2016 Water Column Monitoring Results

Massachusetts Water Resources Authority
Environmental Quality Department
Report 2017-11

Citation

Libby PS, Borkman DG, Geyer WR, Turner JT, Costa AS, Wang J, Codiga D, Taylor D. 2017**. 2016 Water column monitoring results**. Boston: Massachusetts Water Resources Authority. Report 2017-11. 56 p.

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Submitted to

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

Prepared by

P. Scott Libby[1]
David Borkman[2]
Rocky Geyer[3]
Jeff Turner[4]
Amy Costa[5]
Jianjun Wang[6]
Dan Codiga[6]
David Taylor[6]

[1]Battelle
157 Park Row
Brunswick, ME 04011

[2]University of Rhode Island
Narragansett, RI 02882

[3]Woods Hole Oceanographic Institution
Woods Hole, MA 02543

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

[5]Center for Coastal Studies
Provincetown, MA 02657

[6]Massachusetts Water Resources Authority
Boston, MA 02129

November 2017

Report No. 2017-11

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 2016. 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 2016 was the summer *Phaeocystis pouchetii* nuisance species Caution Level threshold. *Phaeocystis* at very low abundance in a single May 2016 sample (36,000 cells L^{-1}) was responsible for the exceedance. Although the threshold was exceeded, there was no associated ecological impact. In 2016 MWRA requested *Phaeocystis* seasonal means be dropped from the Contingency Plan Thresholds, and the Outfall Monitoring Science Advisory Panel (OMSAP) agreed and recommended EPA accept this interim change (October 27, 2016). EPA approved the interim request and it is anticipated it will become final by November 15, 2017.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2016
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: 7.12 SW Basin: 6.33
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 83.9% SW Basin: 70.5%
Bottom water DO rate of decline (mgL^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.019
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	87
	Winter/spring	>199	--	50	89
	Summer	>89	--	51	85
	Autumn	>239	--	90	89
Phaeocystis pouchetii (nearfield mean, cells L^{-1})	Winter/spring	>2,860,000	--	622,000	6,790
	Summer	>357	--	79	1,120
	Autumn	>2,960	--	370	Absent
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	Absent
	Summer	>43,100	--	14,635	954
	Autumn	>27,500	--	10,500	3,310
Alexandrium fundyense (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	15

[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 2016 water column monitoring demonstrated that the treated wastewater discharge from the bay outfall only influenced the local area within 10 to 20 km, nearly exclusively as increased ammonium concentrations, as in previous years and as consistent with earlier predictions from calibrated eutrophication-hydrodynamic models. Noteworthy observations made in the bays during 2016 included:

- 2016 was warmer than normal and unusually dry. The Merrimack and Charles Rivers had the lowest flows for the 25-year monitoring program. Annual total precipitation in the Boston area was the 3rd lowest since 1990 and follows 2015, which was the 4th lowest. The extended duration of low precipitation resulted in severe to extreme drought conditions over nearly 80% of Massachusetts by the end of August 2016 including the greater Boston area.
- The onset of stratification in spring occurred later than in a typical year, due to the low river flow plus mixing by strong May winds. The fall breakdown of stratification occurred earlier than a typical year in the upper water column, and later at depth, also the result of storm event timing.
- 2016 was the fifth 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.
- Ammonium (NH_4) concentrations were typical and within the range of values observed post-diversion – lower in Boston Harbor and higher in the outfall nearfield compared to baseline. There was no discernable change in nearfield NH_4 levels despite the effluent nitrogen load in 2016, primarily in the form of NH_4, being the highest observed since outfall start-up in September 2000.
- No large winter/spring bloom was apparent on the 2016 survey dates; however, satellite observations indicated chlorophyll fluorescence levels peaked between surveys in April to mid-May. Continuous chlorophyll sampling by fluorometer at NERACOOS Buoy A01 off Cape Ann cannot corroborate this, due to a sampling gap from mid-April through early July, but a large decrease in nitrate concentrations with concomitant slight increase in silicate concentrations suggests *Phaeocystis* may have contributed to the April to mid-May bloom shown by the satellite imagery.
- Elevated *Alexandrium* abundances were observed in Massachusetts Bay just south of Cape Ann in May triggering *Alexandrium* Rapid Response Study surveys. Paralytic Shellfish Poison toxicity had earlier been noted in Western Maine, New Hampshire, and north of Cape Ann, but the 2016 bloom event was minor and short lived. The *Alexandrium* threshold of 100 cells L^{-1} for outfall nearfield stations was not exceeded.
- Summer chlorophyll levels were relatively high in the nearfield in comparison to the past 25 years. At many of the Massachusetts Bay stations, chlorophyll concentrations fell within the upper range seen previously, but phytoplankton abundance was lower. Satellite imagery and buoy data indicated moderate chlorophyll concentrations occurred in September extending into the fall.
- In October 2016, a bloom of toxigenic *Pseudo-nitzschia* caused shellfish harvest closures in Maine, southern Massachusetts (Buzzards Bay and south side of Cape Cod) and Rhode Island waters. However, *Pseudo-nitzschia* spp. levels in Massachusetts Bay during 2016 were not high and were orders of magnitude lower than the maximum prior abundance, which was 1.8 million cells L^{-1} observed in 1998.
- Bottom water dissolved oxygen (DO) concentration minima were relatively low in 2016, but did not exceed Contingency Plan thresholds. Bottom water DO levels would have been lower if not for a late May mixing event and September storm/winds which led to an earlier breakdown of stratification at all but the deepest stations in Massachusetts Bay.

- The 2016 annual total phytoplankton abundance was the 22nd lowest recorded over the 25-year monitoring program. The abundances of most major phytoplankton functional groups were relatively low. The lack of a winter/spring diatom bloom, no observed *Phaeocystis* bloom and no fall blooms contributed to the low abundances.
- The abundances of total zooplankton and many dominant taxa were at or above maxima for the 25-year monitoring program at many of the stations in Massachusetts Bay in February to June. The warm temperatures observed in winter/spring 2016 may have contributed.
- 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. Phytoplankton and zooplankton population trends in the nearfield appear to be inversely correlated with each other suggesting grazing pressure is an important factor on the overall abundance of phytoplankton in Massachusetts Bay. In Boston Harbor, phytoplankton and copepod abundance tracked closely from 1992 to 2008, but since 2009, they have been inversely correlated. This change may be related to harbor recovery.

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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 for the outfall discharge periods since the 2000 relocation (MWRA 2004, 2010). The 'baseline' period extends from 1992 to August 2000, the period when Deer Island and/or Nut Island wastewater discharges were directed to the harbor. The outfall discharge period extends from September 2000 through 2016 and encompasses the period wastewater has been discharged from the bay outfall. The 2016 data complete 16 years of monitoring since operation of the bay outfall began on September 6, 2000 and 25 years of monitoring since the program began in 1992. **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 2016 (**Table 1-2**). The nine surveys were designed to provide a synoptic assessment of water quality conditions. The Center for Coastal Studies (CCS) in Provincetown monitors Cape Cod Bay in the same timeframe maximizing spatial coverage. This annual report summarizes the 2016 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 variations 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 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, marine mammal observations, 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 has been obtained by export 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 during each of the nine surveys per year; the 2016 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, including plankton at all stations except N21 directly over the outfall. 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. Nutrient data from these three Cape Cod Bay stations are included in this report. CCS also has an ongoing water quality monitoring program at eight other stations in Cape Cod Bay.[2] MWRA collects samples at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally biweekly frequency.[3] The BHWQM data (nutrient and dissolved oxygen [DO]) collected within 7 days of an AMP survey are included in this report. There were two *Alexandrium* Rapid Response Study (ARRS) surveys in 2016; those dates are in **Table 1-2**. Marine mammal observers were present on all regular bay water quality surveys (i.e., excluding ARRS and BHWQM) in Massachusetts Bay during 2016. Observations made by field staff on the ARRS and BHWQM surveys were documented and are included in this report.

Table 1-2. Water column surveys for 2016.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN161	February 12	February 10	--
WN162	March 23	March 23	March 23
WN163	April 18	April 18	April 25
WN164	May 18	May 19	May 18
AF161	May 25	--	--
AF162	June 1	--	--
WN165	June 21	June 22	June 16
WN166	July 26	July 26	July 25
WN167	August 23	August 23	August 25
WN168	October 3	September 26	October 5
WN169	November 1	November 1	--

[2] CCS station map and data available at http://www.capecodbay-monitor.org/
[3] BHWQM station map available at http://www.mwra.state.ma.us/harbor/graphic/bostonharbor_850.gif

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) Buoy A01. The satellite imagery provides information on regional-scale patterns, while the buoys 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 Buoy A01 is in the northwestern corner of Stellwagen Bank National Marine Sanctuary and ~5 km northeast of 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 three four-month periods: winter/spring is 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 2016.[4]

[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.

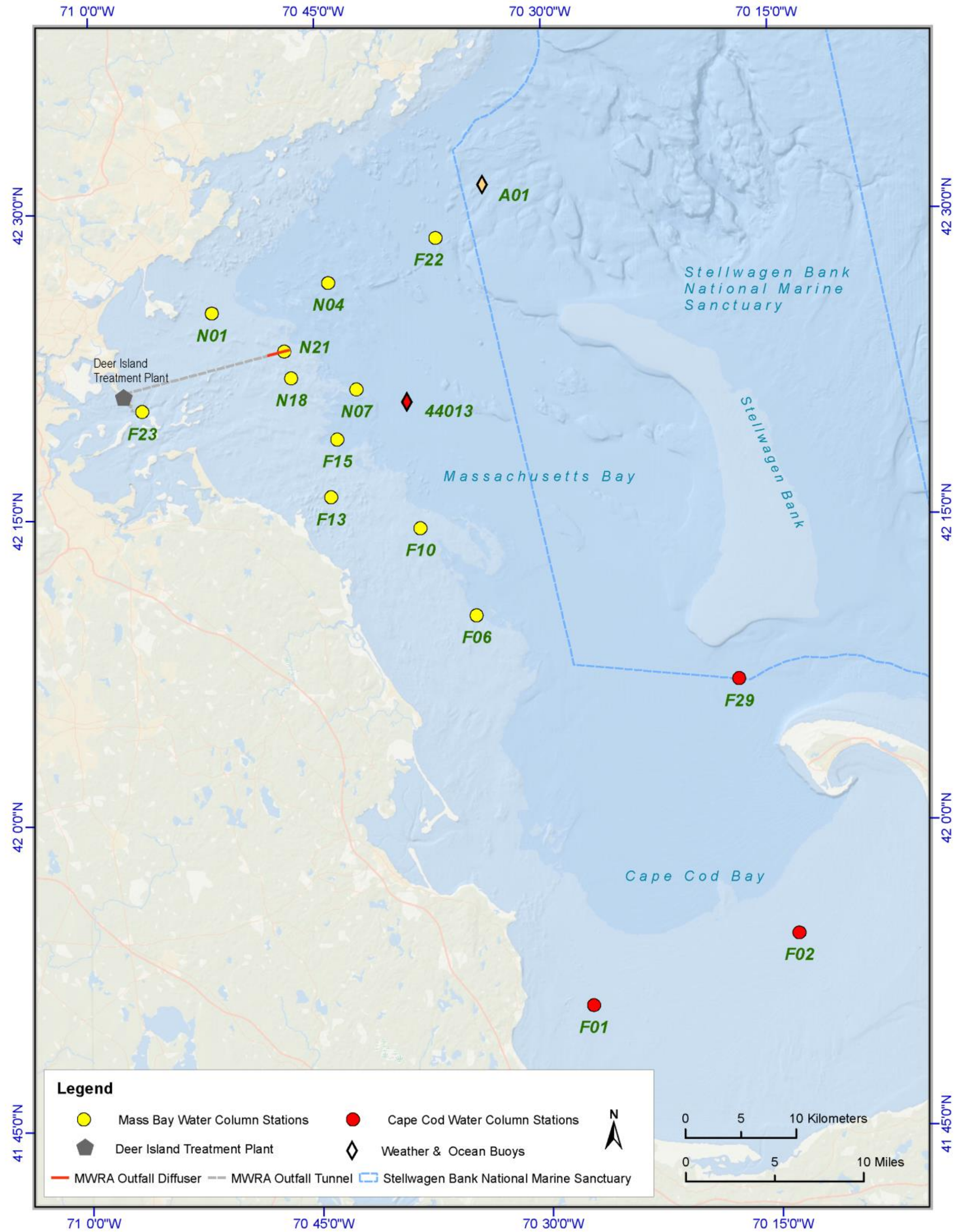


Figure 1-1. Water column monitoring locations.

2 2016 MONITORING RESULTS

2.1 BACKGROUND

The Massachusetts Bay ecosystem exhibits a seasonal cycle during which the system's physical structure, biology, and biogeochemical cycling change. External processes (meteorological and river forcing) and ecological changes have important influences on the seasonal pattern. Details of the cycle can differ across specific areas of the bay system.

During winters, when the water column is vertically well mixed, and light intensities are 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 (e.g., *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*, 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 often has a characteristic vertical structure with mid-depth maximum at or near the pycnocline about 15-25 m deep, where cells have access to both adequate light and nutrients; dissolved oxygen (DO) concentrations have similar mid-depth maximum as influenced by phytoplankton production. 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 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 DO concentrations, which are typically relatively high year-round, 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 25-year dataset (1992-2016). The major features and differences in 2016 are presented below.

2.2 PHYSICAL CONDITIONS

From January through March, observations at the NDBC Buoy 44013 indicated that surface water temperatures were near the long-term maxima (**Figure 2-1**). This was also the case at nearfield station N18 where surface water temperature in February was the highest observed over the monitoring program and remained above the long-term mean through March and April (**Figure 2-2**). Bottom water temperatures were also elevated compared to historic observations at station N18. The warmer waters in early 2016 were consistently observed at stations across Massachusetts Bay. During winter-spring surface water salinity was close to the long-term mean. Merrimack River flow was above average in January-March, while flow in the Charles River was well below average (**Figure 2-3**). The combination of low freshwater inputs and mixing due to strong winds in April and early May resulted in a delay in the onset of stratification in the bay until late May (**Figure 2-4** and **Figure 2-5**).

For the remainder of 2016, river flows were significantly lower and the annual flow for both rivers was the lowest observed over the 25-year monitoring program. Precipitation in Boston was close to normal for the winter/spring, but from June through September fell off sharply and remained well below normal for the year (**Figure 2-6**). Overall, precipitation in the Boston area was the 3rd lowest annual total since 1990; the 4th lowest was 2015. By the end of August 2016, nearly 80% of Massachusetts was under severe (55%) to extreme (23%) drought conditions[5]. The extreme drought conditions were primarily located within and near the greater Boston area.

The low freshwater flows into the system are reflected in the high salinity values observed in both the surface and bottom waters at station N18 where salinity was near or above the long-term maxima from June to November (**Figure 2-2**). Surface and bottom water temperatures at station N18 were also at or near maxima over the summer and fall of 2016. At the NDBC Buoy 44013, some strong cooling events were apparent in June and July in the higher resolution data, which were likely due to a combination of mixing and upwelling. Consistent with the observations at station N18, surface water temperatures at the buoy from late July through the end of the year were unusually warm (**Figure 2-1**).

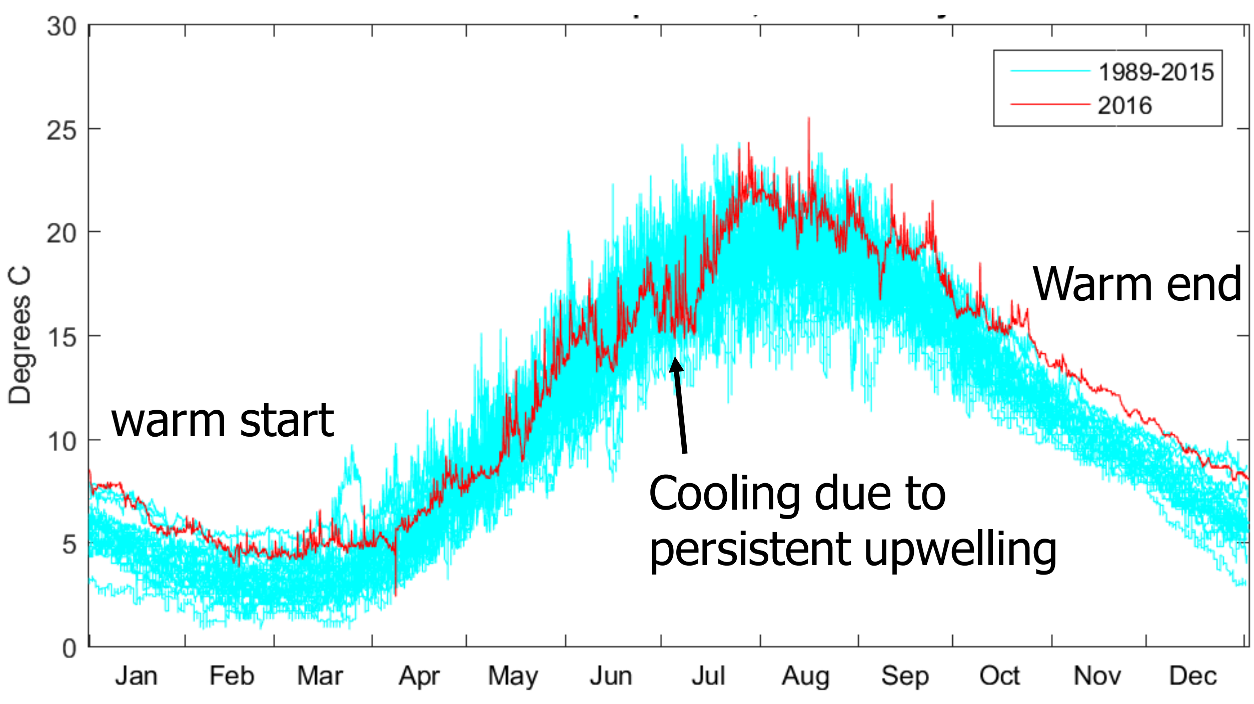


Figure 2-1. Comparison of 2016 surface water temperature (°C) at NDBC Buoy 44013 ("Boston Buoy") in the vicinity of the nearfield (solid red line) with 1989-2015 (light blue lines).

[5] http://www.masslive.com/news/index.ssf/2016/09/drought_conditions_in_massachu.html

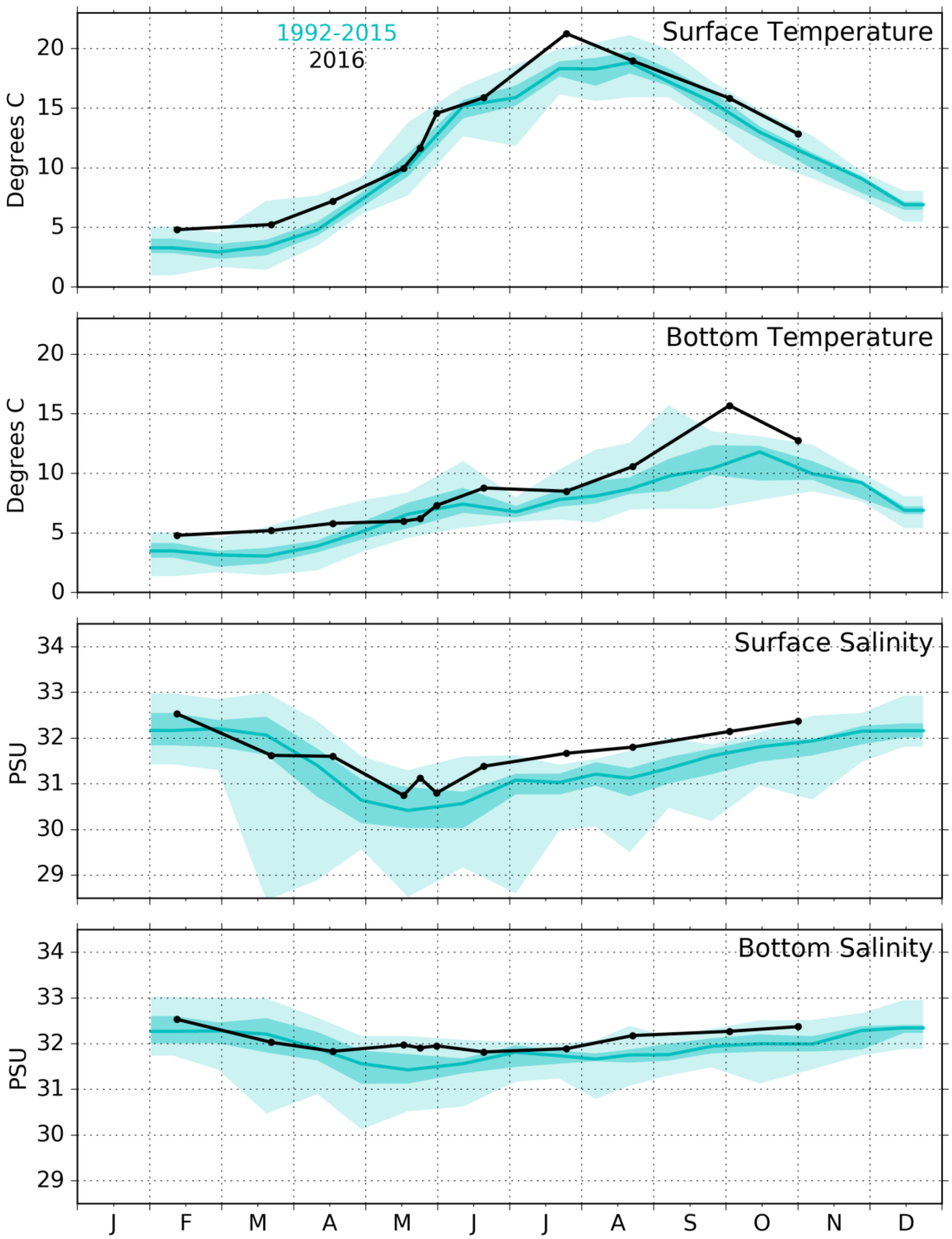


Figure 2-2. Comparison of 2016 surface and bottom water temperature (°C) and salinity (PSU) at nearfield station N18 compared to prior years. 2016 results are in black. Results from 1992–2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

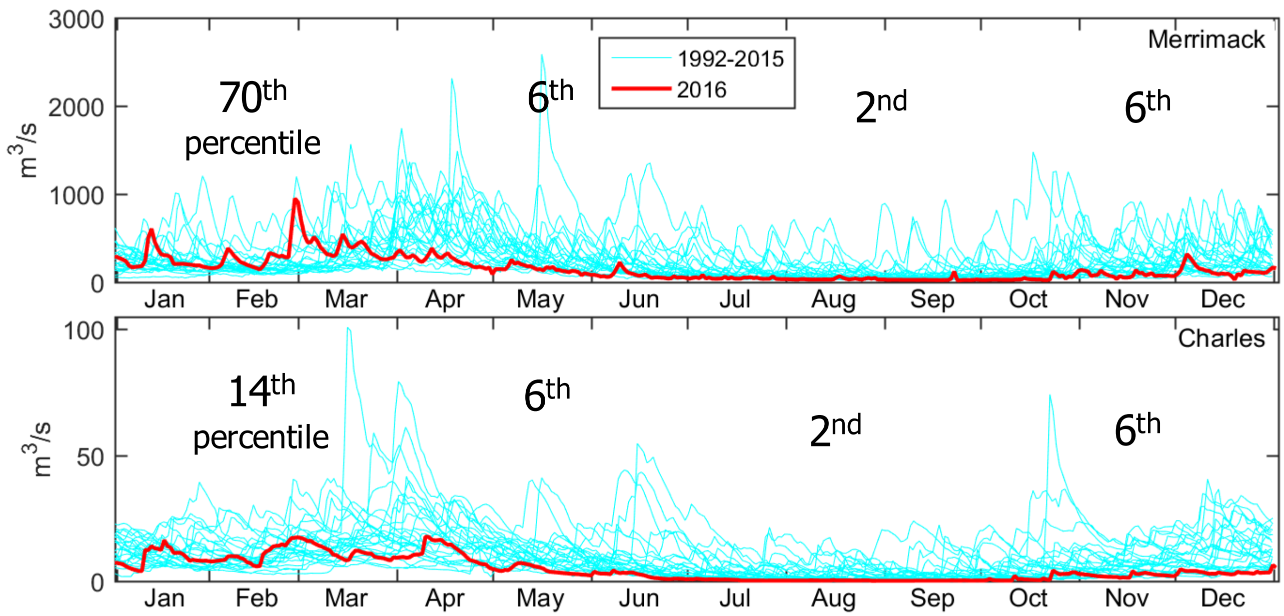


Figure 2-3. **Comparison of 2016 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2015 (light blue lines).** The percentiles listed represent 2016 flow, compared to the entire 25-year record, during each quarter of the year.

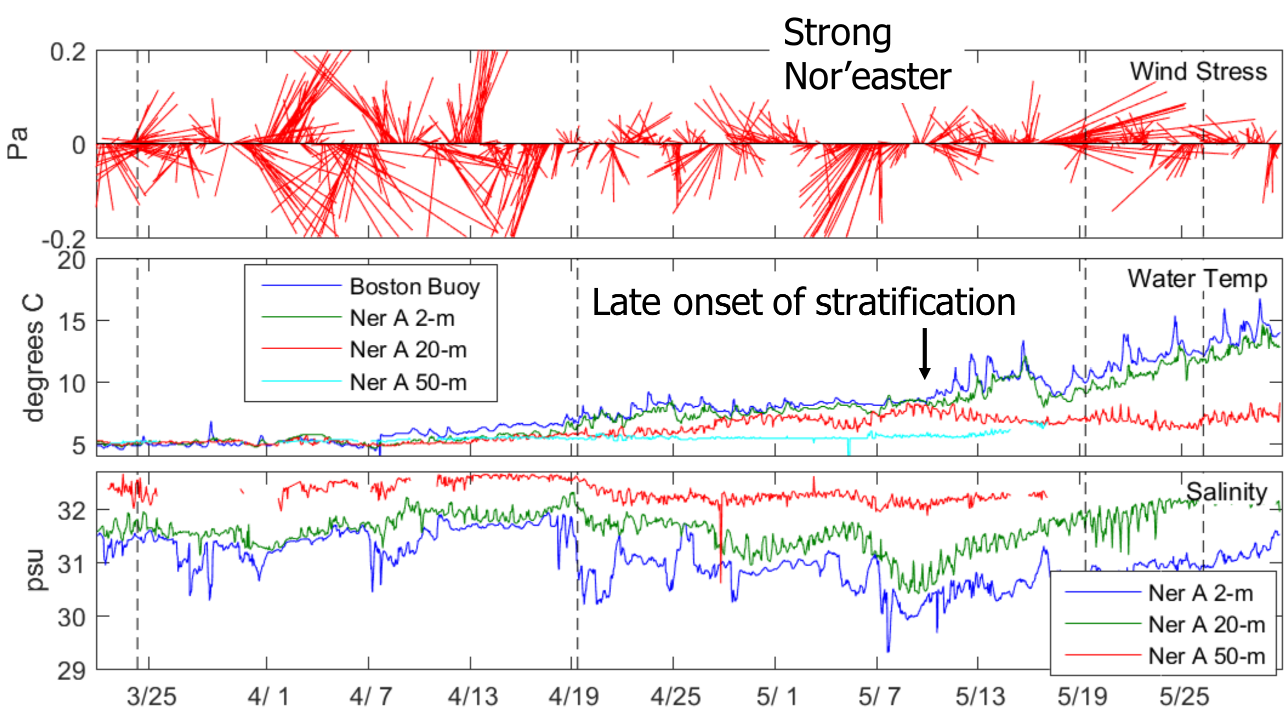


Figure 2-4. **NERACOOS Buoy A01 time series observations in spring 2016.** Top: surface wind strength and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: water temperature at 2, 20 and 50 m depths [NDBC Buoy 44013 ("Boston Buoy") surface temperature superimposed]. Bottom: salinity at 2, 20 and 50 m depths.

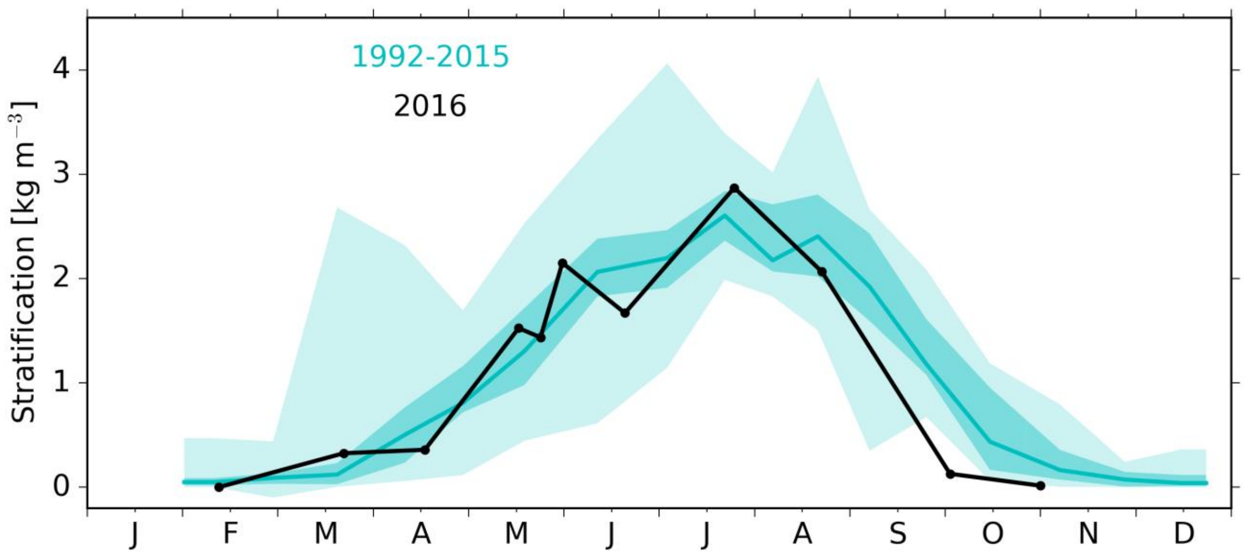


Figure 2-5. Stratification at nearfield station N18 in Massachusetts Bays in 2016 compared to prior years. 2016 results are in black. Results from 1992–2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

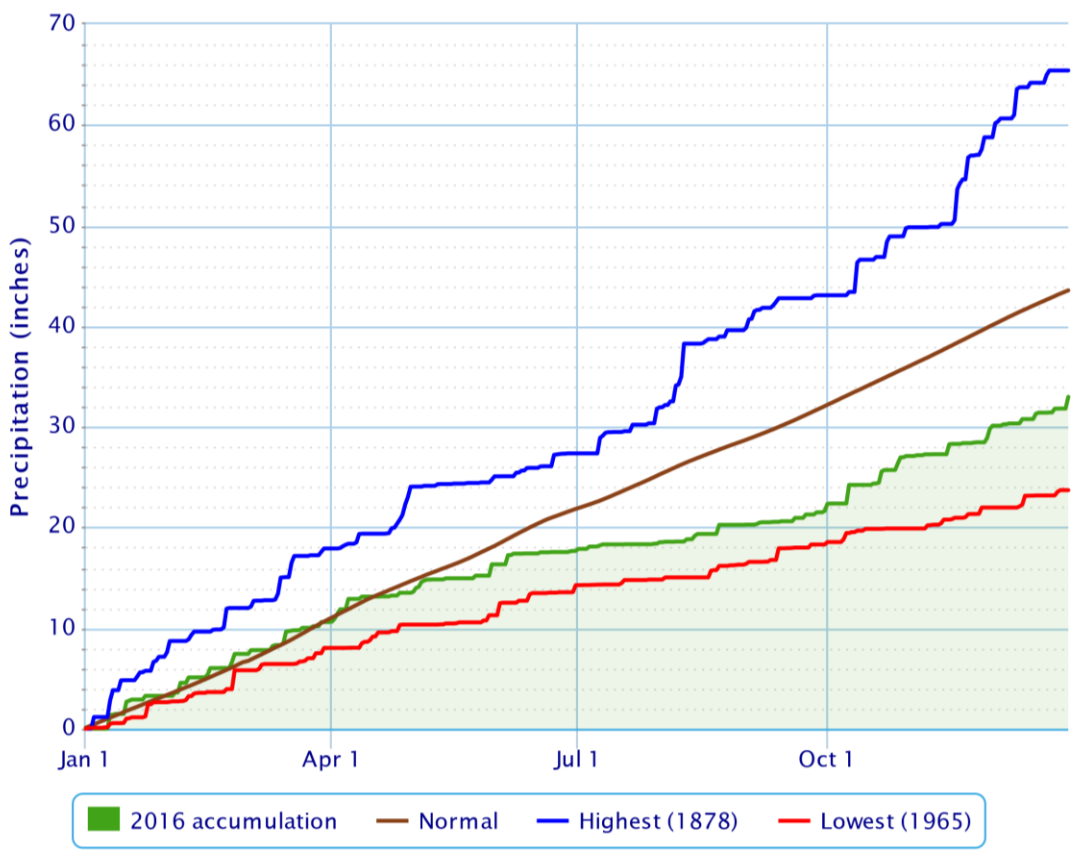


Figure 2-6. Cumulative precipitation in the Boston area in 2016 compared to historic min, max and normal levels. Data and plot obtained from NOAA National Weather Service website – **http://w2.weather.gov/climate/xmacis.php?wfo=box**.

Overall, winds showed a normal pattern of downwelling in the winter and spring months, upwelling in the summer, and downwelling in the fall (**Figure 2-7**). Strong and persistent winds led to particularly strong downwelling and mixing in September and October 2016 and to early mixing in the shallower waters of Massachusetts Bay. The water column at station N18 was well-mixed by the early October survey (**Figure 2-5**), due to mixing from a strong wind event that started in late September. The winds and water properties at NERACOOS Buoy A01 during the fall (**Figure 2-8**) indicate that destratification to 20 m depth (red line on 2nd panel) occurred in conjunction with the late September Northeaster, but the mixing did not extend to 50 m until late October (light blue and magenta lines).

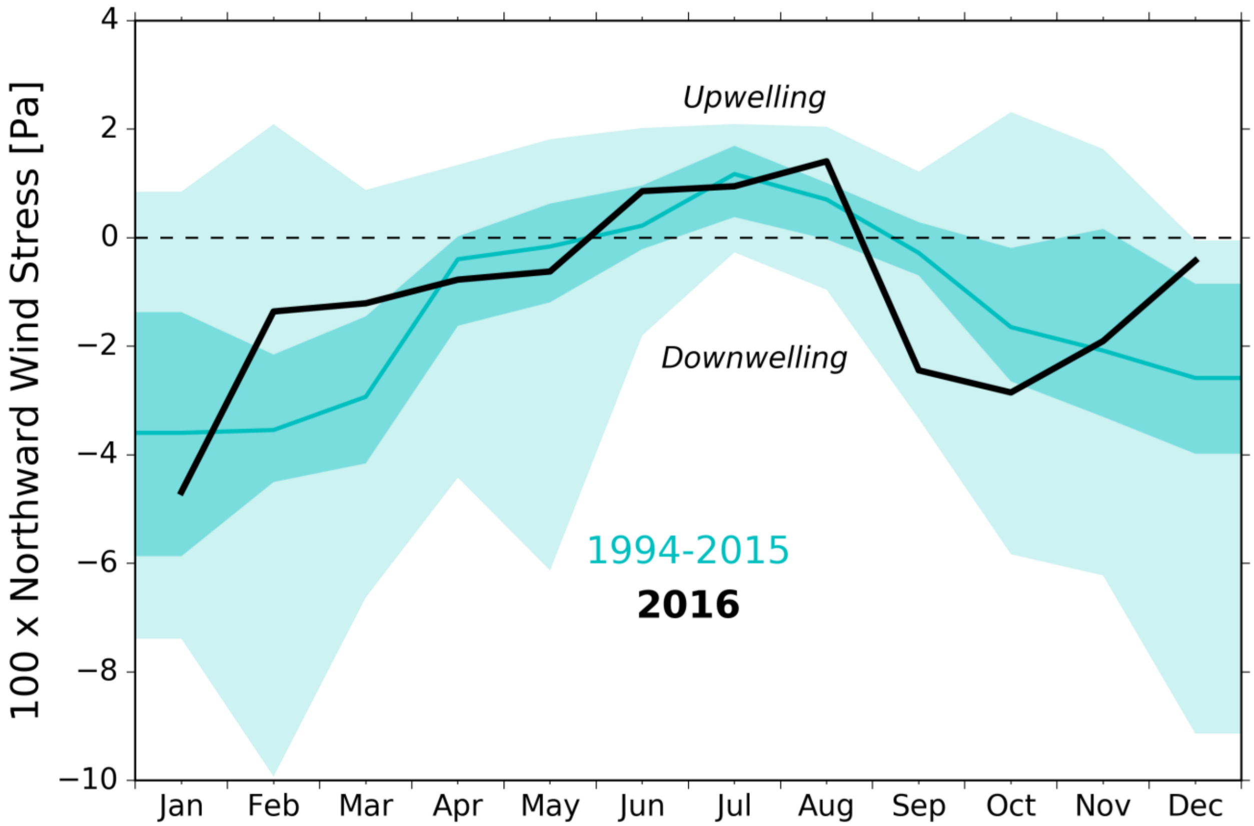


Figure 2-7. Average wind stress at NDBC Buoy 44013. 2016 results are in black. Results from 1992–2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

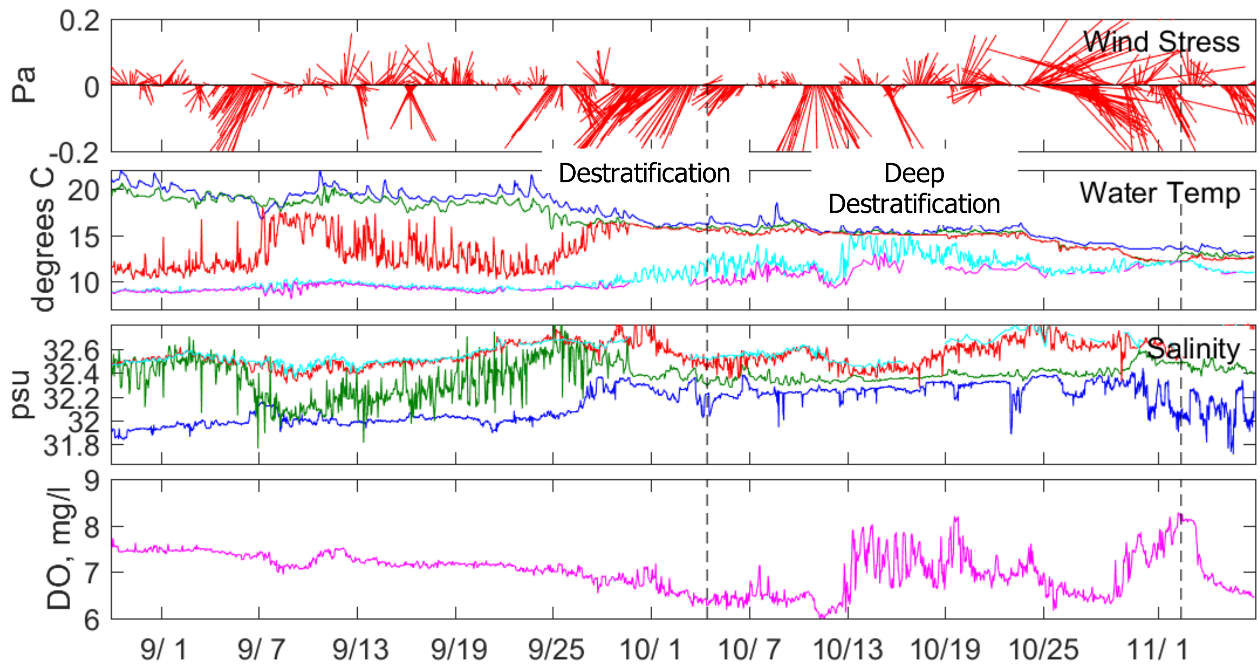


Figure 2-8. NERACOOS Buoy A01 time series observations in fall 2016. Top: surface wind strength and direction (northward up and eastward to the right). Second: water temperature at 2, 20, 50 and 52 m depths [NDBC Buoy 44013 ("Boston Buoy") surface temperature superposed]. Third: salinity at 2, 20, 50 and 52 m depths. Bottom: DO at 52-m depth. Color codes same as Figure 2-4 with 52-m temperature in fuchsia and 52-m salinity in light blue.

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

2.3.1 Nutrients

During most years, at station N18 located 1 km south of the outfall, and over much of Massachusetts and Cape Cod Bay, dissolved inorganic nutrient concentrations show a seasonal pattern, with naturally elevated nitrate (NO_3), silicate (SiO_4) and phosphate (PO_4) concentrations from February into April, relatively low concentrations into August or September, and then increases into November-December (**Figure 2-9**). These patterns are best shown by the dark shaded areas denoting the 25th to 75th percentile range in figures such as this. Ammonium (NH_4) concentrations, because of this station's proximity to the outfall, are more variable and typically do not show the seasonal pattern shown by the other three nutrients.

In winter/spring 2016, the dissolved inorganic nutrient concentrations at station N18 followed their historic seasonal patterns, except for silicate concentrations, which from February through April were low compared to previous years (**Figure 2-9**). The low SiO_4 concentrations during the early February survey suggest that diatoms, which require SiO_4 for growth, were likely dominant during the prior winter months. From February to May, NO_3 levels decreased and were nearly depleted in May. There was little change in SiO_4 over this period. MODIS imagery showed high chlorophyll levels during the period between the April and May survey (see **Figure 2-18**). The relative changes in NO_3 and SiO_4 concentrations and the high chlorophyll levels suggest that a *Phaeocystis* bloom (or mixed assemblage of diatoms and *Phaeocystis*) may have occurred during this period.

From May through September, surface water NO_3 concentrations remained depleted throughout the bays (**Figure 2-10**). The low surface nutrient levels were due to a combination of stratification and consistent biological utilization during the summer. Bottom water nutrient levels increased over this period due to remineralization and physical transport of high-nutrient deep water in to the bay. There were episodic increases in NO_3 and SiO_4 concentrations at mid and bottom depths at some stations in July and August that are consistent with upwelling (**Figure 2-9**), for which meteorological conditions were favorable in summer 2016 (see **Figure 2-7**).

In the nearfield and to the south at station F15, episodic peaks in NH_4 were observed over the summer period that are attributable to the time-varying spatial distribution of the MWRA effluent input to the system through the outfall (**Figure 2-11** and **Figure 2-12**). These peaks in nearfield NH_4 concentrations have been a consistent feature since the bay outfall began operating. Since September 2000, there has been a clear decrease in NH_4 concentrations at Boston Harbor station F23 and an increase at nearfield stations N18 and N21 (**Figure 2-12**). This continued to be the case in 2016 with all depth-averaged NH_4 concentrations at station F23 below baseline levels, while at stations N18 and N21, depth-averaged NH_4 levels were greater than baseline for most 2016 surveys. The NH_4 levels at these nearfield stations were within the range of values observed post-diversion for all except the high concentration observed at station N21 in March 2016. This is of note, because effluent nitrogen loads in 2016 were the highest observed since outfall start-up in September 2000 (Werme et al. 2017), yet there was no discernable change to NH_4 concentrations in the outfall nearfield. Overall, summer and fall nutrient concentrations were like those observed since the bay outfall became operational.

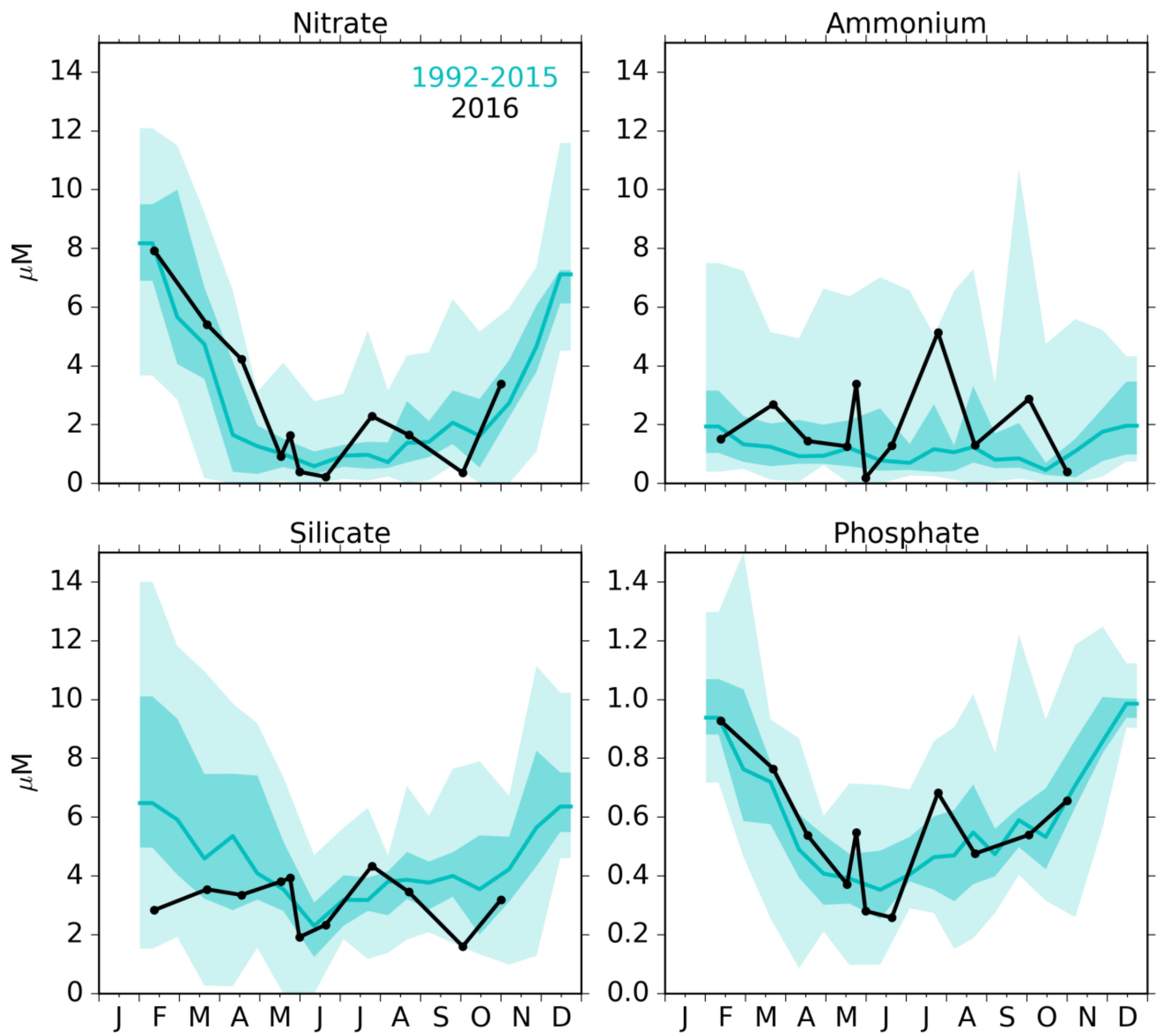


Figure 2-9. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2016 compared to prior years. Note difference in scale for phosphate. 2016 results are in black. Results from 1992–2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

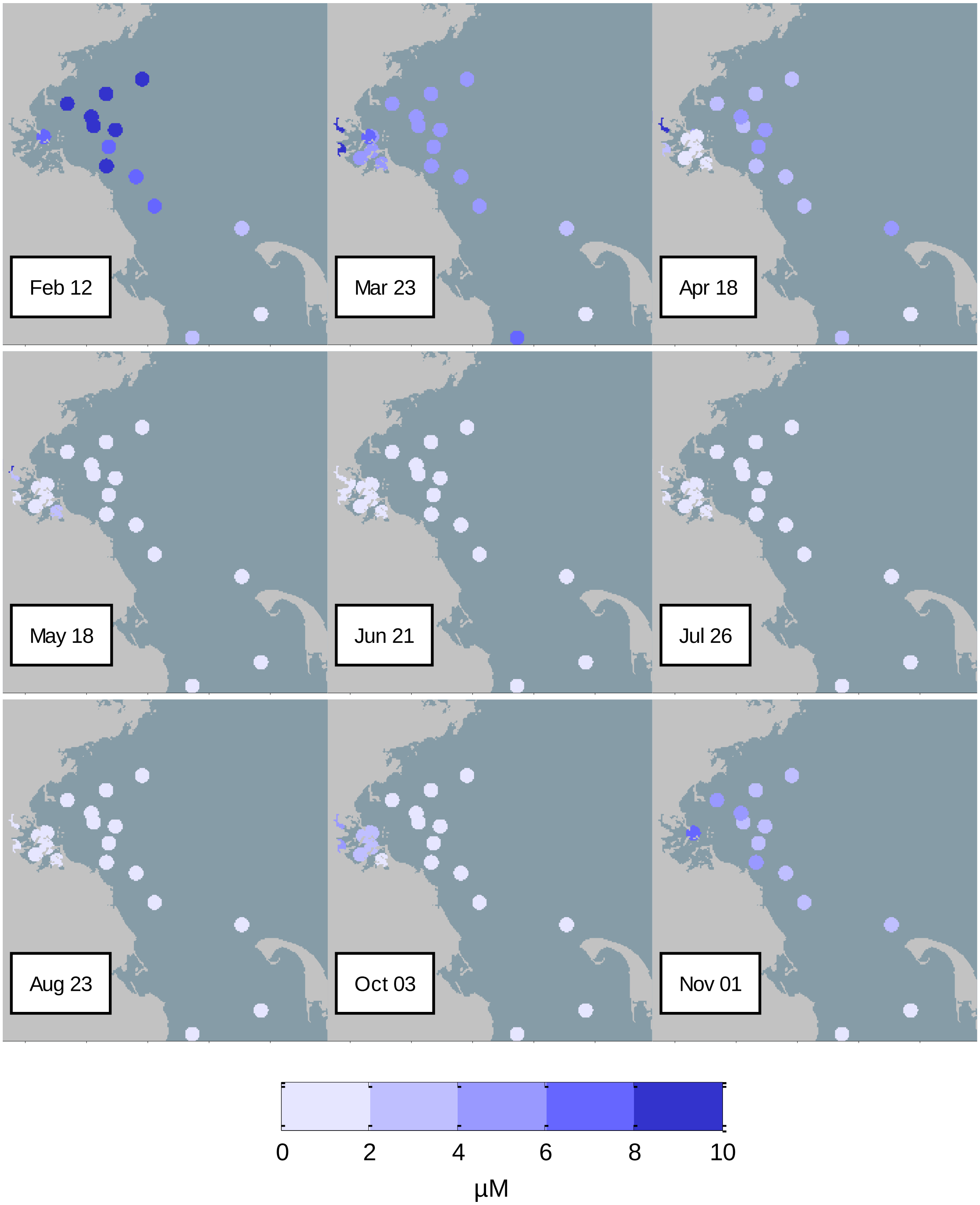


Figure 2-10. Surface NO_3 concentrations (µM) at stations in Massachusetts and Cape Cod Bays in 2016.

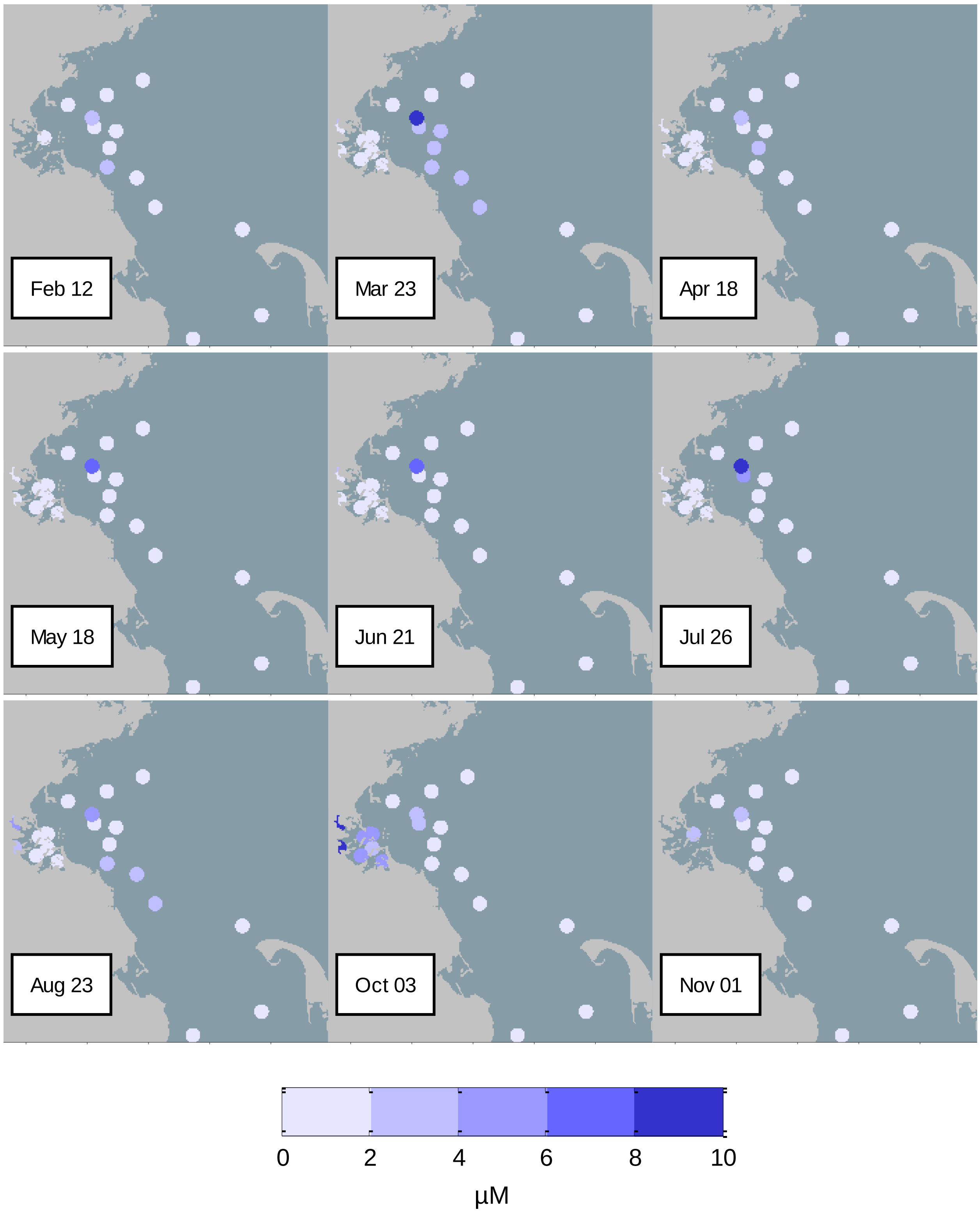


Figure 2-11. Depth-averaged NH_4 concentrations (µM) at stations in Massachusetts and Cape Cod Bays in 2016.

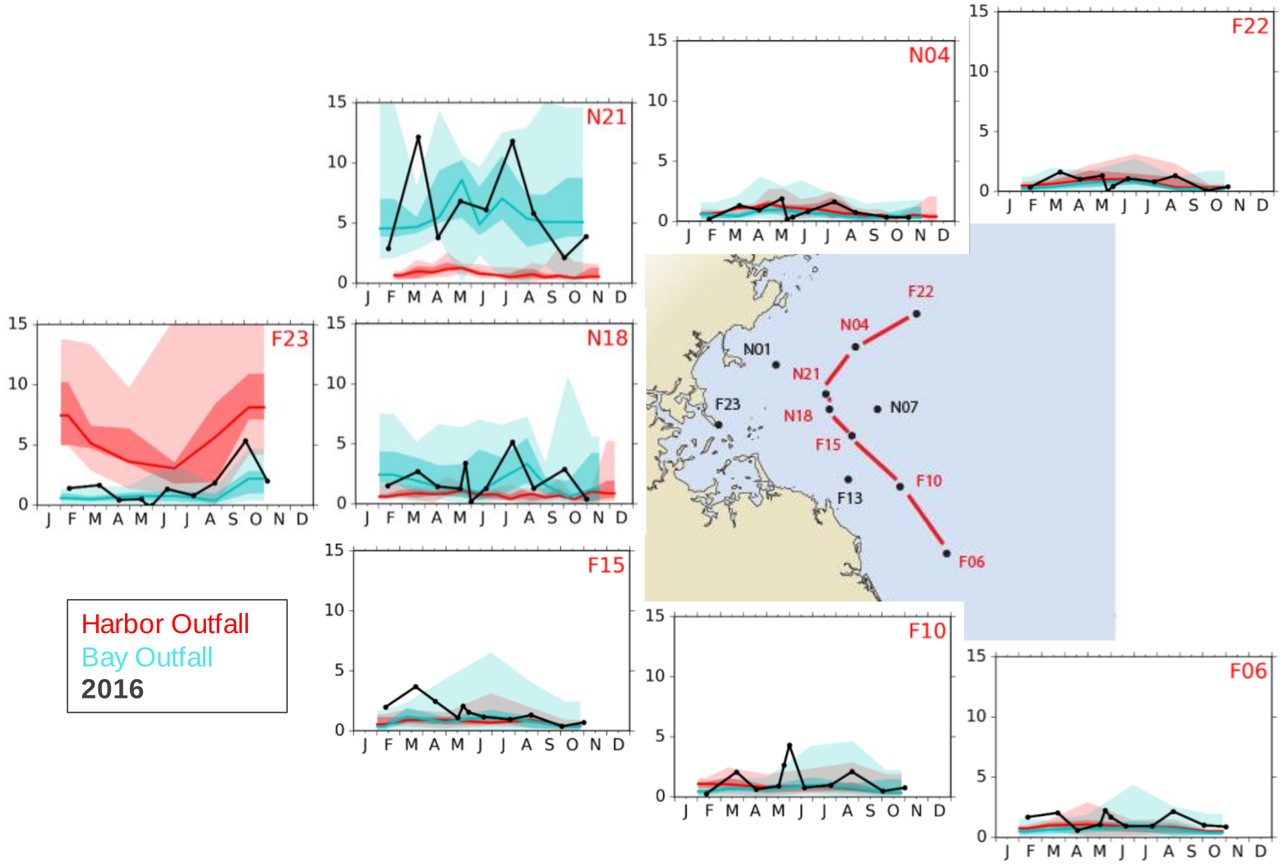


Figure 2-12. Depth-averaged NH_4 (µM) at selected stations in Massachusetts Bay for 2016 compared to prior years. 2016 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2015) results are in light blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

In 2016, as in other years since the bay outfall began operating in 2000, the NH_4 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, when the water column was vertically well mixed, the plume's ammonium signature was seen in the surface waters within the nearfield and to the south at station F15 (**Figure 2-13**). During the July survey, when the water column was vertically stratified with a pycnocline located at approximately 10 m (**Figure 2-14**), the NH_4 signal was seen at or below the pycnocline at stations N21 and N18, the locations closest to the outfall, plus at F15 south of the outfall (**Figure 2-15**). Nitrate concentrations (4-10 µM) were elevated only below the pycnocline, and especially in the deeper offshore bottom waters at the east end of the West-East transect. In July 2016, sub-surface chlorophyll maxima were observed near the pycnocline with elevated values of >8 μgL^{-1} observed at nearfield stations N04 and N18 and 4-6 μgL^{-1} at station F15 (**Figure 2-15**).

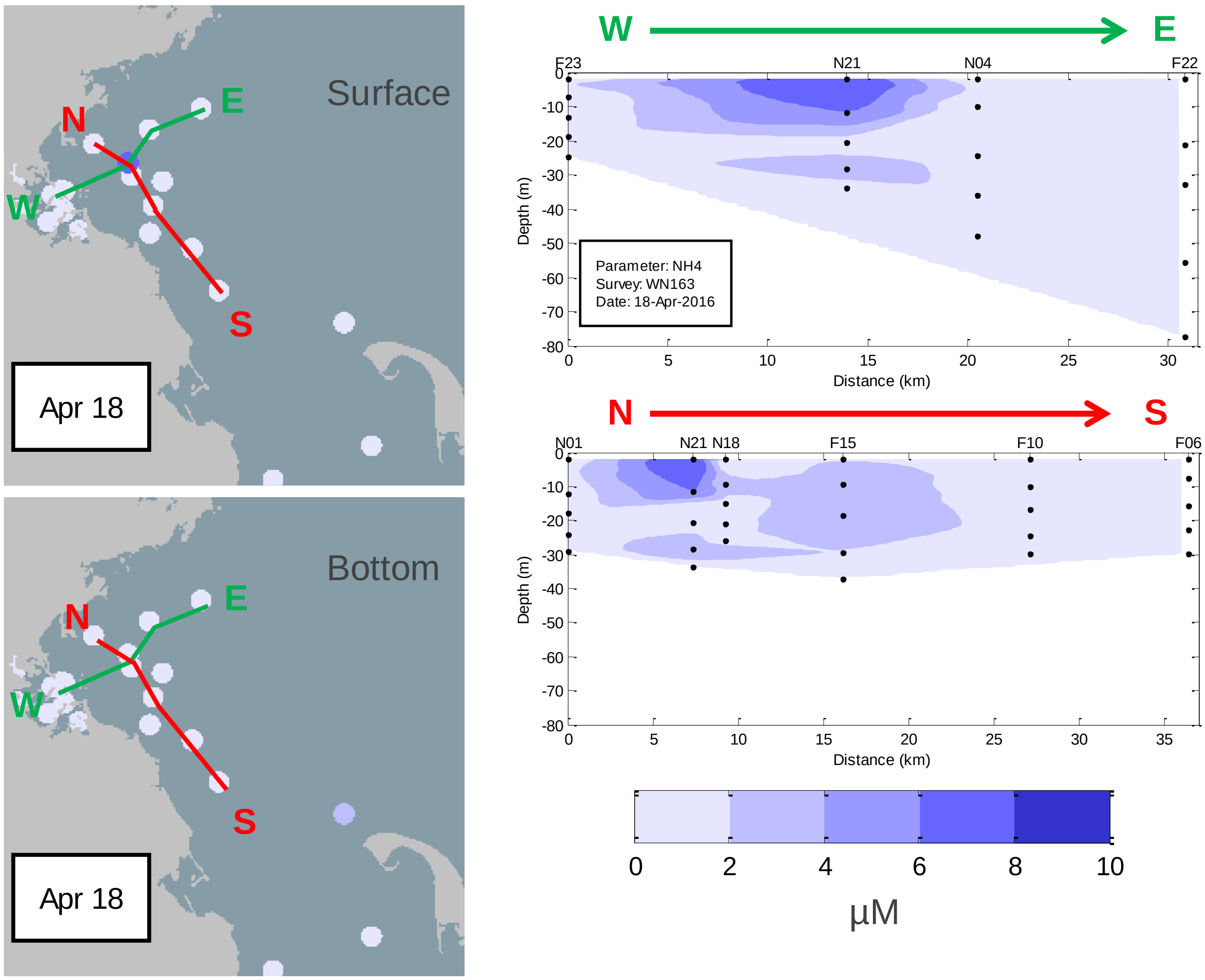


Figure 2-13. (Left) Surface- and bottom-water NH_4 on April 18, 2016 at the monitoring stations during mixed conditions. (Right) Cross-sections of concentrations throughout the water column along transects connecting selected stations. The dots in the plots at right indicate the sampling depths for nutrients.

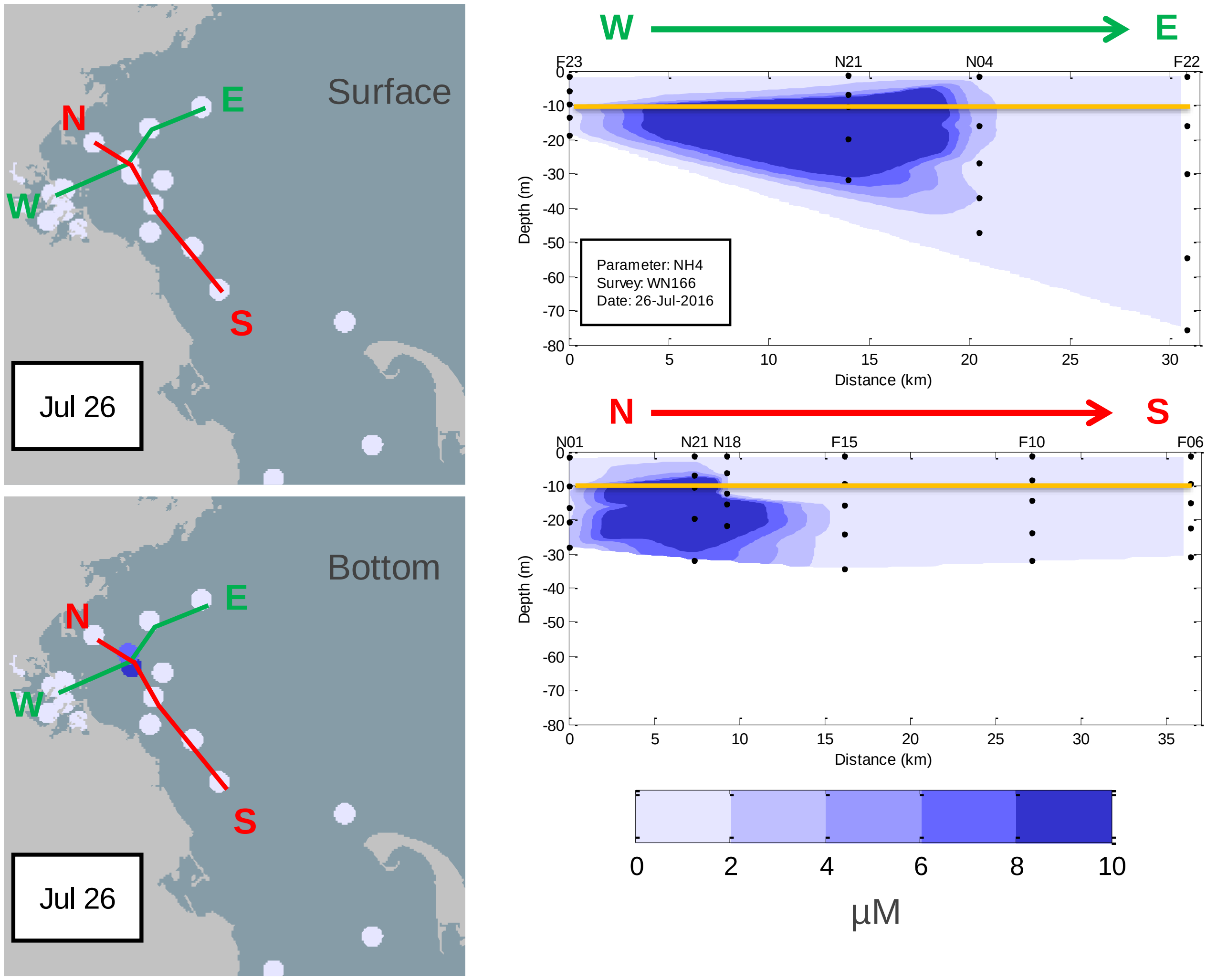


Figure 2-14. (Left) Surface- and bottom-water NH_4 on July 26, 2016 at the monitoring stations during stratified conditions. (Right) Cross-sections of concentrations throughout the water column along transects connecting selected stations. The dots in the plots at right indicate the sampling depths for nutrients. The yellow line indicates the approximate depth of the pycnocline.

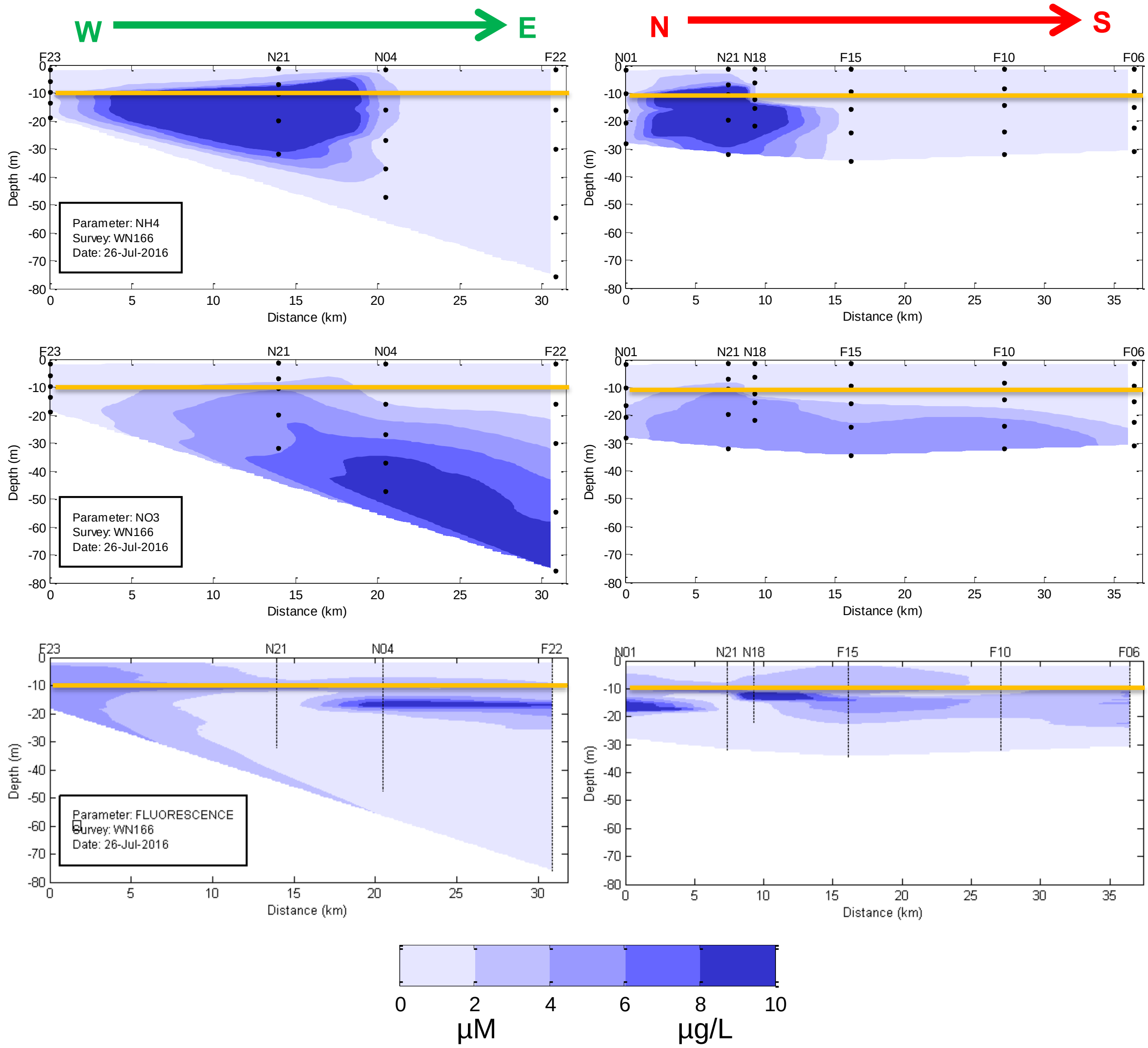


Figure 2-15. Ammonium (top; µM), nitrate+nitrite (middle; µM), and chlorophyll from fluorescence (bottom; µg L^{-1}) concentrations during the stratified July 2016 survey along the east-west and north-south transects shown in Figure 2-14. The dots on the plots indicate the sampling depths for nutrients and the in situ fluorescence profile. The yellow line indicates the approximate depth of the pycnocline.

2.3.2 Phytoplankton biomass

Phytoplankton biomass in Massachusetts Bay can be both spatially and temporally variable, but typically shows a seasonal pattern, with elevated biomass values at intervals during winter-spring, and then again during the fall. Biomass during 2016 showed this same basic pattern, but with minor differences. As can be seen from the shipboard surveys (**Figure 2-16**), biomass at many locations was elevated during the February and April surveys, and then again, but to a much lesser extent in August, and at certain locations, into October 2016. The February biomass values, especially in northern Massachusetts Bay fell in the upper range of what we have seen in the past **(Figure 2-17)**. As observed over the past few years, MODIS satellite chlorophyll fluorescence imagery (**Figure 2-18)** suggests phytoplankton were productive in January and February 2016 with moderate chlorophyll levels (~2-3 µg L^{-1}). In contrast, in March areal chlorophyll levels had gone from near maxima to well below the long-term median with very low levels (<40 mg m^2) across most of Massachusetts Bay, while they remained elevated (>160 mg m^2) at stations off of Cape Cod (**Figure 2-16** and **Figure 2-17**). There was a slight increase in chlorophyll concentrations across Massachusetts Bay in April, but levels remained well below those typically associated with winter/spring bloom events. By the May survey, chlorophyll levels had dropped to <80 mg m^2 across most of the bay.

MODIS fluorescence imagery showed high chlorophyll levels during the period between the April and May survey (**Figure 2-18**). Continuous chlorophyll sampling by fluorometer at NERACOOS Buoy A01 off Cape Ann cannot corroborate this, due to a sampling gap from mid-April through early July (**Figure 2-19**). However, as noted earlier, the relative changes in nutrients from the April to May surveys (sharp decrease in NO_3 and slight increase in SiO_4 concentrations) suggest that a *Phaeocystis* bloom (or mixed assemblage of diatoms and *Phaeocystis*) may have occurred during this period.

Summer increases in nutrient concentrations at depth led to higher subsurface chlorophyll maximum levels near the pycnocline as is typically observed in the bay (see **Figure 2-15**). Overall, 2016 summer chlorophyll levels were relatively high and generally within the upper end of the range observed over the past 25 years (**Figure 2-17**). However, the phytoplankton data as abundances were in the lower quartile compared to previous years (see **Figure 2-25**). The nearfield summer seasonal average chlorophyll of 85 mg m^{-2} met its contingency plan threshold of 89 mg m^{-2}. The winter/spring and fall concentrations too did not exceed their thresholds.

The final two surveys of 2016 were delayed until early October and early November due to vessel issues and weather. In September, there was an increase in chlorophyll concentrations observed in the MODIS imagery and at NERACOOS Buoy A01 with concentrations peaking at ~10 µg/L (**Figure 2-18** and **Figure 2-19**). This September peak in chlorophyll was bracketed by the August and October surveys, which had similar chlorophyll levels. Nutrient levels (see NO_3 in **Figure 2-10**) remained depleted in surface waters into October suggesting that the chlorophyll peak identified in the remote sensing data was likely due to elevated abundances of diatoms in September. Chlorophyll levels remained moderate into November (**Figure 2-16** and **Figure 2-17**). MODIS imagery and NERACOOS data suggests that there was an increase in chlorophyll to relatively high levels over most of Massachusetts and Cape Cod Bays for much of November and December 2016 (**Figure 2-18** and **Figure 2-19**).

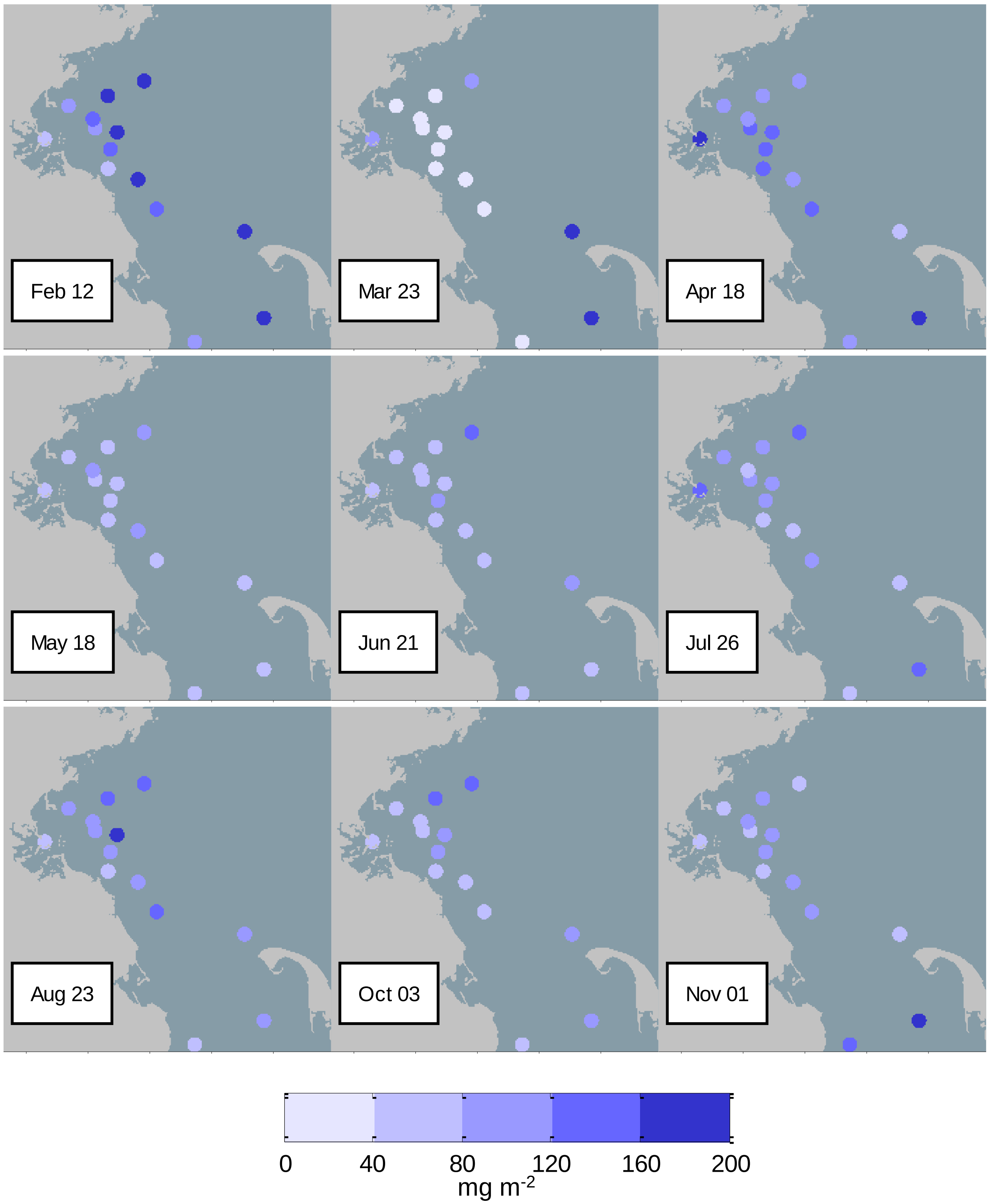


Figure 2-16. Areal chlorophyll fluorescence (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2016.

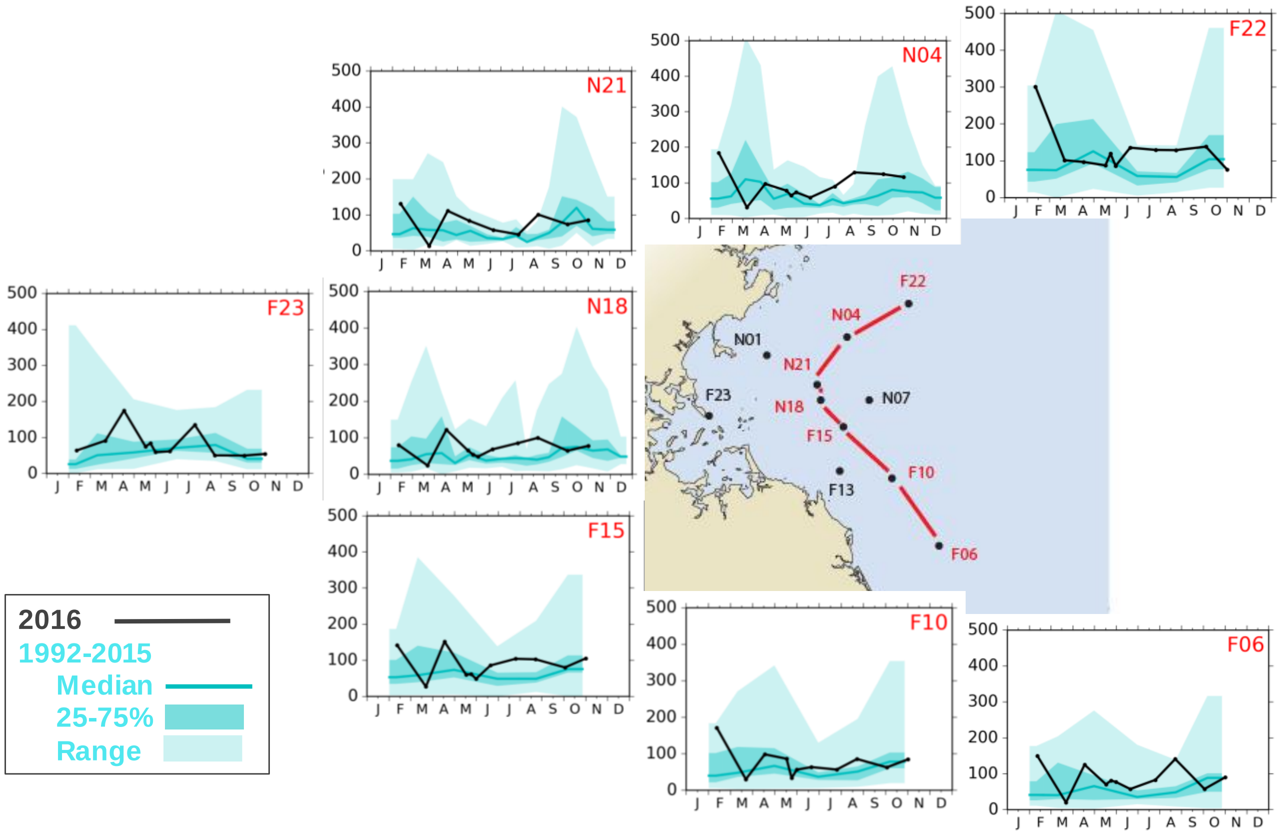


Figure 2-17. Areal chlorophyll fluorescence (mg m^{-2}) at representative stations in Massachusetts Bay for 2016 compared to prior years. 2016 results are in black. Results from 1992–2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

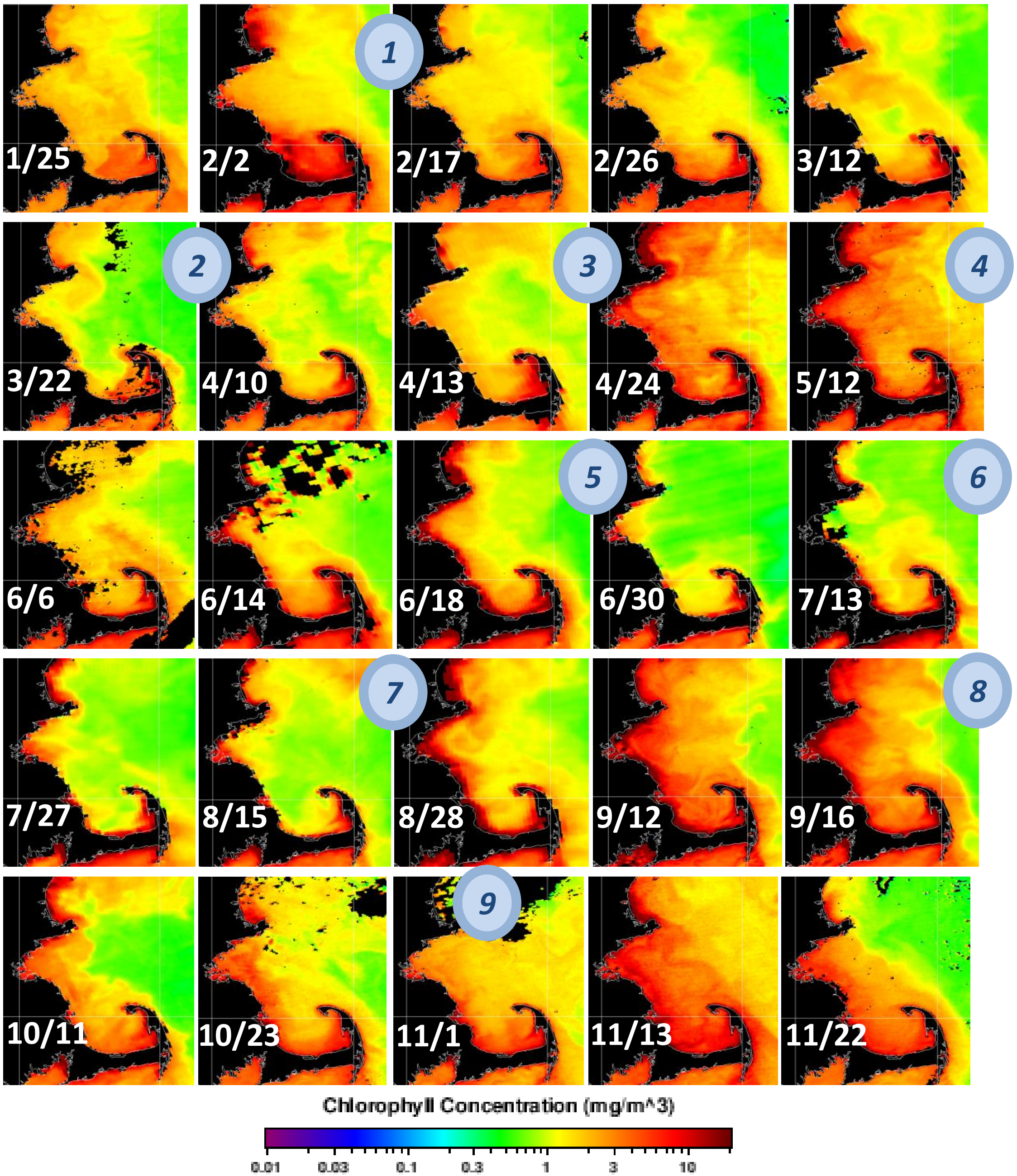


Figure 2-18. Satellite (MODIS) imagery of surface chlorophyll concentrations (mg m^{-3}) in 2016.

Highlights and specific blooms:

1st row – moderate chlorophyll levels January and February;
2nd row – relatively low from mid-March to mid-April;
2nd row – high chlorophyll in late April to early May – likely due to late *Phaeocystis* bloom;
3rd & 4th rows – low summer chlorophyll levels from June through mid-August;
4th row – increase in late August to September (also observed at NERACOOS Buoy A01); and
5th row – moderate chlorophyll levels in October increasing in November.

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

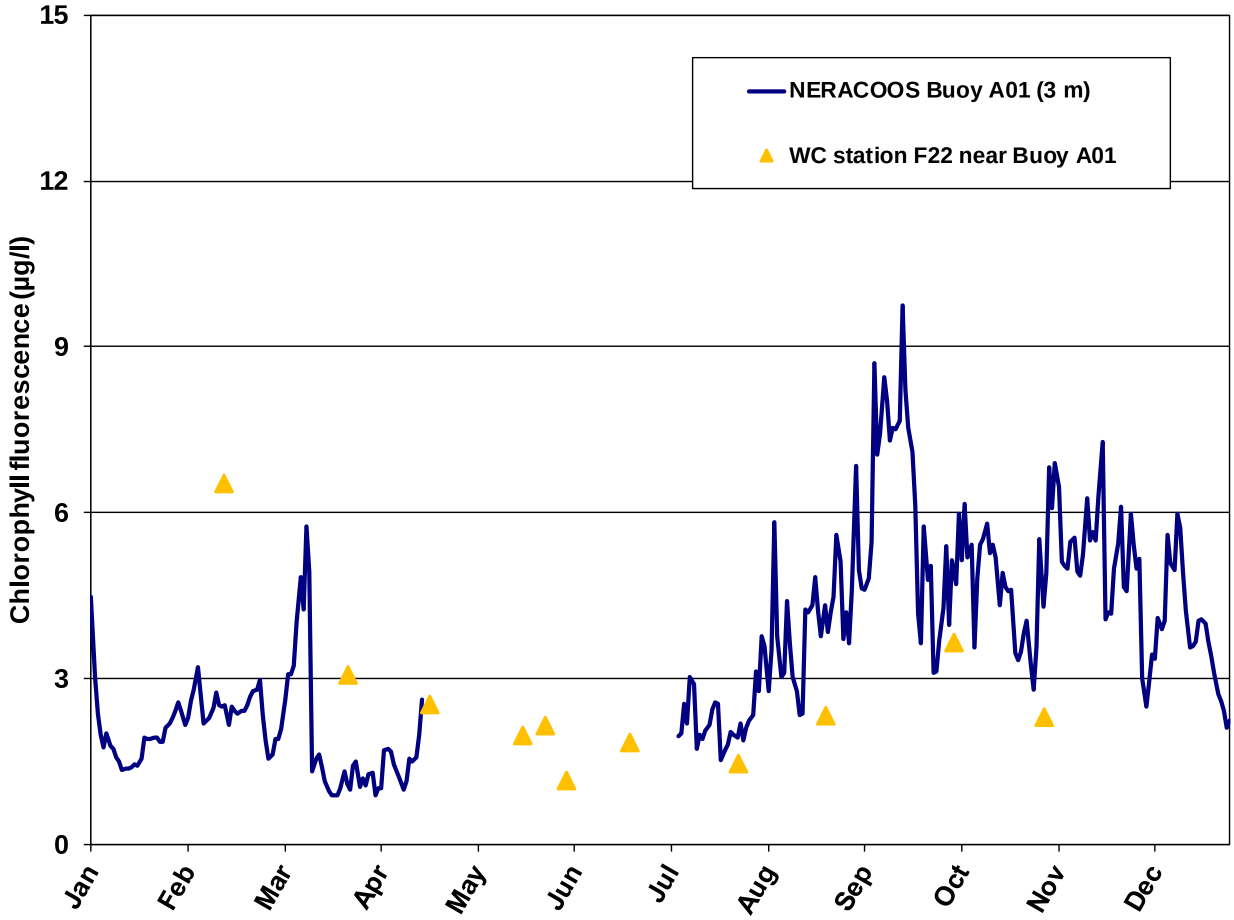


Figure 2-19. Surface water chlorophyll fluorescence (µg L^{-1}) at NERACOOS Buoy A01 and nearby water column (WC) station F22. The buoy values are daily medians.

2.4 BOTTOM WATER DO

Typically bottom water DO declines at a relatively constant rate in Massachusetts Bay from winter/spring maxima to September or October annual minima. In 2016, however, the seasonal decline was punctuated by a mixing event in late May that increased bottom water DO levels by about 0.5 to 1 mg L^{-1} throughout the bay (**Figure 2-20**). Bottom water DO concentrations began the year at levels that were in the lower quartile or below, compared to historical data. This was the case from February to May. This may have been related to the warmer temperatures and low river flow in 2016 discussed previously. The late May mixing event increased bottom water DO concentrations to levels comparable to long-term medians.

Harbor and shallower Massachusetts Bay stations stayed close to long-term averages for bottom water DO for the rest of the year. This was not the case at deeper stations or in Cape Cod Bay, where minima were observed in August, October, and November that were near or below the historic range of values observed (**Figure 2-20** and **Figure 2-21**). In Cape Cod Bay, bottom DO concentration minima were approximately 6 and 5 mg L^{-1} at stations F01 and F02, respectively in October; by the November survey, these shallow stations had become well mixed and DO levels increased to about 8 mg L^{-1}. In Massachusetts Bay, the nearfield average bottom water DO minima of 7.12 mg L^{-1} was also reached in early October, but DO levels continued to decline in deeper waters reaching 6.33 mg L^{-1} at station F22 in November.

As noted previously, a late September storm and persistent winds led to destratification to 20 m depth by early October, but the mixing did not extend to 50 m. The influence of late fall mixing events is evident in NERACOOS buoy A01 DO data from 50 m, which showed large fluctuations in October to mid-November between 6 and 8 mg L^{-1}, before the water column became well mixed to below 50 m in late November (**Figure 2-22**). Overall, survey observations of DO at station F22 compared well to observations at NERACOOS Buoy A01.

The importance of the late May mixing event and the early destratification of the water column in shallower areas to alleviating low DO conditions in bottom water is highlighted by the DO regression model (**Figure 2-23**). The model prediction for 2016 was for very low DO conditions, due to warm bottom waters and high salinities, which are the parameters that drive the model. However, the observed DO was slightly higher than normal. This failure of the model is explained by the fact that it does not include timing of events related to other processes, including downwelling winds, riverine input, and early destratification.

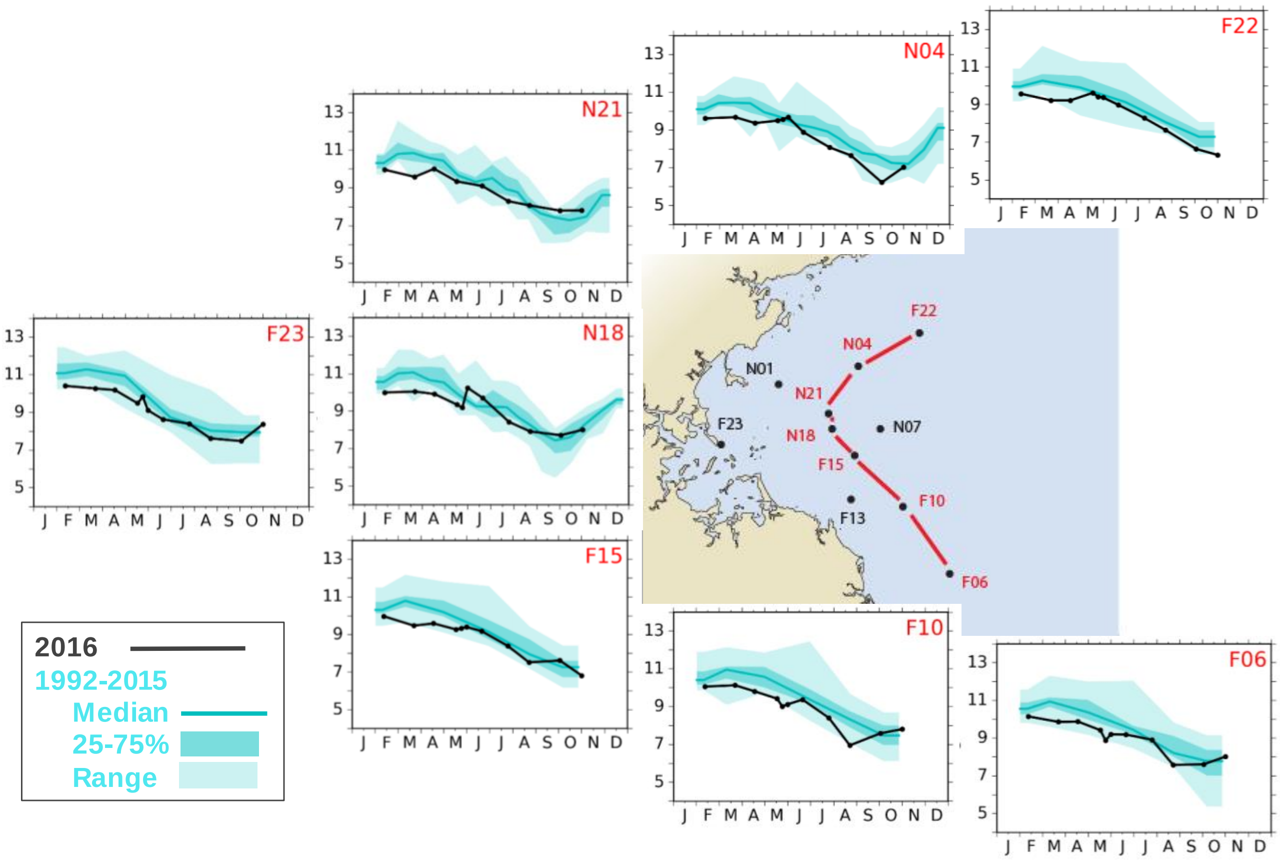


Figure 2-20. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2016 compared to prior years. 2016 results are in black. Results from 1992–2015 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

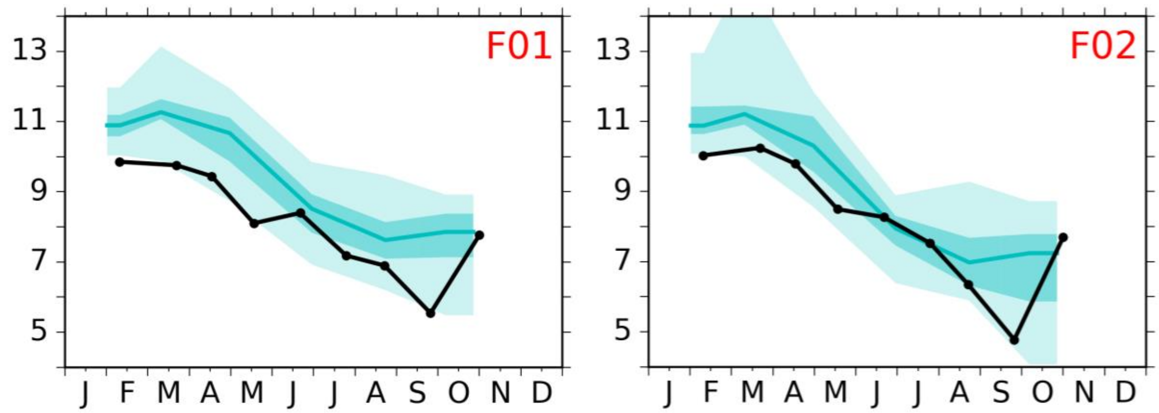


Figure 2-21. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2016 compared to prior years. 2016 results are in black. Results from 1992–2015 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

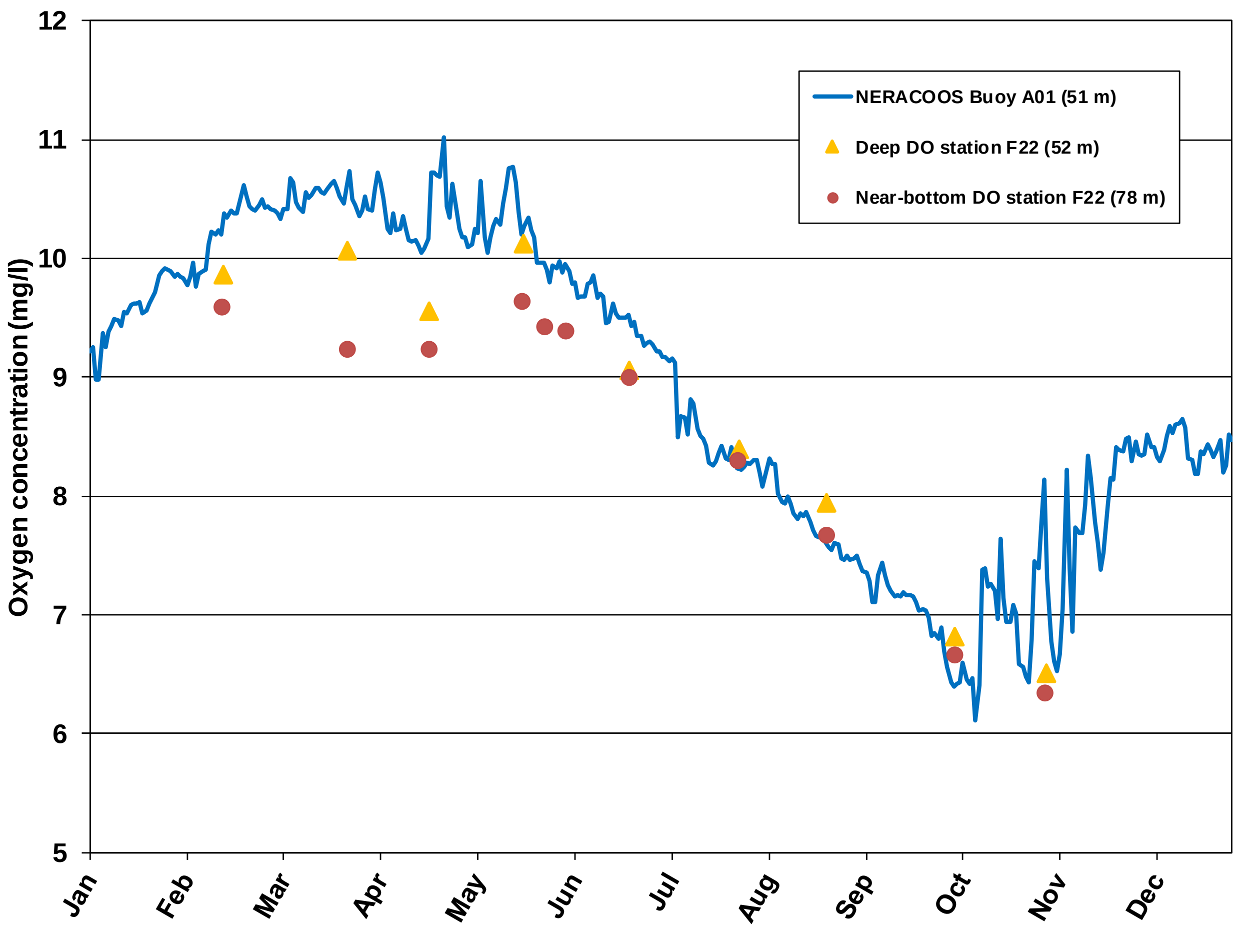


Figure 2-22. Time-series of DO concentration (mg L^{-1}) at NERACOOS Buoy A01 (51 m) and at station F22 from deep (mean 52 m) and bottom (mean 78 m) sampling depths in 2016. The buoy values are daily means.

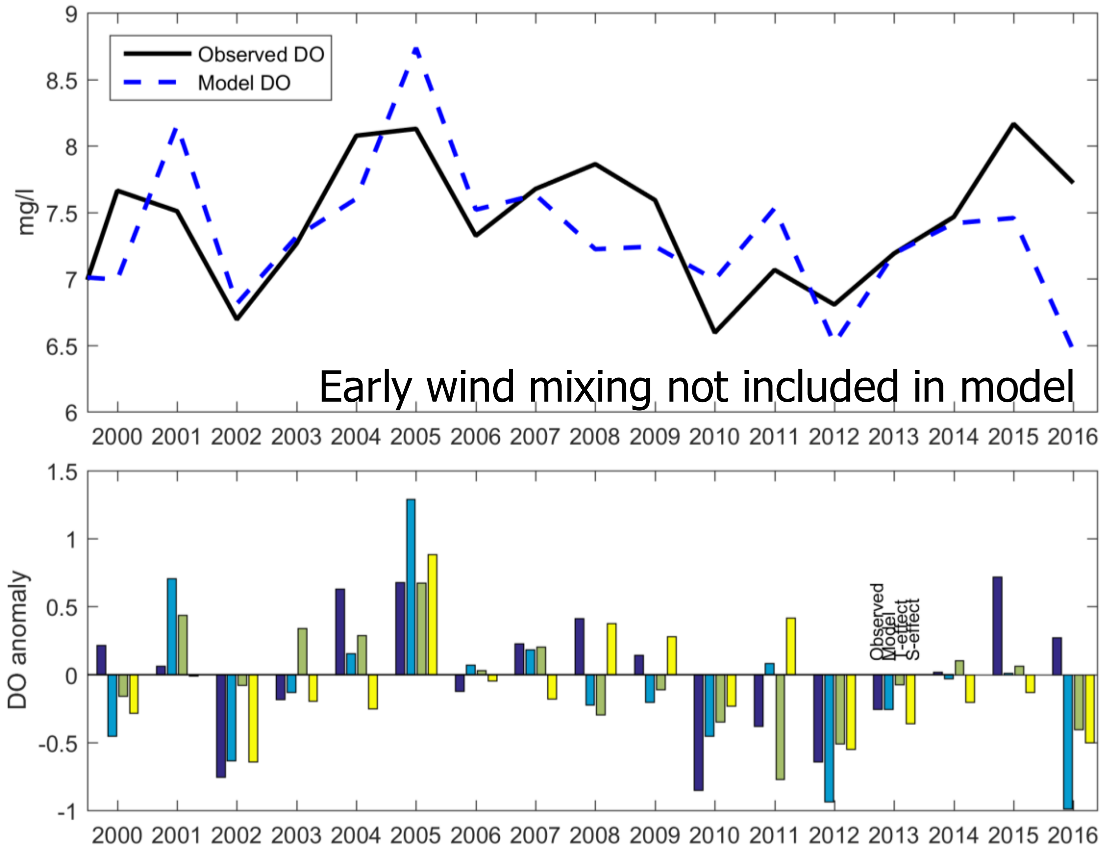


Figure 2-23. Bottom water DO regression model output and observed DO (mg L^{-1}) at station N18. The bottom panel shows the effects of temperature and salinity in the DO anomaly for the model – warmer temperatures and higher salinities drove the model DO to very low levels, which were much different than observed values in 2016.

2.5 PHYTOPLANKTON

Overall, phytoplankton abundance in 2016 was low compared to the range of observations made during 1992-2015. The low 2016 abundance was in part due to the fact that surveys did not sample a large winter-spring bloom of diatoms or *Phaeocystis*. During the first survey in 2016, despite relatively high chlorophyll levels, phytoplankton cell counts were low (**Figure 2-24** and **Figure 2-25**). This suggests that the phytoplankton present in the water column in February 2016 were large or enriched with chlorophyll compared to previous years. Cell chlorophyll content can vary widely, among taxa, and depending on trophic state. In March, phytoplankton abundance and chlorophyll levels were both at or near the minima observed over the 25-year monitoring program.

Total phytoplankton peaked during the April survey with annual maximum abundances for 2016 observed across the sampling area. Spatially, there was gradient in phytoplankton abundance from >2 million cells L^{-1} at Boston Harbor station F23 and coastal station F13, to about 1.5 million cells L^{-1} in the nearfield, and <1 million cells L^{-1} further offshore (**Figure 2-24**). In comparison to previous years, the April 2016 maxima were generally close to the long-term median and much lower than peak abundances observed during past winter/spring diatom or *Phaeocystis* blooms (March/April; **Figure 2-25**). The April peak was largely due to a moderate winter-spring centric diatom bloom dominated by *Thalassiosira* spp. and *Skeletonema* spp.

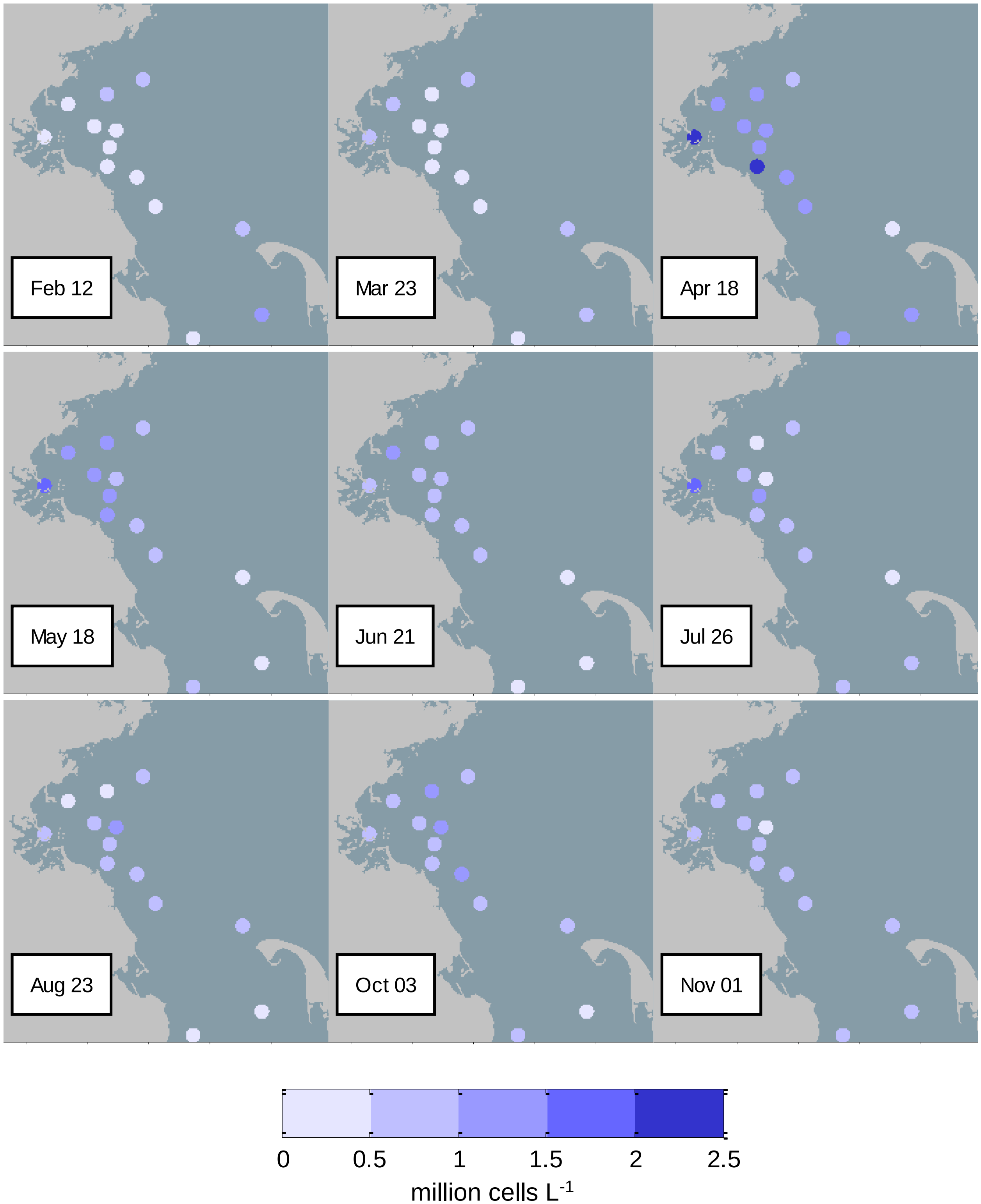


Figure 2-24. Total phytoplankton abundance (million cells L^{-1}) by station in Massachusetts and Cape Cod Bays in 2016.

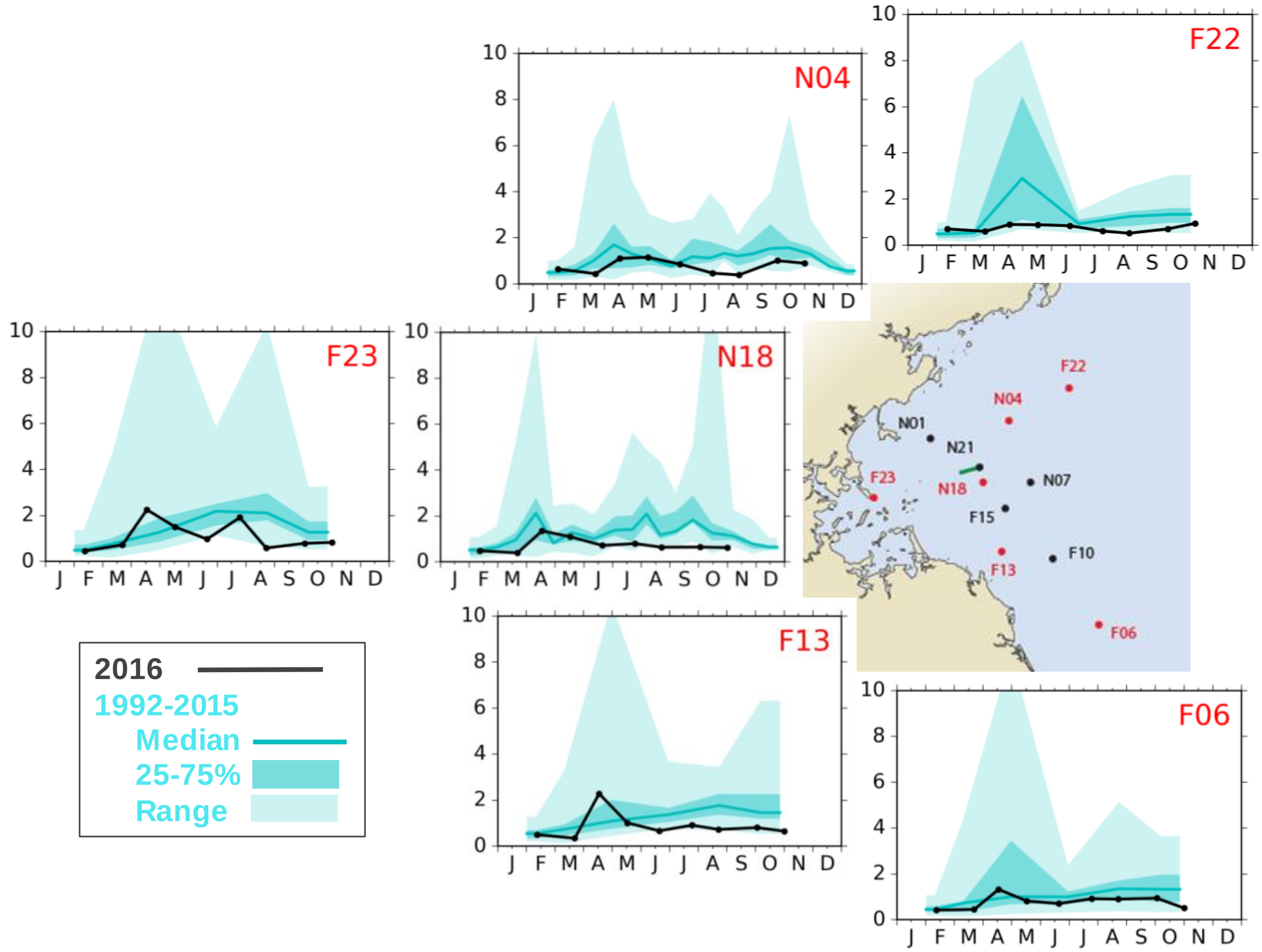


Figure 2-25. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2016 compared to prior years. 2016 results are in black. Results from 1992-2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range).

Skeletonema is usually a summer dominant species in Massachusetts Bay and consists of a genetically diverse group (Kooistra et al. 2008) with several cryptic species contained within the *Skeletonema* spp. complex in the coastal waters of the northeastern US (Canesi and Rynearson 2016). Shifts in the annual cycle of *Skeletonema* spp. from a winter-spring dominated annual cycle to a summer bloom dominated cycle have been detected in Narragansett Bay (Borkman and Smayda 2009); this shift may be related to differential temperature- and nutrient-specific physiology of *Skeletonema* spp. Similar changes in cryptic *Skeletonema* spp. may be driving the shift towards *Skeletonema* dominance of the winter-spring bloom during 2016 in Massachusetts Bay.

Since about 2000, the spring diatom bloom has been followed by a *Phaeocystis* bloom in April (**Figure 2-26)**. In comparison to past *Phaeocystis* blooms, 2016 abundances were very low (<50,000 cells L^{-1}) on both the April and May surveys. This is the fourth year in a row without a major *Phaeocystis* bloom being observed on the monitoring surveys. However, as in 2015, MODIS satellite data and changes in relative nutrient concentrations suggest that a *Phaeocystis* bloom may have occurred between the April and May 2016 surveys. In May, *Phaeocystis* was observed in only one nearfield sample (36,000 cells L^{-1}), and as noted above this observation led to an exceedance of the summer *Phaeocystis* contingency threshold (**Figure 2-26**) despite not being ecologically meaningful. Because this was also true of exceedances in many prior years, in 2016 MWRA requested *Phaeocystis* seasonal means be dropped from the Contingency Plan Thresholds; the Outfall Monitoring Science Advisory Panel agreed, EPA has approved, and the change will become final in late 2017.

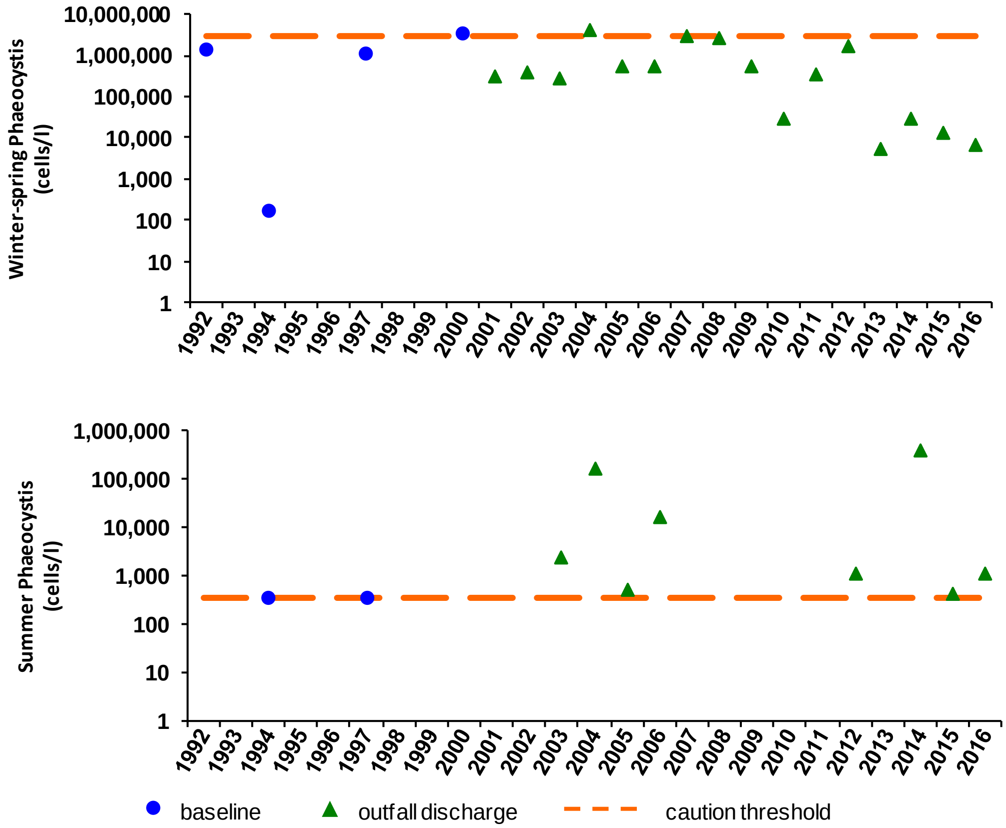


Figure 2-26. Winter/spring (million cells L^{-1}) and summer (cells L^{-1}) seasonal mean nearfield *Phaeocystis* abundance for 1992 to 2016 (zeros not plotted). Contingency Plan threshold value shown as dashed line.

Total phytoplankton abundance decreased from the April peaks to lower levels in May. This decrease was concomitant with an increase in dinoflagellates to annual maxima of >200,000 cells L^{-1} in nearfield and coastal waters (**Figure 2-27**). The dinoflagellate community in May 2016 was dominated by small species including *Prorocentrum minimum*, *Heterocapsa rotundatum*, and *Gymnodinium* spp. Although not numerically important, *Alexandrium* were observed at abundances sufficient (≥100 cells L^{-1}) to trigger ARRS surveys in 2016. Low abundances of *Alexandrium* were seen in the bay in April (**Figure 2-28**). By May 3rd, PSP toxicity was measured by New Hampshire Department of Environmental Services at both their inshore and offshore stations indicating that elevated abundances of *Alexandrium* were present in these western Gulf of Maine waters in early May. A strong Northeaster was present in the region on May 5-7 (Figure 2-4) and conditions were conducive to entraining Gulf of Maine coastal waters into Massachusetts Bay. On May 18th, *Alexandrium* abundance peaked at 241 cells L^{-1} in the surface waters at station F22 just south of Cape Ann. Lower levels (<25 cells L^{-1}) were observed at the other Massachusetts Bay stations. The relatively high abundance at station F22 triggered the ARRS surveys. On May 25th, elevated *Alexandrium* abundances (>100 cells L^{-1}) continued to be observed at stations just south of Cape Ann long with lower counts (<10 cells L^{-1}) in the rest of the bay (**Figure 2-28**). By early June, all counts were ≤15 cells L^{-1} and by June 21st no *Alexandrium* were observed in the bay. Even though elevated *Alexandrium* counts were observed in May in northeastern Massachusetts Bay, no PSP toxicity was measured in the Bay in 2016. PSP toxicity had been noted in Western Maine, New Hampshire, and north of Cape Ann, but the 2016 bloom event was minor and short lived. The nearfield *Alexandrium* threshold of 100 cells L^{-1} was not exceeded (**Figure 2-29**).

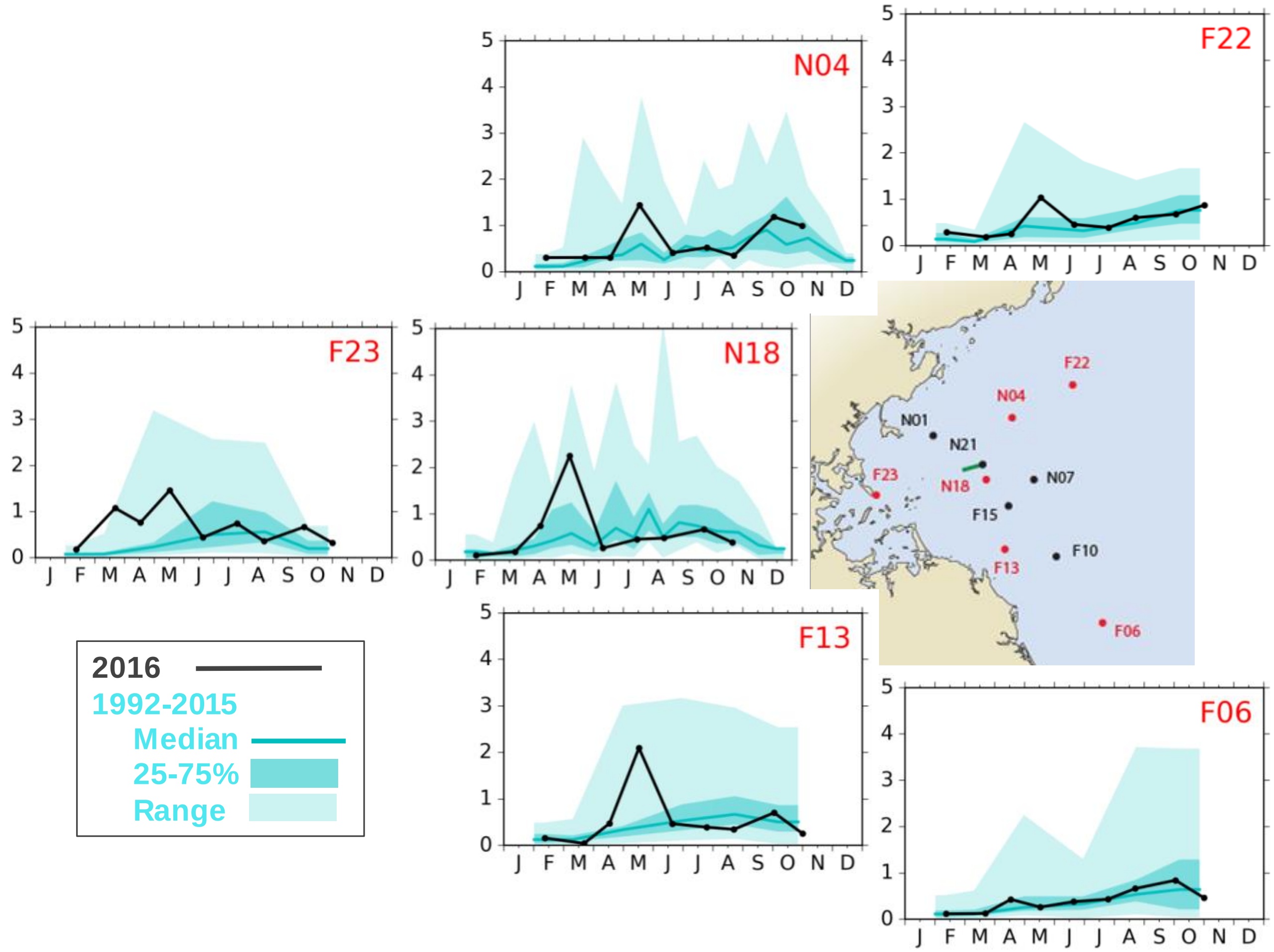


Figure 2-27. Dinoflagellate abundance (100,000 cells L^{-1}) at selected stations in 2016 compared to prior years. 2016 results are in black. Results from 1992-2015 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range).

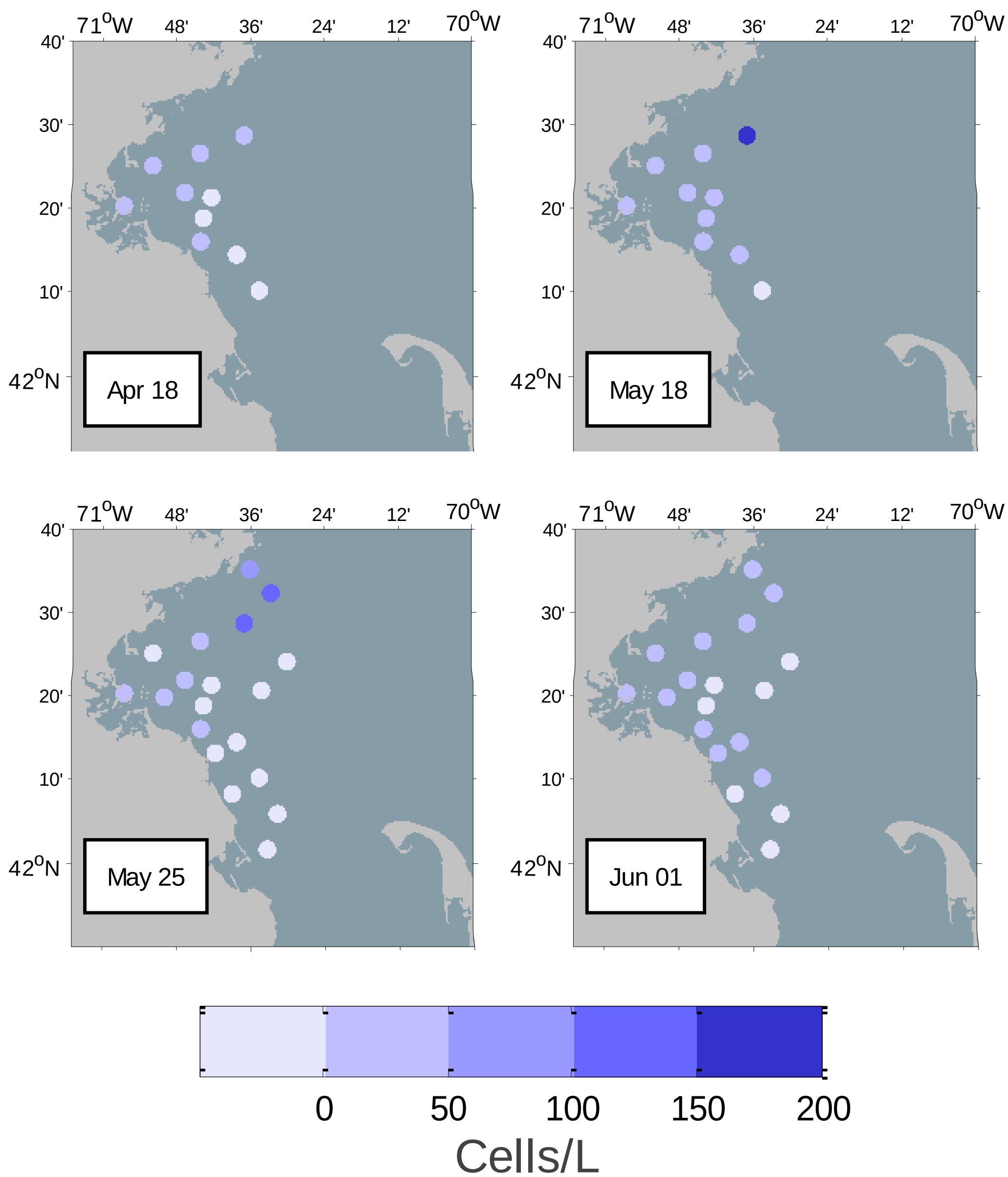


Figure 2-28. ***Alexandrium*** **abundance, station maxima for individual samples (cells L^{-1}).**

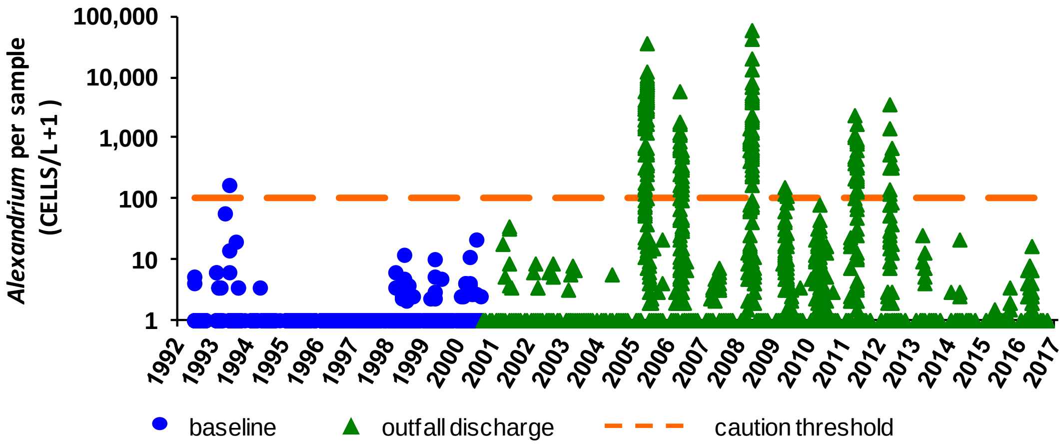


Figure 2-29. Nearfield *Alexandrium* abundance for individual samples (cells L^{-1}). Contingency Plan threshold value shown as dashed line.

Summer total phytoplankton counts fell into the lower quartile of the historic range at the Massachusetts Bay stations in June through September (**Figure 2-25**). In Boston Harbor and nearby coastal stations, a summer diatom bloom peaking at 1.3 million cells L^{-1} was observed in July and was dominated by *Cerataulina pelagica* and *Leptocylindrus danicus*. A notable change in the dominant summer diatom occurred in the harbor. In most years, the summer harbor diatom bloom has been dominated by *Dactyliosolen fragilissimus*, with secondary dominance by *Skeletonema* spp. However, during 2015 and 2016 *Dactyliosolen fragilissimus* was reduced (2015) or absent (2016) in Boston Harbor, being replaced by *Cerataulina pelagica*. Additionally, as noted previously, *Skeletonema* was the dominant centric diatom during the winter-spring bloom and was conspicuously absent in summer 2016. The lack of a major winter/spring bloom and low summer abundances in the nearfield resulted in a 2016 mean centric diatom abundance that was 28% of the long-term mean, with a mean of 78,671 cells L^{-1} (2016 nearfield mean) compared to a long-term mean level of 278,487 cells L^{-1} (1992-2015 nearfield mean; **Table 2-1**).

Unlike the diatoms, the large dinoflagellate *Ceratium* spp. peaked during the summer months and were above long-term mean levels during 2016. *Ceratium* spp. were present at more than double the long-term mean level during 2016; with a mean of 3,716 cells L^{-1} during 2016 compared to a long-term mean of 1,623 cells L^{-1} (**Table 2-1)**. *Ceratium* were the only phytoplankton group having significantly different abundance at the surface vs. the chlorophyll maximum sampling depth (p=0.03). During 2016, *Ceratium* spp., were 2.6-times more abundant at the chlorophyll maximum depth (mean abundance = 5,373 cells L^{-1}) than at the surface (mean abundance = 2,060 cells L^{-1}). Large *Ceratium* are slow growing cells that thrive at the seasonal pycnocline in Massachusetts Bay and in other temperate coastal seas, during the summer stratified period (Cushing 1989). During this period, the large size, high respiration (relative to diatoms) and slow growth rate of the *Ceratia* may be offset by their strategy of vertical migration across the pycnocline (Holligan 1987; Cushing 1989). This strategy allows *Ceratium* to photosynthesize above the pycnocline and assimilate nutrients at or below the pycnocline.

A bloom of the toxigenic pennate diatom *Pseudo-nitzschia* caused shellfish harvest closures in Maine, southern Massachusetts (Buzzards Bay and south side of Cape Cod) and in Rhode Island waters during October 2016. However, *Pseudo-nitzschia* spp. levels in the nearfield area of Massachusetts Bay were not unusually high during 2016; the peak abundance of *Pseudo-nitzschia* (48,000 cells L^{-1}) was observed at station F13 in August 2016 was orders of magnitude lower than the 1992-2015 maximum *Pseudo-nitzschia* spp. abundance of 1.8 million cells L^{-1} observed during August 1998. The 2016 maximum *Pseudo-nitzschia* abundance occurred during August 2016, approximately two months prior to the beginning of the *Pseudo-*

nitzschia spp. bloom in Maine, southern Massachusetts and Rhode Island coastal waters. Overall, pennate diatoms were present at low levels in the nearfield during 2016, with a mean level of 9,693 cells L^{-1} compared to a long-term (1992 to 2015) mean level of 36,651 cells L^{-1} (**Table 2-1**).

Total phytoplankton abundances remained low into October and November – primarily due to the lack of an observed fall diatom bloom. MODIS imagery and NERACOOS Buoy A01 suggested that an early fall bloom occurred in September between surveys. Dinoflagellates exhibited an increase in October (**Figure 2-27**) with peaks in *Dinophysis* spp. and *Prorocentrum* spp. *Prorocentrum* were present at approximately three times the long-term mean level during 2016 (**Table 2-1**). *Prorocentrum* species were present in the nearfield at a mean level of 17,898 cells L^{-1} during 2016 (highest for the 25-year monitoring program) compared to a long-term mean level of 5,201 cells L^{-1}. The elevated *Prorocentrum* abundance during 2016 was due to elevated abundance of *P. minimum* during the spring (May) followed by increased abundance of *P. micans* during October 2016.

Overall, phytoplankton abundance during 2016 was at the low end of the range of observations made during the 25 years of monitoring. Total phytoplankton abundance in the nearfield in 2016 (759,038 cells L^{-1}) was 53% of the long-term mean level of 1,426,238 cells L^{-1} and ranked 22nd for the 25 years of monitoring. (**Table 2-1**). The low 2016 abundance was in part due to the fact that surveys did not sample a large winter-spring bloom of diatoms or *Phaeocystis*; low summer abundances; and a weak fall bloom. The low 2016 abundance continued a declining phytoplankton trend that began in 2008.

Table 2-1. Comparison of 2016 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 N16/N18.

Group	1992-2015 (cells L^{-1})	2016 (cells L^{-1})	Rank (out of 25)	p value	Significant Change
CENTRIC DIATOM	278,487	78,671	22nd	0.2961	
Dactyliosolen fragilissimus	60,806	605	21st	0.0070	Decline
Chaetoceros	31,834	2,571	19th	0.0080	Decline
Skeletonema costatum complex	45,445	22,579	11th	0.1236	
Thalassiosira	38,436	9,794	17th	0.8577	
PENNATE DIATOM	36,651	9,693	20th	0.2519	
Pseudonitzschia	8,924	1,144	20th	0.0379	Decline
DINOFLAGELLATES	61,515	62,936	10th	0.2003	
Ceratium	1,623	3,716	3rd	0.0001	Increase
Dinophysis	268	98	18th	0.1905	
Prorocentrum	5,201	17,898	1st	0.0002	Increase
Phaeocystis pouchetii	213,581	2,173	18th	0.2951	
CRYPTOPHYTES	127,193	129,723	12th	0.0854	
MICROFLAGELLATES	698,022	463,450	19th	0.0031	Decline
TOTAL PHYTOPLANKTON	1,426,238	759,038	22nd	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.

2.6 ZOOPLANKTON

Annual peak zooplankton abundance was much lower than observed in 2015. Peak abundances in 2016 were approximately 250,000 animals m^{-3} (**Figure 2-30**), compared to peak abundances in 2015 of approximately 2.5 million animals m^{-3}. The peak abundances in 2015 were higher than all previous years and were driven by extreme abundances of bivalve veliger larvae in July and August, particularly at station F23 in Boston Harbor. In 2016, bivalve veliger abundance was not unusually high. However, the abundances of total zooplankton and many dominant taxa were at or above maxima for the 25-year monitoring program at many of the stations in Massachusetts Bay from February to June (**Figure 2-30**). The warm temperatures observed in winter/spring 2016 may have contributed to the early increase in zooplankton abundances.

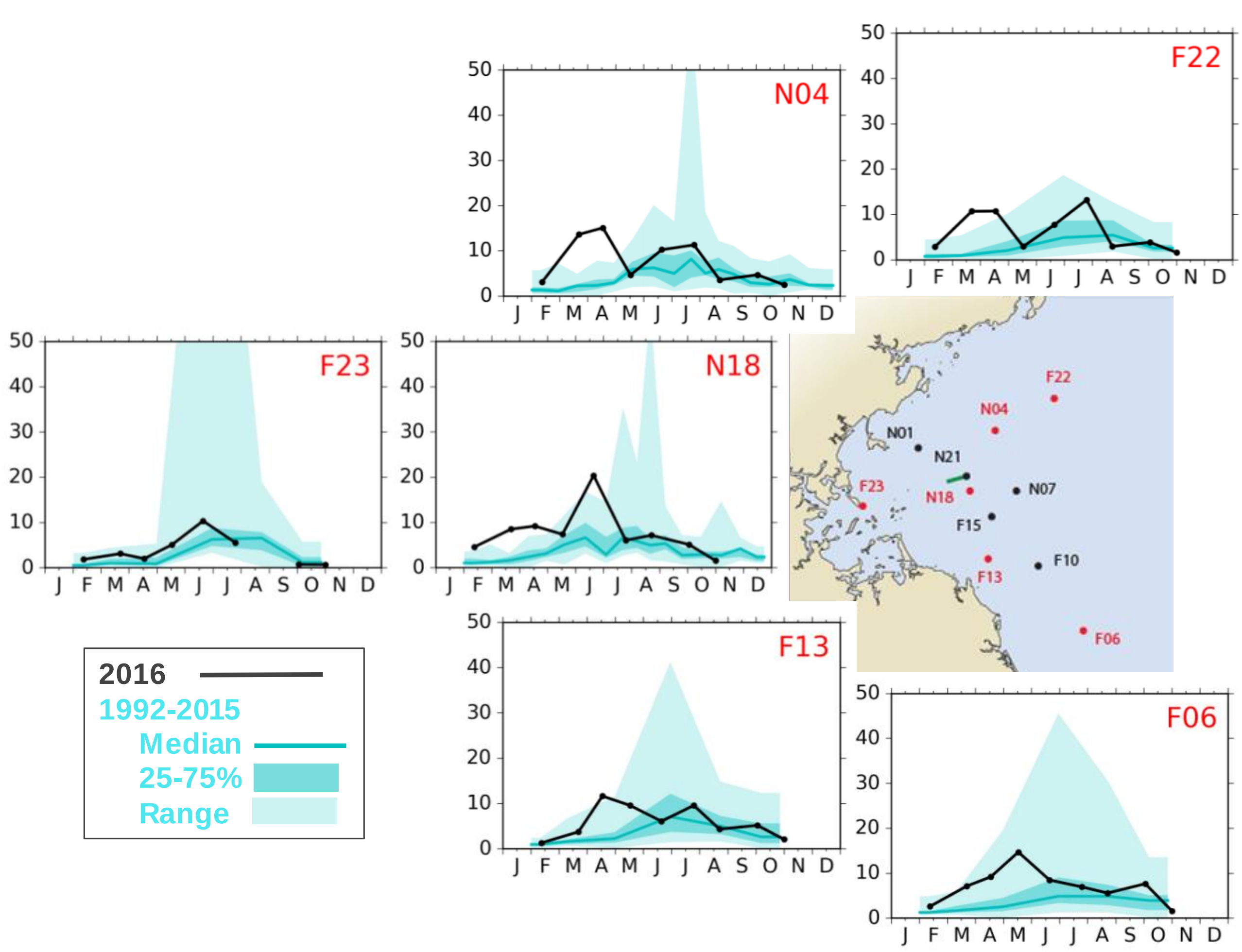


Figure 2-30. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2016 compared to prior years. 2016 results are in black. Results from 1992–2015 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. The peak values exceeding the maximum of the y-axis (>500,000), all measured in 2015, were: N04 = 630,000; F23 = 2,400,000; N18 = 570,000; F13 = 610,000; and F06 = 700,000 individuals m^{-3}.

There were peaks in barnacle nauplii abundance in March and April and in copepod nauplii in April that contributed to the elevated total zooplankton abundances in early 2016. However, the primary driver for the high abundances were copepod adults + copepodites (A+C) which were also at or above previous maxima for the first half of 2016 (**Figure 2-31**). Copepods A+C were dominated by the small cyclopoid copepod *Oithona similis*. There were also relatively high abundances of *Calanus finmarchicus* in April (peaking at ~20,000 individuals m^{-3}). As observed in recent years, grazing by the large zooplankton populations may have contributed to the relatively low phytoplankton cell counts observed during 2016.

Peak abundances of *Acartia* spp. in Boston Harbor were not very high (~10,000 individuals m^{-3}), but as observed with other copepods in Massachusetts Bay, abundances were elevated compared to historic numbers from February to May 2016 (**Figure 2-32**). 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 (2001-2015). In 2016, peak *Acartia* spp. abundance in Boston Harbor occurred in the earlier period (May) as in previous post-diversion years.

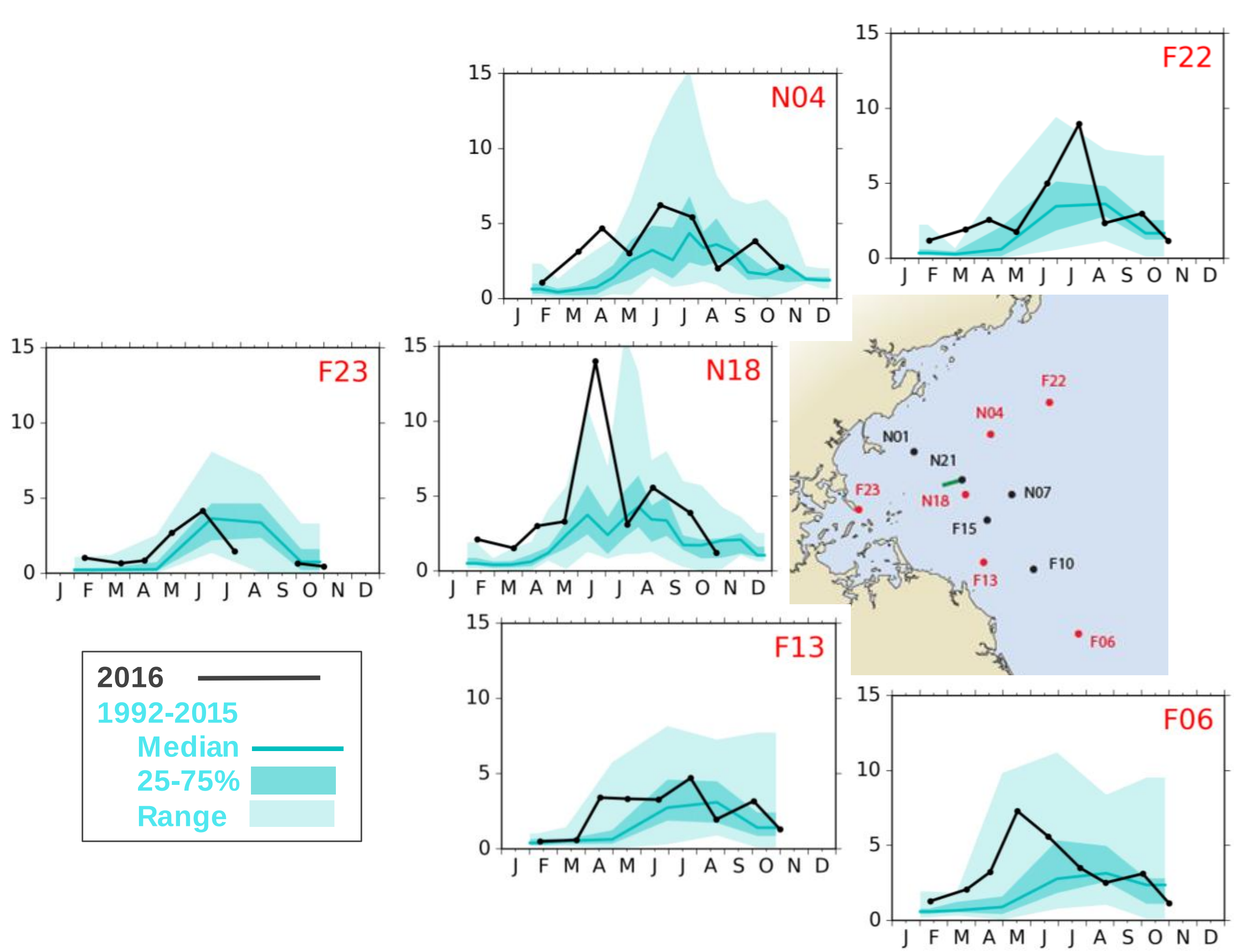


Figure 2-31. Copepod A+C abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2016 compared to prior years. 2016 results are in black. Results from 1992-2015 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

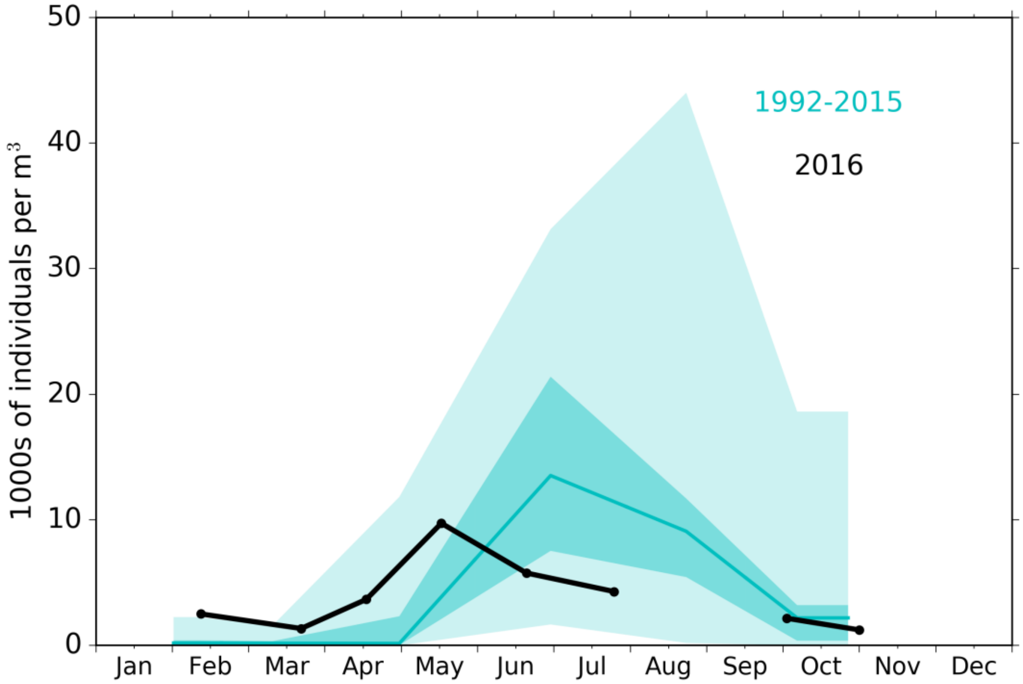


Figure 2-32. ***Acartia* spp. abundance (1,000 individuals m^{-3}) at Boston Harbor station F23 for 2016 compared to prior years.** 2016 results are in black. Results from 1992-2015 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.7 MARINE MAMMAL OBSERVATIONS

The observation of marine mammals during surveys designed and operated for the collection of water quality data places limitations and constraints on the method of observation and on the conclusions that may be drawn from the data. Unlike statistically-based programs or programs that are specifically designed to search for whales (Khan et al. 2016), the MWRA sightings are opportunistic and do not follow dedicated and systematic line transect methodology. Therefore, observations are descriptive and not a statistically robust population census.

In 2016, two North Atlantic right whales (*Eubalaena glacialis*) and three minke whales (*Balaenoptera acutorostrata*) were observed during the water column surveys (**Table 2-2** and **Figure 2-33**). The North Atlantic right whales were both seen in April on survey WN163. Several other marine mammals including one Atlantic white-sided dolphin (*Lagenorhynchus acutus*), two harbor porpoises (*Phocoena phocoena*) and twenty-seven harbor seals (*Phoca vitulina*) were also observed during 2016 surveys.

MWRA has revised its outfall ambient monitoring plan in 2004 and 2011 (MWRA 2004, MWRA 2010), both the number of annual surveys and the monitoring stations sampled during each survey have been reduced through each revision, and the prime whale habitats of Stellwagen Bank and Cape Cod Bay are no longer included in MWRA's marine mammal observations. To provide qualitative information of relative whale abundance through years, whale observations that occurred during surveys before 2011 and within the areas covered by current monitoring plan (see **Figure 1-1**) were identified. The results are summarized in **Table 2-2** and **Figure 2-33**, along with the yearly whale observations since 2011. North Atlantic right whales were not sighted within the current survey areas until recent surveys in year 2012, 2013 and 2016. From 1998-2010, total 5 humpback whales, range 0-2/year; 11 finback whales, range 0-4/year; 34 minke whales, range 0-6/year, and 11 unidentified whales, range 0-3/year, were sighted.

Table 2-2. Number of whale sightings from 1998 to 2016.

Whale species	Total number of sightings (1998-2010)	Range of sightings per year (1998-2010)	2011	2012	2013	2014	2015	2016
Finback	11	0-4	1	0	0	0	0	0
Humpback	5	0-2	0	2	0	0	0	0
Minke	34	0-6	4	0	0	2	0	3
North Atlantic Right	0	0-0	0	2	3	0	0	2
Unidentified	11	0-2	0	3	1	1	0	0

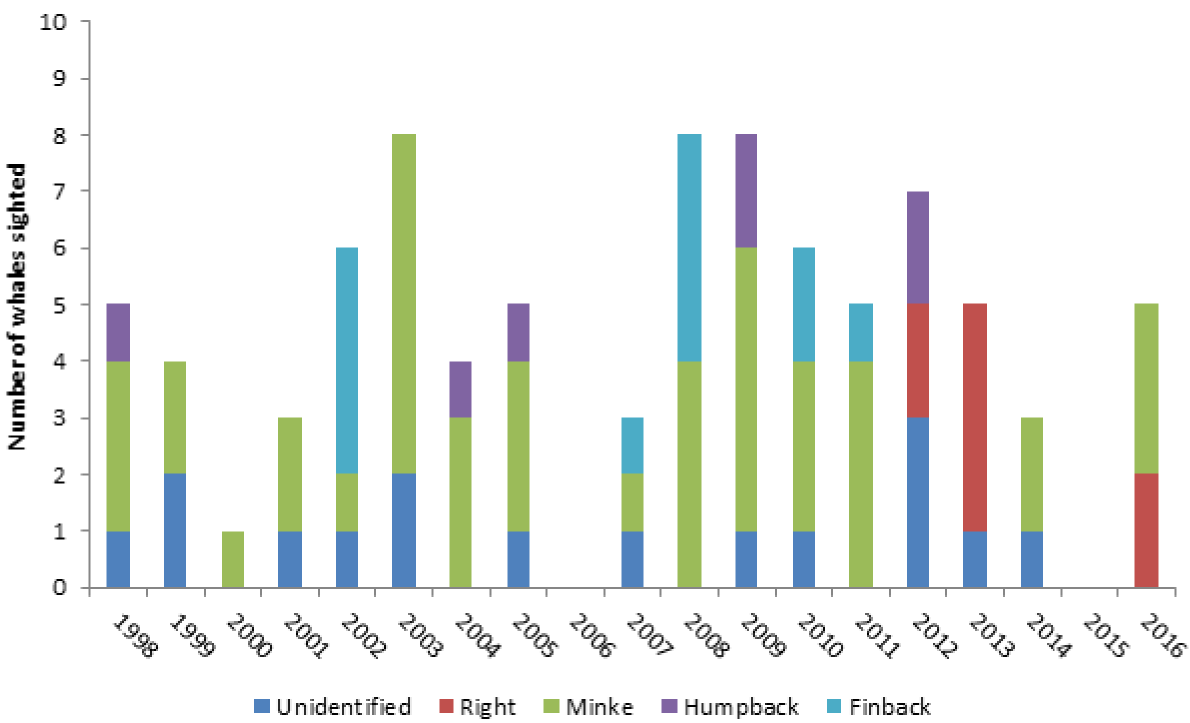


Figure 2-33. Number of whale sightings and whale species sighted in current survey areas (1998 – 2016).

3 LONG-TERM TRENDS

The 2016 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 2-12**). At N18 and N21, NH_4 has been variable with multiple peaks since the discharges started. During baseline years, concentrations at the same locations were much lower and less variable. Despite the NH_4 increase in the outfall nearfield, we have been unable to detect a phytoplankton biomass increase in the same area during the same post-discharge period. In Boston Harbor, since the discharge was moved offshore NH_4 has decreased dramatically, and phytoplankton biomass has also decreased.

The 2016 annual average total phytoplankton abundance in the nearfield (0.76 million cells L^{-1}) was very low in comparison to the long-term mean total phytoplankton abundance of 1.43 million cells L^{-1} ($p = 0.0002$) and ranked 22nd out of the 25 years of monitoring (**Table 2-1**). This is the fourth year in a row the 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 the nearfield in 2016 to about a quarter of 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 characterized 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 in the long-term record of phytoplankton abundance is that nearfield abundances at the surface and at the chlorophyll maximum depth (Cmax), while similar to each other prior to 2001, have differed substantially since then. After 2001, the Cmax and surface trend patterns are qualitatively similar, but total phytoplankton abundance at the Cmax depth has consistently been several hundred thousand cells per liter greater than that at the surface. There are no consistent taxonomic differences in the surface versus Cmax phytoplankton community and it is unclear what factors may be driving the pre/post-2001 differences.

In 2008, total phytoplankton displayed an inflection point in the long-term trend, a change in trend direction from positive (increasing) to negative (declining) in both the surface and Cmax abundance. While the overall total phytoplankton trend has been downward since 2008, not all phytoplankton groups have had this same declining trend. For example, large *Ceratium* spp. have shown cyclical trends during 1992-2016, with relative peaks during 2000 and 2012.

A combination of bottom-up (nutrients, weather) and top-down (grazing) influences likely determine long-term phytoplankton patterns in Massachusetts Bay. Long-term zooplankton trends (**Figure 3-2**) showed an inflection point during 2006 (2 years prior to the phytoplankton inflection point), which was a transition towards increasing zooplankton abundance. That is, the trend towards *declining* phytoplankton abundance that started in 2008 was preceded by a shift towards *increasing* zooplankton abundance that began during 2006. The timing and direction of total phytoplankton and zooplankton trends is consistent with grazing (top down control) as a mechanism responsible for some of the post-2008 declining phytoplankton trend.

Regression analyses conducted on data through 2015 from nearfield stations N04 and N18 indicated that there is a significant relationship between phytoplankton and zooplankton abundance (total and copepod; Libby et al. 2016). Trends in annual total zooplankton and copepod abundance explain 32% and 35%, respectively, 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.

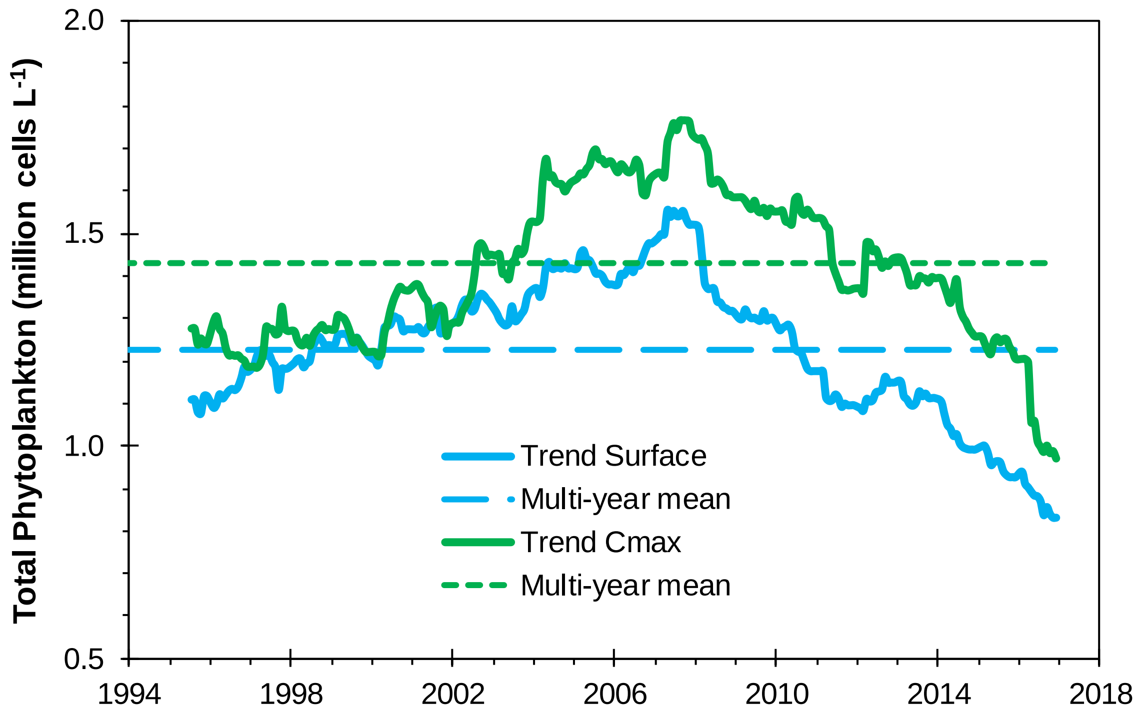


Figure 3-1. Long-term trend (1995 - 2016) in total phytoplankton from surface (light blue) and Cmax (green) depths in the nearfield derived from time series analysis. Data from stations N04 and N18. Data lines based on 15% smoothing window (~3.5 years) as recommended in Broekhuizen and McKenzie (1995) 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 indicates 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). 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 2016 (**Figure 3-2**). The trend for copepod abundances exhibits 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 2007-2016. 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 2009-2016. The unprecedented summer explosion of bivalve veligers in 2015 caused a large upswing in the total zooplankton abundance trend in 2015, but the overall long-term trend in total zooplankton abundance appears to be driven mostly by the trend in copepod abundance.

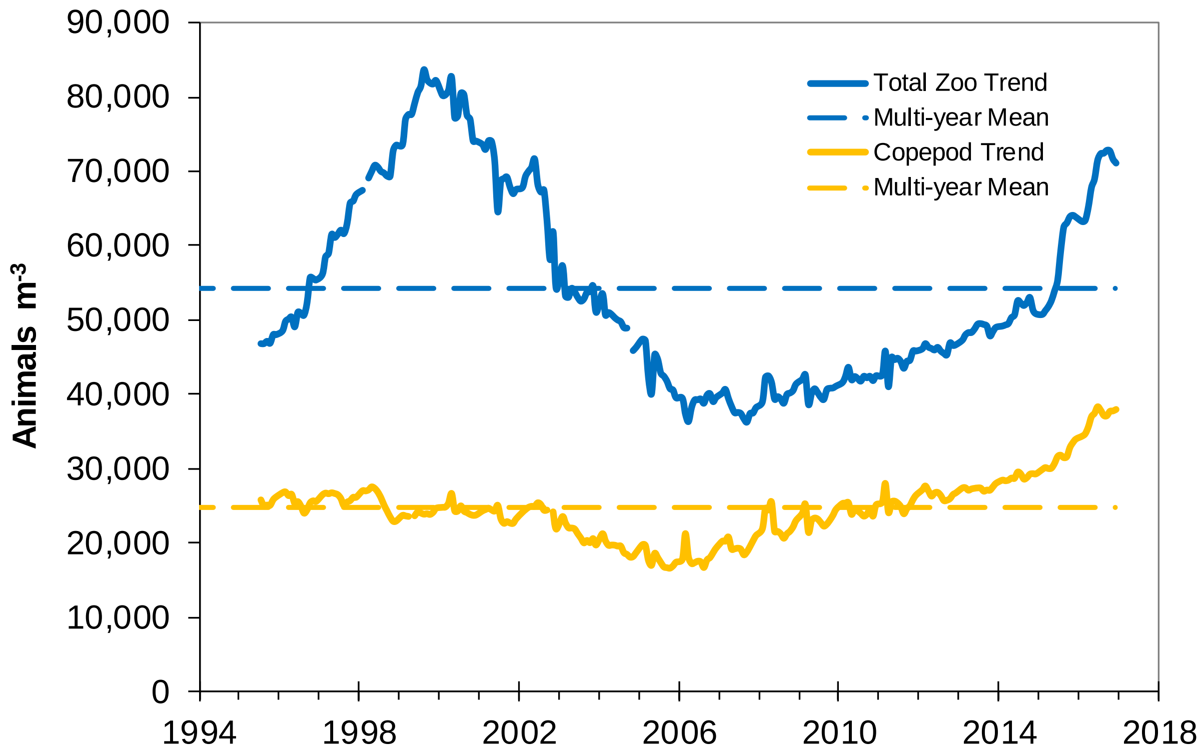
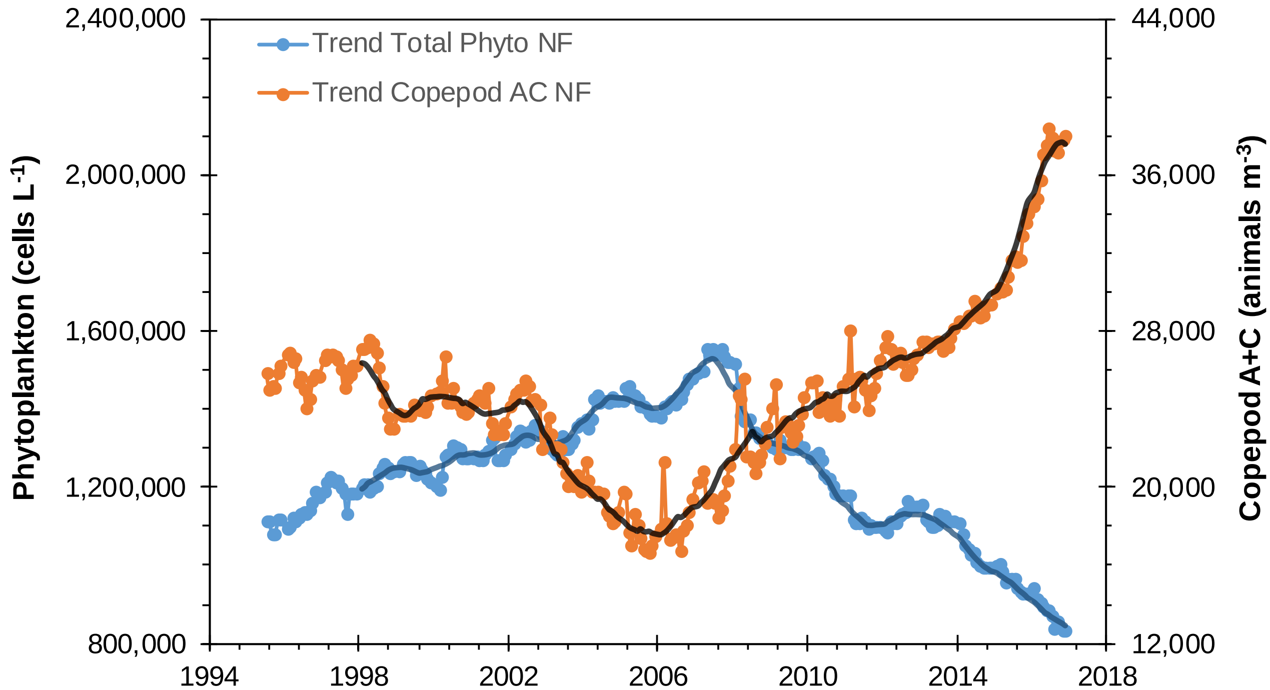


Figure 3-2. Long-term trend (1995 - 2016) in nearfield total zooplankton (blue) and copepod A+C (orange) abundance derived from time series analysis. Long-term mean levels also shown (dashed lines). Data from stations N04 and N18.

The levels of copepods in the nearfield have been above the long-term mean for the last few years. This has been coincident with a decrease in nearfield total phytoplankton abundance. For 2016, the time series analyses were revisited for both nearfield and Boston Harbor station F23 (**Figure 3-3**). These analyses confirm the increasing trend in copepods over the last few years have been coincident with a decrease in total phytoplankton abundances in both areas. Over the last two years (2015 and 2016), abundances of a wide variety of copepods have been relatively high 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 fact that timing of surveys in 2016 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 2008 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 changes in phytoplankton and zooplankton abundance mainly vary at longer-term (decadal) time scales.



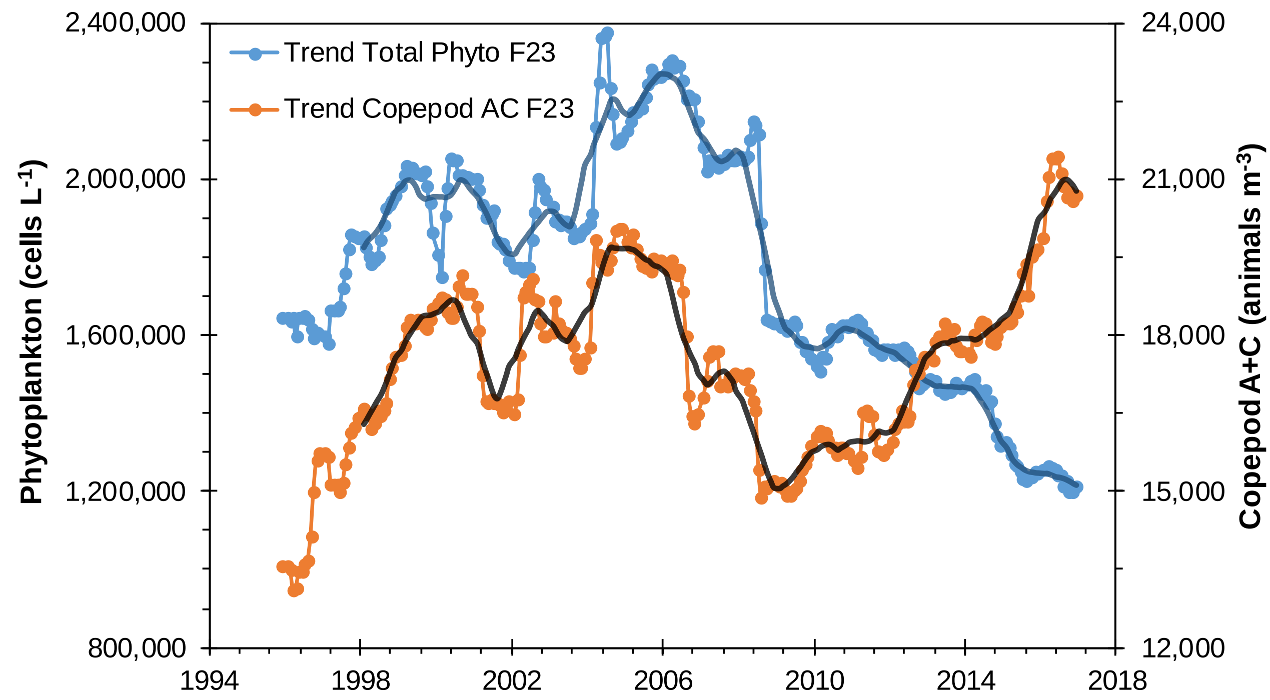


Figure 3-3. Long-term trend (1995-2016) in total phytoplankton (blue) and copepod A+C (orange) abundance in the nearfield (top) and Boston Harbor (bottom) derived from time series analysis. Colored data lines based on 15% smoothing window (~3.5 years) and bold lines for 25% smoothing window (6 years). Nearfield data from stations N04 and N18.

4 SUMMARY

The most notable characteristics of the physical environment of Massachusetts and Cape Cod Bays in 2016 were the warmer than normal temperatures (**Figure 2-1** and **Figure 2-2**), severely dry conditions (**Figure 2-3**), and the impact storms had on onset and breakdown of stratification (**Figure 2-4** and **Figure 2-8**). Precipitation in Boston was close to normal for the winter/spring, but from June through September the rate fell off sharply and remained well below normal for the year (**Figure 2-6**). Overall, precipitation in the Boston area was the 3rd lowest annual total since 1990 following 2015, which was the 4th lowest. The lack of rainfall led to 2015 and 2016 having the lowest flows for the Merrimack and Charles Rivers for the 25-year monitoring program. The extended duration of low precipitation resulted in severe to extreme drought conditions over nearly 80% of Massachusetts by the end of August 2016 including the greater Boston area.

The combination of low freshwater flows/inputs to the system and storm/wind induced mixing in April and early May contributed to a delay in the onset of stratified conditions until late May in Massachusetts Bay (**Figure 2-4**). A combination of mixing and upwelling resulted in strong cooling events in June and July. For the remainder of the summer and fall, Massachusetts Bay was warmer and more saline than for most of the past 25-years. The annual fall overturn and remixing of the water column was observed in stages in the monitoring and buoy data. Strong and persistent winds led to particularly strong downwelling and mixing in September and October 2016 and to early mixing in the shallower waters of Massachusetts Bay (**Figure 2-8**). The winds and water properties at NERACOOS Buoy A01 during the fall indicate that destratification to 20 m depth occurred in conjunction with the late September Northeaster, but the mixing did not extend to 50 m until late October. Survey data showed mixing had still not reached the deep bottom water (>50 m deep) at station F22 by November 1, 2016.

Nutrient concentrations in Massachusetts and Cape Cod Bay generally follow seasonal patterns, with naturally elevated NO_3, SiO_4 and PO_4 concentrations from February into April, low concentrations into August or September, and then increases into November-December (**Figure 2-9**). In the nearfield, where the outfall has a strong influence, NH_4 concentrations are more variable and typically do not show the seasonal pattern shown by the other three nutrients. The most notable deviation from these historic seasonal patterns in 2016 was the relatively low and consistent SiO_4 concentrations from early February through May. The low SiO_4 levels in early February and slightly elevated and steady chlorophyll concentrations over the winter suggest the system remained biologically productive through the winter. Additionally, the observed changes in nearfield NO_3 levels (sharp decrease) relative to SiO_4 (consistent) from February to May along with MODIS fluorescence imagery showing high chlorophyll levels during the period between the April and May survey (**Figure 2-18**) suggest a *Phaeocystis* bloom (or mixed assemblage of diatoms and *Phaeocystis*) occurred during this period.

As has been the case since operation of the bay outfall began in 2000, its effluent plume was observed as elevated NH_4 concentrations in the nearfield in 2016 (**Figure 2-11** and **Figure 2-12**). The elevated NH_4 plume signature was generally seen within 10 to 20 km of the outfall during both well-mixed and stratified conditions, as predicted by pre-diversion model simulations (Signell et al. 1996). Spatial patterns in NH_4 concentrations in the harbor, nearfield and bays since the diversion in September 2000 have consistently confirmed this (Taylor 2016; Libby et al. 2007). In 2016, NH_4 concentrations were typical and within the range observed post-diversion – lower in Boston Harbor and higher in the outfall nearfield compared to baseline (**Figure 2-12**). The levels at stations N18 and N21 were generally within the range of values observed post-diversion. There was no discernable change in nearfield NH_4 levels despite the effluent nitrogen load, primarily in the form of NH_4, in 2016 was the highest observed since outfall start-up in September 2000.

Phytoplankton biomass in Massachusetts Bay can be both spatially and temporally variable, but typically shows a seasonal pattern, with elevated biomass values at intervals during winter-spring, and then again during the fall. In 2016, no large winter/spring bloom was apparent on the 2016 survey dates (**Figure 2-17**); however, satellite observations indicated chlorophyll fluorescence levels peaked between surveys in April to mid-May, which was likely associated with a *Phaeocystis* bloom (**Figure 2-18**). Summer chlorophyll levels were relatively high in the nearfield in comparison to the past 25 years. At many of the Massachusetts Bay stations, summer chlorophyll concentrations fell within the upper range seen during previous years, while phytoplankton abundance was in the lower quartile of the historic range and often near minima from June through August. Satellite imagery and buoy data indicated moderate chlorophyll concentrations occurred in September extending into the fall.

Typically bottom water DO declines at a relatively constant rate in Massachusetts Bay from winter/spring maxima to September or October annual minima. The seasonal decline in bottom water DO levels is closely tied to the onset of stratification in the spring and destratification of the water column in the fall. In 2016, bottom water DO concentration minima were relatively low, but did not exceed Contingency Plan thresholds (**Figure 2-20** and **Figure 2-21**). The DO levels would have been lower if not for the late May mixing event and September storm/winds which led to an earlier breakdown of stratification than in a typical year at most of Massachusetts and Cape Cod Bay by early October. However, DO levels continued to decline in deeper waters reaching a minimum of 6.33 mg L^{-1} at station F22 in November. Relative to previous years, the 2016 bottom water DO concentration minima were low and would have been lower if not for the late May mixing event and September storm/winds.

Overall 2016 had low total phytoplankton abundance, ranking 22nd lowest out of the 25 years of observations, and relatively low abundances were observed for most major phytoplankton functional groups (**Table 2-1**). The fact that surveys did not measure a winter/spring diatom bloom, spring *Phaeocystis* bloom, or fall blooms contributed to the low abundances. Nutrient data and satellite and mooring chlorophyll fluoresce suggest a *Phaeocystis* bloom occurred in late April/early May. *Phaeocystis* at low abundance in a single nearfield sample in May led to a contingency plan threshold exceedance. Although the threshold was exceeded, there was no associated ecological impact. Based on this and previous similar exceedances of this threshold, MWRA requested *Phaeocystis* seasonal means be dropped from the Contingency Plan Thresholds. The OMSAP agreed and recommended EPA accept this interim change. EPA approved the request and it is anticipated it will become final by November 15, 2017.

There were blooms of the toxic species *Alexandrium* and *Pseudo-nitzschia* in western Gulf of Maine waters in 2016. In May, elevated *Alexandrium* abundances were observed in Massachusetts Bay just south of Cape Ann triggering *Alexandrium* Rapid Response Study surveys (**Figure 2-28**). Paralytic Shellfish Poison toxicity had been noted in Western Maine, New Hampshire, and north of Cape Ann, but the 2016 bloom event was minor and short lived and no PSP toxicity was measured in Massachusetts Bay. The *Alexandrium* threshold of 100 cells L^{-1} for outfall nearfield stations was not exceeded. In October 2016, a bloom of toxigenic *Pseudo-nitzschia* caused shellfish harvest closures in Maine, southern Massachusetts (Buzzards Bay and south side of Cape Cod) and Rhode Island waters. However, *Pseudo-nitzschia* spp. levels in Massachusetts Bay during 2016 were not high and were orders of magnitude lower than the maximum prior abundance of 1.8 million cells L^{-1} in 1998. The 2016 maximum *Pseudo-nitzschia* abundance was low (48,000 cells L^{-1}) and occurred in August, approximately two months prior to the beginning of the *Pseudo-nitzschia* spp. bloom in Maine, southern Massachusetts and Rhode Island coastal waters.

An important factor contributing to the low phytoplankton abundance was likely grazing pressure. The 2016 total zooplankton abundances were high continuing a trend observed since 2005 (**Figure 3-2**). The long-term (decadal) shifts in phytoplankton and zooplankton occur over large spatial scales; such broad patterns are not related to the outfall and appear instead to be due to regional ecosystem dynamics in the Gulf of Maine. In Boston Harbor phytoplankton and zooplankton appeared to co-vary prior to the mid-2000s, and since then they appear to be inversely correlated as seen in the nearfield (**Figure 3-3**); it is possible that Boston Harbor plankton dynamics are shifting in response to cleanup efforts and diversion of effluent to the bay.

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Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
www.mwra.com