2014 Water column monitoring results

Massachusetts Water Resources Authority
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Executive Summary

The Massachusetts Water Resources Authority (MWRA), as part of its National Pollutant Discharge Elimination System (NPDES) permit, is required to monitor water quality in Massachusetts and Cape Cod Bays. This report documents the results of water column monitoring for 2014. The objectives of the monitoring are to (1) verify compliance with NPDES permit requirements, (2) evaluate whether the environmental impact of the treated sewage effluent discharge in Massachusetts Bay is within the bounds projected by the Supplemental Environmental Impact Statement from the Environmental Protection Agency, and (3) determine whether change within the system exceeds thresholds of the Contingency Plan attached to the permit.

The only Contingency Plan water column threshold exceeded in 2014 was the summer *Phaeocystis pouchetii* nuisance species Caution Level threshold. This was primarily due to a three to four week delay in the seasonal phytoplankton cycle, due to cold March and April water temperatures. Although the statistical threshold was exceeded, there was no ecological impact or issue associated with this late *Phaeocystis* bloom.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2014
Bottom Water DO [a] concentration (mg L^{-1})	Survey Mean June-October	<6.5[b]	<6.0 [b]	Nearfield: 6.05 SW [c] Basin: 6.23	Nearfield: 7.19 SW Basin: 6.76
Bottom Water DO percent saturation (%)	Survey Mean June-October	<80% [b]	<75% [b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 81.6% SW Basin: 75.0%
Bottom Water DO rate of decline (mgL^{-1} d^{-1})	Seasonal June-October	0.037	0.049	0.024	0.015
Chlorophyll (nearfield mean, mg m^{-2})	Annual	108	144	72	66
	Winter/spring	199	--	50	75
	Summer	89	--	51	68
	Autumn	239	--	90	50
Phaeocystis pouchetii (nearfield mean, cells L^{-1})	Winter/spring	2,860,000	--	622,000	27,800
	Summer	357	--	79	395,000
	Autumn	2,960	--	370	Absent
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	17,900	--	6,735	106
	Summer	43,100	--	14,635	Absent
	Autumn	27,500	--	10,500	270
Alexandrium fundyense (nearfield, cells L^{-1})	Any nearfield sample	100	--	Baseline Max 163	20

[a] DO = Dissolved Oxygen [b] Unless background lower [c]SW = Stellwagen

The 2014 water column monitoring demonstrated that the wastewater discharge from the bay outfall only influenced the local area within 10 to 20 km, as in previous years and as predicted earlier by calibrated eutrophication-hydrodynamic models. Noteworthy observations made in the bays during 2014 included:

- Regional water temperatures were lower than normal in March and April 2014, which may have contributed to a delay in both the *Phaeocystis* and *Alexandrium* blooms in the region.

- 2014 was the third year in a row to exhibit relatively low nutrient concentrations during the February survey and slightly elevated and steady chlorophyll concentrations over the winter, suggesting that the system remained biologically productive through the winter.
- A winter/spring diatom bloom was not observed on 2014 survey dates; however, mooring and satellite observations indicated chlorophyll fluorescence levels peaked between surveys in late April/early May. The May nutrient and phytoplankton field observations suggest that this peak was due to a combination of diatom population increases and the late *Phaeocystis* bloom, which was senescing in May.
- The colder conditions in winter/spring 2014 and shift in the phytoplankton seasonal cycle also appears to have played a role in the lack of an *Alexandrium* bloom in the bays. Elevated *Alexandrium* abundances and paralytic shellfish poison (PSP) toxicity were observed in western Gulf of Maine waters in late May and early June, but northeaster storms known to be capable of transporting *Alexandrium* into the bays had subsided by early May. This was the second year in a row that there were no PSP toxicity shellfishing closures in Massachusetts Bay.
- Blooms of *Dactyliosolen fragilissimus* (July) and *Cerataulina pelagica* (August) at Boston Harbor and nearshore stations were supported by an increase in nutrients during July 2014, likely associated with strong upwelling-favorable wind conditions.
- The timing of the September and October surveys missed the fall peak in chlorophyll concentrations as measured by mooring and satellite.
- Destabilization and re-stratification of the upper water column during and after September and October storm events was captured by mooring observations. The associated winds ventilated bottom waters and kept the dissolved oxygen (DO) concentration minima at moderate levels that easily met Contingency Plan thresholds. The water column was fully mixed as of late October, following a storm.
- The 2014 annual total phytoplankton abundance was the lowest recorded over the 23 years of monitoring. A long-term linear trend in total phytoplankton abundance is not apparent, rather an alternation between elevated abundance during major *Phaeocystis* bloom years and reduced abundance during non-*Phaeocystis* years is evident. In contrast, long-term declines in centric and pennate diatoms have been recorded.
- Zooplankton abundance peaked in June/July in Massachusetts Bay, while in Boston Harbor, where *Acartia* spp. dominated, there were peaks in May and August/September. The earlier *Acartia* spp. peak in the harbor was consistent with a long-term shift to earlier peak abundances of this taxa observed since 2001.
- The total zooplankton and dominant taxa group abundances in 2014 were high relative to previous years and continue a long-term trend of increases since 2005.
- Linear regression analyses indicate variations in annual mean total zooplankton abundance account for 36% of the decreases seen in annual mean total phytoplankton abundance in the nearfield, highlighting the importance of top-down control of phytoplankton.
- There is no plausible outfall-related link or causality associated with the long-term shifts in phytoplankton or zooplankton. The variations occur over large spatial scales; such broad patterns appear instead to be related to regional ecosystem dynamics in the Gulf of Maine.

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1 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) conducts a long-term ambient outfall 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 environmental impact of the treated sewage effluent discharge in Massachusetts Bay is within the bounds projected by the Environmental Protection Agency (EPA) Supplemental Environmental Impact Statement (EPA 1988), and (3) determine whether change within the system exceeds Contingency Plan thresholds (MWRA 2001).

A detailed description of the monitoring and its rationale are provided in the monitoring plans developed for the baseline period prior to relocation of the outfall to Massachusetts Bay (MWRA 1991, 1997) and outfall discharge periods since the 2000 relocation (MWRA 2004, 2010). The 'baseline' period extends from 1992 to August 2000, the period Deer Island and/or Nut Island wastewater discharges were directed to the harbor. The outfall discharge period extends from September 2000 through 2014 and encompasses the period wastewater was discharged from the bay outfall. The 2014 data complete 14 years of monitoring since operation of the bay outfall began on September 6, 2000. **Table 1-1** shows the timeline of major upgrades to the MWRA wastewater treatment system.

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 from primary to secondary treatment completed
October 2004	Upgrades to secondary facilities (clarifiers, oxygen generation)
April 2005	Biosolids line from Deer Island to Fore River completed and operational
2005	Improved removal of total suspended solids (TSS) etc. due to more stable process
2010	Major repairs and upgrades to primary and secondary clarifiers

MWRA's Effluent Outfall Ambient Monitoring Plan (AMP) was last revised in 2010 (MWRA 2010). The 2010 AMP revision builds on the scientific understanding gained over the previous 20 years – the monitoring is now focused on the stations potentially affected by the discharge and reference stations in Massachusetts Bay. There are nine one-day surveys per year (**Table 1-2**) designed to provide a synoptic assessment of water quality conditions. The Provincetown Center for Coastal Studies (PCCS) monitors Cape Cod Bay in the same timeframe maximizing spatial coverage. This annual report summarizes the 2014 results as seasonal patterns, in the context of the annual cycle of ecological events in Massachusetts and Cape Cod Bays, and with respect to Contingency Plan thresholds (MWRA 2001). Long-term interannual patterns are also analyzed.

1.1 DATA SOURCES

The details of field sampling procedures and equipment, sample handling and custody, sample processing and laboratory analysis, instrument performance specifications, and the program's data quality objectives are given in the Quality Assurance Project Plan (QAPP; Libby *et al.* 2014). The survey objectives, station locations and tracklines, instrumentation and vessel information, sampling methodologies, and staffing were documented in the survey plan prepared for each survey. A survey report prepared after each survey summarizes the activities accomplished, details on any deviations from the methods described in the QAPP, the actual sequence of events, tracklines, the number and types of samples collected, and a preliminary summary of *in situ* water quality data. The survey report also includes the results of a rapid analysis of >20 µm phytoplankton species abundance in one sample, whale watch information, and any deviations from the survey plan. Electronically gathered and laboratory-based analytical results are stored in the MWRA Environmental Monitoring and Management System (EM&MS) database. The EM&MS database undergoes extensive quality assurance and technical reviews. All data for this Water Column Summary Report is exported from the EM&MS database.

1.2 WATER COLUMN MONITORING PROGRAM OVERVIEW

Under the AMP (MWRA 2010) all sampling locations (**Figure 1-1**) are visited annually during each of the nine surveys; the 2014 sampling dates are shown in **Table 1-2**. Five stations are sampled in the nearfield and nine stations in the farfield (**Figure 1-1**). The 11 stations in Massachusetts Bay are sampled for a comprehensive suite of water quality parameters, and plankton is sampled at all stations except N21. The three Cape Cod Bay stations are sampled by PCCS (QAPP, Costa et al. 2013). The Massachusetts Bay stations are sampled during one-day surveys; the three Cape Cod Bay stations are sampled by PCCS within 48 hours of the Massachusetts Bay surveys. Samples are collected by MWRA at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally biweekly frequency.[1] Only BHWQM data (nutrient, dissolved oxygen [DO], and *Alexandrium*) collected within 7 days of a Massachusetts Bay survey are included in this report (dates shown in **Table 1-2**).

Table 1-2. Water column surveys for 2014.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN141	February 4	February 4	February 4
WN142	March 18	March 18	March 20
WN143	April 9	April 7	April 2
WN144	May 9	May 9	May 7
WN145	June 14	June 14	June 19
WN146	July 22	July 22	July 22
WN147	August 18	August 19	August 14
WN148	September 3	September 2	September 9
WN149	October 30	October 30	November 5

In addition to survey data, this report includes Moderate-resolution Imaging Spectroradiometer (MODIS) satellite observations provided by the National Aeronautics and Space Administration (NASA), and continuous monitoring data from both the NOAA National Data Buoy Center (NDBC) Buoy 44013 and the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) Mooring A01. The satellite imagery provides information on regional-scale patterns, while the moorings sample multiple depths at a single location with high temporal frequency. NDBC Buoy 44013 is located ~10 km southeast of the outfall, near station N07; NERACOOS Mooring A01 is located in the northwestern corner of Stellwagen Bank National Marine Sanctuary and ~5 km northeast of MWRA station F22 (**Figure 1-1**).

The data are grouped by season for calculation of chlorophyll, *Phaeocystis*, and *Pseudo-nitzschia* Contingency Plan thresholds. Seasons are defined as the following four-month periods: winter/spring is from January through April, summer is from May through August, and fall is from September through December. Comparison of baseline and outfall discharge period data are made for a variety of parameters.

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[1] BHWQM station map available at http://www.mwra.state.ma.us/harbor/graphic/bostonharbor_850.gif

The baseline period is February 1992 to September 6, 2000 and the outfall discharge period is September 7, 2000 through December 2014.[2]

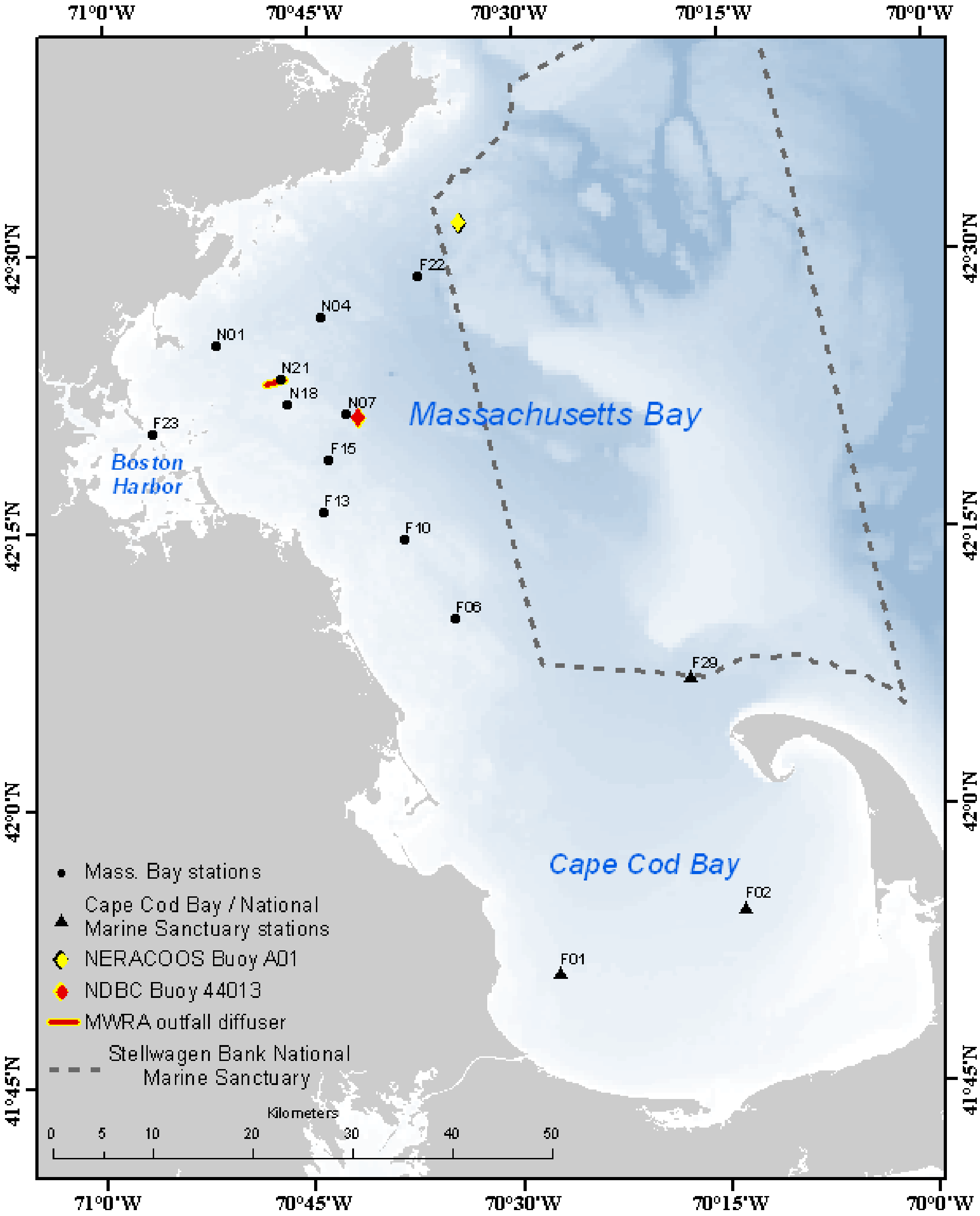

Figure 1-1. Water column monitoring locations. Shading is relative depth.

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[2] Year 2000 data are not used for calculating annual means as the year spans both periods, but are included in plots and analyses broken out by survey and season. Details on how 2000 data are treated are included in the captions and text.

2 MONITORING RESULTS

A winter/spring phytoplankton bloom is typically observed in Cape Cod and Massachusetts Bays as daylight lengthens, temperatures increase, and nutrients are readily available. Since 2000, a winter/spring diatom bloom has usually been followed by a bloom of *Phaeocystis pouchetii* in April. Deviations from this winter/spring pattern occurred in 2014 with survey observations indicating a lack of the winter/spring diatom bloom and a month-long delay in the *Phaeocystis* bloom to late April/May. This may have been due in part to the colder than normal temperatures observed in March/April 2014. These colder conditions and associated ecological shift may have also played a role in the lack of an *Alexandrium* bloom in the bay in 2014.

The summer is generally a period of strong density stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community. Summer meteorological conditions are often characterized by consistent winds out of the south and southwest that induce upwelling in the bay. Summer 2014 was consistent with past trends, with July winds that were strongly upwelling-favorable and likely supported the nearshore diatom bloom that was observed.

In the fall, as temperatures cool, stratification deteriorates and nutrients are again supplied to surface waters from below. This transition often contributes to the development of a fall phytoplankton bloom. DO concentrations are lowest in the bottom waters prior to the fall overturn of the water column – usually in October. The October 2014 survey was conducted after the water column had become well mixed at shallow stations, so DO levels were moderate throughout the bay in comparison to previous years.

The details of the major features observed and differences noted in 2014 relative to the previous 22 years of monitoring are considered below.

2.1 2014 RESULTS

In January, prior to the first survey of 2014, observations at the NDBC Buoy 44013 indicated that surface water temperatures were close to the long-term average (**Figure 2-1**). These conditions continued into February and early March. By mid-March, water temperatures had cooled and were close to the minima historically observed at Buoy 44013 (**Figure 2-1**) and at nearfield station N18 (**Figure 2-2**). Although there was a brief warming at Buoy 44013 in early April, water temperatures remained cold in Massachusetts Bay into May. The trend of cold surface water temperatures was even more pronounced at the NERACOOS Mooring A01 with temperatures (not shown) at the minimum of the range observed since 2001 from early March to early May.

MODIS satellite chlorophyll fluorescence imagery (**Figure 2-3)** and survey nutrient data (**Figure 2-4 and Figure 2-5**) suggest that phytoplankton were productive prior to the February 2014 survey. Chlorophyll fluorescence was moderate (~1-3 $\mu g\ L^{-1}$) in January and February and nutrient concentrations were relatively low in Massachusetts and Cape Cod Bays in February. Silicate (SiO_4) was nearly depleted in both bays in February. These low February nutrient levels suggest that winter diatoms may have been biologically productive prior to the first survey.

There was a large increase in SiO_4 from February to April in Massachusetts Bay (**Figure 2-4**). Mean nitrate (NO_3) and phosphate (PO_4) levels (**Figure 2-5**) were low in Massachusetts Bay compared to previous years for February; during the subsequent few surveys, unlike the sharp decreases that typify previous years, in 2014 they remained relatively constant and were therefore higher than typical by April. These patterns are consistent with the combination of a period of consistent phytoplankton productivity prior to the February survey and the lack of a diatom or *Phaeocystis* bloom from February through April. The phytoplankton data showed a markedly reduced abundance of centric diatoms in winter/spring: *Chaetoceros* spp. and *Thalassiosira* spp., which normally are abundant through most of the winter-spring, were at ~25% of their long-term mean levels.

Cold-water centric diatoms, *Detonula confervacea, Porosira glacialis* and *Lauderia annulata*, which often comprise the earliest successional stage of winter/spring diatoms, were abundant during March and April 2014, with *D. confervacea* the most abundant of the three species. *Detonula confervacea* is an Arctic-Boreal diatom that has its greatest abundance at cold water temperatures of <5˚C. Its abundance level (up to 75,000 cells L^{-1} in March and April) was the highest observed in the Massachusetts Bay monitoring data since 1992. This may have been due to a combination of colder waters being present in, and being transported into, the bay and the lack of competition from the typically more abundant, bloom forming centric diatoms *Chaetoceros* spp. and *Thalassiosira* spp.

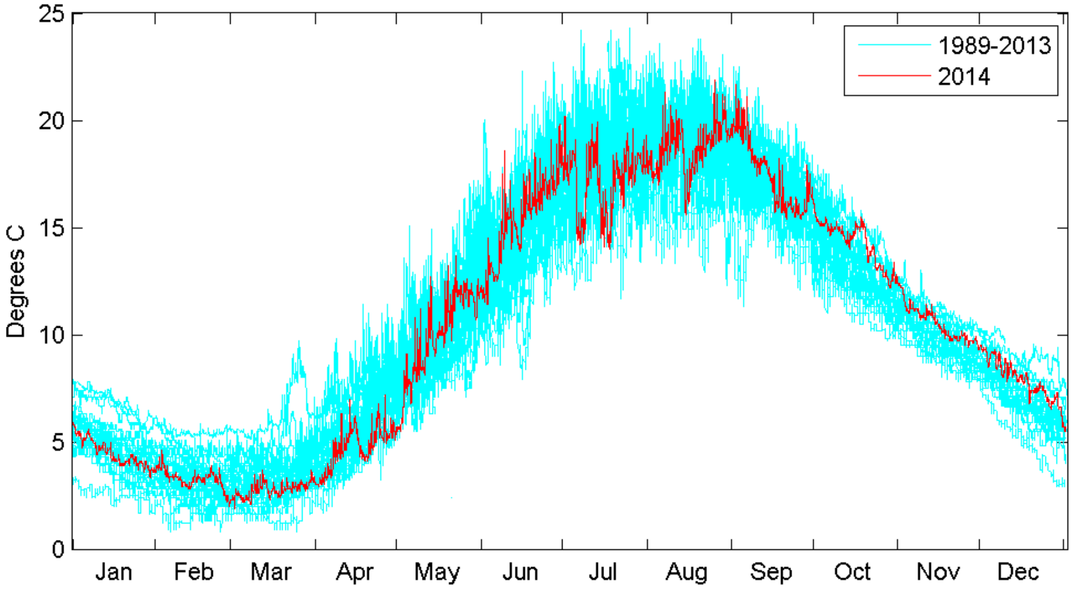

Figure 2-1. **Comparison of 2014 surface water temperature (°C) at NDBC Buoy 44013 in the vicinity of the nearfield (solid red line) with 1992-2013 (light blue lines).**

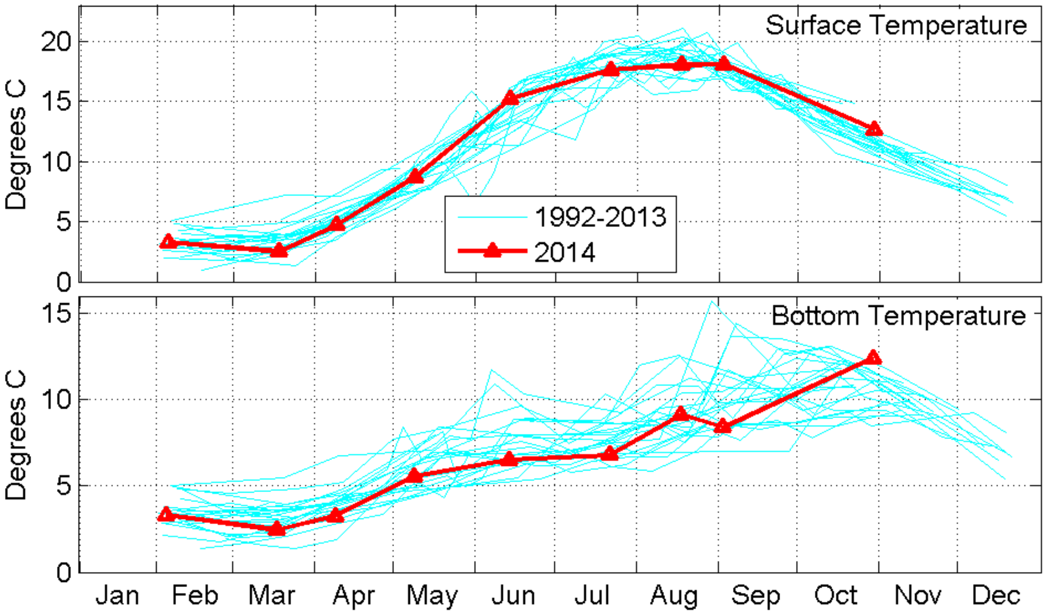

Figure 2-2. **Comparison of 2014 surface and bottom water temperature (°C) at nearfield station N18 (solid red line) with 1992-2013 (light blue lines).**

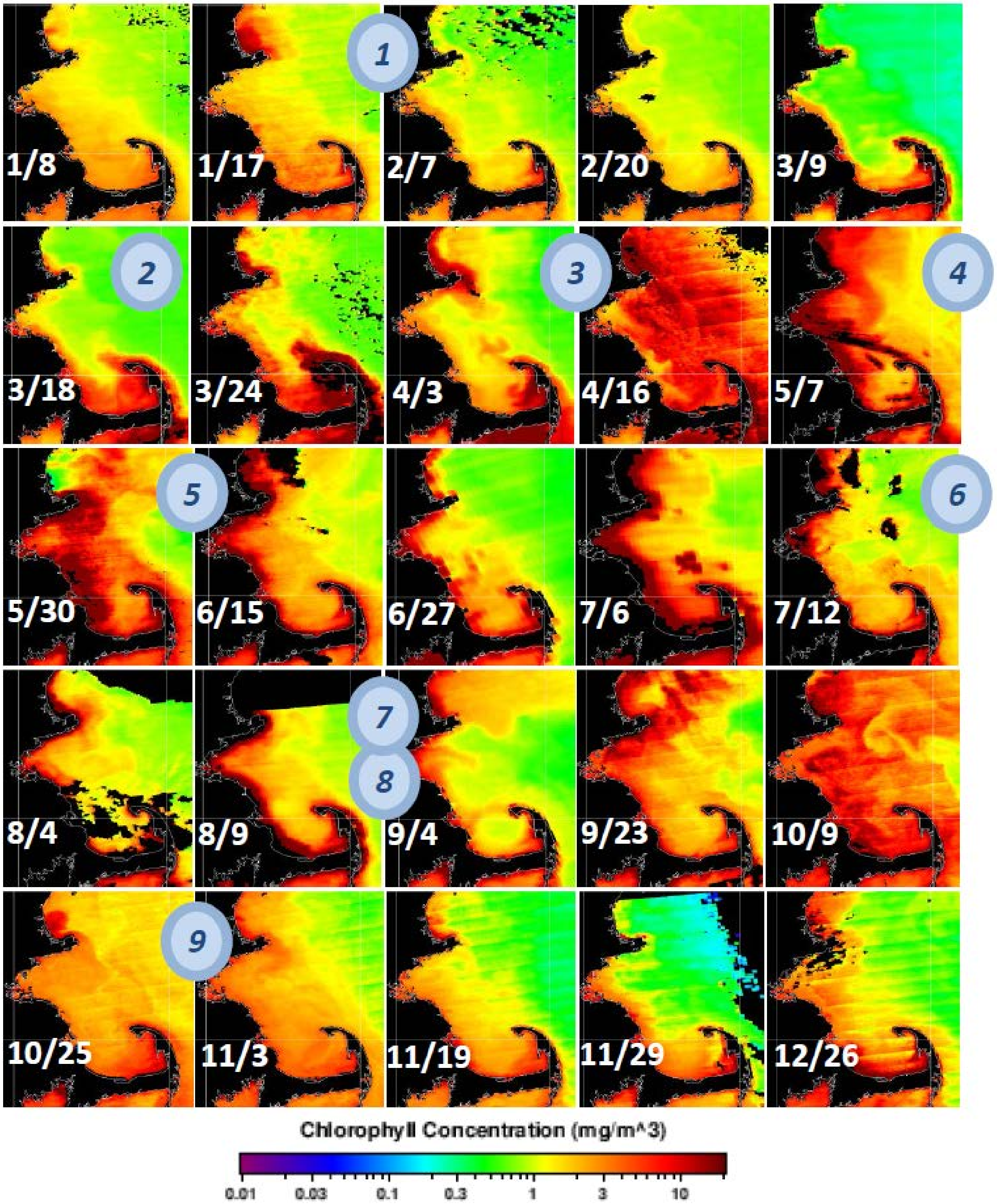

Figure 2-3. **Satellite (MODIS) imagery of surface chlorophyll concentrations (mg m^{-3}) in 2014.**

Highlights and specific blooms:

1st row – moderate chlorophyll levels January 2014 (and November-December 2013; not shown);
1st & 2nd rows – relatively low from February into March – no winter/spring diatom bloom;
2nd & 3rd rows – high chlorophyll April and May – late *Phaeocystis* bloom;
3rd & 4th rows – summer chlorophyll increase - blooms of *Dactyliosolen fragilisima* and *Cerataulina pelagica*;
4th & 5th rows – September and October mixed diatom bloom;
5th row – moderate chlorophyll levels into November and December.

(The image dates are heavily weather dependent and not distributed uniformly in time. The numbered ovals indicate relative timing of the nine MWRA surveys.)

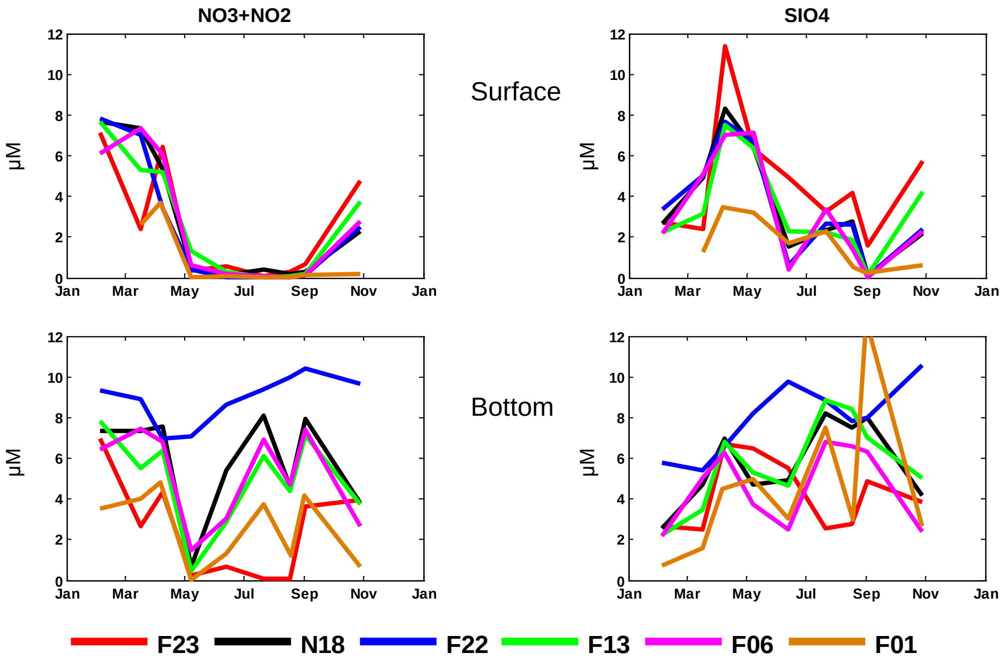

Figure 2-4. Time-series of surface and bottom NO_3+NO_2 and SiO_4 concentrations (µM) at representative stations (see Figure 1-1) in Massachusetts and Cape Cod Bays in 2014.

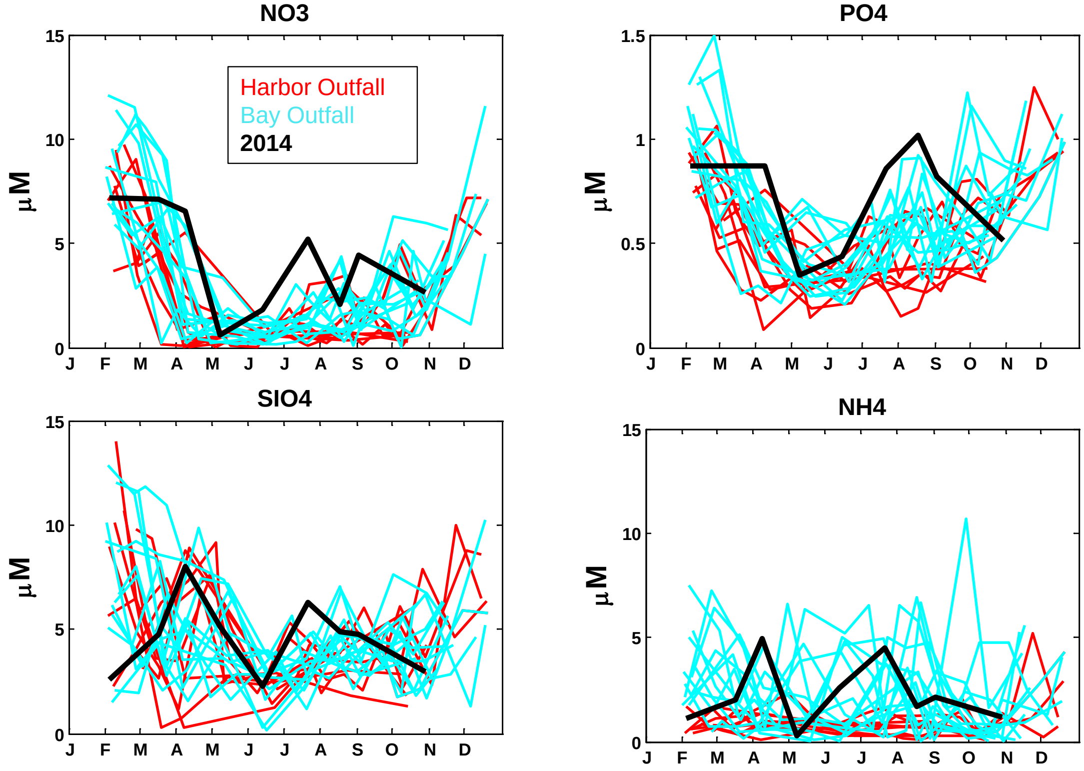

Figure 2-5. Station average nutrient concentrations (µM) near the outfall site (nearfield station N18) for 2014 (black line) compared to the previous 22 years, including baseline (Harbor Outfall; 1992-August 2000; red) and post-diversion (Bay Outfall; September 2000-2013; light blue) observations. Note change in scale for PO_4 plot.

The lack of an observed winter/spring diatom bloom in the survey data contributed to the overall decrease in annual-mean phytoplankton abundance in 2014, which ranked lowest for the 23 years of monitoring. Total phytoplankton abundance during 2014 was 59% of the long-term mean (861,217 cells L^{-1} versus 1,472102 cells L^{-1}; **Table 2-1**). The low observed phytoplankton abundance in 2014 was due to the timing of the nine surveys, which when compared to MODIS imagery suggest that the major peaks in chlorophyll occurred between the April and May and September and October surveys (**Figure 2-3**). These two peaks in chlorophyll fluorescence were also observed in the Mooring A01 data (**Figure 2-6**). Overall, there was good agreement between Mooring A01 and survey chlorophyll fluorescence at nearby station F22 during the nine 2014 surveys. The April/May peak was primarily due to a late *Phaeocystis* bloom that was apparently senescing during the survey on May 9 (discussed below).

Concurrent with the late *Phaeocystis* bloom, nutrient levels decreased sharply from April to May 2014 with survey mean NO_3 nearly depleted at all but the deepest stations (**Figure 2-4 and Figure 2-5**). Silicate concentrations decreased slightly by May suggesting there may have been an increase in diatoms between surveys along with the *Phaeocystis* bloom. This change in nutrients is consistent with the observed peaks in MODIS and Mooring A01 data and the observed increase in chlorophyll from April to May, when annual peak average chlorophyll levels were observed at many stations in Massachusetts Bay (**Figure 2-8**).

Table 2-1. **Comparison of 2014 annual mean phytoplankton abundance in the nearfield (cells L^{-1}) to long-term observations for major groups and species.** Differences between values were assessed using the Mann-Whitney non-parametric statistical hypothesis test; p values of ≤ 0.05 are noted. These are exploratory analyses involving multiple comparisons. Determination of significant changes is complicated by multiple comparison issues and corrections for the associated errors are considered beyond the scope of the analyses.

Group	1992-2013	2014	Rank (out of 23)	p value	Significant Change
CENTRIC DIATOM	309,982	168,101	19th	0.0001	Decline
Dactyliosolen fragilissimus	50,273	70,810	7th	0.3337	
Chaetoceros	41,783	10,575	15th	0.0001	Decline
Skeletonema costatum complex	66,719	14,048	18th	0.3466	Decline
Thalassiosira	32,408	9,318	17th	0.0462	Decline
PENNATE DIATOM	43,454	16,027	17th	0.1076	
Pseudonitzschia	10,492	1,949	18th	0.0244	Decline
DINOFLAGELLATES	53,349	26,902	21st	0.0001	Decline
Ceratium	1,779	2,063	9th	0.3138	
Dinophysis	264	1,212	2nd	0.0001	Increase
Phaeocystis pouchetii	252,505	189,232	9th	0.4687	
CRYPTOPHYTES	117,631	112,449	13th	0.5546	
MICROFLAGELLATES	684,231	340,297	22nd	0.0001	Decline
TOTAL PHYTOPLANKTON	1,472,102	861,217	23rd	0.0001	Decline

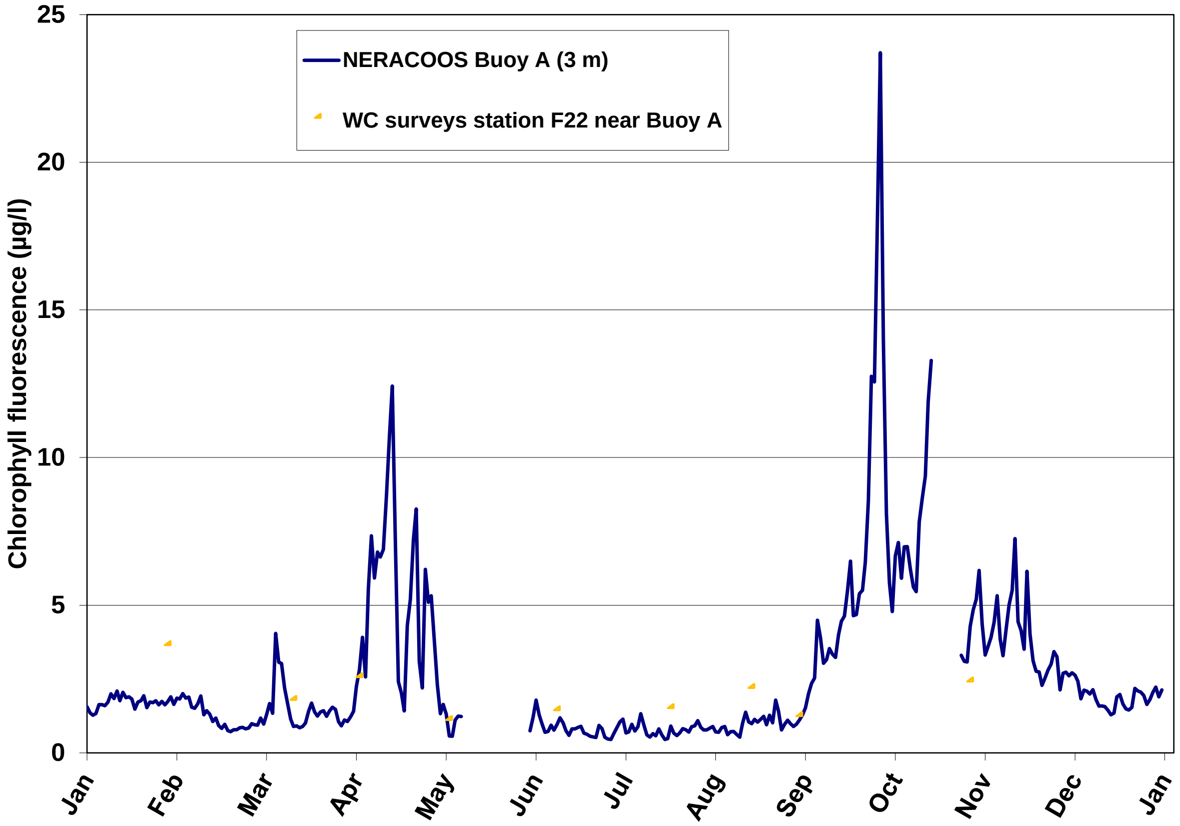

Figure 2-6. **Surface water chlorophyll fluorescence (µg L^{-1}) at NERACOOS Mooring A01 and nearby MWRA station F22.**

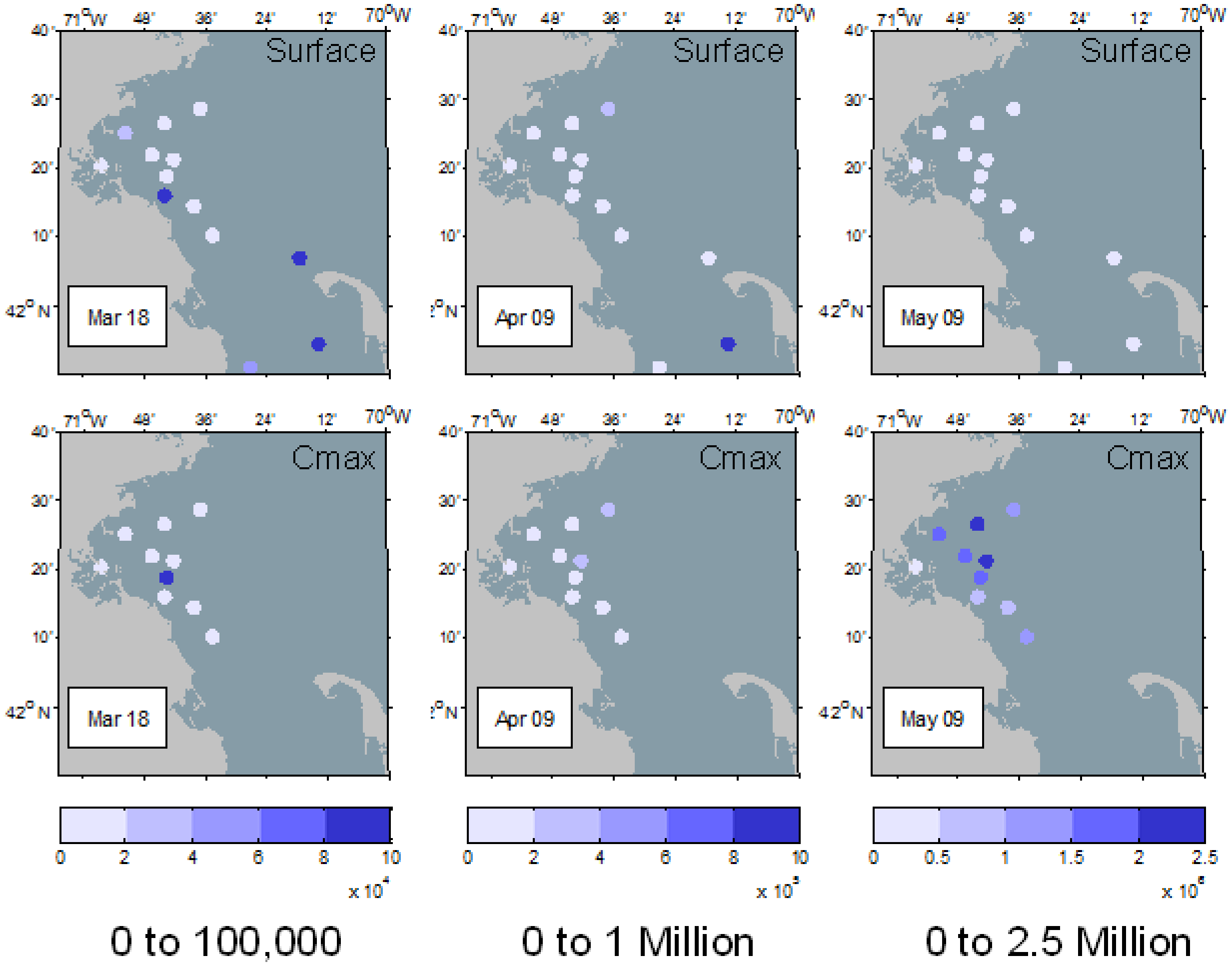

Figure 2-7. ***Phaeocystis* abundance (million cells L^{-1}) by station and sampling depth (near-surface, upper row; depth of chlorophyll maximum 'Cmax', lower row) in Massachusetts and Cape Cod Bays in March, April and May 2014.** Note changes in scales.

The 2014 *Phaeocystis* bloom resulted in an exceedance of the summer contingency threshold. *Phaeocystis* had been observed in the bays since February, but abundances remained relatively low until May (**Figure 2-7**). In comparison to past years, the 2014 bloom occurred about a month later than its typical late March or early April timing. Satellite and mooring observations suggest the bloom may have peaked in late April/early May (**Figure 2-3 and Figure 2-6**). This is consistent with May survey results that suggested a senescent *Phaeocystis* bloom: atypical *in situ* fluorescence profiles with maxima in the bottom waters, elevated phaeophytin concentrations, and high phaeophytin/chlorophyll ratios. The bloom occurred after the unusually cold temperatures had subsided, and likely was delayed by them. The summer contingency plan threshold exceedance that occurred is considered to be due to the calendar-based definitions of seasonal periods used in threshold testing computations, as opposed to indicating an ecologically meaningful result.

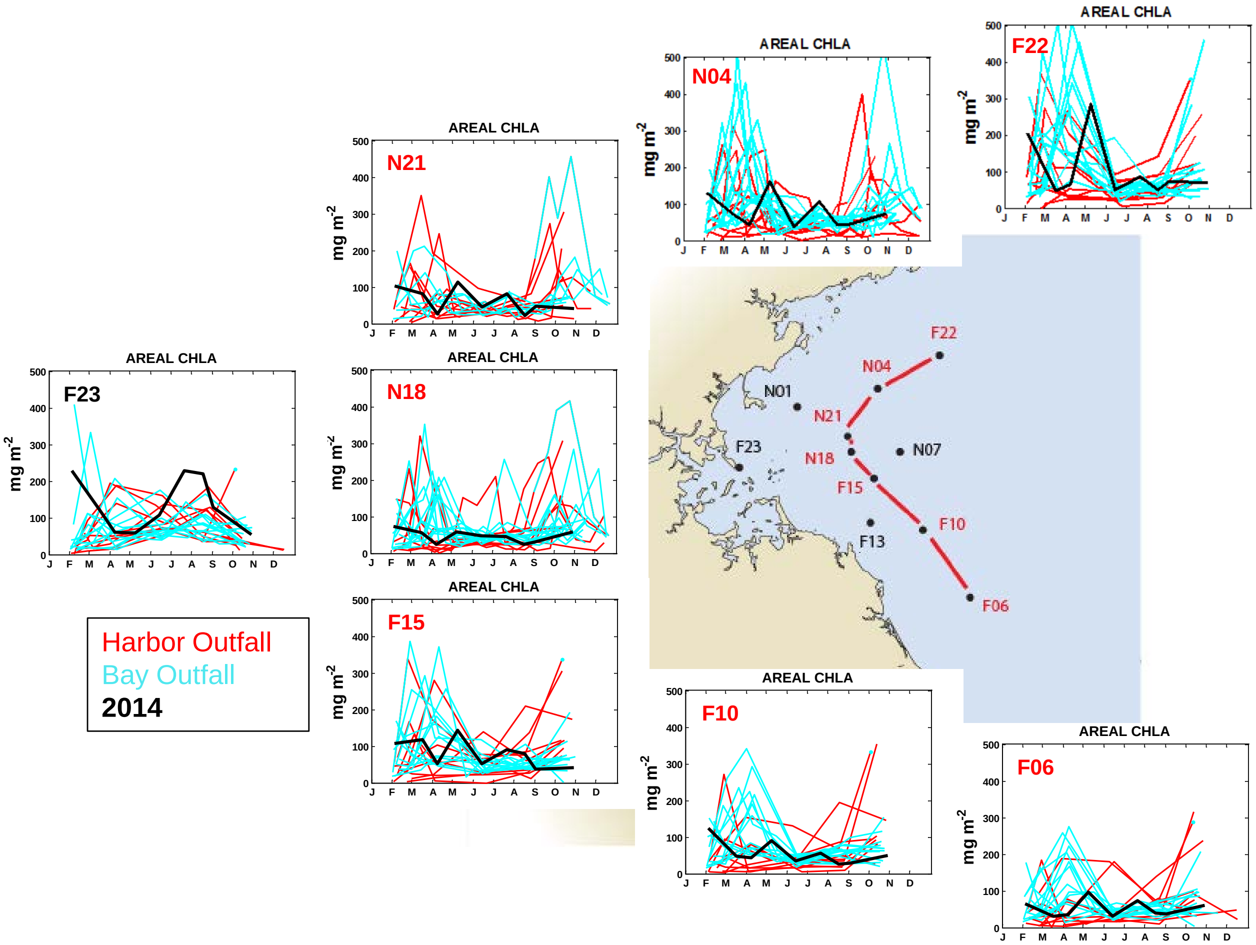

Figure 2-8. Areal chlorophyll fluorescence (mg m^{-2}) at representative stations in Massachusetts Bay for 2014 (black line) compared to the previous 22 years, including baseline (Harbor Outfall; 1992-August 2000; red) and post-diversion (Bay Outfall; September 2000-2013; light blue) observations.

The colder than normal 2014 spring temperatures may also have affected *Alexandrium fundyense* abundances, which were very low in Massachusetts Bay; the maximum was 20 cells L^{-1} at station N01 in May and only seven other samples had any *Alexandrium* cells (all <3 cells L^{-1}). Higher abundances were observed off of Cape Ann and to the north in the western Gulf of Maine at the end of May and early June (pers. comm., Bruce Keafer, http://www.whoi.edu/fileserver.do?id=188264&pt=2&p=196511). These were coincident with elevated PSP toxicity measurements by state agencies and the eventual PSP toxicity closure to shellfishing from Gloucester, Massachusetts, northward into southern Maine in early June. However, no PSP toxicity was measured in Massachusetts and Cape Cod Bays in 2014. This may not have been the case, if not for the delay in the Gulf of Maine *Alexandrium* bloom, as northeaster storms were observed in late April and May that brought (described below) lower salinity waters (and likely *Phaeocystis*, described above) in to the bays (**Figure 2-9**) and could have transported *Alexandrium* as well. In June, winds and currents were not as conducive to transporting western Maine coastal current waters into the bays so the moderate *Alexandrium* bloom observed in the Gulf of Maine north of Cape Ann remained offshore.

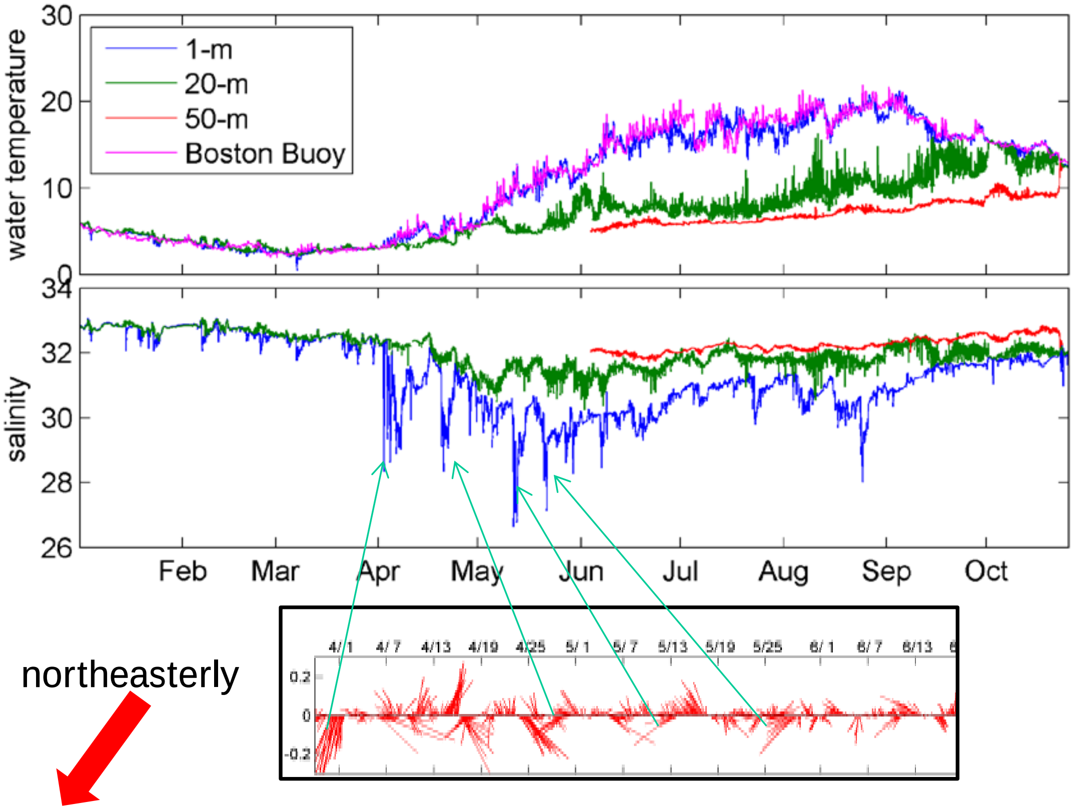

Figure 2-9. **NERACOOS Mooring A01 time series observations in 2014. Top: Water temperature (1, 20 and 50 m depths, with Buoy 44013 ("Boston Buoy") surface temperature superposed). Middle: Salinity (1, 20 and 50 m depths). Bottom: Surface winds.**

The April and May storms and associated winds influenced the physical oceanographic conditions in the bay via both advection and mixing (**Figure 2-9**). The early April storm brought fresher, warmer waters into the bay and appeared to set up early stratification, which was also suggested by the April survey data showing a density difference between shallow and deep samples of about 1 kg m^{-3} at nearfield station N18 (**Figure 2-10**). Subsequent storms, as suggested by the similar temperatures at the 1-m and 20-m depths at Mooring A01, appeared to have destabilized and homogenized the upper water column multiple times in April and early May, with strong and permanent stratification not being established until at least the middle of May. The nearfield waters were strongly stratified through September, but strong and consistent winds out of the south in July led to the strongest upwelling-favorable conditions observed to date during the 23-year monitoring period (**Figure 2-11**).

From May through September, surface water NO_3 concentrations remained depleted in the bays (**Figure 2-4**). The low surface nutrient levels were due to a combination of seasonal stratification and consistent biological utilization during the summer. Bottom water nutrient levels increased over this time period, apparently due to a combination of remineralization and deep physical transport. As observed since operation of the bay outfall began in 2000, the bay outfall effluent plume was observed as elevated ammonium (NH_4) concentrations in the nearfield throughout 2014 (**Figure 2-12**) and the concentrations were higher under seasonally stratified conditions as seen from May through October. The northward extent of the plume is usually limited to within the nearfield area, but elevated NH_4 plume signature is generally seen within 10 to 20 km to the south of the outfall during both well-mixed and stratified conditions. The spatial (horizontal and vertical) distribution of the effluent plume in 2014 continued to compare well with model predictions (Signell *et al*. 1996).

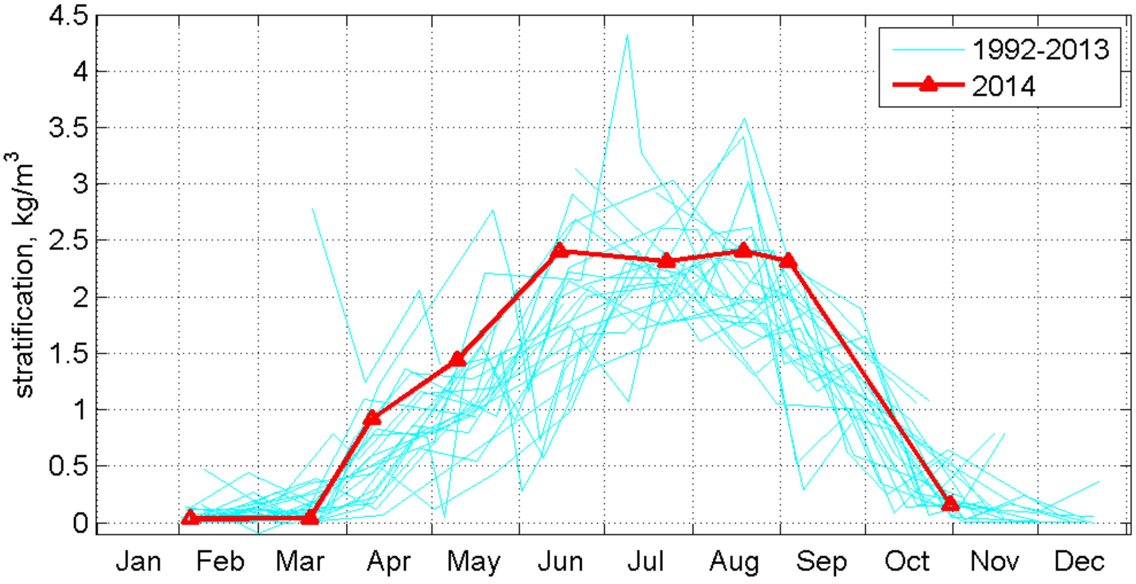

Figure 2-10. **Stratification at nearfield station N18 in Massachusetts Bays in 2014 (red line) and previous 22 years (1992-2013, light blue lines).**

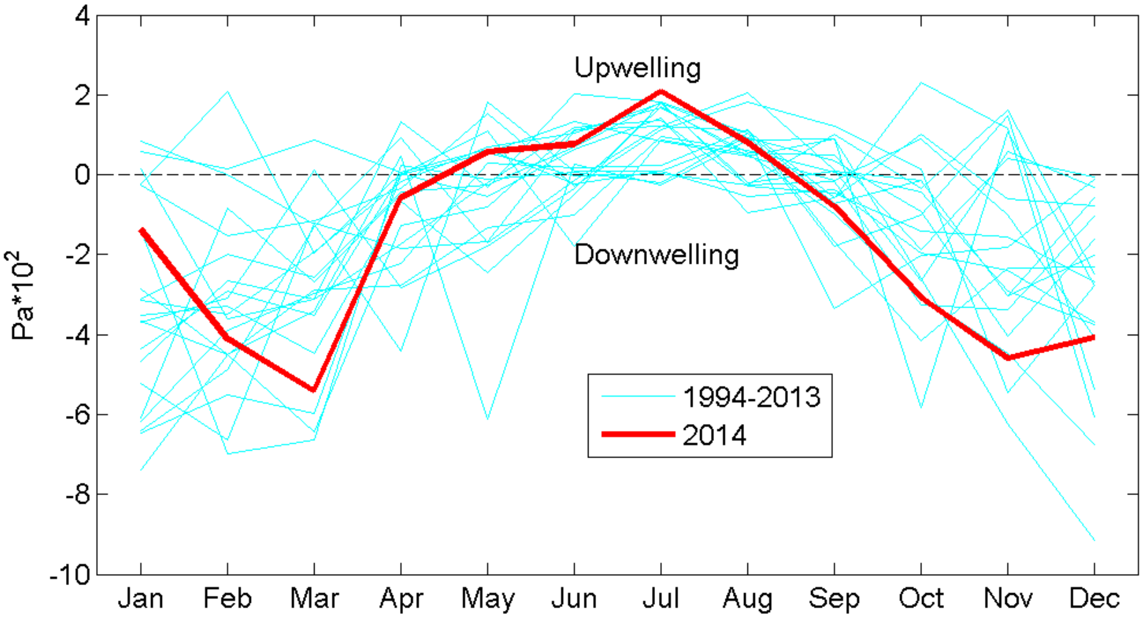

Figure 2-11. **Average wind stress at NDBC Buoy 44013. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.**

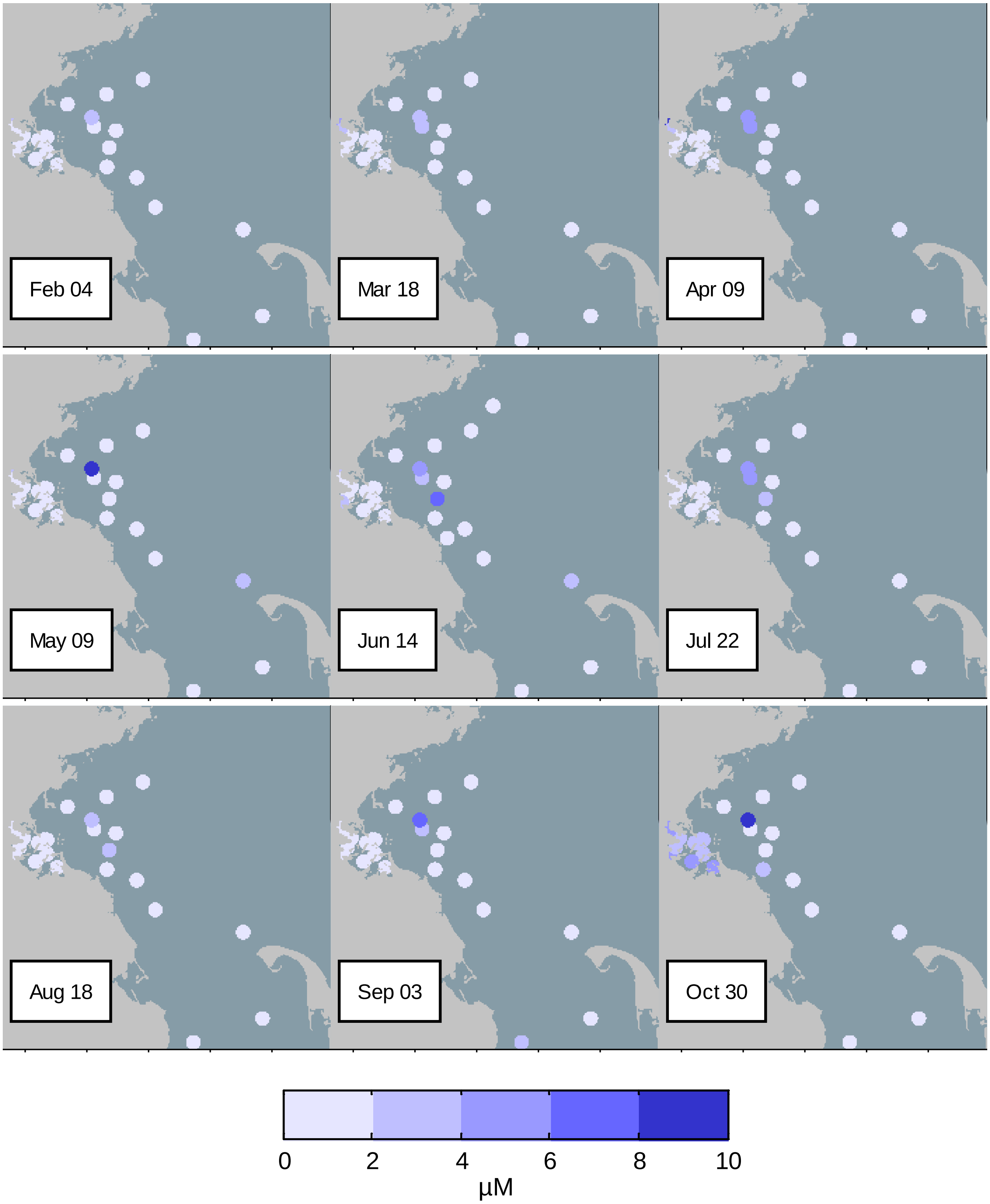

Figure 2-12. **Average NH_4 concentrations (µM) at stations in Massachusetts and Cape Cod Bays in 2014.**

There were episodic increases in nutrient concentrations at mid and bottom depths at some stations in June and July; these are consistent with upwelling, as shown for NO_3 in **Figure 2-13**. A similar signature was observed for NH_4 at stations F15 and N18 where the MWRA effluent plume, characterized by elevated NH_4 concentrations, is often seen. Subsurface chlorophyll maxima were observed just above the pycnocline during these surveys. These coincided with a period of wind stress conducive to coastal upwelling at the highest observed since 1992. In the nearfield and to the south at station F15, episodic peaks in NH_4 observed over the 2014 summer period have been a consistent feature since 2001 and have been attributed to intermittency in the presence of the outfall effluent plume at these stations (**Figure 2-14**). Overall, summer time NH_4 concentrations, as well as the other nutrients, were similar in 2014 to those observed since 2001.

Although increases in NH_4 associated with the effluent plume have been observed in the nearfield since the bay outfall began discharging in September 2000, no related changes to phytoplankton biomass in this region have been observed. At nearfield station N18, biomass (as measured by chlorophyll and particulate organic carbon [POC) and total nitrogen in 2014 were within historical ranges, and often at the lower end of the range (**Figure 2-15**). Total phytoplankton was at or near the minimum of the historical range for each month except for the May peak associated with the senescing *Phaeocystis* bloom observed during that survey (**Figure 2-15**). Despite that it includes NH_4, which is enriched in the nearfield by effluent discharge, total nitrogen at station N18 was low (near minima of historic range) throughout 2014 (**Figure 2-15**), except in July when a combination of outfall input and upwelling-favorable conditions may have brought the plume higher into the water column, increasing NH_4 and total nitrogen. Overall, biomass and total phytoplankton were very low in the nearfield in 2014, compared to baseline and post-diversion levels, and at historic minima during many months.

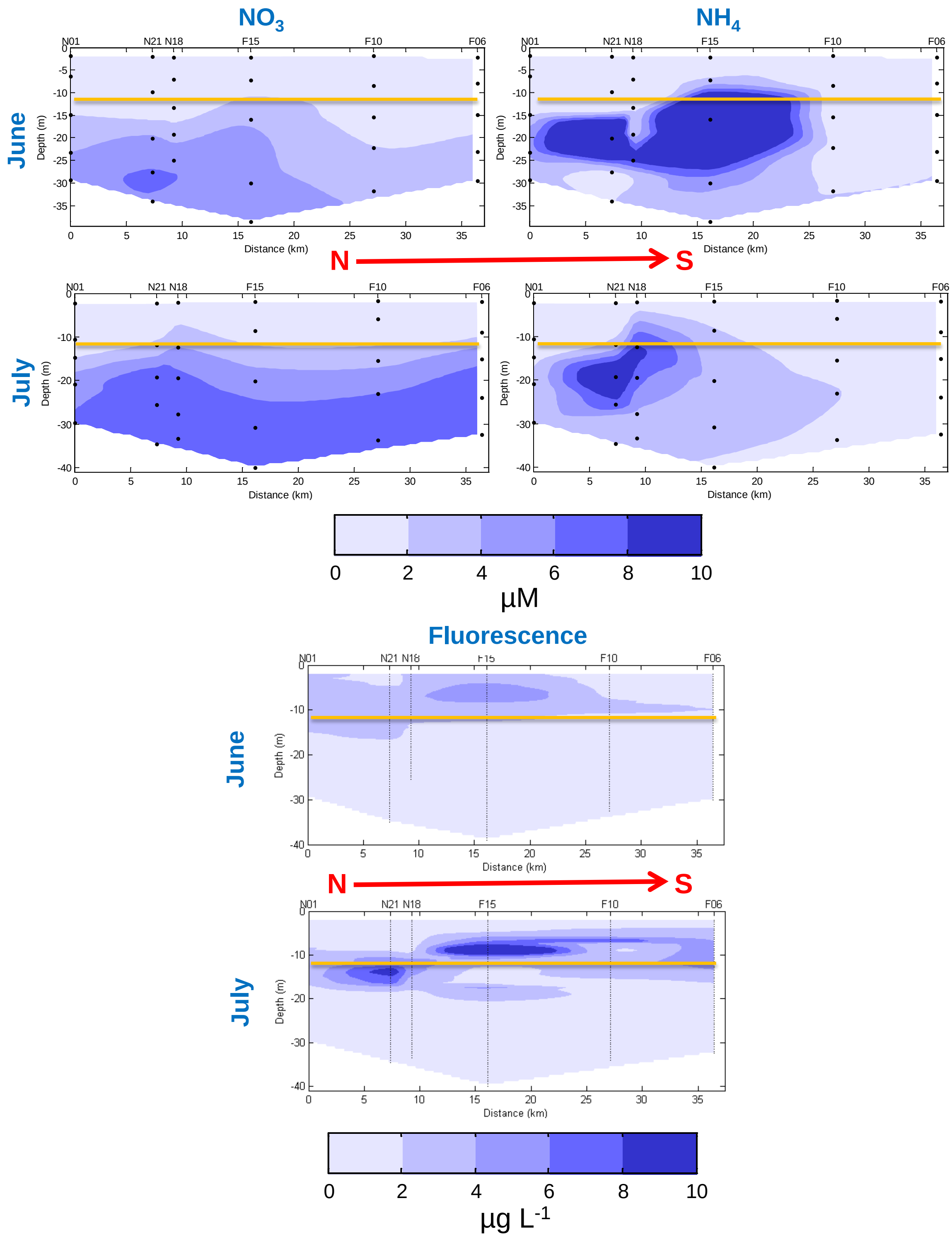

Figure 2-13. **Nitrate, ammonium, and fluorescence concentrations (µM and µg L^{-1}) along a generally north-south transect (see map, Figure 2-23) in Massachusetts Bay in June and July 2014.** The dots on the plot indicate the sampling depths for nutrients and the in situ fluorescence profile. The yellow line indicates the approximate depth of the pycnocline.

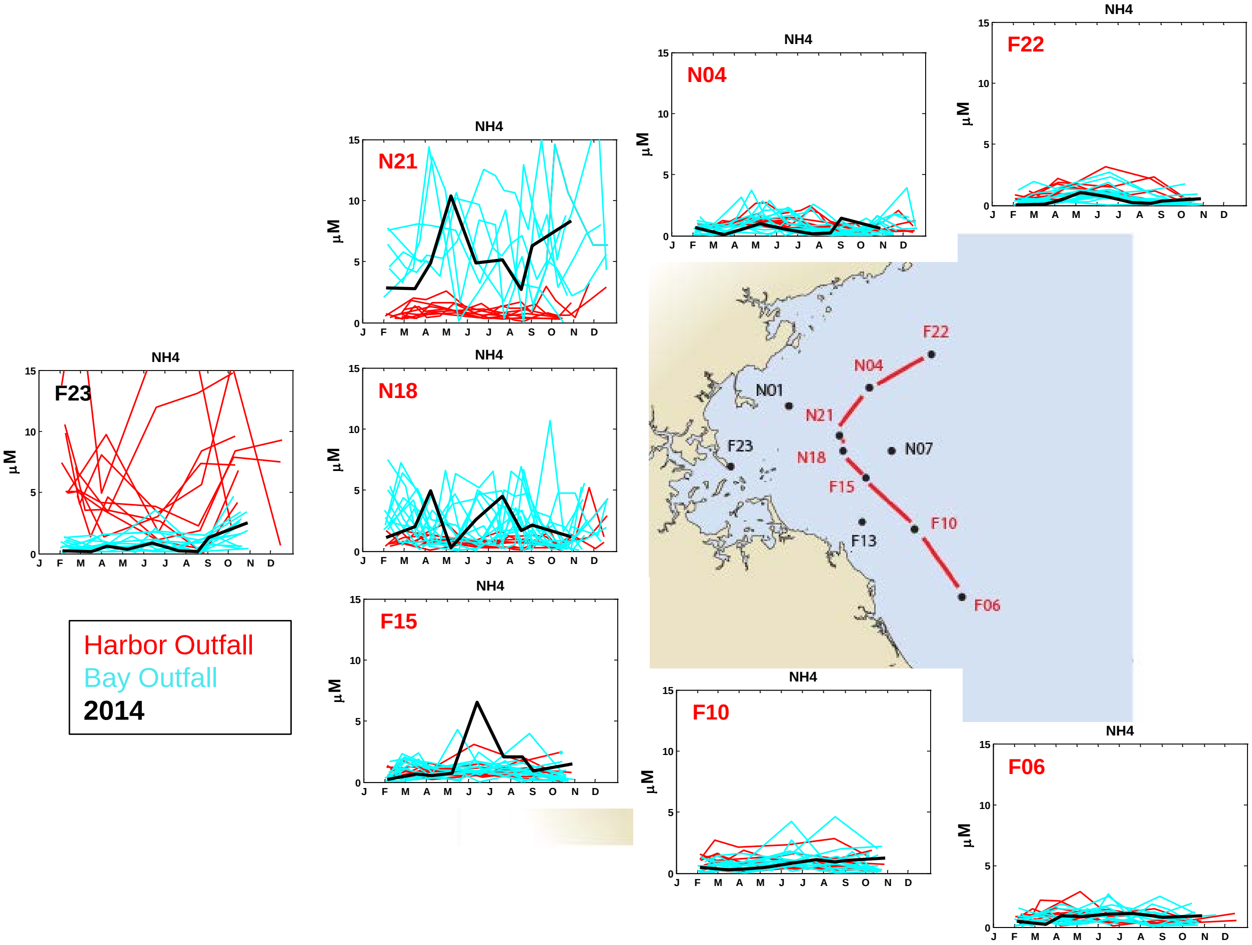

Figure 2-14. **Average NH_4 (µM) at representative stations in Massachusetts Bay for 2014 (black line) compared to the previous 22 years, including baseline (Harbor Outfall; 1992-August 2000; red) and post-diversion (Bay Outfall; September 2000-2013; light blue) observations.**

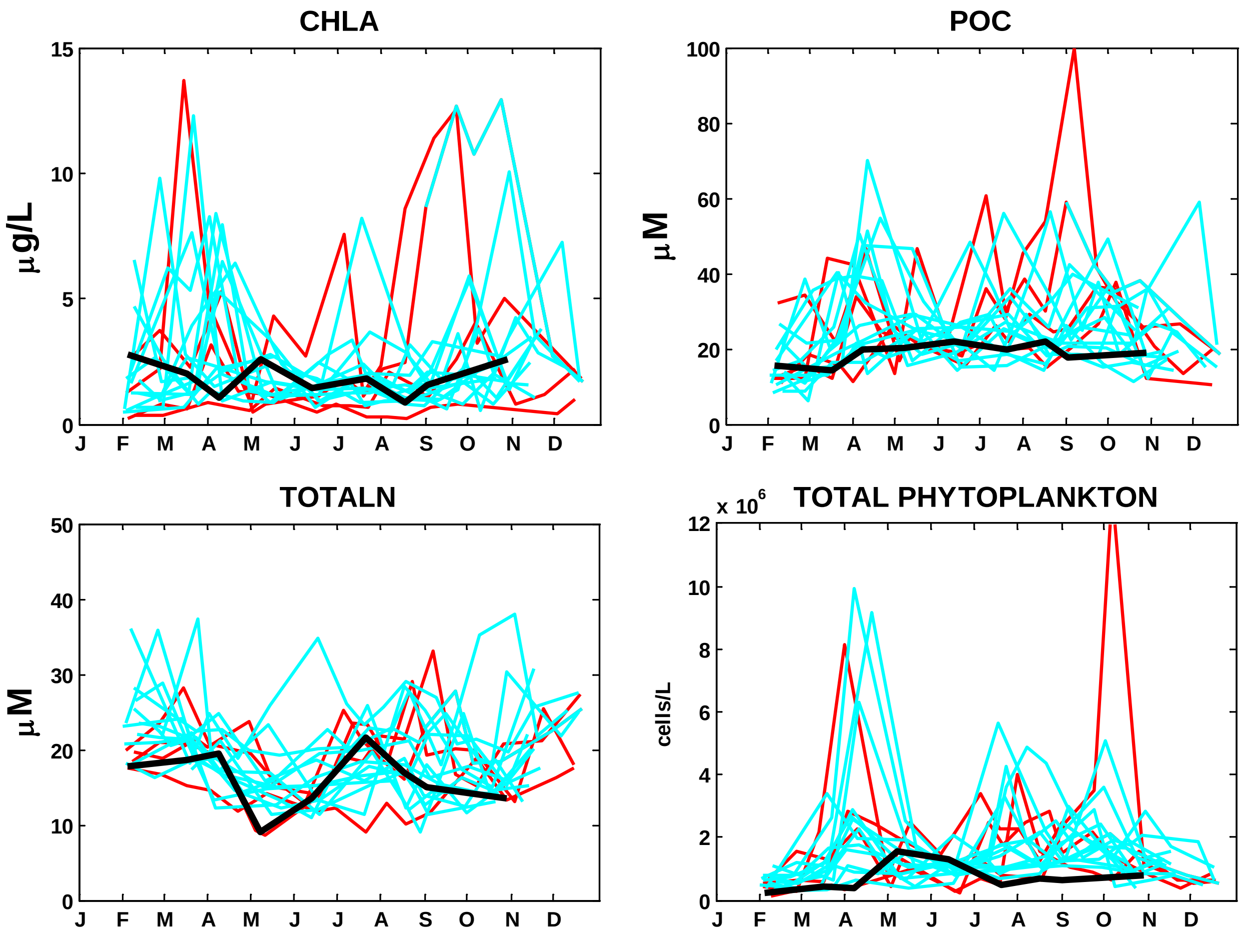

Figure 2-15. Station average chlorophyll (µg L^{-1}), POC (µM), total nitrogen (µM), and total phytoplankton (million cells L^{-1}) near the outfall site (nearfield station N18) for 2014 (black line) compared to the previous baseline (1992-August 2000; red) and post-diversion (September 2000-2013; light blue) observations.

Elevated chlorophyll concentrations were observed in Boston Harbor and at shallower stations in the coastal waters of Massachusetts Bay compared to offshore waters in July and August (**Figure 2-3 and Figure 2-16**) due to nearshore blooms of *Dactyliosolen fragilissimus* (July) and *Cerataulina pelagica* (August). Although annual mean chlorophyll levels were quite low in 2014, these summer blooms led to the highest observed chlorophyll concentrations for July and August at Boston Harbor station F23 during the 1992-2014 period (**Figure 2-8**). The inshore late summer diatom bloom is typically dominated by *Skeletonema* spp., but in 2014 this species was reduced to about 21% of its long-term mean level (14,048 cells L^{-1} versus 66,719 cells L^{-1}; **Table 2-1**).

The summer bloom of centric diatoms (*D. fragilissimus* and *C. pelagica*) at harbor and inshore stations contributed to the peak total phytoplankton abundances during 2014, which occurred in July (**Figure 2-17**). Nonetheless, the 2014 summer abundances continued the recent trend of very low phytoplankton abundances in comparison to earlier monitoring years. The lack of blooms of the typically dominant centric diatom species in the winter/spring (*Chaetoceros* and *Thalassiosira*) and summer (*Skeletonema*) contributed to the very low total phytoplankton levels in 2014.

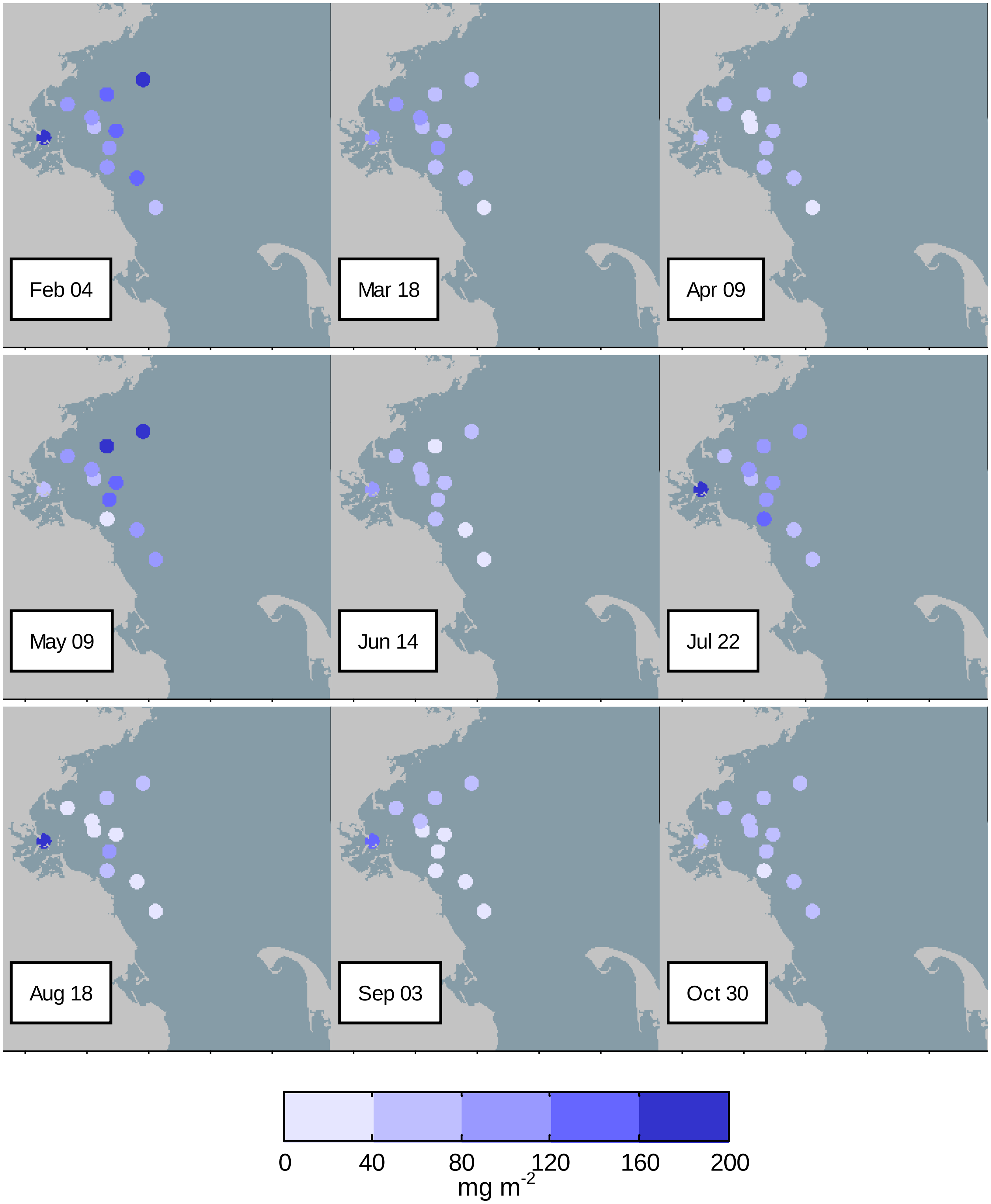

Figure 2-16. **Areal chlorophyll fluorescence (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2014.**

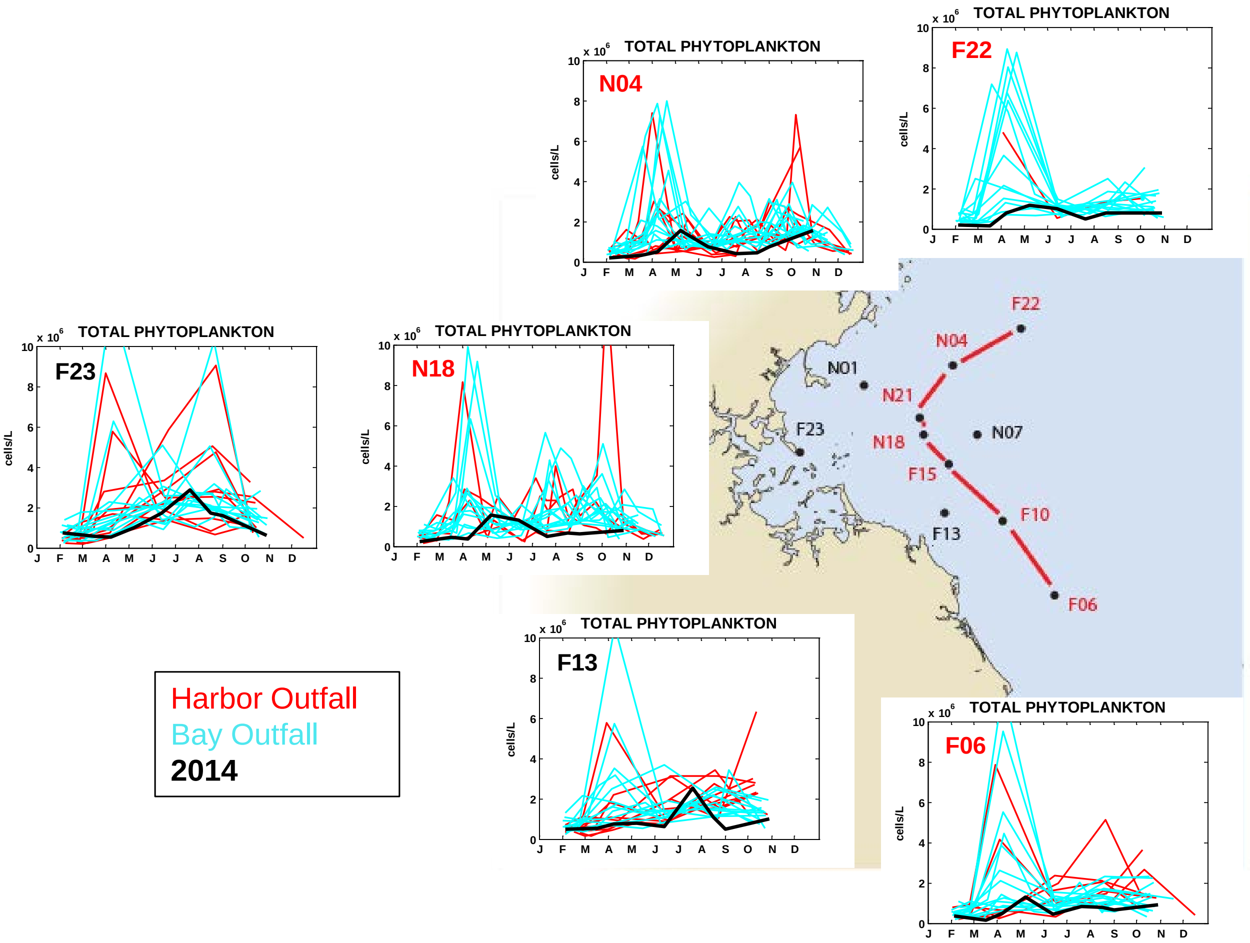

Figure 2-17. **Total phytoplankton abundance (million cells L^{-1}) at representative stations in Massachusetts Bay for 2014 (black line) compared to the previous 22 years, including baseline (Harbor Outfall; 1992-August 2000; red) and post-diversion (Bay Outfall; September 2000-2013; light blue) observations.**

One factor that may have limited phytoplankton abundance in 2014 is grazing. The abundances of total zooplankton and many dominant taxa were at or above maxima for the monitoring program at many of the stations in Massachusetts Bay (**Figure 2-18**). The high total zooplankton abundance in 2014 was primarily due to increased levels of adults and copepodites of *Pseudocalanus* spp. and *Temora longicornis*. Abundances of *Oithona similis* and *Calanus finmarchicus* were also higher at the bay stations.

Total zooplankton abundance in Massachusetts Bay peaked in June and July, while two peaks in abundance (May and August/September) were observed at harbor station F23. In Boston Harbor, *Acartia* spp. were present at moderate levels within the typical range, but peaked in May which is earlier than observed in previous years (**Figure 2-19**). This earlier peak in *Acartia* spp. in the harbor is consistent with a long-term shift to earlier peak abundances of this taxa observed since 2001, coincident with the transfer of effluent discharge to the bay outfall. Patterns in *Acartia* abundance are discussed in more detail in Section 2.2.

By September, chlorophyll levels and phytoplankton abundances had decreased at all but the Boston Harbor station, in many cases reaching minima for the 2014 surveys (**Figure 2-8 and Figure 2-17**). There was also a very sharp decline in zooplankton from July and August levels to low abundances in September, especially at the stations further offshore and to the south (see stations F22, F13, and F06 in **Figure 2-18**).

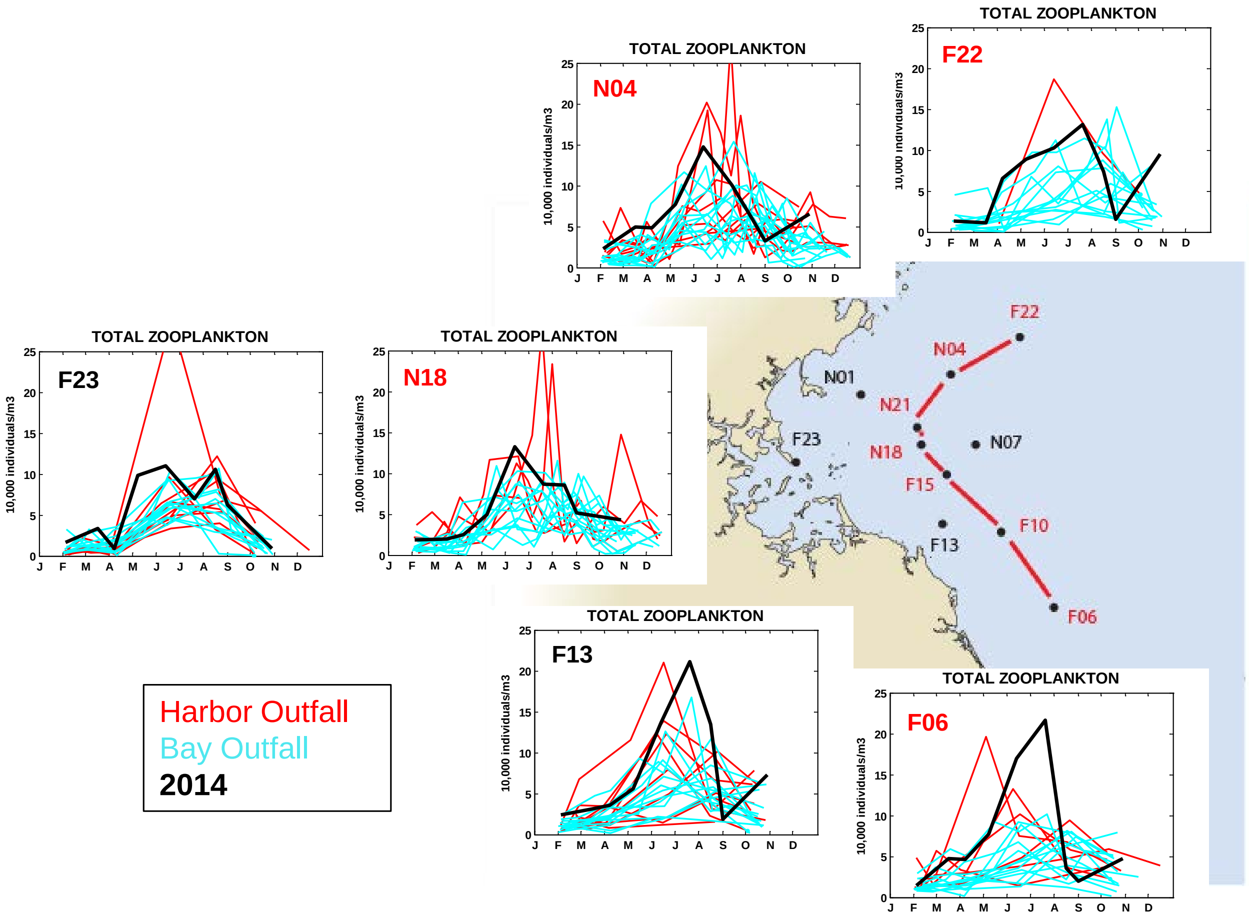

Figure 2-18. **Total zooplankton abundance (10,000 individuals m^{-3}) at representative stations in Massachusetts Bay for 2014 (black line) compared to the previous 22 years, including baseline (Harbor outfall; 1992-August 2000; red) and post-diversion (Bay Outfall; September 2000-2013; light blue) observations.**

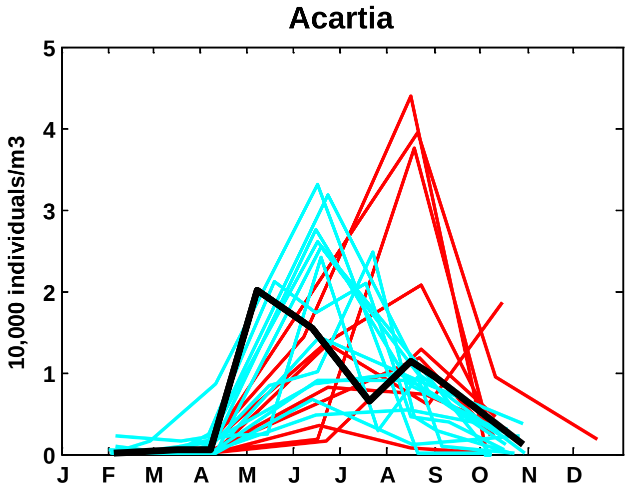

Figure 2-19. ***Acartia* spp. abundance (10,000 individuals m^{-3}) at Boston Harbor station F23 for 2014 (black line) compared to the previous 22 years of baseline (1992-August 2000; red) and post-diversion (September 2000-2013; light blue) observations.**

By mid-September to late October an increase in chlorophyll was observed by satellite and at Mooring A01, with concentrations of > 5 µg/L (**Figure 2-3 and Figure 2-6**). This period was bracketed by the September and October surveys, which showed only a slight increase in chlorophyll levels over this period and missed this fall bloom event. Although the bloom was not observed during the surveys, the satellite and mooring observations put the survey data into context and help characterize fall conditions. Physically the water column was destabilized due to strong storm events (**Figure 2-20**), which brought nutrients into the surface layer supporting the fall bloom. This increase in surface nutrient concentrations was observed between the September and October surveys (**Figure 2-4)**.

Strong northeasterly winds in late September/early October caused early fall mixing to below 20 m at Mooring A01, as indicated by vertically homogenized temperatures in that depth range (**Figure 2-20**). In addition to bringing nutrients to the surface waters, these storms mixed oxygen-rich waters down to deeper depths leading to an increase in bottom water DO concentrations at most stations including station N18 in the nearfield (**Figure 2-21**). Bottom water DO concentrations had declined at a relatively constant rate in Massachusetts Bay from March/April annual maxima to September/October minima (**Figure 2-21**). DO levels in the nearfield in February-May 2014 were in the middle of the range of past years, but were close to long-term minima from June to September. The September and October storms served to ventilate the bottom waters and keep DO concentrations from decreasing to lower levels. At station F22, DO concentration at ~50 m deep was comparable to Mooring A01 measurements from a similar depth suggesting mixing from the surface to that depth had taken place by late October (**Figure 2-22**). However, this mixing did not reach the near-bottom waters deeper than ~50 m at this station, where the minima in Massachusetts Bay of 6.8 mg L^{-1} for 2014 was measured during the October survey, until at least November. This was also the case at the deeper stations in the eastern nearfield (N04 and N07) where bottom water DO concentrations continued to decline into October (**Figure 2-23**). Nonetheless, in comparison to past years, bottom water DO minima were moderate in 2014.

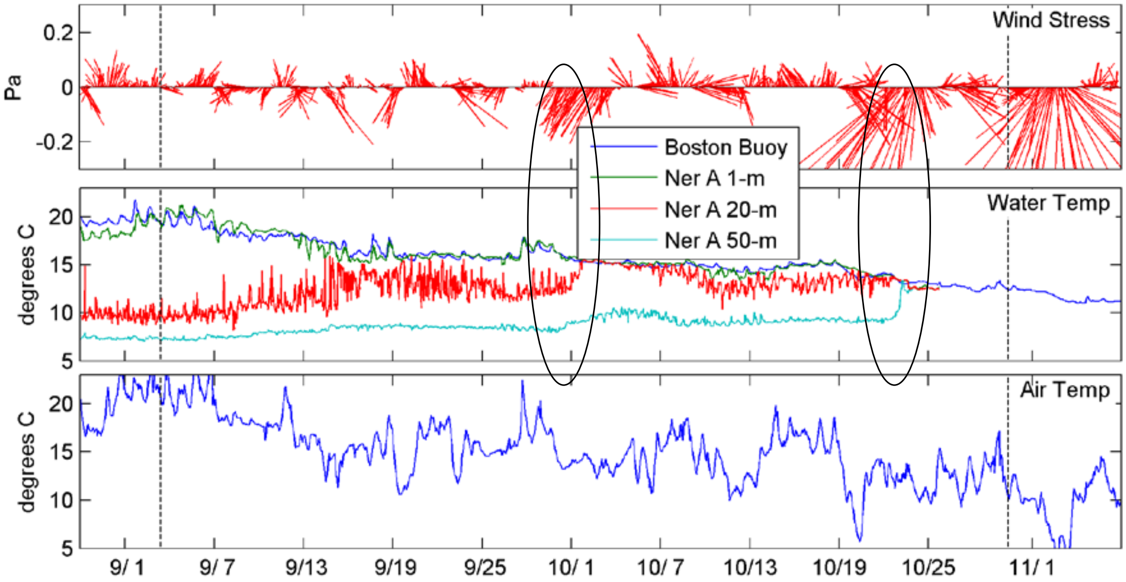

Figure 2-20. Mooring A01 time series observations in 2014. Top: Wind stress. Middle: Water temperature (1, 20 and 50 m depths; surface temperatures from Buoy 44013 ("Boston Buoy") superposed). Bottom: Air temperature. Strong northeasterly winds are circled to highlight the impact on water column mixing.

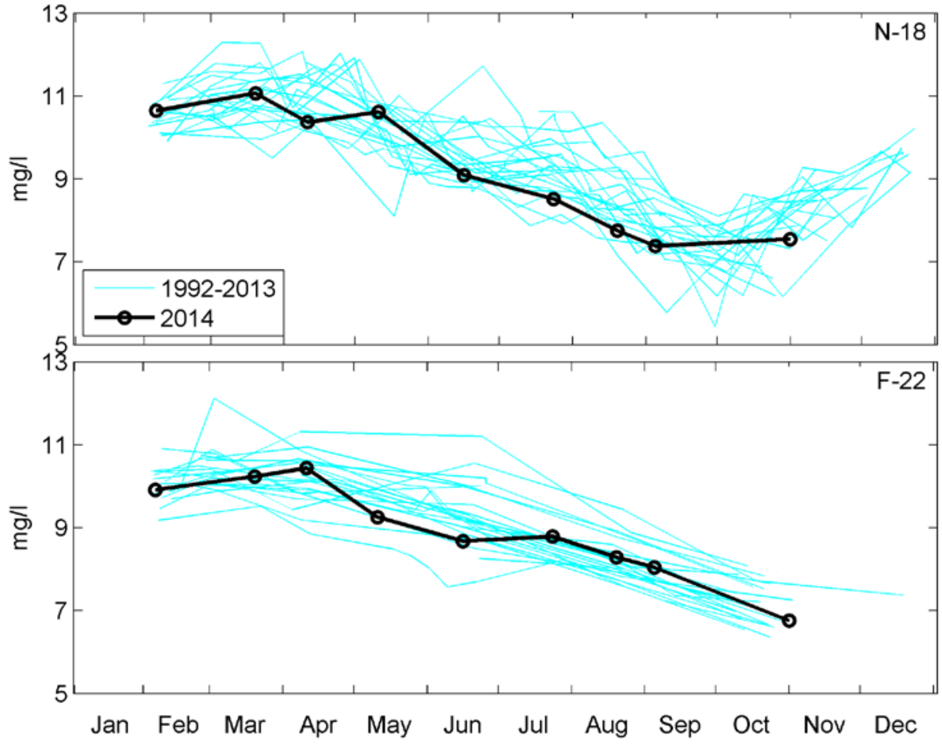

Figure 2-21. Survey bottom water DO concentration (mg L^{-1}) at nearfield station N18 (top) and Stellwagen Basin station F22 (bottom) for 2014 (black) compared to the previous 22 years of observations (1992-2013; light blue).

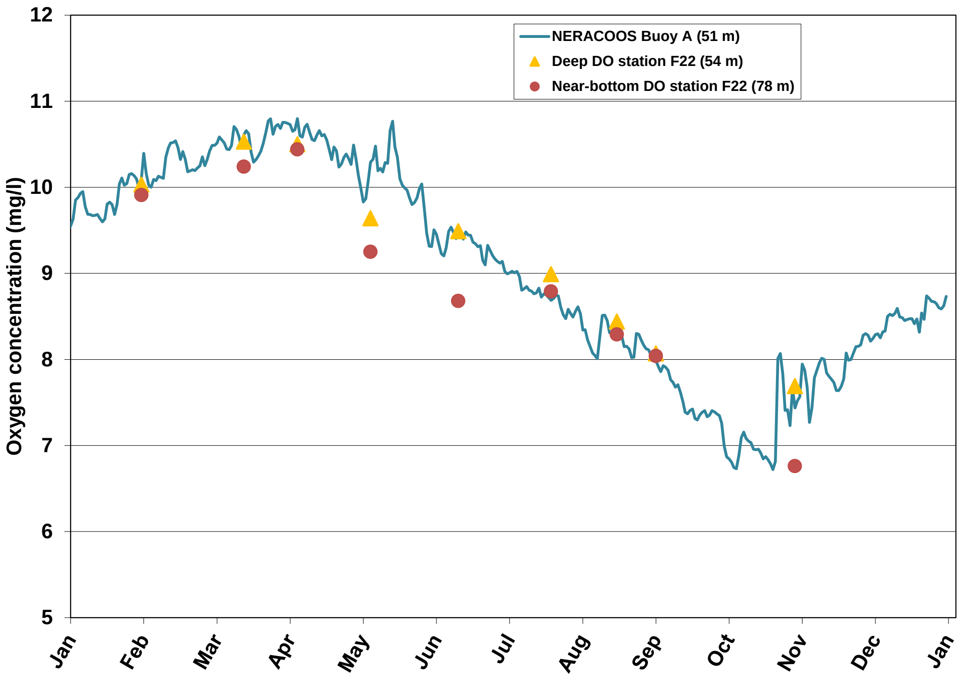

Figure 2-22. Time-series of DO concentration (mg L^{-1}) at Mooring A01 (51 m) and at station F22 from deep (mean 54 m) and bottom (mean 78 m) sampling depths in 2014.

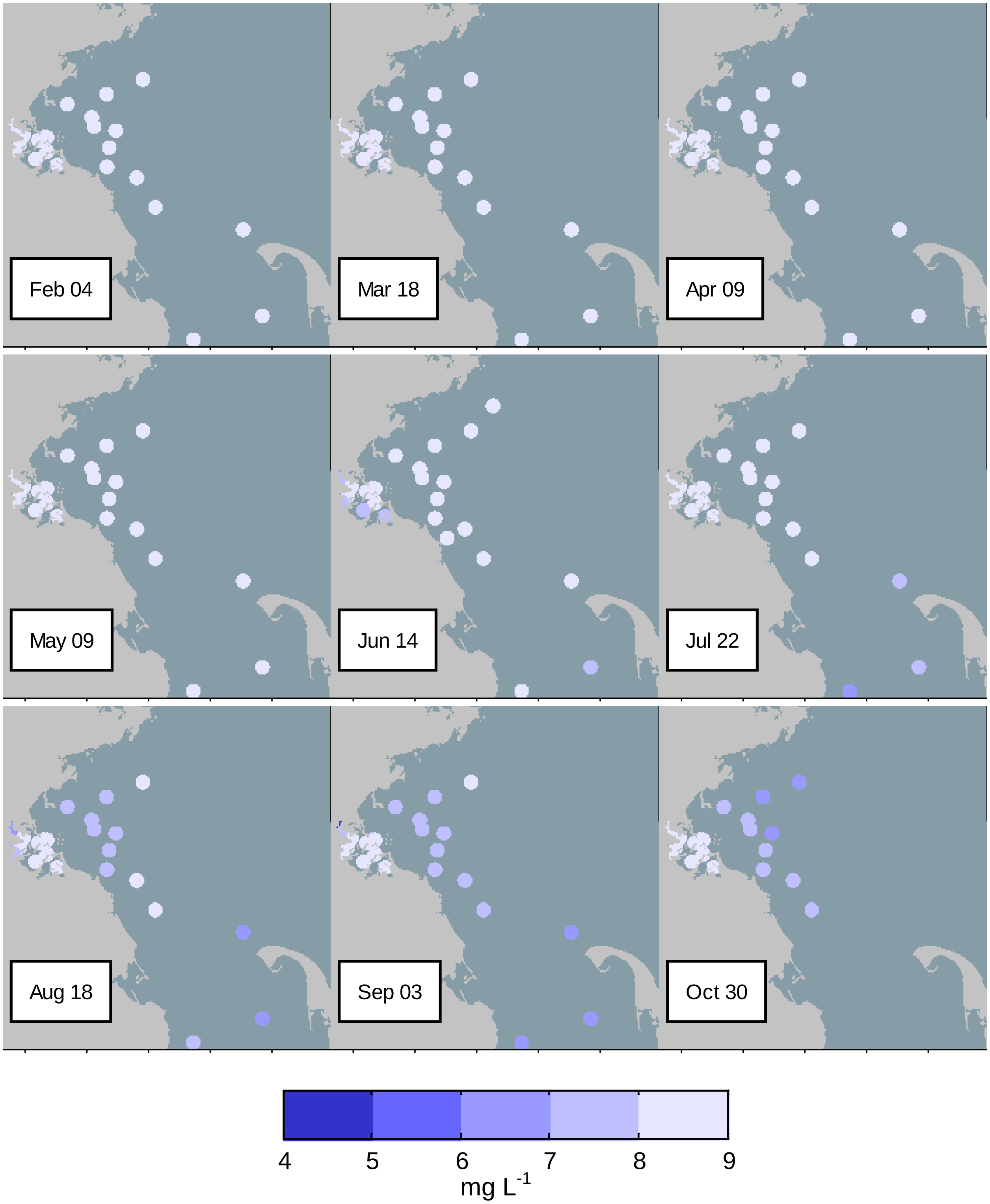

Figure 2-23. **Bottom water DO concentration (mg L^{-1}) at stations in Massachusetts and Cape Cod Bays in 2014.**

2.2 LONG-TERM TRENDS

The 2014 observations were consistent with the general trends and patterns observed during both the baseline (1992-2000) and outfall discharge (2001-present) time periods. Previous monitoring (Libby *et al*. 2007) demonstrated that the annual cycle for nitrate and silicate was unaffected by the effluent discharge, which began in late 2000. This can be seen in **Figure 2-5** in which the NO_3 data from 1992-2014 show a very consistent seasonal pattern, while the SiO_4 data have been highly variable seasonally from the start of the monitoring; as noted above, both NO_3 and SiO_4 concentrations were relatively low in February 2014 and all four nutrients show a clear spike in concentrations in July 2014 associated with upwelling favorable conditions. In contrast, ammonium and phosphate concentrations in the nearfield have clearly shown increases since the offshore outfall began discharging. This can be seen in **Figure 2-5** for NH_4 as multiple peaks and minima throughout the year (including 2014). Baseline years showed much less month to month variability, and are clustered near the bottom of the plot. For PO_4, the change from baseline to discharge is less pronounced, but has resulted in an upward shift of about 0.5 µM overall, and increased variability with intermittent peaks from survey to survey within each year. Although increases in NH_4 associated with the effluent plume have been observed in the nearfield, no related changes to phytoplankton biomass in this region have been observed (see **Figure 2-15**).

The 2014 abundance of the major phytoplankton groups in the nearfield was compared to long-term (1992-2013) levels using a Mann-Whitney test (**Table 2-1**). The 2014 annual average total phytoplankton abundance (0.86 million cells L^{-1}) was very low in comparison to the long-term mean total phytoplankton abundance level of 1.47 million cells L^{-1}. The statistical test ranked 2014 total phytoplankton lowest for the 23 years of monitoring. Similar to 2013, the 2014 phytoplankton annual cycle was marked by low winter-spring phytoplankton abundance. The abundance of centric diatoms, a major component of the Massachusetts Bay winter-spring flora, was markedly reduced in winter-spring 2014, in the nearfield to about half the long-term mean level (**Table 2-1**).

The low 2014 total phytoplankton abundances resulted from decreases in all of the major phytoplankton taxa groups – centric diatoms, pennate diatoms, dinoflagellates, cryptophytes, and microflagellates. However, even though the mean abundance of total phytoplankton in 2014 was the lowest of all years monitored, no long-term linear trend is apparent in total phytoplankton abundance (**Figure 2-24**). Instead, an alternation between elevated abundance (e.g., 2000, 2004, and 2007) during major *Phaeocystis* bloom years and reduced abundance during non-*Phaeocystis* years (e.g., 1999, 2001, 2003, 2005) is evident (Borkman *et al.* 2015). Similarly, microflagellate, dinoflagellate and cryptophyte abundance (not shown) showed no linear trends, but had long-term mean abundance patterns that suggest there are cycles in the abundance of these groups. Centric diatom abundance, however, has displayed a significant long-term linear decline in mean abundance even though centric diatom abundance during the past five years (2010-2014) has rebounded slightly from the low levels observed 2004-2009 (**Figure 2-24**). Likewise, pennate diatom abundance has displayed a significant long-term linear decline during 1992-2014. Although there are no clear causal factors for these decreases, initial regression analyses of phytoplankton data from nearfield stations N04 and N18, chosen because they have been sampled for plankton consistently since 1998, suggests trends in annual total zooplankton abundance explain 36% of annual total phytoplankton abundance variability (**Figure 2-25**). Grazing pressure may have played a role in the observed annual phytoplankton trend.

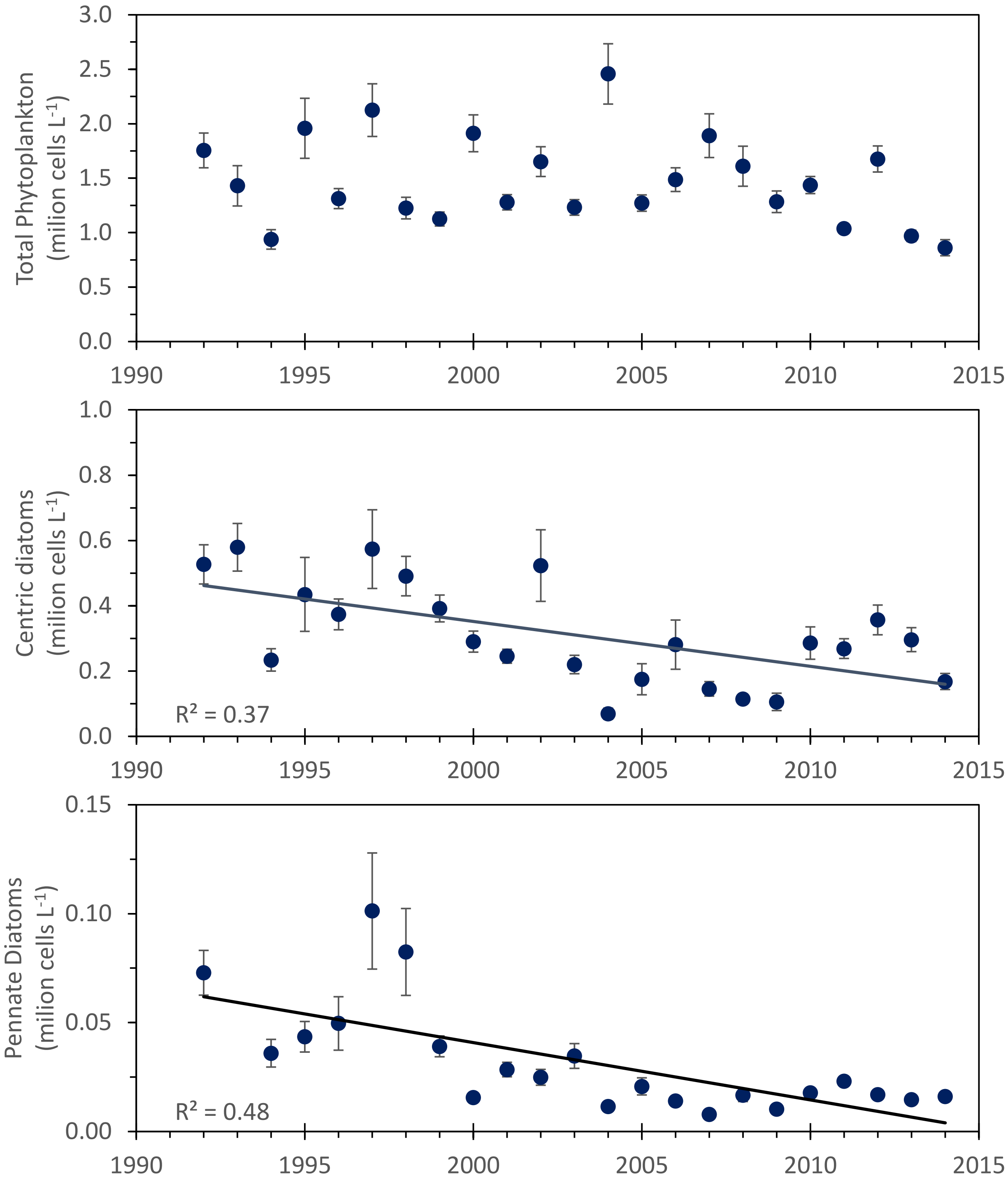

Figure 2-24. **Annual mean abundance (million cells L^{-1}) of total phytoplankton, centric diatoms, and pennate diatoms. Based on all MWRA stations sampled. Error bars represent ±1 standard deviation.**

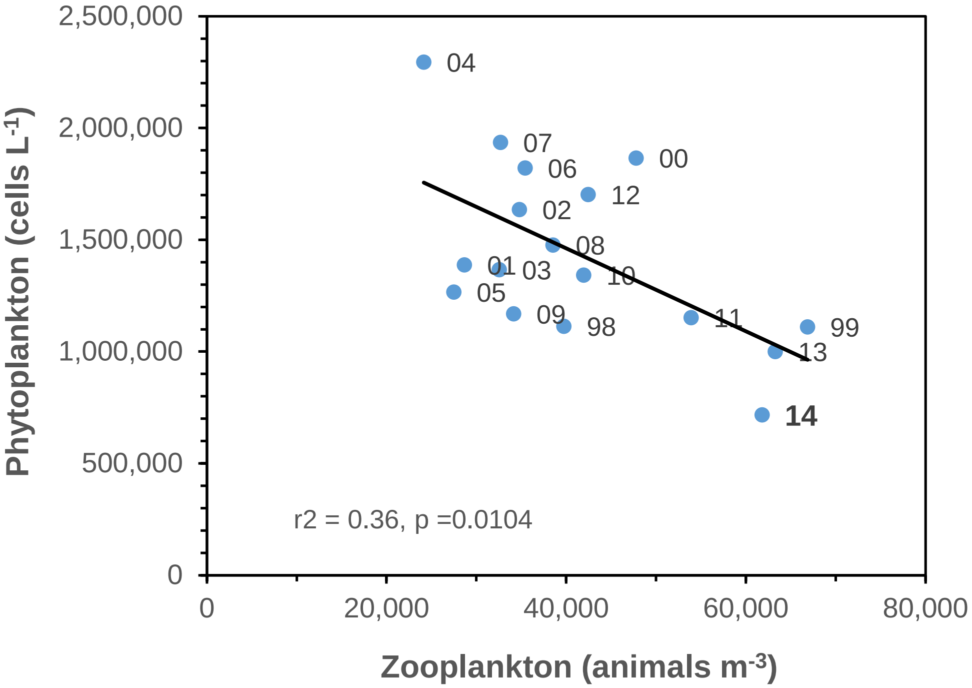

Figure 2-25. Annual mean abundance (million cells L^{-1}) of total phytoplankton versus annual mean abundance (animals m^{-3}) of total zooplankton at nearfield stations N04 and N18.

The last few years have been characterized by an increase in zooplankton abundance from the lower numbers observed during the early 2000s. Time series analysis indicated that there had been a substantial long-term decline in total zooplankton abundance in the nearfield from 2001-2005 due to a decline in total copepods (Libby *et al*. 2009). Given the recent rebound in total zooplankton and copepod abundances, the time series analyses were revisited using nearfield total zooplankton data through 2014 (**Figure 2-26**), which confirm the increasing trend and that current levels of zooplankton have been above the long-term mean for the last few years. This has been commensurate with a decrease in nearfield total phytoplankton abundances (**Figure 2-26**). The higher zooplankton abundance in 2014 was due to increases in a wide variety of species including adults and copepodites of *Pseudocalanus* spp., *Temora longicornis*, *Oithona similis*, and *Calanus finmarchicus*. The lower phytoplankton abundance was due to overall low abundances and that timing of surveys in 2014 missed peak chlorophyll levels in the winter/spring and fall, which is a confounding factor when trying to understand the linkages between the two apparent trends. As shown in **Figure 2-26**, the phytoplankton and zooplankton population trends appear to be generally inverse or out of phase with each other and over the last couple years the region has entered a period in which relatively high zooplankton and low phytoplankton have been observed.

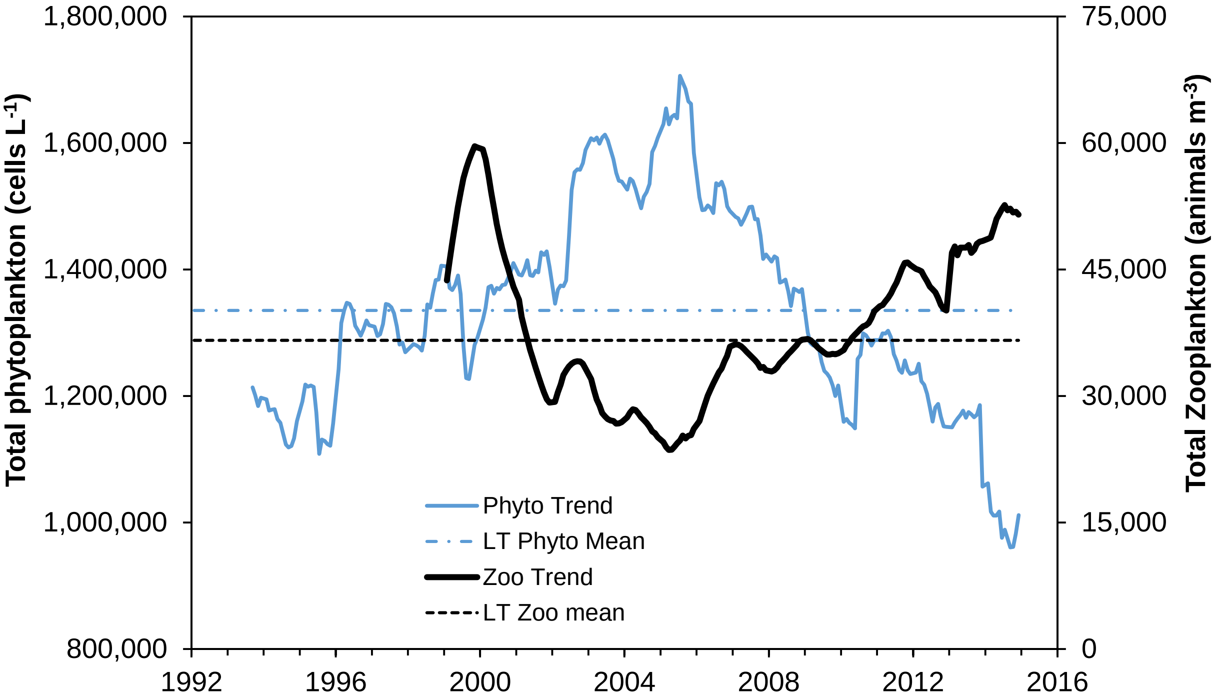

Figure 2-26. **Long-term trend (1998 - 2014) in total phytoplankton and total zooplankton abundance derived from time series analysis. Long-term mean levels also shown (dashed lines). Phytoplankton data from all nearfield station sampled and zooplankton data from stations N04 and N18 only.**

The reasons for the long-term variability and changes in zooplankton abundance are unclear. Research efforts in the Gulf of Maine have assessed zooplankton communities in areas adjacent to Massachusetts Bay, but it is difficult to directly compare these zooplankton datasets due to differences in sampling methods (Turner *et al*. 2011) and differences in time periods sampled by various programs. For instance, the Marine Resources Monitoring, Assessment, & Prediction program (MARMAP; reviewed by Kane 2007) and the Gulf of Maine Continuous Plankton Recorded (CPR) program (reviewed by Pershing *et al.* 2005) both found increases in zooplankton abundance on Georges Bank and in the Gulf of Maine in the 1990s. These increases were linked to reduced salinity in the Gulf of Maine from fresher water flowing into the gulf from the Arctic. Reduced salinity was thought to have caused increased stratification, thereby increasing phytoplankton food for zooplankton in the winter. The zooplankton increases were mainly for what was designated by Mountain and Kane (2010) as “smaller” copepod taxa. Included in this category were *Centropages typicus*, *Metridia lucens*, *Temora longicornis*, *Pseudocalanus* spp. and *Oithona* spp. These copepods were small compared to the “larger” copepods, such as *Calanus finmarchicus* copepodites and adults sampled by these programs. However, due to the coarser mesh nets used by these programs (333 µm in MARMAP and 270 µm for the CPR), direct comparisons with MWRA results, sampled with 102 µm-mesh nets, are problematic. The sampling nets lead to a differences in the species considered small/large, and most numerically dominant. For the MARMAP and CPR studies, *C. typicus* and *T. longicornis* referred to as ‘smaller’ and are numerically dominant, while for the MWRA data these species are considered large and are relatively rare. The MWRA dataset is dominated by the smaller and much more abundant *Oithona similis*, which would not be efficiently sampled using the larger mesh nets.

However, during the period that these programs overlapped with MWRA measurements (1998-2004), all three programs noted decreases in what were designated as ‘small’ copepods beginning around 2000-2001, and continuing through 2003 to 2004. All three programs also noted increases or continuing high abundance of *Calanus finmarchicus* coinciding with higher salinities for most of the period of 2002-2004. These declines in zooplankton during this period were correlated with decreases in chlorophyll concentrations and phytoplankton abundance levels from 2000-2004 for the MWRA program (Turner *et al*. 2011) are similar to those observed during the MARMAP program. MWRA data reveal a significant inverse correlation between annual means for phytoplankton cell abundance and zooplankton abundance for the period of 1998 through 2014. The lack of other long-term zooplankton sampling programs since 2004 in the Gulf of Maine make it difficult to place the MWRA results within the context of long-term hydrographic variations such as the freshening of the Gulf of Maine through most of the 1990s, followed by an apparent reversal of this trend beginning around 2000 (Drinkwater *et al.* 2003; Greene and Pershing 2003, Pershing *et al*. 2005). This is an area of active research in the Gulf of Maine as many groups are examining the impacts of climate change on the physical, chemical, and biological processes in the region (e.g., Townsend *et al*. 2010; Kane 2011; Balch *et al*. 2012). The MWRA dataset will prove a valuable resource as trends in Massachusetts Bay and the influence of the greater Gulf of Maine on the bay ecosystem continue to be examined.

A more localized trend that has been observed is the earlier occurrence of peak *Acartia* abundance at station F23 in Boston Harbor (**Figure 2-19**). Copepods of the genus *Acartia* are primarily found in estuarine embayments (Tester and Turner 1991). This is believed to be due to combinations of low salinity and seasonal temperatures appropriate for the hatching of diapause fertilized eggs from the benthos into planktonic nauplii in the water column. In estuaries of southern New England and the mid-Atlantic coast of the United States, there are two dominant seasonal congeners of *Acartia*, with *A. hudsonica* found during colder periods of the late fall through early summer and *A. tonsa* found during warmer periods of summer through fall (Conover 1956; Sullivan and McManus 1986; Sullivan *et al.* 2007). South of Cape Hatteras, *A. hudsonica* disappears to be replaced year-round by *A. tonsa* (Turner 1981). North of Cape Cod, *A. tonsa* is found mainly during the warmest months of late summer and early fall, and *A. hudsonica* is found year-round (Lee and McAlice 1979; McAlice 1981). In Boston Harbor, *A. hudsonica* is found year-round, but is most abundant during warmer periods. Adults of *A. tonsa* appear in late summer and fall, but rarely outnumber those of *A. hudsonica*. Copepodites of *A. hudsonica* and *A. tonsa* cannot be reliably distinguished.

The increase in *Acartia* spp. in Boston Harbor at station F23 in May of 2014 was mostly due to *Acartia* spp. copepodites, and to a lesser extent *Acartia hudsonica* adult females and males (**Figure 2-27**). Similarly, the *Acartia* spp. at this station in June, although less abundant than in May, were all either *Acartia* spp. copepodites or *A. hudsonica* adults. *A. tonsa* adults were not recorded at abundance levels equal to those of *A. hudsonica* adults until September. Thus, the “classic” seasonal succession from *A. hudsonica* to *A. tonsa* in June, followed by a reversal in November-December that has been recorded for estuaries of the southern coast of New England such as Long Island Sound (Conover 1956) and Narragansett Bay (Sullivan and McManus 1986; Sullivan *et al.* 2007) does not apply to *Acartia* spp. in Boston Harbor. The presence and usual dominance of *A. hudsonica* over *A. tonsa* in Boston Harbor suggests that seasonal cycles of resting egg versus presence in the plankton for the *Acartia* congeners is different north of Cape Cod from patterns south of Cape Cod. This is in agreement with Cape Cod being the general boundary between different marine biogeographic regions that was proposed by Ekman (1953). The reason for the earlier peak of *A. hudsonica* and *Acartia* spp. copepodites in Boston Harbor in May of 2014 is unknown. It continues a trend that seems to have started in 2000 coincident with relocation of the MWRA outfall to offshore. There may be a connection related to changes in loading to the harbor or changes in the salinity regimes, but it could also be associated with more regional changes like those affecting the greater Gulf of Maine.

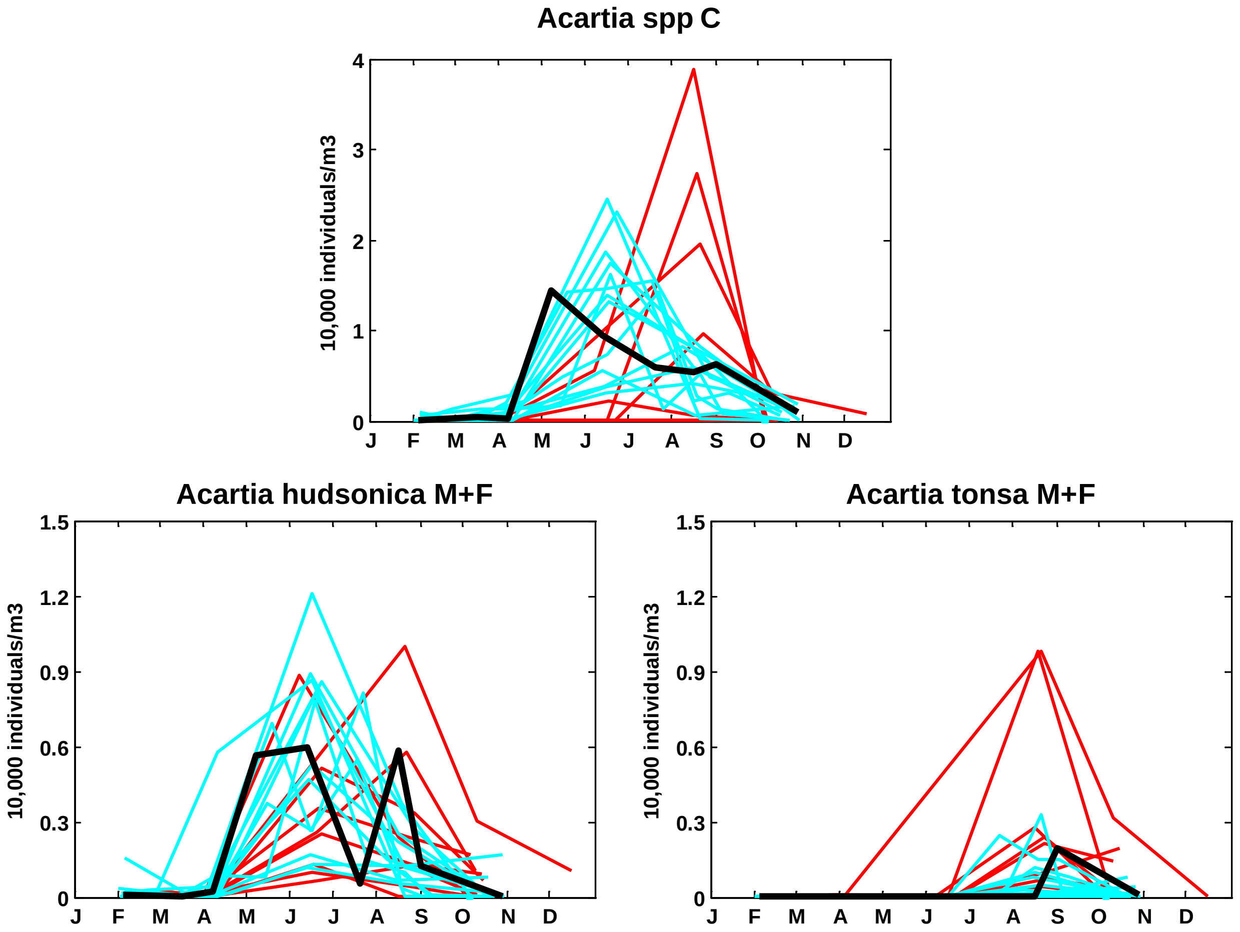

Figure 2-27. *Acartia* spp. copepodite, *A. hudsonica* adult, and *A. tonsa* adult abundance (10,000 individuals m^{-3}) at Boston Harbor station F23 for 2014 (black line) compared to the previous 22 years of baseline (1992-August 2000; red) and post-diversion (September 2000-2013; light blue) observations. Note change in scales from copepodite to adult plots.

3 SUMMARY

The most notable characteristic of the physical environment of Massachusetts Bay in 2014 was the colder than normal temperatures in March and April. The extended period of colder temperatures may have contributed to a delay in the development of *Phaeocystis* and *Alexandrium* blooms in the region. Stratification appeared to have set up by the early April survey, but Mooring A01 data showed the influence of storms and strong northeast wind events in remixing the water column later in April and into May. Seasonal stratification was not consistently established until later in May, about a month later than typically observed. The summer of 2014 was a period of upwelling favorable conditions that peaked in July at the highest levels observed since 1994. The annual fall overturn and remixing of the water column was observed in stages in the buoy data. The upper 20 m at the NERACOOS Buoy was well mixed by early October and to 50 m later that month. The two mixing events in this period were each preceded by strong wind events. The entire water column did not become fully mixed until after the late October survey.

2014 was the third year in a row to exhibit relatively low nutrient concentrations in February. Similar to 2013, winter satellite imagery (November 2013 to February 2014) showed relatively steady and slightly elevated chlorophyll concentrations over the winter. Combined with the relatively low nutrient concentrations (especially NO_3 and SiO_4) observed in February, this suggests that the system may have remained biologically productive through the winter. Additionally, as during the previous year, a winter/spring diatom "bloom" was not observed during the 2014 surveys. However, Mooring A01 and satellite observations indicate that chlorophyll fluorescence levels peaked between the April and May surveys. Nutrient levels had decreased sharply by May when a *Phaeocystis* bloom was observed across the bays. Silicate concentrations decreased from April to May, but were not depleted in the surface waters suggesting that at least a portion of the chlorophyll signal observed by the mooring and satellite sensors may have been due to an increase in diatoms. However, *Phaeocystis* dominated the phytoplankton community in May and likely depleted nitrogen from the surface waters. The May 2014 survey results were indicative of a senescent *Phaeocystis* bloom with *in situ* fluorescence profiles showing maxima in the bottom waters, elevated phaeophytin concentrations, and high phaeophytin/chlorophyll ratios. The colder waters observed in the winter/spring of 2014 likely shifted the seasonal bloom cycle by about a month.

The cold winter/spring 2014 conditions and a concomitant shift in the phytoplankton seasonal cycle appears to have played a role in the lack of an *Alexandrium* bloom in Massachusetts and Cape Cod Bays in 2014. A low to moderate bloom with elevated cell abundances and PSP toxicity was observed in western Gulf of Maine waters, but not until late May and early June. This delay resulted in a disconnect between the timing of the *Alexandrium* bloom in the western Gulf of Maine and the meteorological and physical processes needed to bring such a bloom into Massachusetts Bay. If the bloom had occurred earlier, the northeaster storms that occurred in April and early May would likely have transported the *Alexandrium* into the bays. Fortunately this did not occur and there were no PSP toxicity shellfishing closures in the bays in 2014. This was the third year (2007, 2013 and 2014) since the major *Alexandrium* bloom in 2005 that there were no PSP closures in Massachusetts Bay.

By late May, seasonal stratification had been established in Massachusetts Bay and conditions were more in line with typical seasonal trends for June through October. The summer is generally a period of strong stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community, which was the case in 2014. The strong upwelling favorable conditions in July 2014 appear to have led to increased delivery of nutrients to the surface layer and likely supported the blooms of *Dactyliosolen fragilissimus* (July) and *Cerataulina pelagica* (August) observed at Boston Harbor and nearshore stations. The summer bloom of these centric diatoms at these inshore stations was the annual peak in survey-measured total phytoplankton abundances, but overall 2014 survey data had very low phytoplankton abundances in comparison to previous monitoring years.

Chlorophyll and phytoplankton abundance remained low during the September and October surveys in comparison to previous years. However, as occurred in the spring, the survey timing did not capture important events. Specifically, the fall peak in chlorophyll was missed, based on satellite and Mooring A01 observations, which showed chlorophyll concentrations of > 5 µg/L from mid-September to late October. The combination of survey, satellite, and mooring observations allowed for a more complete understanding of the physical and biological conditions.

Bottom water DO concentrations declined at a relatively constant rate in Massachusetts Bay, from the March/April annual maxima to monthly minima during June to September that were at or near the low end of historic ranges. The September and October storms served to ventilate the bottom waters and keep DO concentrations from decreasing to lower levels. These mixing events were captured in the temperature and DO measurements from Mooring A01, which indicated mixing to 50 m by late October. However, until after the October survey, mixing did not reach the near bottom waters at deeper stations in the eastern nearfield, or at station F22 where the annual DO minima for Massachusetts Bay of 6.8 mg L^{-1} was measured during the late October survey. Relative to previous years, the 2014 bottom water DO concentration minima was moderate. The Mooring A01 time series continues to demonstrate that the cycle of near-bottom DO in the nearfield closely tracks that observed at both the Stellwagen station F22 and Mooring A01, confirming that horizontal advective processes are very important in setting interannual variations of DO and that interannual variations of DO at the outfall site are more regional than local.

Total phytoplankton abundance in 2014 ranked last out of the 23 years of observations and relatively low abundances were observed for most major phytoplankton functional groups. As noted, the timing of the surveys missed the winter/spring and fall blooms in Massachusetts Bay in 2014, which contributed to the lower abundance measurements. Another important factor was likely grazing pressure as 2014 total zooplankton abundances were high in comparison to previous years. The high zooplankton abundance in 2014 continues a long-term trend of increasing abundances since 2005. There is no plausible outfall-related link or causality associated with these shifts in phytoplankton or zooplankton as they occur over large spatial scales; such broad patterns appear instead to be related to regional ecosystem dynamics in the Gulf of Maine.

As observed since operation of the bay outfall began in 2000, the bay outfall effluent plume was observed as elevated NH_4 concentrations in the nearfield throughout 2014. The elevated NH_4 plume signature was generally seen within 10 to 20 km of the outfall during both well-mixed and stratified conditions. The change in observed NH_4 concentrations continues to be consistent with pre-diversion 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 slightly in the nearfield (Signell *et al*. 1996). The model also predicted that there would be seasonal differences in how the increased NH_4 load to the nearfield would be distributed – reaching the surface during well mixed winter conditions and confined below the pycnocline under seasonally stratified conditions. This change was predicted to have little impact on concentrations in the rest of Massachusetts and Cape Cod Bays. Spatial patterns in NH_4 concentrations in the harbor, nearfield and bays since the diversion in September 2000 have consistently confirmed this (Taylor 2006; Libby *et al*. 2007). Although increases in NH_4 associated with the effluent plume have been observed in the nearfield, no related changes to phytoplankton biomass in this region have been observed.

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