0.42	0.0484*	0.89	0.0135*
	Nearfield	0.89	0.0007*	0.28	0.0072*	1.09	<0.0001*
PO_4	Boston Harbor	-0.34	<0.0001*	-0.28	<0.0001*	-0.67	<0.0001*
	Cape Cod Bay	0.07	0.1000	0.06	0.1521	0.14	0.0010*
	Coastal	-0.02	0.5279	0.01	0.8630	-0.03	0.6832
	MB North	0.11	0.0173*	0.03	0.2487	0.06	0.1966
	MB Offshore	0.09	0.0076*	0.01	0.6727	0.04	0.3797
	MB South	0.07	0.0039*	0.05	0.0341*	0.09	0.0136*
	Nearfield	0.10	0.0001*	0.06	0.0020*	0.07	0.0012*
POC	Boston Harbor	-5.50	0.0019*	-17.77	<0.0001*	-7.01	<0.0001*
	Cape Cod Bay	1.01	0.7554	4.05	0.1069	0.04	0.9868
	Coastal	1.64	0.6594	1.36	0.7045	-4.44	0.2935
	MB North	0.04	0.9833	4.66	0.1283	-1.66	0.6199
	MB South	3.27	0.1611	-0.92	0.6230	-5.72	0.0049*
	Nearfield	4.35	0.0009*	3.76	0.0034*	-1.49	0.2434
SiO_4	Boston Harbor	-1.74	0.0223*	-0.51	0.4229	-1.91	0.0175*
	Cape Cod Bay	0.05	0.9237	-0.08	0.9068	-0.45	0.4090
	Coastal	-1.04	0.0271*	0.36	0.2663	0.28	0.6936
	MB North	0.29	0.5664	-0.39	0.1047	-0.07	0.8822
	MB Offshore	-0.32	0.4638	-0.38	0.3332	-0.38	0.5094
	MB South	-0.90	0.0061*	-0.05	0.7659	-0.21	0.6288
	Nearfield	-0.16	0.5056	-0.25	0.0901	0.10	0.6330

* Pre-diversion average differs significantly from post-diversion average at the $P \leq 0.05$ significance level.

Several generalizations can be drawn based on the results presented in **Figure** 4-3 and **Table** 4-1. First, it is clear that there has been a decrease in NH_4 concentrations in Boston Harbor. All of the comparisons show a decreasing pattern in NH_4 concentrations and all of them are significant. Some coastal waters and even station N10 in the nearfield have also undergone a significant decrease in NH_4 concentrations – likely due to continued influence of harbor water quality at these stations. Second, there has been an increase in NH_4 concentrations at the three nearfield stations closest to the outfall and at the Broad Sound station F18 (summer only), just to the northwest of the nearfield.

Nitrate concentrations increased at nearly all of the nearfield stations during each of the seasons (only exception was N04 summer). Significant NO_3 increases (>1 µM) were noted at stations N01, N07, N18 and N20 in the fall, which were accompanied by increases throughout the bays (**Figure** 4-4). See for example, fall NO_3 concentration at the northern boundary stations F26 and F27 ($P<0.05$ at F27). Significant increases in NO_3 concentration were also observed at stations F13, F14, F18, and N20 in the summer and at station F18 in the fall. 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 a regional change 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.), changes in seasonal biological patterns (i.e. fewer and less intense fall blooms), or related to more circulation shifts related to larger scale processes (e.g. North Atlantic Oscillation).

Station F18 presents an interesting case in that summer (NH_4, NO_3, and PO_4) and fall (NO_3, PO_4, and SiO_4) concentrations increased significantly. This station is to the northwest of the nearfield and is located in an area susceptible to upwelling. While increases in NH_4 and PO_4 concentrations might be due to proximity to the bay outfall, the lack of a similar signal at the peripheral nearfield stations (station N01 lies between the outfall and F18) suggests that this change may be due to a change in upwelling favorable conditions (or at least the timing of them to coincide with surveys) during the post-diversion period. This is not to say that the NH_4 and PO_4 signal is not related to the outfall, but rather that the upwelling provided both ambient (all four) and effluent derived (NH_4 and PO_4) nutrients from offshore bottom waters to this shallow, coastal station.

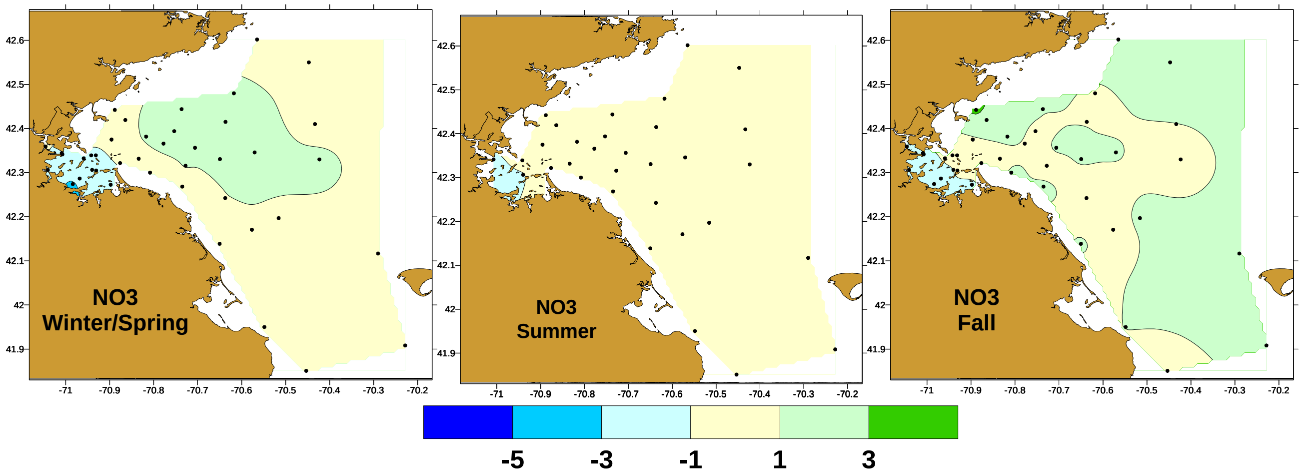


Figure 4-4. Change in seasonal NO_3 concentrations (µM) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

With the exception of SiO_4, 12% or more of the individual station based P-values were less than 0.05, suggesting that there are differences between parameter status and trends before and after diversion. For the other six parameters, between 12% and 45% of the P-values are less than 0.05. **Table** 4-1 provides similar P-values by parameter, season and station group. In **Table** 4-1, where power for change detection is greater since the analyses are based on aggregated data, a very high percentage (ranging from 19% for SiO_4 to 67% for NO_3) of the P-values for each parameter are less than 0.05, providing strong statistical evidence of status and trend differences between pre- and post-diversion water quality parameter values.

The primary issue being addressed by this statistical analysis is whether or not outfall diversion (the intervention) has resulted in significant changes in the immediate Boston Harbor and Massachusetts Bay environment. The power for detecting such changes, if they exist, is enhanced by employing statistical models for pre- and post-diversion parameter concentrations that validly represent the temporal and spatial patterns and correlations that are present in the data. The results of this intervention analysis corroborate many of the findings discussed previously and indicate that statistically significant changes in these nutrient and biomass parameters have occurred. The most obvious changes were observed in Boston Harbor nutrient levels. In this analysis, low P-values (<0.001) were calculated in most instances for dissolved inorganic nutrients in the harbor indicating significant changes in these parameters. Levels of NH_4, NO_3 and PO_4 have all decreased significantly in the harbor which was has been a consistent finding in other studies (Taylor 2006). However, significant changes in levels and temporal patterns have also occurred for other parameters throughout most areas of the bays. Many of these changes were noted on a station-by-station basis and also suggested that there were some regional patterns evident in the nutrient data such as the increase in NO_3 concentrations in the fall. More sophisticated intervention models may need to be employed to characterize the significance of these patterns.

An example of a more sophisticated model would be one that allows analysis of the data for all seasons simultaneously while properly taking into consideration the serial autocorrelation among parameter concentrations from season to season. Another example would be a model that allows one to analyze the data from a group of stations simultaneously while properly taking into consideration the spatial correlation patterns in parameter concentrations from stations that are geographically close to each other. The use of these more sophisticated models will be explored in future reports. The primary goal will be to efficiently synthesize information in the monitoring data into knowledge concerning intervention effects on the Massachusetts Bay environment. Thus, a balance will be sought between two competing goals: (A) more complicated models that better represent the physical environment, and (B) less complicated models that translate into easily understood knowledge.

4.3 Phytoplankton Biomass

Patterns 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 monitoring questions ask whether 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 patterns and concentrations of phytoplankton biomass. The problem in detecting such changes lies in the interannual variability in these biological parameters and the regional nature of the large phytoplankton blooms that drive much of the interannual variability (see Appendices B and D).

An earlier comparison of seasonal and annual mean areal chlorophyll in the nearfield shows that there has been an increase in seasonal and annual mean levels since the bay outfall began discharging (see **Table** 3-2 and **Figure** 3-16). Those comparisons were deemed not significant based on t-test comparison of the mean values, but here the data are examined using the regression model approach, which has been shown to be a more appropriate tool. On a per station basis, 12% of the pre- to post-transfer differences in areal fluorescence had $P \leq 0.05$ and for extracted chlorophyll 22% of the differences had $P < 0.05$. Using the weight of evidence approach, the significant results for areal fluorescence are relatively low, but when examined for timing and location their significance takes on added meaning. All of the significant increases occurred in the winter/spring and during this season all stations except F01 showed an increase in seasonal mean areal fluorescence. In **Table** 4-1, the station grouping results indicated that 38% of the areal fluorescence and 22% of the chlorophyll comparisons were significant ($P \leq 0.05$). Additionally, all of the significant increases were found during the winter/spring with areal fluorescence increasing in all regions except Cape Cod Bay and chlorophyll concentrations increasing in the harbor, nearfield and MB South. Only three other combinations were significant, with harbor summer mean areal fluorescence and chlorophyll decreasing and MB South areal fluorescence decreasing in the fall (**Table** 4-1).

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** 4-5 may be due to a natural cycle in blooms rather than any localized change. The winter/spring increase in areal chlorophyll fluorescence was coincident with increases in POC concentrations throughout most of Massachusetts and Cape Cod Bays (**Figure** 4-6). Regression analyses noted significant increases in areal fluorescence everywhere but Cape Cod Bay and significant increases in POC in the nearfield for the winter/spring (**Table** 4-1). For POC, 33% of the pre- to post-transfer differences were significant (6 out of 18). This included significant decreases in POC during all three seasons in Boston Harbor and significant increases in POC in the nearfield in winter/spring and summer.

Summertime areal fluorescence and POC levels tended to decrease along the South Shore and especially in Boston Harbor, while increasing further offshore (**Figure** 4-5 and **Figure** 4-6). Summer mean chlorophyll concentrations decreased significantly in the harbor. POC concentrations decreased in the summer in the Boston Harbor (significant $P < 0.0001$) and MB south regions and increased in all the other regions (significant increase in the nearfield $P = 0.0034$). The patterns evident in the summer plots for both areal fluorescence and POC are interesting in that the areas where decreases are noted (harbor and South Shore coastal) are the areas where both the model and measurements show a “harbor” nutrient signal during the baseline period (Signell *et al*. 1996; Libby *et al*. 2004). Tidal exchange kept nutrient concentrations and in turn phytoplankton biomass high in these harbor influenced coastal waters. This highlights the fact that the diversion to the bay outfall has removed this source of surface nutrients and trapped it below the pycnocline during the summer stratified conditions. Note that in July 2006 effluent NH_4, as well as elevated ambient concentrations of NH_4 and the other nutrients, were carried into the euphotic zone by upwelling and contributed to the development of the atypical July diatom bloom.

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 most of Massachusetts Bay. There were significant decreases in POC in the harbor and MB South (**Table** 4-1).

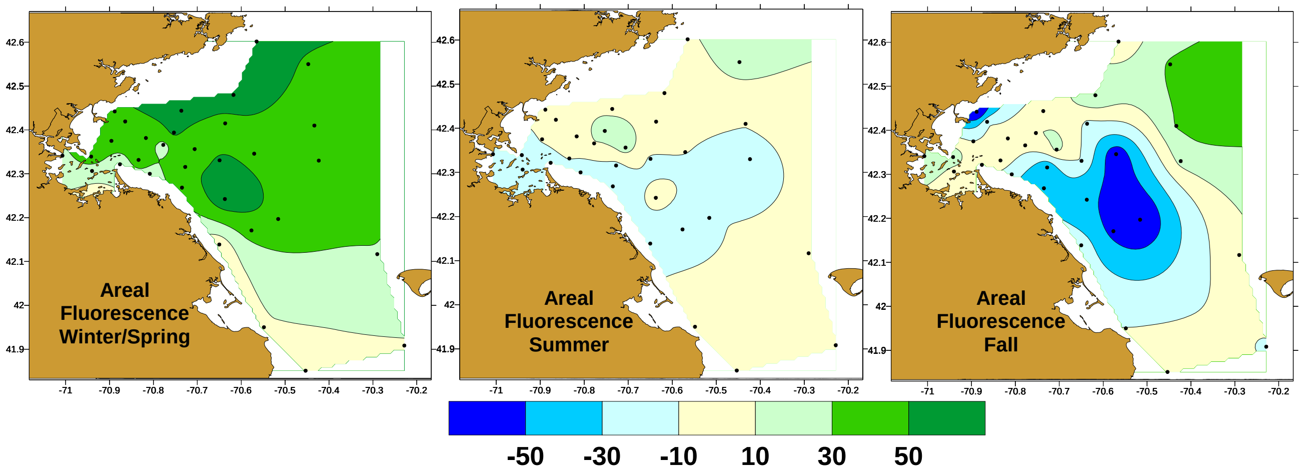


Figure 4-5. Change in seasonal areal fluorescence (mg m^{-2}) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

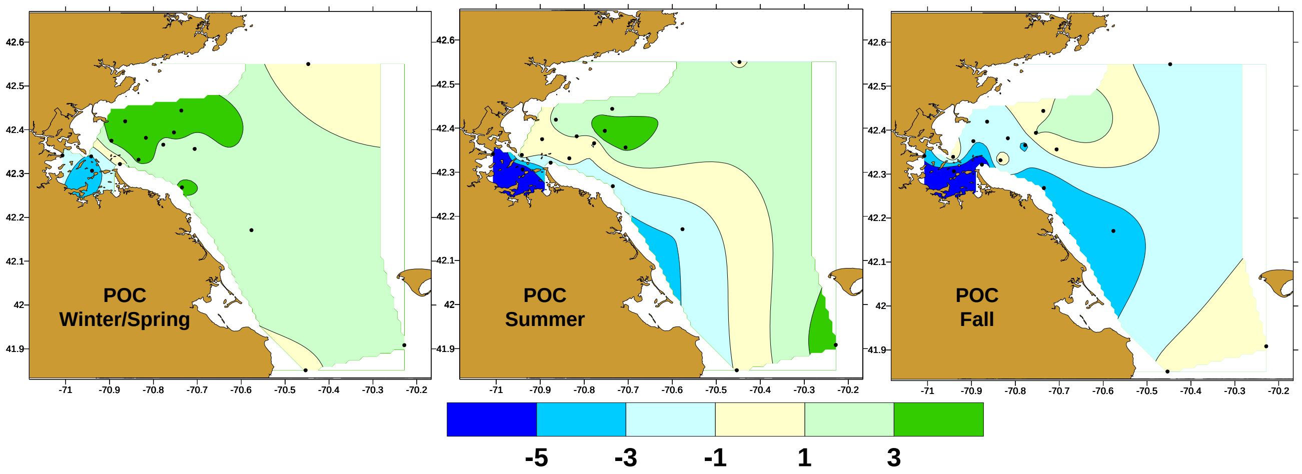


Figure 4-6. Change in seasonal POC concentrations (µM) from baseline to post-transfer. Based on the difference of means calculated over all depths from each station, survey, season, and period.

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 the only significant changes observed are winter/spring increases in areal fluorescence, chlorophyll and POC and summer increases in POC. The winter/spring increases in these parameters are coincident with significant increases in areal fluorescence and chlorophyll throughout most of the regions of the bays (**Table** 4-1). 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 those observed in the nearfield and other temperate coastal waters. The spatial pattern of summer decreases in chlorophyll and POC in Boston Harbor and nearby coastal waters along the South Shore is as might have been predicted based on the removal of the source of the surface water nutrients that supported the high biomass during the baseline. A clear relationship between changes in nutrients and chlorophyll levels in other areas, however, has not been observed in spatial and temporal means over the first six years of post-transfer monitoring. Data from the three productivity stations are addressed in the next section to provide additional insight into the potential impact of diverting the MWRA nutrient load from Boston Harbor to the nearfield.

4.4 Productivity

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. Changes in the nutrient regimes in the nearfield and harbor might be expected to have an effect on the seasonal patterns, seasonal peaks, and overall magnitude of production.

As discussed in Section 3.3, 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. Timing of these events, however, is somewhat different from baseline years. As the *Phaeocystis* bloom has become a consistent event since 2000, the post-transfer productivity rate in April has increased above the baseline mean and is now the annual survey maximum in production in the nearfield. During the first few years of the post-transfer period, the harbor production data suggested a seasonal pattern more typical of temperate waters with a winter/spring peak, lower summer rates, and a late summer/early fall peak (Libby *et al.* 2004). In 2001-2003, the occurrence of spring blooms suggested that the harbor station might be exhibiting a pattern of productivity similar to the nearfield stations, presumably due to the reduction in nutrients following the diversion of the outfall. In 2004-2006, no spring bloom was evident at the harbor station and the annual maximum in productivity occurred during June or August similar to the baseline period (**Figure** 3-17). It does not seem likely that the harbor station is rapidly shifting to the nearfield pattern, but the overall decline in productivity seen at the Boston Harbor station does indicate a shift to a less-enriched environment.

The magnitude of seasonal peak productivities during baseline and post-transfer years were compared for the nearfield and harbor stations in Appendix C. The greatest effect of the outfall relocation is apparent in seasonal and annual productivity levels in the harbor. The magnitude of the spring bloom in the harbor doubled from 623 mg C m^{-2} d^{-1} pre-relocation to 1,314 mg C m^{-2} d^{-1} post-relocation, but the increase is not significant. During the summer, the harbor showed the opposite pattern with a post-diversion mean of 1,193 mg C m^{-2} d^{-1} compared to a pre-diversion mean of 3,754 mg C m^{-2} d^{-1}. The post-diversion harbor production is 32% of the baseline mean summer production and represents an ecologically and statistically significant change ($P=0.002$). During the fall, the values for the harbor followed a similar pattern to that seen in the summer with high values pre-diversion (3,221 mg C m^{-2} d^{-1}) and low values post-diversion (1,802 mg C m^{-2} d^{-1}), but this decrease was not significant. There was little change in seasonal peak productivity at the nearfield stations with a small increase in the spring and small decreases in the summer and fall, but none of the changes were significant.

Interannual variability in annual production can be quite substantial (**Table** 4-2). Even so, 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** 4-7). The changes in nearfield station annual production (-3.6% and -22% at N04 and N18, respectively) are not large nor are they significant. In Boston Harbor, however, the data indicate that there has been a significant ($P=0.04$) reduction in annual production from baseline to post-diversion rates of ~48%. In Boston Harbor, routine monitoring by MWRA shows decreases in annual mean chlorophyll (-26%) and POC (-28%); both are significant at $P\leq0.05$ levels in the first five years after diversion to the bay outfall (Taylor 2006). All of these changes in production and biomass are coincident with significant decreases in NH_4 concentrations in the harbor. As discussed previously, there were significant increases in seasonal mean NH_4 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.

Table 4-2. Annual mean production (gC m^{-2} y^{-1}).

Year	F23	N16-18	N04
1995	763	544	390
1996	1087	482	533
1997	862	612	480
1998	224	213	191
1999	658	503	395
2000	494	664	511
2001	404	559	569
2002	587	607	532
2003	311	293	295
2004	332	207	247
2005	251	244	343
2006	382	302	314
Baseline Mean	719	471	398
Post-transfer Mean	378	369	383
Percent Change	-48%	-22%	-3.6%

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

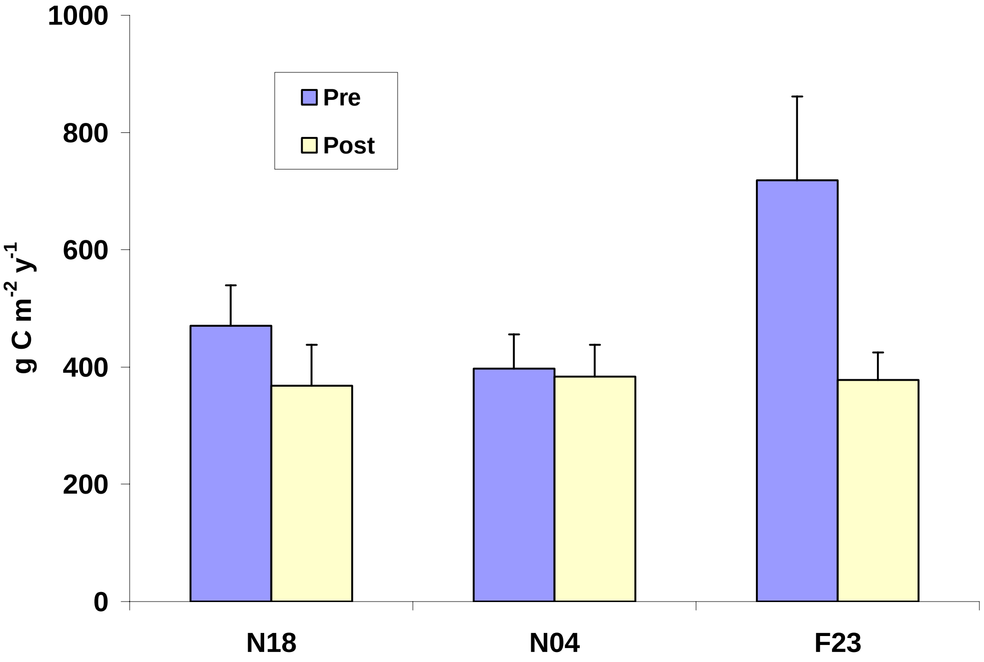


Figure 4-7. Annual potential production ($gCm^{-2}yr^{-1}$) for stations F23, N04 and N16/N18 baseline (1995-1999) and post-diversion (2001-2006). (Data from 2000 not included)

With only two exceptions, from 1992 to 2006 annual primary production was lowest during years with neutral winter North Atlantic Oscillation (NAO) index periods (**Figure** 4-8). Annual production in 1998 and 2002-2006 was all ≤300 g C m^{-2} y^{-1} at nearfield station N16/N18 and occurred during NAO winter indices of between -1 to +1. The interpretation is hypothesized to be that the very low wind conditions and enhanced stratification during the neutral index years result in a lack of nutrients in the surface waters during these strong periods of stratification that in turn reduces primary production. The linkages between hemispherical processes such as NAO and productivity or other water quality properties/rates in Massachusetts Bay are just beginning to be examined. In the coming years, as more data are collected, it is expected that the linkages well be more clearly characterized and the system better understood.

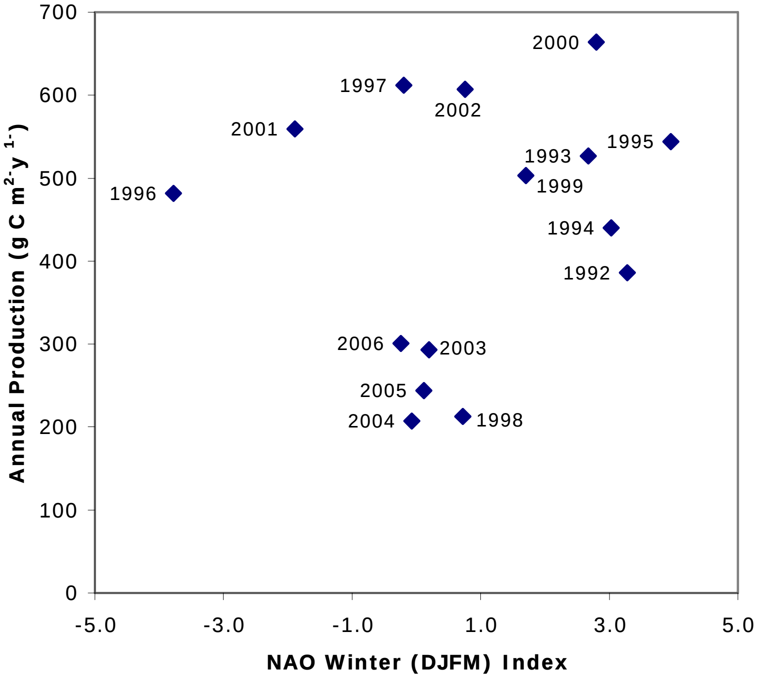
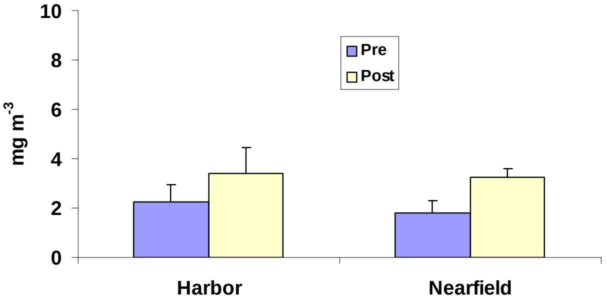


Figure 4-8. Annual potential production (gCm^{-2}yr^{-1}) at nearfield stations N16/N18 versus NAO winter index (December, January, February, and March) for 1992-2006. NAO winter index available at http://www.cru.uea.ac.uk/tiempo/portal/datanao.htm.

Although there were no significant differences between pre and post diversion production at the nearfield stations, the data do show slightly higher post diversion peak spring production at the nearfield stations, which is particularly interesting given the overall decline in annual productivity at all three stations. Additionally, the data do show significantly higher post diversion surface chlorophyll a (F = 6.55, P = 0.02) and significantly higher maximum chlorophyll a (F = 5.05, P = 0.04) over the spring bloom period (February-April) at the nearfield productivity stations (**Figure** 4-9). These changes are coincident with similar increases in the harbor. A significant but variable positive relationship additionally exists between peak spring production and both average chlorophyll in the surface water (F=6.45, P=0.02) and maximum surface chlorophyll (F=5.09, P=0.03) during the bloom period (Appendix C).

(a) Avg. Chl - Spring Bloom Surface



(b) Chl - Maximum Spring Bloom

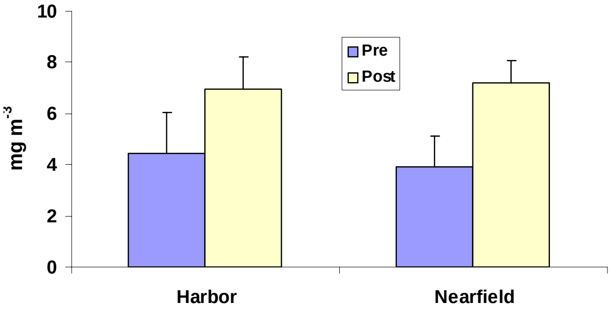


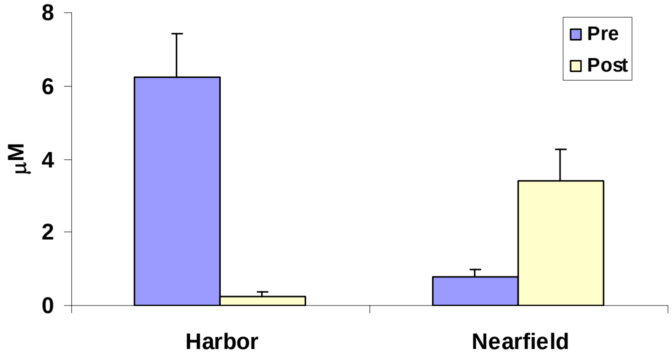
Figure 4-9. Pre- (1995-2000) vs. post- (2001-2006) diversion comparison of (a) average surface chlorophyll and (b) maximum chlorophyll concentrations (mg m^{-3}) for the nearfield and Boston Harbor for the spring bloom period (February-April).

These above changes are coincident with significant increases in surface concentrations of NH_4 (F = 9.87, P = 0.005) and DIN (F = 5.21, P = 0.032) in the nearfield and significant decreases in NH_4 (F = 13.14, P = 0.005) and DIN (F = 13.29, P = 0.005) in Boston Harbor over the spring bloom period (Appendix C). By comparing early February nutrient concentrations to post bloom concentrations, an apparent decrease or delta value can be calculated to indicate relative biological utilization (**Figure** 4-10). At the nearfield stations, there is also a significant increase in the amount of NH_4 (F = 8.92, P = 0.007) and DIN (F = 8.39, P = 0.008) utilized during the spring bloom. At nearfield stations, the change in DIN over the spring bloom period was ~7.5 μM prior to diversion to the bay outfall. After diversion, delta DIN increased to 13.6 μM at N18 and 8.6 μM at N04. This increase was primarily due to increases observed in delta NH_4 for both stations from less than 1 μM NH_4 to about 6 μM at N18 and 1 μM at N04. In contrast, apparent uptake of both DIN (F = 3.4, P = 0.09) and NH_4 (P = 24.35, P = 0.006) decreased relative to pre-diversion levels in the harbor over the spring bloom period. There is a variable but significant (F = 10.13, P = 0.004) positive relationship between the peak spring productivity level in the surface water and the change in surface nitrogen concentration over the bloom period. The availability of an additional source of DIN, namely the NH_4 rich effluent in the nearfield, could be fueling the apparent increase in production observed. Similarly significant relationships were noted between average and surface chlorophyll a during the bloom period and nutrient uptake. The changes observed in pre and post production and nutrient utilization during the spring bloom are the focus of ongoing examination.

After six years of post diversion monitoring, the data indicate that production in Boston Harbor has significantly decreased, while nearfield production has declined slightly but not significantly. These results might prompt one to ask are we done or do we need to continue to measure primary production in the bay. The findings to date indicate that nearfield productivity correlates with the physical state of the system, degree of stratification, which may be part of the North Atlantic climate. We can correlate reduced productivity at the harbor mouth with reduced nutrients due to outfall relocation, statistically.

Finally, changes in nutrient concentrations in the nearfield during the spring bloom period appear to be correlated with increased biological utilization and increased peak bloom chlorophyll biomass even though no statistically significant changes in spring productivity have been observed.

(a) Delta NH4 over Spring Bloom



(b) Delta DIN over Spring Bloom

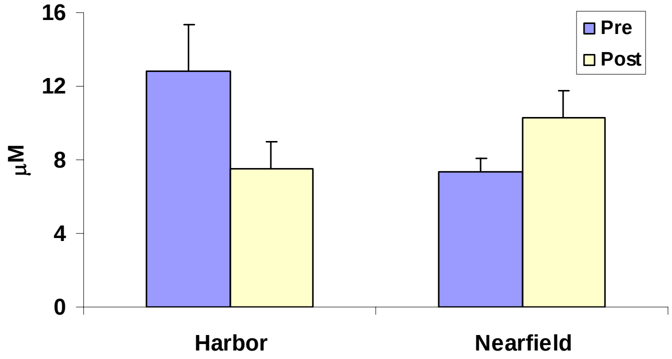


Figure 4-10. Pre- (1995-2000) vs. post- (2001-2006) diversion comparison of (a) delta surface NH_4 and (b) delta surface DIN concentrations (µM) for the nearfield and Boston Harbor. The delta is calculated based on the change in these parameters from February to April over the spring bloom period.

4.5 Phytoplankton Community Structure

Phytoplankton communities are mixtures of many species, with the abundance and composition of the community changing due to each species' responses to changing environmental influences on the habitat (e.g. annual changes in irradiance, temperature, nutrient, grazer abundance). A "normal" seasonal succession in Massachusetts and Cape Cod Bay has been observed in the 1992-2000 baseline monitoring data, and in the post-baseline years since 2001. In whole-water phytoplankton samples, microflagellates and cryptomonads 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 also dominant in Massachusetts and Cape Cod Bays during the periods identified below:

> <u>Winter (primarily February) and Spring (March, April, May)</u> – diatoms are usually abundant, including species of the genera *Chaetoceros* and *Thalassiosira*, *Guinardia delicatula*, and spring blooms of *Phaeocystis pouchetii* (mainly in April);
>
> <u>Summer (June, July, August)</u> – microflagellates are at peak abundance, with cryptomonads and the diatoms *Skeletonema costatum*, *Leptocylindrus danicus, Dactyliosolen fragilissimus, Guinardia delicatula,* and various species of *Chaetoceros*;
>
> <u>Fall (September through December)</u> – 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 major 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 (**Figure** 3-22). Although such blooms may be intermittent, they tend to occur regionally and are usually observed throughout Massachusetts and Cape Cod Bay and beyond. Why such species bloom in some years but not others remains unclear. Interannual comparisons of phytoplankton abundances for baseline and post-transfer survey means indicate that there has been little change in the general seasonal trends, overall magnitude of abundances, or interannual variability in abundances. A couple of clear differences are readily apparent – cycles of *Phaeocystis* blooms and 2005 and 2006 *Alexandrium* blooms – and have been discussed in Section 3.4.1. In this section, statistical analyses are used to examine the phytoplankton data for more subtle changes in community structure.

4.5.1 Pre- versus Post-diversion Comparisons

One purpose of this monitoring is to identify any potential outfall effects on plankton abundance and community composition. Here, a statistical comparison of pre- and post-diversion abundance levels of various phytoplankton taxa is conducted to test the hypothesis that there were differences in the pre- and post-diversion abundance levels. Phytoplankton data were averaged into regional means [six regions: boundary (F27), Cape Cod Bay (F01 and F02), coastal (F13, F24, and F25), Boston Harbor (F23, F30, and F31), nearfield (N04, N16, and N18), and offshore (F06); see **Figure** 2-1 for locations] by event ID and were further binned by the two depths sampled (near surface and mid-depth or chlorophyll maximum depth). These stations were selected because they have been sampled during all or most of the monitoring program (1992-2006). Stations that were sampled less frequently for phytoplankton have not been included. Details on the analyses can be found in Appendix D.

Total phytoplankton had statistically significant (P of Mann-Whitney U test <0.05) pre-post differences in three of the six regions monitored (**Table** 4-3). Nearfield total phytoplankton had slight increases in the time period since the offshore diversion at both the surface and mid-depth. Surface total phytoplankton increased by 4% (from 1.4 to 1.5 million cells L^{-1}) at the surface and increased by 8% (from 1.5 to 1.6 million cells L^{-1}) at the mid-depth. The boundary station F27 also displayed a large increase of 65% in total phytoplankton, increasing from 1.0 million cells L^{-1} (pre-diversion) to 1.6 million cells L^{-1} (post-diversion). Cape Cod Bay was the only region displaying a decrease in total phytoplankton, with a 23% decline in surface phytoplankton from 1.6 million cells L^{-1} to 1.2 million cells L^{-1} during the post-diversion period.

Diatom abundance declined in all regions except the boundary region since September 2000. Declines of between 29% (Boston Harbor, mid-depth) to 80% (offshore, surface) were observed and no increases in total diatoms were detected for any region or depth (**Table** 4-3). The greatest declines in diatoms were detected in the offshore region where total diatoms declined from ~0.4 to 0.08 million cells L^{-1} (80% decline) at both surface and mid-depth. Six diatom taxa (*Chaetoceros* spp., *Thalassiosira* spp., *Thalassionema nitzschioides*, *Pseudo-nitzschia* spp., *Skeletonema costatum*, and *Dactyliosolen fragilissima*) were also analyzed for changes since September 2000. Declines were detected for *Chaetoceros* spp., *Thalassiosira* spp., *Thalassionema nitzschioides* and *Pseudo-nitzschia* spp.; increases were detected for *Dactyliosolen fragilissima*; and both increases and declines were detected for *Skeletonema costatum* (**Table** 4-4). *Chaetoceros* declines were dramatic, on the order of 80 to 95%, and occurred in all regions except the boundary region. Declines in *Thalassiosira* spp., *Thalassionema nitzschioides* and *Pseudo-nitzschia* spp. were limited to specific areas and depths. A second *Pseudo-nitzschia* spp. metric, based on the MWRA *Pseudo-nitzschia* threshold, was also examined. This yielded pre-post declines in Cape Cod Bay, coastal, nearfield and Boston Harbor waters of 65% (nearfield mid-depth) to 94% (harbor surface) (**Table** 4-4). *Skeletonema costatum* displayed a mixed pattern, with a doubling - an increase of 103% - observed in the nearfield mid-depth when comparing the pre and post-diversion abundance levels. However, in Cape Cod Bay a decline of ~50% was detected at the mid-depth. No change in *Skeletonema* abundance was detected at any other region/depth combination. *Dactyliosolen fragilissima* was the only diatom to show consistent increases since September 2000, likely due to a large summer bloom of this species in 2006. *D. fragilissima* abundance increased significantly in the boundary, coastal, harbor and nearfield regions. Post-diversion increases were large in these regions, with a pre-post difference that doubled at boundary station F27, and increased ~3-fold in Boston Harbor (surface) and at both depths in the nearfield. The largest increases were detected in the mid-depth of the coastal region where mean *D. fragilissima* abundance increased from ~24,000 to 96,000 cells L^{-1} (+ 300%) and at mid-depth in the harbor where abundance increased ~360% from 32,000 to 150,000 cells L^{-1} (**Table** 4-4).

Microflagellates displayed increases in four regions (boundary, Cape Cod Bay, coastal and nearfield) and declined in the harbor. No change was detected at the offshore station F06. Only declines were detected in total dinoflagellates, with declines of 28% to 48% detected in the coast, nearfield and offshore regions. Much of this decline appears to be due to declines in *Ceratium* spp. which declined by ~ 50% since September 2000 at both the surface and mid-depth in the nearfield region (**Table** 4-3). *Phaeocystis pouchetii* abundance increased during the post-diversion period in three regions: coastal, harbor and nearfield. These increases ranged from 14% (harbor mid-depth) to 74% (nearfield surface) and increases occurred at both depths in these three regions (**Table** 4-3). A separate analysis was run looking at monthly means rather than annual means for *Phaeocystis* across the areas/depths. For the monthly results, there were significant increases ($P<0.05$) in April *Phaeocystis* abundance in all the areas and for the May surface water mean in the nearfield. The *Phaeocystis* increases noted here are consistent with the previously observed increase in the frequency of *Phaeocystis* blooms since 2000 and the recurring exceedance of the summer *Phaeocystis* threshold due to its presence in the nearfield in May.

Table 4-3. Comparison of mean abundance levels (million cells L^{-1} and cells L^{-1} for 20-µm screened data for total dinoflagellates and *Ceratium* spp.) of various phytoplankton taxa during the pre- and post-diversion. Pre- and post- means compared by Mann-Whitney U test. Only statistically significant differences ($P \le 0.05$) shown. Note that out of the 72 comparisons (6 groups × 6 areas × 2 depths) conducted 51% were significant at $P \le 0.05$ (37 of 72).

Area	Depth	Mean (Pre)	Mean (Post)	% Difference	P-value
Total Phytoplankton					
Boundary	C	0.997	1.647	65	0.0114
Cape Cod Bay	A	1.574	1.209	-23	0.0333
Nearfield	A	1.446	1.511	4	0.0028
Nearfield	C	1.5	1.624	8	0.0001
Total Diatoms					
Cape Cod Bay	A	0.5657	0.1889	-67	<0.001
Cape Cod Bay	C	0.5592	0.233	-58	<0.001
Coast	A	0.7543	0.3889	-48	0.0003
Coast	C	0.6574	0.3543	-46	0.0005
Harbor	A	0.8755	0.541	-38	0.0009
Harbor	C	0.7997	0.5699	-29	0.0003
Nearfield	A	0.5158	0.3295	-36	0.0102
Offshore	A	0.3866	0.0783	-80	0.0031
Offshore	C	0.3747	0.0834	-78	0.0172
Total Microflagellates					
Boundary	A	0.5447	0.6714	23	0.0431
Boundary	C	0.4603	0.6936	51	0.0016
Cape Cod Bay	A	0.6329	0.789	25	0.0184
Cape Cod Bay	C	0.6923	0.8192	18	0.0003
Coast	A	0.7469	0.8418	13	0.0001
Coast	C	0.7095	0.7846	11	0.0004
Harbor	A	0.9601	0.8555	-11	0.0016
Harbor	C	0.9866	0.8667	-12	0.0005
Nearfield	A	0.6567	0.8139	24	0.0001
Nearfield	C	0.605	0.8128	34	0.0001
Phaeocystis					
Coastal	A	0.2086	0.316	51	0.0109
Coastal	C	0.2508	0.4233	69	0.0015
Harbor	A	0.2094	0.357	70	0.0098
Harbor	C	0.3237	0.3675	14	0.0024
Nearfield	A	0.1023	0.1778	74	0.0006
Nearfield	C	0.2615	0.3136	20	0.0008
Total Dinoflagellates					
Coast	C	873	450	-48	0.0215
Nearfield	A	1,425	1,022	-28	0.0038
Nearfield	C	1,934	1,045	-46	<.0001
Offshore	C	1,456	976	-33	0.0391
***Ceratium* spp.**					
Coast	C	398	208	-48	0.0026
Nearfield	A	908	440	-52	0.0001
Nearfield	C	1,370	586	-57	0.0001
Offshore	C	802	725	-10	0.0476

Table 4-4. Comparison of mean abundance levels (cells L^{-1}) of various diatom taxa during the pre- and post-diversion. Pre- and post- means compared by Mann-Whitney U test. Only statistically significant differences ($P \leq 0.05$) shown. Note that out of the 84 comparisons (7 groups × 6 areas × 2 depths) conducted 46% were significant at $P \leq 0.05$ (39 of 84).

Area	Depth	Mean (Pre)	Mean (Post)	% Difference	P-value
***Chaetoceros* spp.**					
Cape Cod Bay	A	135,000	19,800	-85	<0.0001
Cape Cod Bay	C	157,800	20,600	-87	<0.0001
Coast	A	139,700	15,800	-89	<0.0001
Coast	C	146,200	17,600	-88	<0.0001
Harbor	A	217,600	16,300	-93	<0.0001
Harbor	C	195,300	13,900	-93	<0.0001
Nearfield	A	65,200	11,800	-82	<0.0001
Nearfield	C	97,100	15,100	-84	0.025
Offshore	A	61,300	5,800	-91	0.0104
Offshore	C	107,100	10,100	-91	0.0126
Skeletonema costatum					
Cape Cod Bay	C	75,500	36,200	-52	0.0163
Nearfield	C	23,300	47,200	103	0.0003
***Thalassiosira* spp.**					
Cape Cod Bay	A	68,600	23,100	-66	0.0002
Cape Cod Bay	C	64,600	29,200	-55	0.0081
Coast	A	61,900	34,800	-44	<0.0001
Coast	C	62,200	33,800	-46	<0.0001
Harbor	A	89,400	37,600	-58	<0.0001
Harbor	C	76,100	35,800	-53	<0.0001
Thalassionema nitzschioides					
Cape Cod Bay	A	17,100	4,800	-72	0.0075
Cape Cod Bay	A	17,100	4,800	-72	0.0075
Coast	A	15,200	10,300	-32	0.0013
Nearfield	A	10,200	7,800	-24	0.0146
Dactyliosolen fragilissima					
Boundary	C	700	1,400	100	0.042
Coast	C	23,800	95,900	303	0.0131
Harbor	A	51,500	154,500	200	0.008
Harbor	C	32,300	149,700	363	0.0295
Nearfield	A	39,800	106,800	168	0.011
Nearfield	C	25,900	90,600	250	0.0125
***Pseudo-nitzschia* spp.**					
Boundary	A	10,400	5,000	-52	0.0014
Cape Cod Bay	A	16,300	8,900	-45	0.0295
Nearfield	A	16,700	7,800	-53	0.0038
Nearfield	C	13,400	8,800	-34	0.0046
***Pseudo-nitzschia* spp.(MWRA threshold)**					
Cape Cod Bay	A	10,300	1,700	-83	0.0014
Cape Cod Bay	C	16,700	3,000	-82	0.0166
Coast	A	12,600	900	-93	0.0033
Coast	C	14,000	1,000	-93	0.0008
Harbor	A	12,000	700	-94	0.0004
Harbor	C	9,400	700	-93	0.0055
Nearfield	C	6,600	2,300	-65	0.0124

Overall, these pre- versus post-diversion comparisons indicate several changes in phytoplankton during the MWRA monitoring period. While changes in total phytoplankton were generally not detected, and detected changes were not apparent in all regions, changes in some phytoplankton functional groups have been more dramatic and more widespread. Diatoms appear to have declined significantly across most regions, with the key genera *Chaetoceros* spp. and *Thalassiosira* spp. showing declines in most regions. One diatom, *Dactyliosolen fragilissima*, increased in abundance by 2-fold to 5-fold in the boundary, coastal, harbor and nearfield regions since September 2000. Dinoflagellates, led by the decline in *Ceratium* spp., declined in the coast, nearfield and offshore regions. Simultaneous with this, microflagellates saw generally modest long-term increases in most regions, except in Boston Harbor, where microflagellate abundance has declined by ~10% since September 2000. April *Phaeocystis* abundance has increased over all of the regions post-diversion. The relatively minor changes in total phytoplankton abundance mask a series of apparent phytoplankton shifts embedded within the total phytoplankton community. In these, it appears that diatoms (with the exception of *Dactyliosolen fragilissima*) and dinoflagellates have generally declined while microflagellates and *Phaeocystis pouchetii* have had relative increases since the September 2000 offshore diversion.

4.5.2 Nearfield Phytoplankton Time Series Analysis

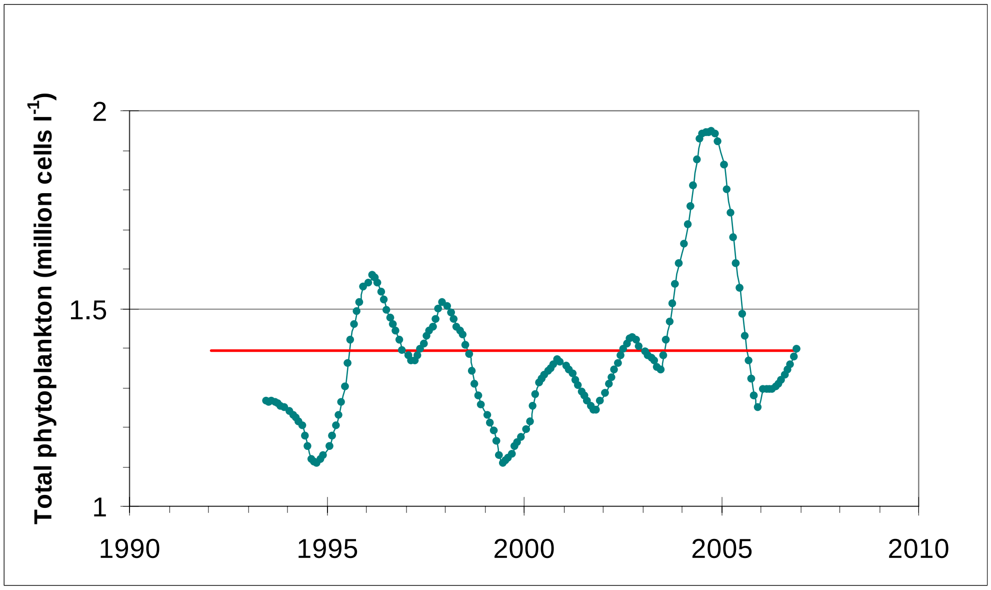
The pre-post comparisons described above identified some changes in the phytoplankton community before versus after the September 6, 2000 offshore diversion of the outfall. However, these changes may be part of a trend, rather than a step-wise function that starts/stops at a discrete time. The changes detected in the pre-post comparisons may actually be due to long-term abundance trends that started prior to or after the September 6, 2000 date of interest. Similarly, long-term periodic or cyclical abundance patterns will not be detected by the pre-post analysis. Time series analysis (Broekhuizen and McKenzie 1995) was applied to the dominant phytoplankton groups to identify long-term abundance trends and cycles during the 15 years (1992-2006). This method is robust to strongly seasonal time series, such as those observed in some plankton species. A 10% (18 month) moving average smoother was applied as the estimate of long-term trend. This estimated long-term trend represents the de-seasonalized abundance level about which the seasonal pattern fluctuates. Additional details on the method and complete results are presented in Appendix C.

Total phytoplankton was near the long-term mean abundance level (1.4 million cells L^{-1}) during 2006 (**Figure** 4-11a). Total phytoplankton was relatively low (1.1 to 1.3 million cells L^{-1}) during 1992-1994, this may be due to a methodological issue (counting at low magnification) during those years. During 1995-1998 total phytoplankton abundance rebounded to near long-term mean levels then declined in 1999 to a relative low point (1.1 million cells L^{-1}). Total phytoplankton abundance then increased progressively during 1999 through 2005 to a peak of 1.9 million cells L^{-1} in early 2005. During 2005 total phytoplankton abundance declined and then returned to near mean levels in 2006.

The long-term trend in microflagellate abundance shows three distinct periods: a period of relatively low abundance (1992-1994), a period of elevated abundance 1995-1996, and then a gradual long-term increase from 1998 through 2006 (**Figure** 4-11b). The 1992-1994 versus 1995-1996 change corresponds to changes in methodology (different magnification and phytoplankton analysts) suggesting a methodological rather than environmental basis for the trend during this period. It is unclear how these changes affected other phytoplankton data comparisons (i.e. total phytoplankton). Since 1997, there appears to have been a gradual increase in nearfield microflagellate abundance from near 0.55 million cells L^{-1} (1999) to near 0.85 million cells L^{-1} during 2004. In 2005 and 2006, microflagellate abundance has declined to near the long-term mean level of about 0.69 million cells L^{-1}.

Nearfield diatom abundance has shown a dramatic long-term decline during 1992-2006, with 2005 - 2006 levels that were only ~25% of the peak level observed during 1994 (**Figure** 4-12). Within this long-term decline there were relative peaks in abundance in 1994, 1998 and 2002 – every four years. An explanation for this periodicity is not presently known. However, the relative peaks in diatom abundance roughly correspond with relative nadirs in *Phaeocystis* abundance (**Figure** 4-12). Correlation analysis of these two trends yielded a Pearson r value of -0.54 (P<0.0001) indicating that a long-term negative interaction (competition) may be occurring between *Phaeocystis* and diatom abundance in the nearfield. This interaction is likely operative in the winter-spring only, given that is the time of *Phaeocystis* presence in the bay, and throughout the bays, but it may have lag effects on diatom abundance into the remainder of the year.

(a) Total Phytoplankton



(b) Total Microflagellates

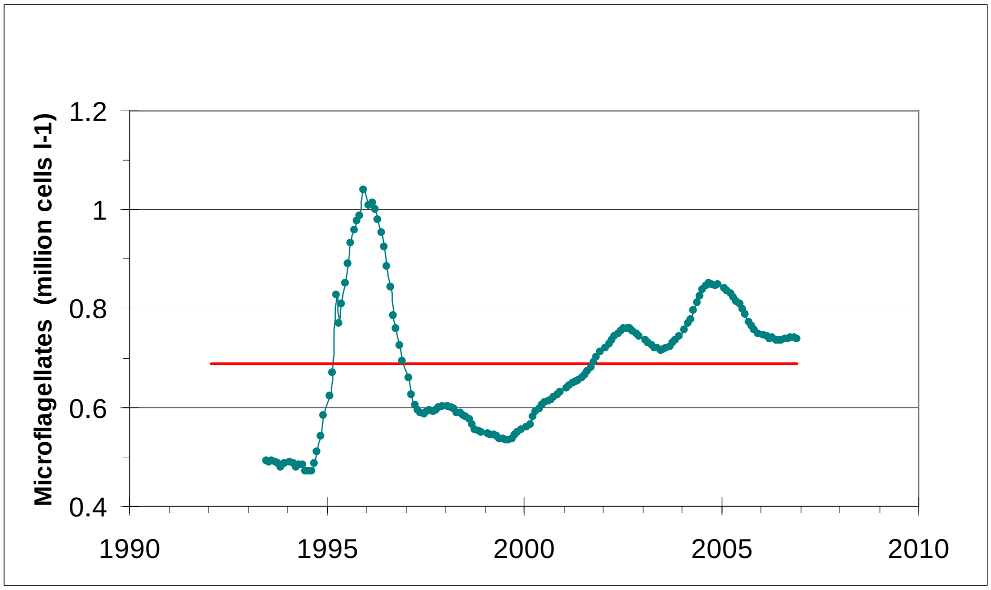


Figure 4-11. Long-term trend in (a) total phytoplankton and (b) total microflagellate abundance in the nearfield (1992- 2006) derived from time series analysis. Long-term mean levels are also shown (red).

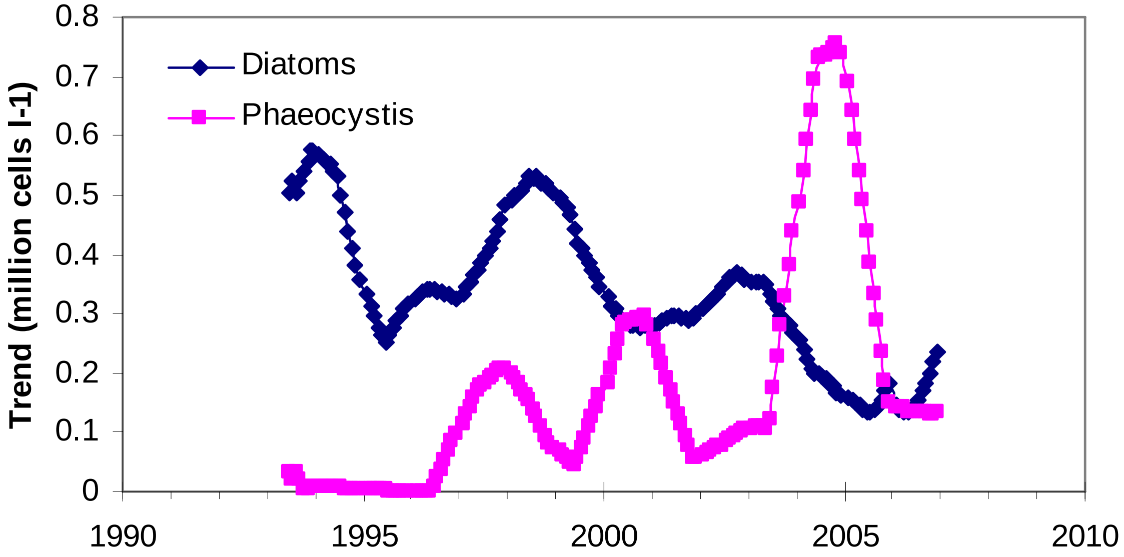


Figure 4-12. Long-term trend (1992- 2006) in total diatom and *Phaeocystis pouchetii* abundance in the nearfield derived from time series analysis. Pearson r value of two trends was -0.54 (p <0.0001).

Trends for specific diatoms were mixed and are presented in Appendix D. One pennate diatom of particular interest due to its domoic acid producing toxic species, *Pseudo-nitzschia* spp., appears to be declining in the nearfield (**Figure** 4-13*). Pseudo-nitzschia* spp. abundance was near or below the long-term mean level during 1992- 1997 and 2001- 2006 with an intervening period (1998-2000) of elevated abundance. *Pseudo-nitzschia* abundance during the peak of the 1998- 2000 period (40,000 cells L^{-1}) was approximately four times the long-term mean level. There appears to have been a decline in *Pseudo-nitzschia* spp. in the nearfield since 1999. If the MWRA *Pseudo-nitzschia* species threshold criterion, rather than all *Pseudo-nitzschia* spp., is examined, this post 1999 *Pseudo-nitzschia* decline is even more evident (**Figure** 4-13).

Dinoflagellate abundance (**Figure** 4-14) displayed a period of near long-term mean abundance during 1992-1994, relatively low abundance during 1995-1998 followed by a peak in abundance in 2001 and then a decline to a relatively low abundance period of 500 cells L^{-1} from 2003 to 2006. The long-term *Ceratium* abundance trend followed a similar pattern (**Figure** 4-14), with the trend in nearfield *Ceratium* spp. positively correlated with the total dinoflagellate trend (Pearson r = + 0.93, P< 0.0001). The relative contribution of *Ceratium* spp. to total dinoflagellate abundance has declined from about 50% - 90% during 1996-2002 to ~20% during 2005 and 2006.

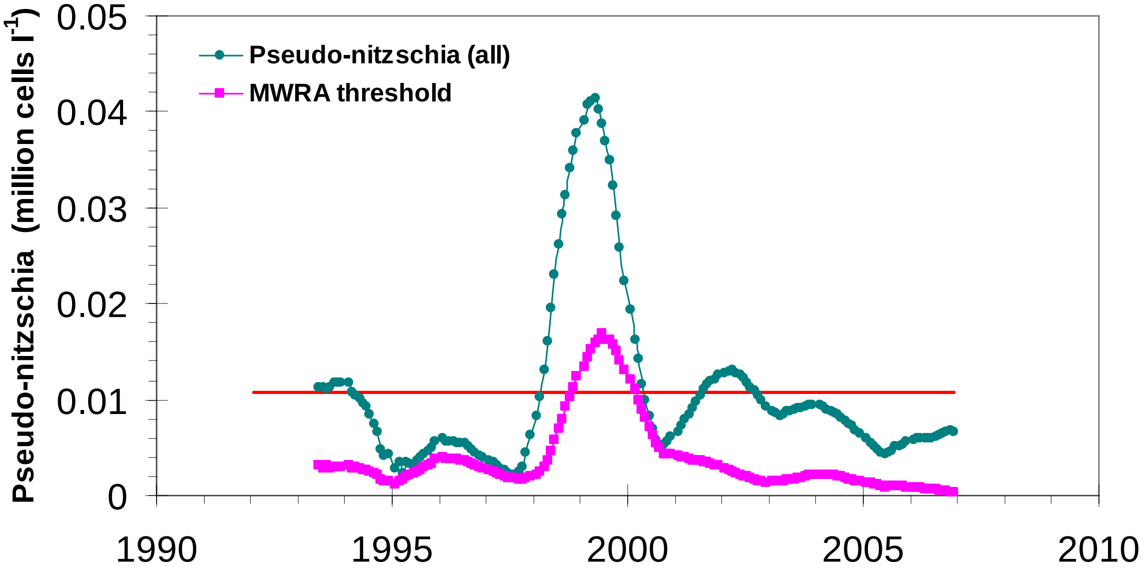


Figure 4-13. Long-term trend (1992-2006) in *Pseudo-nitzschia* spp. abundance for *Pseudo-nitzschia* spp. and the MWRA *Pseudo-nitzschia* threshold grouping in the nearfield derived from time series analysis. Long-term means for *Pseudo-nitzschia* (all) is also shown (red).

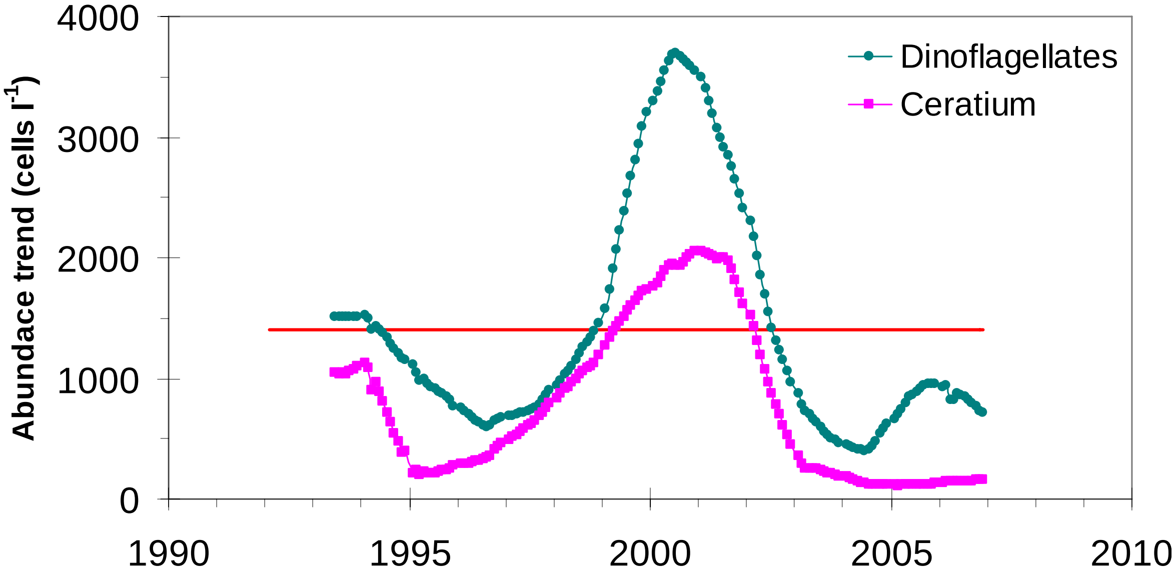


Figure 4-14. Long-term trend (1992-2006) total dinoflagellate and *Ceratium* spp. abundance in the nearfield derived from time series analysis. The two trends were significantly positively correlated (Pearson r of + 0.93, P< 0.0001). Long-term mean total dinoflagellate level is also shown (red).

4.5.3 Multivariate Phytoplankton Community Analyses

Multivariate analyses were used to 1) identify patterns of long-term phytoplankton community variation and 2) identify those phytoplankton species/groups most influencing those long-term patterns. The statistical analysis software Primer (Plymouth Routines In Multivariate Ecological Research; Clarke and Gorley 2001) was used for this multivariate analysis. The same 1992-2006 phytoplankton data set used for the pre-post and time series analyses was examined. The final data matrix was reduced by averaging samples by monthly phytoplankton abundance in the six regions (boundary, Cape Cod Bay, coast, harbor, nearfield, offshore), but keeping surface and chlorophyll max data separate. The final data matrix was 1,002 samples in length, with each sample having the abundance of 249 distinct species or phytoplankton groups. The data matrix was analyzed by calculation of a Bray-Curtis similarity matrix and the goal was to identify dominant patterns of variation (i.e., spatial by region or by depth; temporal; by years or months; or by a putative treatment effect such as pre- post-offshore outfall) in all samples. Once the dominant modes of variation were identified, the samples were binned by category (i.e., year, month, depth, region, etc.) and analyzed by the SIMPER procedure (Clarke and Gorley 2001) that identified the contribution each phytoplankton species/groups contributes to the discrimination of each identified group. The goal was to identify the variables (phytoplankton species/groups) most responsible for the long-term patterns of phytoplankton variation during 1992-2006. Additional details are provided in Appendix D.

The MDS analysis of all phytoplankton samples yielded a plot that was of moderate utility in identifying long-term variation, as assessed by the stress value of 0.21. Coding the 1,002 samples by year resulted in discrimination of distinct three periods (**Figure** 4-15): 1992-1994 (far left of plot), 1995-1997 (far right of plot) and 1998-2006 (middle of plot). These three periods correspond to methodological changes in phytoplankton counting, with each period having different phytoplankton analysts and/or different phytoplankton methods. During 1992-1994 phytoplankton were counted at a lower magnification (250X) in a Sedgwick-Rafter counting cell, likely resulting in an underestimation of the smallest and most abundant components of the phytoplankton such as microflagellates. These years clustered together at the far left of the MDS plot. Note that the time series analyses indicated reduced microflagellate abundance during this period. During 1995-1997, there was a change in both phytoplankton analyst and a switch to the use of an inverted microscope. High multiplier factors associated with the inverted scope method may have resulted in elevated microflagellate abundance during this period. The 1995-1997 samples clustered at the far right of the MDS plot. In 1998, there was again a change in phytoplankton analyst (reverting to the same analyst as during 1992-1994) and a change in methodology: counting the smallest component of the phytoplankton at 500X. The 1998-2006 samples largely occupy the center of the MDS plot, indicating their similarity. Thus, the majority of 1992-2006 temporal variation in phytoplankton community structure appears to be coincident, and likely related to, changes in phytoplankton methodology/analysts. The differences between the three methodologies employed during 1992-2006 were mainly related to differences in the estimation of the smallest component (i.e., microflagellates) of the phytoplankton community.

Seasonal abundance and species composition patterns mark temperate marine phytoplankton generally, including the phytoplankton of MWRA monitoring region. However, a strong seasonal pattern was not apparent in the MDS plot of all species and samples. A weak seasonal pattern was apparent in the MDS plot coded by quarter that suggested there is primarily a winter-spring versus summer-autumn, rather than a quarterly, difference in phytoplankton community composition. Winter (first quarter) and spring (second quarter) samples tended to be at the left of the MDS plot (indicative of reduced microflagellate abundance) while third and fourth quarter samples were located more centrally (Appendix D).

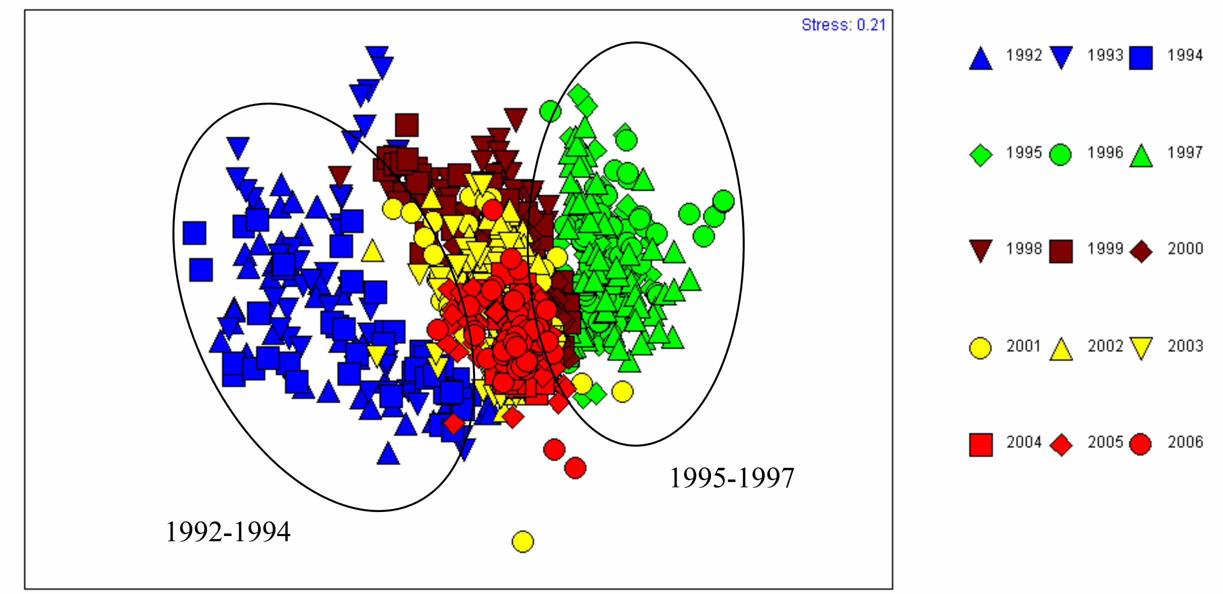


Figure 4-15. Location of 1,002 MWRA phytoplankton samples on MDS plot coded by the 15 years (1992-2006) of phytoplankton observations.

The MWRA monitoring program samples phytoplankton both near surface and at the chlorophyll maximum depth (typically 10-15 meters depth). Coding the samples by depth showed no distinct pattern, indicating that overall there are no distinct surface or mid-depth phytoplankton communities within the range of stations and seasons sampled by the MWRA monitoring program. Further partitioning of the entire phytoplankton data set into separate seasons and regions may highlight depth differences in the phytoplankton community, such as the mid-depth *Ceratium*-dominated community that was observed (especially during 1999-2001) in the nearfield and Cape Cod Bay regions during the summer months. However, overall there is no depth-related difference in phytoplankton community composition evident in the MDS analysis of all samples.

Another potential source of phytoplankton community composition variation is the spatial location or region. The six regions (boundary, Cape Cod Bay, coastal, harbor, nearfield, and offshore) do not span a large salinity gradient – the harbor phytoplankton samples are relatively close to the mouth of the harbor. Although freshwater forms (*Asterionella formosa*, *Scenedesmus* spp.) are frequently encountered in low numbers at all stations, the monitoring program does not sample a strong estuarine gradient, and a strong regional effect on phytoplankton community composition was not anticipated. Coding phytoplankton samples bears this out as no distinct regional clusters of samples are apparent (Appendix D).

It is possible to identify the subset (from the entire 249 species / category list) of phytoplankton species that discriminate one group from another, such as which species are most representative of each of the six regions (boundary, Cape Cod Bay, coastal, harbor, nearfield, and offshore), or which species discriminate one time period from another using the SIMPER procedure (Clarke and Gorley, 2001). The results of this analysis for identifying the species/categories responsible for discriminating each region are shown in **Table** 4-5. This table shows that the <20 µm component of the phytoplankton (i.e., Unid. micro-phytoflag sp. <10 µm, *Cryptomonas* sp. <10 µm, *Gymnodinium* sp. 5-20 µm) are responsible for most of the characterization of the phytoplankton regions. For example, these three small species/categories listed contribute 39% of the similarity in each region. Note that some species show regional differences. For example, *Skeletonema costatum* which was important in Cape Cod Bay, coastal, harbor and nearfield regions was not an important determinant of phytoplankton community

Table 4-5. Phytoplankton species or categories most responsible for discriminating between six regions sampled by MWRA monitoring. The species responsible for 90% of the similarity within each region are listed, with the 1992-2006 mean abundance of each species shown by region. Species with no abundance shown for some regions (i.e., *Skeletonema costatum* in region 1) *do not* indicate that the species was not present, but rather indicate that the species is not an important determinant of the phytoplankton community in that region. The mean contribution across all regions of each species/category shown in descending order of importance.

	Mean Abundance (cells L^{-1}) by Region						Mean Contribution
Species or Category	**Boundary**	**CCB**	**Coastal**	**Harbor**	**Nearfield**	**Offshore**	**(%)**
Unid. micro-phytoflag sp. <10	652,733	721,785	784,264	880,659	722,364	706,381	17
Cryptomonas sp. <10 microns	86,514	77,095	122,024	186,132	98,240	82,547	14
Gymnodinium sp. 5-20 microns	36,943	36,316	34,339	22,087	36,748	40,300	8
Thalassionema nitzschioides	4,928	13,079	14,509	15,425	9,964	7,452	7
Centric diatom sp. <10 microns	18,075	26,049	65,715	104,886	42,361	37,511	7
Phaeocystis pouchetii	303,663	197,796	273,748	314,603	134,242	281,078	6
Cylindrotheca closterium	2,427	4,840	6,656	9,949	4,735	3,179	6
Skeletonema costatum		42,147	141,822	196,430	51,331		5
Cryptomonas sp.len >10 microns	15,526	14,906	35,597	69,010	22,696	19,522	5
Heterocapsa rotundata	11,576	5,580	14,242	16,734	14,243	8,105	4
Unid. micro-phytoflag length >10	6,953	7,397	14,707	13,431	9,127	6,916	4
Gymnodinium sp. 21-40 microns	1,571	2,016	1,998	1,896	1,801	2,022	4
Chaetoceros sp. 10-30 microns		17,396	9,880	10,492	7,571	4,712	3
Leptocylindrus minimus		70,723	20,213	14,126	20,519		2
Thalassiosira sp. 10-20 microns	5,025	4,895	10,828	12,857	5,967	6,235	2
Dactyliosolen fragilissimus		26,675	58,441	93,396	86,199	18,970	2
Pyramimonas sp. 10-20 microns			7,861	12,342			2
Leptocylindrus danicus		27,908	77,824	60,495			2
Rhizosolenia delicatula		15,859					2
Chaetoceros debilis		18,551	9,727	7,768			2
Asterionellopsis glacialis		11,754		29,670			1
Pseudonitzschia delicatissma cmplx	3,699		24,735	18,032	7,260		1
Pseudonitzschia pungens					3,821		1

composition in the boundary and offshore regions. Similar nearshore-offshore patterns were apparent for *Chaetoceros* spp. 10-30 µm in size and *Leptocylindrus minimus*. Both 'background' species that are present in practically all samples (such as Unid. micro-phytoflag sp. <10 µm, Cryptomonas sp. <10 µm, Gymnodinium sp. 5-20 µm) and bloom species that are seen only sporadically (*Asterionellopsis glacialis*) or seasonally (*Phaeocystis pouchetii*) were important in determining the regional differences in phytoplankton community composition. Similar analyses were applied to seasonally, annually and "pre-post" binned data (tables not shown). The same species / phytoplankton categories shown in **Table** 4-5 were also dominant in these other analyses.

Overall, the multivariate analyses of all samples using all 249 phytoplankton species variables indicate a phytoplankton flora in the MWRA monitoring area that is regionally similar, shows no distinct depth properties, and has winter-summer seasonality. The six regions displayed differences in abundance level (magnitude, see **Table** 4-5) and a few differences in community species composition. Some of the long-term (1992-2006) phytoplankton species composition variation may be due to methodological changes. Further refinement of the species list, such as removal of categories suspected to be biasing the long-term phytoplankton data (like microflagellates) and subsequent MDS analyses decreased the degree of differentiation between 1992-1994, 1995-1997, and 1998-2006 samples (plots not shown), but did not change the above interpretation. Future efforts of further reconciling the influence of noted methodological changes and taxonomic inconsistencies (species name changes, changes in species categories, etc.) in the MWRA phytoplankton data set are ongoing and will aid future analyses and interpretation of long-term phytoplankton changes.

4.6 Zooplankton Community Structure

The variability in abundance and structure of the zooplankton community in 2006 in Massachusetts and Cape Cod Bays appears similar to patterns recorded since the beginning of sampling in 1992. Assemblages have been dominated by copepod nauplii, *Oithona similis*, and *Pseudocalanus* spp. copepodites, throughout the year. A variety of subdominant species include other copepods such as *Calanus finmarchicus*, *Paracalanus parvus*, *Centropages typicus* and *C. hamatus*, and sporadic pulses of various meroplankters such as bivalve and gastropod veligers, barnacle nauplii, and polychaete larvae. Zooplankton abundance generally increased from February through mid- to late summer, and then progressively declined through the fall and into winter.

Comparison of baseline and post-transfer zooplankton abundance and total copepod abundance in the nearfield suggests that there has been a decrease in abundance in 2001-2006 vs. 1992-2000 (**Figure** 3-32). The post-transfer decrease in total copepods has also been observed at stations in the boundary and offshore locations (**Figure** 3-33). However, not all copepod taxa have exhibited this decrease. *Calanus finmarchicus*, a relatively large zooplankter, has been present in the nearfield, boundary, Cape Cod Bay and offshore regions at abundances approximating the baseline mean and within the baseline range during most of the year with a large increase in abundances being observed in April-June (**Figure** 3-34). Two statistical approaches are used in this section to discern whether or not these trends are significant.

4.6.1 Zooplankton pre-post changes

Comparison of the abundance levels of various zooplankton taxa prior to and following the September 2000 offshore effluent diversion were made to identify any changes in zooplankton abundance that may be associated with that event. The same method (check data for normal distributions with Kolmogorov-Smirnov test; compare means during the two periods with Mann-Whitney U test) and the regional averaging (6 regions) that was used in the phytoplankton pre-post comparison was applied to the zooplankton pre- post comparisons (see Appendix D).

Changes in total zooplankton were detected in four of the six regions; all changes were declines in total zooplankton. Total zooplankton declined by 37% to 55% in the nearfield, offshore, coastal and boundary regions after September 2000 (**Table** 4-6). Total copepods also displayed declines of 31% to 49% in the nearfield, offshore and boundary regions. Copepod nauplii had a similar pre-post decline, with decreases of 32% to 55% in these same three regions. *Oithona* spp. declined in five of the six regions, with declines of between 30% to 52%. *Calanus finmarchicus* was the only zooplankton taxon that displayed a pattern of consistent increase since September 2000. *C. finmarchicus* abundance increased 12% in the nearfield, 235% in the offshore region and over 300% in Cape Cod Bay (**Table** 4-6). Other zooplankton (i.e. meroplankton) declined by -63% to -78% in all six regions. Zooplankton changes were of similar magnitude and direction in regions in the vicinity (nearfield) and distant (offshore, boundary and Cape Cod Bay) from the bay outfall. Overall, the pre-post comparisons indicate a general decline in zooplankton abundance (with the exception of one species: *C. finmarchicus*) since September 2000.

Table 4-6. Comparison of mean abundance levels of various zooplankton taxa during the pre- and post- diversion time periods. Pre- and post- means compared by Mann-Whitney U test. Only statistically significant differences (P≤0.05) shown. Note that out of the 36 comparisons (6 groups × 6 areas) conducted 67% were significant at P≤0.05 (24 of 36).

Area	Mean (Pre)	Mean Post)	% Difference	P-value
Total Zooplankton				
Boundary	26451	11971	-55	0.0013
Coast	48504	26848	-45	0.0001
Nearfield	46382	29335	-37	0.0001
Offshore	44864	25700	-43	0.0043
Total Copepods				
Boundary	29278	14811	-49	0.0049
Nearfield	38307	26329	-31	0.0001
Offshore	36307	23205	-36	0.0351
Copepod Nauplii				
Boundary	12572	5697	-55	0.0026
Nearfield	14985	10120	-32	0.0001
Offshore	15077	8041	-47	0.0130
***Calanus* spp.**				
Cape Cod Bay	363	1552	328	0.0001
Nearfield	972	1091	12	0.0149
Offshore	506	1694	235	0.0150
***Oithona* spp.**				
Boundary	9281	4459	-52	0.0016
Coast	7559	4472	-41	0.0001
Harbor	3366	2371	-30	0.0001
Nearfield	12989	8339	-36	0.0001
Offshore	12817	7778	-39	0.0101
Other Zooplankton				
Boundary	5236	1424	-73	0.0001
Cape Cod Bay	7505	2813	-63	0.0001
Coast	10652	2360	-78	0.0001
Harbor	10174	2276	-78	0.0001
Nearfield	10988	2578	-77	0.0001
Offshore	8317	2379	-71	0.0001

4.6.2 Nearfield Zooplankton Time Series Analysis

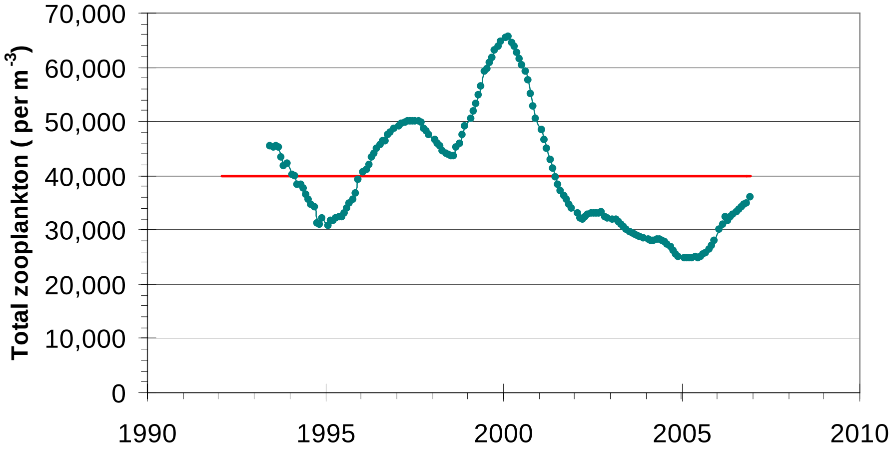
The time series analysis method of Broekhuizen and McKenzie (1995) which decomposes a time series into seasonal pattern and long-term trend was applied in the same manner as used for the nearfield phytoplankton data. A 10% (18 month) moving average smoother was applied as the estimate of long-term trend. This estimated long-term trend represents the de-seasonalized abundance level about which the seasonal pattern fluctuates. Details are provided in Appendix D.

Total zooplankton had a pattern of increasing abundance from 1992 to a peak in 2000 followed by a rapid decline in 2001 to less than long-term mean values during 2002 through 2006 (**Figure** 4-16). It appears that total zooplankton abundance may be on the increase in 2006 following the 2005 nadir. Copepods and copepod nauplii comprised the bulk of total zooplankton, so it is not surprising to see that the long-term trend in copepod abundance and copepod nauplii abundance were similar to that of total zooplankton. The copepod trend had the same relative nadir in 1994-1995 and a relative peak in 2000 followed by a decline in 2001-2002 to below long-term mean levels from 2002 through 2006 (**Figure** 4-16). As with total zooplankton, copepod abundance appears to have increased in 2006 relative to the low levels observed during 2005. The long-term trend in nearfield nauplii abundance showed reduced levels, below the long-term mean level during 1992 – 1996, a peak in abundance in 1997 and then a decline, with relative peaks in 2000 and 2003, to levels of <10,000 animals m^{-3} in 2005. 2006 nauplii abundance also increased relative to that of 2005.

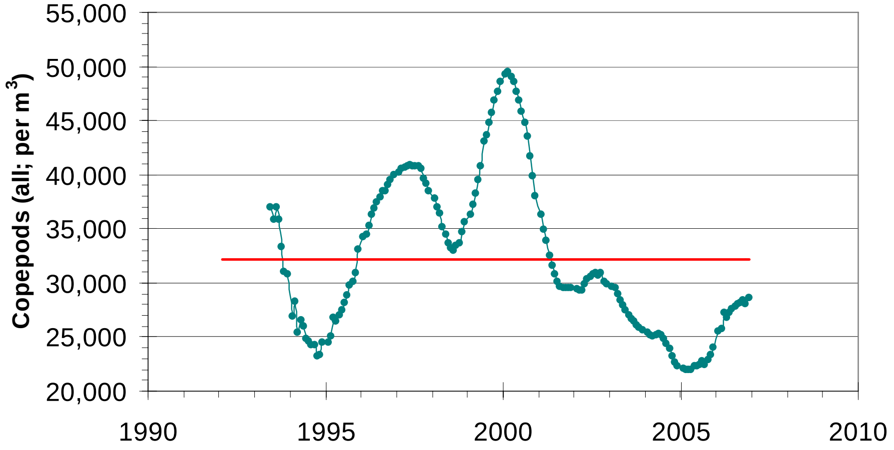
Oithona spp. abundance oscillated from 20,000 animals m^{-3} during 1992-1993 and 1997-1998 to <10,000 animals m^{-3} during 1994-1995. Following the 1998 peak, *Oithona* abundance declined to near mean levels (12,500 animals m^{-3}) from 1999 to 2001 and then declined further to reduced levels of 7,000 animals m^{-3} during 2003-2006. Other zooplankton also had a peak and then rapid decline in the early 2000s. Other zooplankton varied within 50% of mean levels (7,400 animals m^{-3}) from 1992 to 1998, followed by a rapid increase to a peak value of ~16,000 animals m^{-3} during 1999 – 2000. As seen with total copepod abundance, other zooplankton abundance declined rapidly in the early 2000s and was at reduced levels (2,000 animals m^{-3}) during 2002 to 2005. Other zooplankton abundance appears to have increased to near long-term mean abundance during late 2005 and 2006. *Calanus finmarchicus* was the only zooplankton to show increases in the pre-post tests and its long-term trend is consistent with this. *C. finmarchicus* in the nearfield has shown progressive increases over 1992- 2006 punctuated by three relative peaks in 1996, 2000 and 2003 and relative nadirs in 1998 and 2001, and perhaps 2005 (**Figure** 4-16).

It is unclear why zooplankton abundances have been lower in recent years than previously. One factor that has been discussed is increased predation of zooplankton/copepods by ctenophores. However, there is no data for this, beyond anecdotal observations of elevated ctenophore abundances during a very limited set of surveys. Blooms of the ctenophore *Mnemiopsis leidyi* were not apparent from the beginning of sampling in 1992 until October 2000. Since then, however, this ctenophore has been present in varying degrees. The fall 2000 appearance of ctenophores was primarily in October, and primarily in Boston Harbor. Subsequent blooms in 2002 and 2003 were observed in October over a larger area, and in 2002 persisted to November in the nearfield. However, in this sampling program, ctenophores are screened out of samples prior to formalin preservation (to prevent ctenophore tissue from turning into something akin to glue which complicates sorting of other zooplankton). In 2002, the screened ctenophores began to be measured for volume displacement and revealed their presence in fall 2002 and 2003. In more recent years (2004-2006) ctenophores have not been abundant enough to be noticed in the field or require screening, and thus cannot be used to explain the declines in other zooplankton during these years.

(a) Total Zooplankton



(b) Total Copepods



(c) *Calanus finmarchicus*

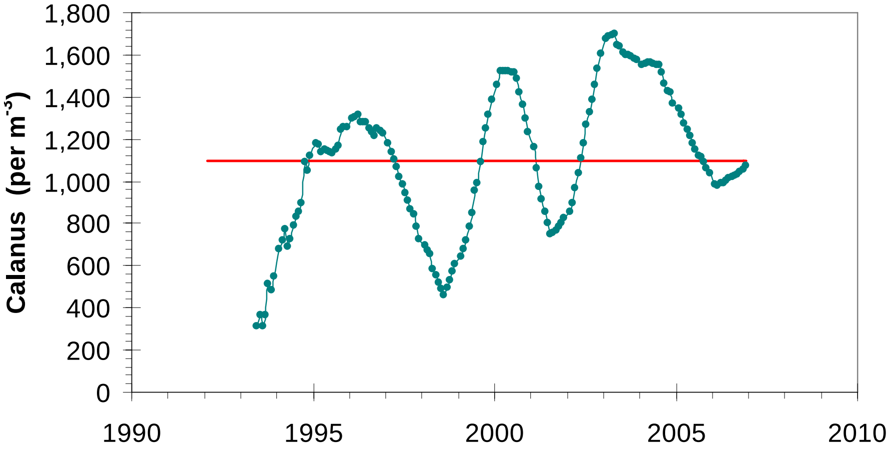


Figure 4-16. Long-term trend (1992- 2006) in (a) total zooplankton, (b) total copepods and (c) *Calanus finmarchicus* abundance derived from time series analysis. Long-term mean levels are also shown (red).

Since *Phaeocystis* blooms have occurred consistently since 2000, these pre- and post-transfer trends in zooplankton abundance suggest that there may be a link between the *Phaeocystis* blooms and zooplankton dynamics. The MWRA Massachusetts Bay nearfield *Phaeocystis* and zooplankton abundance data was further examined by Libby *et al*. (2006d) to identify and quantify any relationships between *Phaeocystis* and zooplankton abundance. Their analyses suggest a mixed, seasonally varying and taxon-specific response to *Phaeocystis* in Massachusetts Bay. A number of patterns were observed in association with the blooms such as elevated *Calanus* early in the season (Feb-Mar), reduced *Oithona* and total zooplankton abundance late in the season (April-May), followed by increased *Oithona* later in the summer. These patterns 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; Turner *et al*. 2006) having different fauna (*Calanus*-dominated vs. *Oithona* dominated) may be operative in and co-varying with *Phaeocystis* vs. non-*Phaeocystis* bloom years. Additionally, annual variability in winter-spring temperature may alter the rates of *Phaeocystis* bloom development and/or rates of zooplankton development, which may in turn modify grazing interaction between zooplankton and *Phaeocystis*.

Related to annual temperature variability, it might be tempting to speculate that if the apparent decreases in zooplankton abundance are being driven by anomalously high zooplankton and copepod abundances in 1999 and 2000, that these might somehow be related to climatic variability, such as has been suggested for abundance of *Calanus finmarchicus* in relation to the NAO (Turner *et al.* 2006). Although this possibility can of course be statistically explored further using data already in hand, at first glance, such a scenario seems unlikely. The extremely high abundances in both total zooplankton and total copepods in 1999 and 2000 occurred in summer, whereas the major effect of the NAO, particularly on *Calanus finmarchicus*, appears to be in the winter. Although Turner *et al*. (2006) found significant negative correlations in winter between the NAO winter index and abundance of *Calanus finmarchicus* at nearfield stations N04 and N18, and a significant negative correlation between the winter NAO index and total copepods (February-April) at Station N04, but not at Station N16, how these might relate to the extremely high abundances of total zooplankton and copepods (primarily *Oithona similis*) in the nearfield in the summers of 1999 and 2000 is presently unclear.

5.0 CONCLUSIONS

5.1 Overview of System Characteristics

Over the course of the ambient water quality monitoring program, general temporal and spatial patterns in water quality characteristics have emerged from the data collected in Massachusetts and Cape Cod Bays. The 2006 data continue to document these general observations and increase confidence that the status and trends, while variable, may in many cases be slowly changing. The patterns 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 strongly 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 and temperatures rise. 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 at deeper stations 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 and is further strengthened by warming of surface waters. 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 grazed by zooplankton.

Late spring also brings the threat of blooms of the ‘red tide’ organism *Alexandrium fundyense*. Since the ambient water quality monitoring program began in 1992, *A. fundyense* has been rarely found in the bays. The presence or absence of *A. fundyense* 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 *A. fundyense* (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 both 2005 and 2006 when meteorological conditions were such that an ongoing bloom of *A. fundyense* in the western GOM was transported into Massachusetts and Cape Cod Bays (Anderson *et al.* 2005a).

The summer is generally a period of strong stratification, depleted surface water nutrients, low biomass, 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 while respiration continues to consume 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 increased respiration and slower currents (higher residence time), respectively, both of which result 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 water weakens stratification 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 nearly monospecific 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 late fall or early winter, the water column becomes well mixed and resets to winter conditions. In winter, the combination of wind mixing and low light levels serve to inhibit primary production thus keeping biomass and phytoplankton abundance low until the following year's winter/spring bloom.

5.2 Monitoring Questions

Much has been learned about the Massachusetts and Cape Cod Bays system over the course of the ambient water quality monitoring 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 ways we envision the bay outfall might or might not impact the bays. No longer is the system viewed as a simple upstream to downstream conveyor belt, but rather one that has a weak and seasonal counterclockwise circulation pattern that is often obscured by tidal and local/regional wind forcing. The substantial and seasonal influence from the Gulf of Maine has been observed on circulation, nutrient loading, DO, and nuisance algal 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 and forms the basis for addressing the monitoring questions (MWRA 1991).

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.

The monitoring questions basically ask whether we understand specific components of the Massachusetts and Cape Cod Bays ecosystem and have they changed as a result of outfall relocation. Significant progress towards answering many of these questions has been achieved. Our understanding of the physical oceanographic conditions in the bays continues to develop and has been detailed herein, in previous reports (e.g. Libby *et al*. 2006b), and in numerous papers (e.g. Butman 1975, Geyer *et al.* 1992, Signell *et al.* 1996, Anderson *et al.* 2005a). Additionally, there have been limited or no changes noted between baseline and post-transfer DO levels or patterns as documented in Section 3.1.1 and in previous reports (Libby *et al*. 2003, 2004, 2006a, 2006b). Furthermore, modeling and statistical analyses indicate that bottom water DO levels in Massachusetts Bay are highly correlated with conditions along the bay/Gulf of Maine boundary and that regional processes and advection are the primary factors governing bottom water DO concentrations in the bay (HydroQual 2001, Geyer *et al*. 2002, Jiang *et al*. 2007).

The observed changes in the nutrient regimes following diversion are unambiguous – NH_4 has dramatically decreased in Boston Harbor (by ~80%) and nearby coastal waters while increasing in the nearfield (by ~50%). The signature levels of NH_4 in the plume are generally 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 in the nearfield and most of Massachusetts Bay. In Boston Harbor, the dramatic decrease in NH_4 has been concomitant with significant decreases in other nutrients (NO_3 and PO_4) and these results are consistent with findings of others (Taylor 2006). However, significant changes in levels and temporal patterns have also occurred for other parameters throughout most areas of the bays. Many of these changes were noted on both a station-by-station and grouped station basis. There were some regional patterns evident in the nutrient data such as the increase in NO_3 concentrations in the fall.

In the nearfield, graphical comparisons of survey, seasonal, and annual mean chlorophyll and POC values suggest that there has not been a substantial change since the diversion of effluent. Seasonal and annual mean chlorophyll concentrations in the nearfield have increased, but the only significant changes observed are winter/spring increases in areal fluorescence, chlorophyll and POC and summer increases in POC. The winter/spring increases in these parameters are coincident with significant increases in areal fluorescence and chlorophyll throughout most of the regions of the bays. In Boston Harbor, there has been both a change in the seasonal chlorophyll and POC patterns and in the magnitude of the values. The harbor has exhibited patterns in these parameters (and productivity) that are comparable to that observed in the nearfield and other temperate coastal waters. The spatial pattern of summer decreases in chlorophyll and POC in Boston Harbor and nearby coastal waters along the South Shore is consistent with model predictions. A clear relationship between changes in nutrients and chlorophyll levels in other areas, however, has not been observed in spatial and temporal means over the first six years of post-transfer monitoring.

Post-diversion production data indicate there has been a significant decrease in Boston Harbor, while nearfield production has declined slightly but not significantly. Reduced productivity at the harbor mouth is correlated with reduced nutrients due to outfall relocation and is statistically significant. In 2001-2003, the presence of spring blooms suggested that the harbor station might be exhibiting a pattern of productivity similar to the nearfield stations, with the cause presumably the reduction in nutrients. In 2004-2006, no spring bloom was evident at the harbor station and the annual maximum in productivity occurred during June or August similar to the baseline period. It does not seem likely that the harbor station is rapidly shifting to the nearfield pattern, but the overall decline in productivity seen at the Boston Harbor station does indicate a shift to a less-enriched environment. The findings to date indicate that nearfield productivity correlates with the physical state of the system and degree of stratification, which may be related to the overall North Atlantic climate cycles. Finally, changes in nutrient concentrations in the nearfield during the spring bloom period appear to be correlated with increased biological utilization and increased peak bloom chlorophyll biomass even though no statistically significant changes in spring productivity have been observed.

Two major changes observed in the phytoplankton community since monitoring began in 1992 were addressed in this report. Indications are that there was no regional outfall effect on the 2005 and 2006 *A. fundyense* blooms. Clear evidence of a local impact has not been observed either, although this is part of ongoing analyses. The other change that has been noted in interannual phytoplankton patterns is the annual occurrence of a spring *Phaeocystis* bloom from 2000-2006, which is more consistent than the apparent ~3 year cycle observed during the baseline period. Again there are no clear indications of an outfall effect on these regional blooms (Libby *et al.* 2006d). Statistical analyses indicate that phytoplankton flora in the bays is regionally similar, shows no distinct depth properties, and has winter-summer seasonality. Some long-term (1992-2006) phytoplankton species composition variation may be due to methodological changes (i.e. microflagellates). Removal of microflagellates from the MDS analyses decreased the degree of differentiation between 1992-1994, 1995-1997, and 1998-2006 samples, but did not change the interpretation that there are differences between these periods that are related to the methods used. Efforts to reconcile the influence of noted methodological changes and taxonomic inconsistencies (species name changes, changes in species categories, etc.) in the MWRA phytoplankton data set are ongoing and will aid future analyses and interpretation of long-term phytoplankton changes.

Comparison of baseline and post-transfer zooplankton abundance suggests that there has been a decrease in abundance from 1992-2000 to 2001-2006 in the nearfield, offshore and boundary areas of Massachusetts Bay. However, not all copepod taxa have exhibited this decrease. *Calanus finmarchicus*, has been present at abundances approximating the baseline mean and within the baseline range during most of the year with a large increases in abundances being observed in May-July in these three areas and Cape Cod Bay. It is unclear why zooplankton abundances have been lower in recent years than previously. The statistical analyses employed confirmed these patterns, but do not provide an indication as to why they occurred. It may be that the post-transfer decreases in total zooplankton abundance and copepod abundance are driven by a few anomalously high values such as for the nearfield in 1999 and 2000 that are skewing the mean values. The changes in zooplankton abundance could also be related to a variety of factors from physical hemispheric processes (i.e. NAO), to bottom-up control via *Phaeocystis* blooms in the spring (poor food source) or lack of substantial fall blooms (reduced food source), to top-down controls due to grazing by ctenophores or other predators. 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 relative impact of these factors in not clear at this time, but the decline in zooplankton abundance will continue to be a focus of the monitoring program.

The MWRA ambient water quality 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 changes that have been observed in the harbor and nearfield and in the plankton community structure. 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, motivation for pursuing this should be balanced by the lack of substantive adverse impact from the outfall relocation. Long-term datasets are of extraordinary value scientifically, and therefore careful thought should be given before this highly informative and important program is modified substantially.

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