2015 Water column monitoring results

Massachusetts Water Resources Authority
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2015 Water Column Monitoring Results

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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 2015. 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 (EPA), and (3) determine whether change within the system exceeds thresholds of the Contingency Plan[1] attached to the permit.

The only Contingency Plan water column threshold exceeded in 2015 was the summer *Phaeocystis pouchetii* nuisance species Caution Level threshold. This was due to an apparent delay in the seasonal phytoplankton cycle by about a month, likely related to cold winter water temperatures that persisted later than in a typical year. *Phaeocystis* at very low abundance in a single May 2015 sample was responsible for the exceedance. Although the statistical threshold was exceeded, there was no associated ecological impact.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2015
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: 7.56 SW Basin: 7.44
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 84.5% SW Basin: 79.6%
Bottom water DO rate of decline (mgL^{-1} d^{-1})	Seasonal June-October	0.037	0.049	0.024	0.018
Chlorophyll (nearfield mean, mg m^{-2})	Annual	108	144	72	87
	Winter/spring	199	--	50	122
	Summer	89	--	51	58
	Autumn	239	--	90	94
Phaeocystis pouchetii (nearfield mean, cells L^{-1})	Winter/spring	2,860,000	--	622,000	13,800
	Summer	357	--	79	408
	Autumn	2,960	--	370	Absent
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	17,900	--	6,735	51
	Summer	43,100	--	14,635	925
	Autumn	27,500	--	10,500	294
Alexandrium fundyense (nearfield, cells L^{-1})	Any nearfield sample	100	--	Baseline Max 163	3

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

[1] MWRA's discharge permit includes Contingency Plan thresholds, indicators that may indicate a need for action. The thresholds are based on permit limits, state water quality standards, and expert judgment. "Caution-level" thresholds indicate a need for a closer look at the data to determine the reason for an observed change. "Warning-level" thresholds are a higher level of concern, and the permit requires a series of steps to evaluate whether adverse effects occurred and if so, whether they were related to the discharge. If exceedances were related to the discharge, MWRA might need to implement corrective action.

The 2015 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 2015 included:

- Regional water temperatures were lower than normal in February to April 2015.
- 2015 was the fourth year in a row to exhibit relatively low to moderate nutrient concentrations during the February survey and slightly elevated and steady chlorophyll concentrations over the winter, suggesting that the system may have remained biologically productive through the winter.
- Consistent with observations in 2014, a winter/spring diatom bloom was not apparent on the 2015 survey dates; however, mooring and satellite observations indicated chlorophyll fluorescence levels peaked between surveys in late April/mid-May. A large decrease in nitrate concentrations with little concomitant change in silicate concentrations from April to May suggests the elevated chlorophyll levels were due to a late *Phaeocystis* bloom.
- The colder conditions in winter/spring 2015 and possible 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 New Hampshire waters in late May. However, currents that could deliver them in to the bays did not materialize in 2015 due to the timing of meteorological conditions. This was the third year in a row that there were no PSP toxicity shellfishing closures in Massachusetts Bay.
- Summer chlorophyll concentrations and phytoplankton abundances were low in 2015. Elevated levels of both were observed in October. Satellite imagery suggested elevated chlorophyll concentrations occurred during the period between the September and October surveys.
- Bottom water dissolved oxygen (DO) concentration minima in 2015 were moderate and easily met Contingency Plan thresholds.
- The 2015 annual total phytoplankton abundance was the 21st lowest recorded during the past 24 years. The abundances of most major phytoplankton functional groups were relatively low. The lack of winter/spring and fall diatom blooms, no observed *Phaeocystis* bloom and no summer blooms in coastal water contributed to the low abundances.
- Total zooplankton abundances during 2015 were nearly 10 times greater than the typical levels of the prior 24 years. Bivalve veliger abundances were exceptionally high in July/August 2015, peaking at over 2 million m^{-3} in Boston Harbor and over 1 million m^{-3} in Massachusetts Bay. The previous maximum for bivalve veligers was <150,000 m^{-3}.
- Abundances of dominant copepod taxa were very high in 2015 and continued a long-term trend of increases seen since 2005.
- Variations in annual mean copepod abundance accounted for 35% of the variance in annual mean phytoplankton abundance in the nearfield. Grazing by zooplankton was at least partly responsible for the bay's low phytoplankton abundance in 2015.
- Massachusetts Bay and Boston Harbor phytoplankton and zooplankton have undergone long-term (decadal) changes since monitoring started in 1992. Regional processes in the Gulf of Maine unrelated to the outfall have been responsible for the changes.

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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 2015 and encompasses the period wastewater was discharged from the bay outfall. The 2015 data complete 15 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 online
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 online
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. Nine one-day surveys were undertaken in 2015 (**Table 1-2**). The nine surveys were designed to provide a synoptic assessment of water quality conditions. The Center for Coastal Studies in Provincetown (CCS) monitors Cape Cod Bay in the same timeframe maximizing spatial coverage. This annual report summarizes the 2015 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 variation in annual 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 2015 sampling dates are shown in **Table 1-2**. Five stations are sampled in the nearfield and nine stations in the farfield. 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 Massachusetts Bay stations were sampled during one-day surveys; within a day of those dates the three Cape Cod Bay stations were sampled by CCS, who also have an ongoing water quality monitoring program at eight other stations in Cape Cod Bay.[2] Nutrient data from all Cape Cod Bay stations are included in this report. MWRA also collects samples at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally biweekly frequency.[3] The BHWQM data (nutrient, dissolved oxygen [DO], and *Alexandrium*) collected within 7 days of an AMP survey are included in this report.

Table 1-2. Water column surveys for 2015.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN151	February 4	February 8	
WN152	March 20	March 20	March 24
WN153	April 13	April 12	
WN154	May 11	May 9	May 7
WN155	June 23	June 24	June 25
WN156	July 21	July 21	July 23
WN157	August 18	August 18	August 19
WN158	September 9	September 10	
WN159	October 21	October 21	October 20

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 National Oceanic and Atmospheric Administration (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.

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

[2] PCCS station map available at http://www.coastalstudies.org/what-we-do/cc-bay-watch/stations.htm
[3] BHWQM station map available at http://www.mwra.state.ma.us/harbor/graphic/bostonharbor_850.gif

from January through April, summer is from May through August, and fall is from September through December. Comparisons of baseline and outfall discharge period data are made for a variety of parameters. The baseline period is February 1992 to September 6, 2000 and the outfall discharge period is September 7, 2000 through December 2015.[4]

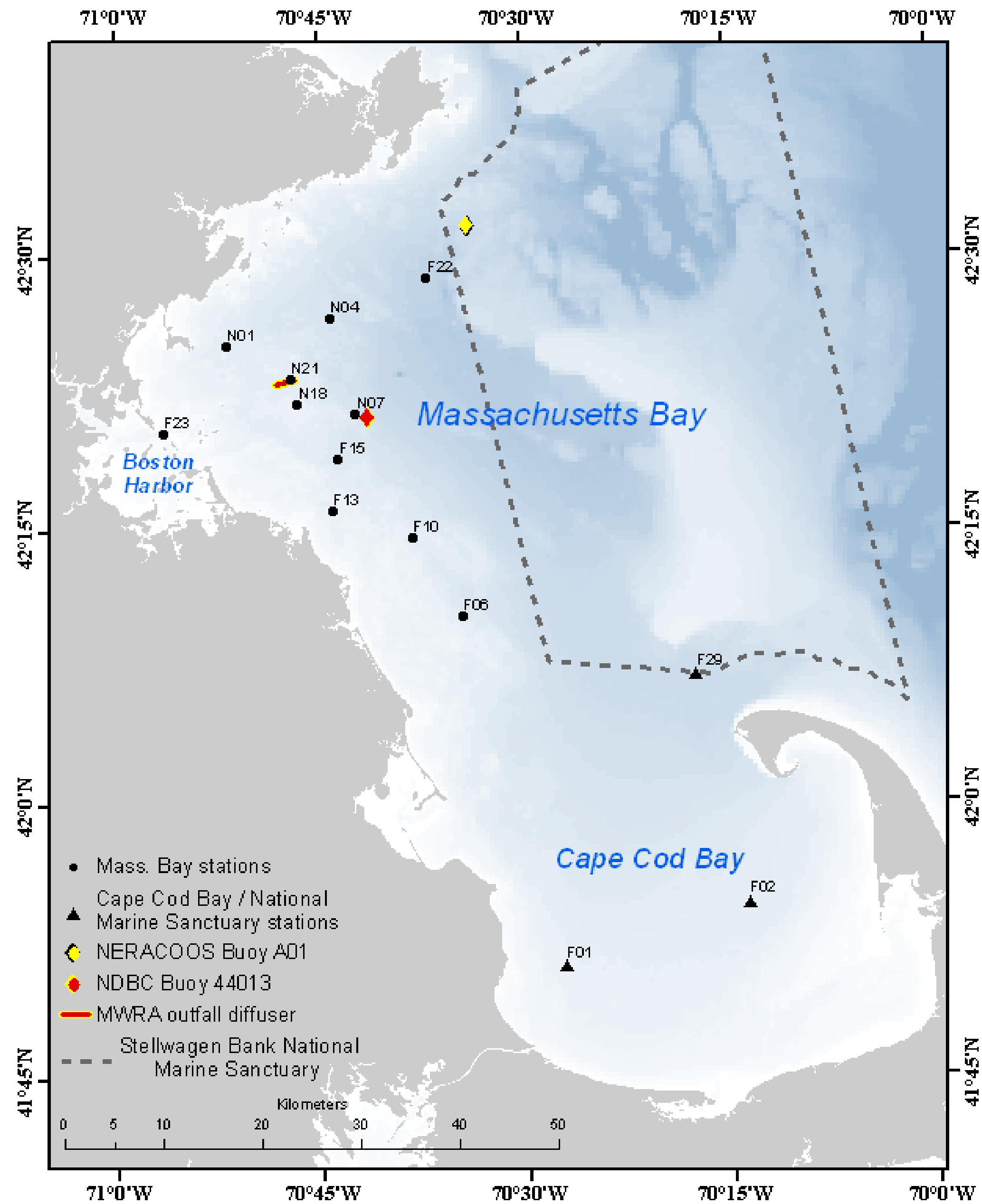


Figure 1-1. Water column monitoring locations.

[4] Year 2000 data are not used for calculating annual means as the year spans both the baseline and post-discharge 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 2015 MONITORING RESULTS

2.1 BACKGROUND

The Massachusetts Bay ecosystem shows a seasonal cycle during which the system's physical structure, biology, and biogeochemical cycling change. External processes (meteorology, river inputs, winds, and currents) and changes within the ecosystem (biological changes) all have important influences on the seasonal pattern. Details of the cycle might also differ across specific areas of the bay system.

During winters, when the cold water column is vertically well mixed, and light intensities low, nutrient concentrations in the bay are typically elevated. The amounts of phytoplankton in the water column are moderate to low, but this varies year to year. Zooplankton counts are also low over the winter. During most, but not all years, as light intensities and temperatures increase in late winter, phytoplankton show a winter/spring bloom. The size of the bloom can vary greatly, as can its timing. In certain years, the bloom can occur earlier than the typical March-April period and other years it occurs later. Diatoms (*Chaetoceros, Skeletonema)* are usually responsible for the winter/spring bloom, and in certain years, these blooms are followed by blooms of the prymnesiophyte *Phaeocystis pouchetii*. During May through June of certain years, *Alexandrium fundyense* populations, the organism responsible for paralytic shellfish poisoning, is transported from the north into the bay. The extent to which *Alexandrium* are transported into the bay varies greatly between years due to variability in the occurrence of the offshore populations and in the oceanographic currents needed to bring them into Massachusetts Bay.

During the transition into summer, as the water column becomes stratified, and nutrient concentrations in the surface waters become depleted, phytoplankton biomass typically declines. Phytoplankton biomass during this season is often elevated at the pycnocline, where the cells have access to both adequate light and nutrients. During summers, zooplankton counts in the bay are often elevated, but the size and the nature of the zooplankton communities can vary widely year to year. *Oithona similis*, *Pseudocalanus* spp. and *Calanus finmarchicus* are often the bay's most abundant zooplankton taxa during summers. However, episodic spawning events can lead to large spikes in the abundance of meroplankton (e.g. bivalve veligers, barnacle nauplii), which dominate total zooplankton when they occur.

Later in the fall the water column destratifies, as incident irradiance intensities decline, water temperatures decrease, and vertical mixing increases due to more intense winds. This provides nutrients to the surface waters and leads to increases in phytoplankton populations. The sizes and precise timing of these fall blooms can vary widely year to year. Taxa responsible for the fall blooms typically include *Skeletonema* spp. and *Dactyliosolen fragilissimus*. During summers when water temperatures are elevated, and the water column stratified, bottom-water dissolved oxygen (DO) concentrations, which year-round in the bay are relatively high, decline. Vertical mixing of the water column in the fall, often facilitated by storms, re-aerates the water column. The extent to which bottom-water DO concentrations decline during the summer into fall, and the date in fall when they begin to increase can also vary widely year to year.

This general sequence has been evident every year of this 24-year dataset (1992-2015). The major features and differences in 2015 are presented below.

2.2 PHYSICAL CONDITIONS

In January and early February, prior to the first survey of 2015, observations at the NDBC Buoy 44013 indicated that surface water temperatures were slightly above the long-term average (**Figure 2-1**). From late February through early April water temperatures were unusually low. At NDBC Buoy 44013 water temperatures during this period were among the lowest since 1989. At nearfield station N18, temperatures during the March and early April surveys were among the lowest since 1992. February 2015 was also a very stormy period with numerous winter storms and northeast winds that contributed to very strong downwelling favorable conditions (**Figure 2-2**). Much of the precipitation fell as snow, which in combination with the cold temperatures and limited melting, meant Merrimack River and Charles River flows were low. Surface and bottom water salinity values in February to April were the highest since monitoring started in 1992 (**Figure 2-3**). Surface water temperatures increased rapidly from April, and thereafter fell in the upper range since monitoring started. Temperatures at NDBC Buoy 44013 showed a short-term drop in late May/early June. Surface salinity at N18 showed a short-term decline in May, probably caused by the spring freshet. Stratification at N18 started later and was more rapid than in many other years (**Figure 2-4**). With the exception of the June survey, stratification intensity during mid-year fell in the mid to upper range of values seen in previous years. A late northeaster in late May/early June (**Figure 2-5**) was responsible the decline in stratification we observed during the June survey.

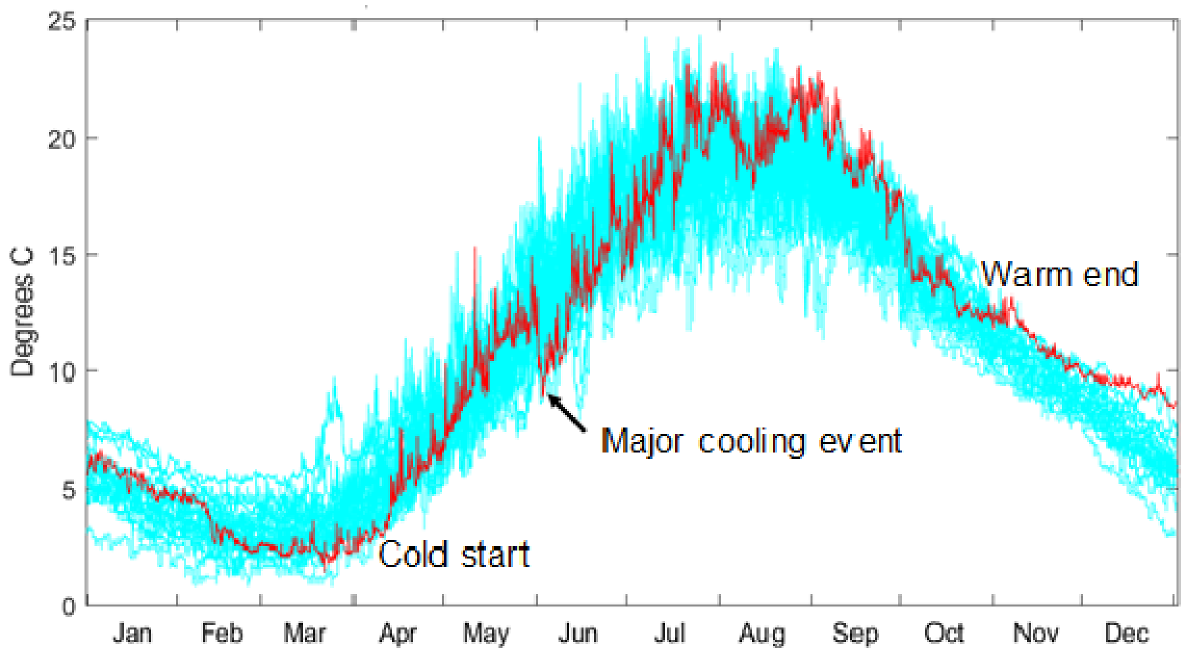


Figure 2-1. Comparison of 2015 air and surface water temperature (°C) at NDBC Buoy 44013 (“Boston Buoy”) in the vicinity of the nearfield (solid red line) with 1992-2014 (light blue lines).

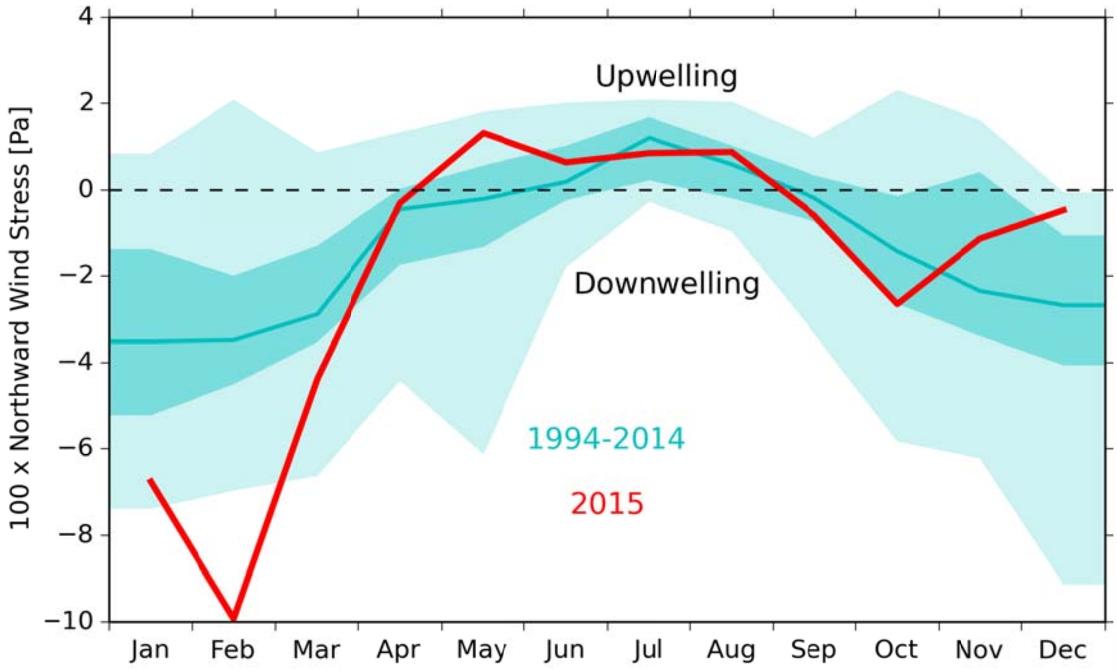


Figure 2-2. **Average wind stress at NDBC Buoy 44013.** 2015 results are in red. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

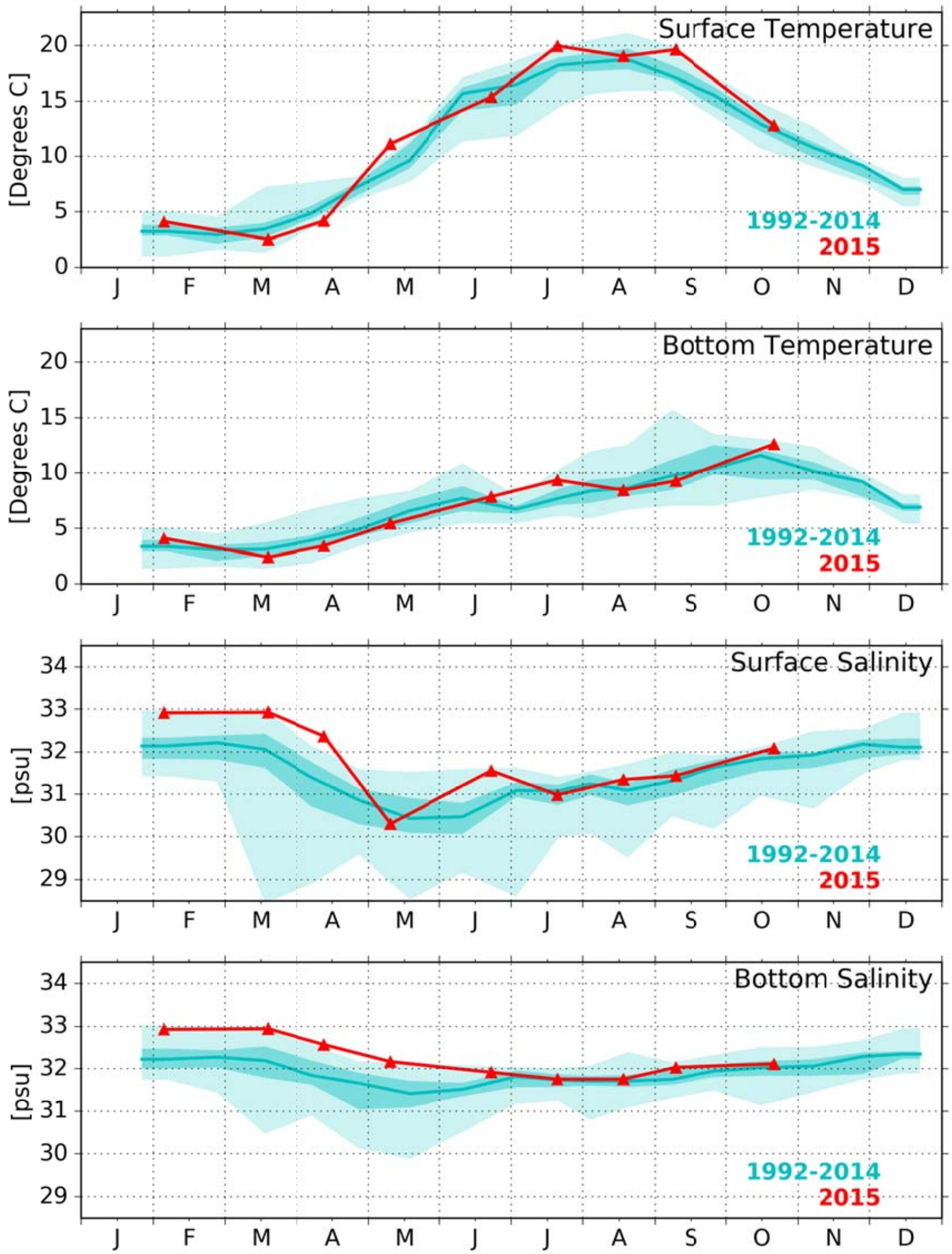


Figure 2-3. Comparison of 2015 surface and bottom water temperature (°C) and salinity (PSU) at nearfield station N18 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is the 50^{th} percentile, dark shading spans the 25^{th} to 75^{th} percentile, and light shading spans the range.

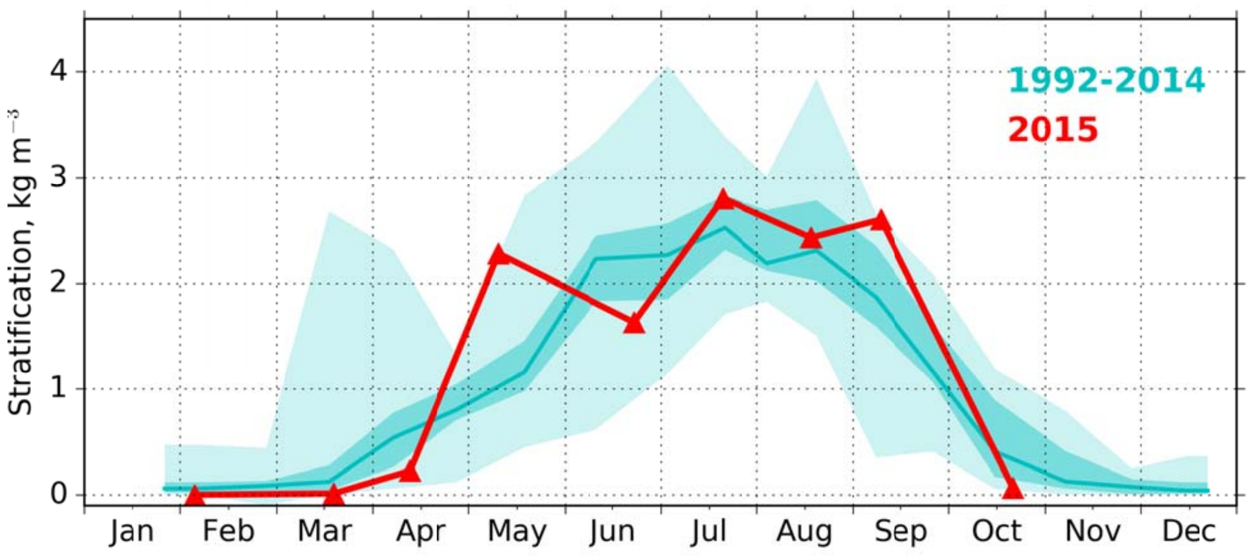


Figure 2-4. Stratification at nearfield station N18 in Massachusetts Bays in 2015 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

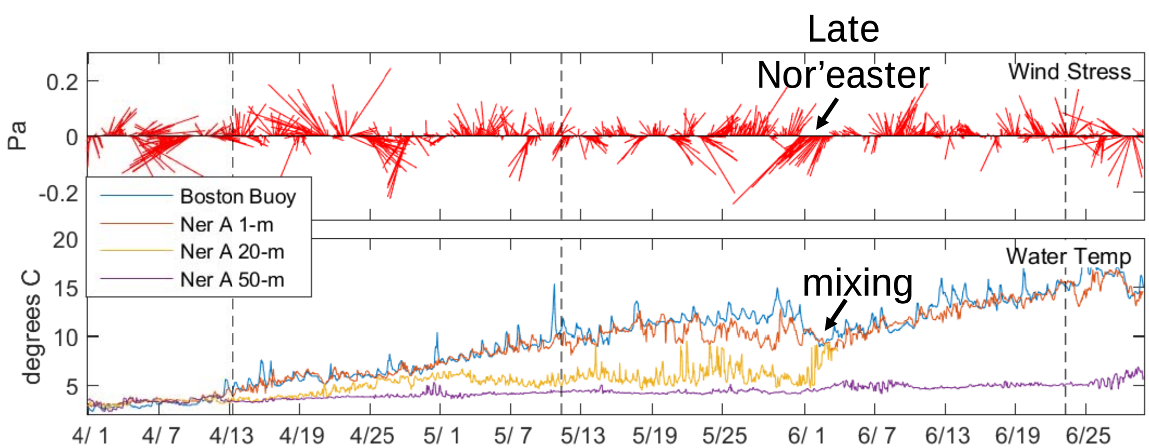


Figure 2-5. NERACOOS Mooring A01 time series observations in spring 2015. Top: surface wind strength and direction. Bottom: water temperature [1, 20 and 50 m depths, with NDBC Buoy 44013 ("Boston Buoy") surface temperature superposed].

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

2.3.1 **Nutrients**

At station N18 near the outfall, winter/spring 2015 (February and March surveys), nutrient concentrations averaged through the water column were low to moderate and near the long term median (**Figure 2-6**). Nitrate and phosphate concentrations followed the typical seasonal decline from February to May 2015. By May, nitrate was nearly depleted from the water column, while silicate remained elevated (maximum survey depth-averaged concentration for 2015 at station N18). Ammonium concentrations increased from March to May and remained at or above the maxima that have been observed at this station for most of the summer (except July 2015). Nitrate concentrations remained depleted and close to the long term median through July. Silicate and phosphate levels fluctuated over the summer, but remained within the typical range. Nutrient concentrations in October 2015 were lower than the median and close to minima for the year.

The summer increase in ammonium concentrations was primarily observed at stations near the outfall (N18 and N21; **Figure 2-7** and **Figure 2-8**). At individual stations in the bay, depth-averaged ammonium concentrations were typically <2 µM for each of the 2015 surveys. The elevated ammonium concentrations observed at stations N18 and N21, and to a lesser extent at station F15 (and F10 in July) in 2015 were comparable to levels that have been observed in these locations since the bay outfall became operational.

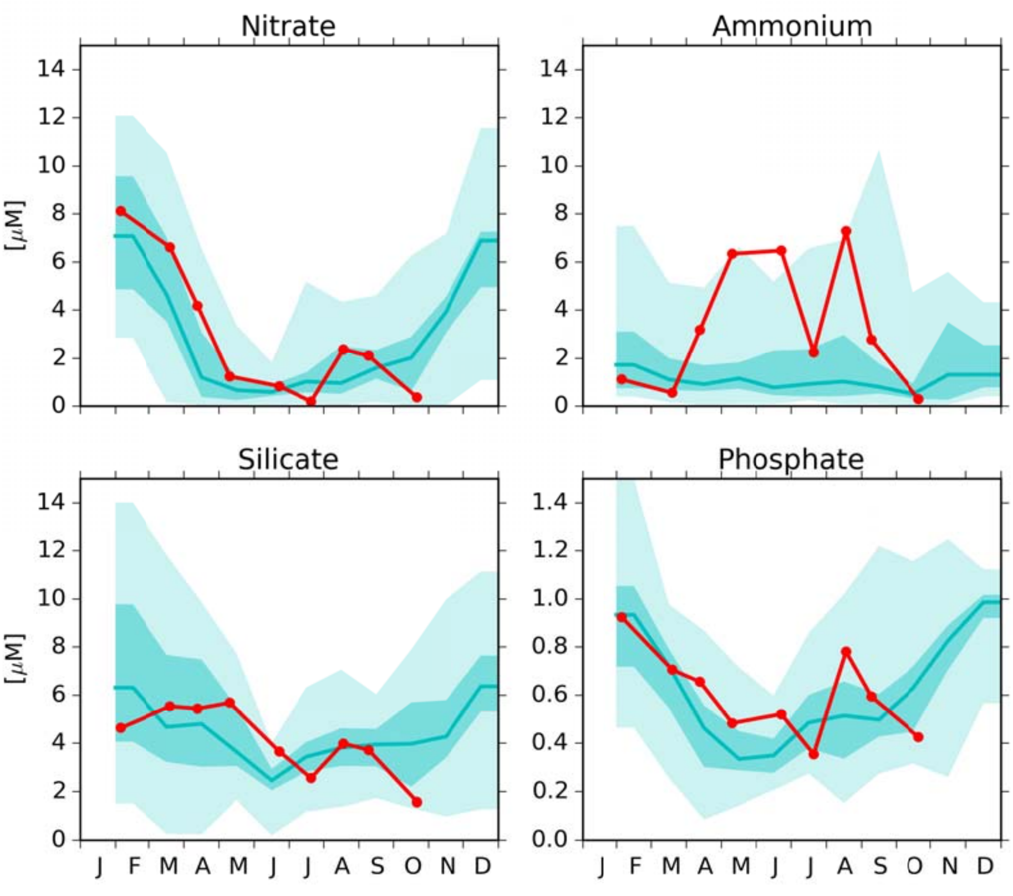


Figure 2-6. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18 in 2015, one kilometer south of the outfall, compared to prior years. Note difference in scale for phosphate. 2015 results are in red. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

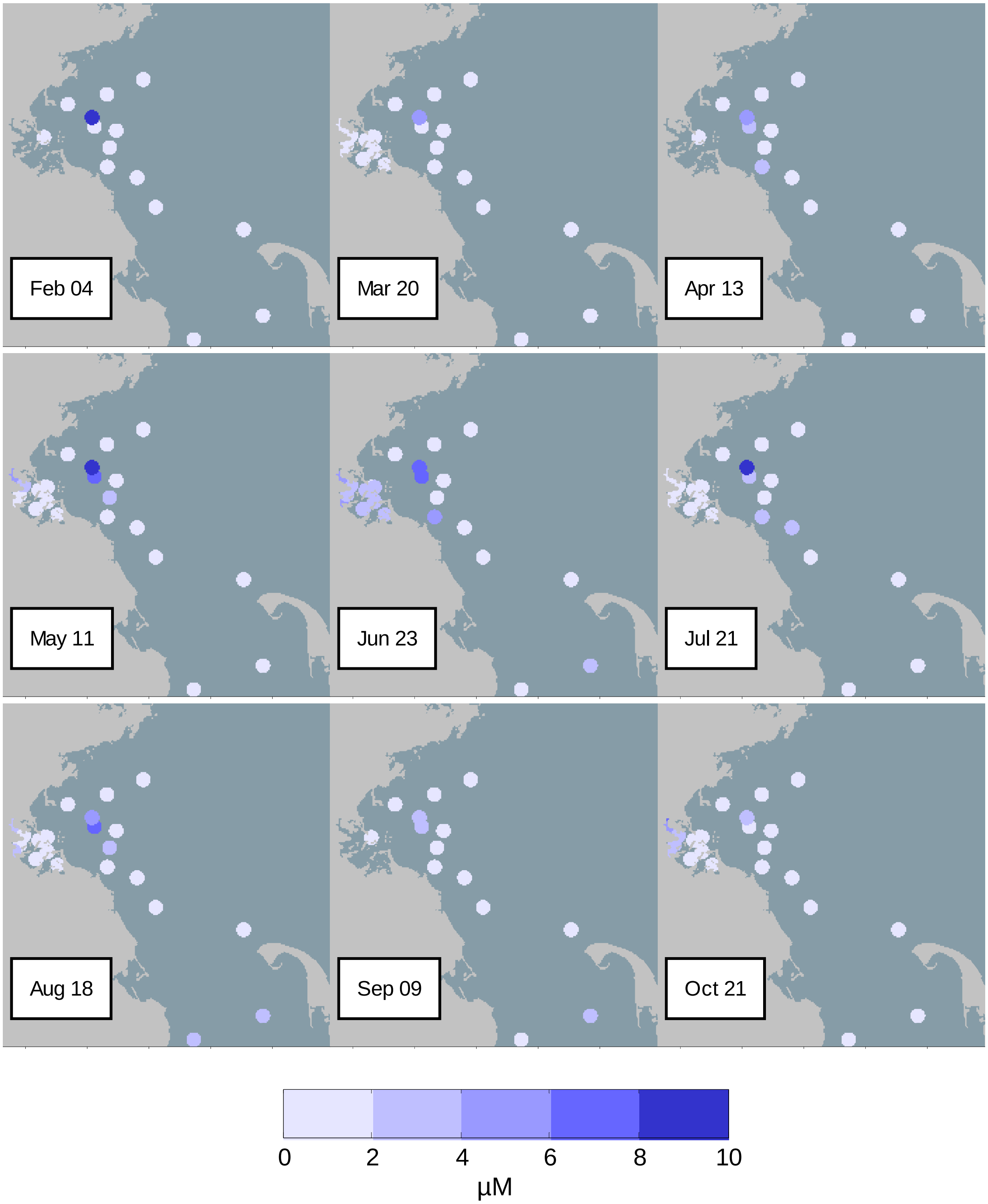


Figure 2-7. Depth-averaged NH_4 concentrations (µM) at stations in Massachusetts and Cape Cod Bays in 2015.

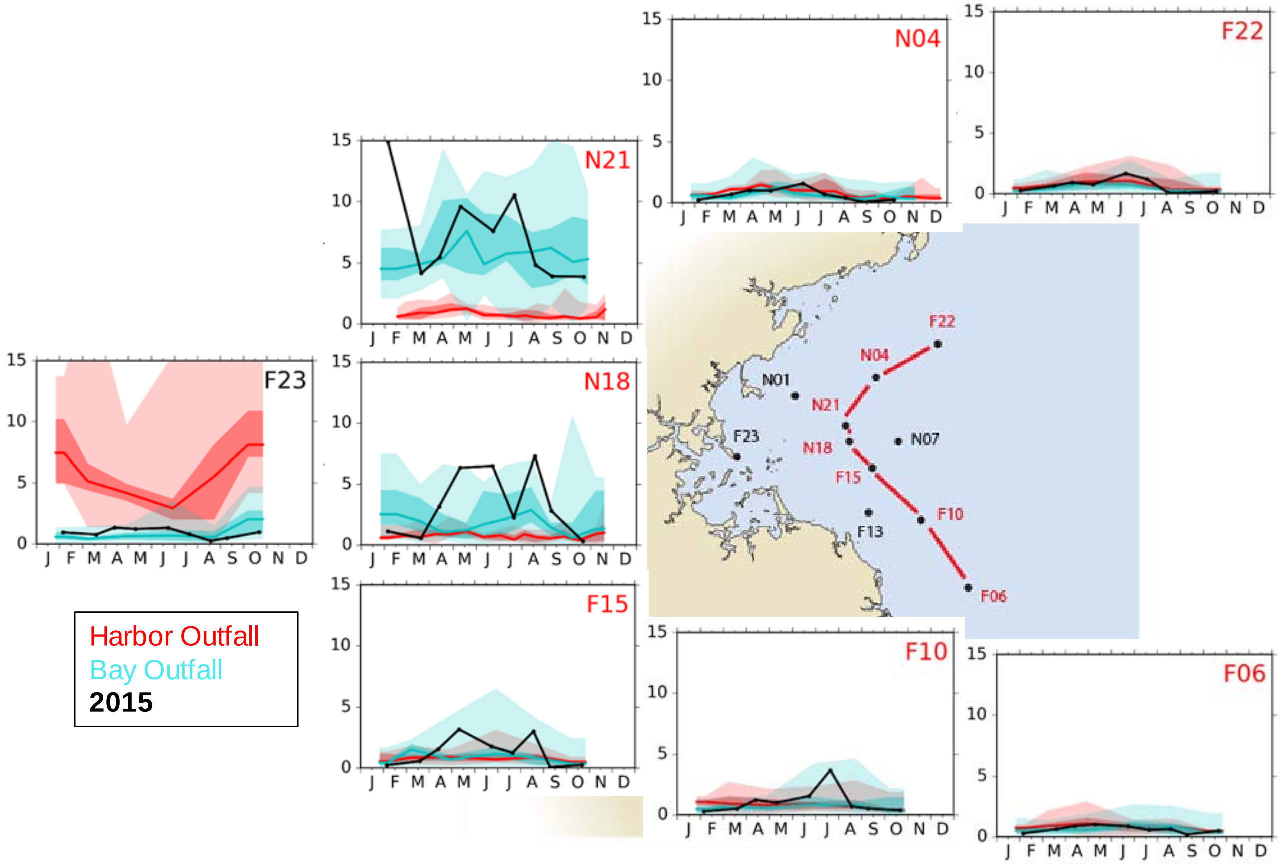


Figure 2-8. Depth-averaged NH_4 (µM) at selected stations in Massachusetts Bay for 2015 compared to prior years. 2015 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2014) results are in light blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

2.3.2 Phytoplankton biomass.

The ship-board surveys showed a seasonal chlorophyll pattern in the bay with elevated concentrations over much of the bay during the February, March, and October surveys (**Figure 2-9**). With the exception of a single location (station F22) on the May survey, areal chlorophyll concentrations were <120 mg m^{-2} on all the other surveys. MODIS satellite chlorophyll fluorescence imagery (**Figure 2-10)** suggests phytoplankton were productive in January and February 2015 with moderate chlorophyll levels (~2-3 µg L^{-1}). On the February survey, phytoplankton biomass at most locations was relatively high compared to historic values **(Figure 2-11).** In March, values were near the middle of the historic range**.** During the reminder of the year, the chlorophyll values at the most locations fell within the lower end of the range seen in previous years. Satellite chlorophyll data and surface chlorophyll fluorescence data from the NERACOOS A01 mooring (**Figure 2-12**) indicate the bay experienced a large system-wide bloom during late April/early May. It may be that the extended cold winter into spring delayed the onset of a spring bloom. The remote sensing data and relative changes in nutrient concentrations between the April and May surveys suggest that this was a Phaeocystis bloom, but there are no plankton data available to confirm this conclusion. The NERACOOS mooring detected a large increase in chlorophyll in early September, unfortunately there are no mooring data for October. However, the MODIS satellite imagery data suggest that elevated levels of chlorophyll continued to be present in the bay through October and the October survey data also exhibited elevated chlorophyll concentrations suggesting a fall bloom.

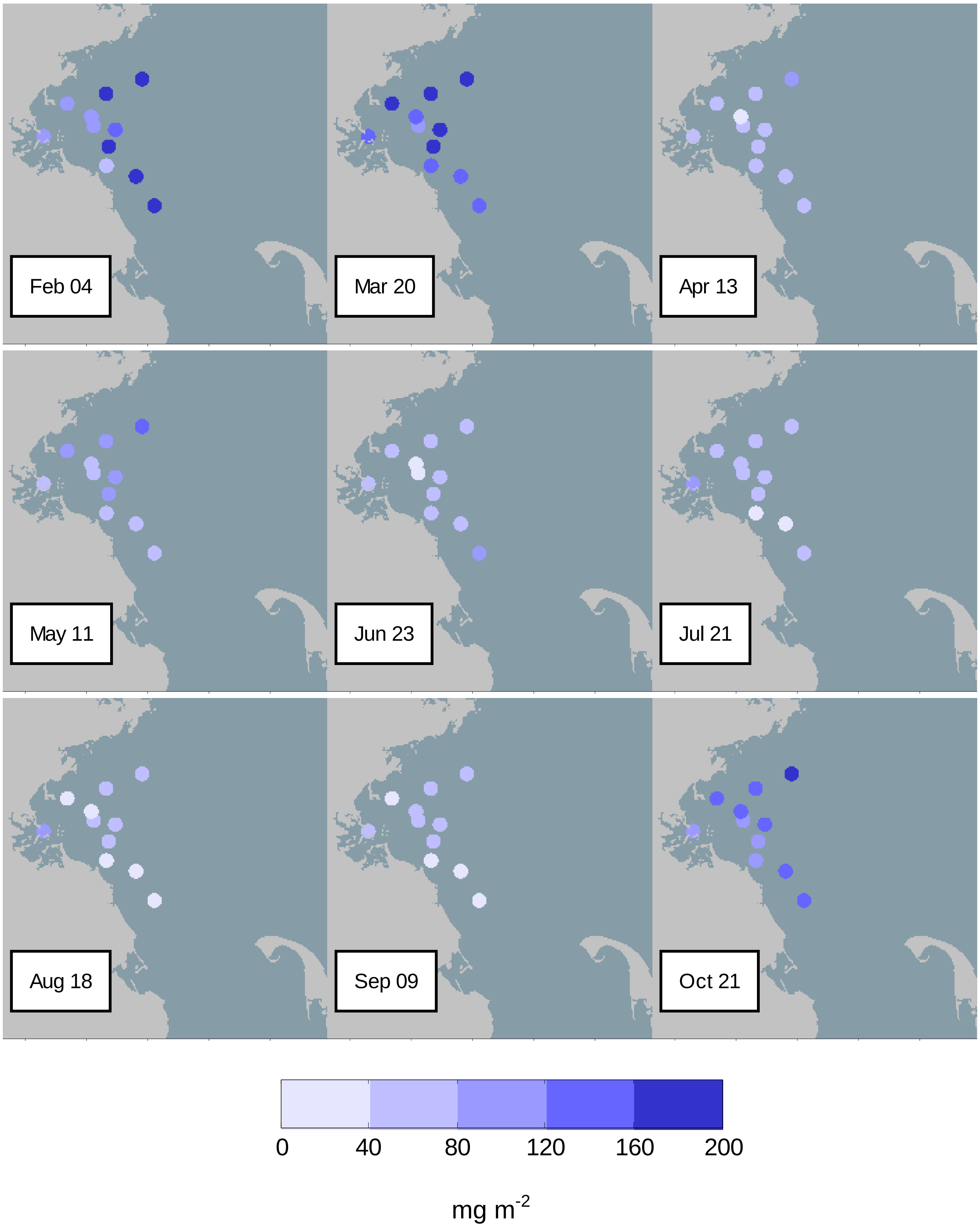


Figure 2-9. Areal chlorophyll fluorescence (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2015.

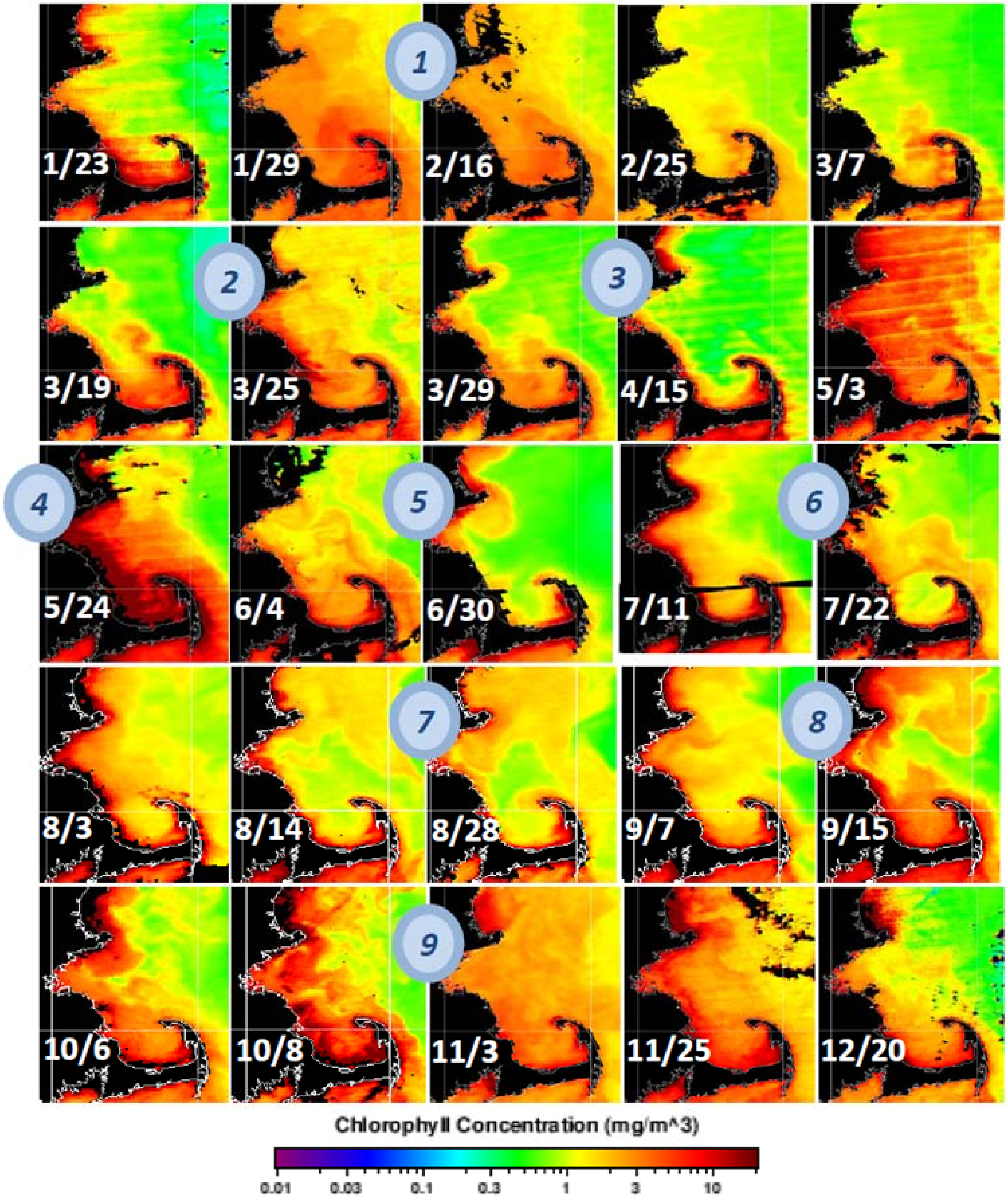


Figure 2-10. Satellite (MODIS) imagery of surface chlorophyll concentrations (mg m^{-3}) in 2015.

Highlights and specific blooms:

1st row – moderate chlorophyll levels January and February 2015 (and November-December 2014; not shown);
1st & 2nd rows – relatively low from late February to mid-April (slight increase in late March);
2nd row – high chlorophyll in early May – late *Phaeocystis* bloom;
3rd & 4th rows – variable summer chlorophyll levels from June through August;
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.)

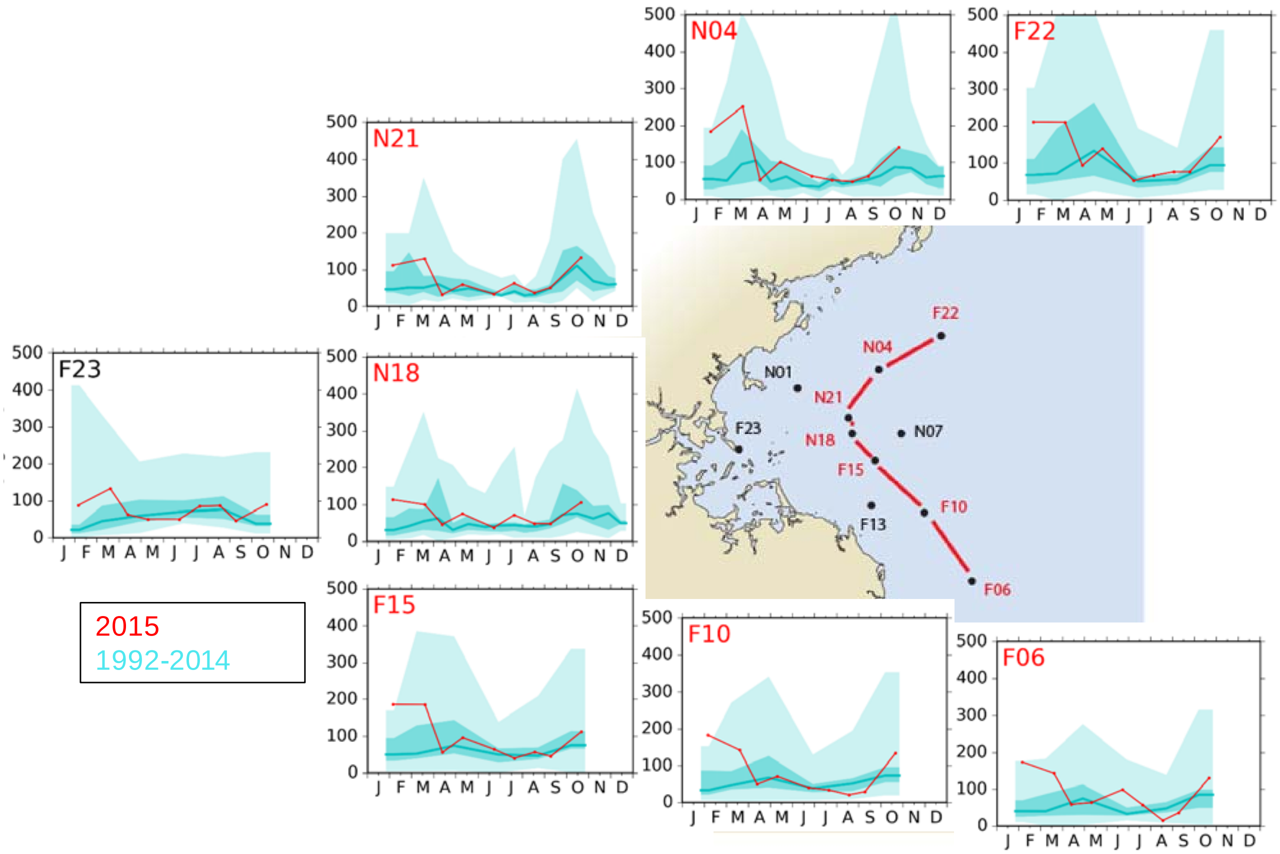


Figure 2-11. Areal chlorophyll fluorescence (mg m^{-2}) at representative stations in Massachusetts Bay for 2015 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

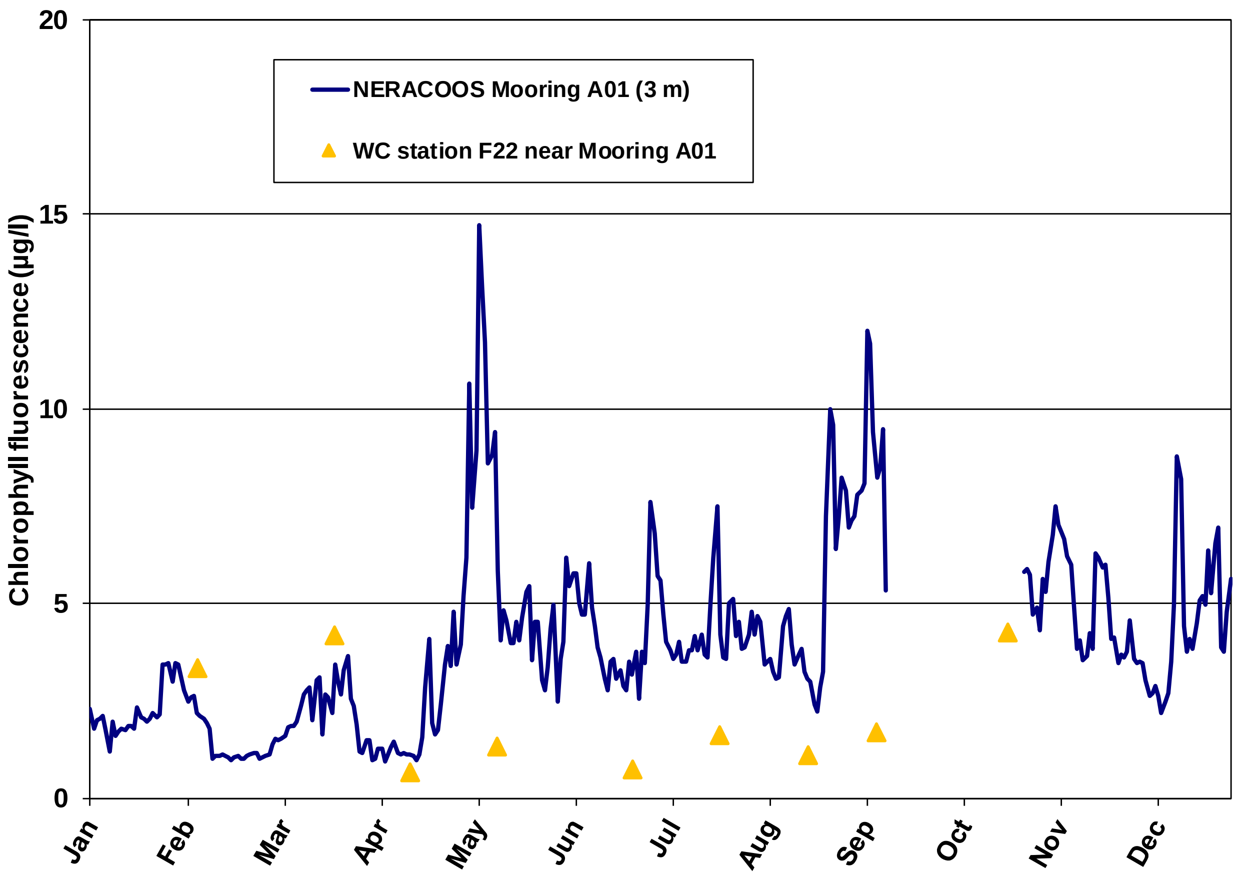


Figure 2-12. Surface water chlorophyll fluorescence (µg L^{-1}) at NERACOOS Mooring A01 and nearby MWRA station F22. The mooring values are daily medians.

In 2015, as in other years since the bay outfall was brought on line, the ammonium signal from the effluent discharge plume was only observed within 10 to 20 km of the outfall (**Figure 2-13** and **Figure 2-14**). In April, the water column was well mixed and the plume's ammonium signature was seen in the surface waters within the nearfield. During the August survey, the water column was vertically stratified with a pycnocline located at approximately 10-15 m. Under these physical conditions, the elevated ammonium concentrations contributed by the outfall were seen at or below the pycnocline at stations N21 and N18, the locations closest to the outfall, and F15 south of the outfall (**Figure 2-15**). Nitrate concentrations were depleted in the surface waters and slightly elevated (>2 µM) below the pycnocline along the transects due to the influence of higher concentrations in the deeper bottom waters (such as station F22 located 15 km northeast of the outfall). During stratified periods, the availability of both light and nutrients near the pycnocline often leads to the presence of a sub-surface chlorophyll fluorescence maxima in the vicinity of the pycnocline. In August 2015, sub-surface chlorophyll maxima were observed just above the pycnocline with elevated values of >4 µgL^{-1} observed at stations N18 and F15 along the north-south transect.

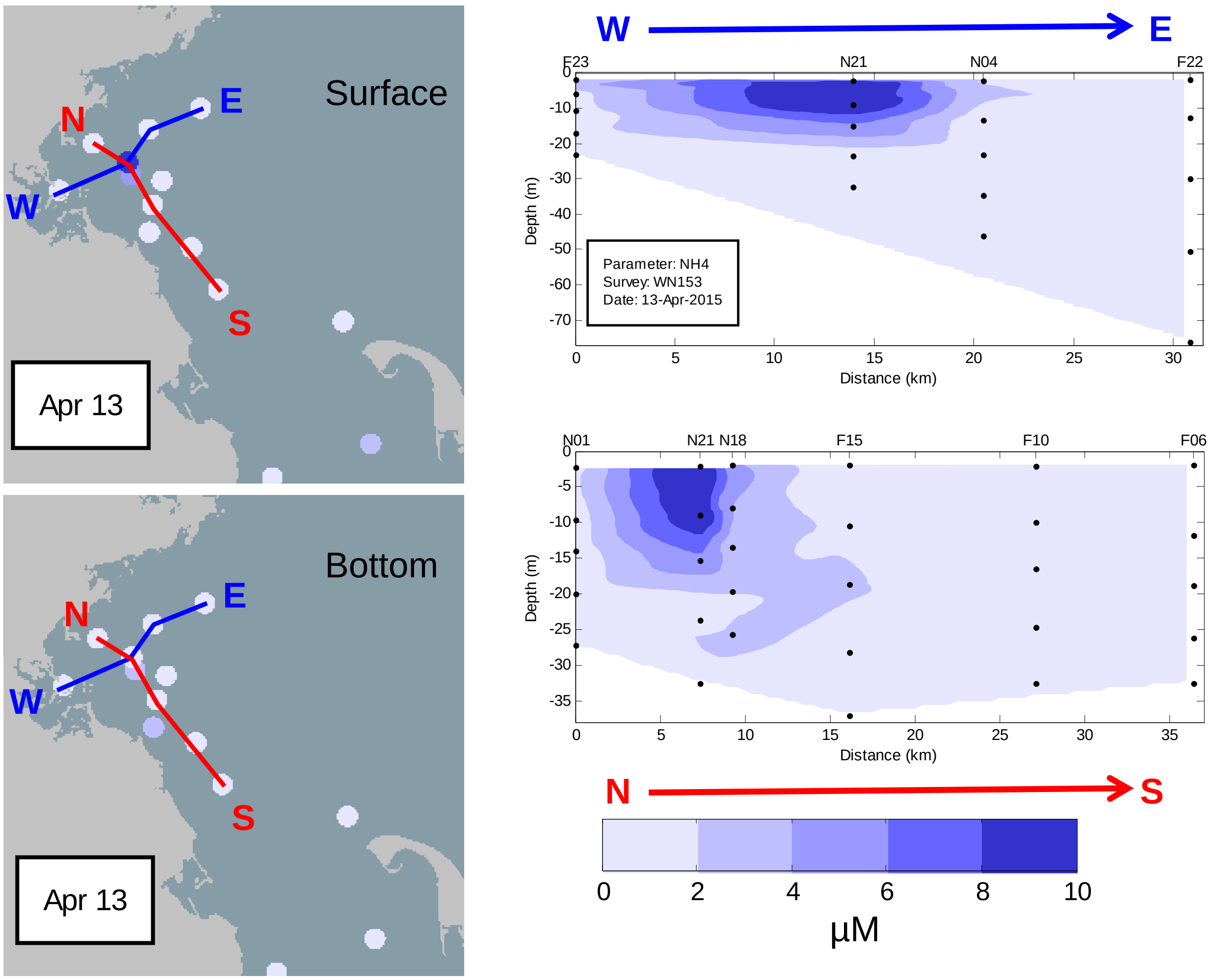


Figure 2-13. **(Left) Surface- and bottom-water ammonium on April 13, 2015 at the monitoring stations during mixed conditions. (Right) Cross-sections of concentrations throughout the water column along transects connecting selected stations.**

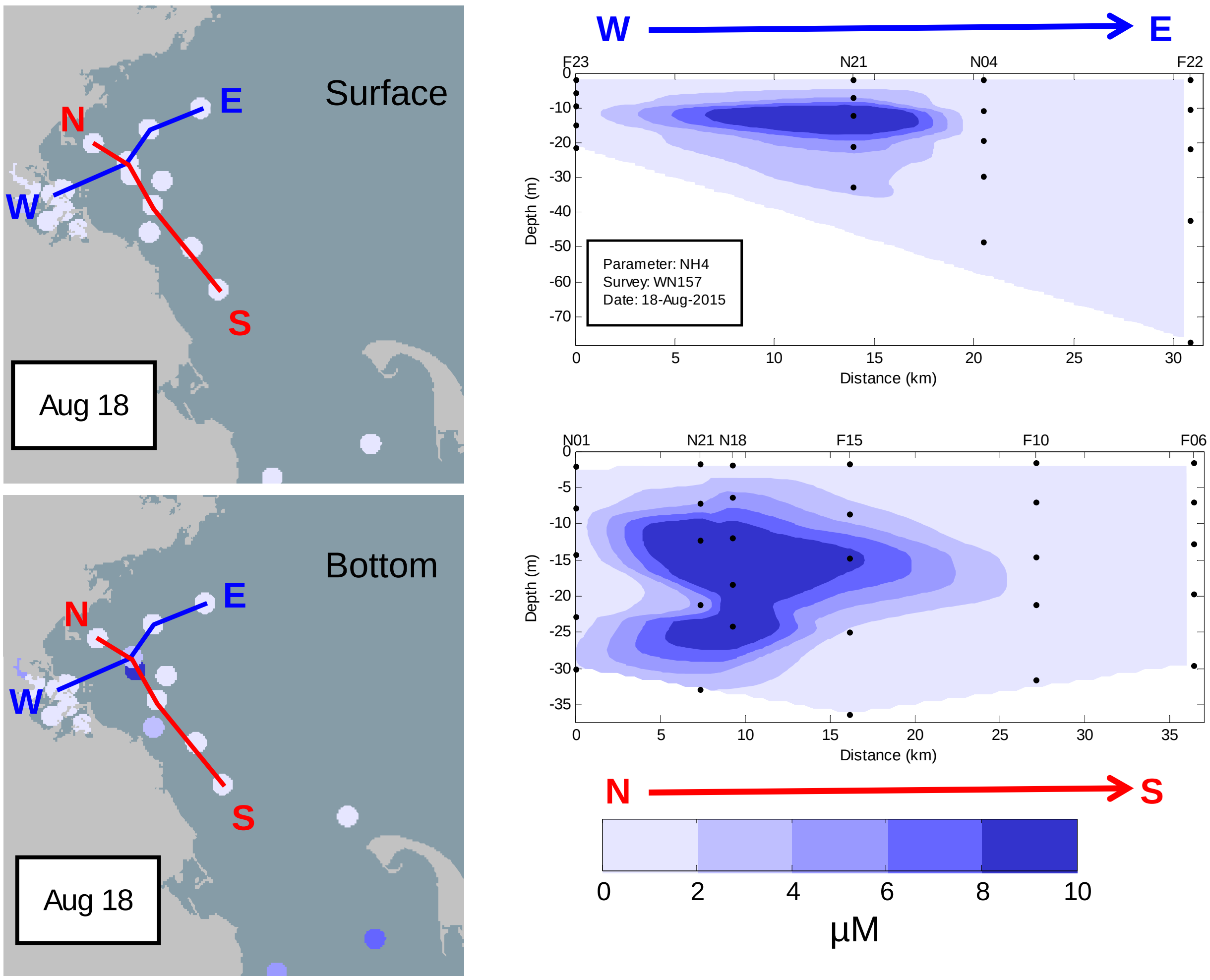


Figure 2-14. (Left) Surface- and bottom-water ammonium on August 18, 2015 at the monitoring stations during mixed conditions. (Right) Cross-sections of concentrations throughout the water column along transects connecting selected stations.

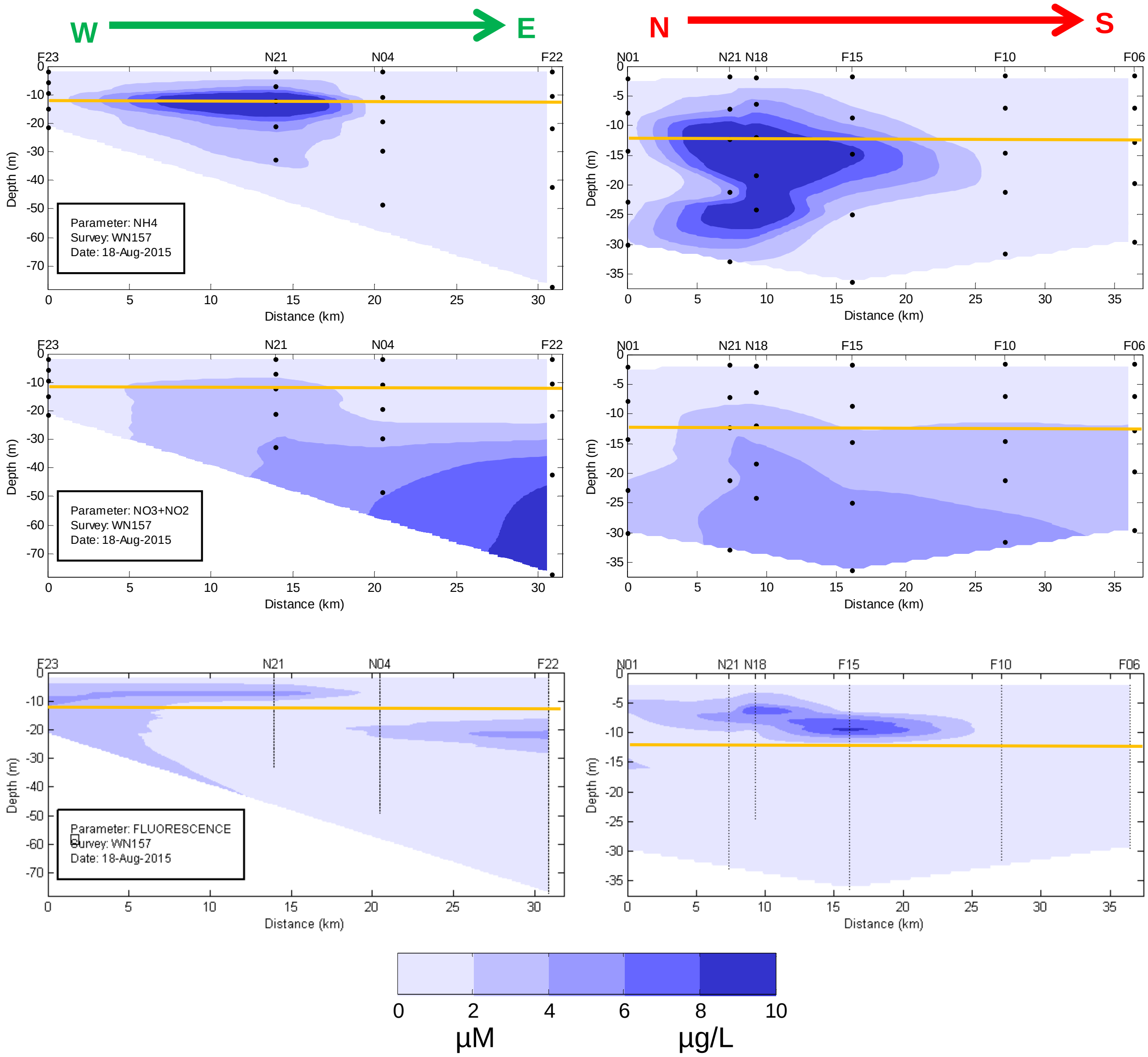


Figure 2-15. Ammonium (top), nitrate+nitrite (middle), and fluorescence (bottom) concentrations (µM and µg L^{-1}) in August 2015 along the east-west and north-south transects shown in Figure 2-14. The dots on the plot indicate the sampling depths for nutrients and the in situ fluorescence profile. The orange line indicates the approximate depth of the pycnocline.

2.4 PHYTOPLANKTON

During the first two surveys in 2015, despite relatively high chlorophyll levels, phytoplankton cell counts were low (**Figure 2-16**). This suggests that the phytoplankton present in the water column in February and March 2015 were large or enriched with chlorophyll compared to previous years. Cell chlorophyll content can vary widely among taxa and also depending on trophic state. During this late winter/spring period, a suite of cold-water centric diatoms (*Detonula confervacea, Porosira glacialis* and *Lauderia annulata*) were present. However, despite the cold water temperatures experienced during winter 2015, these species did not reach elevated abundance levels. This condition was quite different from the winter/spring of 2014 when abundance of these cold water species, especially *Detonula confervacea*, was elevated.

During 2015, counts of the centric diatoms that typically comprise a large portion of the winter/spring phytoplankton were low. *Chaetoceros* spp. counts, for example, were present at only ~30% of their long-term level during 2015 (**Table 2-1**). Since about 2000, the spring diatom bloom has been followed by a *Phaeocystis* bloom in April (**Figure 2-17)**. In comparison to past *Phaeocystis* blooms, the 2015 abundances were low. However, April *Phaeocystis* abundances in Cape Cod Bay were in the 100,000s cells L^{-1} range and *Phaeocystis* were also observed in May, suggesting a bloom likely occurred between the two surveys in Massachusetts Bay. This is consistent with the bay-wide increase in chlorophyll observed in late April/early May 2015 satellite and mooring data, but cell count data are unavailable to confirm this. *Phaeocystis* was observed in only one nearfield sample (13,000 cells L^{-1}) in May 2015, and this observation led to an exceedance of the summer *Phaeocystis* contingency threshold.

Very few *Alexandrium fundyense* cells were seen during the 2015 surveys ($\leq$3 cells L^{-1}) and no paralytic shellfish poison (PSP) toxicity was measured in Massachusetts Bay or along the shore from Gloucester, Massachusetts to New Hampshire (**Figure 2-18**). PSP toxicity had been noted in western Maine and New Hampshire, but the bloom was minor and short lived. *Alexandrium*, when it occurs in Massachusetts Bay, typically does so in May through early July. Both the low spring 2015 water temperatures and lack of northeaster storms, which produce currents necessary to bring these offshore blooms into Massachusetts Bay, in late April and May likely have contributed to the low 2015 counts in the bay. A late northeaster storm occurred in early June, but by that time PSP was already declining at New Hampshire's Star Island PSP monitoring station, and presumably *Alexandrium* cells in the water being transported into the bay from the north were low.

Summer total phytoplankton counts fell in the middle to low historic range, due in part to the low abundances of the typical summer diatom bloom in the harbor and coastal regions. *Skeletonema* spp. often dominates the late summer diatom bloom inshore, but in 2015 its abundance was reduced to 39% of its long-term mean in the nearfield (17,947 cells L^{-1} versus 46,410 cells L^{-1}). *Skeletonema* spp. and *D. fragilissimus,* that together usually peak in late summer, were responsible for the bay's fall phytoplankton bloom. A combination of summer grazing pressure (discussed further below) and the persistence of relatively warm and calm conditions into late September/October may have been responsible for the low summer abundances and subsequent increases in these taxa in fall. For 2015 as a whole, total phytoplankton abundance in the nearfield (determined from station N04 and N18 survey data) was 56% of the long-term mean (806,262 cells L^{-1} versus 1,447,991 cells L^{-1}) and ranked 21st for the 24 years of monitoring.

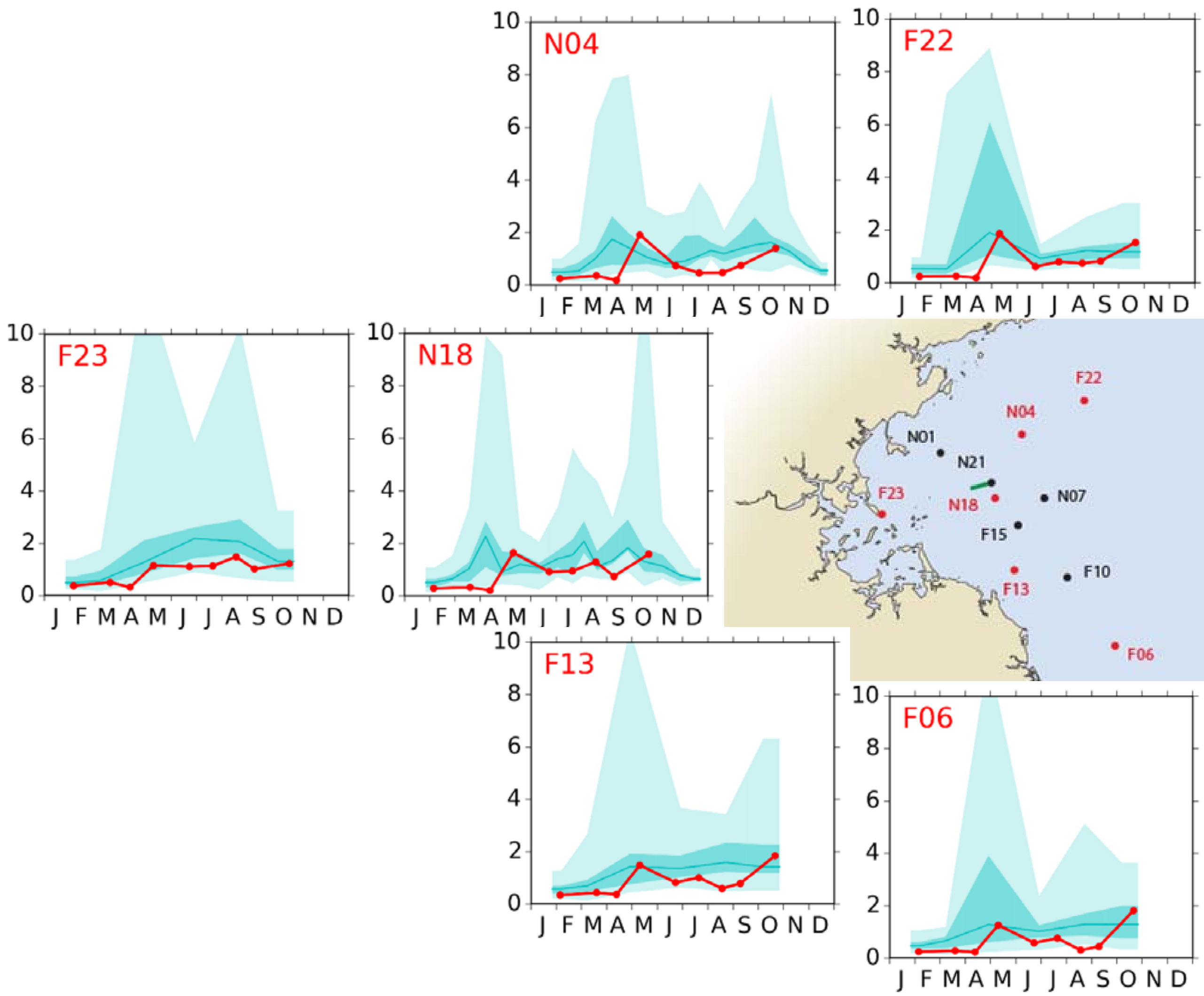


Figure 2-16. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2015 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range).

Table 2-1. Comparison of 2015 annual mean phytoplankton abundance in the nearfield (cells L^{-1}) to long-term observations for major groups and species. Data are from the surface and chlorophyll maximum sampling depths at stations N04 and N18.

Group	1992-2014 (cells L^{-1})	2015 (cells L^{-1})	Rank (out of 24)	p value	Significant Change
CENTRIC DIATOM	284,470	107,959	19th	0.0566	
Dactyliosolen fragilissimus	61,941	28,457	13th	0.9632	
Chaetoceros	32,615	9,582	14th	0.5159	
Skeletonema costatum complex	46,410	17,947	13th	0.2063	
Thalassiosira	39,120	18,927	13th	0.5536	
PENNATE DIATOM	37,677	7,434	22nd	0.0044	Decline
Pseudonitzschia	9,213	690	22nd	0.0001	Decline
DINOFLAGELLATES	61,737	55,377	13th	0.1423	
Ceratium	1,625	1,553	10th	0.2141	
Dinophysis	268	267	13th	0.5037	
Prorocentrum	4,979	11,810	3rd	0.4624	
Phaeocystis pouchetii	220,898	5,069	17th	0.5984	
CRYPTOPHYTES	125,842	165,682	5th	0.6986	
MICROFLAGELLATES	706,482	456,916	19th	0.0005	Decline
TOTAL PHYTOPLANKTON	1,447,991	806,262	21st	0.0002	Decline

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.

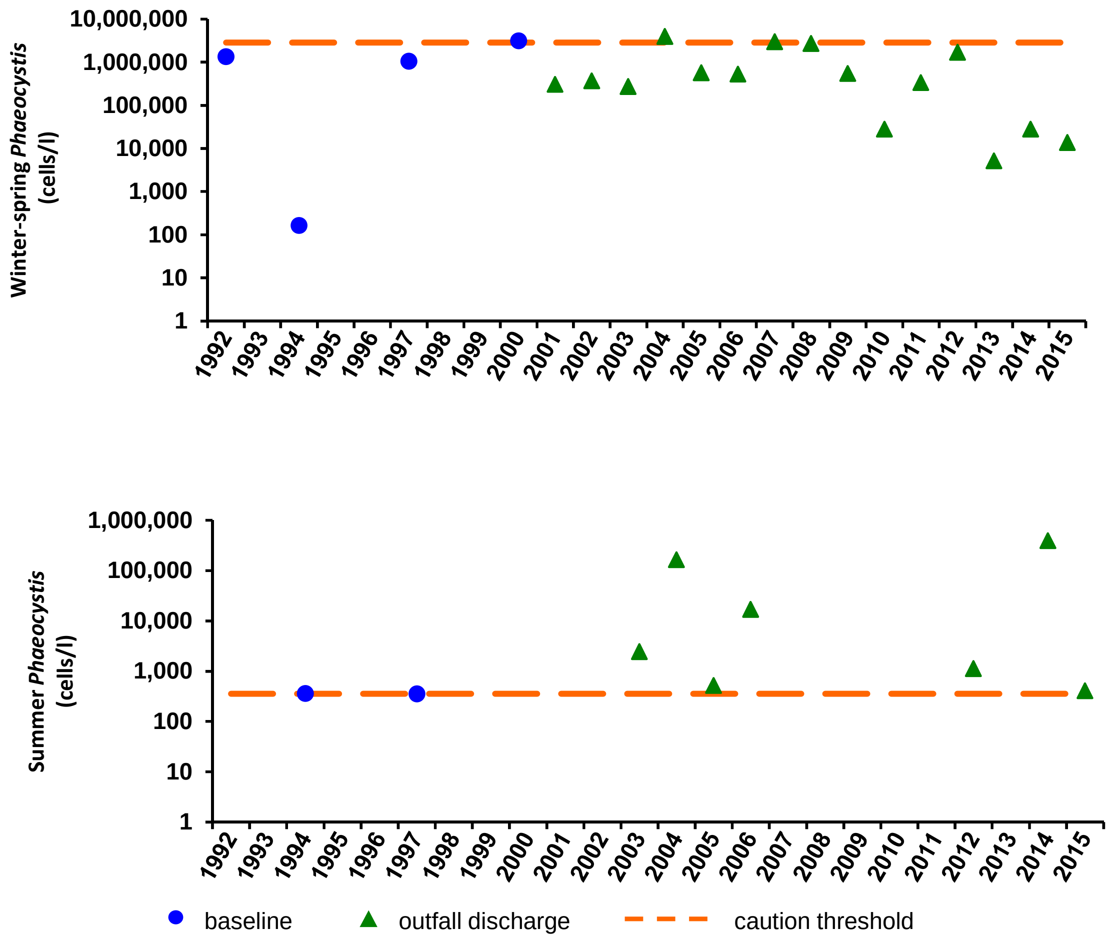


Figure 2-17. Winter/spring (million cells L^{-1}) and summer (cells L^{-1}) seasonal mean nearfield *Phaeocystis* abundance for 1992 to 2015 (zeros not plotted). Contingency Plan threshold value shown as dashed line.

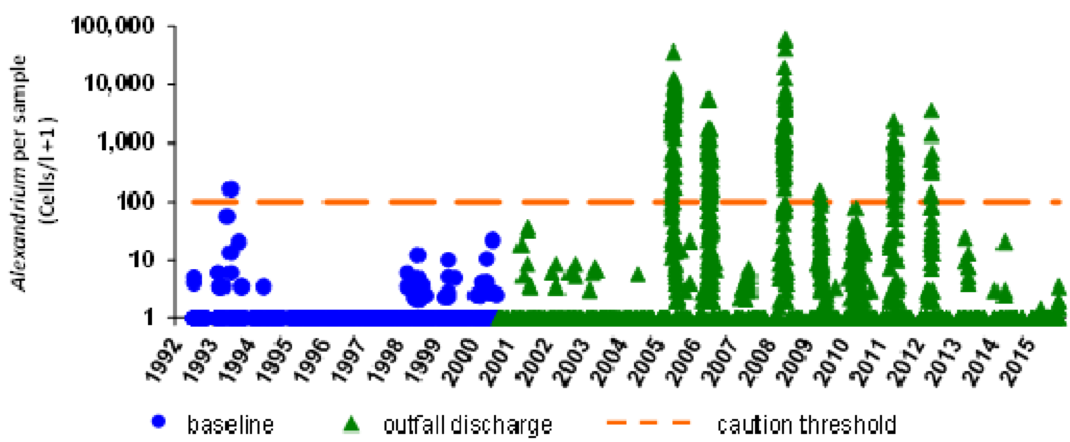


Figure 2-18. Nearfield *Alexandrium* abundance for individual samples (cells L^{-1}). Contingency Plan threshold value shown as dashed line.

2.5 ZOOPLANKTON

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 2-19**). Peak abundances in 2015 were nearly 10 times higher than in all previous years (1992-2014). Extreme abundances of bivalve veliger larvae in July and August, particularly in Boston Harbor, were largely responsible for the elevated peaks. In July, bivalve veliger abundance exceeded 2 million m^{-3} at station F23 in Boston Harbor, and exceeded 1 million m^{-3} at station N01 off Nahant. Previous maxima for bivalve larvae were <150,000 m^{-3}. Abundances of copepod adults + copepodites (A+C) were also high from June to October often at or above previous maxima (**Figure 2-20**). These peaks were driven primarily by the small cyclopoid copepod *Oithona similis*, which were approximately double those observed in 2014. There were also relatively high abundances of other copepod taxa in 2015 including *Pseudocalanus* spp. and *Calanus finmarchicus*. Grazing by the large zooplankton populations may have contributed to the relatively low phytoplankton cell counts also observed during 2015.

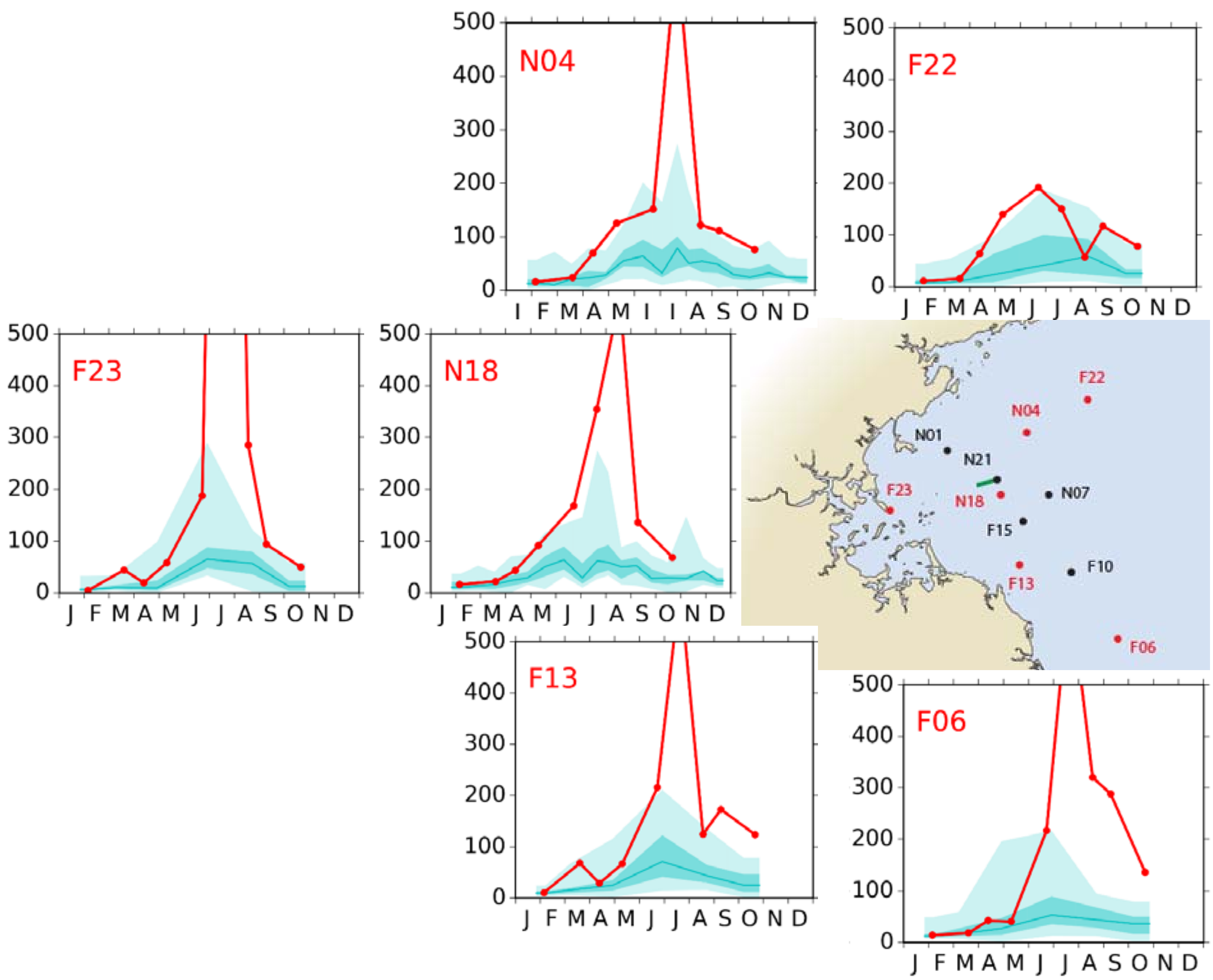


Figure 2-19. Total zooplankton abundance (1,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2015 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. Peak values for 2015 exceeding the length of the y-axis maximum of 500,000 were stations N04 = 630,000; F23 = 2,400,000; N18 = 570,000; F13 = 610,000; and F06 = 700,000 individuals m^{-3}.

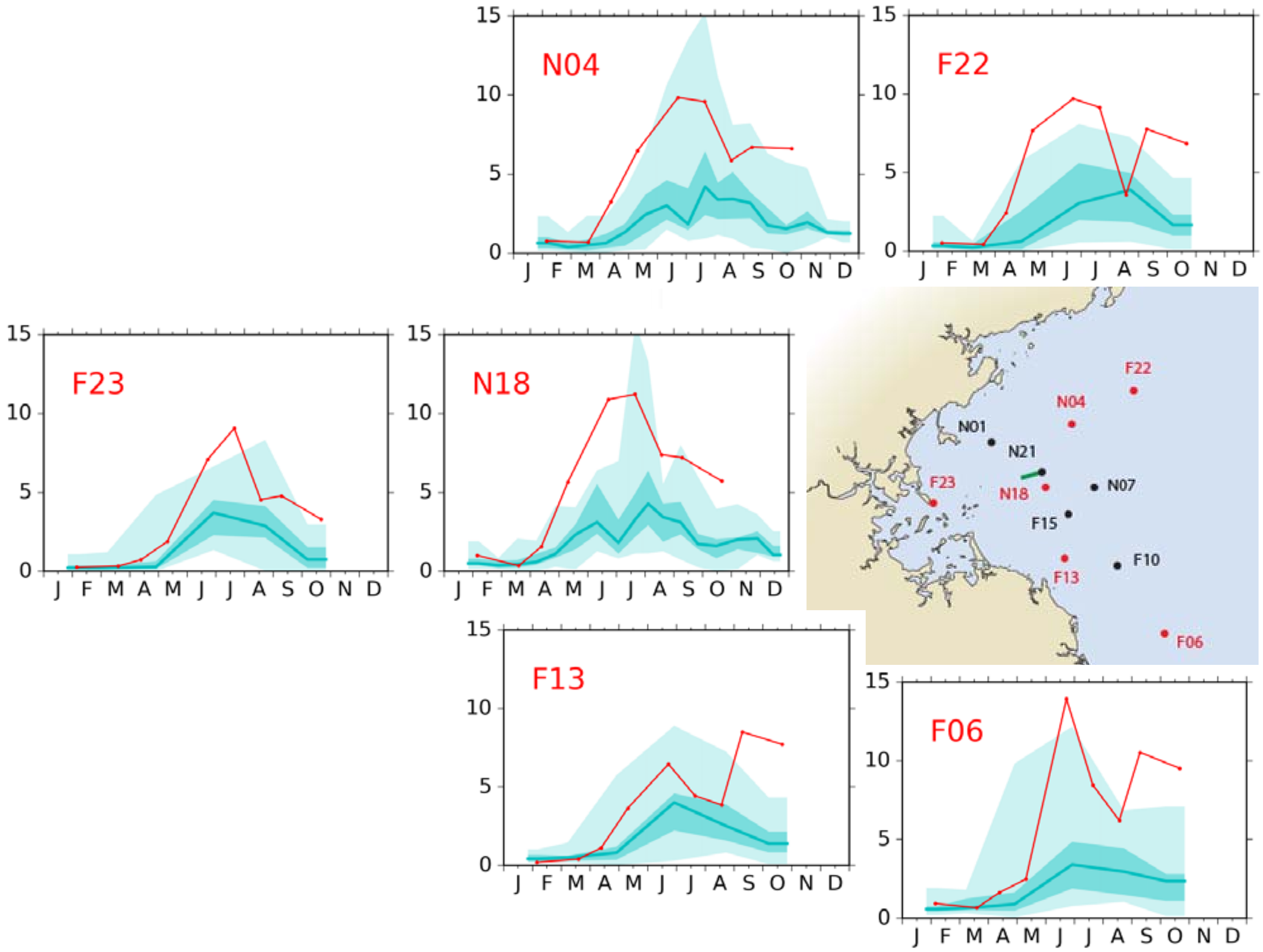


Figure 2-20. Copepod A+C abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2015 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Peak abundances of *Acartia* spp. in Boston Harbor were approximately twice those of the previous year, with two peaks in 2015 in July and September (**Figure 2-21**). During the baseline period (1992-2000) *Acartia* spp. peaks in Boston Harbor would usually occur in August-September, but after diversion of the outfall, peaks occurred earlier in the summer in May-June (2001-2014). In 2015, peaks of *Acartia* spp. abundance in Boston Harbor occurred in both the earlier period (May) as in previous post-diversion years, as well as in the later period (August) typical of the baseline period.

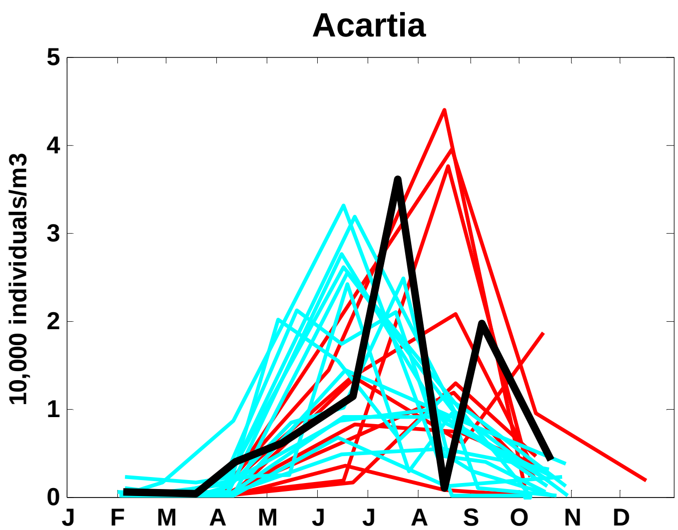


Figure 2-21. ***Acartia* spp. abundance (10,000 individuals m^{-3}) at Boston Harbor station F23 for 2015 compared to prior years.** 2015 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2014) results are in light blue.

2.6 BOTTOM WATER DO

As has been observed in most of the prior years, bottom water DO declined at a relatively constant rate in Massachusetts Bay from winter/spring maxima to September or October annual minima in 2015 (**Figure 2-22**). The lowest bottom water DO levels in 2015 were observed at Cape Cod Bay station F02 in August (5.9 mgL^{-1}; **Figure 2-23**). Wind and temperature data from the NERACOOS Mooring A01 showed that an early October northeaster storm had mixed the water column down to 50 m (**Figure 2-24**). This storm mixed oxygen-rich surface waters to deeper depths, leading to an increase in bottom water DO concentrations at many shallower stations including station N18 in the nearfield. There was an increase in DO concentrations at 51 m at Mooring A01, but these deeper waters had re-stratified by the October survey and did not become fully mixed until November (**Figure 2-25**). Even with the extended period of stratification at the deeper stations, the DO minima were relatively high with concentrations >7 mg L^{-1}. Overall, bottom water DO levels in Massachusetts Bay were moderate in 2015 compared to levels observed in 1992-2014.

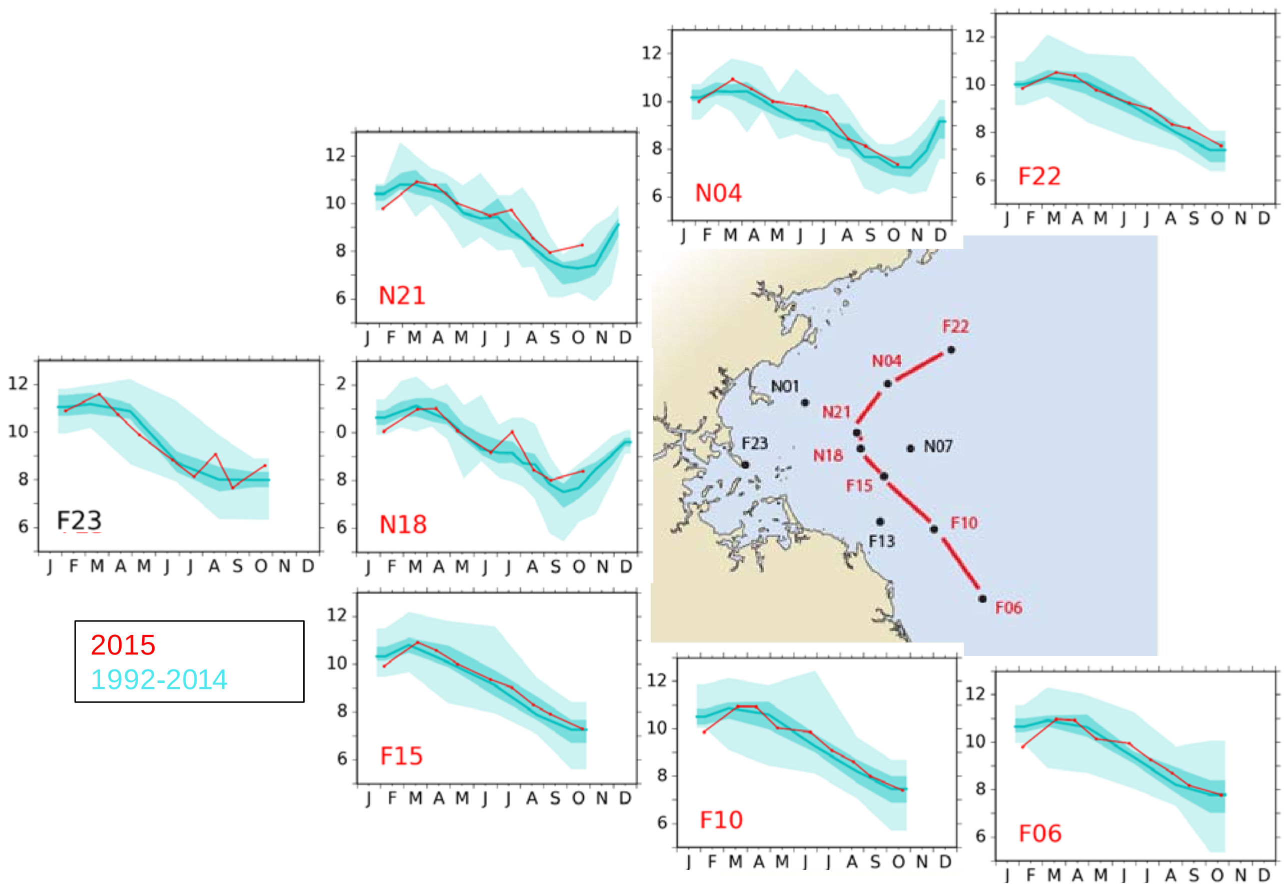


Figure 2-22. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2015 compared to prior years. 2015 results are in red. Results from 1992–2014 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

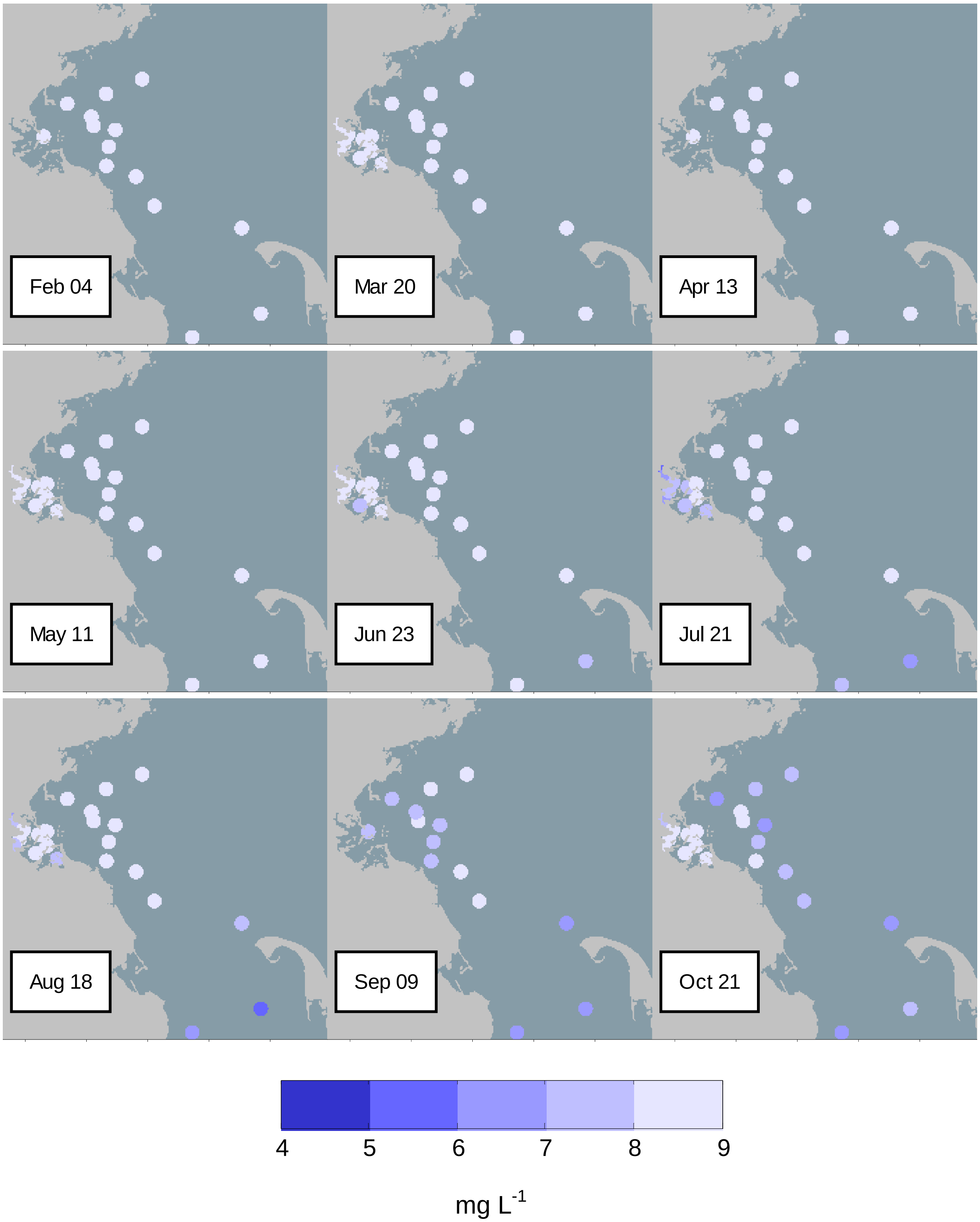


Figure 2-23. Bottom water DO concentration (mg L^{-1}) at stations in Massachusetts and Cape Cod Bays in 2015.

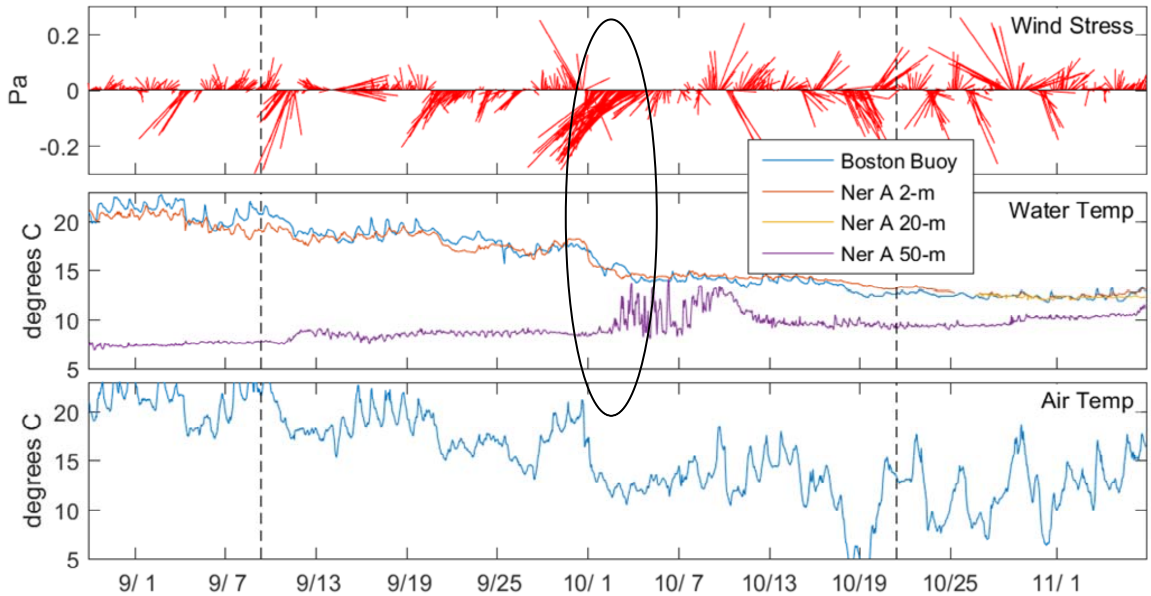


Figure 2-24. Mooring A01 time series observations in fall 2015. Top: wind stress; middle: water temperature [1, 20 and 50 m depths; surface temperatures from NDBC Buoy 44013 ("Boston Buoy") superimposed]; bottom: air temperature. Strong northeasterly winds are circled to highlight the impact on water column mixing.

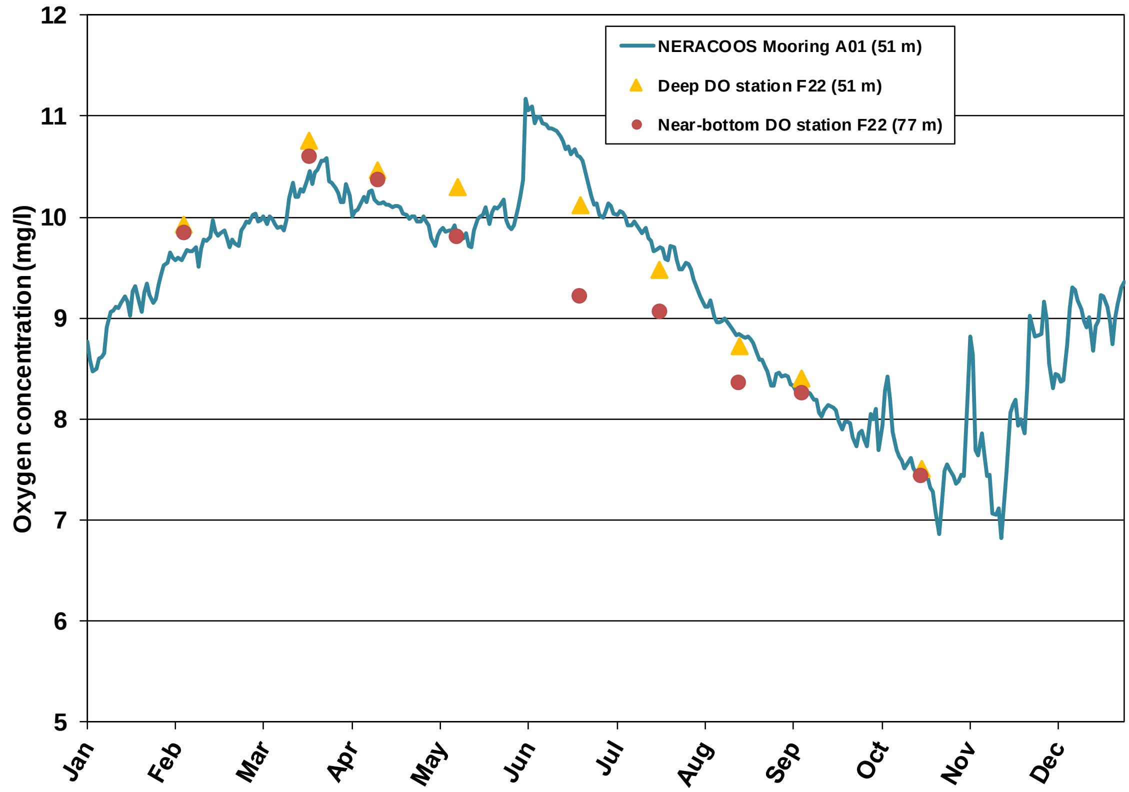


Figure 2-25. Time-series of DO concentration (mg L^{-1}) at Mooring A01 (51 m) and at station F22 from deep (mean 51 m) and bottom (mean 77 m) sampling depths in 2015. The mooring values are daily means.

3 LONG-TERM TRENDS

The 2015 observations were consistent with the general trends and patterns observed since 1992 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. In contrast, ammonium and phosphate concentrations have increased in the nearfield since the offshore outfall began discharging (Figure 2-8). At N18 and N21 NH_4 has shown multiple peaks and minima since the discharges started. During baseline years, concentrations at the same locations were much lower and less variable. NH_4 showed a dramatic decrease in the harbor. Despite the NH_4 increase in the nearfield, we have been unable to detect a phytoplankton biomass increase in the same area during the same post-discharge period.

The 2015 annual average total phytoplankton abundance (0.81 million cells L^{-1}) was very low in comparison to the long-term mean total phytoplankton abundance of 1.45 million cells L^{-1} ($p = 0.0002$) and ranked 21st out of the 24 years of monitoring. Similar to 2013 and 2014, the 2015 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 2015, in the nearfield to less than half the long-term mean level. This continues a decline in phytoplankton abundance that has been ongoing since 2008 (**Figure 3-1**). This decline has been driven by reduced abundance of microflagellates, reduced winter/spring and summer centric diatom abundance, and the lack of large *Phaeocystis pouchetii* blooms in recent years. Of note is that the trends at the surface (mean depth = 2m) and at the chlorophyll maximum (Cmax; mean depth = 14.5 m) depths diverge in 2001. After 2001, the Cmax and surface trend patterns track each other, but total phytoplankton abundance at the Cmax depth has consistently been several hundred cells per liter greater than that at the surface. No taxonomic differences in the surface versus Cmax phytoplankton community are known and it is unclear what factors may be driving the consistent, post-2001 divergence in surface versus Cmax phytoplankton abundance in the nearfield.

The low 2015 total phytoplankton abundances resulted from decreases in most of the major phytoplankton taxa groups – centric diatoms, pennate diatoms, dinoflagellates, and microflagellates. However, as seen in 2014, even though the mean abundance of total phytoplankton in 2015 was significantly lower than the long-term mean of all years monitored, no long-term linear trend was apparent in total phytoplankton abundance. There are no clear causal factors for this decrease, but regression analyses of phytoplankton data from nearfield stations N04 and N18 indicate that there is a significant relationship between phytoplankton and zooplankton abundance (total or copepod; **Figure 3-2**). Trends in annual total zooplankton abundance explain 32% of annual total phytoplankton abundance variability. Given the exceptionally high total zooplankton abundance in 2015 due to the bivalve veligers, this comparison was also done versus total copepods (adults and copepodites), which explains 35% of the variation in annual mean nearfield phytoplankton abundance. Hence, top-down control of phytoplankton likely plays a role in the observed annual phytoplankton trend.

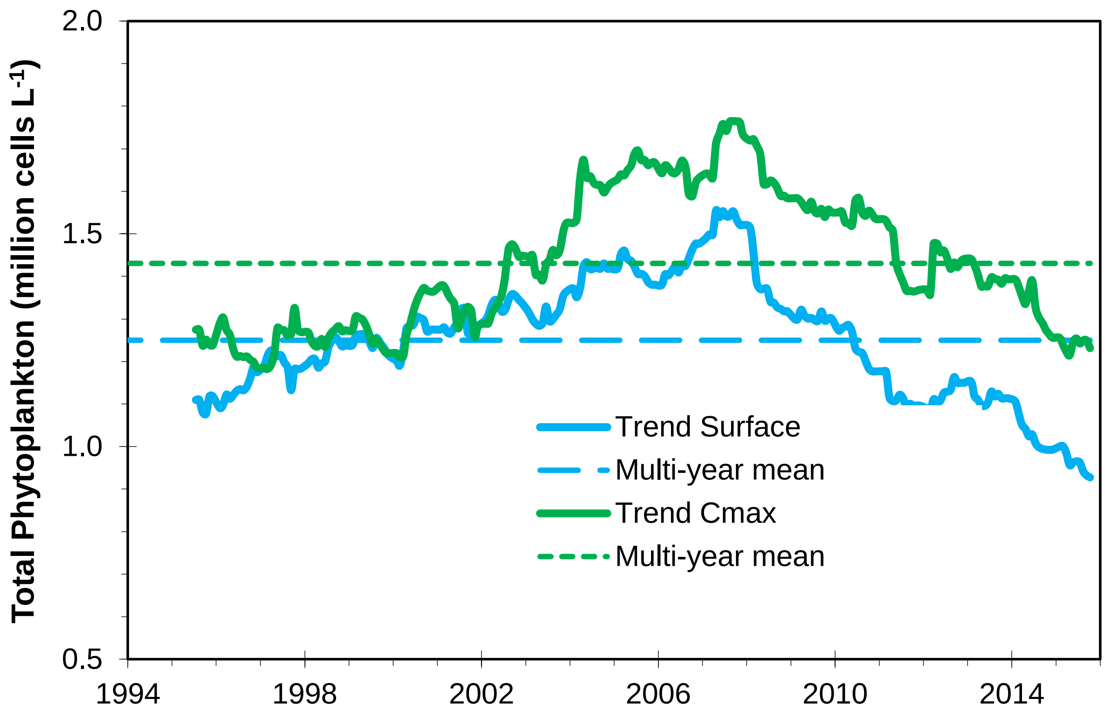
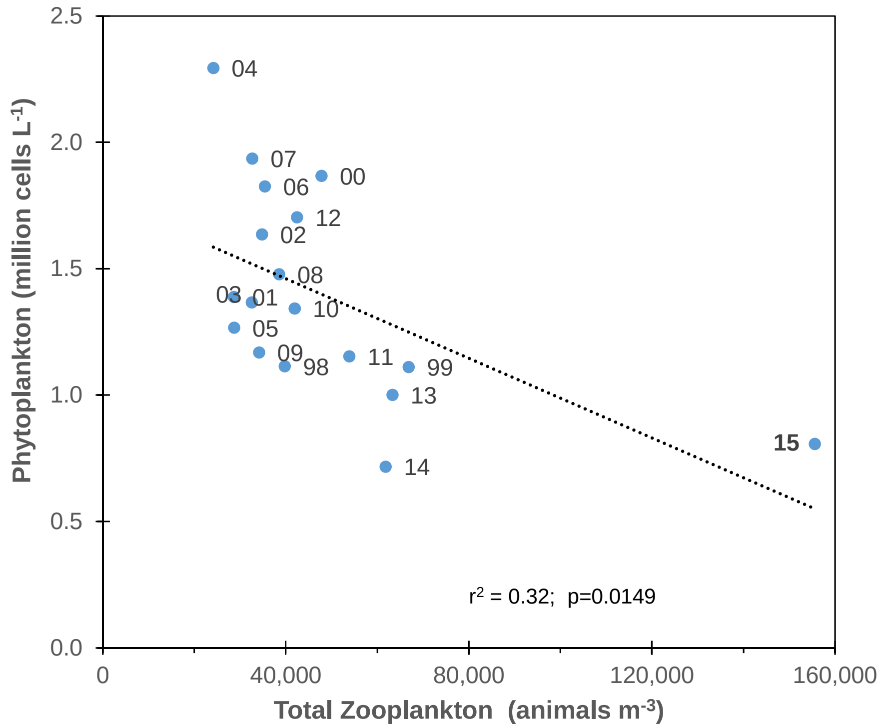


Figure 3-1. Long-term trend (1998 - 2015) in total phytoplankton from surface (light blue) and Cmax (green) depths in the nearfield derived from time series analysis. Data from stations N04 and N18. Data lines based on 15% smoothing window (~3.5 years) as recommended in Broekhuizen and McKenzie (1995) for examining seasonally variable data.

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 2015 (**Figure 3-3**). Total zooplankton abundance increased from 1992 to 2000, followed by a decline from 2001 to 2006-2008, followed by another sustained increase from 2009 to 2015. Interestingly, the trend for copepod abundances exhibited small oscillations about the long-term mean from 1992 to 2003, followed by a slight decline from 2003 to 2006, with a subsequent sustained increase from 2007-2015. Although copepod abundances were lower than total zooplankton abundances, as expected, the trends for the sustained increases in both total zooplankton and copepod trends paralleled each other from 2009-2015. The unprecedented summer explosion of bivalve veligers in 2015 was the sentinel zooplankton event for the year, and it caused a large upswing in the total zooplankton abundance trend for 2015, but the overall long-term trend in total zooplankton abundance appears to be driven mostly by the trend in copepod abundance.



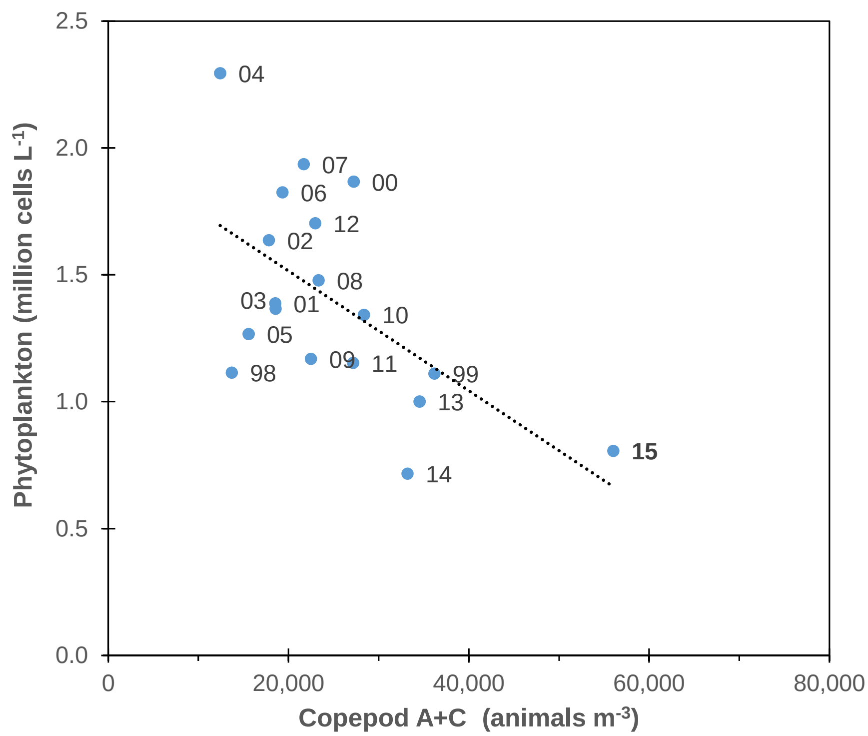


Figure 3-2. **Annual mean abundance (million cells L^{-1}) of total phytoplankton versus annual mean abundance (animals m^{-3}) of total zooplankton (top) and copepod A+C (bottom) at nearfield stations N04 and N18.** Numbers indicate year.

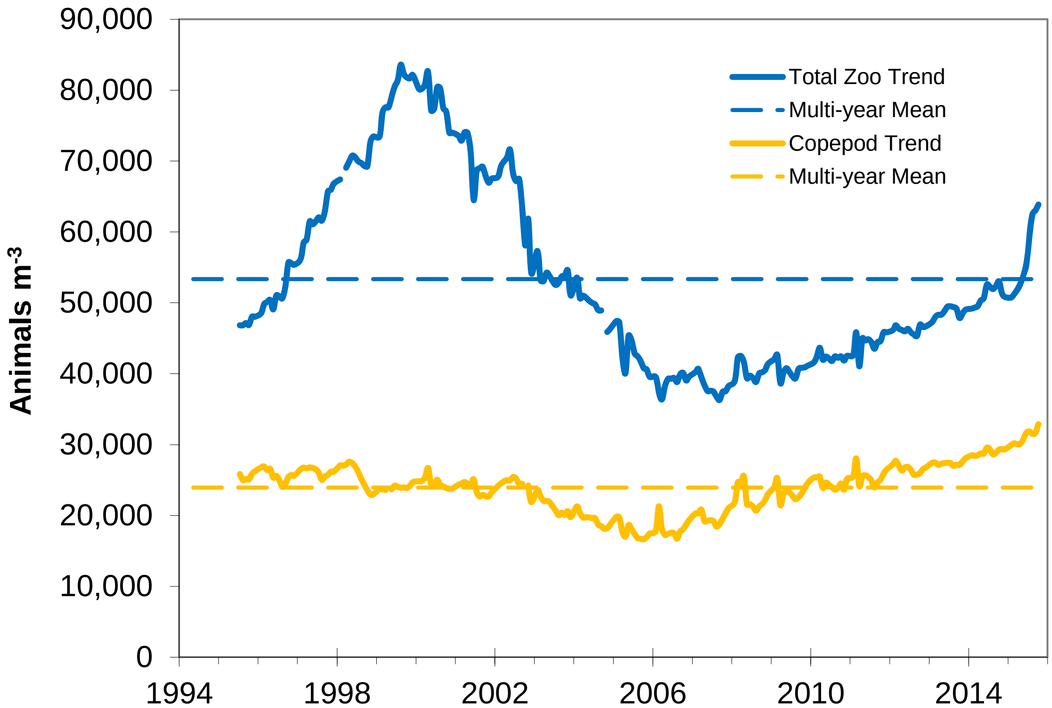
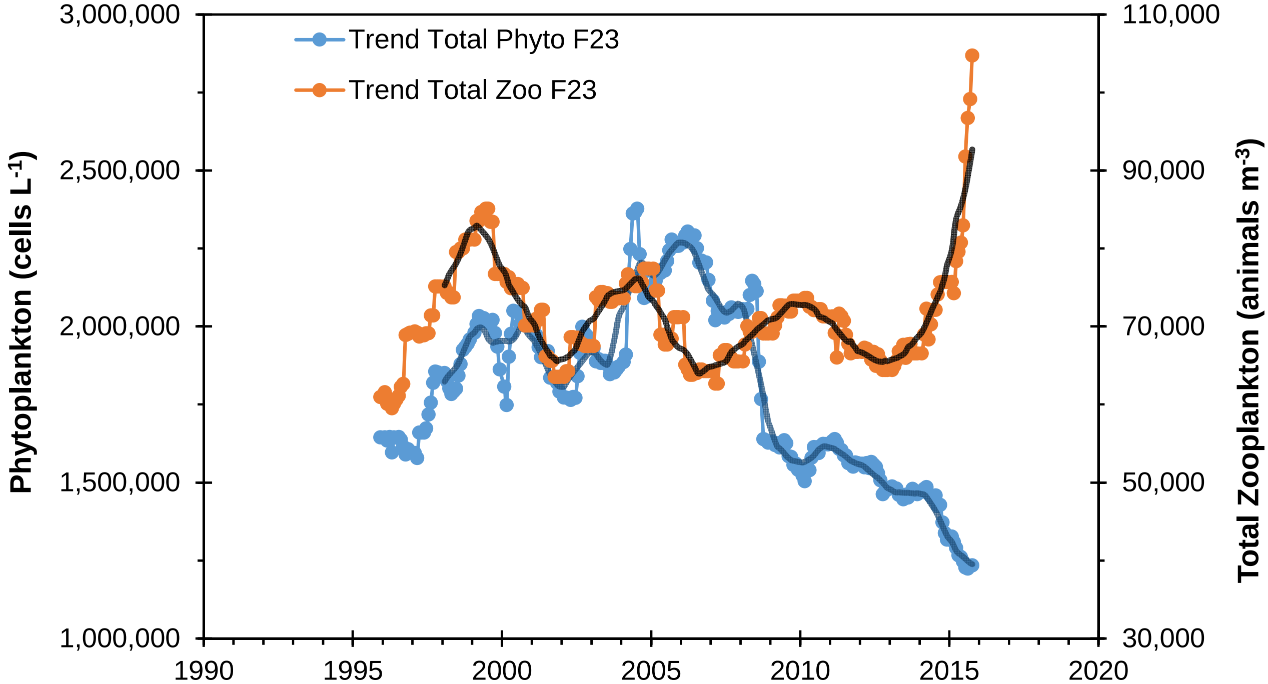


Figure 3-3. Long-term trend (1998 - 2015) in nearfield total zooplankton and copepod A+C abundance derived from time series analysis. Long-term mean levels also shown (dashed lines). Data from stations N04 and N18.

The levels of zooplankton in the nearfield have been above the long-term mean for the last few years. This has been commensurate with a decrease in nearfield total phytoplankton abundance. For 2015, the time series analyses were revisited for both Boston Harbor station F23 and the nearfield (**Figure 3-4** and **Figure 3-5**). These analyses confirm the increasing trend in both total zooplankton and copepods over the last few years have been commensurate with a decrease in total phytoplankton abundances in both areas. The very high total zooplankton abundances in 2015 were due to extraordinarily high abundances of bivalve veligers in July and August, but abundances of a wide variety of copepods also increased including adults and copepodites of *Pseudocalanus* spp., *Oithona similis*, and *Calanus finmarchicus*. The lower phytoplankton abundance was due to overall low abundances of many dominant species and the timing of surveys in 2015 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.

Over the last few years the region has entered a period in which relatively high zooplankton and low phytoplankton levels have been observed. As noted by Libby *et al.* (2015), the reasons for the long-term variability and changes in zooplankton abundance are unclear. The phytoplankton and zooplankton population trends in the nearfield appear to be generally inverse or out of phase with each other and suggest that grazing pressure is an important factor on the overall abundance of phytoplankton in the nearfield. Interestingly, in Boston Harbor, phytoplankton abundance tracked closely from 1992 to 2005 with total zooplankton and until 2012 with copepods. One could speculate that the difference between the early trends and similarity over the last few years between Boston Harbor and the nearfield may be related to harbor recovery due to effluent diversion and that zooplankton grazing is now more tightly coupled with phytoplankton abundance. The overall trends for both the 3.5 and 6 year smoothing windows are very similar, which suggests that the factors driving large changes in phytoplankton and zooplankton abundance mainly vary at longer-term (decadal) time scales.



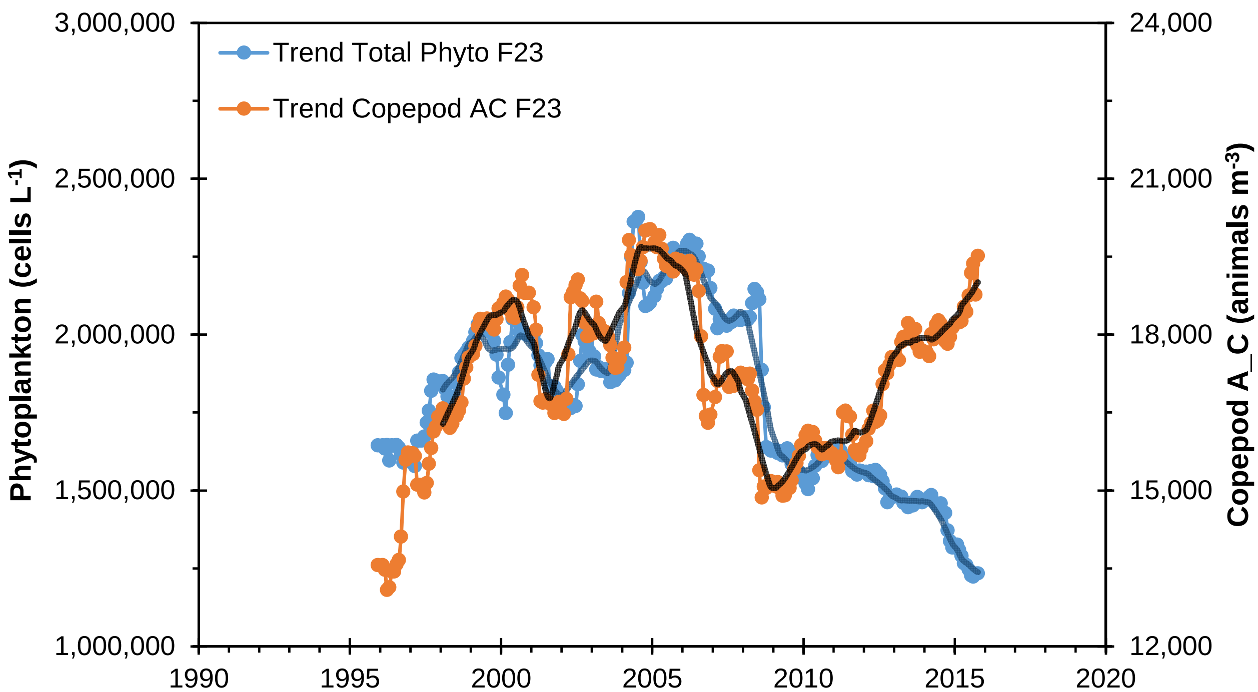


Figure 3-4. Long-term trend (1998-2015) in total phytoplankton, total zooplankton (top), and copepod A+C (bottom) abundance in Boston Harbor derived from time series analysis. Colored data lines based on 15% smoothing window (~3.5 years) and black or blue bold lines for 25% smoothing window (6 years). Data from station F23.

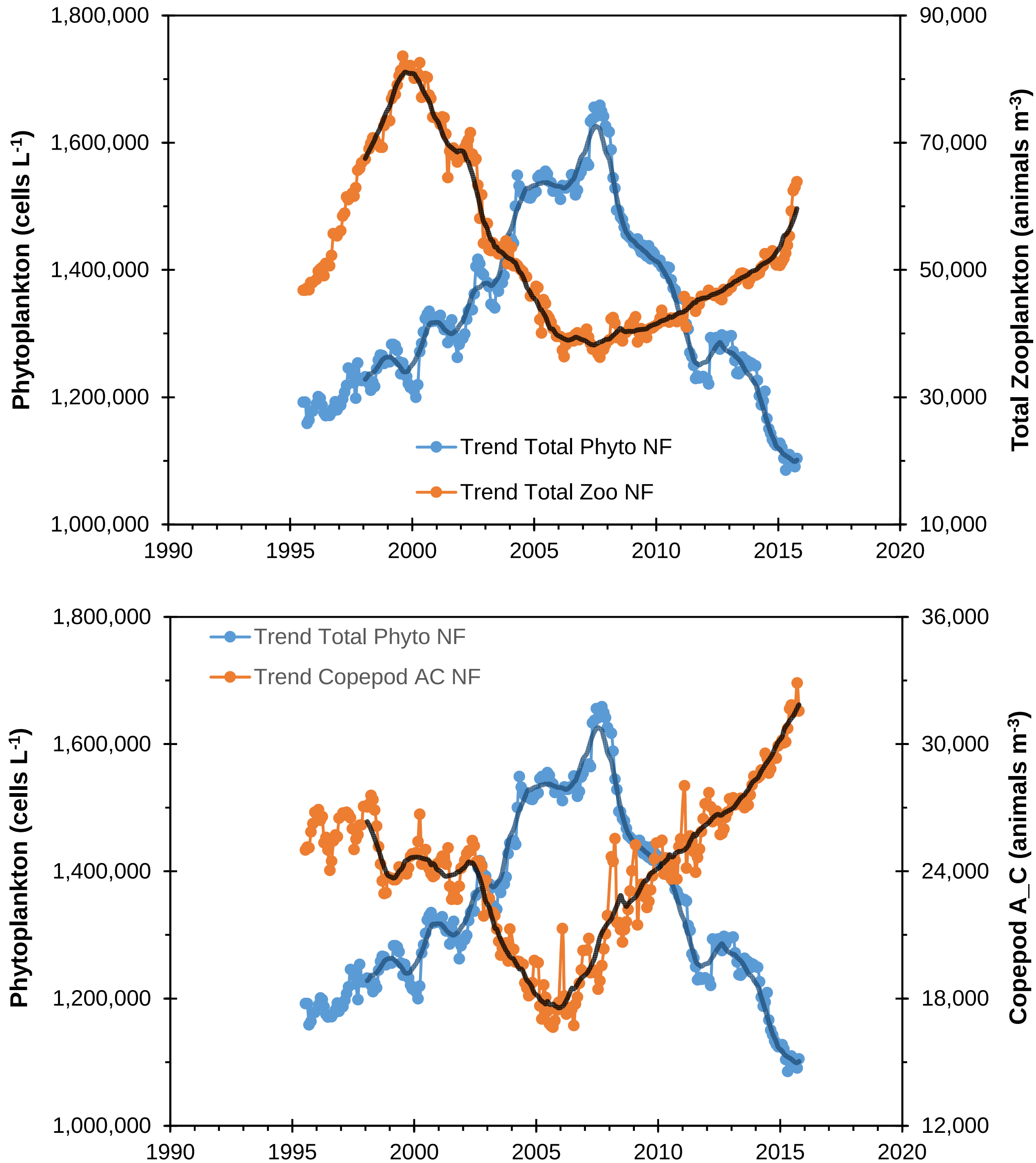


Figure 3-5. **Long-term trend (1998-2015) in total phytoplankton, total zooplankton (top), and copepod A+C (bottom) abundance in the nearfield derived from time series analysis.** Colored data lines based on 15% smoothing window (~3.5 years) and black or blue bold lines for 25% smoothing window (6 years). Data from stations N04 and N18.

4 SUMMARY

The most notable characteristics of the physical environment of Massachusetts and Cape Cod Bays in 2015 were the colder than normal temperatures (**Figures 2-1 and 2-3)** and winter storms (**Figure 2-2**) from February into April. The extended period of colder temperatures may have contributed to a delay in the development of the *Phaeocystis* and *Alexandrium* blooms in the region. The winter/spring storms kept the water column well mixed into April. The water column did not begin to stratify until late April, but by the May survey the water column was strongly stratified in the nearfield, about a month later than typically observed (**Figure 2-4**). A strong storm in early June mixed the surface layer down below 20 m at NERACOOS Mooring A01 (**Figure 2-5**). The summer of 2015 was a period of moderate upwelling favorable conditions. The annual fall overturn and remixing of the water column was observed in stages in the monitoring and buoy data. A strong storm in early October mixed the water column at the shallower, inshore stations and down to 50 m at Mooring A01. Increases in bottom water DO at shallow stations from September to October suggest they remained well mixed, while the water column re-stratified at the deeper stations and did not become fully mixed until November.

Similar to 2013 and 2014, winter satellite imagery (November 2014 to February 2015) showed relatively steady and slightly elevated chlorophyll concentrations over the winter (**Figure 2-10**). Combined with the relatively low nutrient concentrations (NO_3 and SiO_4) observed in February (**Figure 2-6**), this suggests that the system may have remained biologically productive through the winter. Again as during the previous two years, a winter/spring diatom "bloom" was not observed during the 2015 surveys (**Figure 2-11**). However, just as was observed in 2014, Mooring A01 and satellite observations indicate that chlorophyll fluorescence levels peaked between the April and May 2015 surveys (**Figure 2-12**). Nitrate levels had decreased sharply by May and were depleted across the bays, while there were increases in SiO_4 concentrations from April to May. This suggests that the elevated chlorophyll levels that were observed in the remote sensing datasets between the two survey was likely due to a regional *Phaeocystis* bloom as it primarily utilizes nitrogen (unlike diatoms that require silica and take it up proportionately to nitrogen).

Phaeocystis were present at very low abundances in May 2015 with only one sample with 13,000 cells L^{-1} observed in the nearfield, but this was high enough to lead to a summer contingency plan threshold exceedance for this nuisance species (**Figure 2-17**). This exceedance is due more to the calendar-based seasonal threshold computation, than an ecologically meaningful result. As was the case in 2014 (Libby *et al.* 2015), the cold waters observed in winter 2015 likely shifted the *Phaeocystis* bloom to occur in late April/early May, which is a month later than typically observed. The cold winter/spring 2015 conditions and a concomitant shift in the phytoplankton seasonal cycle may also have played a role in the lack of an *Alexandrium* bloom in Massachusetts and Cape Cod Bays in 2015 (**Figure 2-18**). A low to moderate bloom with elevated cell abundances and PSP toxicity was observed in western Gulf of Maine waters off of New Hampshire, but not until late May. This plus the lack of northeaster storms in May 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. The *Alexandrium* bloom had ended in the Gulf by the time the late northeaster storm occurred in early June. There were no PSP toxicity shellfishing closures in the bays in 2015, which is the third consecutive year without 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 2015. Although there were upwelling favorable conditions from June through September, summer chlorophyll concentrations and phytoplankton abundances remained low. The typical coastal water blooms of centric diatoms *Skeletonema* spp., *Dactyliosolen fragilissimus*, *Cerataulina pelagica* and others remained low compared to previous monitoring years (**Table 2-1**).

Chlorophyll and phytoplankton abundance remained low during the September survey, but had increased by the October survey in comparison to previous years. MODIS imagery showed elevated chlorophyll concentrations between these two fall surveys. A strong northeaster storm in early October mixed the water column down to 50 m at the mooring bringing nutrients into the surface layer to support this late centric diatom bloom. In both the winter/spring and fall of 2015, 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 August to October (**Figure 2-22**). The August and October monthly minima were moderate compared to historic ranges. The early October storm ventilated the bottom waters at shallower stations and DO concentrations increased from September to October across the nearfield. This mixing event was characterized by the temperature and DO measurements from Mooring A01, which indicated mixing to 50 m in early October (**Figures 2-24 and 2-25**). However, the water column re-stratified and mixing did not reach the near bottom waters at the mooring until November. Relative to previous years, the 2015 bottom water DO concentration minima were moderate. 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 2015 ranked 21st lowest out of the 24 years of observations and relatively low abundances were observed for most major phytoplankton functional groups (**Table 2-1**). As noted, the timing of the surveys missed the winter/spring and fall blooms in Massachusetts Bay in 2015, which contributed to the lower abundance measurements. Another important factor was likely grazing pressure as 2015 total zooplankton abundances were very high in comparison to previous years. This was primarily due to unprecedented summer abundances of bivalve veligers, which was the sentinel zooplankton event of 2015. However, abundances of copepods were also near or above maxima observed during the monitoring program. The high zooplankton abundance in 2015 continues a long-term trend of increasing abundances since 2005 (**Figure 3-3**). There is a significant negative correlation between total phytoplankton abundance and both total zooplankton and copepod abundance in the nearfield (**Figure 3-5**). The correlation at Boston Harbor station was not significant. Prior to the mid-2000s, phytoplankton and zooplankton appeared to co-vary in the harbor, but now appear to be inversely correlated similar to the nearfield (**Figure 3-4**). Perhaps Boston Harbor plankton dynamics are shifting in response to cleanup efforts and diversion of effluent to the bay. The long-term (decadal) shifts in phytoplankton and zooplankton occur over large spatial scales; such broad patterns appear instead to be related to regional ecosystem dynamics in the Gulf of Maine.

As has been the case since operation of the bay outfall began in 2000, the bay outfall effluent plume was observed as elevated NH_4 concentrations in the nearfield. 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).

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