

2017 Water column monitoring results

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2017 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 2017. 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 Plan¹ attached to the permit.

The only Contingency Plan water column threshold exceeded in 2017 was the *Alexandrium* nuisance species Caution Level threshold. Although the threshold was exceeded, the bloom was due to offshore populations being brought into Massachusetts Bay via surface water currents and was unrelated to the bay outfall. No paralytic shellfish poisoning (PSP) toxicity was detected by Massachusetts Department of Marine Fisheries (DMF) in the bay in 2017. The *Alexandrium* bloom was advected into the bay, was persistent but remained offshore, and did not impact shellfisheries in the bay.

| Parameter | Time Period | Caution Level | Warning Level | Baseline/ Background | 2017 |
|--|--------------------------|-------------------|-------------------|--|-------------------------------------|
| 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: 7.33 SW Basin: 7.36 |
| Bottom water DO percent saturation (%) | Survey Mean June-October | <80% ^b | <75% ^b | Nearfield: 65.3% SW Basin: 67.2% | Nearfield: 78.9% SW Basin: 77.2% |
| Bottom water DO rate of decline (mgL ⁻¹ d ⁻¹) | Seasonal June-October | >0.037 | >0.049 | 0.024 | 0.013 |
| Chlorophyll (nearfield mean, mg m ⁻²) | Annual | >108 | >144 | 72 | 77 |
| | Winter/spring | >199 | -- | 50 | 88 |
| | Summer | >89 | -- | 51 | 58 |
| | Autumn | >239 | -- | 90 | 99 |
| <i>Pseudo-nitzschia pungens</i> (nearfield mean, cells L ⁻¹) | Winter/spring | >17,900 | -- | 6,735 | 68 |
| | Summer | >43,100 | -- | 14,635 | 273 |
| | Autumn | >27,500 | -- | 10,500 | 1,780 |
| <i>Alexandrium catenella</i> (nearfield, cells L ⁻¹) | Any nearfield sample | >100 | -- | Baseline Max 163 | 494 |

^aDO = Dissolved Oxygen

^bUnless background lower

^cSW = 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 2017 water column monitoring confirmed 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 2017 included:

- Warmer waters were consistently observed at stations across Massachusetts Bay in early 2017 and mark the second year in a row with warm winter temperatures. Merrimack River flow was high from April to June and high regional riverine inputs resulted in below normal salinities in Massachusetts Bay contributing to the onset of stratification in the bay in April.
- Several Nor'easters occurred from mid-May to early June, resulting in strong currents transporting the Merrimack River plume into the bay. This contributed to anomalously strong stratification in early June. There was a long period of upwelling-favorable, southerly winds in June/July, that led to cooler, more saline surface waters and an increase in nutrient concentrations. A brief decrease in the strength of these winds in mid-June resulted in a "relaxation" of the upwelling and caused a shift in the current to a more onshore, southwestward direction.
- 2017 nutrient concentrations in the bay were broadly consistent with what we have seen since the outfall became operational. Ammonium (NH_4) concentrations were typical and within the range since 2000: lower in Boston Harbor, and higher in the outfall nearfield, compared to pre-diversion baseline conditions. During summer stratified conditions, elevated concentrations were observed below the pycnocline at stations F15 and F10, about 10 and 20 km south of the outfall, respectively.
- Except for somewhat elevated chlorophyll concentrations at four of the stations (one in the harbor and the other three in the bay) in June and July, chlorophyll concentrations during 2017 were moderate. Chlorophyll concentrations in the nearfield met Contingency Plan Caution Level thresholds.
- In June *Alexandrium* were observed in Massachusetts Bay at abundances (≥ 100 cells L^{-1}) exceeding the Contingency Plan caution threshold. This triggered the first of four springtime *Alexandrium* Rapid Response Study (ARRS) surveys in 2017. During the ARRS survey, *Alexandrium* abundances were consistently highest (100s to 1,000s cells L^{-1}) at offshore stations.
- Bottom water dissolved oxygen (DO) concentration minima were moderate over most of Massachusetts Bay in 2017 and well above Contingency Plan thresholds. Bottom water DO levels would have been lower if not for June upwelling that raised concentrations by 0.5 to 1 mg L^{-1} . However, fall destratification was later than typical, in November, resulting in bottom water DO minima at southern Massachusetts Bay and Cape Cod Bay stations in the lower range of historic values (though still >6 mg L^{-1}).
- Annual total phytoplankton abundance measured during the 2017 MWRA surveys was low and ranked 21st for the 26-year monitoring program. The relatively low 2017 total phytoplankton abundance was in part due to the lack of a large winter-spring diatom or *Phaeocystis* bloom. There are indications over the past couple years of a shift to a two-part winter spring bloom featuring an early (January-February) *Thalassiosira*-dominated winter bloom which terminates due to grazing and nutrient draw-down, followed by a later (April) *Skeletonema*-dominated bloom.
- High PSP toxicity was measured in the western Gulf of Maine resulting in shellfishing closures from Cape Ann, Massachusetts to Eastern Maine. However, PSP toxicity was not detected at any of the MA DMF stations within Massachusetts Bay proper. This is consistent with the overall distribution of elevated abundances observed at offshore stations during MWRA surveys. The northeast winds likely entrained *Alexandrium* into the bay, while subsequent upwelling favorable winds out of the south kept the *Alexandrium* bloom offshore and away from shellfish resources.
- A bloom of the toxic pennate diatom *Pseudo-nitzschia* caused shellfish harvest closures in Maine and Rhode Island waters in 2017. However, in Massachusetts Bay, *Pseudo-nitzschia* spp.

levels were low and no amnesic shellfish poisoning (ASP) closures were required in Massachusetts Bay.

- There was an unusual dinoflagellate bloom of *Karenia mikimotoi* in September 2017 with elevated abundances seen from Massachusetts Bay to Casco Bay by MWRA and other regional monitoring programs. *K. mikimotoi* had not been observed in the previous 25 years of MWRA monitoring nor is it typical of the Gulf of Maine regional phytoplankton flora. Its presence in the bay is unrelated to the outfall.
- Total zooplankton exhibited unusual bimodal peaks in abundance in May/June and August/September 2017, rather than the single peak in July or August seen in typical past years. Abundances of total zooplankton and many dominant taxa (including *Calanus finmarchicus* and *Oithona similis*) were at or above maxima for the 26-year monitoring program at many stations in Massachusetts Bay in 2017. The warm temperatures observed in winter/spring 2017 may have contributed to the early zooplankton peaks.
- 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. Inter-annual variations in phytoplankton and zooplankton populations in the nearfield appear to be inversely correlated suggesting grazing pressure is an important factor on the overall abundance of phytoplankton in Massachusetts Bay. In Boston Harbor, inter-annual variations in phytoplankton and copepod abundance generally co-varied from 1992 to 2008, but since 2009, they have been inversely correlated. This change may be related to harbor recovery.
- A total of 15 whales were observed during various MWRA monitoring surveys in 2017 including a record high for the program of eight North Atlantic right whales – four in Massachusetts Bay in March and four in Cape Cod Bay in April.

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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) and for the ‘outfall discharge’ period since the 2000 relocation (MWRA 1997; and updates MWRA 2004, 2010). The baseline period extends from 1992 to September 1, 2000, when Deer Island and/or Nut Island wastewater discharges were released directly within the harbor. The outfall discharge period extends from September 6, 2000 through 2017, when wastewater has been discharged from the bay outfall and not into the harbor. The 2017 data complete 17 years of monitoring since operation of the bay outfall began on September 6, 2000 and 26 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 now focusses on the stations potentially affected by the discharge and reference stations in Massachusetts Bay. Nine one-day surveys were undertaken in 2017 (**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 2017 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

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. 2018). 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 2017 sampling dates are shown in **Table 1-2**. Five stations are sampled in the nearfield (N01, N04, N07, N18, and N21) and nine stations in the farfield (F01, F02, F06, F10, F13, F15, F22, F23, and F29). 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. Four additional surveys were conducted in June and July 2017 as part of an *Alexandrium* Rapid Response Study (ARRS) triggered by elevated abundances of this toxic species (Libby et al. 2013)⁴; those dates are listed 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 2017. Observations made by field staff on the ARRS and BHWQM surveys were documented and are included in this report. Note the ARRS data have been included in many of the figures presented in this report. However, historical ARRS data are not included in the quartile calculations presented in the shaded percentile plots (e.g. **Figure 2-2**). The ARRS data are not included in the calculation of 2017 seasonal chlorophyll threshold values.

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 (**Figure 1-1**). The time series current observations from NERACOOS Buoy A01 presented and interpreted here are the non-tidal flow, isolated from tidal variations by application of a low-pass filter.

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/harbor_sampling_locations_detail.jpg

⁴ ARRS station map available at <http://www.mwra.state.ma.us/harbor/enquad/pdf/2013-06.pdf>

The data are grouped by season for calculation of chlorophyll 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 2017.⁵

Table 1-2. Water column surveys for 2017.

| Survey | Massachusetts Bay Survey Dates | Cape Cod Bay Survey Dates | Harbor Monitoring Survey Dates |
|--------|--------------------------------|---------------------------|--------------------------------|
| WN171 | February 18 | February 19 | February 15 |
| WN172 | March 25 | March 25 | March 23 |
| WN173 | April 24 | April 17 | April 20 |
| WN174 | May 16 | May 16 | -- |
| WN175 | June 13 | June 13 | June 12 |
| AF171 | June 21 | -- | -- |
| AF172 | June 28 | -- | June 26 |
| AF173 | July 8 | -- | July 6 |
| AF174 | July 16 | -- | -- |
| WN176 | July 26 | July 26 | July 31 |
| WN177 | August 23 | August 23 | August 29 |
| WN178 | September 6 | September 6 | -- |
| WN179 | November 1 | November 1 | November 7 |

WN = the nine surveys undertaken each year; AF = *Alexandrium* Rapid Response surveys triggered in response to elevated *Alexandrium* counts.

⁵ 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.

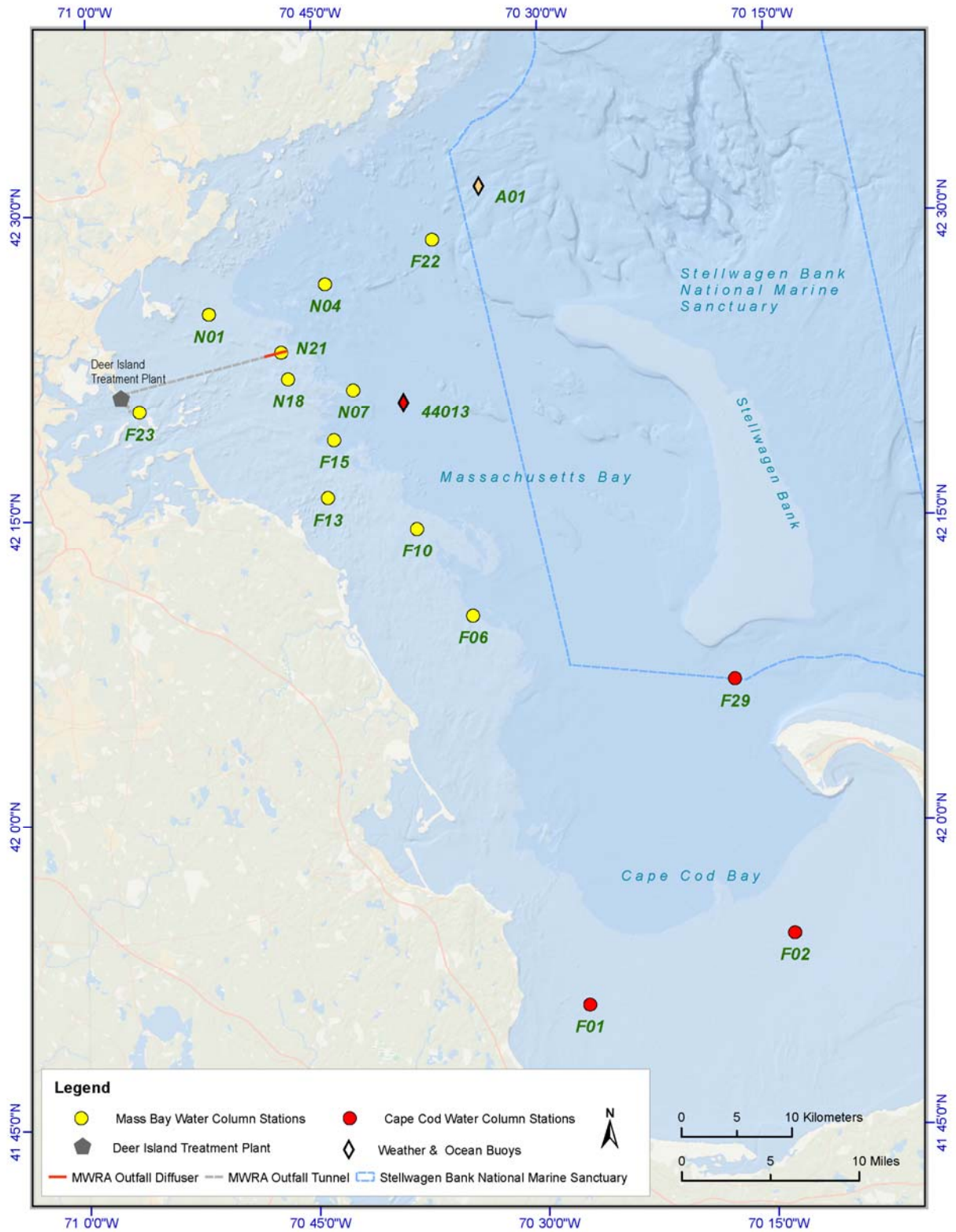


Figure 1-1. Water column monitoring locations.

2 2017 MONITORING RESULTS

2.1 BACKGROUND

The Massachusetts Bay ecosystem exhibits a seasonal cycle during which its physical structure, biology, and biogeochemical cycling change. External processes (meteorological and river forcing, exchange with offshore waters) 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 growth increases and develops into a winter/spring bloom. The intensity 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 catenella*, 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, the water column becomes stratified, nutrient concentrations in the surface waters are depleted by phytoplankton consumption, and 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.

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 returns nutrients to 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 26-year dataset (1992-2017). The major features and differences in 2017 are presented below.

2.2 PHYSICAL CONDITIONS

From January through early March, observations at the NDBC Buoy 44013, about 10 km southeast of the outfall, indicated surface water temperatures were above 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 (**Figure 2-2**). Bottom water temperatures were also elevated at station N18 compared to previous monitoring results. The warmer waters in early 2017 were consistently observed at stations across Massachusetts Bay and mark the second year in a row with warm winter water temperatures. Surface and bottom water temperatures cooled into April and May to typical levels.

During winter (January through March), river flow for the Merrimack and Charles Rivers was well below the long-term median (**Figure 2-3**). Surface and bottom water salinities during this period were in the upper quartile of long-term range at station N18 (**Figure 2-2**).

One notable condition in 2017 was the wet spring, with prolonged high discharge of the Merrimack River in April, May and June (**Figure 2-3**; note the Charles River was near median levels in the spring). The regional river inputs resulted in below normal (lower quartile) salinities in Massachusetts Bay as seen in both the surface and bottom water at station N18 in May and June (**Figure 2-2**) and contributed to the onset of stratification in the bay in April (**Figure 2-4**). For the remainder of 2017, river flows were generally near normal levels.

Winds from mid-May to early June showed several Nor'easters (**Figure 2-5**), during which the surface currents at the NERACOOS A01 buoy showed strong flow, ~ 0.5 m/s or ~ 50 km/day, to the southeast. This resulted in substantial drops in surface salinity at the NERACOOS A01 buoy in May and June indicating the presence of the Merrimack River plume. This freshwater inflow in the surface layer down to 20 m contributed to anomalously strong stratification in early June (**Figure 2-4**).

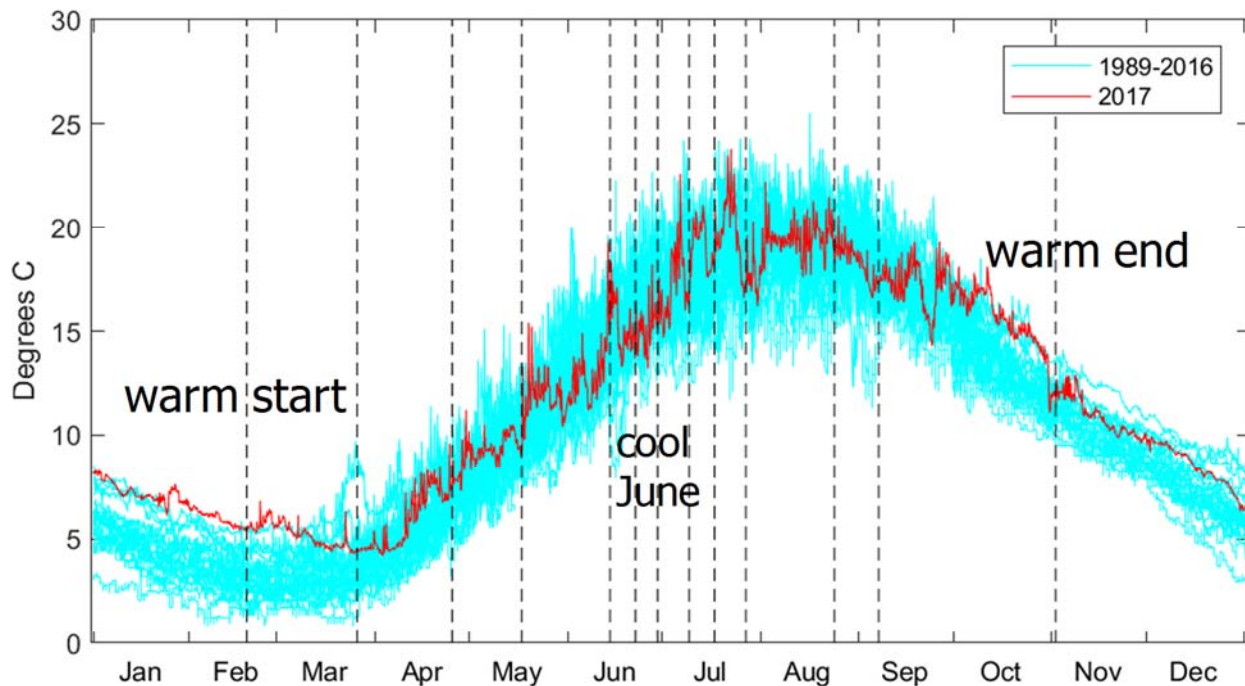


Figure 2-1. Comparison of 2017 surface water temperature ($^{\circ}\text{C}$) at NDBC Buoy 44013 (“Boston Buoy”) in the vicinity of the nearfield (solid red line) with 1989-2016 (light blue lines). The vertical dashed lines are when the 13 surveys were conducting in 2017.

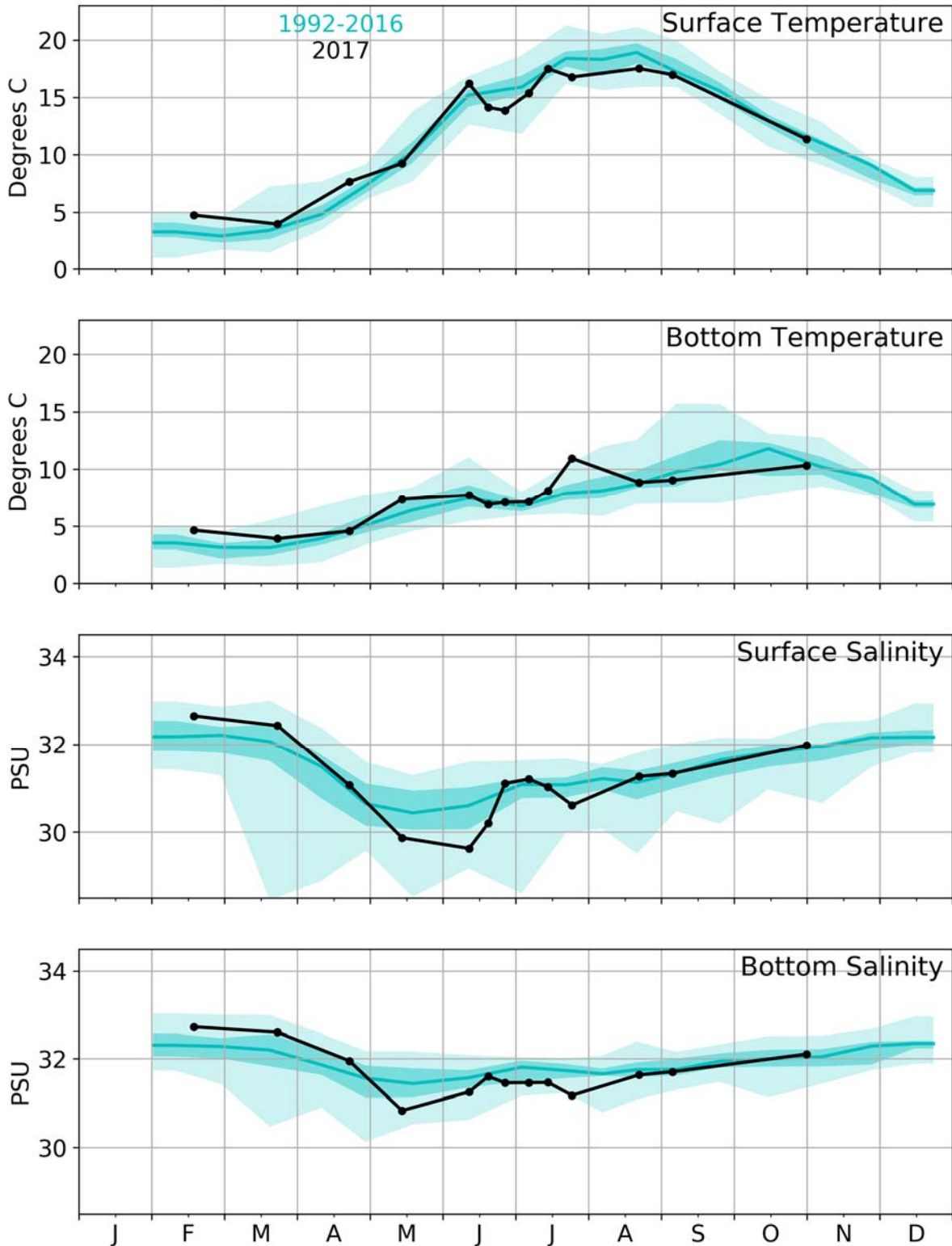


Figure 2-2. Comparison of 2017 surface and bottom water temperature and salinity at nearfield station N18 compared to prior years. 2017 results are in black. Results from 1992–2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

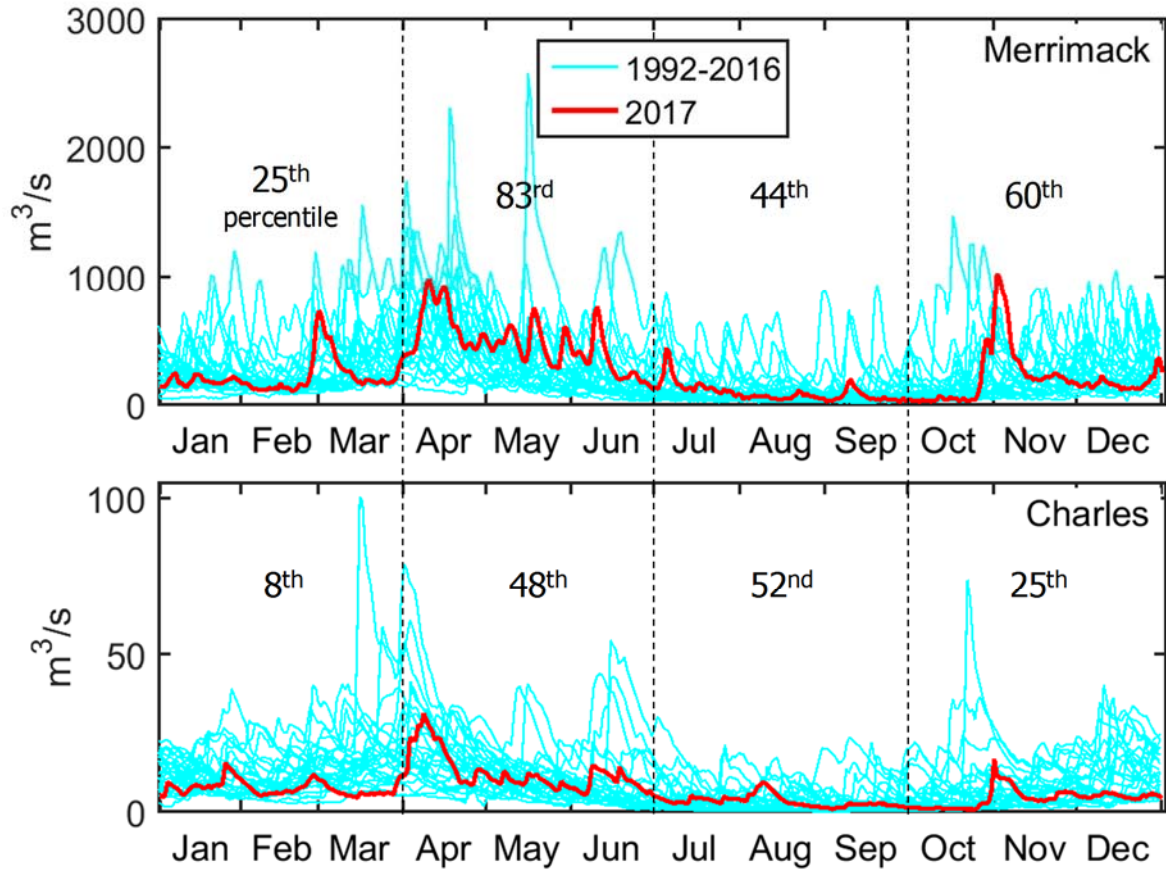


Figure 2-3. Comparison of 2017 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2016 (light blue lines). The percentiles shown represent 2017 flow, compared to the entire 26-year record, during each quarter of the year.

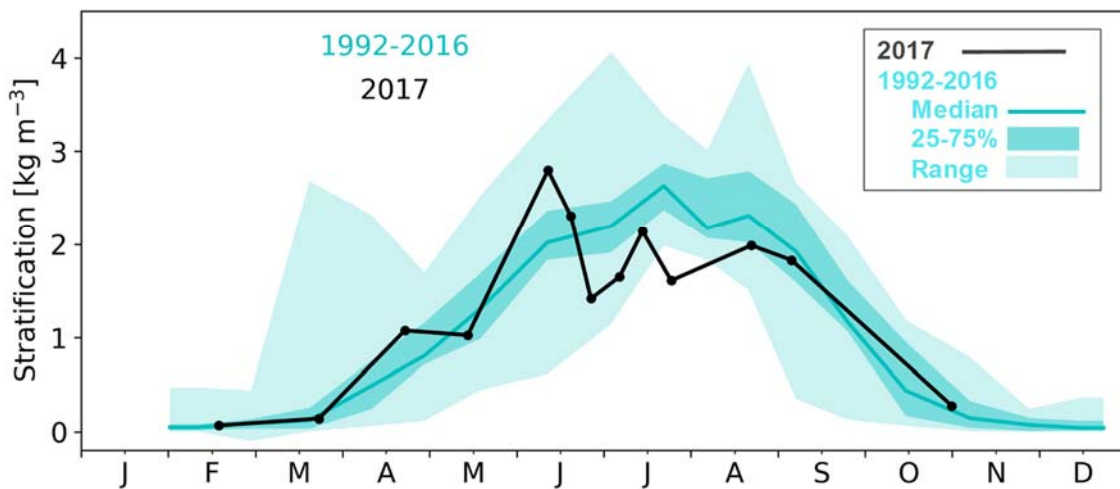


Figure 2-4. Stratification at nearfield station N18 in Massachusetts Bays in 2017 compared to prior years. 2017 results are in black. Results from 1992–2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

After the early June Nor'easter, there was a long period of upwelling-favorable, southerly winds (**Figure 2-5**). Upwelling led to a decrease in surface temperatures and increases in surface salinity at station N18 over the course of June into early July (**Figure 2-2**). Stratification during this period (mid-June to late July) in 2017 was weaker than in most previous years (**Figure 2-4**). The southerly winds also produced weak currents at NERACOOS A01 and cooler than normal near-surface water temperatures in Massachusetts Bay. A strong upwelling event occurred on June 17-18, followed by a reduction in wind strength and a slight reversal on June 21 (**Figure 2-6**). This drop in wind strength resulted in a “relaxation” of the upwelling, meaning that the warm waters moved back toward the coast, as indicated by a sharp rise in temperature at the Boston buoy around June 21 (**Figure 2-1**). This also caused a shift in the current to more onshore from southward to southwestward. One of the ARRS surveys was conducted during this period and this change in current influenced the transport and distribution of *Alexandrium* in the bay (see Section 2.5).

The month-long period of predominantly southerly winds led to anomalously high upwelling index for June 2017 (**Figure 2-7**) and a coincident decrease in stratification over the course of the month (**Figure 2-4**). In contrast, the upwelling index in July 2017 was low compared to historic values. This variability continued through the remainder of the year, with strongly downwelling favorable conditions through September and anomalously strong upwelling in October due to strong southerly winds (**Figure 2-7**). Stratification at station N18 from August through early November remained close to typical values and the water column was relatively well mixed in the nearfield by the final survey on November 1st (**Figure 2-4**). The water column remained stratified at offshore station F22 into November (not shown) with a thermocline/pycnocline at 35 m and a $\Delta \sigma\text{-T} > 1$ between surface and bottom waters.

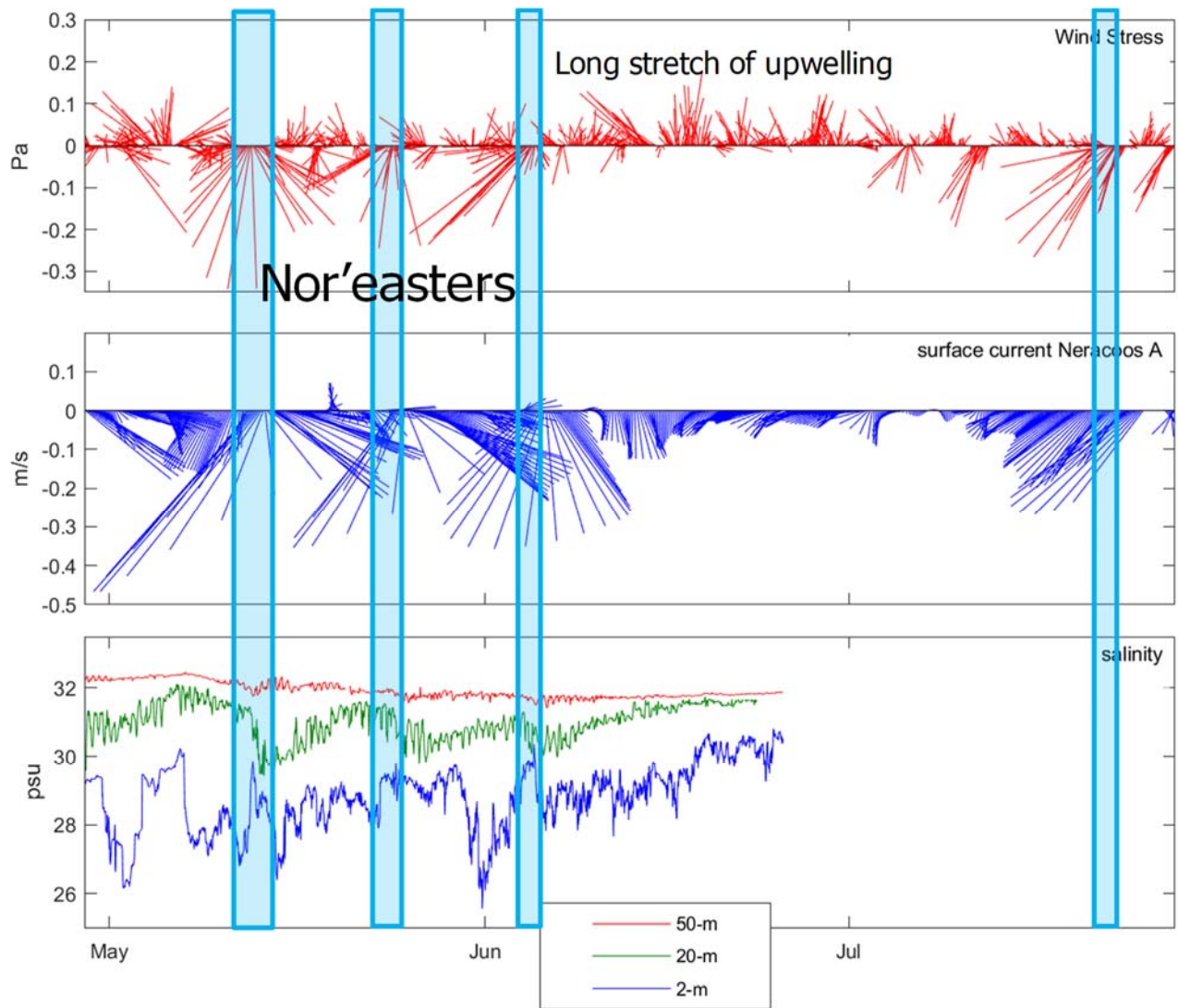


Figure 2-5. NERACOOS Buoy A01 time series observations in May – July 2017. Top: surface wind strength and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: surface currents at 2 m depth. Bottom: salinity at 2, 20, and 50 m depths. Vertical rectangles show dates during which the winds were predominantly from the northeast.

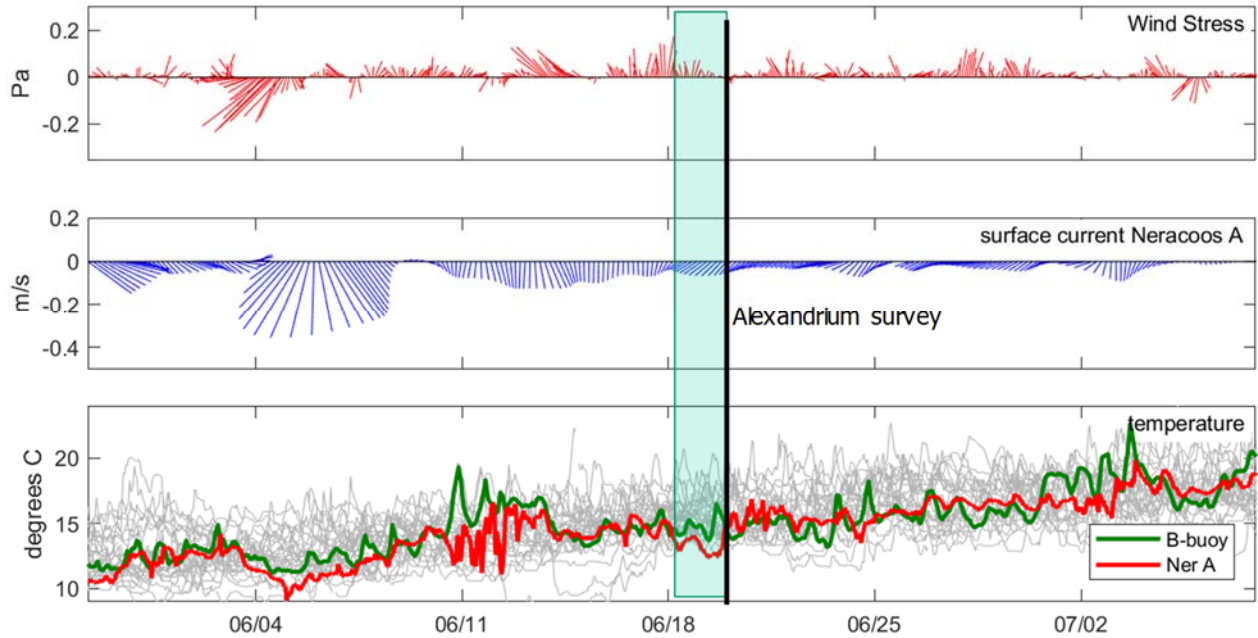


Figure 2-6. NERACOOS Buoy A01 time series observations in June – July 2017. Top: surface wind strength and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: surface currents at 2 m depth. Bottom: temperature at 2 m depth (NERACOOS A01 in red; NDBC Buoy 44013 or “Boston buoy” in green). Vertical green panel shows period during which wind strength decreased, and direction of flow shifted from south to more southwestward.

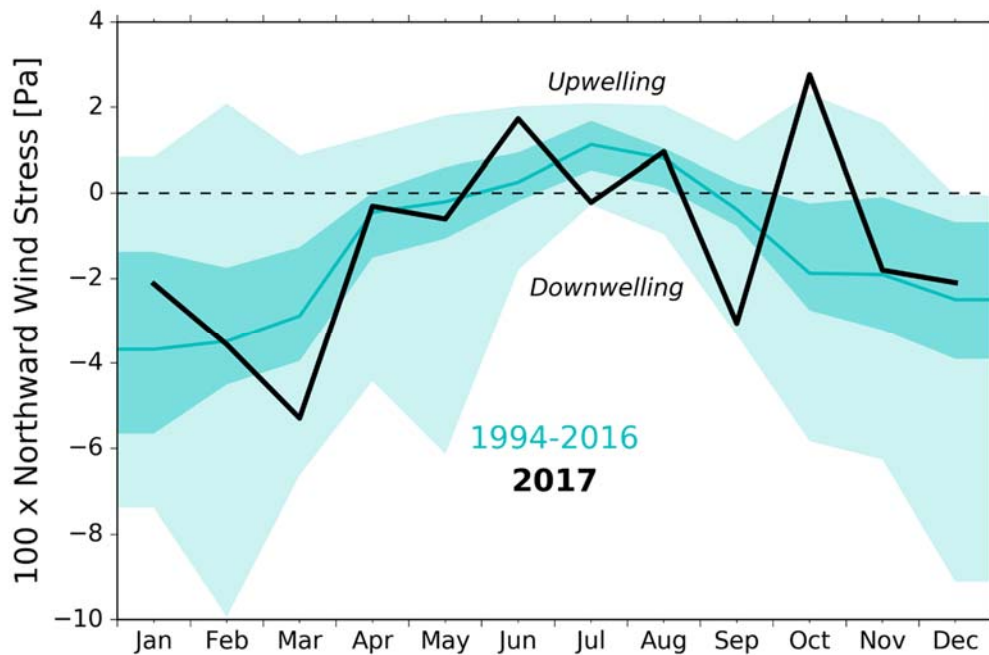


Figure 2-7. Average wind stress at NDBC Buoy 44013. 2017 results are in black. Results from 1992–2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

2.3.1 Nutrients

During most years, over much of Massachusetts and Cape Cod Bays, concentrations of the dissolved inorganic nutrients, nitrate (NO_3), silicate (SiO_4) and phosphate (PO_4), are naturally elevated from February into April, relatively low from May into August or September, and then increase into November-December. Observations from station N18, located 1 km south of the outfall, are representative (**Figure 2-8**; see dark shaded areas denoting the 25th to 75th percentile). Ammonium (NH_4) concentrations (**Figure 2-8**, upper right) are more variable, and typically do not exhibit the seasonal pattern.

In winter/spring 2017, dissolved inorganic nutrient concentrations at station N18 followed their historic seasonal patterns, except for SiO_4 concentrations, which from February through April were low compared to previous years (**Figure 2-8**). This pattern was also observed in 2016. The low SiO_4 concentrations during the early February survey suggest that diatoms, which require SiO_4 for growth, were likely dominant and productive during the prior winter months. From February to May, NO_3 levels decreased, though remaining high relative to historic levels in March and April. By May, NO_3 levels were nearly depleted across all stations (**Figure 2-9**). This was coincident with a slight increase in SiO_4 from April to May as seen at station N18 (**Figure 2-8**). The relative changes in NO_3 and SiO_4 concentrations could be due to the increased riverine inputs or an increase in *Phaeocystis* abundances.

Strong upwelling in June led to increased nutrient concentrations (**Figure 2-8**), in the upper quartile observed since 1999, during the June survey and each of the first three ARRS surveys. By the late July survey, concentrations were again depleted at station N18 and much of Massachusetts Bay. From late July through early November, NO_3 (and SiO_4 and PO_4) concentrations generally increased, with NO_3 and SiO_4 reaching monthly maxima for the monitoring program on the November survey.

In the nearfield (stations N07, N18, and N21) and to the south at stations F15 and F10, episodic peaks in NH_4 were observed over the summer period due to the time-varying spatial distribution of the MWRA effluent from the outfall (**Figure 2-10** and **Figure 2-11**). 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 2-11**). This continued to be the case in 2017 with nearly all depth-averaged NH_4 concentrations at station F23 below baseline levels (except in June), while at stations N18 and N21, depth-averaged NH_4 levels were greater than baseline for most 2017 surveys. The NH_4 levels at station N21 were close to the median values observed post-diversion, while at station N18 there were a number of surveys that exhibited high concentrations in the upper quartile for post-diversion values (March, April, June, and August). Elevated NH_4 concentrations in comparison to historic levels were observed at station F15 in May and late July. During the late July survey, elevated NH_4 concentrations were also seen further south at station F10. Overall, summer and fall nutrient concentrations were like those observed since the bay outfall became operational.

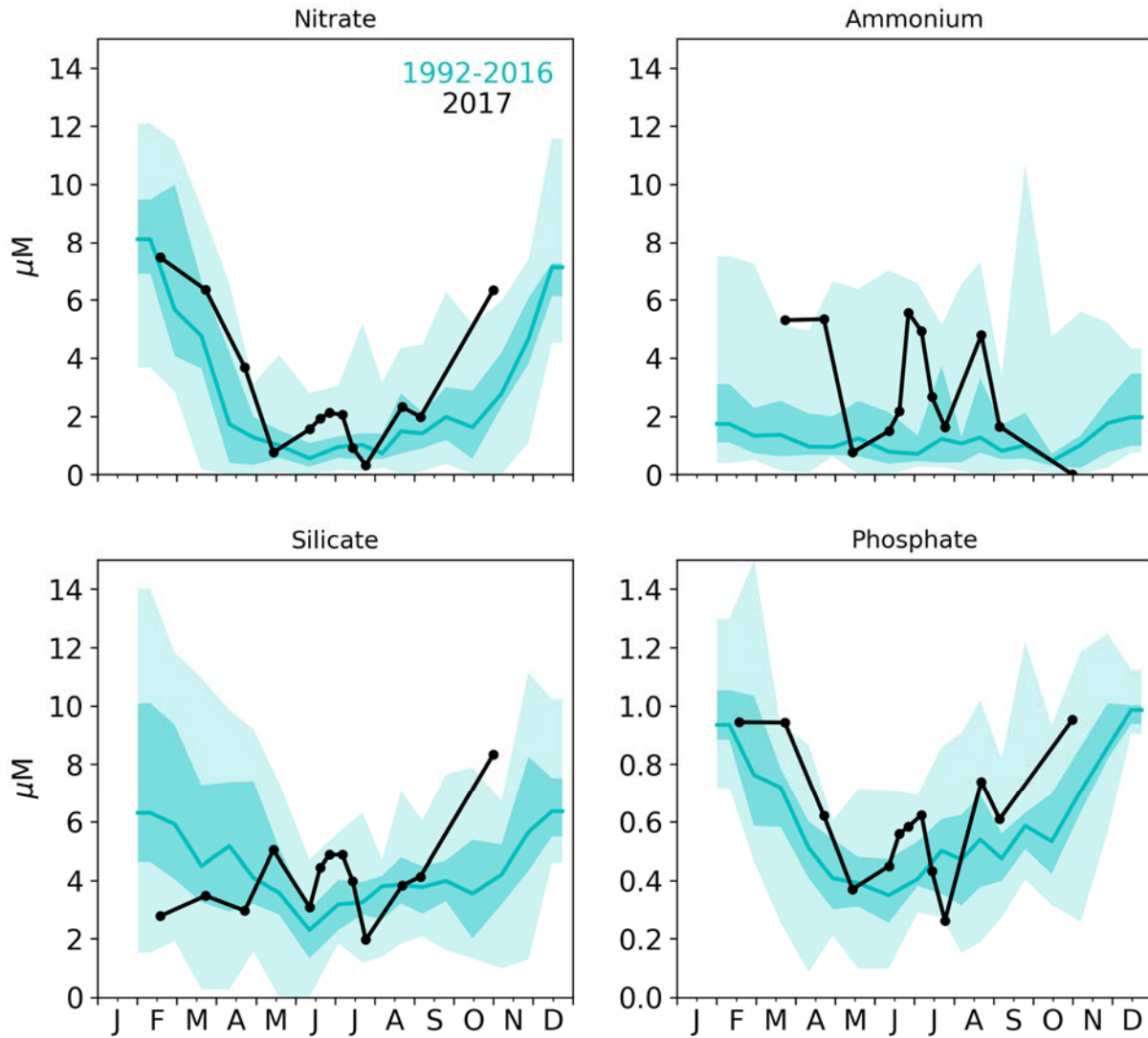


Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (μM) at station N18, one kilometer south of the outfall, in 2017 compared to prior years. Note difference in scale for phosphate. 2017 results are in black. Results from 1992–2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. Note no NH_4 data are available for the February 2017 survey.

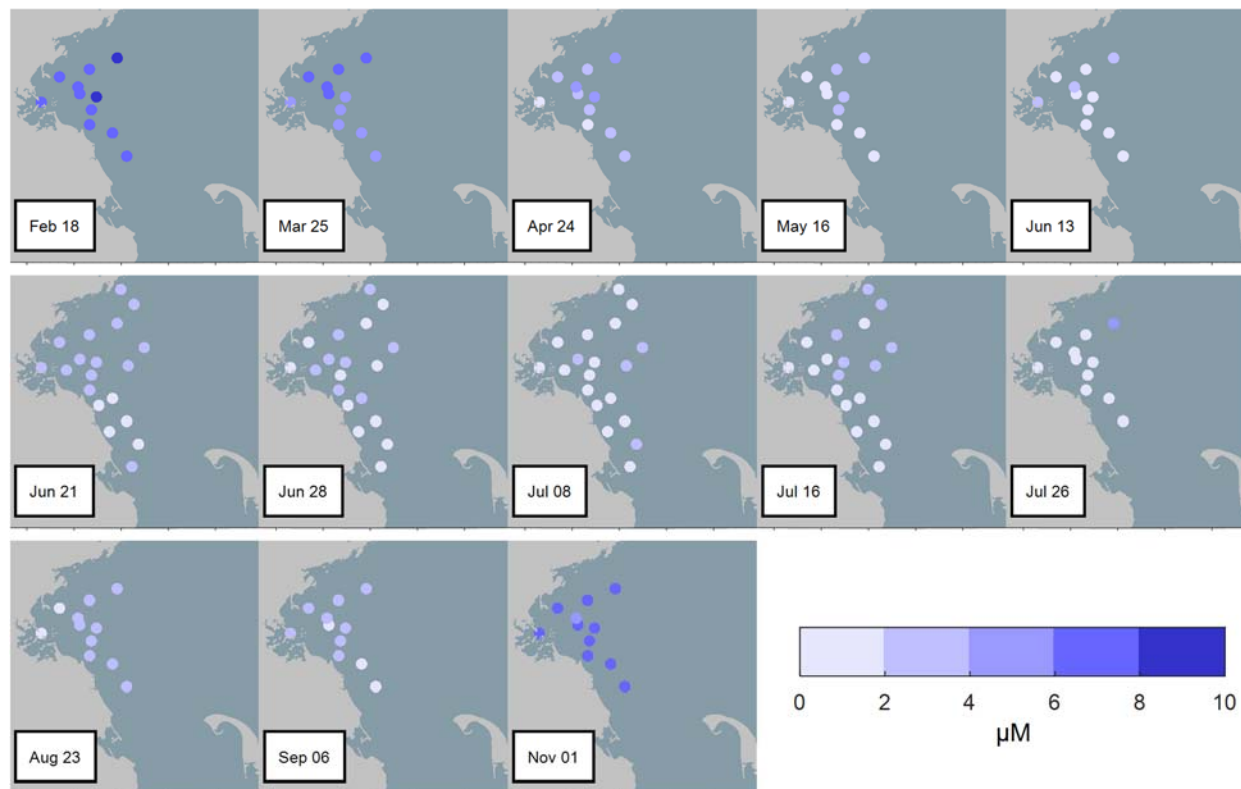


Figure 2-9. Depth-averaged NO_3 concentrations (μM) at stations in Massachusetts and Cape Cod Bays in 2017.

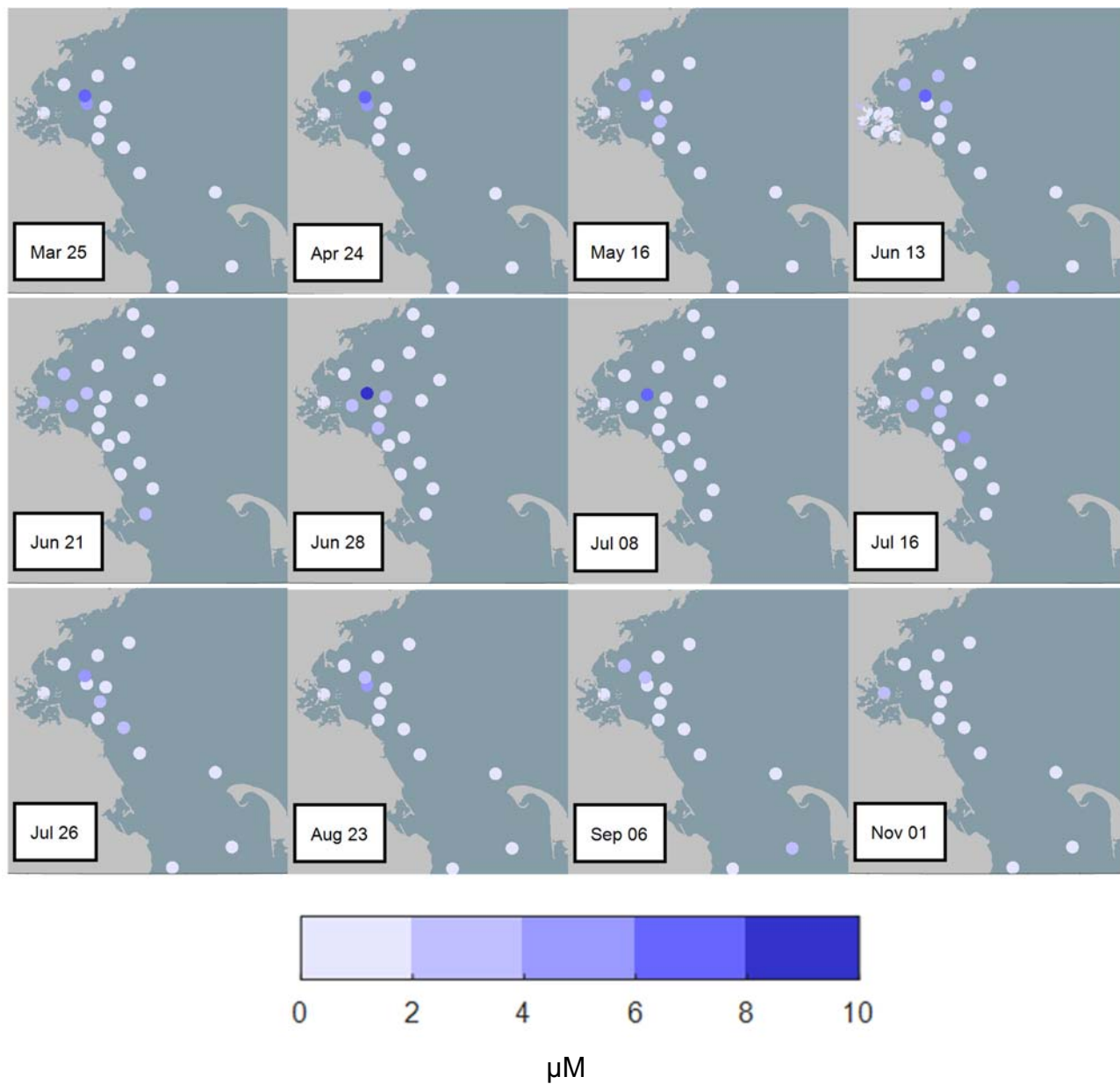


Figure 2-10. Depth-averaged NH_4 concentrations (μM) at stations in Massachusetts and Cape Cod Bays in 2017. (Note – no NH_4 data were available for February 2017).

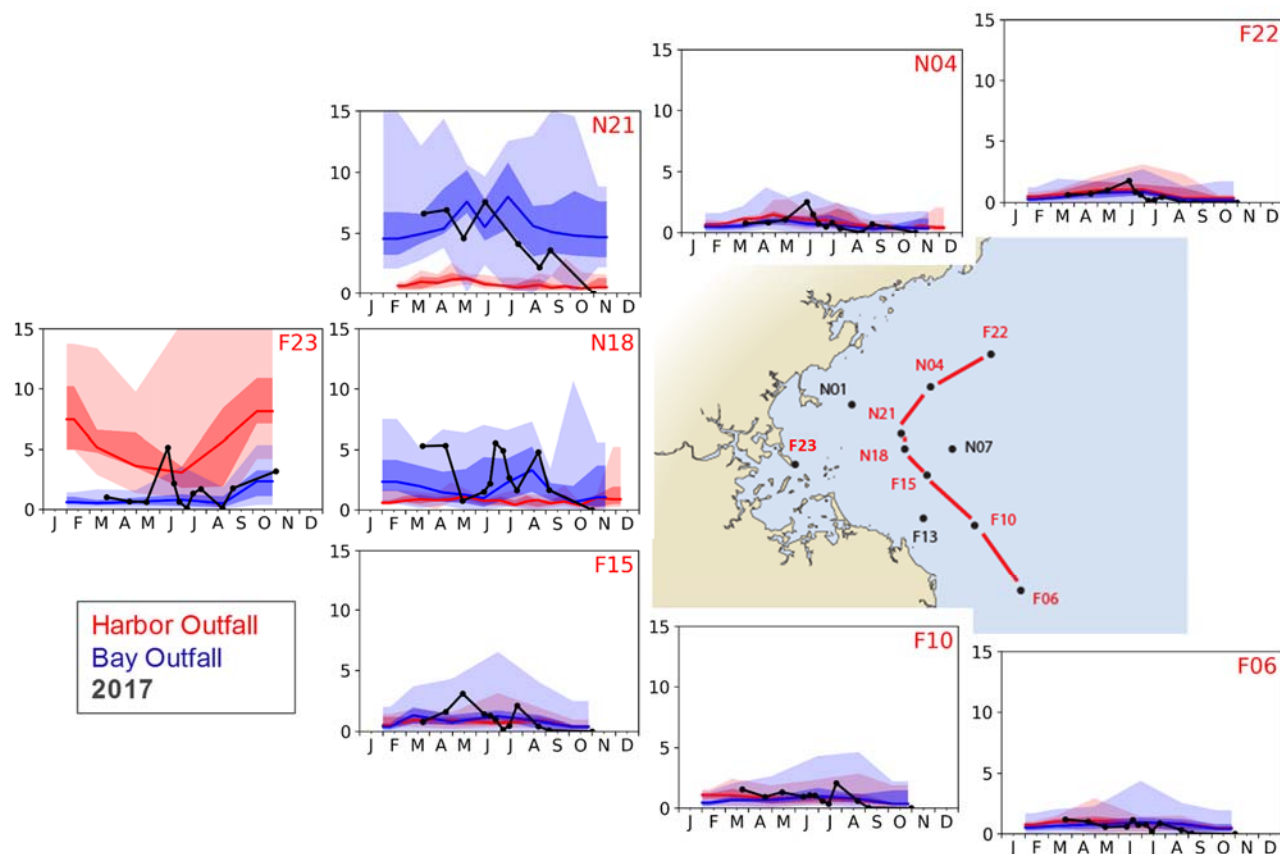


Figure 2-11. Depth-averaged NH_4 (μM) at selected stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black; baseline (1992–August 2000) results are in red; and post-diversion (September 2000–2016) results are in purple. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. This figure includes the ARRS survey data.

In 2017, as in other years since the bay outfall began operating in 2000, the NH_4 signal from the effluent discharge plume was observed within 10 to 20 km of the outfall (**Figure 2-12** and **Figure 2-13**). In March, when the water column was vertically well mixed, the plume NH_4 signature was only observed in the surface waters in the nearfield. During the July survey, when the water column was vertically stratified with a pycnocline located at approximately 10 to 15 m, the NH_4 signal was observed at or below the pycnocline at stations N21 and N18, the locations closest to the outfall; it was also observed at stations F15 and F10, about 10 and 20 km south of the outfall, respectively (**Figure 2-14**). 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 2017, sub-surface chlorophyll maxima were observed near the pycnocline with elevated values of $>8 \mu\text{gL}^{-1}$ observed at stations N18 and F15 (**Figure 2-14**).

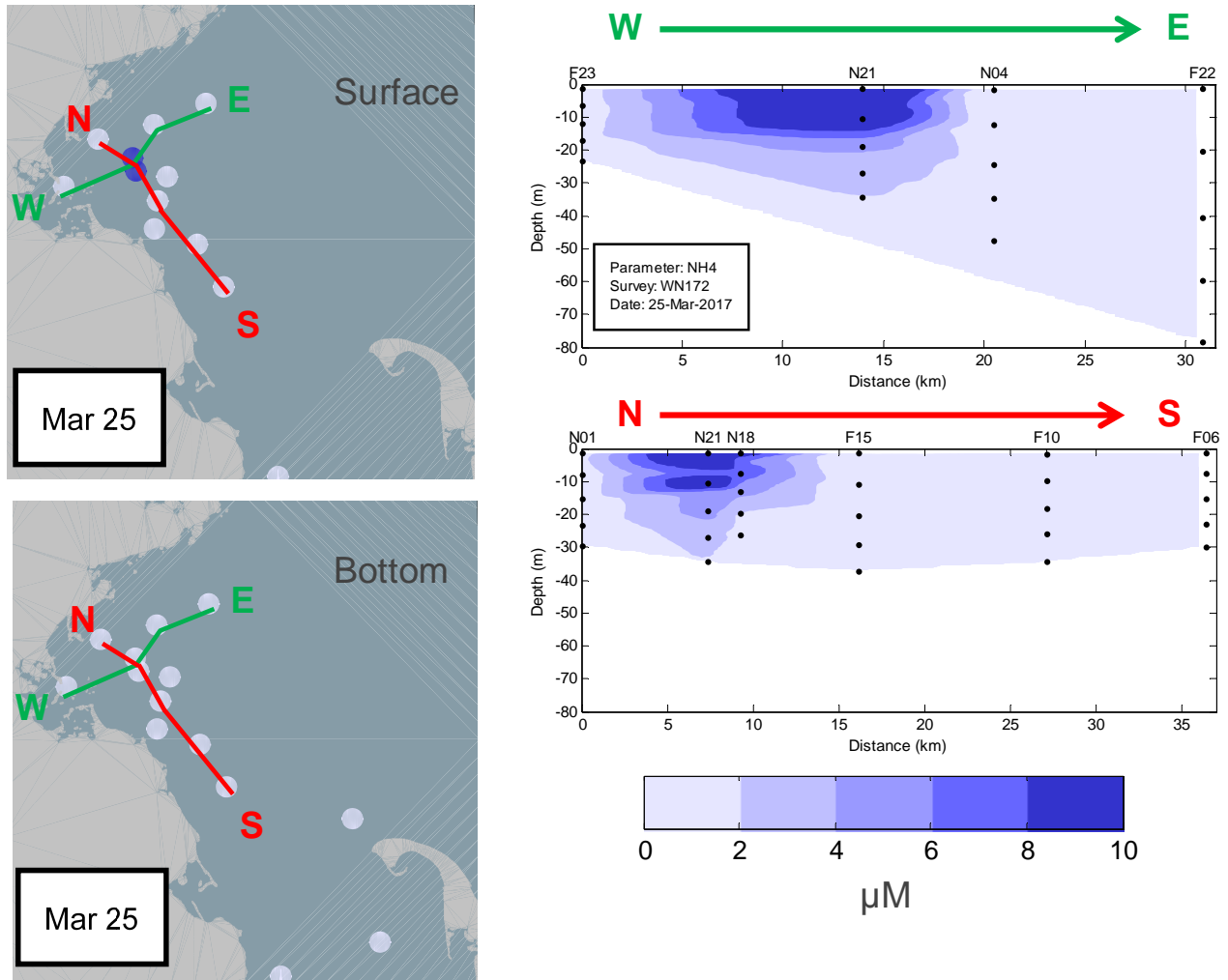


Figure 2-12. (Left) Surface- and bottom-water NH₄ on March 25, 2017 during mixed conditions. (Right) Cross-sections of water column concentrations along transects connecting selected stations. Small black dots in the plots at right indicate the sampling depths for nutrients.

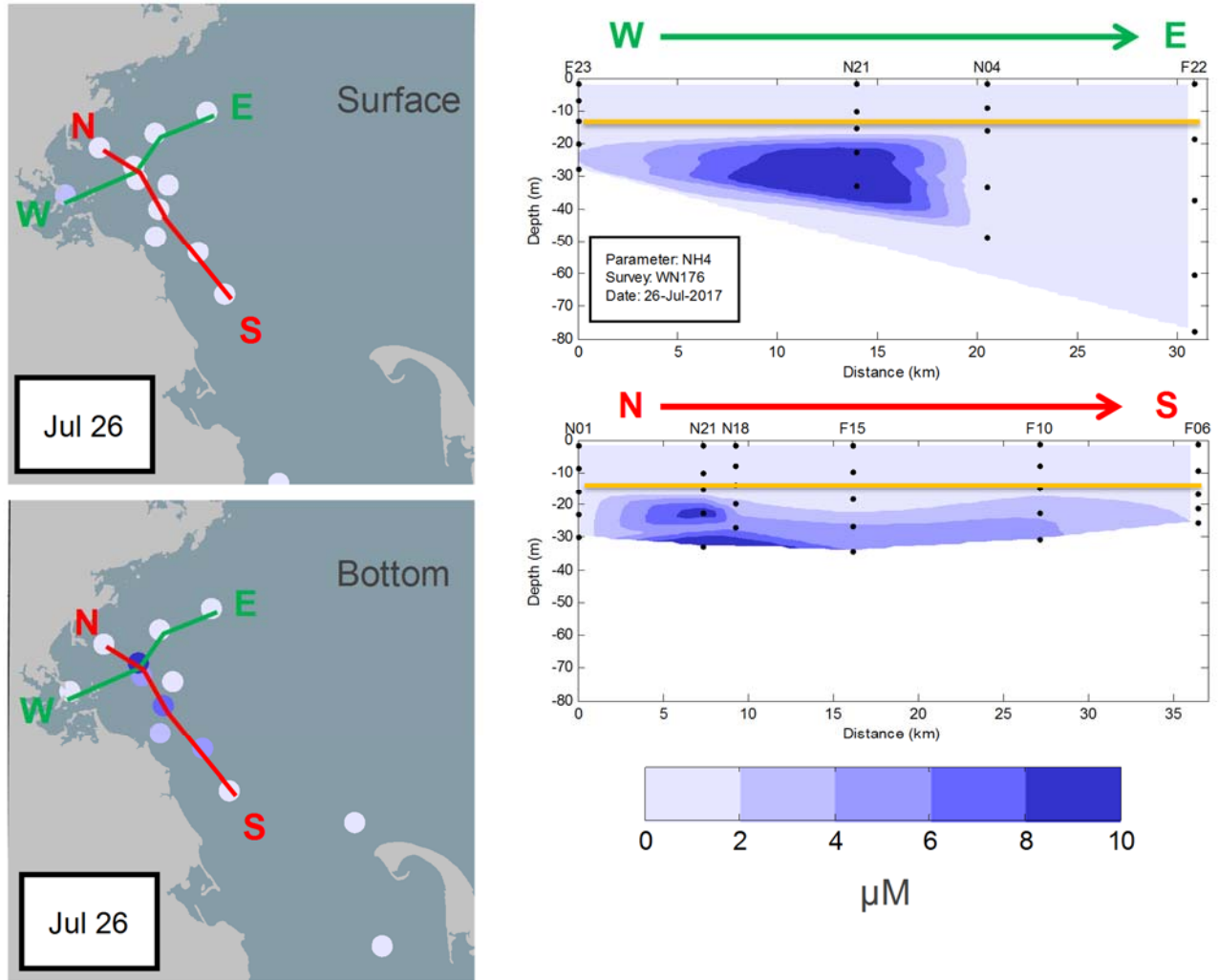


Figure 2-13. Surface- and bottom-water NH₄ on July 26, 2017 during stratified conditions. Presented as Figure 2-12, with orange line in frames at right indicating the approximate depth of the pycnocline.

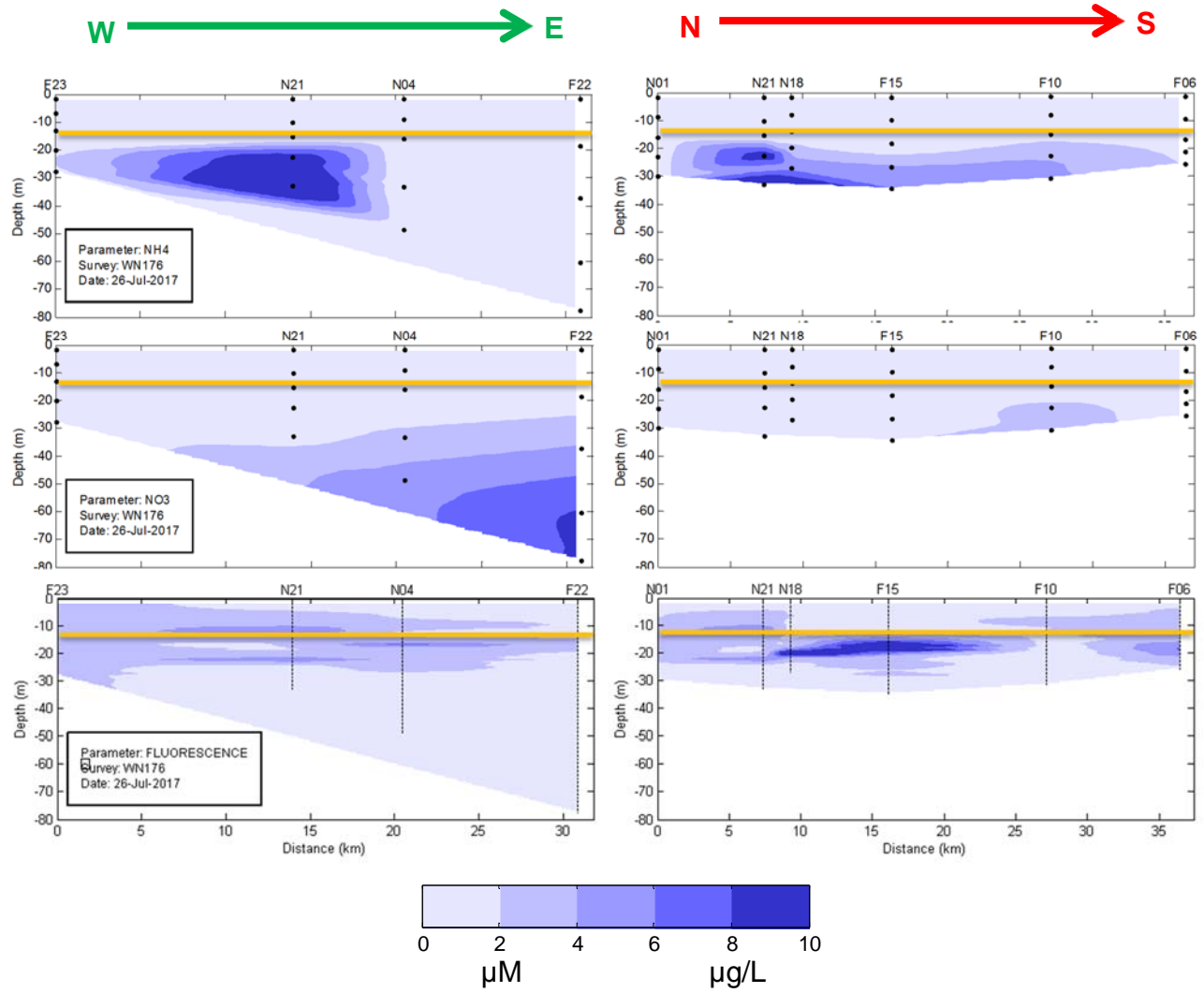


Figure 2-14. Ammonium (top; μM), nitrate (middle; μM), and chlorophyll from fluorescence (bottom; $\mu\text{g L}^{-1}$) concentrations during the stratified July 2017 survey along the east-west and north-south transects shown in Figure 2-13. Dots indicate the sampling depths. The orange line indicates the approximate depth of the pycnocline.

2.3.2 Phytoplankton Biomass

Phytoplankton biomass (vertically summed chlorophyll concentrations, or areal chlorophyll) in Massachusetts Bay typically shows a seasonal pattern, with elevated values during winter-spring, and then again during the fall as seen in the historical results (shaded regions) in **Figure 2-15**. During the nine regular (non-ARRS) shipboard surveys biomass during 2017 showed a similar seasonal pattern (**Figure 2-16**). Peak areal chlorophyll levels for the year were observed during the last three ARRS surveys in late June through early July (June 28, July 8, July 16). The elevated biomass values during these three surveys were likely related to the prolonged period of upwelling and decreased stratification (see **Figure 2-7** & **Figure 2-4**) supplying nutrients to the upper water column during this period.

As observed over the past few years, chlorophyll fluorescence from MODIS satellite imagery (**Figure 2-17**) suggests phytoplankton were productive in January and February 2017 with moderate chlorophyll levels ($\sim 2\text{-}3 \mu\text{g L}^{-1}$). The February biomass values were in the upper range seen in the past at most of the stations in the bay and Boston Harbor (**Figure 2-15**). By March, areal chlorophyll levels had gone from near maxima to at or below the long-term median with low levels ($<50 \text{ mg m}^2$) across most of Massachusetts Bay. In April, levels increased to $\geq 100 \text{ mg m}^2$ at offshore stations in Massachusetts Bay (**Figure 2-16**). By the May survey, chlorophyll levels had dropped to $<100 \text{ mg m}^2$ across most of the bay.

Continuous chlorophyll sampling by fluorometer at NERACOOS Buoy A01 off Cape Ann showed elevated surface water chlorophyll fluorescence during most of April and May (**Figure 2-18**). 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.

The upwelling favorable conditions from mid-June to mid-July led to increases in nutrient concentrations at depth and higher subsurface chlorophyll maximum levels near the pycnocline as is typically observed in the bay (**Figure 2-14**). Overall, 2017 summer chlorophyll levels were relatively high peaking in early to mid-July during the ARRS surveys (**Figure 2-15** and **Figure 2-16**). However, these surveys are not conducted on a consistent basis and are not incorporated in the calculation of the summer seasonal average chlorophyll for the nearfield which was low for 2017 (58 mg m^{-2}) compared to the winter/spring and fall averages (88 and 99 mg m^{-2} , respectively). Elevated chlorophyll levels were observed during the September and early November surveys in the nearfield and northern Massachusetts Bay (**Figure 2-16**). This was consistent with MODIS imagery and NERACOOS Buoy A01 observations showing higher chlorophyll fluorescence during this period (**Figure 2-17** and **Figure 2-18**). The high chlorophyll levels in late October-early November were coincident with a late fall bloom of *Skeletonema*.

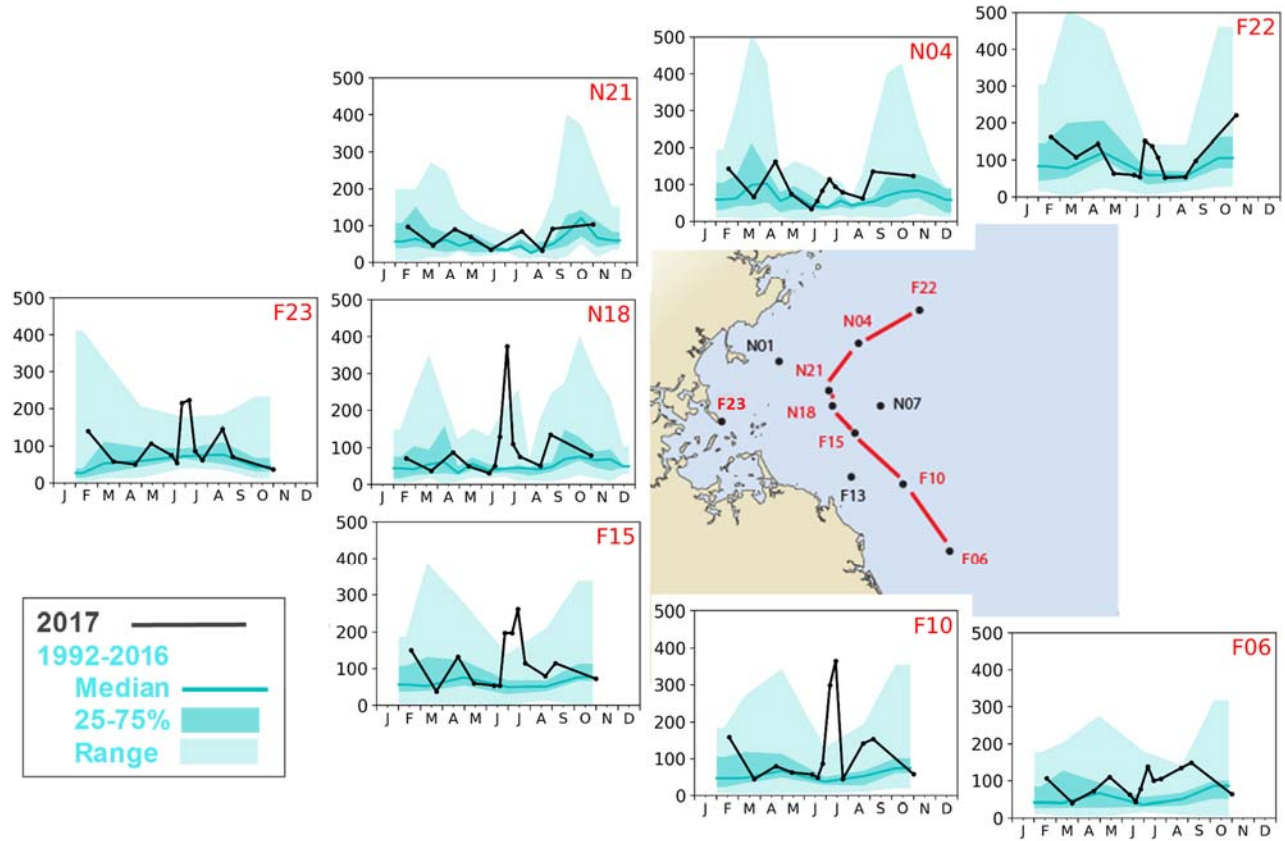


Figure 2-15. Areal chlorophyll fluorescence (mg m^{-2}) at representative stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992–2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. Note the summer peak areal chlorophyll fluorescence values occur during the ARRS surveys.

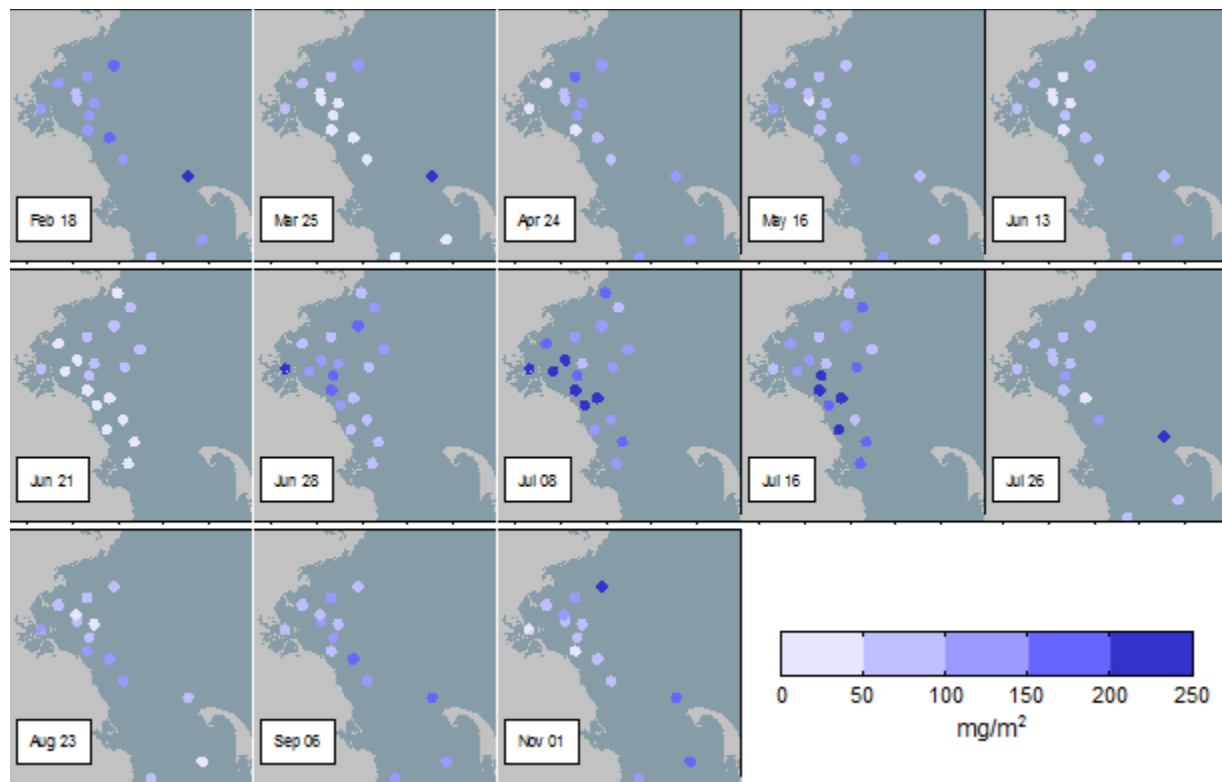


Figure 2-16. Areal chlorophyll fluorescence (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2017.

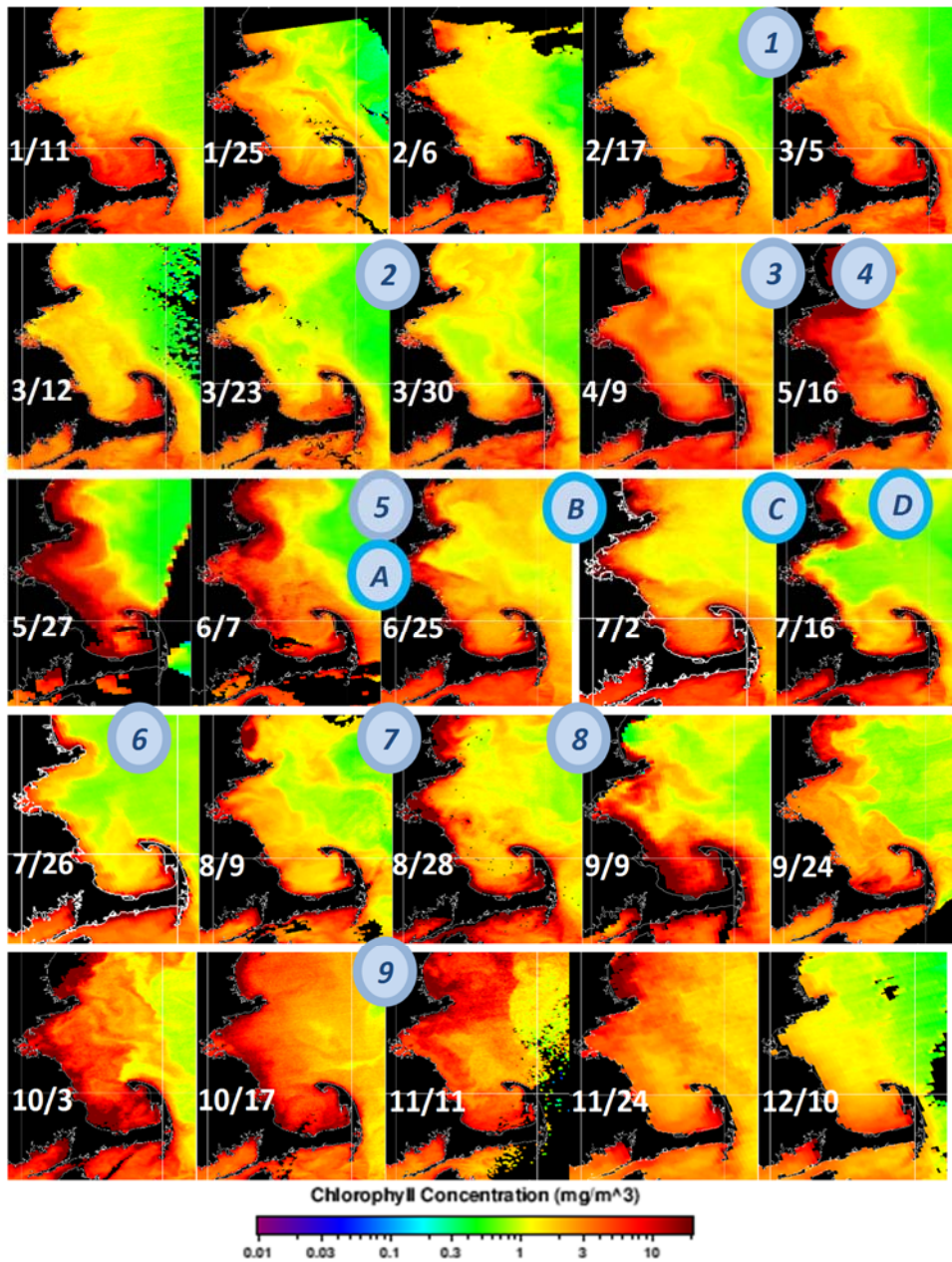


Figure 2-17. Satellite (MODIS) imagery of surface chlorophyll concentrations (mg m^{-3}) in 2017.

Highlights and specific blooms:

1st row – moderate chlorophyll levels January and February - *Thalassiosira*;

2nd row – relatively low in late March;

2nd row – high chlorophyll in April/May – mixed *Skeletonema/Phaeocystis* bloom;

3rd row – high chlorophyll levels from late May to mid-July coincident with *Alexandrium* bloom;

4th row – elevated summer chlorophyll levels in harbor and coastal water – *Skeletonema* and *Leptocylindrus*; and

4th and 5th rows – elevated chlorophyll levels in late September through November – *Skeletonema*.

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

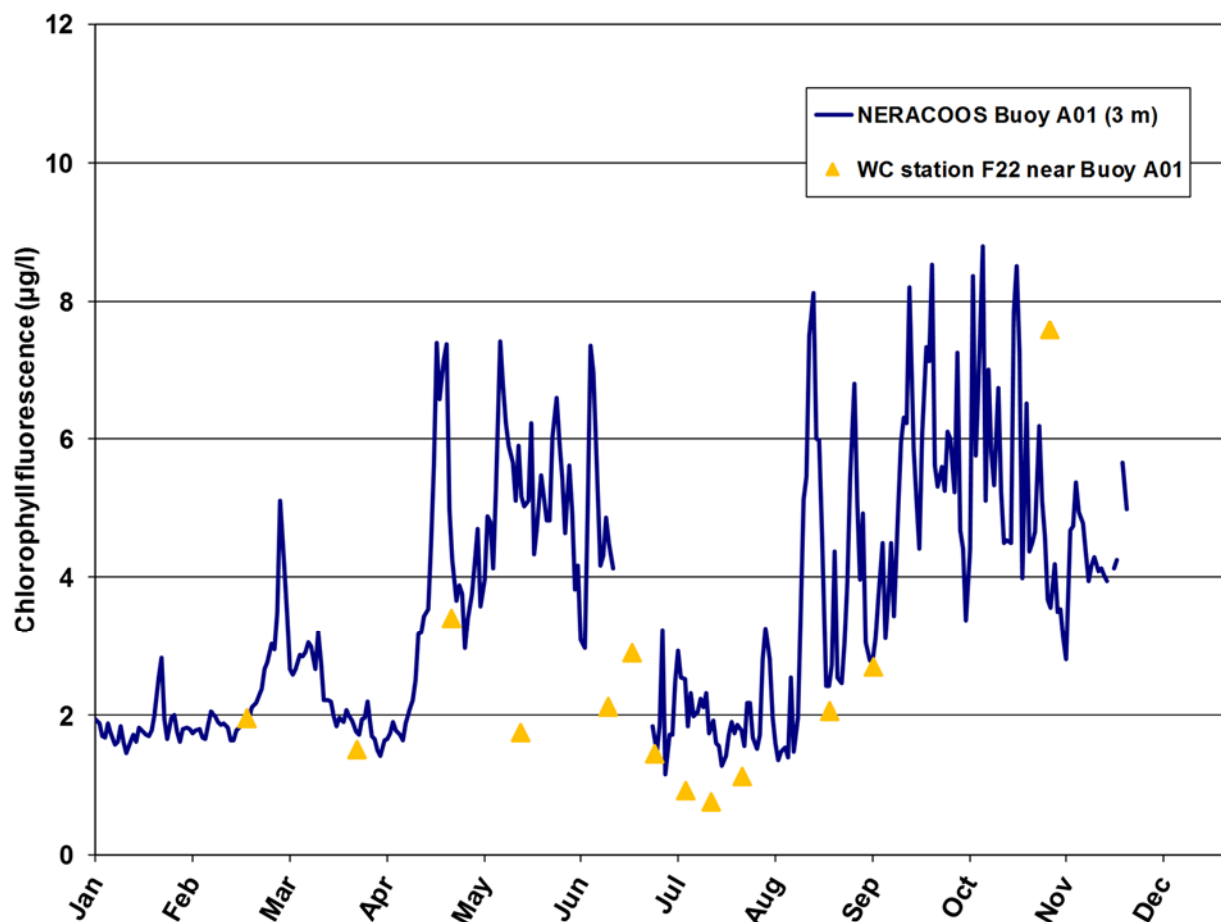


Figure 2-18. Surface water chlorophyll fluorescence ($\mu\text{g L}^{-1}$) at NERACOOS Buoy A01 and nearby water column (WC) station F22. The buoy values are daily medians.

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. This was generally the case in 2017 (**Figure 2-19**). During 2017, as in 2016, the seasonal decline was punctuated by upwelling in June and July that increased bottom water DO levels by about 0.5 to 1 mg L^{-1} throughout most of the bay (**Figure 2-20**). Bottom water DO concentrations began the year at seasonally low levels that were in the lower quartile compared to historical data. This was the case from February to early June and then persistent upwelling from mid-June to early July resulted in increased bottom water DO concentrations to levels comparable to long-term average. Boston Harbor and most of the 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 stations F06 and F10 in southern Massachusetts Bay or station F01 in Cape Cod Bay, where minima were observed in November that were within the lower range of historic values observed (**Figure 2-20** and **Figure 2-21**). These relatively shallow stations typically become well mixed earlier in the fall, but the delay in water column mixing into November resulted in relatively low bottom water DO compared to historic levels (though annual minima at these stations were above 6 mg L^{-1} , meeting Contingency Plan Caution and Warning Level thresholds). The influence of late fall mixing events is evident in NERACOOS buoy A01 DO data from 50 m, which showed DO did not increase at this depth until mid-November (**Figure 2-22**).

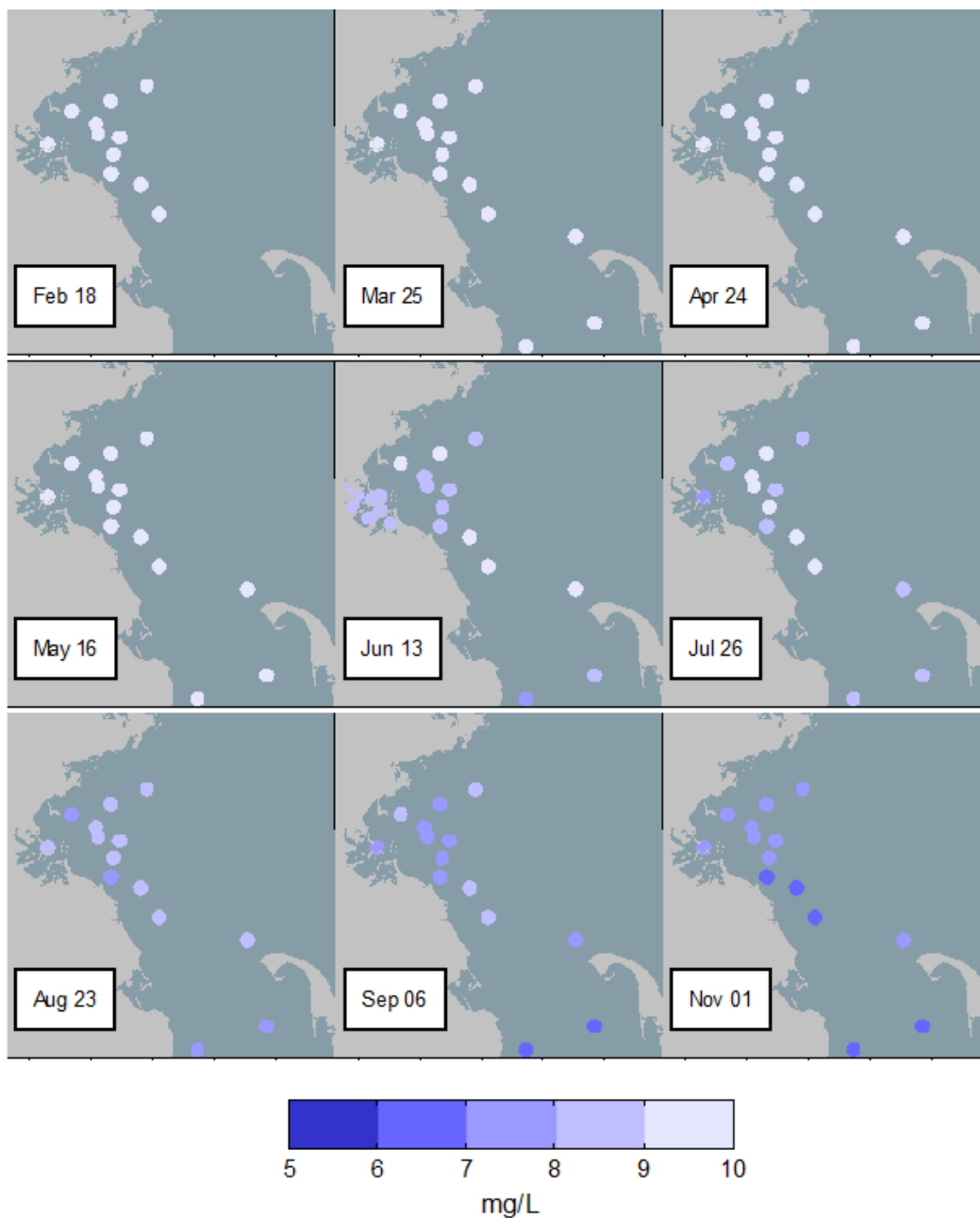


Figure 2-19. Near bottom DO (mg L^{-1}) by station in Massachusetts and Cape Cod Bays in 2017.

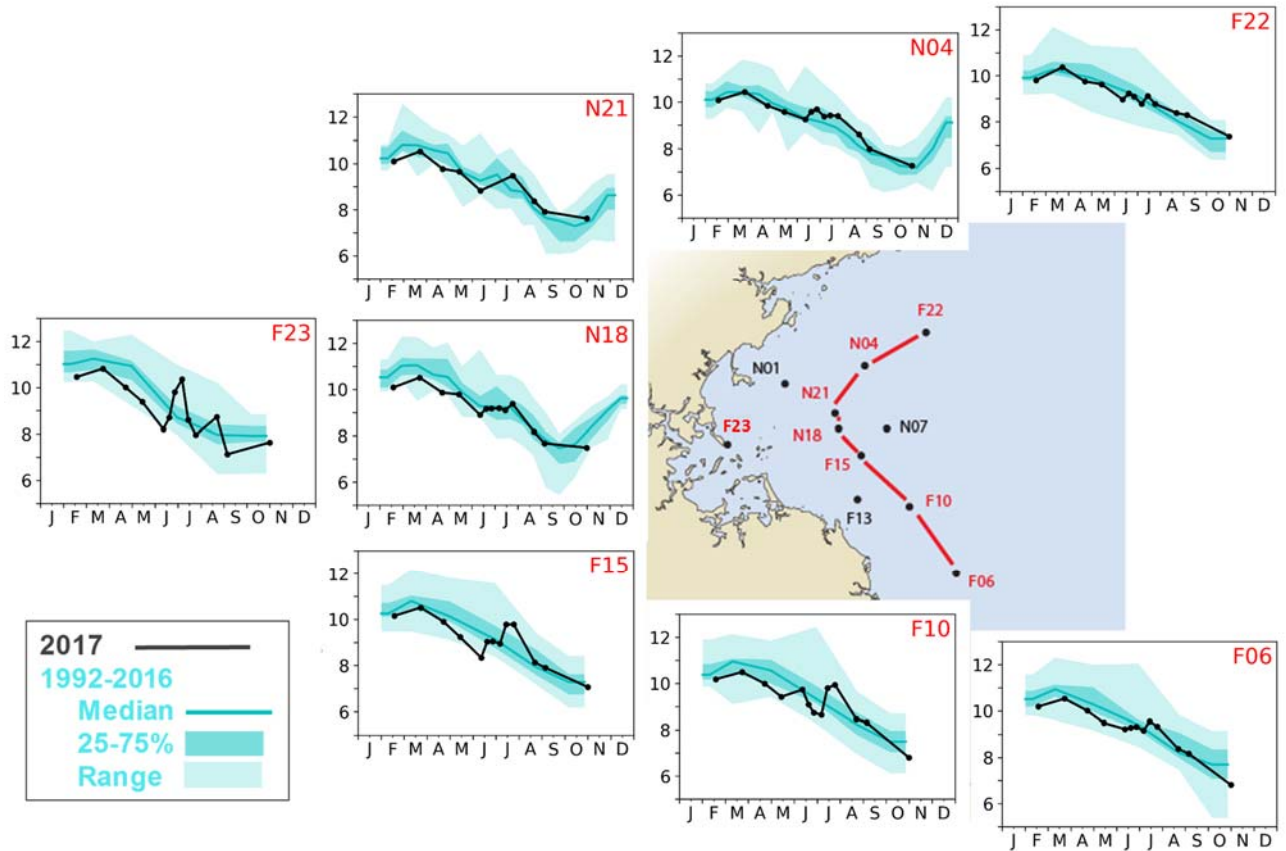


Figure 2-20. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992–2016 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

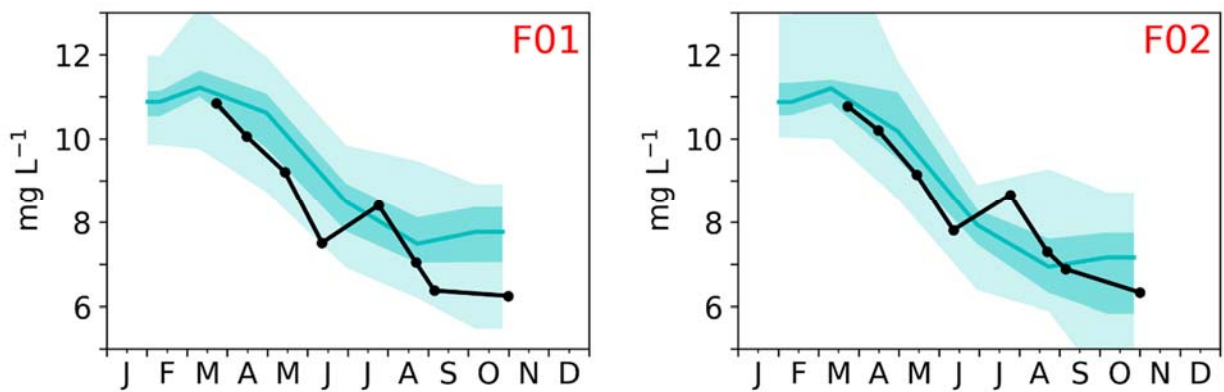


Figure 2-21. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992–2016 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

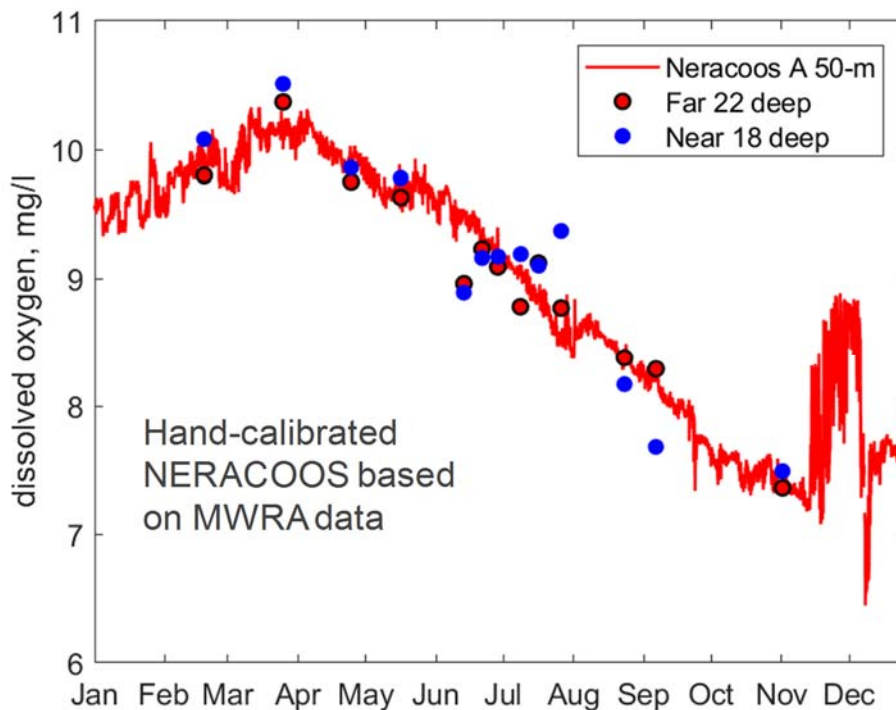


Figure 2-22. Time-series of DO concentration (mg L^{-1}) at NERACOOS Buoy A01 (50 m) and at stations F22 (red) and N18 (blue) sampling depths in 2017. The buoy values are daily means.

2.5 PHYTOPLANKTON

Overall, phytoplankton abundance measured during the nine surveys in 2017 was low compared to the range of observations made during 1992-2016. Total phytoplankton abundance in the nearfield in 2017 (0.89 million cells L^{-1}) was 65% of the long-term mean level of 1.36 million cells L^{-1} and ranked 21st for the 26-year monitoring program (**Table 2-1**). The relatively low 2017 total phytoplankton abundance was in part due to the lack of a large winter-spring diatom or *Phaeocystis* bloom. While low compared to the long-term mean, 2017 total phytoplankton abundance was approximately 15% greater than that observed during 2016 monitoring.

The 2017 phytoplankton annual cycle featured two abundance peaks (**Figure 2-23** and **Figure 2-24**). There was a relatively late spring (April/May) peak in total phytoplankton abundance of 1.5 to 2 million cells L^{-1} at stations across most of the bay and Boston Harbor. This was followed by a summer period of reduced (<1 million cells L^{-1}) phytoplankton abundance. In Boston Harbor and coastal waters, there was a smaller secondary peak in abundance in August, while in the nearfield and further offshore annual maximum phytoplankton abundances were seen in November.

Although centric diatom abundance was near-average for 2017, two species of diatoms contributed to the late spring and summer/fall peaks observed in total phytoplankton (**Table 2-1** and **Figure 2-25**). Winter centric diatom abundance was dominated by a mix of *Thalassiosira* spp. present at near- to slightly above-long-term mean levels during February to March 2017. The low SiO_4 concentrations in early February and high MODIS chlorophyll fluorescence in January suggest *Thalassiosira* spp. (or another diatom) was productive in over the winter months preceding the first survey. In April (bay) and May (harbor), centric diatoms increased to approximately twice the long-term mean levels and this late spring bloom was dominated by *Skeletonema* spp.

Table 2-1. Comparison of 2017 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 | 1992-2016 (cells L ⁻¹) | 2017 (cells L ⁻¹) | 2017 Rank (out of 26) | p value | Significant Change |
|-------------------------------------|---------------------------------------|----------------------------------|--------------------------|---------|-----------------------|
| CENTRIC DIATOM | 262,320 | 226,314 | 13 th | 0.3062 | |
| <i>Dactyliosolen fragilissimus</i> | 53,158 | 16,087 | 16 th | 0.1526 | |
| <i>Chaetoceros</i> | 29,950 | 2,538 | 20 th | 0.0051 | Decline |
| <i>Skeletonema costatum</i> complex | 44,818 | 46,751 | 9 th | 0.2105 | |
| <i>Thalassiosira</i> | 34,826 | 8,630 | 19 th | 0.0251 | Decline |
| PENNATE DIATOM | 36,317 | 39,799 | 5 th | 0.9291 | |
| <i>Pseudonitzschia</i> | 8,221 | 2,016 | 15 th | 0.8308 | |
| DINOFLAGELLATES | 61,589 | 63,477 | 10 th | 0.1925 | |
| <i>Ceratium</i> | 1,782 | 3,554 | 4 th | 0.0037 | Increase |
| <i>Dinophysis</i> | 265 | 810 | 3 rd | 0.0032 | Increase |
| <i>Prorocentrum</i> | 5,373 | 9,295 | 7 th | 0.0001 | Increase |
| <i>Phaeocystis pouchetii</i> | 207,708 | 492 | 21 st | 0.0215 | Decline |
| CRYPTOPHYTES | 127,308 | 144,866 | 10 th | 0.2794 | |
| MICROFLAGELLATES | 659,725 | 398,223 | 22 nd | 0.0001 | Decline |
| TOTAL PHYTOPLANKTON | 1,357,764 | 889,317 | 21 st | 0.0128 | 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.

This was the second consecutive year in which *Skeletonema* was the late winter-spring bloom dominant. This shift to a later (April), *Skeletonema*-dominated winter-spring bloom may be partially a response to changing climate, that favors *Skeletonema* spp. There are several possible mechanisms for this including the variable temperature- and nutrient-specific physiology of morphologically cryptic *Skeletonema* spp. (Borkman and Smayda, 2009; Nixon et al 2009; Canesi and Rynearson, 2016) and the possibility of a shift to a two-part winter-spring bloom featuring an early (January-February) *Thalassiosira*-dominated winter spring bloom which terminates due to grazing and nutrient draw-down followed by a later (April) *Skeletonema*-dominated bloom.

Since about 2000, the spring diatom bloom has been followed by a *Phaeocystis* bloom in April. In comparison to past *Phaeocystis* blooms, 2017 abundances were very low (<35,000 cells L⁻¹) on both the April and May surveys. This is the fifth year in a row without a major *Phaeocystis* bloom being observed on the monitoring surveys. However, as in 2015 and 2016, MODIS satellite data and changes in relative nutrient concentrations suggest that a *Phaeocystis* bloom may have occurred between the April and May 2017 surveys. In May, *Phaeocystis* was observed in only one nearfield sample (15,000 cells L⁻¹).

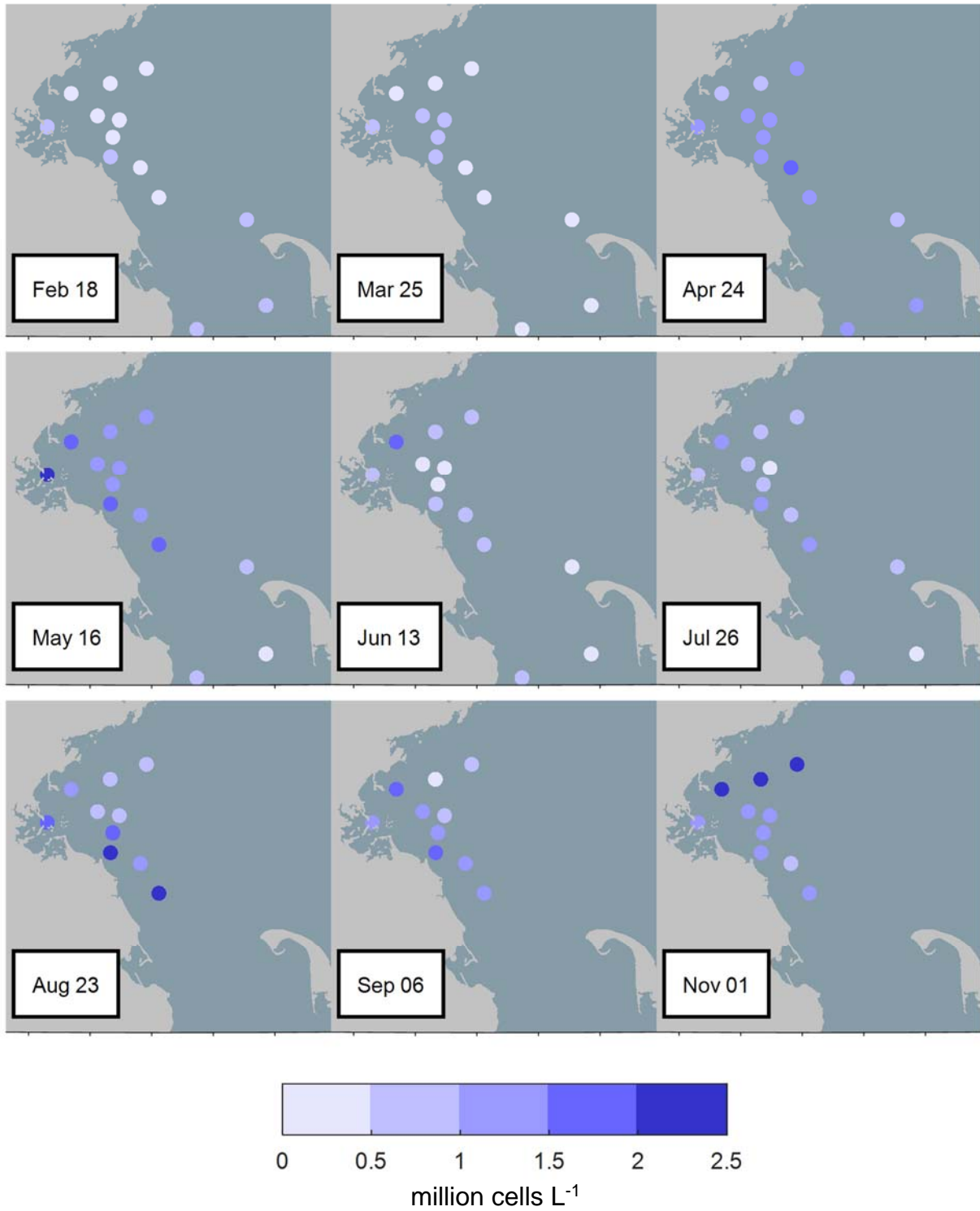


Figure 2-23. Total phytoplankton abundance (million cells L⁻¹) by station in Massachusetts and Cape Cod Bays in 2017.

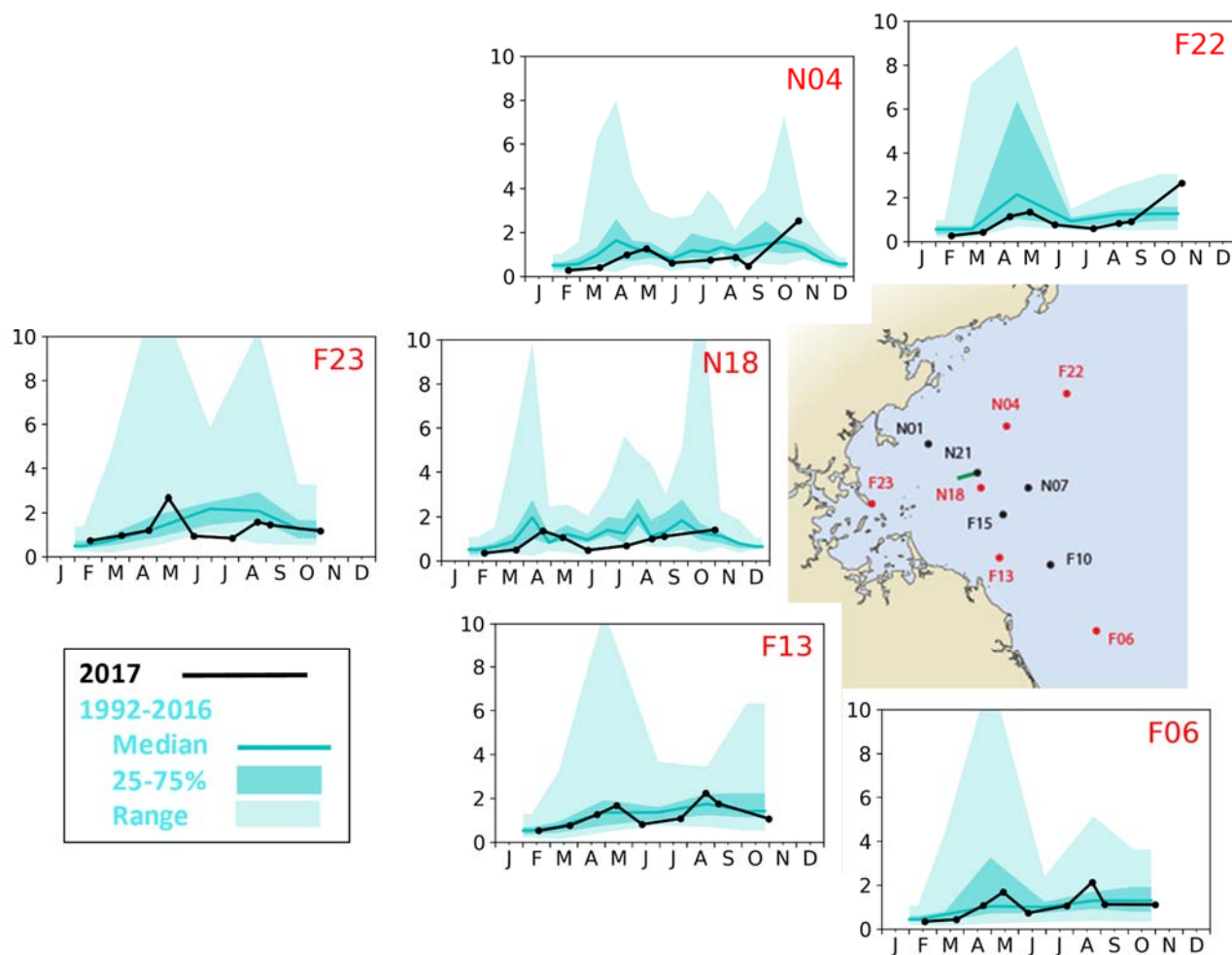


Figure 2-24. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2017 compared to prior years. 2017 results are in black. Results from 1992-2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range). The map insert highlights the stations where an extended plankton dataset is available and presented here and in subsequent phytoplankton and zooplankton figures.

Total phytoplankton abundance increased slightly from April to May at most stations (**Figure 2-24**). Part of this was due to increases *Skeletonema* spp. (harbor) and microflagellates and cryophytes, but it was also concomitant with an increase in dinoflagellates to annual maxima of $>200,000$ cells L^{-1} in harbor and coastal waters (**Figure 2-26**). The dinoflagellate community in May 2017 was dominated by the small species *Prorocentrum minimum*. In July, elevated abundances of the large dinoflagellate *Ceratium* spp. were observed at many Massachusetts Bay stations with a maximum of nearly 65,000 cells L^{-1} observed in the nearfield at station N18. This observation was the highest *Ceratium* spp. abundance recorded at station N18 since monitoring began at that station in 1997. Overall, *Ceratium* spp. were present at a mean level in 2017 nearly double the long-term level (**Table 2-1**).

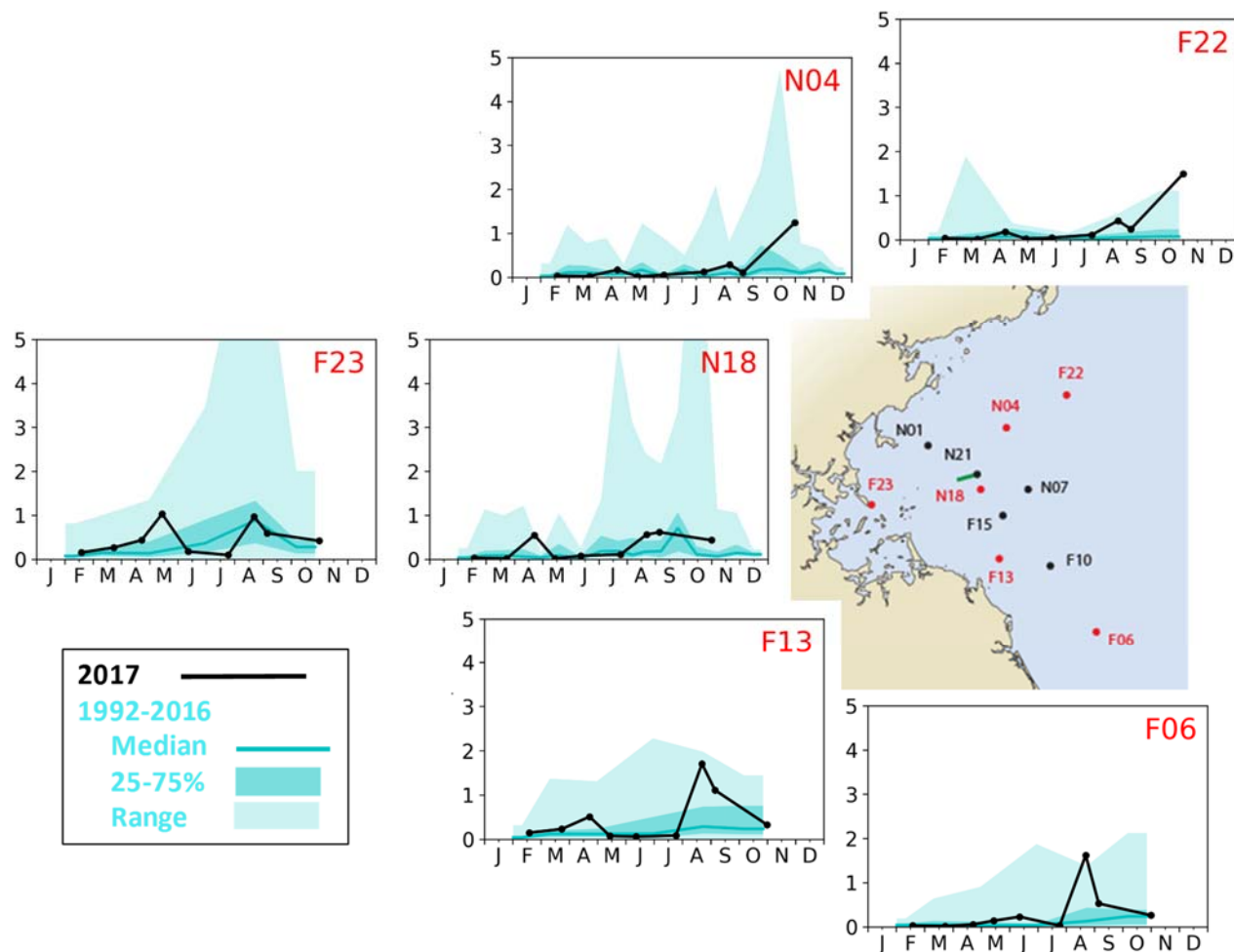


Figure 2-25. Centric diatom abundance (million cells L⁻¹) at selected stations in 2017 compared to prior years. 2017 results are in black. Results from 1992-2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range).

Overall summer total phytoplankton counts fell into the lower quartile of the historic range at the Massachusetts Bay stations in June and July (**Figure 2-24**; note phytoplankton analyses were limited to *Alexandrium* counts during the ARRS surveys). In Boston Harbor and nearby coastal stations, a late summer diatom bloom of *Leptocylindrus danicus* was observed that contributed to total phytoplankton abundances of ~2 million cells L⁻¹ in these inshore waters (**Figure 2-24** and **Figure 2-25**). This continues a notable change in the dominant summer diatom in the harbor which has observed over the past two years. In most years, the summer harbor diatom bloom had been dominated by *Dactyliosolen fragilissimus*, with secondary dominance by *Skeletonema* spp. However, over the last three years *Dactyliosolen fragilissimus* was reduced to very low abundances in Boston Harbor, being replaced by *Cerataulina pelagica* and *Leptocylindrus danicus*.

The autumn diatom bloom in early November 2017 was again dominated by *Skeletonema* spp. with abundances of 200,000 to 500,000 cells L⁻¹ in Boston Harbor and offshore waters.

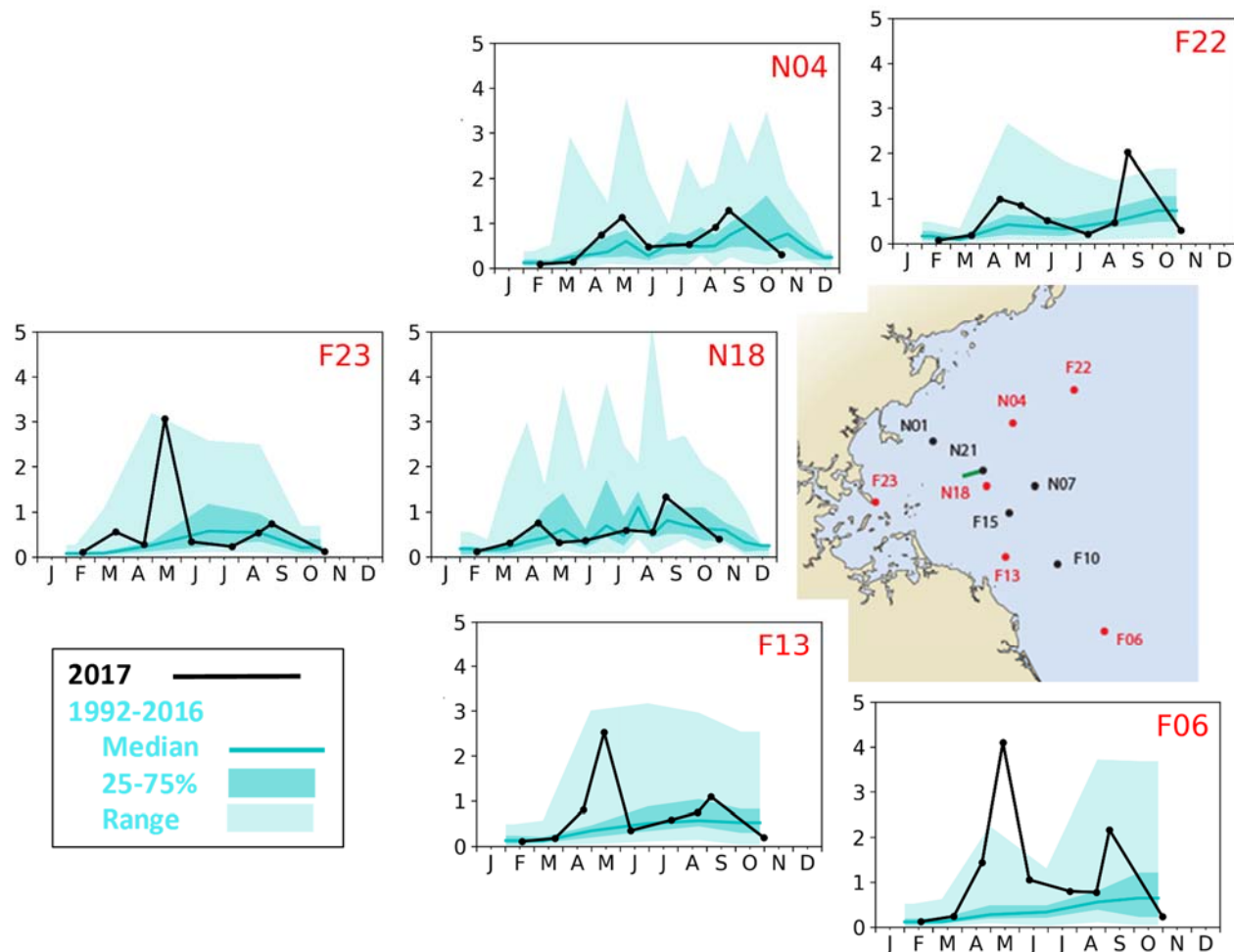


Figure 2-26. Dinoflagellate abundance ($100,000 \text{ cells L}^{-1}$) at selected stations in 2017 compared to prior years. 2017 results are in black. Results from 1992-2016 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range).

Alexandrium catenella

Although not numerically important, *Alexandrium* were observed at abundances sufficient ($\geq 100 \text{ cells L}^{-1}$) to trigger ARRS surveys in 2017. The Experimental Gulf of Maine *Alexandrium catenella* Nowcast/Forecast Simulation provided by NOAA⁶ was projecting moderate *Alexandrium* cell counts in Massachusetts Bay in late April. However, the April and May surveys showed only a few samples with *Alexandrium* at very low abundances ($< 10 \text{ cells/L}$; **Table 2-2** and **Figure 2-27**). On May 31, mussel samples from NH DES stations showed a marked increase in PSP toxicity from nondetectable ($< 44 \mu\text{g}/100 \text{ g}$) the previous week to 99.3 and 774.4 $\mu\text{g}/100 \text{ g}$ at Hampton (inshore) and Star Island (offshore), respectively. The action limit for shellfish harvesting closures is 80 $\mu\text{g}/100 \text{ g}$. This dramatic increase in PSP toxicity along with the model forecast and strong winds out of the Northeast (**Figure 2-5**; conducive for flow into Massachusetts Bay around Cape Ann) in late May and early June led MWRA to move the June water column survey up a week from June 20 to June 13 in order to characterize conditions in Massachusetts Bay in the context of the offshore *Alexandrium* bloom.

⁶ <https://products.coastalscience.noaa.gov/hab/gomforecast.aspx>

Table 2-2. Summary of *Alexandrium* abundance for water column and ARRS surveys in May-July 2017.

| Event Id | Date | # samples collected | # samples with <i>Alexandrium</i> | # <i>Alexandrium</i> cells/L | | | MAX value station (depth) |
|----------|---------|---------------------|-----------------------------------|------------------------------|-----|-------|---------------------------|
| | | | | MEAN | MIN | MAX | |
| WN174 | May 16 | 20 | 5 | 0.6 | 0 | 6 | F23 (14 m) |
| WN175 | June 13 | 20 | 16 | 55 | 0 | 494 | N04 (2 m) |
| AF171 | June 21 | 43 | 16 | 87 | 0 | 2,033 | AF8 (2 m) |
| AF172 | June 28 | 43 | 25 | 51 | 0 | 800 | AF9 (2 m) |
| AF173 | July 8 | 43 | 35 | 109 | 0 | 2,221 | AF9 (10 m) |
| AF174 | July 16 | 43 | 30 | 8 | 0 | 109 | AF9 (2 m) |
| WN176 | July 26 | 20 | 6 | 0.2 | 0 | 1 | multiple |

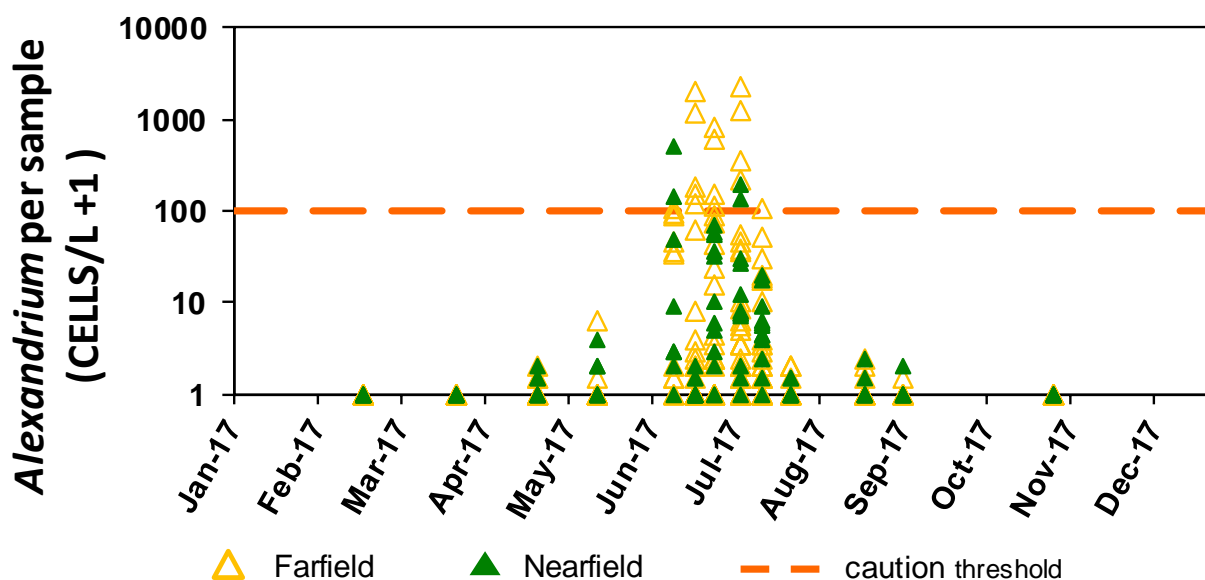


Figure 2-27. *Alexandrium* abundance at individual farfield and nearfield stations in 2017 (cells L⁻¹).

On June 13, *Alexandrium* were observed at all 10 stations sampled, and in 16 of the 20 samples collected, at abundances of 1 to 494 cells L⁻¹ (Figure 2-27 and Figure 2-28). The maximum was from surface water at station N04 and exceeded the contingency plan caution threshold of 100 cells L⁻¹. The 100 cells L⁻¹ abundance is also the trigger for conducting additional targeted *Alexandrium* monitoring, leading to four additional ARRS surveys.

On the first ARRS survey (June 21), elevated cell counts were seen at the three stations south of Cape Ann (stations AF8, AF9, and F22) (Figure 2-28). The highest abundance of 2,033 cells L⁻¹ was at station AF8 (near NERACOOS Buoy A01) with counts of 62-177 cells/L seen at nearby stations AF9 and F22. Stations AF8, AF9 and F22 are the furthest offshore and the elevated *Alexandrium* abundances were likely due to the influx of Western Gulf of Maine water (see Figure 2-6) carrying established populations of this species into northeastern Massachusetts Bay. Elevated cell counts were again seen at the three stations south of Cape Ann during the second ARRS survey on June 28. Abundances had decreased since the previous week's

survey but remained quite high with a maximum of 800 cells/L in the surface water at station AF9. Elevated counts of 53-155 cells/L were observed at offshore nearfield stations N04 and N07 and station F15 just to the south of the nearfield area (**Figure 2-28**). The presence of higher cell abundances within Massachusetts Bay proper was not expected given the predominantly offshore winds out of the S and SW over the previous week. Abundances were lower or absent at nearshore stations and stations further to the south toward Cape Cod Bay.

In early July, the distribution and counts of *Alexandrium* were similar to the late June survey with the highest cell counts observed just south of Cape Ann and elevated abundances extending to the offshore nearfield stations N04 and N07, and station F15 just to the south of the nearfield area (**Figure 2-28**). By July 16, *Alexandrium* abundances had decreased sharply, indicating the Massachusetts Bay red tide “event” was finally winding down. However, it was not until the routine water column survey on July 26, which measured very low abundances (only 1 cell/L) of *Alexandrium* in 6 out of 20 samples collected, that the *Alexandrium* bloom was over and the ARRS concluded for 2017.

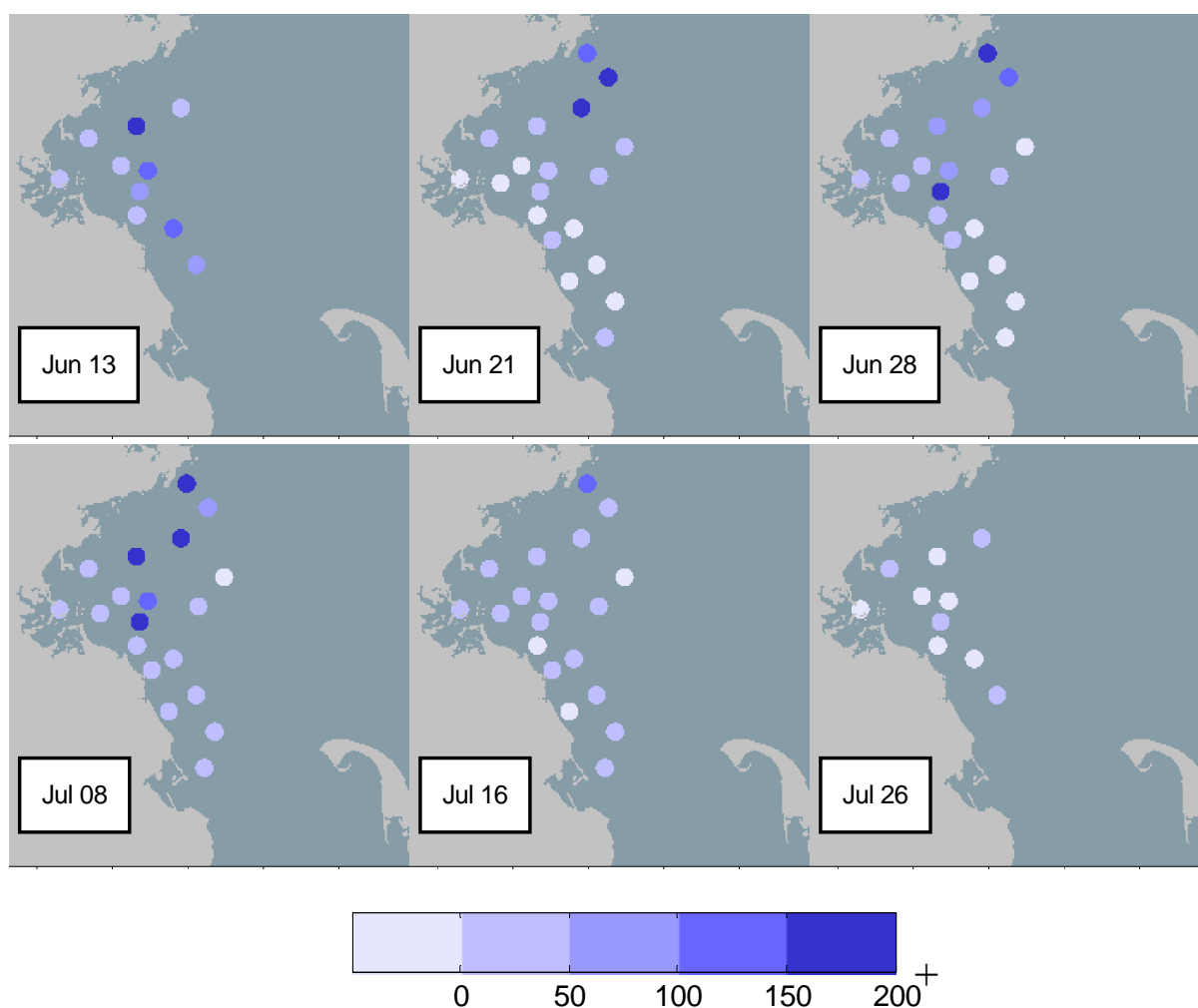


Figure 2-28. Station maximum *Alexandrium* abundances (cells/L) during the June and July 2017 water column and ARRS surveys.

The 2017 *Alexandrium* bloom led to high PSP toxicity along the shores of the western Gulf of Maine and resulted in shellfishing closures from Cape Ann, Massachusetts to Eastern Maine which is indicative of a moderate bloom. Along the Massachusetts coast north of Cape Ann, PSP toxicity was first detected in Plum Island Sound on June 2, but remained $<80 \mu\text{g}/100 \text{ g}$ (shellfish closure level) at all stations until June 22 when the Conomo Pt in Essex Bay reached $81 \mu\text{g}/100 \text{ g}$. MA DMF issued a shellfishing closure on June 23 for Essex Bay and after a measurement of $106 \mu\text{g}/100 \text{ g}$ on June 26 at Conomo Pt, it closed shellfishing areas from Gloucester to the New Hampshire border to blue mussel harvesting. However, PSP toxicity was not detected at any of the MA DMF stations within Massachusetts Bay proper. This suggests the *Alexandrium* cells observed in the bay remained offshore and did not impact the inshore water. This is consistent with the overall distribution of elevated abundances observed at offshore stations during the six MWRA surveys in June and July 2017. The northeast winds likely entrained Gulf of Maine waters into Massachusetts Bay with *Alexandrium*, while subsequent upwelling favorable winds out of the south kept the *Alexandrium* bloom offshore and away from shellfish resources.

Pseudo-nitzschia

A bloom of the toxigenic pennate diatom *Pseudo-nitzschia* caused shellfish harvest closures in Maine and Rhode Island waters in 2017. *Pseudo-nitzschia* is a genus of potentially toxigenic pennate diatoms that can cause amnesiac shellfish poisoning (ASP). While closures were seen to the north (Maine waters) and south (Rhode Island waters), *Pseudo-nitzschia* spp. levels in the nearfield area of Massachusetts Bay were not unusually high during 2017 and no ASP shellfish closures were required in Massachusetts Bay during 2017. Overall, nearfield *Pseudo-nitzschia* abundance during 2017 was low at only 25% of the long-term mean level of $8,221 \text{ cells L}^{-1}$ (**Table 2-1**) and the maximum *Pseudo-nitzschia* spp. abundance recorded during 2017 monitoring was $25,961 \text{ cells L}^{-1}$ in August 2017. To put this 2017 value in context, the maximum abundance of *Pseudo-nitzschia* spp. observed during 1992 to 2017 monitoring was 1.8 million cells L^{-1} in August 1998.

Karenia mikimotoi

An unusual dinoflagellate bloom was captured by MWRA monitoring in September 2017. A bloom of the athecate dinoflagellate *Karenia mikimotoi* was observed in samples collected during August and September of 2017. *K. mikimotoi* is characterized as a harmful species (Gentien, 1998), due to known toxicity of other *Karenia* spp.; however, toxins from *K. mikimotoi* are not well-understood (Yamasaki et al., 2004), and negative effects of *K. mikimotoi* blooms are limited to death of sessile shellfish and finfish located in confined environments such as fish farm pens (Turner et al., 1987). Fortunately, no direct negative impacts on human health are known.

K. mikimotoi cells were observed at low levels of 800 to 14,000 cells L^{-1} during August and by September 2017 a maximum *K. mikimotoi* abundance of 337,800 cells L^{-1} was recorded in the nearfield. During the September bloom, *K. mikimotoi* abundance was greatest at the offshore stations, with $>100,000 \text{ cells L}^{-1}$ recorded at stations F22, N04, N07, F10, F06 and F10. *K. mikimotoi* abundance was reduced in Boston Harbor (maximum of 37,000 cells L^{-1}), suggesting this was an offshore bloom. In addition, *K. mikimotoi* abundance was highest at the chlorophyll maximum, with six of seven observations of $>100,000 \text{ cells L}^{-1}$ occurring at the subsurface chlorophyll maximum depth. By October 2017, *K. mikimotoi* cells were absent at most stations or present at very low levels ($<5,000 \text{ cells L}^{-1}$).

The September 2017 *K. mikimotoi* bloom was a regional event with elevated levels in Massachusetts Bay, concentrations of $\sim 800,000 \text{ cells L}^{-1}$ in Salem Harbor, MA (D. Borkman, personal communication) and at water-discoloring levels of millions of cells L^{-1} in Casco Bay/Portland Harbor, ME (Portland Press, Maine DMR, September 26, 2017). The appearance of *K. mikimotoi* over $\sim 160 \text{ km}$ of coastline from Portland, ME to Boston, MA at high abundance is very unusual. *K. mikimotoi* had not been observed in the previous 25 years of MWRA monitoring and is not recorded as a member of the Gulf of Maine regional phytoplankton flora. Geographically, the closest record of *K. mikimotoi* is an identification from the Gulf of St. Lawrence (Dahl and Tangen, 1993; Blasco et al., 1996). A similar species (*Gyrodinium aureolum*) is known from

Woods Hole, MA (Hulburt, 1957) and coastal Rhode Island (Hansen et al., 2000) areas, but this species is generally confined to lower salinity, enclosed salt ponds and estuaries.

K. mikimotoi is characterized as an oceanic frontal zone and thin layer species that can be transported over long distances along frontal zones (Smayda, 2002). Consistent with this, note that in the September 2017 bloom the greatest cell counts were offshore and at the subsurface chlorophyll maximum depth. *K. mikimotoi* also has a history of ‘invasions’ into new waters where it was not previously observed. For example, the phytoplankton flora of the North Sea was studied for nearly a century before the novel appearance and establishment of *K. mikimotoi* in the North Sea in the 1960s (Partensky and Sournia, 1986). Monitoring the presence of *K. mikimotoi* in Massachusetts Bay will be important to determine if it becomes established in the phytoplankton flora of the region.

2.6 ZOOPLANKTON

Seasonal patterns of zooplankton abundance were normal, with increases from winter lows through to spring and summer peaks, followed by fall declines. At many of the locations in Massachusetts Bay, zooplankton abundances were at or above maxima for the 26-year monitoring program (**Figure 2-29**). In 2017, there were bimodal peaks in abundance of total zooplankton in May/June and August/September, rather than the normal single peak in July or August. Peak total zooplankton abundances in 2017 ($> 250,000$ animals m^{-3}) were slightly higher than those in 2016, but nearly ten times lower 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. Although lower than 2015, total zooplankton abundances were in the upper quartile of historic values in May/June and August/September 2017 at many stations (**Figure 2-29**). Additionally, the abundances of many dominant taxa were at or above maxima for the 26-year monitoring program at many of the stations in Massachusetts Bay from February to June and again in August/September. As in 2016, the warm temperatures observed in winter/spring 2017 may have contributed to the early increase in zooplankton abundances.

Copepod nauplii and copepod adults + copepodites (A+C) were largely responsible for the high total zooplankton abundances from February to May/June (**Figure 2-30** and **Figure 2-31**). Copepod nauplii had relatively high abundances (30,000 to 130,000 animals m^{-3}) from March to June and peaks in abundance above historic maxima were observed in the offshore waters of Massachusetts Bay (stations N04, N18, F06, and F22). Copepod A+C abundances typically peak during the summer, but in 2017 the patterns were atypical with bimodal peak abundances in May and August/September (**Figure 2-31**). In May, Copepod A+C were dominated by the large copepod *Calanus finmarchicus* in peaking at 20,000 to 40,000 individuals m^{-3} at nearfield stations N04 and N18 and offshore station F22 where this species comprised 21-36% of total copepods. There were comparable abundances of the small cyclopoid copepod *Oithona similis*. The May 2017 peaks in abundance of *C. finmarchicus* and *O. similis* were at or above historic maxima. The elevated zooplankton abundances in August/September were primarily driven by *O. similis* with maxima at stations N04, N18 and F22 of 60,000 to 120,000 animals m^{-3} which were all above the range of historic values.

Although much lower than abundances observed in 2015, episodic pulses of bivalve veligers were observed in 2017 with peaks of 40,000 to 50,000 animals m^{-3} in both June and September 2017. Abundances of another meroplankton, barnacle nauplii, also exhibited relatively high abundances in 2017 with values in and above the upper range of historic values (**Figure 2-32**). Barnacle nauplii abundances constitute a minor portion of total zooplankton numbers, but 2017 continues a recent trend of frequent elevated barnacle nauplii levels observed over the past 5 years. The peak abundances observed for barnacle nauplii in **Figure 2-32** all have occurred since 2013, except for the June 2002 peak at station N04. This is coincident with more frequent observation of barnacles during the MWRA hardbottom surveys (pers. com. B. Hecker) in recent years.

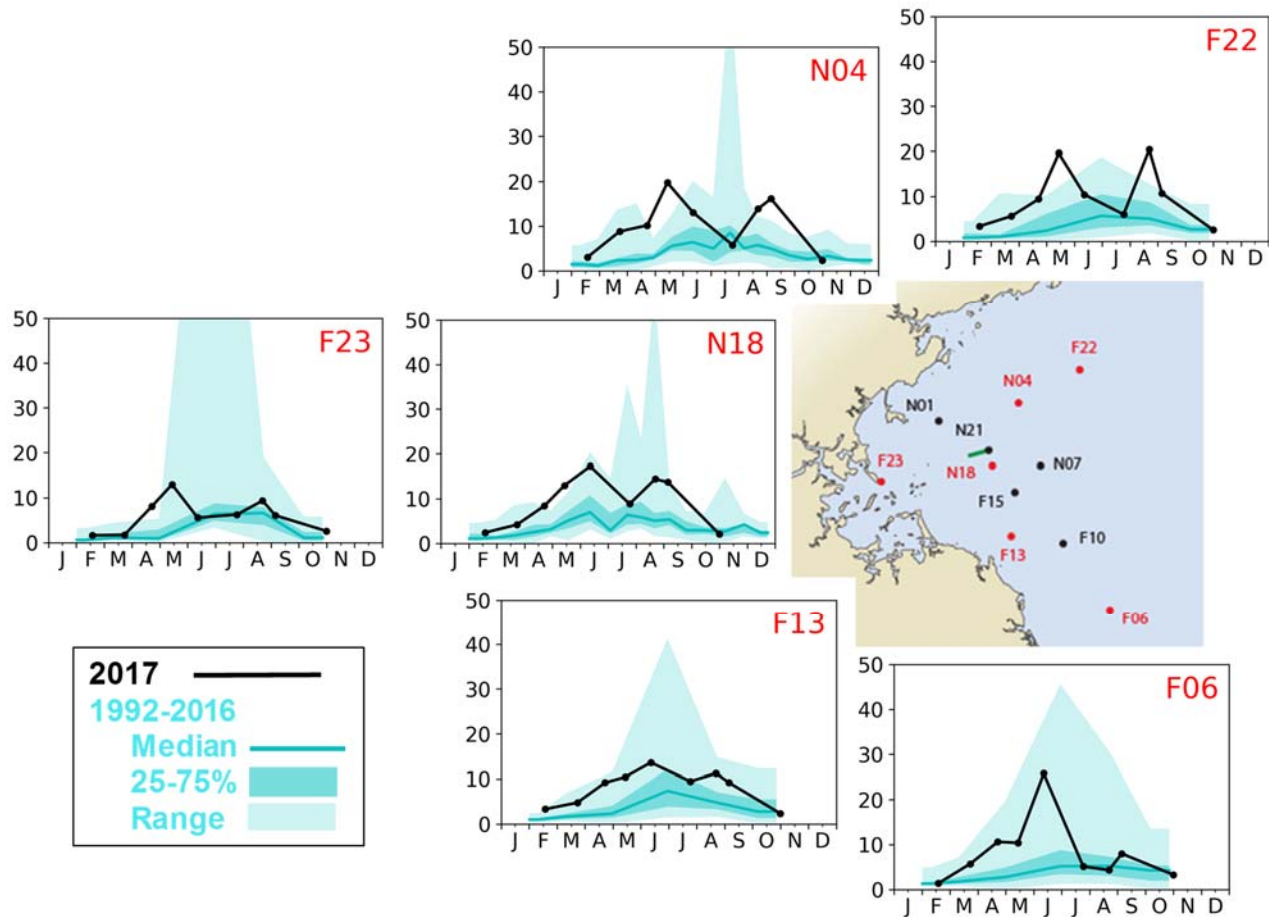


Figure 2-29. Total zooplankton abundance (10,000 individuals m⁻³) at selected stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992–2016 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the 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.

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 in April 2017 compared to historic levels. 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 (2001-2016). In 2017, peak *Acartia* spp. abundance in Boston Harbor occurred even earlier with an April maximum.

It is unclear what may have caused the early occurrence of these high abundances in copepods in 2017 – the warm winter/spring temperatures may have played a role. As observed in recent years, grazing by the large zooplankton populations may have contributed to the relatively low phytoplankton cell counts observed during 2017.

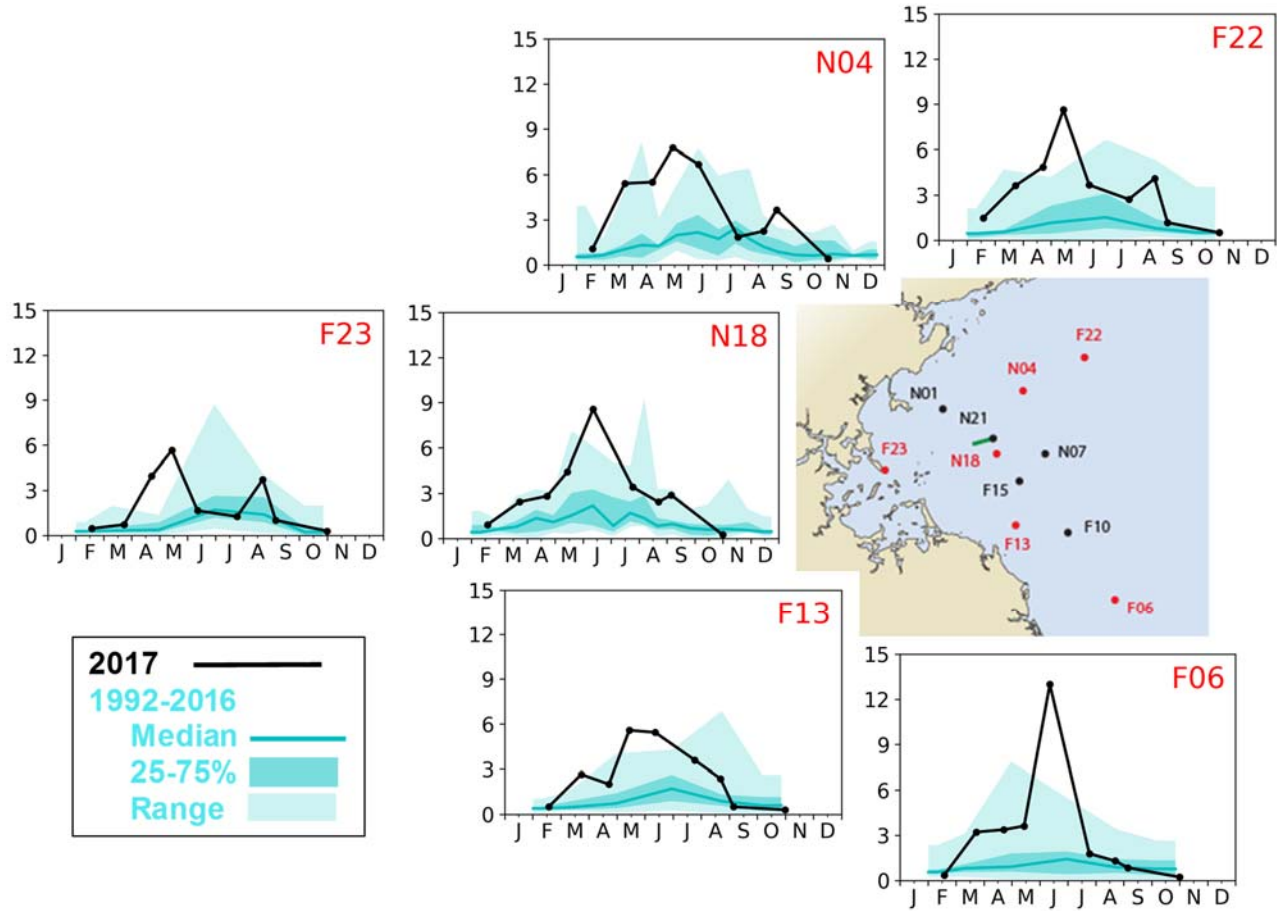


Figure 2-30. Copepod nauplii abundance (10,000 individuals m⁻³) at selected stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992-2016 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

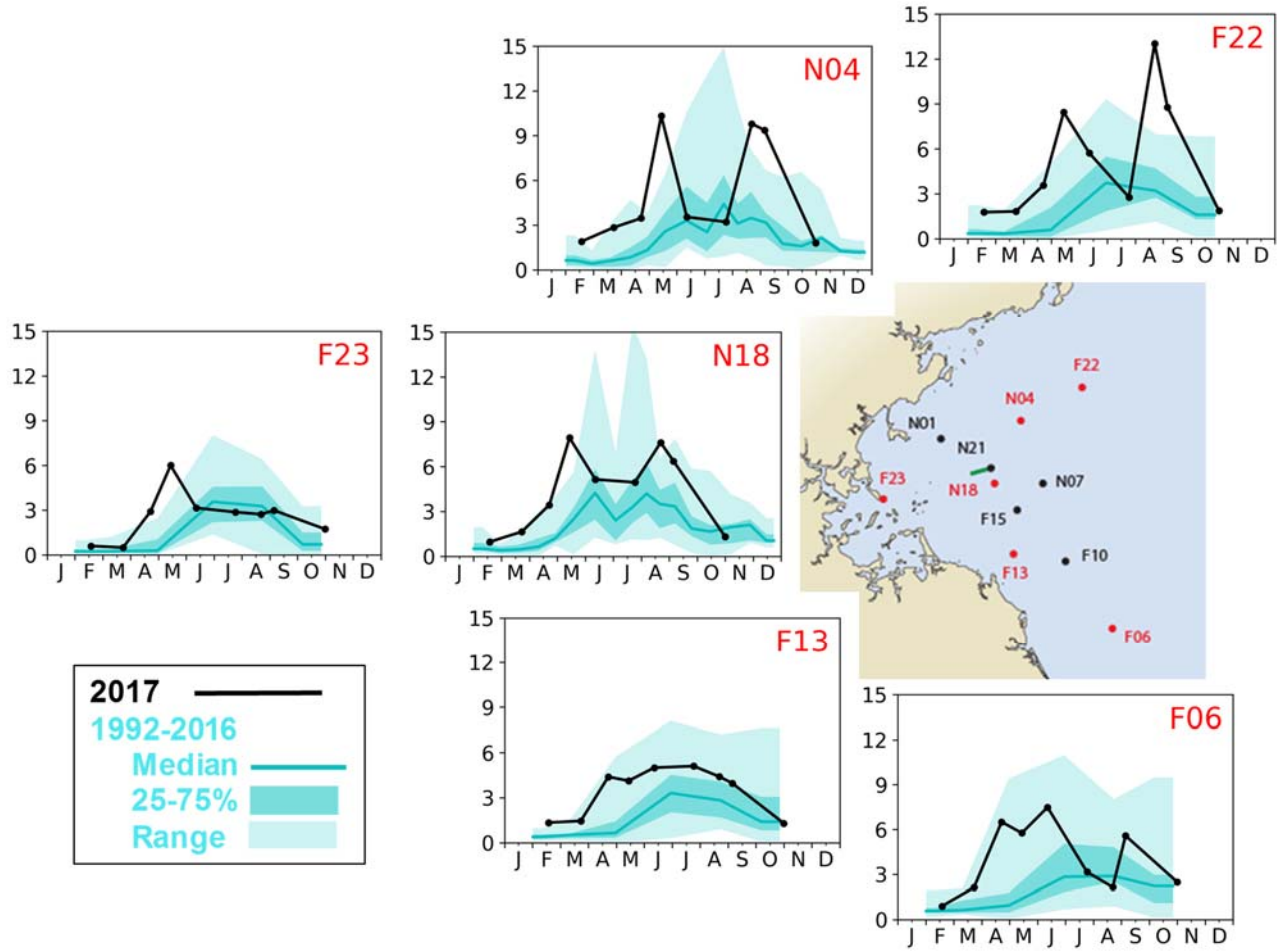


Figure 2-31. Copepod A+C abundance (10,000 individuals m⁻³) at selected stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992-2016 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

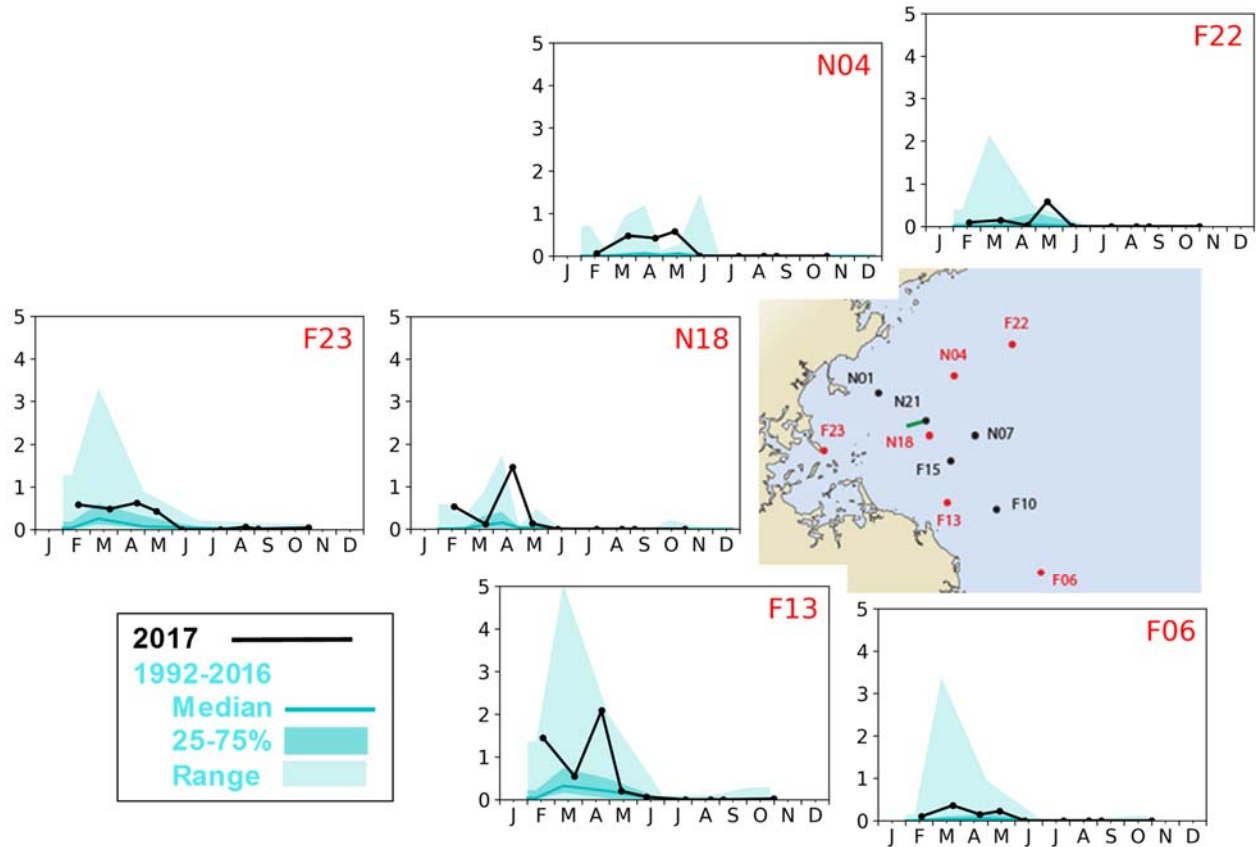


Figure 2-32. Barnacle nauplii abundance (10,000 individuals m⁻³) at selected stations in Massachusetts Bay for 2017 compared to prior years. 2017 results are in black. Results from 1992-2016 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the 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. 2018), 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 addition, 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. The prime whale habitats of Stellwagen Bank and Cape Cod Bay are no longer included in MWRA’s marine mammal observations.

In 2017, a total of eight North Atlantic right whales (*Eubalaena glacialis*) were observed in Massachusetts Bay. Four were seen during MWRA’s HOM water column and Massachusetts Bay bacteria surveys in March. Four additional right whales were observed in Cape Cod Bay during the annual HOM flounder survey in April. Three minke whales (*Balaenoptera acutorostrata*) were observed during MWRA bacteria surveys in Massachusetts Bay in March, May, and June (Table 2-3 and Figure 2-33). Several other marine mammals including twelve harbor porpoises (*Phocoena phocoena*) and twenty-five harbor seals (*Phoca vitulina*) were also observed during 2017 surveys.

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 2-3** 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, 2016, and 2017. From 1998-2010, a total of 4 humpback whales (range of 0-1/year), 11 finback whales (0-4/year), 30 minke whales (0-6/year), and 15 unidentified whales (0-2/year) were sighted.

Table 2-3. Number of whale sightings from 1998 to 2017.

| Whale species | Total number of sightings (1998-2010) | Range of sightings per year (1998-2010) | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|----------------------|---------------------------------------|---|------|------|------|------|------|------|------|
| Finback | 11 | 0-4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Humpback | 4 | 0-1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| Minke | 30 | 0-6 | 4 | 0 | 0 | 2 | 0 | 3 | 3 |
| North Atlantic Right | 0 | 0-0 | 0 | 2 | 4 | 0 | 0 | 2 | 8 |
| Unidentified | 15 | 0-2 | 0 | 3 | 1 | 1 | 0 | 0 | 4 |

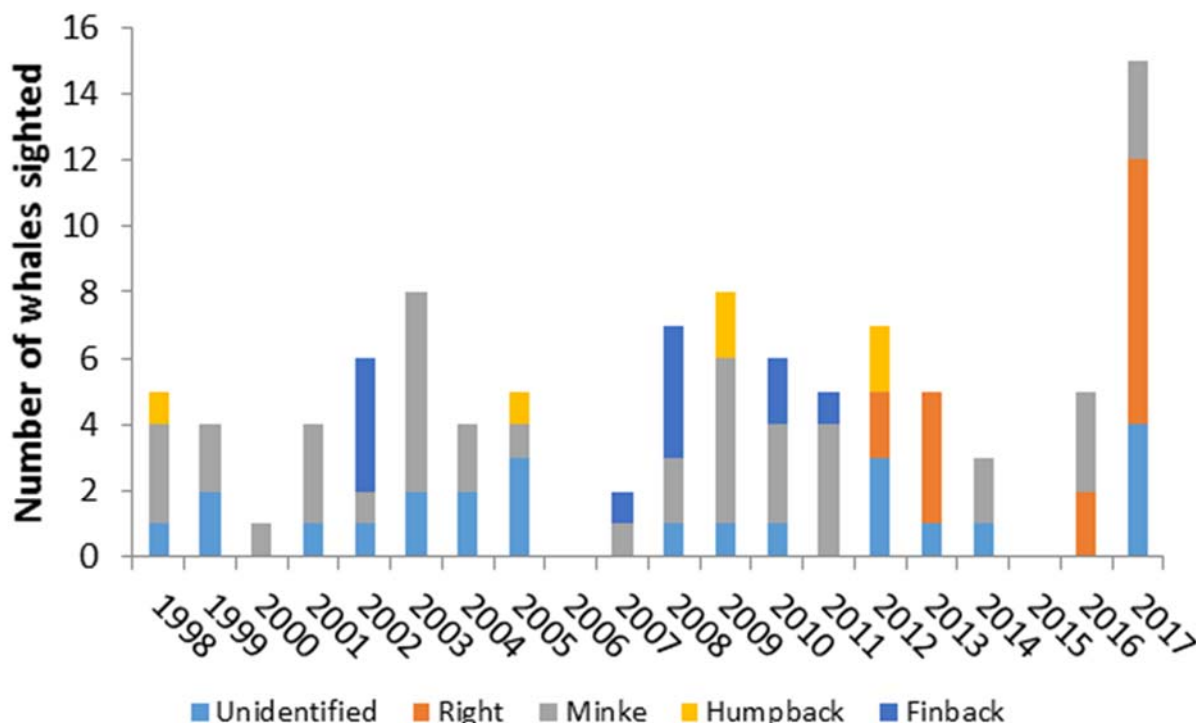


Figure 2-33. Number of whale sightings and whale species sighted in current survey areas (1998 – 2017).

3 LONG-TERM TRENDS

The 2017 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 2-11**). At N18 and N21, NH_4 has been variable with multiple peaks per year 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 2017 annual average total phytoplankton abundance in the nearfield (0.89 million cells L^{-1}) was low in comparison to the long-term mean total phytoplankton abundance of 1.36 million cells L^{-1} ($p = 0.01$) and ranked 21st out of the 26 years of monitoring (**Table 2-1**). Some groups, like diatoms, exhibited abundances similar to long-term mean levels, while other phytoplankton groups (some dinoflagellates) had relatively high abundance levels. However, the lack of a large *Phaeocystis* bloom and low microflagellate levels resulted in 2017 continuing an approximately 10-year declining total phytoplankton trend. Time series analysis reiterate this, with long-term trends of total phytoplankton at low levels during 2017 at both surface and chlorophyll maximum depths (**Figure 3-1**). This has been driven by decreasing trends of both microflagellates and centric diatoms compared to long-term means.

Of note in the long-term record of phytoplankton abundance is that nearfield abundances at the surface and at the chlorophyll maximum depth (C_{max}), while similar to each other prior to 2001, have differed substantially since then. After 2001, the C_{max} and surface trend patterns are qualitatively similar, but total phytoplankton abundance at the C_{max} 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 C_{max} phytoplankton community and it is unclear what factors may be driving the pre/post-2001 differences. The difference between the two depth strata has decreased in the last two years (**Figure 3-1**).

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 C_{max} 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 inter-annual increases and decreases during 1992-2017, with relative peaks during 2000 and 2012. *Ceratium* spp. annual abundances have increased over the past two years with overall ranking in 2016 and 2017 of 3rd and 4th out of 26 years of monitoring (**Table 2-1**).

A combination of bottom-up (nutrients), oceanographic (water mass composition), and top-down (grazing) influences likely determine long-term phytoplankton patterns in Massachusetts Bay. The past 10 years of declining total phytoplankton trend are simultaneous with a period of increasing zooplankton abundance (**Figure 3-2**) suggesting zooplankton grazing as a mechanism at least partially responsible for the past decade of declining phytoplankton abundance in Massachusetts Bay. 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.

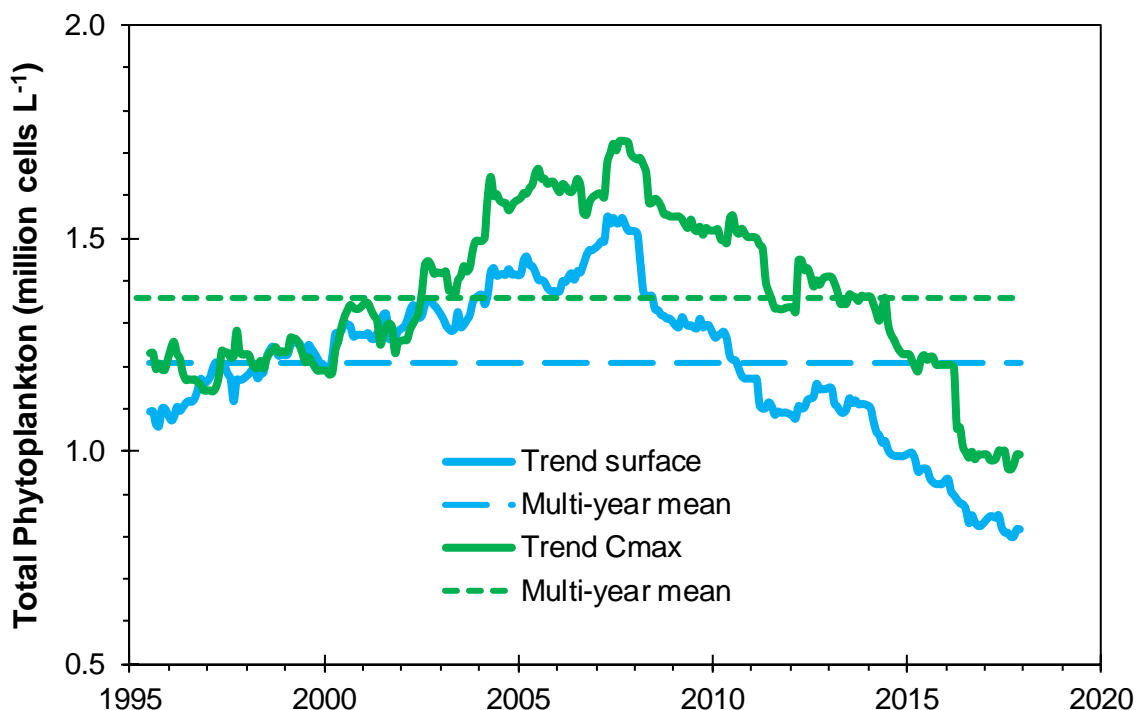


Figure 3-1. Long-term trend (1995 - 2017) in total phytoplankton from surface (light blue) and Cmax (green) depths in the nearfield derived from time series analysis. Data from stations N04 and N18, which have been sampled consistently since 1995. Data lines based on 15% smoothing window (~3.5 years) as recommended in Broekhuizen and McKenzie (1995) for examining seasonally variable data.

Long-term zooplankton trends show 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 indicated there is a significant relationship between phytoplankton and zooplankton abundance in the nearfield (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.

Interestingly, in Boston Harbor, interannual variations in phytoplankton abundance from 1992 to 2008 include increases and decreases that roughly parallel increases and decreases in copepod abundance (**Figure 3-2**). Since about 2008, in contrast, the main feature of phytoplankton and copepod abundances is an inverse relationship more akin to what has been observed in the bay since 1995 as just described. One could speculate that this apparent change since 2008 may be related to harbor recovery due to effluent diversion, with copepod grazing now more tightly coupled with phytoplankton abundance.

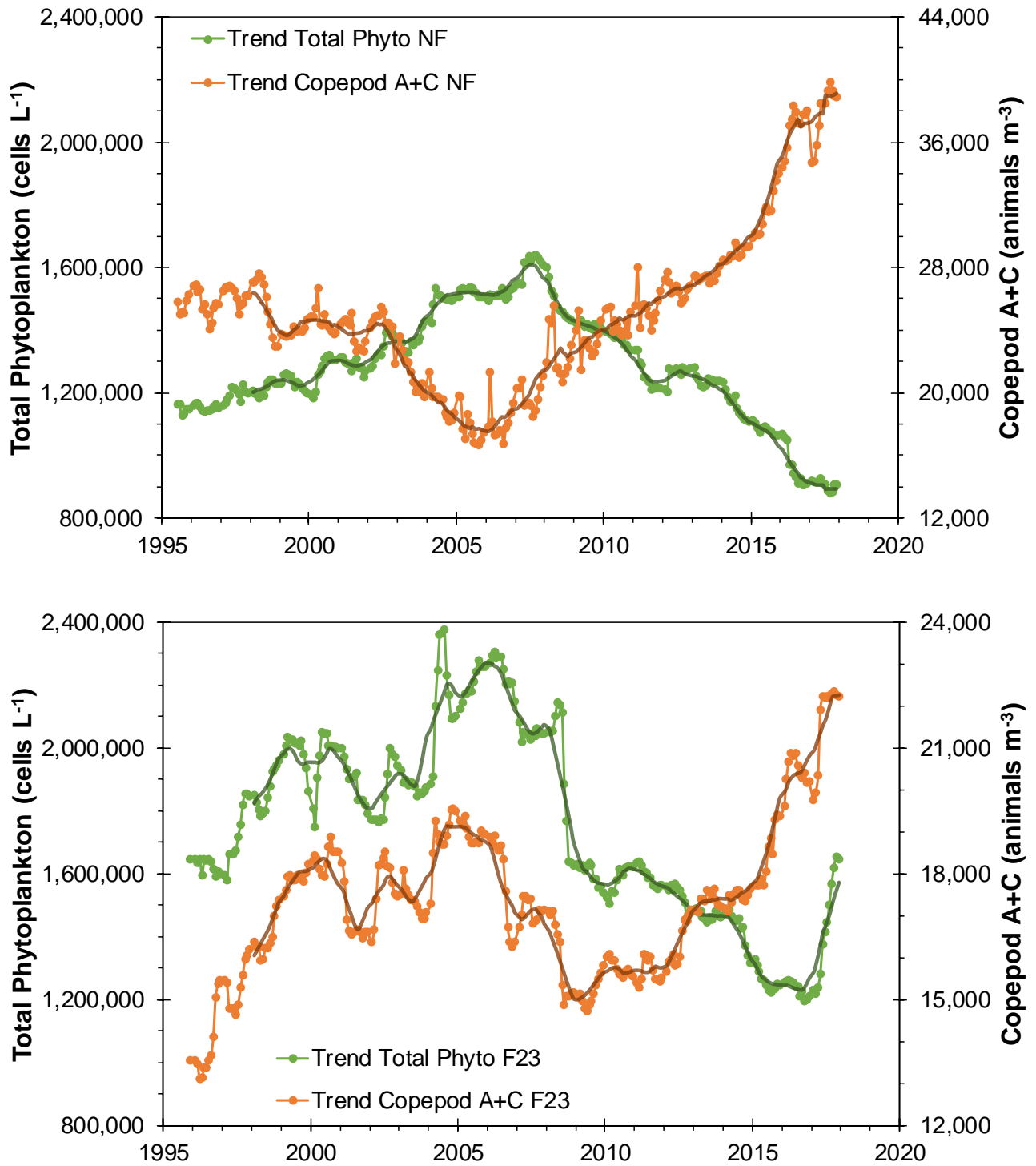


Figure 3-2. Long-term trend (1995-2017) in total phytoplankton (green) and copepod A+C (orange) abundance in the nearfield (top) and Boston Harbor (bottom) derived from time series analysis. Colored data lines based on 15% smoothing window (~3.5 years) and bold lines for 25% smoothing window (6 years). Nearfield data from stations N04 and N18.

4 SUMMARY

From January through early March, water temperatures were above the long-term maxima (**Figure 2-1** and **Figure 2-2**). The warmer waters in early 2017 were consistently observed at stations across Massachusetts Bay and mark the second year in a row with warm winter water temperatures. The wet spring and high regional riverine inputs resulted in below normal salinities in Massachusetts Bay (**Figure 2-2**) and contributed to the onset of stratification in the bay in April (**Figure 2-4**). Several Nor'easter storms occurred from mid-May to early June (**Figure 2-5**) with strong flow (~ 50 km/day) to the southeast. The effect of these currents in Massachusetts Bay was seen as significant drops in surface salinity at NERACOOS Buoy A01 in May and June indicating the presence of the Merrimack River plume. This freshwater inflow in the surface layer down to ~20 m contributed to anomalously strong stratification in early June (**Figure 2-4**). After the early June Nor'easter, there was a long period of upwelling-favorable, southerly winds (**Figure 2-5**). This led to cooler, saltier surface waters and an increase in nutrient concentrations in the bay as surface waters were advected offshore and deeper bottom waters towards shore. A strong upwelling event occurred on June 17-18, followed by a reduction in wind strength and a slight reversal on June 21 (**Figure 2-6**). The decrease in wind strength resulted in a "relaxation" of the upwelling and caused a shift in the current to a more onshore, southwestward direction. As with the earlier June Nor'easter, the changes in currents likely influenced the transport and distribution of *Alexandrium* in the bay.

Nutrient concentrations in Massachusetts and Cape Cod Bays followed their typical 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 2-8**). As in previous years, NH_4 concentrations during 2017 were more variable and did not show the seasonal pattern shown by the other three nutrients. The most notable deviation from these historic seasonal patterns in 2017 was the relatively low and consistent SiO_4 concentrations from early February through April. Phytoplankton drawdown of SiO_4 may have been responsible for the low concentrations.

As has been the case since operation of the bay outfall began in 2000, the effluent plume was observed as elevated NH_4 concentrations in the nearfield in 2017 (**Figure 2-10** and **Figure 2-11**). The NH_4 signature, when evident, was confined within 10 to 20 km of the outfall. This applied during both well-mixed and stratified conditions and was 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 2017, 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 2-11**). The levels at stations N18 and N21 were generally within the range of values observed post-diversion and elevated concentrations were observed at stations F15 and F10 which are about 10 and 20 km south of the outfall, respectively (**Figure 2-14**).

In 2017, biomass measured during the regular water column surveys followed the typical seasonal pattern with elevated biomass in February and April, low levels over the summer, and then increasing in late fall (**Figure 2-16**). The interesting deviation from this trend were the very high chlorophyll levels observed in late June through early July during the ARRS surveys. These peaks were annual maxima at many of the monitoring stations and were also higher than historical summer values (**Figure 2-15**). The ARRS surveys were conducted during a period of upwelling favorable conditions leading to increases in nutrient availability and subsequently higher chlorophyll levels.

Bottom-water DO concentrations in 2017 showed their typical decline from their winter/spring maxima to September or October annual minima. In 2017, as in 2016, the seasonal decline was punctuated by upwelling increasing bottom water DO levels in June and July (**Figure 2-20**). Bottom water DO concentrations began the year at seasonally low levels and the June mixing event increased bottom water DO concentrations to levels comparable to long-term average. Boston Harbor and most of the Massachusetts Bay stations stayed close to long-term averages for bottom water DO for the rest of the year. However, with the delay in water column mixing into November, bottom water DO levels were in the lower range of

historic values southern Massachusetts Bay and in Cape Cod Bay though remained above 6 mg L⁻¹. NERACOOS Buoy A01 DO data indicated the water column did not become mixed to 50 m depth until mid-November (**Figure 2-22**).

2017 phytoplankton abundance was low compared to the range of observations from 1992-2016. Total phytoplankton abundance in the nearfield in 2017 was 65% of the long-term mean and ranked 21st for the 26-year monitoring program (**Table 2-1**). The lack of a large winter-spring diatom or *Phaeocystis* bloom was at least partly responsible for the low 2017 total phytoplankton counts. The 2017 phytoplankton annual cycle featured two abundance peaks in late spring (April/May) and in August (harbor/coastal) and November (nearfield/offshore; **Figure 2-24**). *Skeletonema* spp. dominated the late spring bloom, as was the case in 2016. This shift to a later (April), *Skeletonema*-dominated bloom may be partially a response to changing climate. *Skeletonema* spp. physiology may provide an advantage under variable temperature and nutrient conditions. The late spring bloom may also be part of a shift to a two-part winter-spring bloom featuring an early *Thalassiosira*-dominated bloom followed by a later *Skeletonema*-dominated bloom. The late summer diatom bloom in Boston Harbor and nearby coastal water stations was dominated by *Leptocylindrus danicus* and the early November bloom was dominated by *Skeletonema* spp. in the offshore waters of Massachusetts Bay.

Blooms of three harmful phytoplankton species, *Alexandrium*, *Pseudo-nitzschia*, and *Karenia mikimotoi*, were documented in Massachusetts Bay (and other western Gulf of Maine waters) in 2017. MWRA monitoring, which was supplemented by additional ARRS surveys, identified a moderate *Alexandrium* bloom in northern Massachusetts Bay from June to July 2017. The elevated *Alexandrium* abundances were likely due to a combination of an influx of western Gulf of Maine water into northeastern Massachusetts Bay (see **Figure 2-6**) carrying established populations of this species and localized growth due to availability of upwelled nutrients and was unrelated to the bay outfall.

The 2017 *Alexandrium* bloom led to high PSP toxicity along the shores of the western Gulf of Maine and resulted in shellfishing closures from the Cape Ann, Massachusetts to Eastern Maine. Abundances of *Alexandrium* sufficient to cause PSP toxicity were present in Massachusetts Bay over a period of several weeks in June/July, but fortunately PSP toxicity was not detected at any of the MA DMF stations within Massachusetts Bay proper. This suggests the *Alexandrium* cells observed in the bay remained offshore and did not impact the inshore shellfish. This is consistent with the overall distribution of elevated abundances observed at offshore stations during the six MWRA surveys in June and July 2017. The northeast winds likely entrained Gulf of Maine waters into Massachusetts Bay with *Alexandrium*, while subsequent upwelling favorable winds out of the south kept the *Alexandrium* bloom offshore and away from shellfish resources.

Overall, nearfield *Pseudo-nitzschia* abundance during 2017 was low at only 25% of the long-term mean levels (**Table 2-1**) and orders of magnitude lower than the maximum prior abundance of 1.8 million cells L⁻¹ in 1998. *Pseudo-nitzschia* blooms caused shellfish harvest closures in Maine and Rhode Island waters in 2017, but not in Massachusetts Bay. An unusual bloom of dinoflagellate, *Karenia mikimotoi*, occurred in Massachusetts Bay in September 2017, with abundances of >100,000 cells L⁻¹ at many of the offshore stations. *K. mikimotoi* has not been observed in the previous 25 years of MWRA monitoring. It is known to have a history of 'invasions' into new waters.

Peak zooplankton abundances in 2017 (> 250,000 animals m⁻³) were slightly higher than those in 2016, but nearly ten times lower than 2015 when extreme abundances of bivalve veliger larvae were observed. Total zooplankton exhibited unusual bimodal peaks in abundance in May/June and August/September 2017 (**Figure 2-29**), rather than the normal single summer peak. Total zooplankton abundances were in the upper quartile of historic values in May/June and August/September 2017. Additionally, the abundances of many dominant taxa (including *Calanus finmarchicus* and *Oithona similis*) were at or above maxima for the 26-year monitoring program at many of the stations in Massachusetts Bay from February to June and again in

August/September. It is unclear what may have caused the early occurrence of these high abundances in copepods in 2017, but the warm winter/spring temperatures may have played a role.

The high zooplankton abundances in 2017 continue a trend of increasing numbers observed since 2005 (**Figure 3-2**). This increase and associated grazing pressure likely play an important role in the concomitant trend of decreasing phytoplankton abundance. 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 copepods appeared to co-vary prior to the mid-2000s, and since then they appear to be inversely correlated as seen in the nearfield; it is possible that Boston Harbor plankton dynamics have shifted in response to cleanup efforts and diversion of effluent to the bay.

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