2018 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 during 2018. 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 discharged at the MWRA outfall in Massachusetts Bay is within the bounds projected by the Supplemental Environmental Impact Statement from the Environmental Protection Agency (EPA), and (3) determine whether thresholds of the Contingency Plan[1] attached to the permit have been exceeded. There were no Contingency Plan water column threshold exceedances in 2018.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2018
Bottom water DO[a] concentration (mg L^{-1})	Survey Mean June-October	<6.5[b]	<6.0[b]	Nearfield[c]: 6.05 SW[d] Basin: 6.23	Nearfield: 6.83 SW Basin: 7.07
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 75.5% SW Basin: 76.3%
Bottom water DO rate of decline (mg L^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.010
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	71
	Winter/spring	>199	--	50	73
	Summer	>89	--	51	58
	Autumn	>239	--	90	95
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	122
	Summer	>43,100	--	14,635	245
	Autumn	>27,500	--	10,500	518
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	4

[a]DO = Dissolved Oxygen [b]Unless background lower [c]Stations within 5 km of the outfall are referred to as "nearfield" and those further away are "farfield" [d]SW = Stellwagen

The 2018 monitoring confirmed that the treated wastewater discharge from the bay outfall 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 2018 are as follows.

- The most notable physical oceanographic events in 2018 were a strong Nor'easter in early March, and a rare late-summer Nor'easter which provided mixing and ventilation of the deep water that kept dissolved oxygen from dropping as much as it otherwise would have.

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[1] MWRA's discharge permit includes a Contingency Plan with thresholds that may indicate a need for action if exceeded. 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, for which 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 early March Nor'easter was a very intense and long duration storm. Sustained winds were nearly 20 m/s and wave height reached 10 m at the peak of the storm. The time-integrated wave stress at the seafloor, an indicator of potential wave-induced erosion, was larger during this storm than any other storm since 1990.
- Overall, river flow was higher than normal in 2018 due to high precipitation. An exception was April to June during the spring freshet, when the Merrimack River flow was lower than typical.
- Periods of upwelling-favorable, southwesterly winds in June/July led to cooler offshore surface waters (at Buoy A01 and station F22). This was not evident in the nearfield, perhaps due to the southwesterly wind direction being more favorable to upwelling in the northern rather than central part of Massachusetts Bay.
- The late summer Nor'easter resulted in warmer water at depth, consistent with downwelling driven by the storm, at both nearfield and offshore stations. This led to bottom water temperatures higher than the 1992-2017 maximum for late summer at nearfield station N18.
- Nutrient concentrations in the bay during 2018 were broadly consistent with those observed since the outfall was diverted offshore in 2000. Ammonium (NH_4) concentrations were typical: compared to pre-diversion baseline conditions they were lower in Boston Harbor, higher in the outfall nearfield and vicinity, and unchanged in the farfield. During both winter (unstratified) and summer (stratified) conditions, modestly elevated NH_4 concentrations were observed up to about 10 km south of the outfall.
- Overall, chlorophyll concentrations were low in 2018. Locally higher chlorophyll concentrations were observed offshore in northeastern Massachusetts Bay and Cape Cod Bay in April and October 2018. Chlorophyll concentrations in the nearfield met Contingency Plan thresholds.
- Bottom water dissolved oxygen (DO) concentration minima were moderate over most of Massachusetts Bay in 2018 and higher than Contingency Plan thresholds. Bottom water DO levels would have been lower if not for June upwelling that raised concentrations. The late summer Nor'easter ventilated offshore waters (at Buoy A01 and station F22) down to 50 m, but not the near-bottom water (77 m deep) at station F22.
- Annual total phytoplankton abundance in the nearfield was low in 2018 and ranked 23rd for the 27-year monitoring program. This was in part due to the lack of a strong bay-wide winter/spring diatom or *Phaeocystis* bloom. As observed the last few years, there was an April diatom bloom dominated by *Skeletonema* in northeastern Massachusetts Bay. The large diatom *Rhizosolenia* was also abundant at these stations. There was a *Phaeocystis* bloom in Cape Cod Bay in April with moderate abundances (~2.5 million cells L^{-1}).
- There were no blooms of *Alexandrium catenella* or the toxigenic pennate diatom *Pseudo-nitzschia* in Massachusetts Bay in 2018 and no toxicity detected at MA Department of Marine Fisheries shellfish stations within the bay. The dinoflagellate *Karenia mikimotoi* was observed in September 2018, but at abundances about 100 times lower than observed in 2017, when a large bloom was detected for the first time in these waters.
- Total zooplankton abundances were above the long-term average for the program, as in the past several years. Copepod nauplii and adult abundances were in the upper 75th percentile of historic results for May and June 2018. *Oithona similis* was the dominant copepod species and reached abundance maxima for the 27-year monitoring program at many stations in Massachusetts Bay in 2018.
- Massachusetts Bay and Boston Harbor phytoplankton and zooplankton have undergone long-term (decadal) changes since monitoring started in 1992, due to regional processes in the Gulf of Maine unrelated to the outfall. Inter-annual variations in phytoplankton and zooplankton (both copepods and microzooplankton) populations in the nearfield appear to be inversely correlated, suggesting grazing pressure is an important factor on the abundance of phytoplankton.

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 thresholds of the Contingency Plan (MWRA 2001) attached to the NPDES permit.

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 5, 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 2018, when wastewater has been discharged from the bay outfall and not into the harbor. The 2018 data complete 18 years of monitoring since operation of the bay outfall began and 27 years of monitoring since the program began in 1992. **Table 1-1** shows the timeline of major upgrades to the MWRA wastewater treatment system.

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 focuses on the stations potentially affected by the discharge and reference stations in Massachusetts Bay. Nine one-day surveys were undertaken in 2018 (**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 sampled Cape Cod Bay in the same timeframe (**Table 1-2**), extending the spatial extent of the monitoring. This annual report summarizes the 2018 results, with emphasis on 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.

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

Table 1-2. Water column surveys for 2018.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN181	February 6	February 6	January 31
WN182	March 20	March 20	March 19
WN183	April 10	April 10	April 3
WN184	May 15	May 14	May 14
WN185	June 22	June 20	June 18
WN186	July 24	July 24	July 23
WN187	August 21	August 21	August 23
WN188	September 5	September 5	September 6
WN189	October 23	October 23	October 25

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, the 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 have 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 2018 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 two days 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) collected within 7 days (**Table 1-2**) of an AMP survey are included in this report. Marine mammal observers were present on all regular bay water quality surveys in Massachusetts Bay

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[2] CCS station map and data available at http://www.capecodbay-monitor.org/

[3] BHWQM station map ("nutrient monitoring") at http://www.mwra.state.ma.us/harbor/graphic/harbor_sampling_locations_detail.jpg

during 2018. Marine mammal observations made by MWRA field staff on the BHWQM surveys were documented and are also included in this report.

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. Buoy 44013 is located ~10 km southeast of the outfall, near station N07; 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 Buoy A01 presented and interpreted here are the non-tidal flow, isolated from tidal variations by application of a low-pass filter.

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 5, 2000 and the outfall discharge period is September 6, 2000 through December 2018. Year 2000 data are not used for calculating annual means, as the year spans both the baseline and post-discharge periods, but they are included in plots and analyses broken out by survey and season.

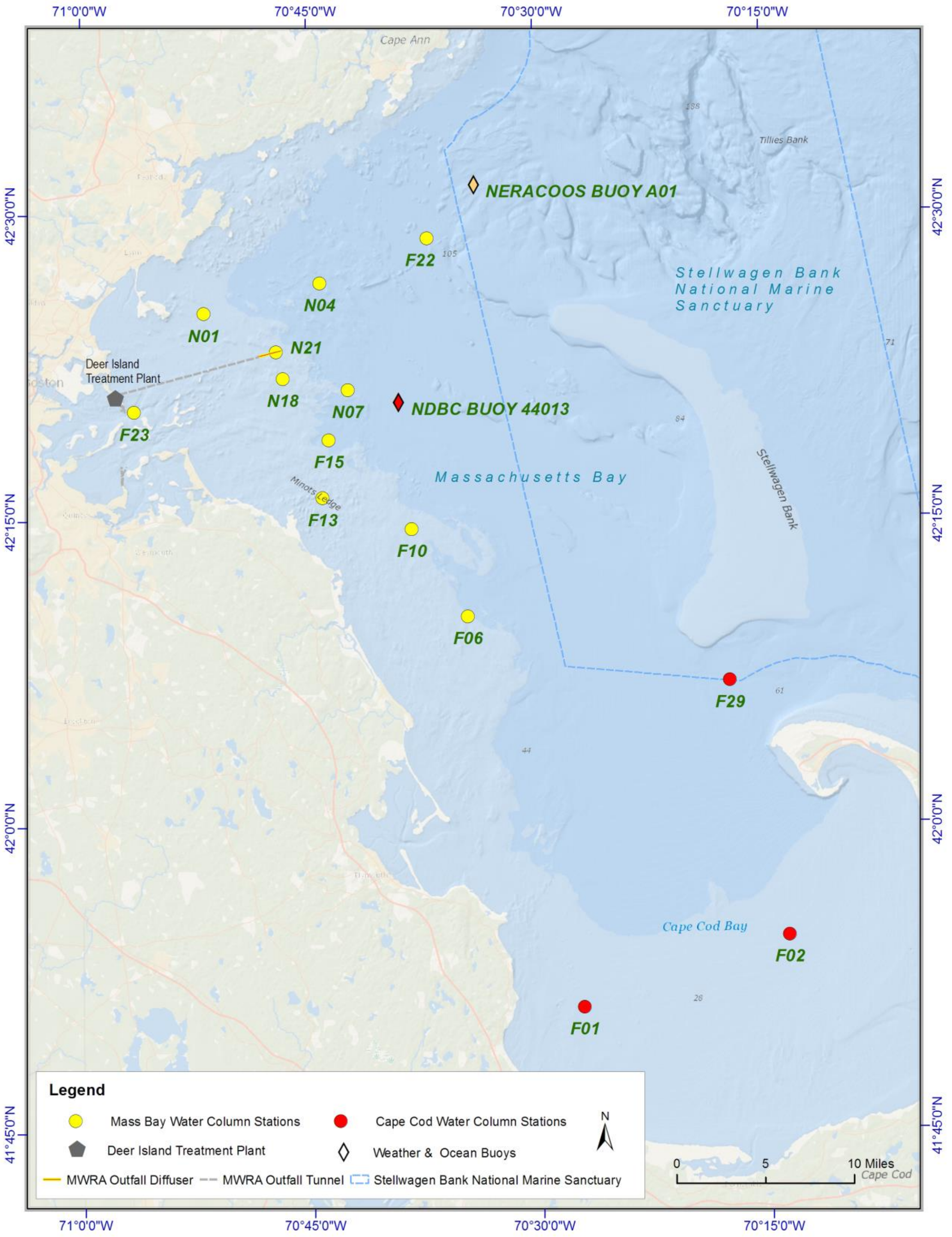

Figure 1-1. **Water column monitoring locations.**

2 2018 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 influence the seasonal pattern. Details of the cycle can differ across specific areas of the bay system.

During winter, when the water column is vertically well mixed and light intensities are low, nutrient concentrations in the bay are typically relatively high. 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 the 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 to 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 summer, zooplankton abundance in the bay is typically relatively high, but the size and 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 summer. 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.

During summer when water temperatures are high and the water column is 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.

In the fall, the water column de-stratifies 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*.

This general sequence has been evident every year of this 27-year dataset (1992-2018). The major features and differences in 2018 are described below.

2.2 PHYSICAL CONDITIONS

Surface water temperatures were close to average from January to June 2018 at Buoy 44013, about 10 km southeast of the outfall (**Figure 2-1**). At nearfield station N18, surface and bottom water temperatures began the year near the historic median levels and stayed close to them through June (**Figure 2-2**). Salinity was also at median values for February and March 2018.

Physical oceanographic conditions in Massachusetts Bay are dominated by regional forcing and inter-annual variability is often event-driven. In 2018 the most notable events were a pair of strong Nor'easter storms, one in March and the other in late summer. The March storm was intense and of long duration with sustained winds of nearly 20 m/s (40 knots) and wave heights reached 10 m (**Figure 2-3**). An analysis of the winds and waves using the IWaveS calculation based on Butman et al. (2008) showed the long duration of the waves generated by the early March Nor'easter. The time-integrated bottom stress, an indicator of potential wave-induced erosion, was larger during this storm than any other storm since 1990.

The water column was already well mixed during the large storm, so there was not a clear signal in the physical parameters measured at the buoys or on the MWRA surveys. However, due to that storm and subsequent, less-intense Nor'easters later in the month, the index of upwelling/downwelling was more downwelling-favorable in March 2018 than previously observed in any month over the 1994-2018 period (**Figure 2-4**).

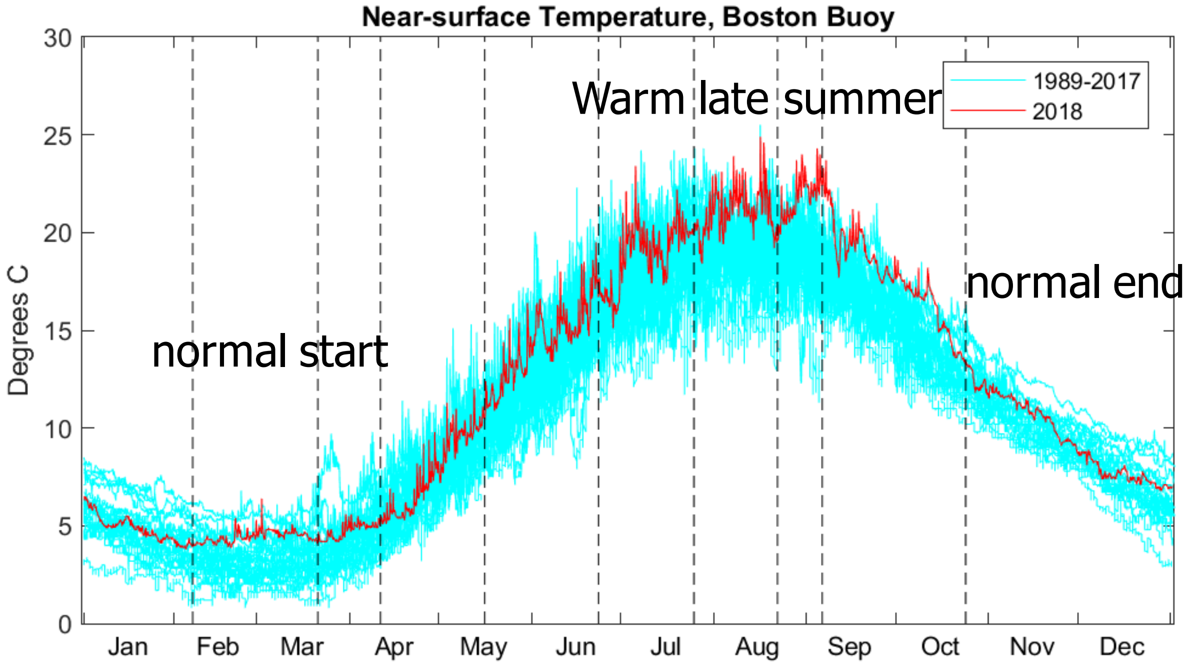

Figure 2-1. Comparison of 2018 (solid red line) surface water temperature (°C) at Buoy 44013 ("Boston Buoy") in the vicinity of the nearfield with 1989-2017 (cyan lines). The vertical dashed lines are when the 9 surveys were conducted in 2018.

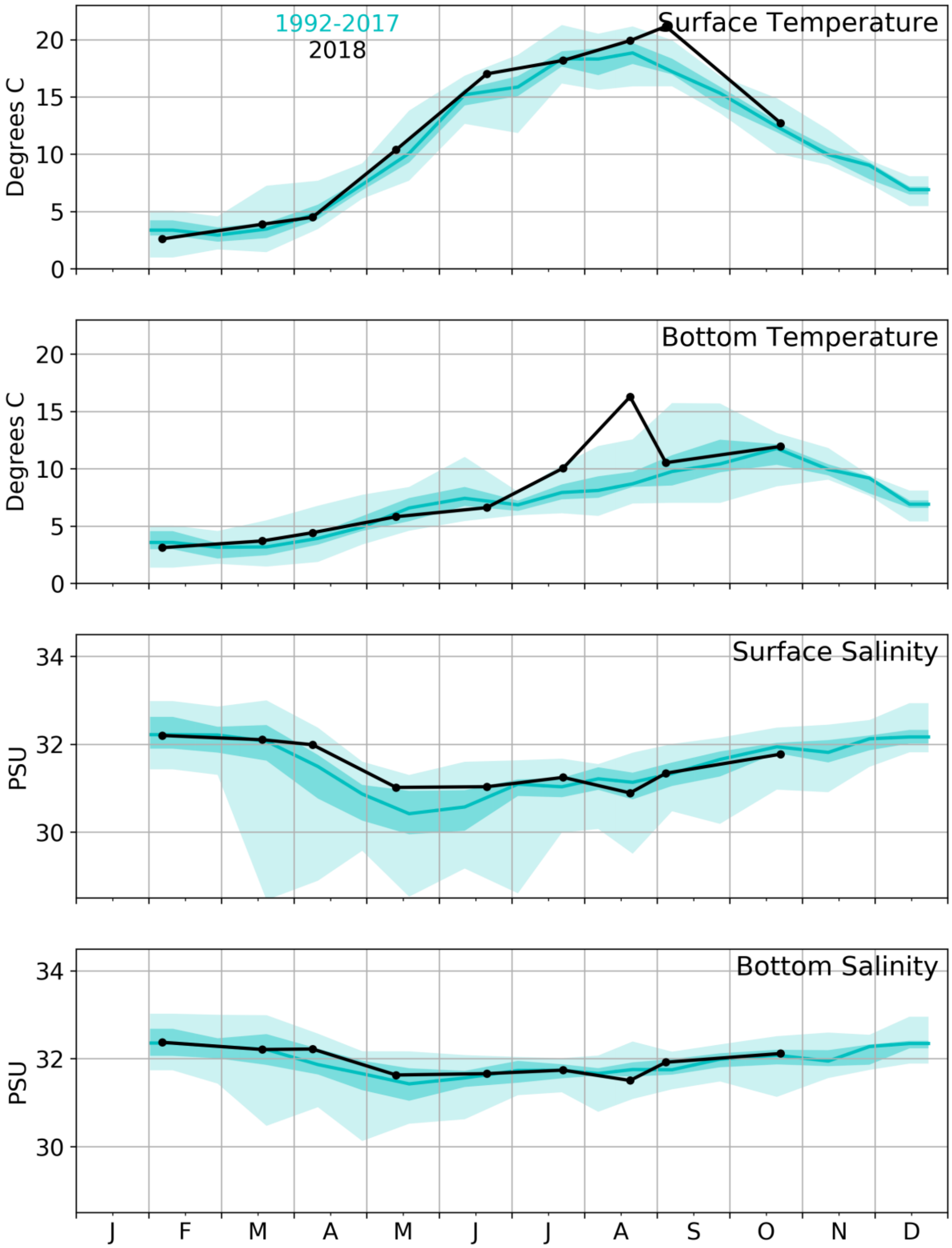

Figure 2-2. Comparison of 2018 surface and bottom water temperature and salinity at nearfield station N18 compared to prior years. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

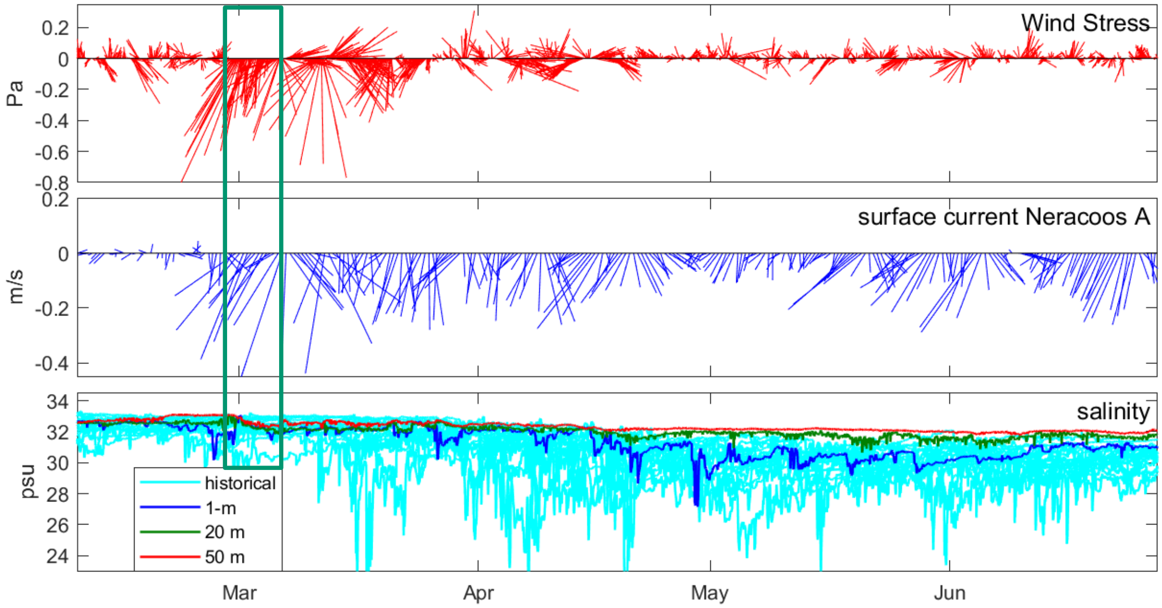

Figure 2-3. **Buoy A01 time series observations in February – June 2018.** Top: surface wind strength and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: surface currents at 2 m depth. Bottom: salinity at 1 m (blue), 20 m (green), and 50 m (red) depths. Cyan lines show records from all prior years (1989-2017) at 1 m depth. The vertical rectangle highlights the winds and currents during the large Nor'easter in early March.

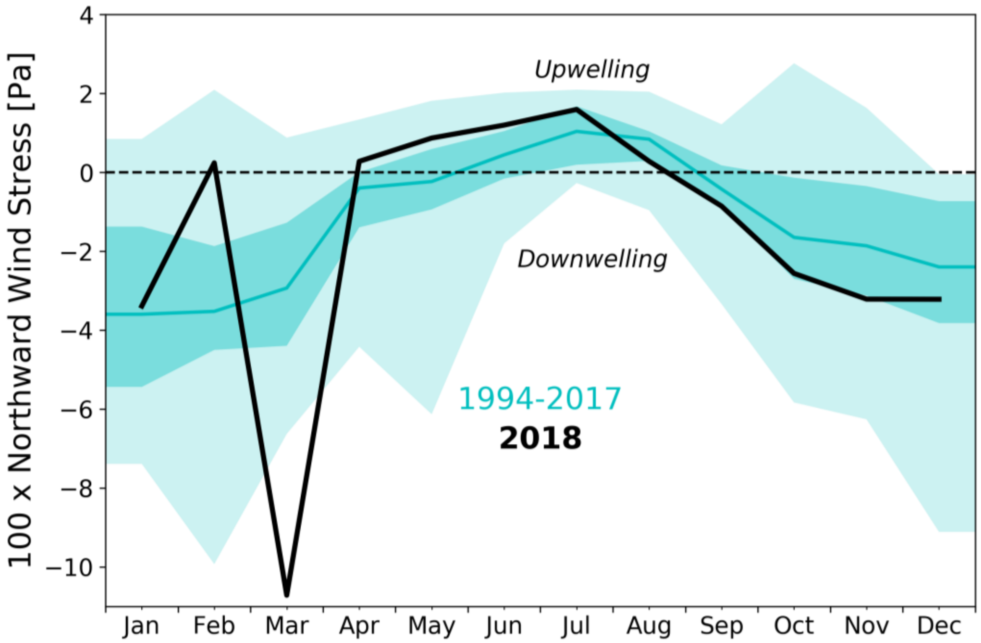

Figure 2-4. **Average wind stress at Buoy 44013.** 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

Precipitation and river flow were generally higher than normal in 2018 (**Figure 2-5**). The main exception was for the period from April to June in the Merrimack River, where the spring freshet was relatively weak. This was coincident with elevated surface water salinity in Massachusetts Bay in April and May, which was in the upper 75th percentile compared to historic values (**Figure 2-2**).

By May 2018, the surface waters had warmed, and the water column had become stratified across the bay especially at the deeper offshore stations including station F22 south of Cape Ann (**Figure 2-6**). Winds in June and July were conducive for relatively strong upwelling in the bay (**Figure 2-4**). The June and July stress and water temperature at Buoy A01 provide two clear examples of upwelling events that caused a drop in temperature of the surface water (**Figure 2-7)**. The surface temperature at station N18 and Buoy 44013 (B-buoy) did not show a similar drop during these events, perhaps because the southwesterly wind direction is more favorable to upwelling in the northern part of Massachusetts Bay than in the nearfield region.

A rare late-summer Nor'easter occurred in late August just before the August water column survey. Wind stress and temperature at Buoy A01 shows the warming influence of a strong Nor'easter around August 17 (**Figure 2-7**). The water temperature at 20 m had actually started warming on August 12, apparently in association with a weak wind-reversal that generated strong surface currents to the southwest. The impact of this storm did not reach into the deeper bottom water at station F22, but at shallower stations like nearfield station N18 there was a large increase in bottom water temperature to levels well above historic maxima (**Figure 2-2**). The increase in bottom temperatures caused a marked drop in stratification at the shallower stations like N18 to levels near the historic minima (**Figure 2-6**). At station F22, the surface water cooled as the Nor'easter brought cooler offshore waters ashore, but the effect of the storm induced mixing/downwelling did not reach the deeper bottom waters and stratification remained near maximum historic levels in August and September 2018 at station F22. A subsequent Nor'easter in early September had a similar effect of cooling near-surface water and warming temperature at 20-m depth at the Buoy A01 (**Figure 2-7**).

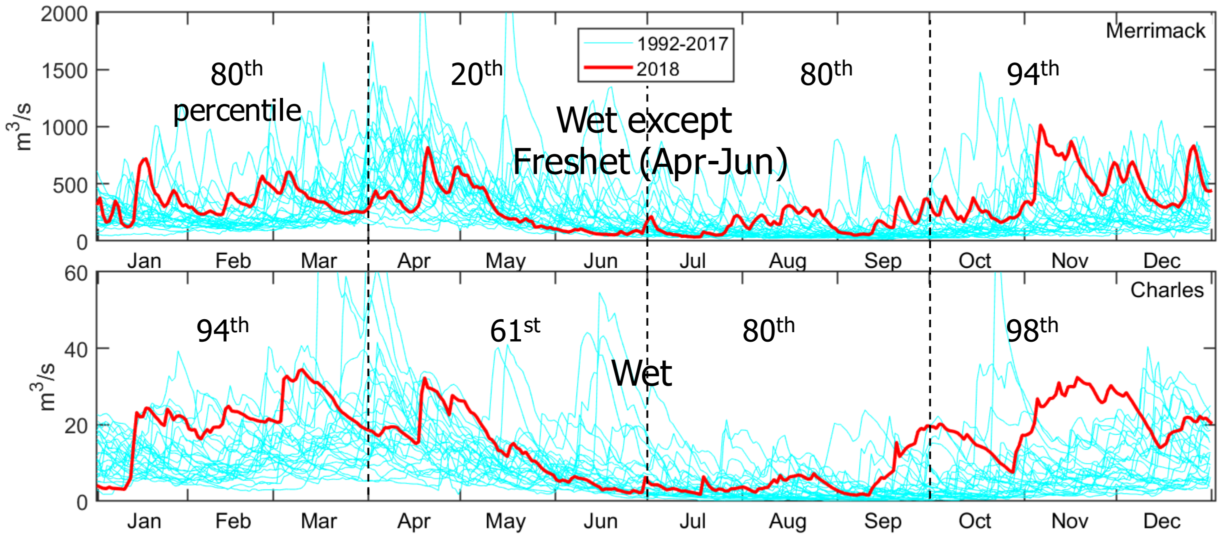

Figure 2-5. Comparison of 2018 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2017 (light blue lines). The percentiles shown represent 2018 flow, compared to the entire 27-year record, during each quarter of the year.

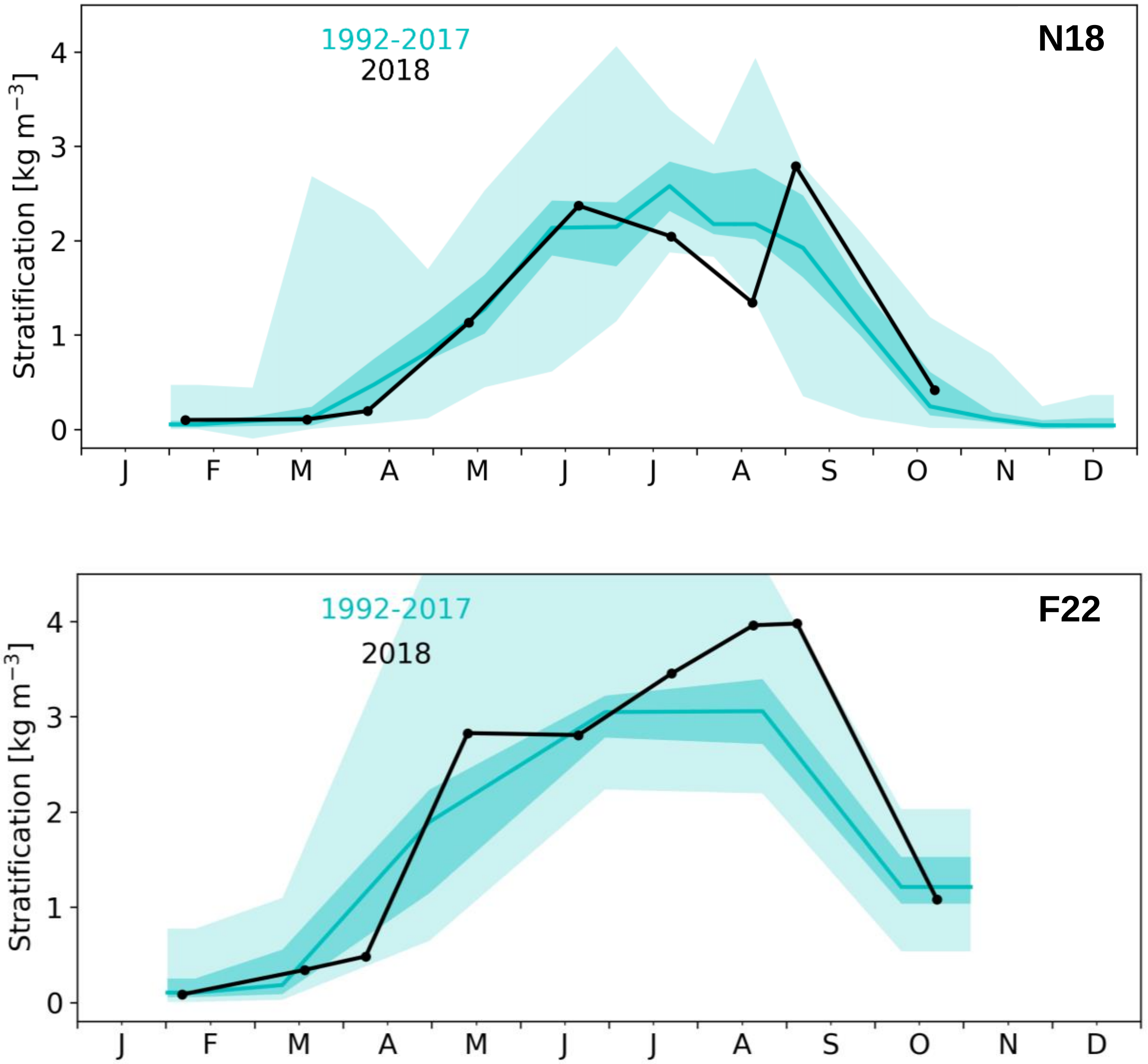

Figure 2-6. Stratification at nearfield station N18 (top) and offshore station F22 (bottom) in Massachusetts Bays in 2018 compared to prior years. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

A return to cooler/normal air temperatures (**Figure 2-1**) and a period of unsettled weather and strong wind events in late September and early October (**Figure 2-7**) led to cooling surface waters and weaker stratification during the October 23 survey (**Figure 2-2** and **Figure 2-6**). However, the water column remained stratified at offshore station F22 in late October with a thermocline/pycnocline at 40 m and a Δ sigma-T > 1 between surface and bottom waters. Buoy A01 DO data indicate the water column did not become well mixed in these deeper waters until after the October survey (see **Figure 2-21**).

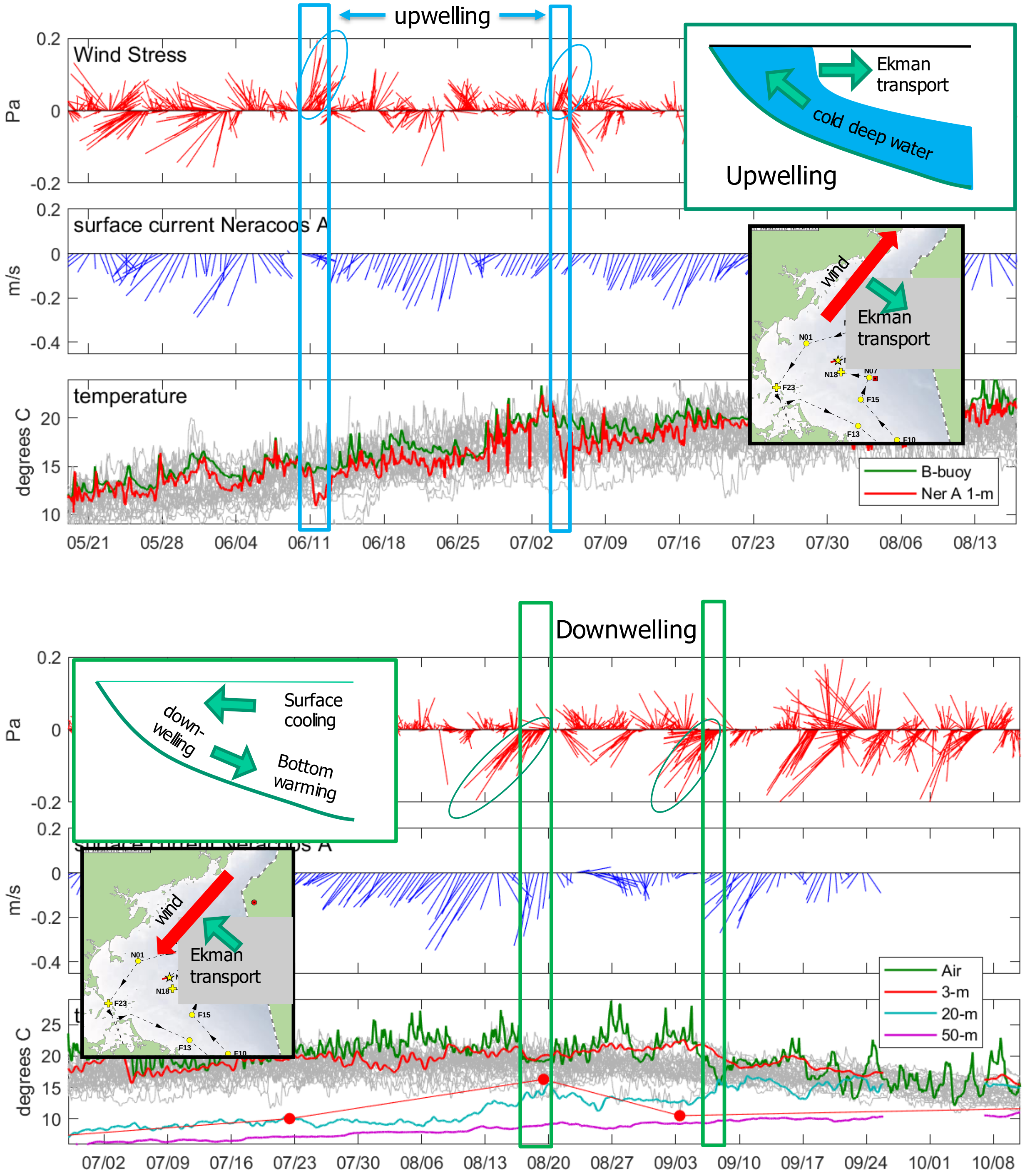

Figure 2-7. **Buoy A01 time series observations in May – October 2018 highlighting upwelling (top) and downwelling (bottom) conditions.** Top: surface wind strength and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: surface currents at 2 m depth. Bottom: temperature as denoted on plots (upper frame is Buoy 44013 and Buoy A01; lower frame is Buoy A01 from three depths, with air temperature and red dots show bottom temperature at station N18) and gray lines represent historical (1989-2017) surface temperature at Buoy 44013. Vertical boxes show periods of upwelling and downwelling conducive conditions.

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) reflect the seasonal cycle of nutrient inputs from rivers and Gulf of Maine and phytoplankton uptake. They are 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.

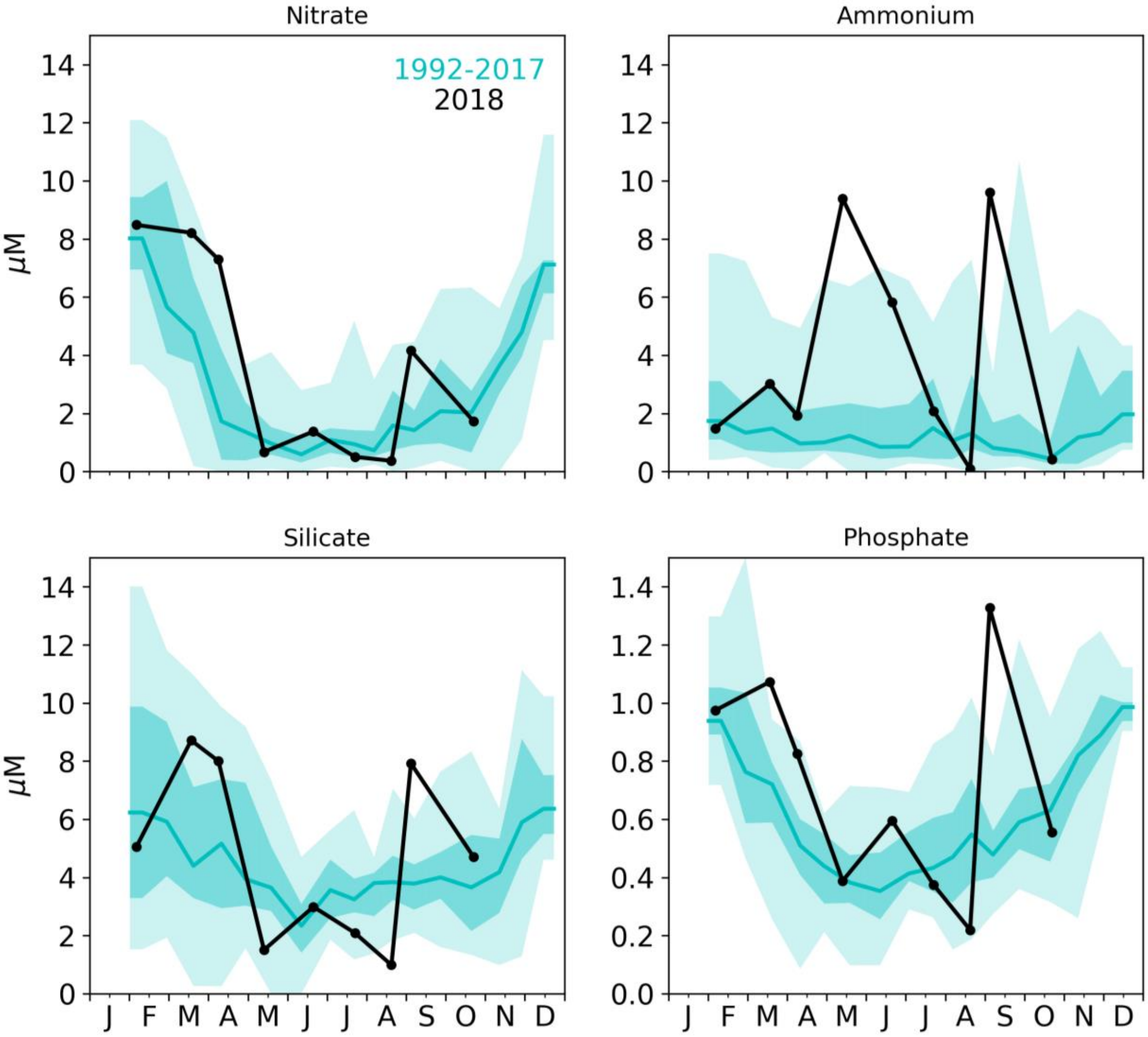

Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2018 compared to prior years. Note difference in scale for phosphate. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

In February 2018, NO_3 concentrations were moderate with levels at the long-term median in Massachusetts Bay (**Figure 2-8**). However, SiO_4 concentrations were low during February, suggesting that diatoms, which require SiO_4 for growth, were likely abundant during the prior winter months. During March and April 2018, the NO_3, SiO_4, and PO_4 concentrations were above the 75th percentile of historic values.

By May, average NO_3 levels were nearly depleted (<1 µM) across the bay and remained so through the summer until September (**Figure 2-9**). This was coincident with similarly low levels of PO_4 and SiO_4 (**Figure 2-8**). There was a slight increase in nutrient concentrations in June which may have been related to upwelling in mid-June (see **Figure 2-4**). In September, nutrient concentrations increased sharply at nearly all stations, apparently due to mixing associated with the late summer Nor'easter. At stations N18 and N21 nearest the outfall, the increased September concentrations rose to levels at or above the historic range and similar increases were seen at nearshore station F15 and to a lesser degree at other Massachusetts Bay stations. By October, nutrient concentrations decreased to more typical levels (**Figure 2-8**).

In the nearfield (stations N18 and N21) and to the south at station F15, episodic peaks in NH_4 were observed that are attributed to MWRA effluent (**Figure 2-10**). May and September peaks at station N18 were above historic NH_4 maxima. These short-term peaks in nearfield NH_4 concentrations have been a consistent feature since the bay outfall began operating. NH_4 levels at other Boston Harbor, Massachusetts Bay, and Cape Cod Bay stations were low and consistent with post-diversion levels.

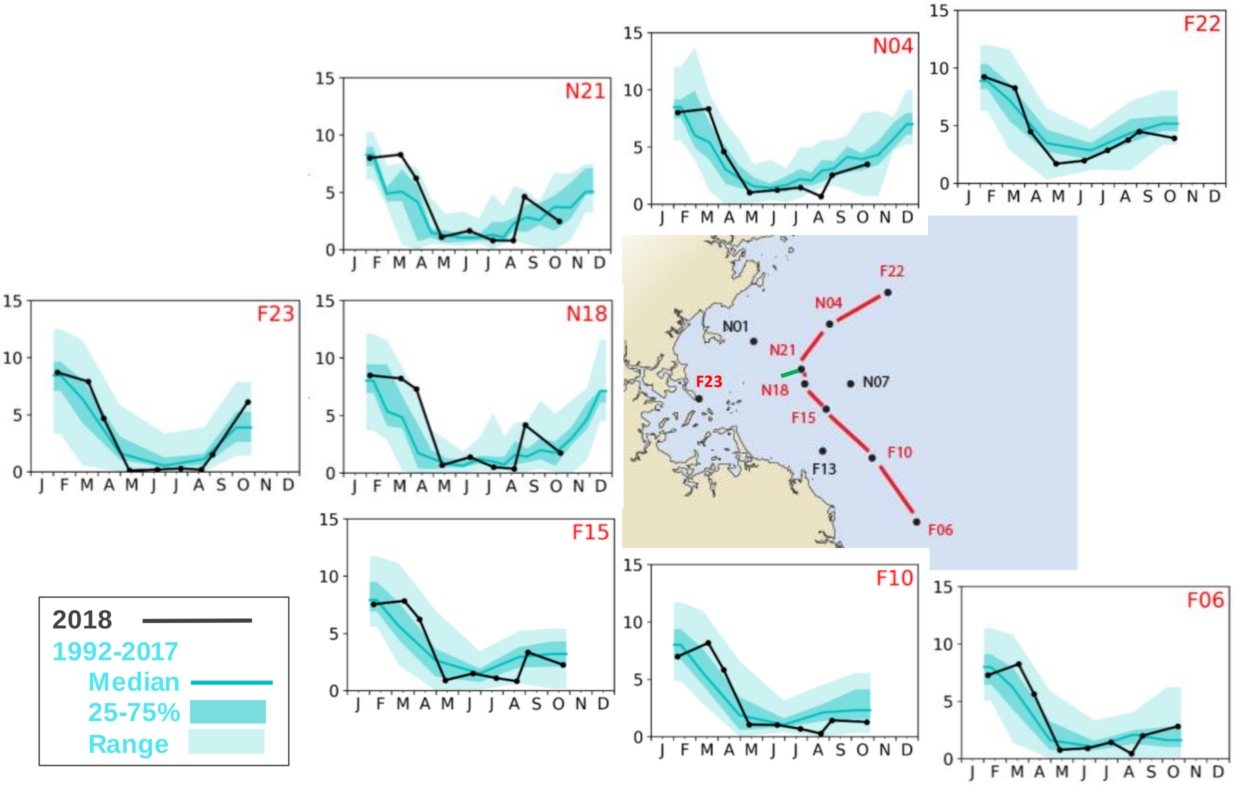

Figure 2-9. Depth-averaged NO_3 (µM) at selected stations in Massachusetts Bay for 2018 compared to prior years. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

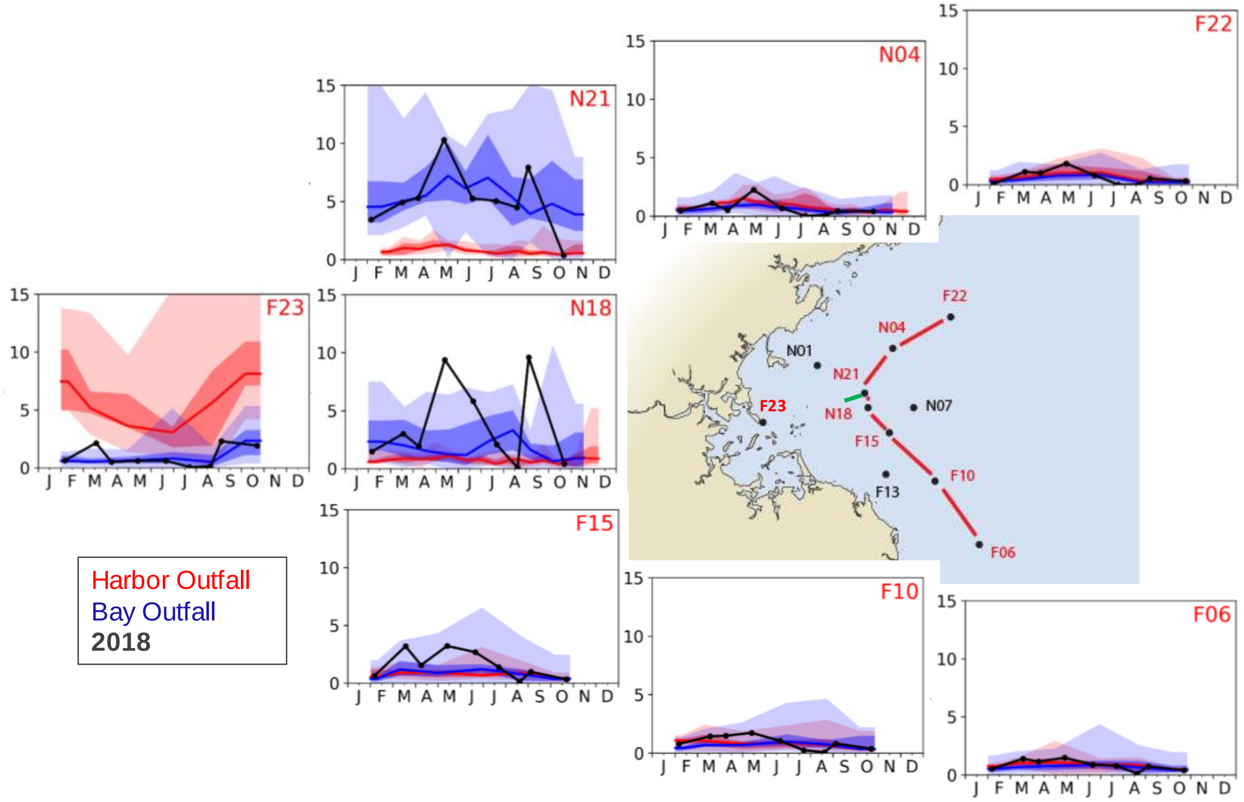

Figure 2-10. Depth-averaged NH_4 (µM) at selected stations in Massachusetts Bay for 2018 compared to prior years. 2018 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2017) results are in blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Compared to the baseline period (1992-August 2000), NH_4 concentrations in the post-diversion period through 2017 (September 2000-2017) are lower at Boston Harbor station F23 and higher at nearfield stations N18 and N21 (**Figure 2-10**). This continued to be the case in 2018 with all depth-averaged NH_4 concentrations at station F23 below baseline levels, while at stations N18 and N21, depth-averaged NH_4 levels were greater than baseline for nearly all of the 2018 surveys, as expected. The NH_4 levels at stations N18 and N21 were variable and close to the median values observed post-diversion in the winter/spring and some summer months, higher in May and September, and lower in August at station N18 and at both stations in October. Elevated NH_4 concentrations in comparison to historic levels were observed at station F15 in March, May and June. Overall, summer and fall nutrient concentrations in 2018 were like those observed since the bay outfall became operational.

In 2018, 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 2-11** and **Figure 2-12**). In March, when the water column was vertically well mixed, the plume NH_4 signature was most pronounced in the nearfield surface waters, but levels >2 µM extended about 10 km south to station F15 (**Figure 2-11**). During the June survey, when the water column was vertically stratified with a pycnocline located at about 10 m, high NH_4 levels (>8 µM) were observed at or below the pycnocline at stations N21 and N18, the locations closest to the outfall; elevated concentrations (4-8 µM) were also observed at station F15

(**Figure 2-12**). During the stratified June survey, nitrate concentrations (2 to 6 µM) were elevated only below the pycnocline, especially in the deeper offshore bottom waters at the east end of the west-east transect, and sub-surface chlorophyll maxima were observed near the pycnocline with values reaching >6 µg L^{-1} at station F15 (**Figure 2-13**).

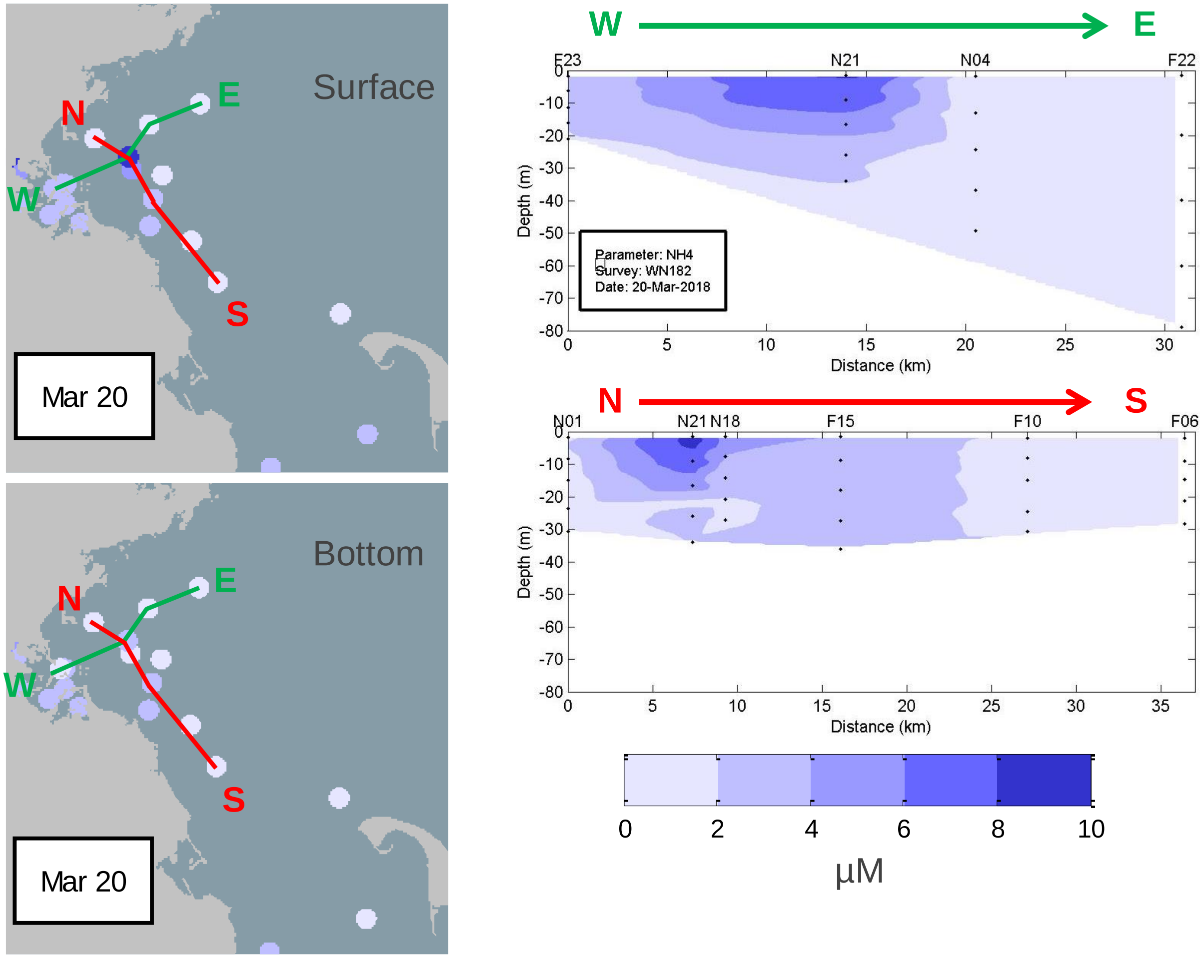

Figure 2-11. (Left) Surface- and bottom-water NH_4 on March 20, 2018 during unstratified conditions. (Right) Cross-sections of water column concentrations along transects connecting selected stations. Small black dots in the plots at right indicate the sampling depths for nutrients.

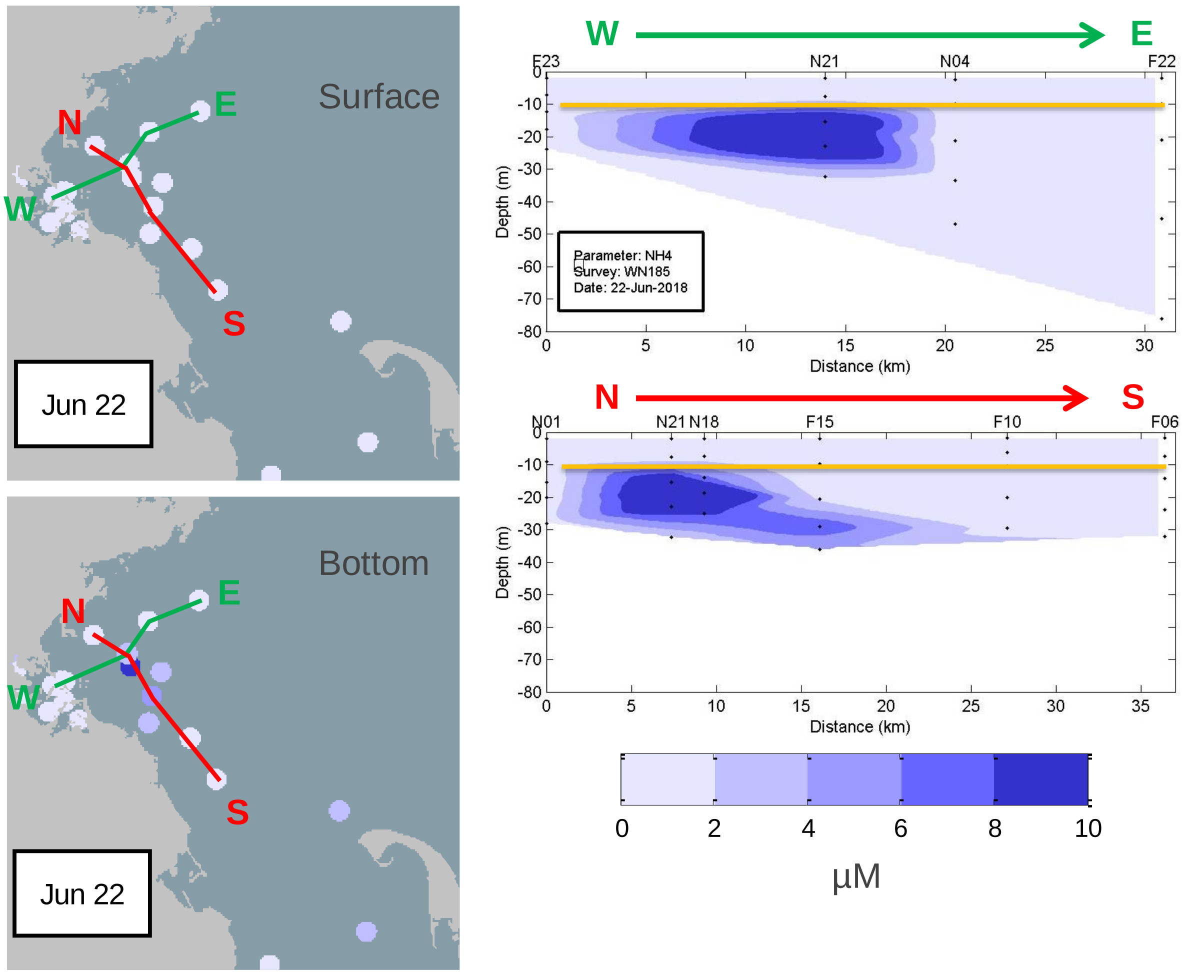

Figure 2-12. **Surface- and bottom-water NH_4 on June 22, 2018 during stratified conditions.** Presented as Figure 2-11, with orange line in frames at right indicating the approximate depth of the pycnocline.

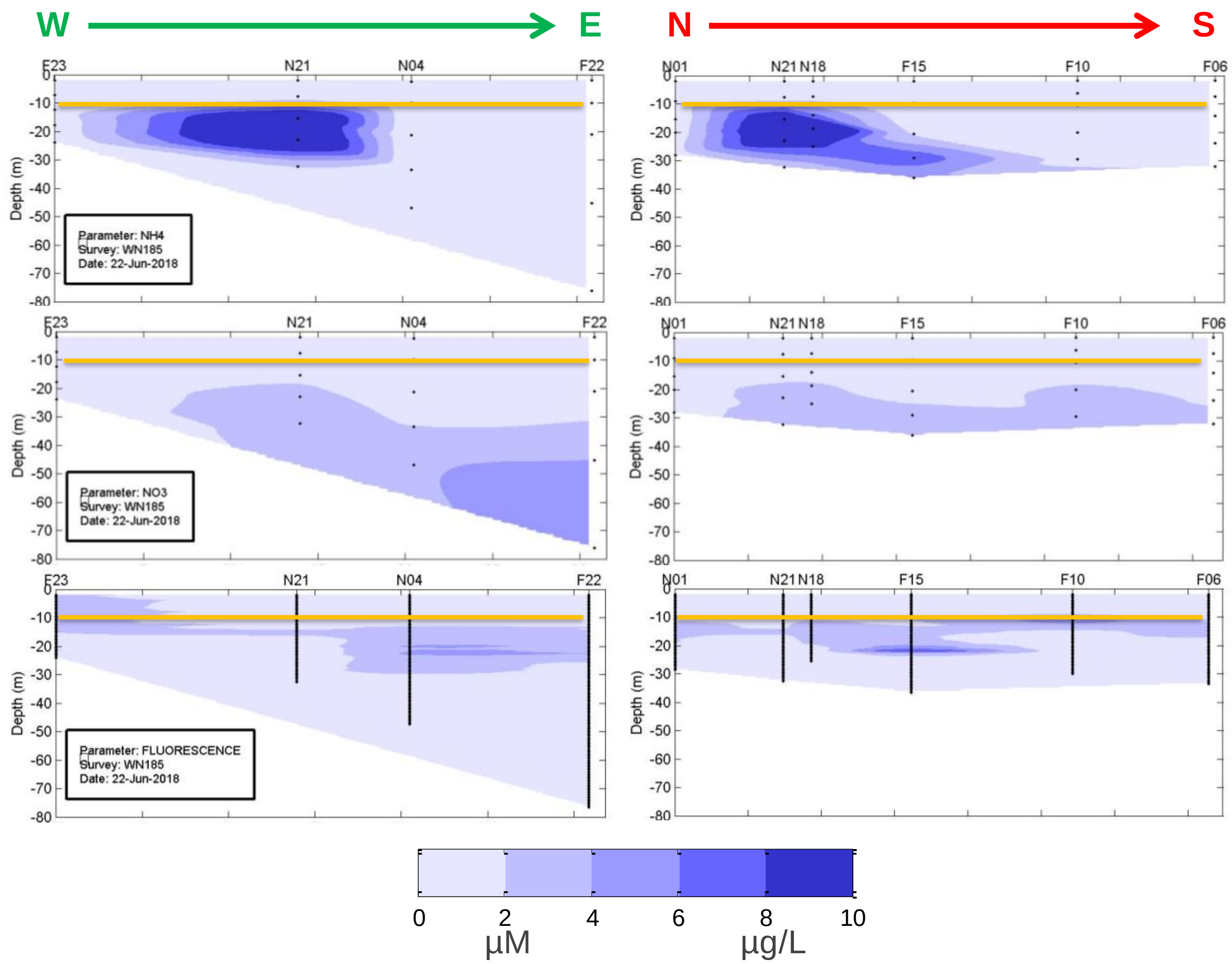

Figure 2-13. Ammonium (top; µM), nitrate (middle; µM), and chlorophyll from fluorescence (bottom; µg L^{-1}) concentrations during the stratified June 2018 survey along the east-west (left column) and north-south (right column) transects shown in Figure 2-12. Dots (nutrients) and lines (fluorescence) indicate the sampling depths and downcast profile in situ 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 2-14**. A similar seasonal pattern was observed during the 2018 surveys though the occurrence of winter/spring and fall peaks varied across the region. Peak areal chlorophyll levels for the year were observed during the April survey in Boston Harbor, northern Massachusetts Bay and Cape Cod Bay, while elevated levels were seen across both bays during the fall bloom in October (**Figure 2-15**).

As observed during winters the past few years, from November 2017 to February 2018 MODIS satellite imagery (**Figure 2-16**; only the last two months of that range are shown) showed relatively high chlorophyll levels. This would be consistent with sustained phytoplankton productivity having occurred throughout the winter months. There was a large peak in surface chlorophyll fluorescence in mid to late February at Buoy A01 (annual maxima; **Figure 2-17**), which decreased sharply after the strong

Nor'easter in early March 2018. Low chlorophyll levels were observed throughout the survey area in March and this continued into April at the stations in western Massachusetts Bay (**Figure 2-14** and **Figure 2-15**). However, there was an April peak in chlorophyll at stations in Boston Harbor, offshore Massachusetts Bay, and Cape Cod Bay. This peak was due to an increase in centric diatoms (mostly *Skeletonema* spp.) at the Boston Harbor and Massachusetts Bay stations and *Phaeocystis* at the stations in Cape Cod Bay. The April chlorophyll peak observed at offshore Massachusetts Bay stations also occurred at Buoy A01 (**Figure 2-17**).

Summer 2018 chlorophyll levels were lower than the rest of the year, and close to the historic median values (**Figure 2-14**). The 2018 summer seasonal average chlorophyll for the nearfield was low (58 mg m^{-2}) compared to the caution threshold level of 89 mg m^{-2}. This continued into the fall with a seasonal average of 95 mg m^{-2} versus a threshold value of 239 mg m^{-2}. This was primarily driven by chlorophyll values close to and below the 25th percentile in September (**Figure 2-14**). By the October survey, there was a bay-wide bloom of *Skeletonema* that led to elevated chlorophyll levels at or above the 75th percentile across Massachusetts Bay. This was consistent with MODIS imagery showing an increase in chlorophyll fluorescence from September into October and November (**Figure 2-16**).

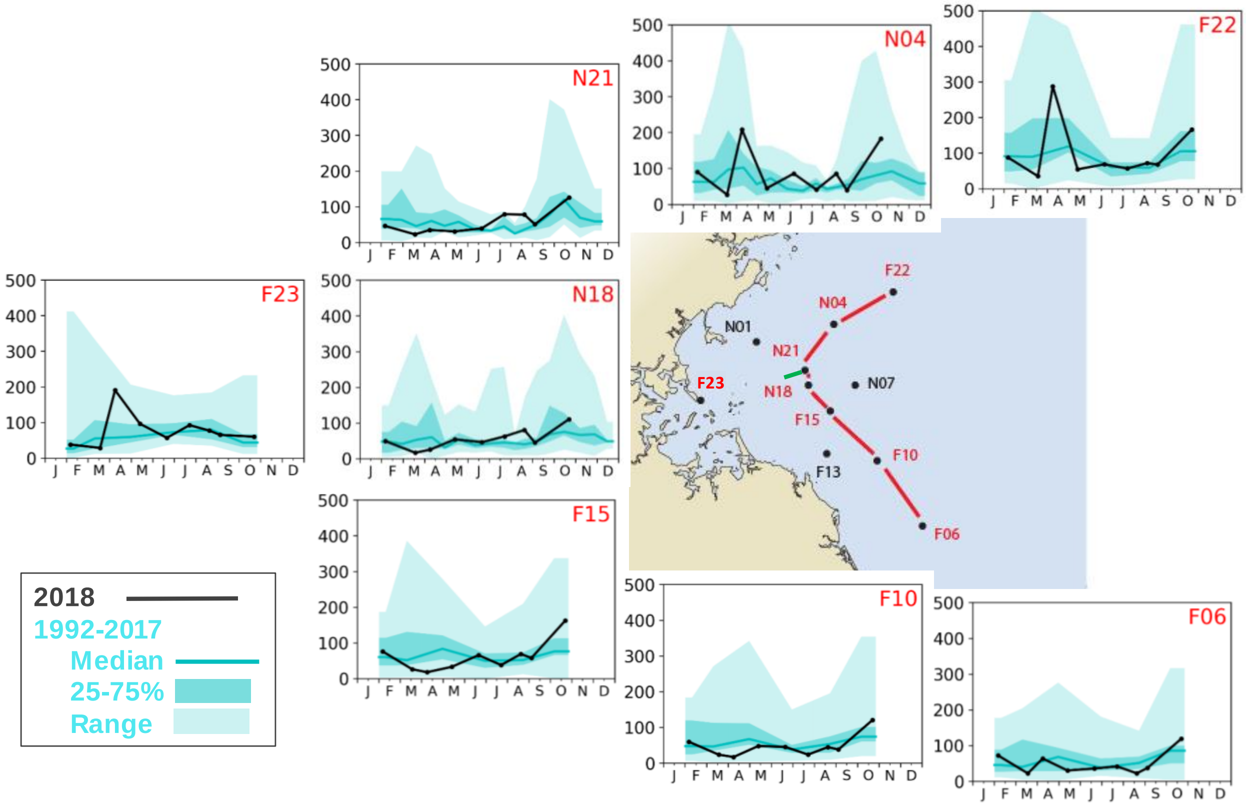

Figure 2-14. Areal chlorophyll from fluorescence (mg m^{-2}) at representative stations in Massachusetts Bay for 2018 compared to prior years. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

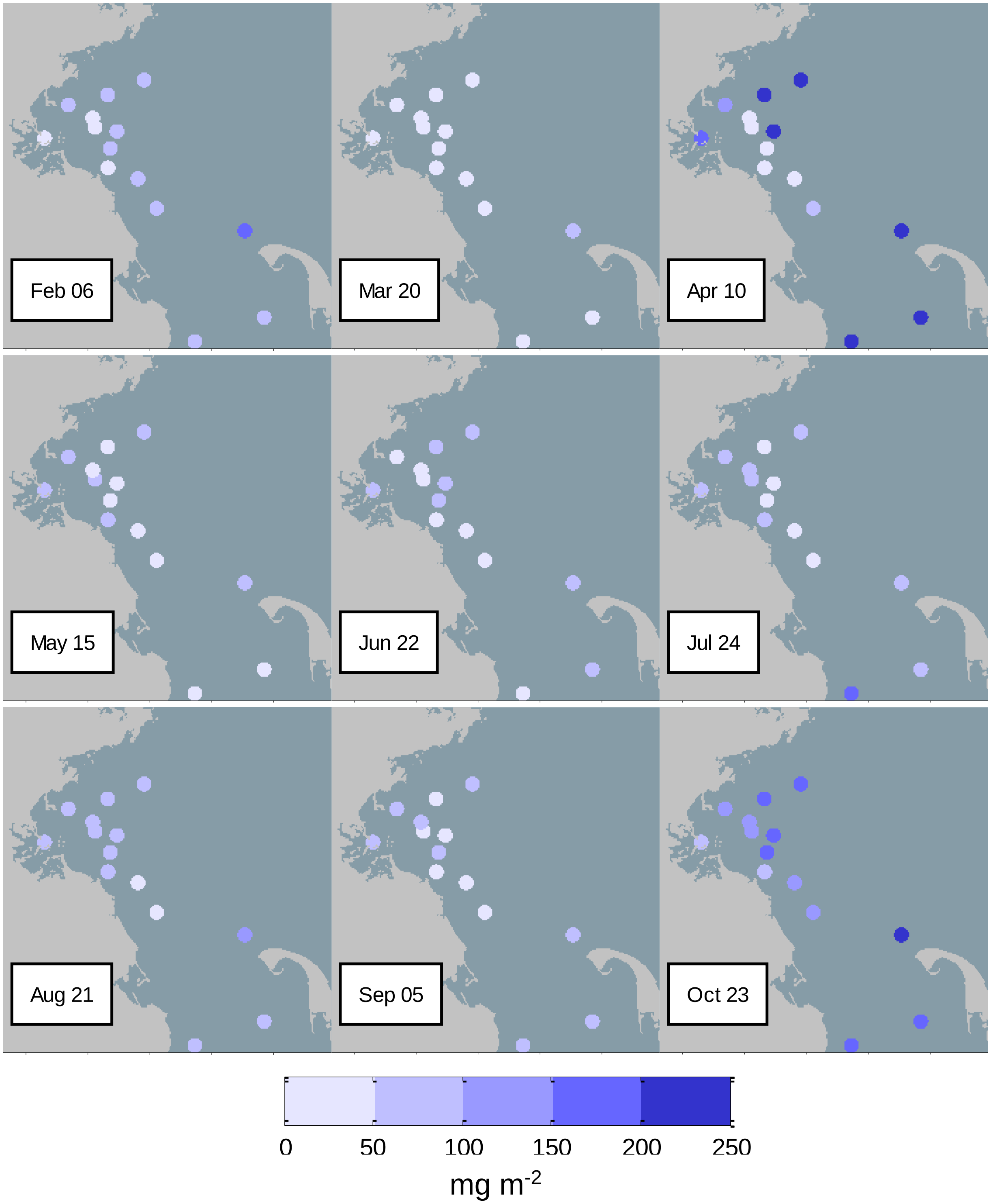

Figure 2-15. Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2018.

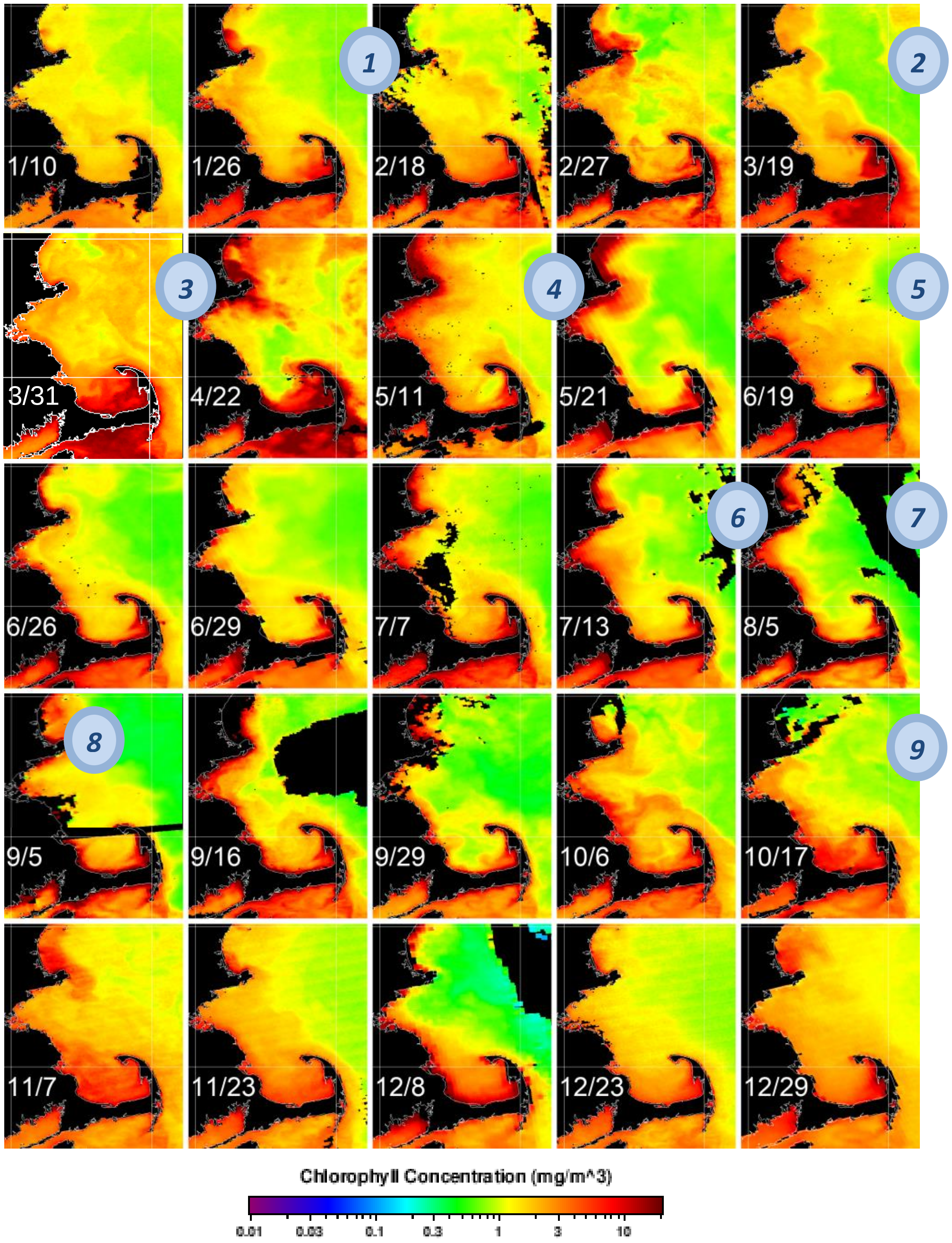

Figure 2-16. **Satellite (MODIS) imagery-based estimates of surface chlorophyll concentrations (mg m^{-3}) in 2018. Black areas over water indicate missing data due to clouds.**

Highlights and specific blooms:

1st row – moderate chlorophyll levels January and February, increasing late February and March;
1st & 2nd row – Cape Cod Bay had a large *Phaeocystis* bloom in March and April, stations N04 & F22 dominated by *Rhizosolenia* in April;
2nd & 3rd row – variable chlorophyll from May to August, elevated levels in harbor and nearby coastal waters due to mixed centric diatom bloom;
4th row – increasing chlorophyll levels in October – *Skeletonema*; and
5th row – elevated chlorophyll levels in November and December.

The image dates are heavily weather dependent and not distributed uniformly in time. The numbered ovals indicate relative timing of the nine MWRA surveys (between dates of adjacent frames, except survey 8 which was the same day as the 9/5 image).

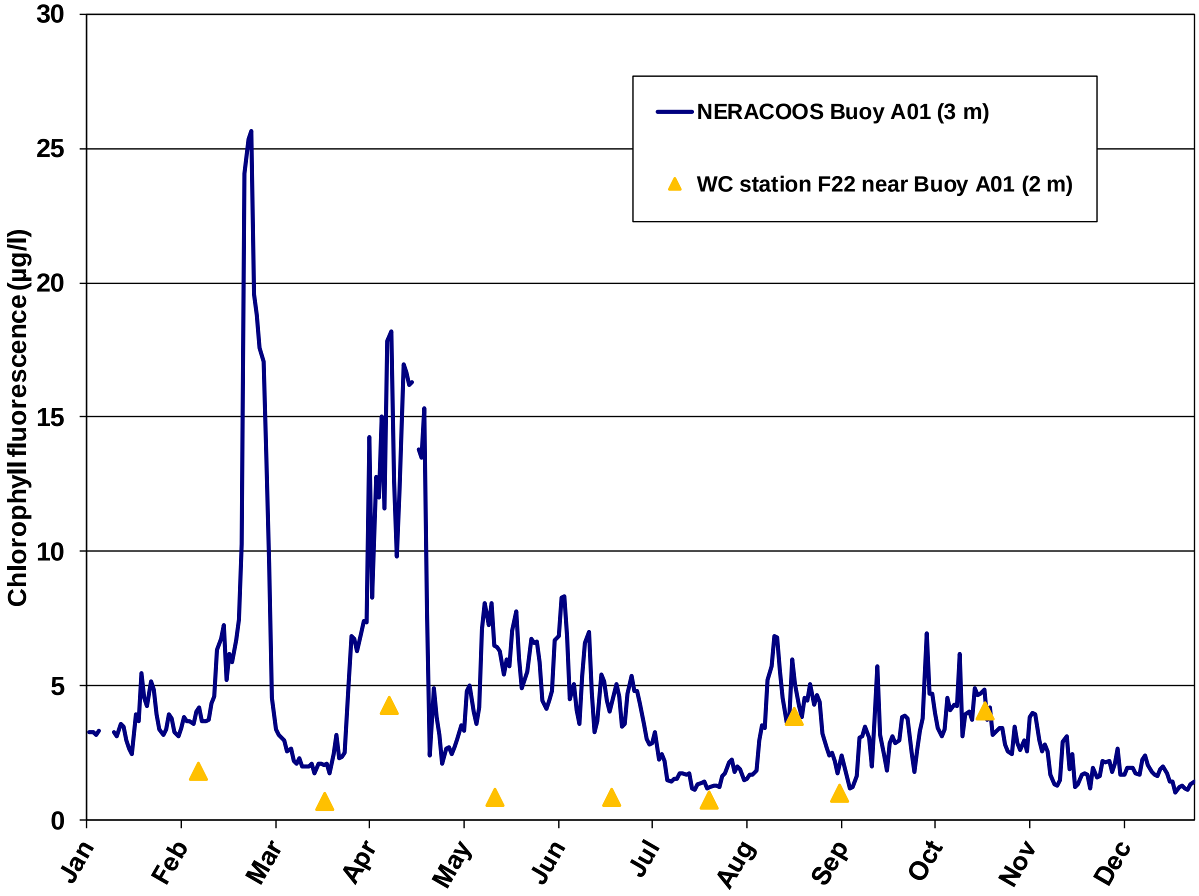

Figure 2-17. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (blue line) and water samples at nearby water column (WC) station F22 (yellow symbols). The buoy values are daily medians.

2.4 BOTTOM WATER DISSOLVED OXYGEN

Typically, bottom water dissolved oxygen (DO) declines at a relatively constant rate in Massachusetts and Cape Cod Bays from winter/spring maxima to September or October annual minima. This was generally the case in 2018 (**Figure 2-18**). Bottom water DO concentrations began the year close to the historic medians and remained at or below the median for most of the year in Massachusetts Bay (**Figure 2-19**). Bottom DO levels were more variable in Cape Cod Bay with values in the lower quartile in March, May and June, above the median in April and July, reaching seasonal minima in September and then returning to higher levels after the water column mixed in October (**Figure 2-20**).

At offshore station F22, the 2018 seasonal decline was punctuated by mixing events in June and August. The near-bottom DO in June was about 0.5 mg L^{-1} higher than in May, and the August Nor'easter led to a decrease in the rate of its decline. Both events were observed at Buoy A01 slightly farther offshore (**Figure 2-21**). In June, the impact of the mixing event/upwelling was most pronounced in the buoy data which leveled off at ~9.5 mg L^{-1} from mid-May to mid-June. Survey data from station F22 showed little sign of this at the sampling depth closest to 50 m but at the near-bottom depth (77 m) there was a large increase from May to June (**Figure 2-21**). In contrast, the late summer Nor'easter decreased the rate of DO decline in the ~50 m waters at the buoy and station F22, but the effect did not appear to reach into the deeper, near-bottom waters at station F22.

In 2018, the annual DO minima in Massachusetts Bay were moderate with levels ≥6.5 mg L^{-1}. Annual DO minima were reached in Boston Harbor in August, at shallower Massachusetts Bay stations in September, and at the deeper stations in October (**Figure 2-18** and **Figure 2-19**). Buoy data indicate that the water column became mixed to below 50 m in late October after the final MWRA survey (**Figure 2-21**). In Cape Cod Bay, there were "reaeration" events at stations F01 and F02 from June to July, similar to those described above, which likely kept bottom water DO levels from decreasing near historic minima in September (**Figure 2-20**).

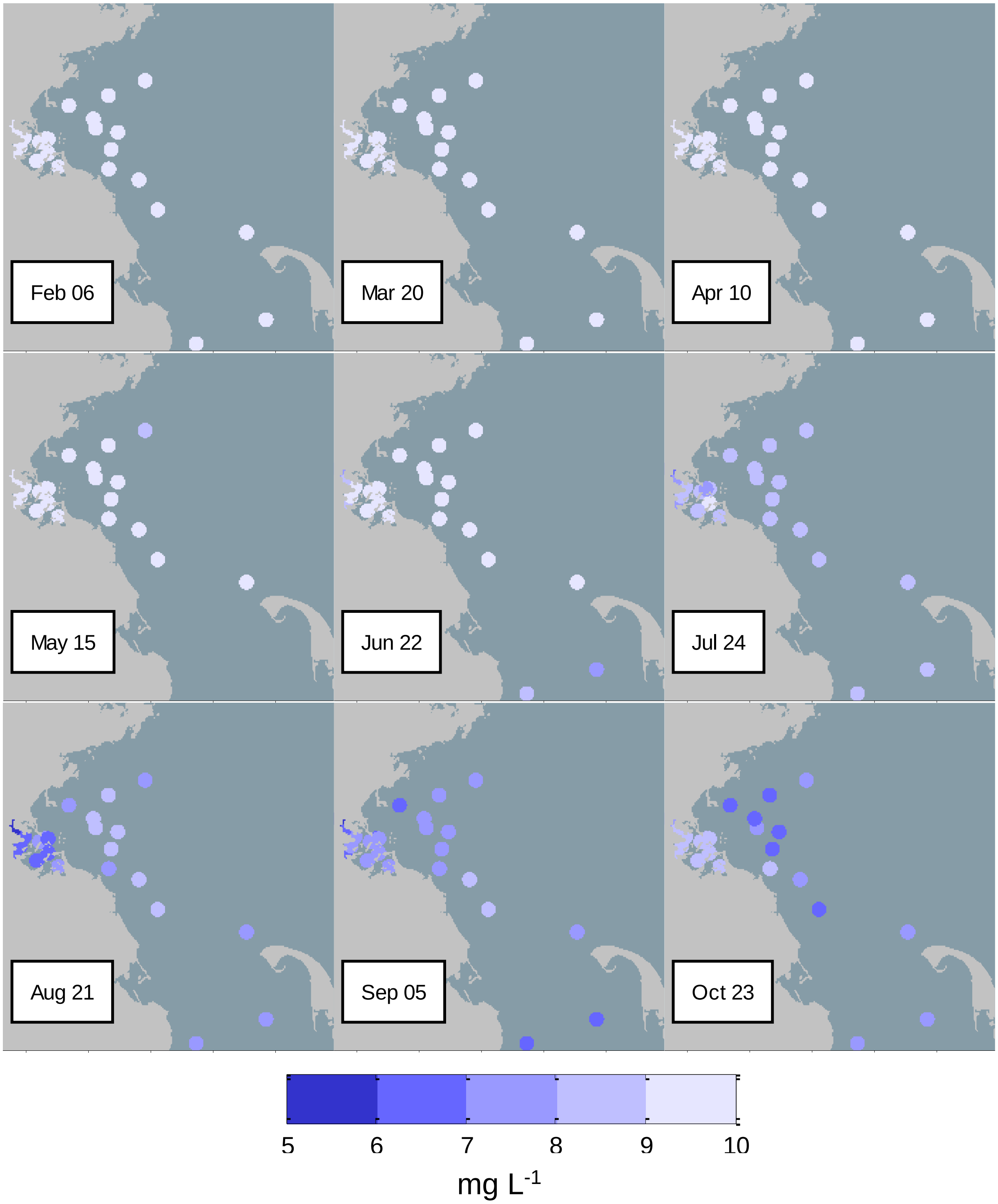

Figure 2-18. Near bottom dissolved oxygen (mg L^{-1}) by station in Massachusetts and Cape Cod Bays in 2018.

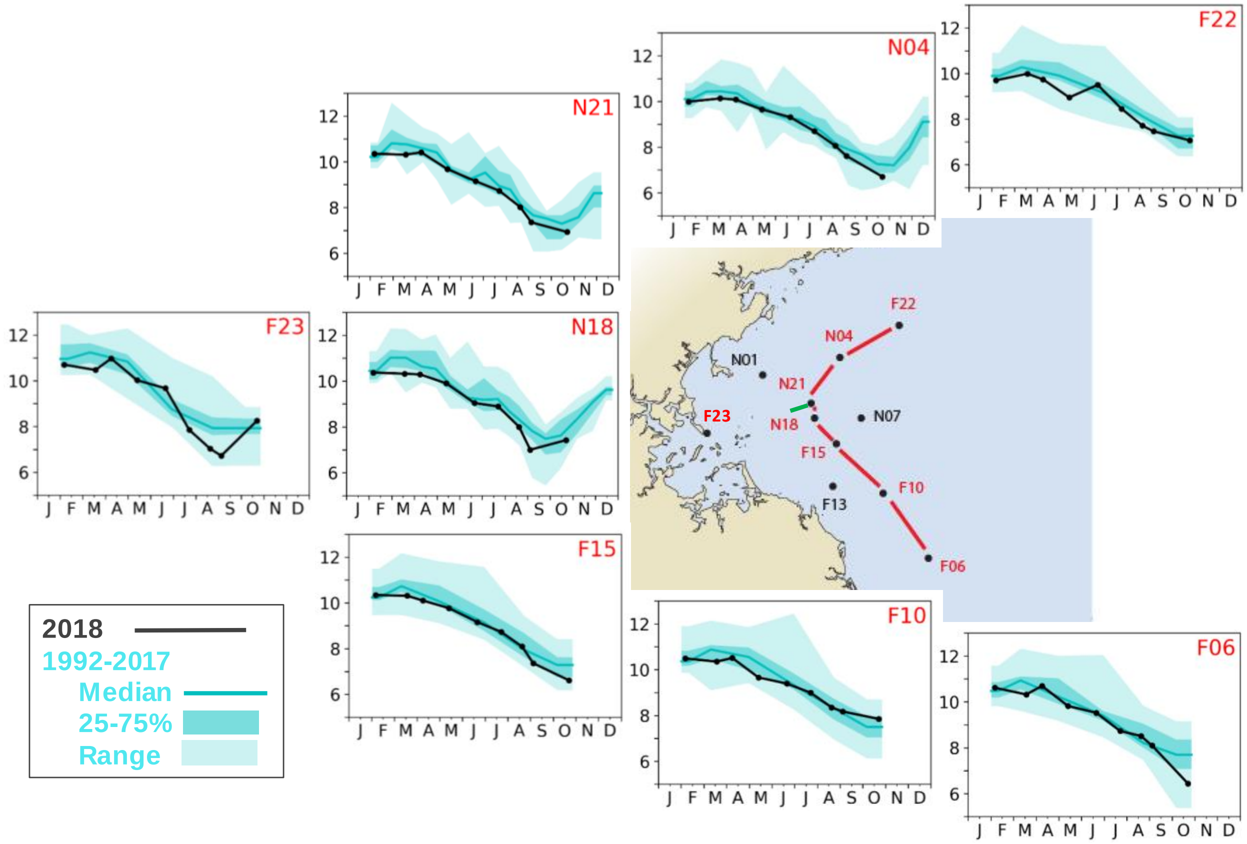

Figure 2-19. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2018 compared to prior years. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

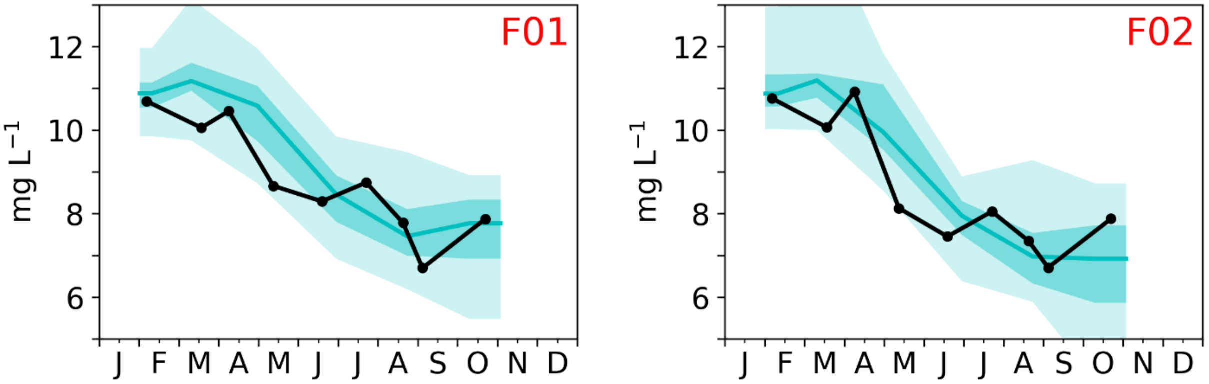

Figure 2-20. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2018 compared to prior years. 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

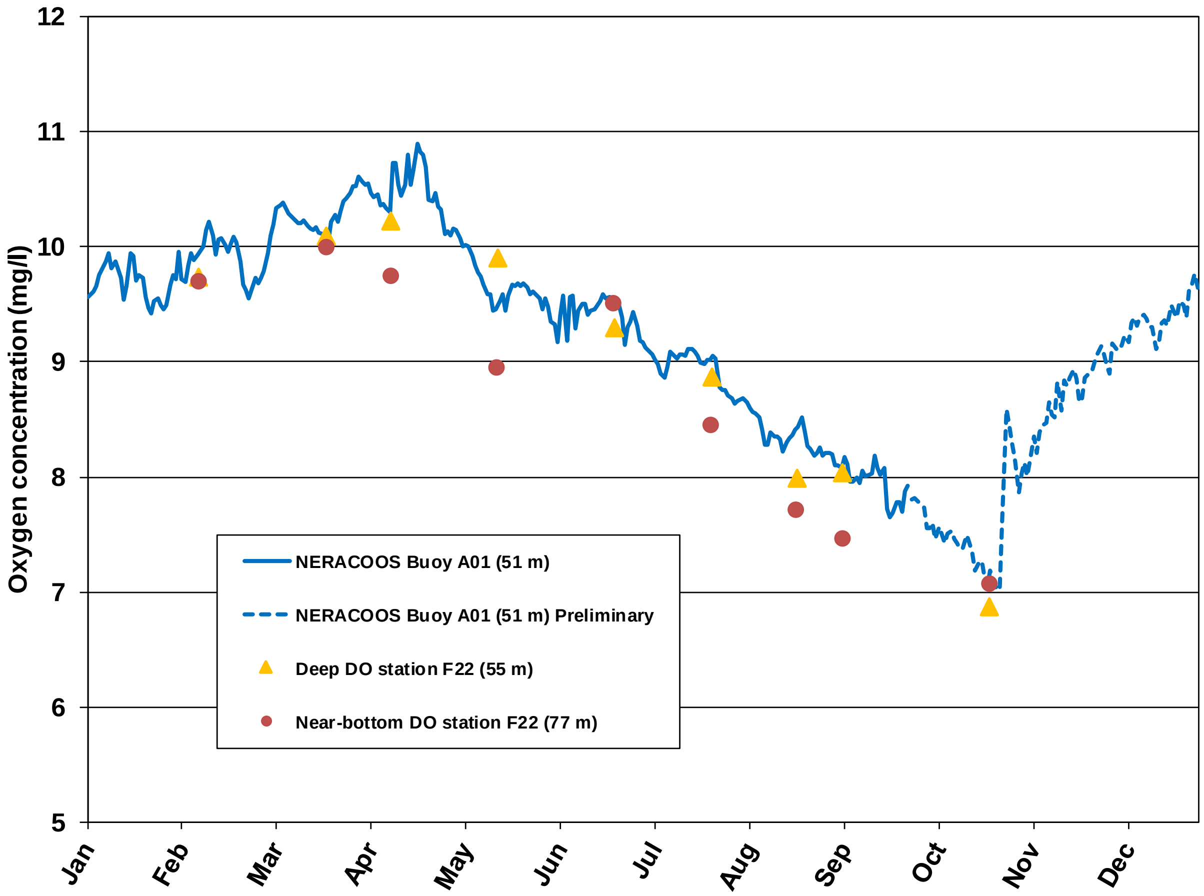

Figure 2-21. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (51 m) and at the deep and near-bottom sampling depths at station F22 in 2018. The buoy values are daily means.

2.5 PHYTOPLANKTON

Overall, phytoplankton abundance measured in 2018 was low compared to the range of 1992-2017 observations. Total phytoplankton abundance in the nearfield in 2018 (0.78 million cells L^{-1}) was 56% of the long-term mean level (1.39 million cells L^{-1}) and ranked 23rd for the 27-year monitoring program (**Table 2-1**). The relatively low 2018 total phytoplankton abundance was in part due to the lack of a strong bay-wide winter/spring diatom or *Phaeocystis* bloom. Another factor was reduced microflagellate abundance in 2018 relative to long-term mean levels. The annual mean 2018 nearfield microflagellate abundance (0.49 million cells L^{-1}) was significantly less than the long-term mean abundance (0.68 million cells L^{-1}).

An apparent winter/spring bloom observed as the annual maximum peak in chlorophyll fluorescence at Buoy A01 was not captured in the whole water samples collected during the 2018 water column surveys (see **Figure 2-17**). February through July 2018 total phytoplankton abundance was at the low end of the range of previous observations (**Figure 2-22**). In Cape Cod Bay, there was a large *Phaeocystis* bloom in April, which was the most pronounced phytoplankton bloom for both bays in the 2018 monitoring results (**Figure 2-23**). Phytoplankton abundance peaked in Massachusetts Bay in August and October but remained well below 2 million cells L^{-1} and close to the long-term median, contributing to the low overall abundances in 2018.

Table 2-1. Comparison of 2018 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	**1992-2017** (cells L^{-1})	**2018** (cells L^{-1})	**2018 Rank (out of 27)**	**p value**	**Significant Change**
CENTRIC DIATOM	271,120	137,093	18th	0.2120	
Dactyliosolen fragilissimus	57,377	9,530	19th	0.3743	
Chaetoceros	29,989	4,811	16th	0.2522	
Skeletonema costatum complex	44,908	68,131	6th	0.4893	
Thalassiosira	36,583	5,690	24th	0.5317	
PENNATE DIATOM	36,040	9,756	21st	0.4485	
Pseudonitzschia	8,465	1,846	18th	0.2273	
DINOFLAGELLATES	61,430	42,987	21st	0.1409	
Ceratium	1,754	1,867	12th	0.8747	
Dinophysis	286	215	11th	0.8083	
Prorocentrum	5,727	6,608	10th	0.8067	
Phaeocystis pouchetii	200,100	2,035	20th	0.2808	
CRYPTOPHYTES	127,663	82,947	10th	0.0490	Decline
MICROFLAGELLATES	680,764	489,910	19th	0.0166	Decline
MICROZOOPLANKTON (2011-2018)	4,602	7,188	1st	0.0030	Increase
TOTAL PHYTOPLANKTON	1,388,137	778,161	23rd	0.0119	Decline

Phaeocystis pouchetii was present at low abundance levels during the spring of 2018. A maximum of ~100,000 *Phaeocystis* cells L^{-1} was observed during April 2018 in the nearfield area. For comparison, tens of millions of cells per liter may be found during a large *Phaeocystis* bloom in Massachusetts Bay. Companion sampling by CCS indicated *Phaeocystis* reached an abundance of ~2.5 million cells L^{-1} during April 2018. During 2018 the April *Phaeocystis* bloom was confined to Cape Cod Bay and did not occur in Massachusetts Bay.

Although centric diatom abundance was low for 2018 (half the long-term mean), two species of diatoms (*Rhizosolenia herbetata* and *Skeletonema costatum*) made major contributions to the late spring phytoplankton community and the summer/fall peaks observed in total phytoplankton. Total phytoplankton abundance did not indicate winter/spring increases which would suggest a bloom, but high areal chlorophyll levels were observed at stations N04 and F22 in the northeastern corner of Massachusetts Bay (see **Figure 2-14** and **Figure 2-15**). This was due to elevated abundances (10,000 to 20,000 cell L^{-1}) of *Rhizosolenia herbetata* plus a mix of *Skeletonema costatum* and *Thalassiosira* spp. *Rhizosolenia* are large diatoms (>100 µm) with lots of chloroplasts, so even though their relative numbers are a small component of the total phytoplankton, they contribute substantially to the chlorophyll concentration.

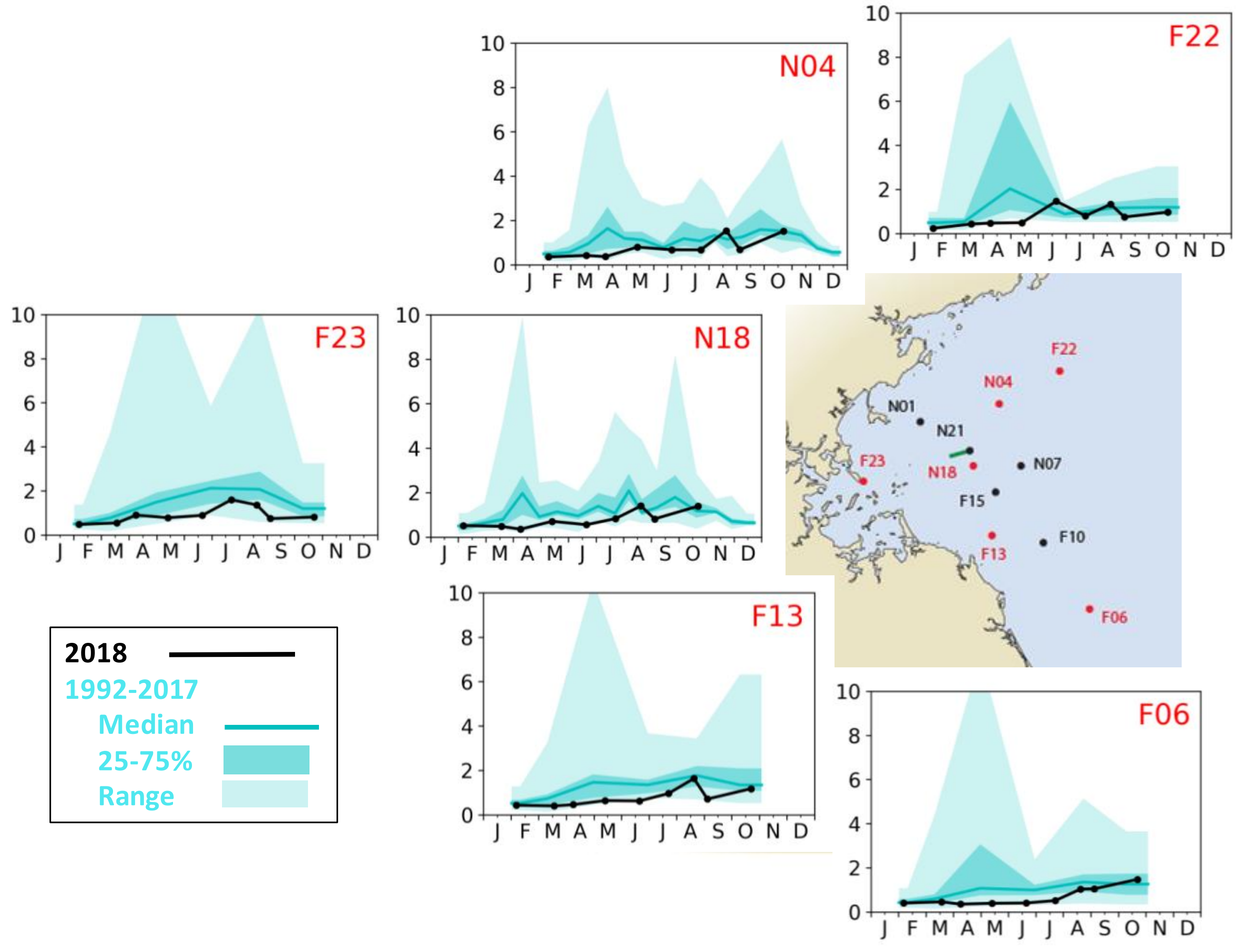

Figure 2-22. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2018 compared to prior years. 2018 results are in black. Results from 1992-2017 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The map insert highlights stations where an extended plankton dataset is available, which is presented here and in subsequent phytoplankton and zooplankton figures.

In late spring 2018, centric diatom abundance was dominated by *Skeletonema* which peaked in the upper 75th percentile during the May survey (**Figure 2-24**). This was the third consecutive year in which *Skeletonema* was the late winter/spring bloom dominant. This shift to a later (April in 2016 and 2017, and May 2018) *Skeletonema*-dominated spring bloom may be partially a response to changing climate. Climate change may favor later growth due to the variable temperature- and nutrient-specific physiology of morphologically cryptic *Skeletonema* spp. (Borkman and Smayda, 2009; Nixon et al 2009; Canesi and Rynearson, 2016). There also may be 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/May) *Skeletonema*-dominated bloom.

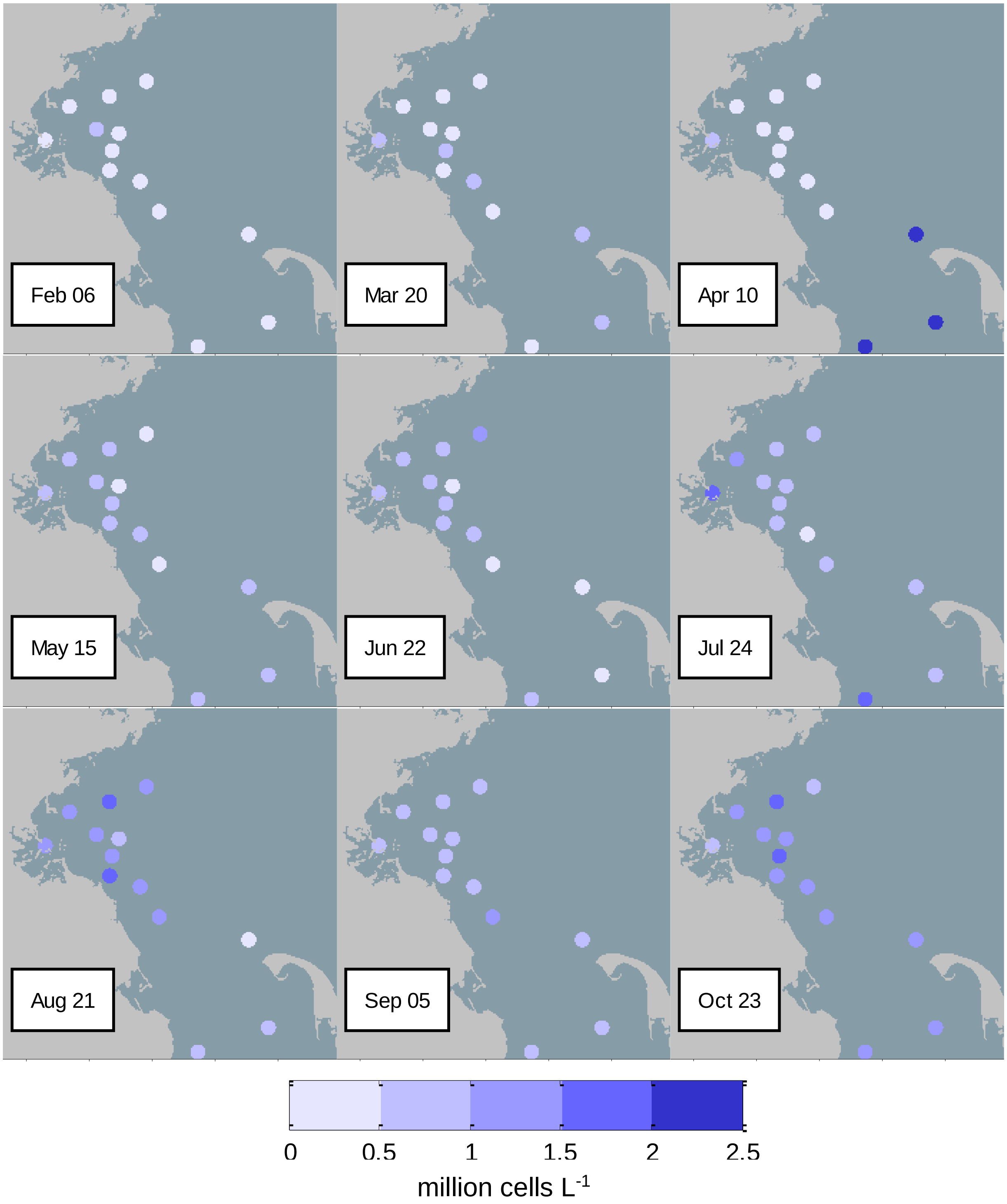

Figure 2-23. Total phytoplankton abundance (million cells L^{-1}) by station in Massachusetts and Cape Cod Bays in 2018.

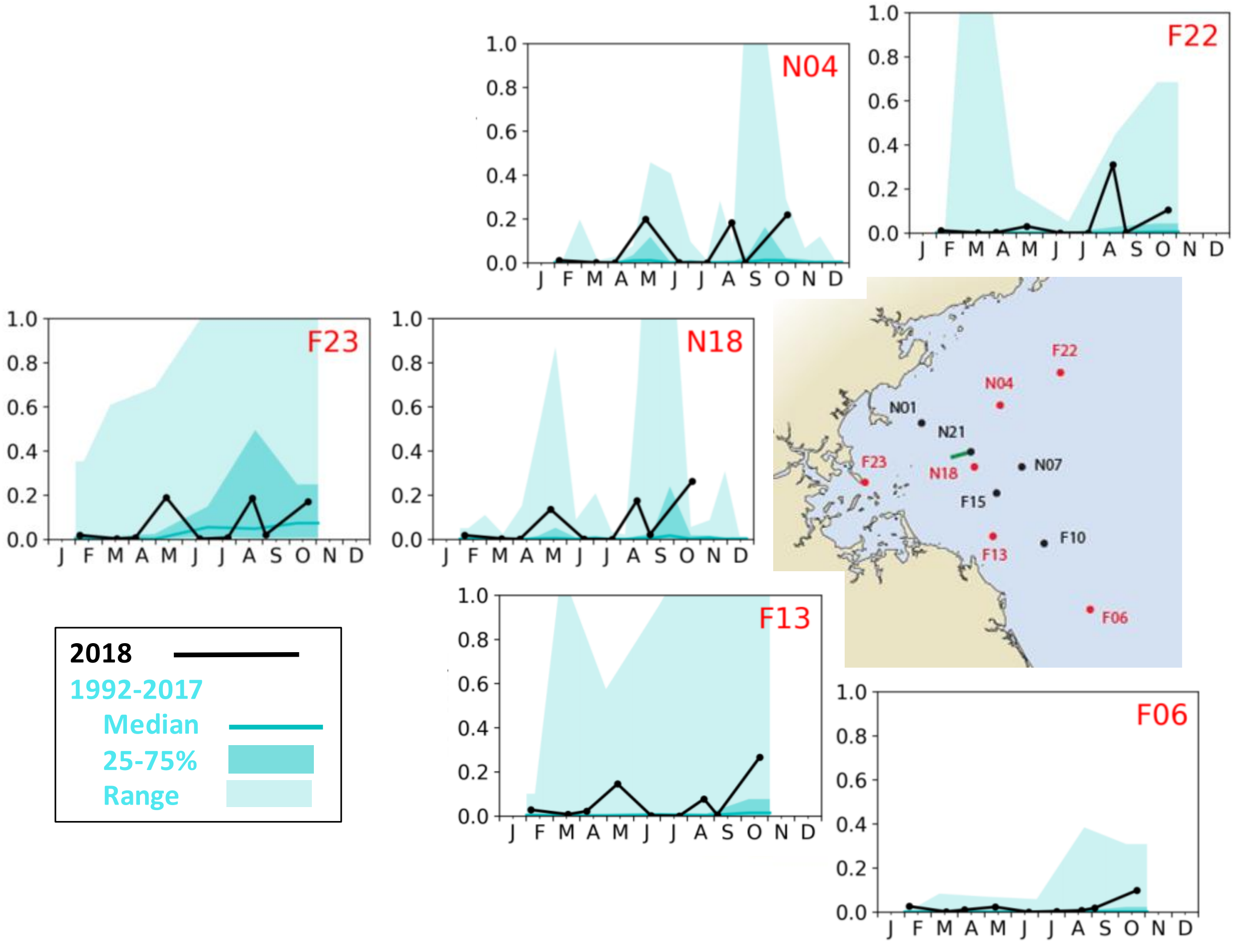

Figure 2-24. ***Skeletonema costatum* abundance (million cells L^{-1}) at selected stations in 2018 compared to prior years.** 2018 results are in black. Results from 1992-2017 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

In addition to an increase in *Skeletonema* in May 2018, there was an increase in small dinoflagellates (*Gymnodinum* spp. <20 µm, *Heterocapsa triquetra*, *Heterocapsa rotundata*) in April and May. Annual abundance of all dinoflagellates was about 66% of the long-term mean in 2018 (**Table 2-1**). Dinoflagellate abundance peaked in summer and fall and was dominated by larger forms (*Ceratium* spp. and *Dinophysis* spp. in summer; *Prorocentrum* spp. in October). The August 2018 peaks in total phytoplankton were primarily driven by the elevated abundances of *Ceratium* spp. and *Skeletonema* (**Figure 2-22** and **Figure 2-24**). Total phytoplankton abundances in August 2018 were close to the long-term mean.

Phytoplankton abundance was low in September 2018 with many stations having abundances near or below long-term minima (**Figure 2-22**). In October 2018, the autumn diatom bloom was dominated by *Skeletonema* spp. with abundances of 100,000 to 300,000 cells L^{-1} in Boston Harbor and Massachusetts Bay (**Figure 2-24**). The dinoflagellate, *Prorocentrum*, peaked in abundance (up to 15,000 cells L^{-1}) in October 2018. Elevated abundance of *Prorocentrum* spp., especially elevated *P. micans* abundance, during the late autumn (October-November) has occurred in many recent years in Massachusetts Bay. *Prorocentrum* spp. were present at greater than long-term mean levels during 2018, with a mean *Prorocentrum* abundance (6,608 cells L^{-1}) higher than the long-term mean level (5,727 cells L^{-1}; **Table 2-1**).

There were no issues with nuisance or potentially toxic algae in Massachusetts Bay in 2018. As noted above, a *Phaeocystis* bloom was observed in Cape Cod Bay, but only low abundances were seen in Massachusetts Bay. *Alexandrium catenella* were essentially absent from the bays in 2018 with counts <10 cells L^{-1} (**Figure 2-25**) and no paralytic shellfish poison (PSP) shellfish closures were required in Massachusetts Bay in 2018. *Pseudo-nitzschia* abundance was also low during 2018 with an annual mean of 1,846 cells L^{-1} compared to a long-term mean of 8,465 cells L^{-1}. To put the 2018 mean *Pseudo-nitzschia* abundance value in context, the maximum abundance of *Pseudo-nitzschia* spp. observed during 1992 to 2018 MWRA monitoring was 1.8 million cells L^{-1} in August 1998.

An unusual bloom of the athecate dinoflagellate *Karenia mikimotoi* was observed in samples collected during August and September of 2017, with a maximum observed abundance of 337,800 cells L^{-1}. This was cause for concern in 2017 as *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 no direct negative impacts on human health are known. In 2018, *K. mikimotoi* was also observed during September, but abundances (~4,000 cells L^{-1}) were much lower than during 2017.

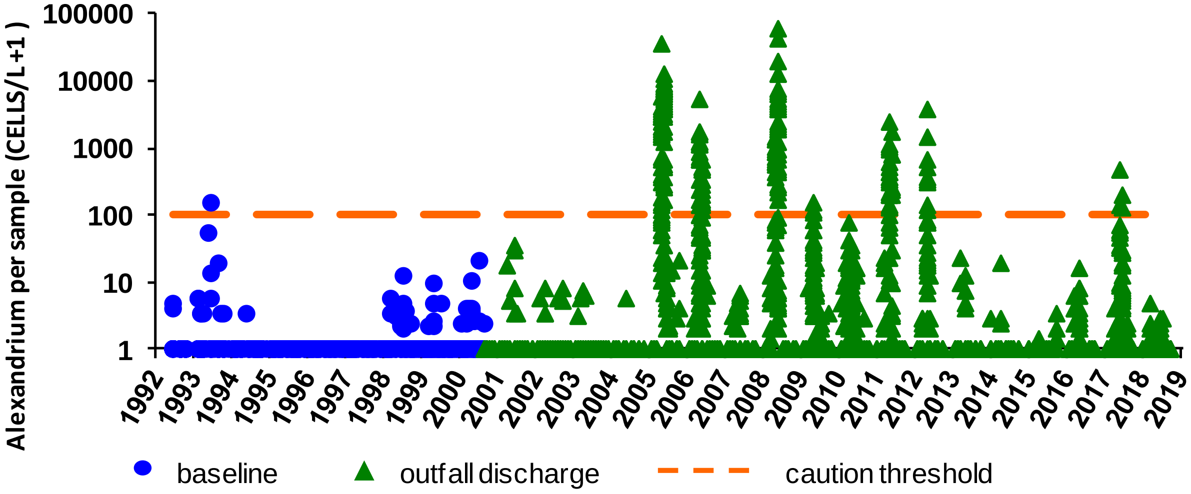

Figure 2-25. Nearfield *Alexandrium* abundance (cells L^{-1} +1) from 1992 to 2018. The dashed line represents the Contingency Plan caution threshold of 100 cells L^{-1}.

2.6 ZOOPLANKTON

Seasonal patterns of zooplankton abundance were normal, with increases from winter lows to spring and summer peaks, followed by fall declines. At many of the locations in Massachusetts Bay, zooplankton abundances peaked in the upper 75th percentile for the 27-year monitoring program (**Figure 2-26**). In 2018, there were peaks in abundance of total zooplankton in May/June at most stations. The zooplankton was usually dominated by typically-recorded taxa, including copepod nauplii and copepod adults and copepodites ("A+C"; **Figure 2-27**). Peak total zooplankton abundances in 2018 (~150,000 animals m^{-3}) were slightly lower than those seen in 2016 and 2017. Although lower than historically high abundances in 2015 due to bivalve veliger larvae, total zooplankton abundances were in the upper quartile of historic values in May and June 2018 at many stations (**Figure 2-26**). Abundances of many dominant taxa were in the upper quartile or above maxima for the 27-year monitoring program at many of the stations in Massachusetts Bay.

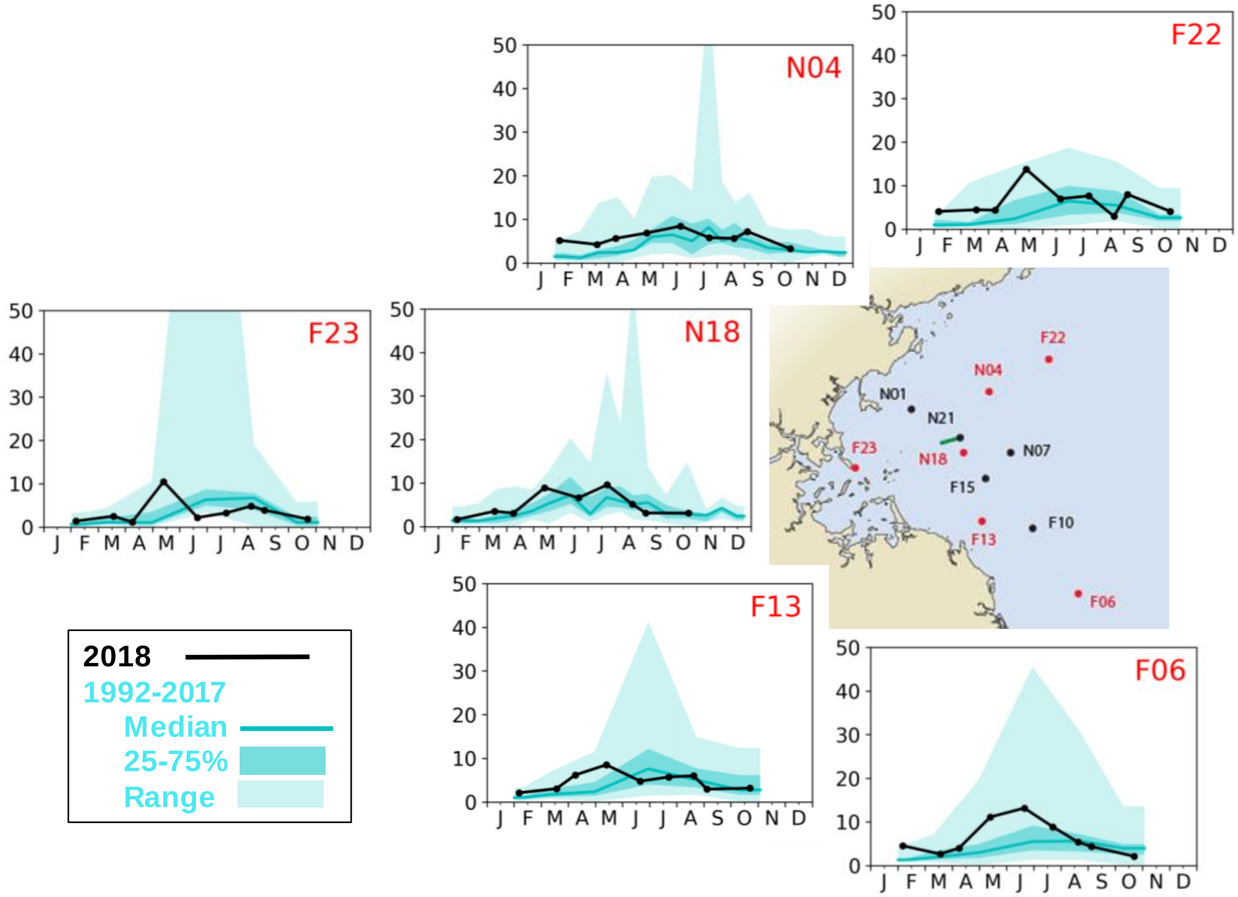

Figure 2-26. **Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2018 compared to prior years.** 2018 results are in black. Results from 1992–2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans 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 individuals m^{-3}.

Copepod nauplii and copepod A+C abundances at most stations were somewhat higher than the 1992-2017 median and less than the 75th percentile. Peak abundances of copepod A+C at most stations were in May or July with secondary peaks in late summer (**Figure 2-27**). The copepod A+C abundance was driven primarily by *Oithona similis* abundance, which was nearly above or above the historic range in May 2018 (**Figure 2-28**). There were typical low abundances (< 2,000 m^{-3}) of *Calanus finmarchicus* at all stations except for levels approaching 10,000 m^{-3} at stations F13 and N04 in April. These peak *Calanus* abundances were high compared to historic values, but overall were about 25% of the peak abundances observed in the bay in 2017 (20,000 to 40,000 cells L^{-1}). *Acartia* spp. (*A. hudsonica* and *A. tonsa*) were generally found at typical low abundances, mainly in Boston Harbor at station F23. There were minor peaks in abundance of some meroplankton such as barnacle nauplii (> 20,000 m^{-3} in May at station F23 in Boston Harbor). Otherwise, meroplankton abundances were at typical low levels. The main difference in meroplankton abundance in 2018 and some previous years was the absence of a major bivalve veliger peak such as in the summer of 2015.

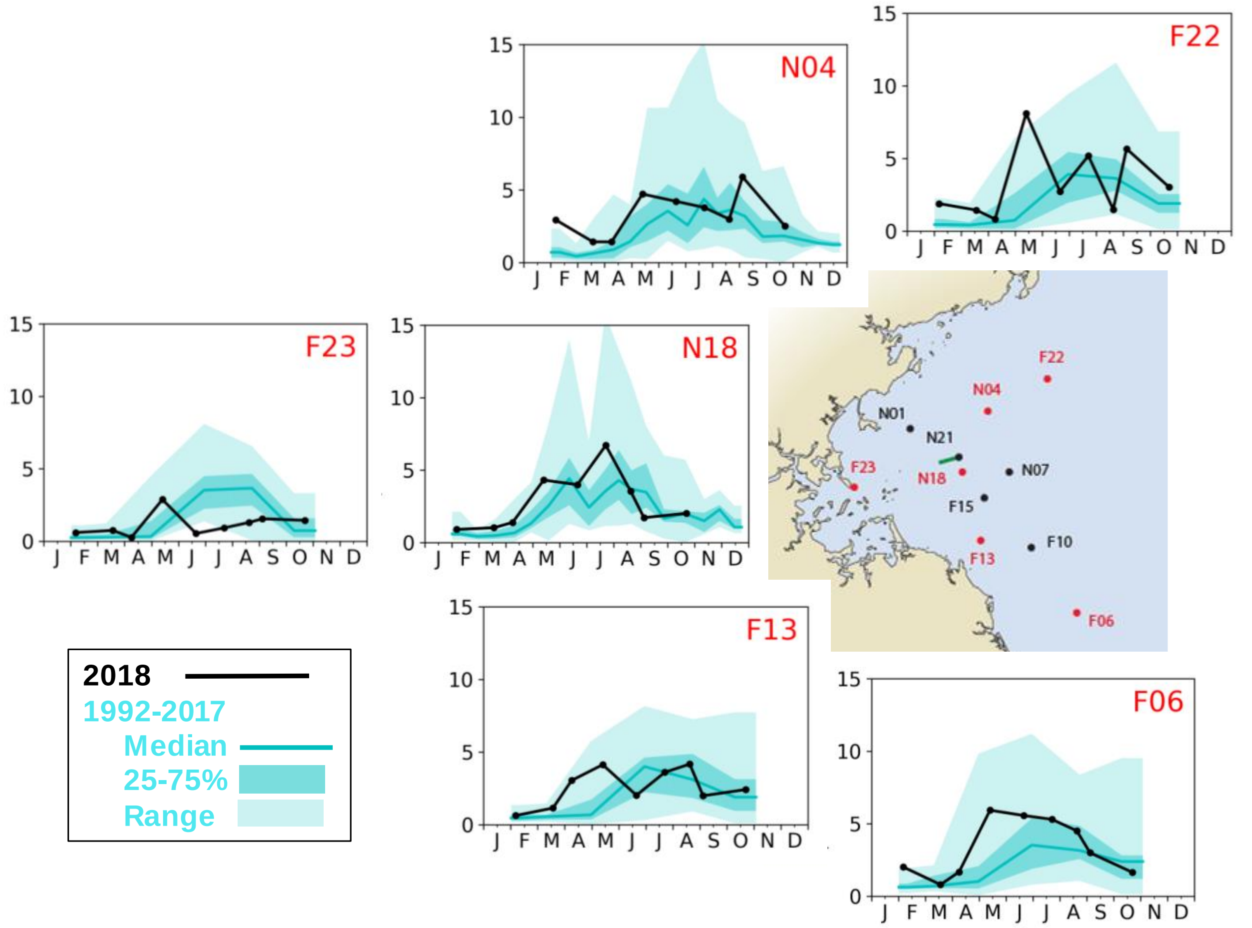

Figure 2-27. Copepod A+C abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2018 compared to prior years. 2018 results are in black. Results from 1992-2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

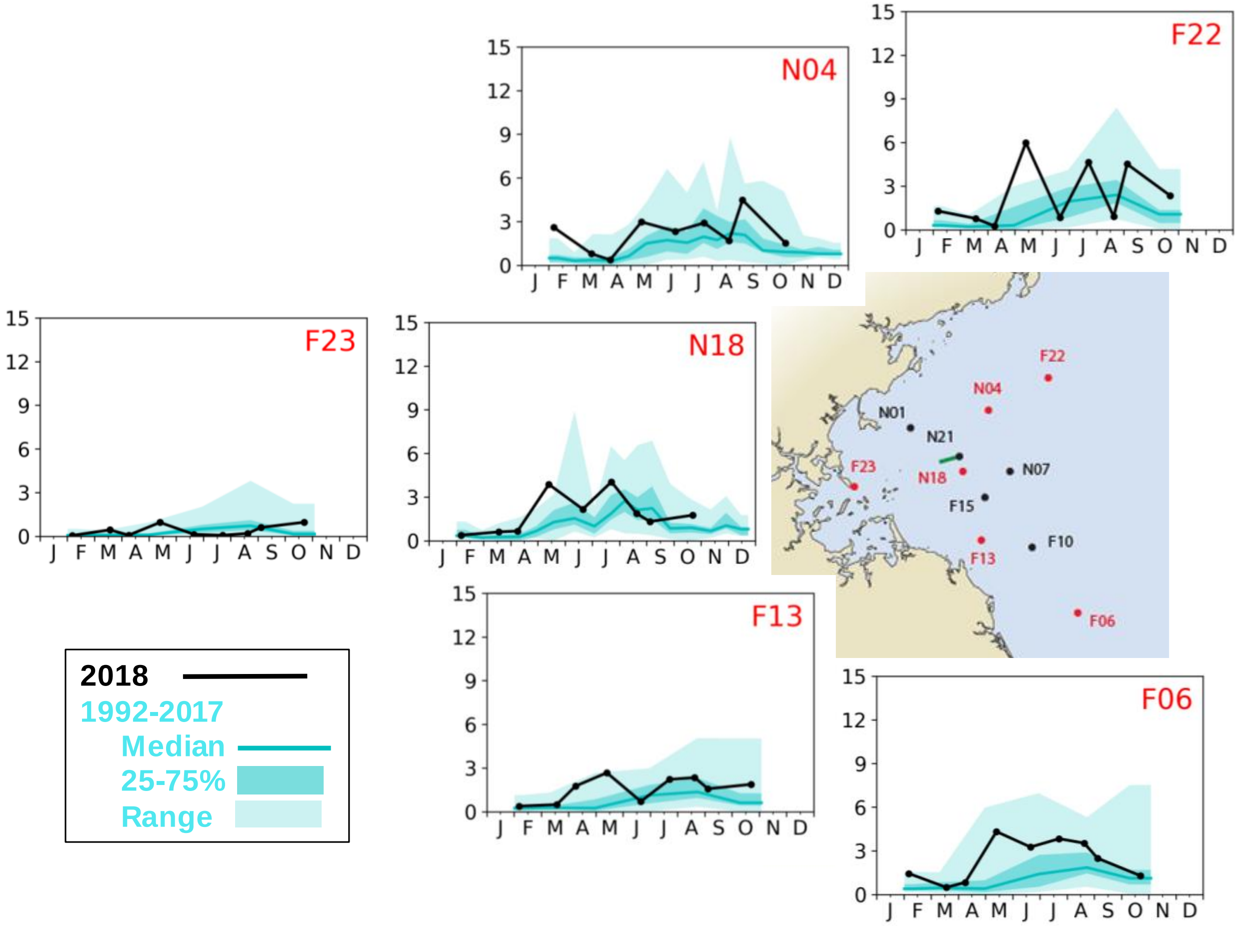

Figure 2-28. ***Oithona* abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2018 compared to prior years.** 2018 results are in black. Results from 1992-2017 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.7 MARINE MAMMAL OBSERVATIONS

The marine mammal observations are made during surveys designed and operated for the collection of water quality measurements, which places limitations and constraints on both the observation method and 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 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, which were sampled during water column surveys prior to 2011, are no longer included in MWRA's marine mammal observations.

In 2018, one finback whale (*Balaenoptera physalus*) and four minke whales (*Balaenoptera acutorostrata*) were observed during the water column surveys in Massachusetts Bay (**Table 2-2** and **Figure 2-29**). No North Atlantic right whales were sighted during 2018 surveys. Several other marine mammals including three harbor porpoises (*Phocoena phocoena*), 26 harbor seals (*Phoca vitulina*) and 25 Atlantic white-sided dolphin (*Lagenorhynchus acutus*) were also observed.

To provide qualitative information of relative whale abundance through years, whale observations that occurred during surveys before 2011 and within the areas covered by the current monitoring plan were identified. The results are summarized in **Table 2-2** and **Figure 2-29**, along with the yearly whale observations since 2011. North Atlantic right whales were not sighted within the current survey areas until recent surveys in years 2012, 2013, 2016 and 2017.

Table 2-2. Number of whale sightings from 1998 to 2018.

Whale species	Total number of sightings (1998-2010)	Range of sightings per year (1998-2010)	2011	2012	2013	2014	2015	2016	2017	2018
Finback	11	0-4	1	0	0	0	0	0	0	1
Humpback	4	0-1	0	2	0	0	0	0	0	0
Minke	30	0-6	4	0	0	2	0	3	3	4
North Atlantic Right	0	0-0	0	2	4	0	0	2	8	0
Unidentified	15	0-2	0	3	1	1	0	0	4	2

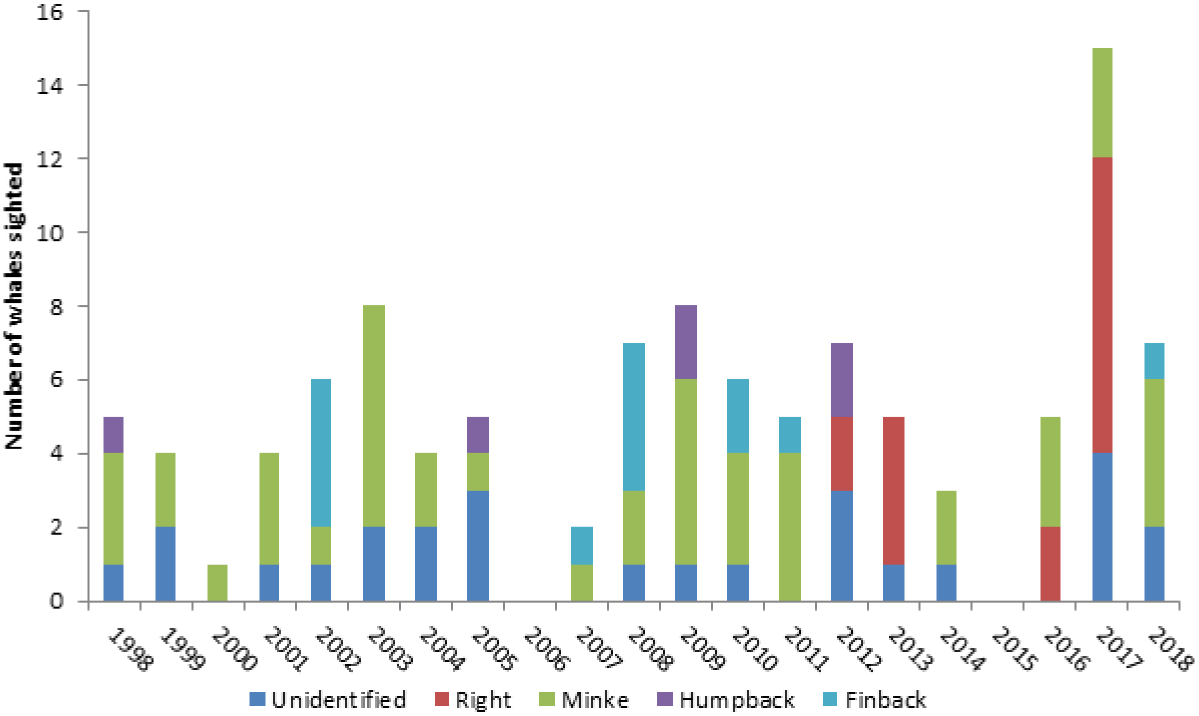

Figure 2-29. Number of whale sightings and whale species sighted in current survey areas (1998 – 2018).

3 LONG-TERM TRENDS

The 2018 observations were consistent with the general 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, NH_4 and PO_4 concentrations have increased in the nearfield since the offshore outfall began discharging (**Figure 2-10**). 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, no phytoplankton biomass increase has been detected in the same area during the same post-discharge period.

However, phytoplankton abundance in the Massachusetts Bay nearfield area has been declining since 2008, as a result of grazing by zooplankton (**Figure 3-1**). De-seasonalized mean total phytoplankton abundance in recent years (~0.8 million cells L^{-1}) has been substantially lower than levels observed in the 1990s and early 2000s (1 to 1.5 million cells L^{-1}; **Figure 3-1**). Decreased abundance of several important phytoplankton groups have contributed to the decline. Abundance of microflagellates, which are the most abundant phytoplankton numerically in the MWRA monitoring area and coastal waters globally, has been in decline since 2008. The decline in microflagellate abundance is synchronous with, and a driver of, the long-term decline in total phytoplankton abundance. Microzooplankton abundance appears to have increased in recent years, with 2018 microzooplankton abundance (7,188 cells L^{-1}) that was approximately one and a half times the 2011 to 2017 average level (4,602 cells L^{-1}; **Table 2-1**). Increased microzooplankton grazing may be driving the declining trend in microflagellate abundance.

Phaeocystis pouchetii abundance has also been low in recent years. *Phaeocystis* blooms of greater than one million cells L^{-1} were routinely seen in Massachusetts Bay during the 1990s and early 2000s with 16 of 21 years during 1992 to 2013 having *Phaeocystis* of greater than 1 million cells L^{-1} during the late winter to spring period. In contrast, only one year (2014) of the last six years had *Phaeocystis* blooms of greater than one million cells L^{-1} in the nearfield. In addition, the winter/spring abundance of centric diatoms has declined relative to levels observed in the 1990s (**Figure 3-1**). For the nearfield area of Massachusetts Bay, February to April average diatom abundance has declined from near 300,000 cells L^{-1} during the 1990s to about 100,000 cells L^{-1} during the 2000s and 2010s. Summer and autumn centric diatom abundance, while variable, has also declined, though less dramatically. The net result has been a long-term decline in centric diatom abundance.

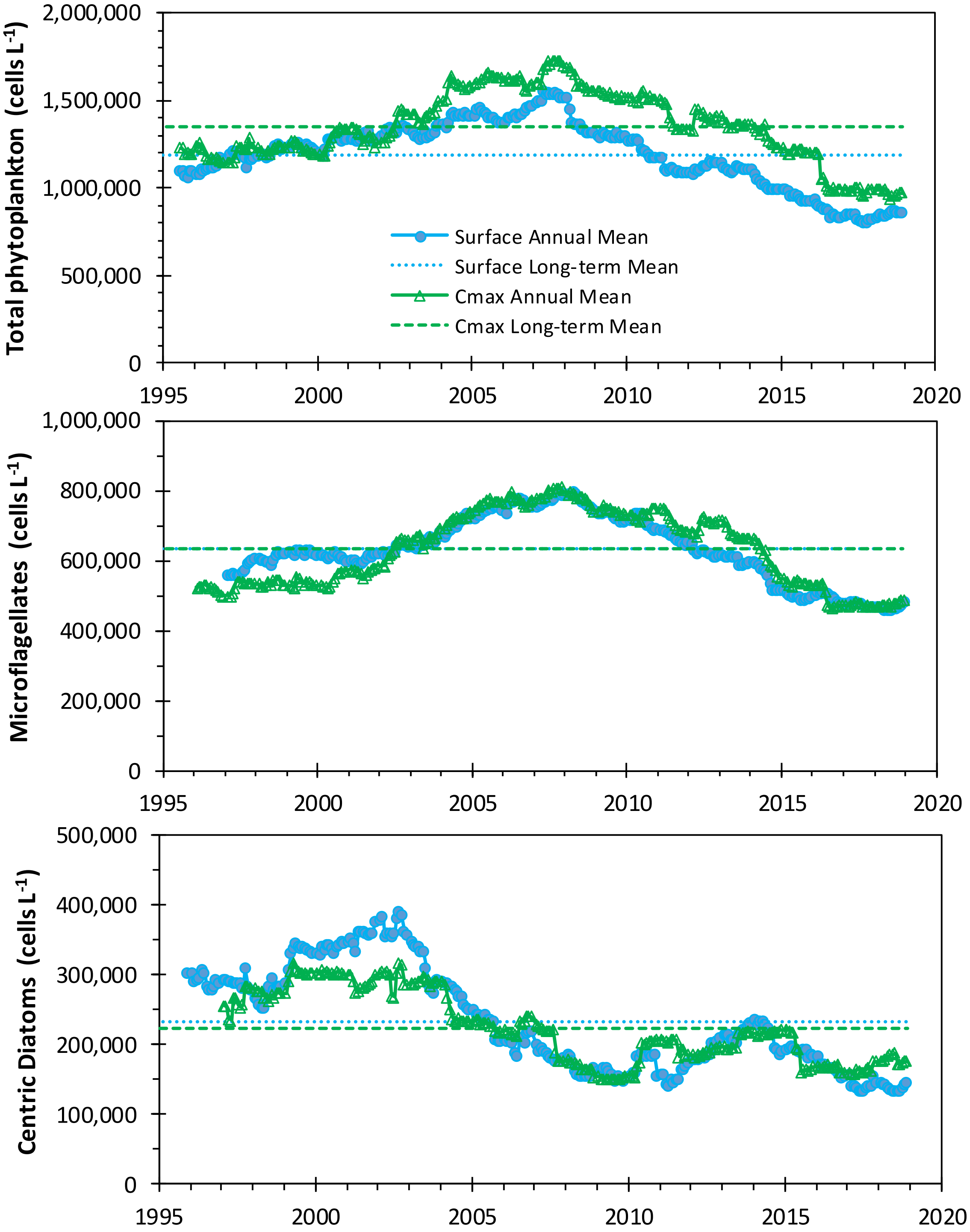

Figure 3-1. **Estimated long-term (1992-2018) abundance levels of phytoplankton groups in the nearfield region (stations N04 and N16/N18) derived from time series analysis.** Each panel shows the de-seasonalized annual mean abundance at the surface (blue) and at the chlorophyll maximum depth (green) during 1992-2018. Horizontal dashed lines are 1992-2018 mean levels. Panels show total phytoplankton (top panel), microflagellates (middle panel), and centric diatoms (bottom panel). Data lines based on 15% smoothing windows (~4 years).

Although the mechanisms are not known well, phytoplankton abundance and community composition in the Massachusetts Bay nearfield area have had three main phases during 1992 to 2018. A multivariate ordination technique was used to visualize the similarity of monitoring years (1992 to 2018) in terms of phytoplankton species composition and abundance. Observations from the top ten phytoplankton taxa by abundance were used to construct a similarity matrix (log x+1 transformed, Bray-Curtis similarity index) and PRIMER software was used (procedure MDS) to construct a non-dimensional scaling diagram of phytoplankton years (**Figure 3-2**). In this diagram, years that are near each other had more similar species composition and abundance than are years that are located further apart on the diagram. Three clusters of phytoplankton years are evident:

- 1992 to 1999 (left side of plot) dominated by centric diatom blooms, with the exception of 1992 and 1997 which had higher *Phaeocystis* abundance, and 1994 which had reduced total abundance.
- 2000 to 2012 (cluster on right side of plot) large *Phaeocystis* blooms in the spring and summer-fall diatom blooms.
- 2013 to 2018 (cluster at center of plot) reduced or absent *Phaeocystis* abundance (except in 2014), reduced winter/spring diatom abundance and reduced total phytoplankton abundance.

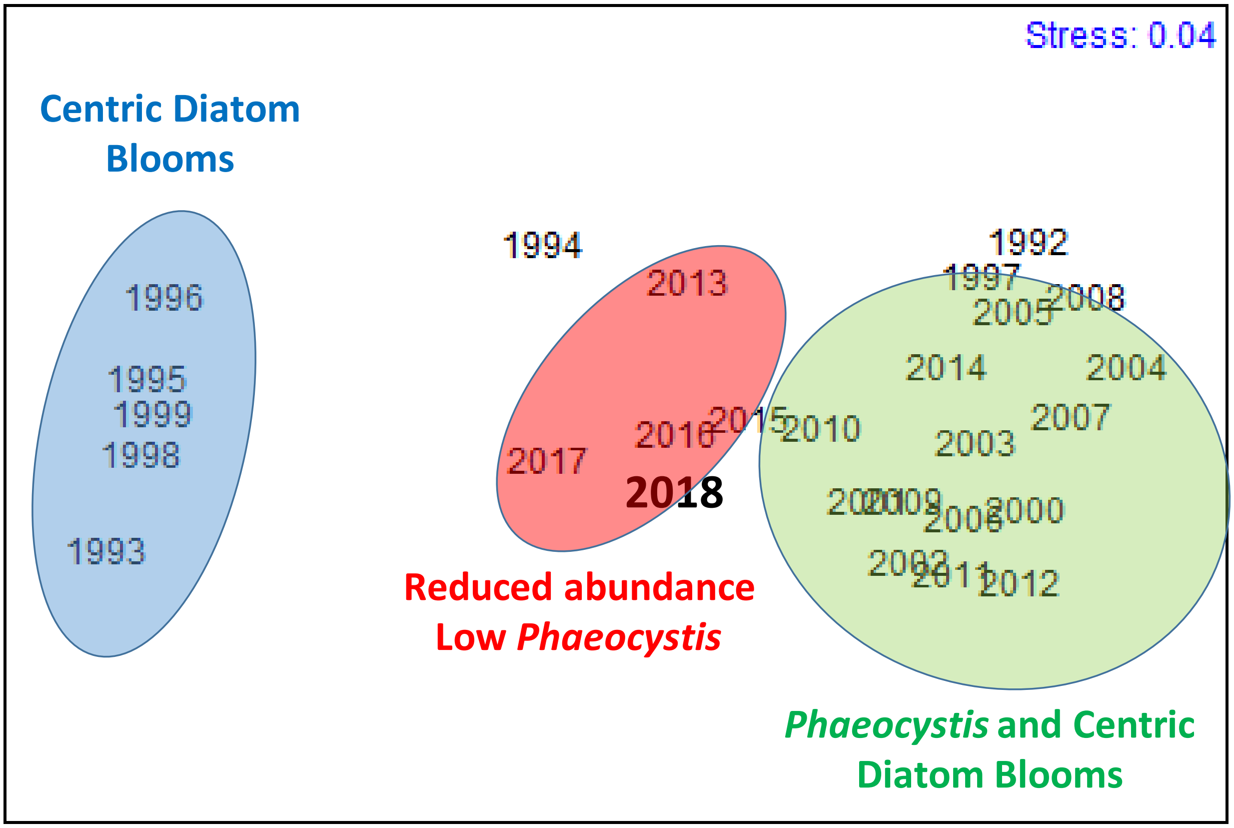

Figure 3-2. MDS plot of nearfield phytoplankton years in terms of phytoplankton community composition and abundance from 1992-2018. Based on the top 10 taxa, log x+1 transformed data, Bray-Curtis similarity index.

A combination of bottom-up (nutrients), oceanographic (currents, water mass composition) and top-down (grazing) processes likely determine long-term phytoplankton patterns in Massachusetts Bay. The past 10 years of declining total phytoplankton trend have been simultaneous with a period of increasing zooplankton abundance (both copepods and microzooplankton, **Figure 3-3**), which suggests zooplankton grazing is a mechanism at least partially responsible.

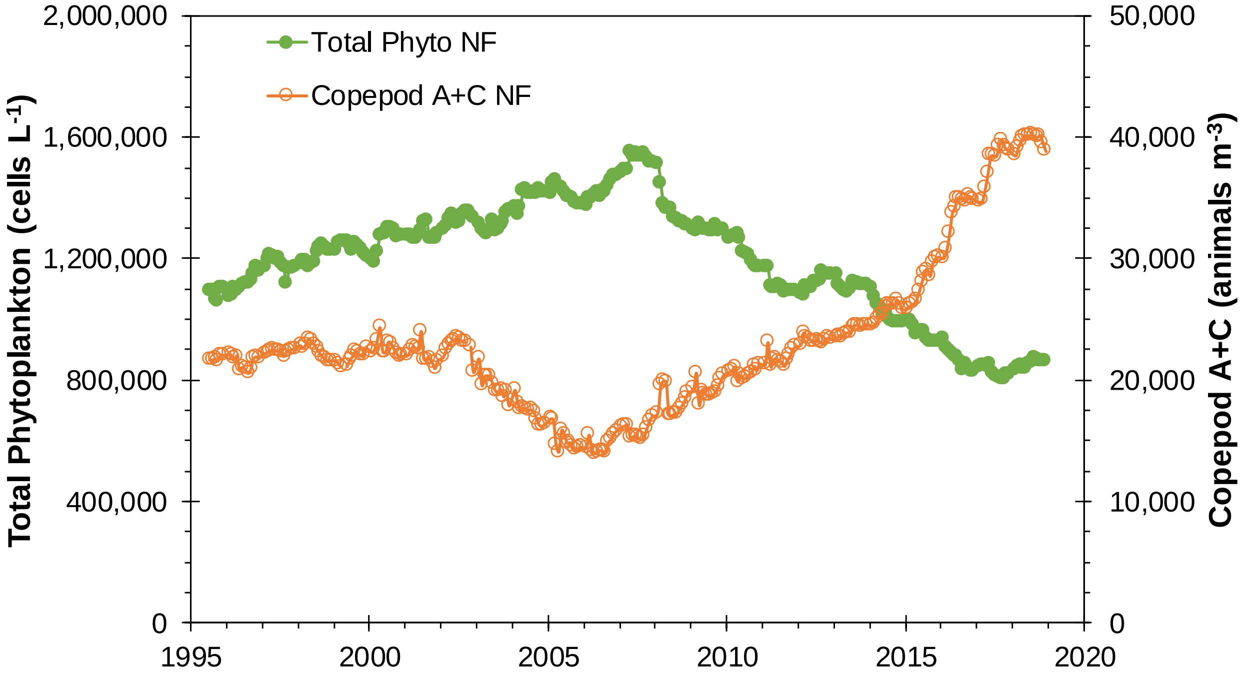

Figure 3-3. Estimated long-term (1995-2018) abundance levels of total phytoplankton (green) and copepod A+C (orange) abundance in the nearfield (stations N04 and N16/N18) derived from time series analysis. Data lines based on 15% smoothing windows (~4 years).

The last few years were characterized by an increase in zooplankton abundance compared to the early 2000s. Time series analysis indicates there had been a substantial long-term decline in total zooplankton abundance in the nearfield from 2001-2005 due to a decline in total copepods (Libby et al. 2009). Total zooplankton abundance increased from 1995 to 2000, followed by a decline from 2001 to 2006-2008, followed by another sustained increase from 2009 to 2017 which appears to have leveled off in 2018 (**Figure 3-4**). Both the 1995-2000 increase and the 2000-2006 decrease in total zooplankton seem unrelated to copepod abundance, which exhibits small oscillations about the long-term mean from 1992 to 2003 followed by a slight decline from 2003 to 2006. Although copepod abundances were lower than total zooplankton abundances, as expected, the sustained increases in both total zooplankton and copepod trends paralleled each other from 2009-2017 and both appear to be leveling off in 2018. The unprecedented high abundances of bivalve veligers in 2015 caused a large increase in the total zooplankton abundance in 2015, but the overall long-term trend in total zooplankton abundance appears to be driven mostly by the trend in copepod abundance.

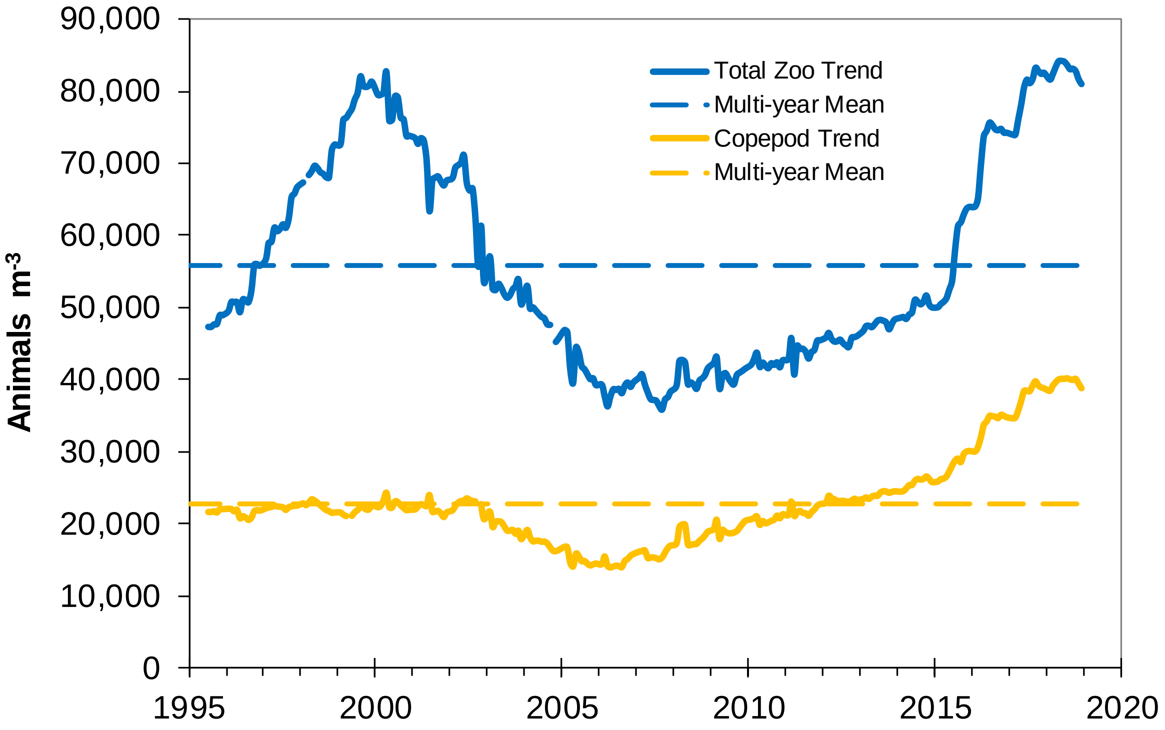

Figure 3-4. Estimated long-term (1995-2018) abundance levels of total zooplankton (blue) and copepod A+C (orange) in the nearfield (stations N04 and N16/N18) derived from time series analysis. Long-term mean levels also shown (dashed lines). Data lines based on 15% smoothing windows (~4 years).

4 SUMMARY

The most notable physical events in 2018 were the Nor'easter in early March, and the rare late-summer Nor'easter. The early March Nor'easter was a very intense and long duration storm (**Figure 2-3**). Sustained winds were nearly 20 m/s and significant wave height peaked at 10 m. The time-integrated bottom stress, an indicator of wave-induced erosion, was larger during this storm than any other storm since 1990. The late summer Nor'easter ventilated the deep water and kept DO from dropping as low as it otherwise would have.

Overall, river flow was higher than normal in 2018, consistent with high precipitation (**Figure 2-5**). An exception was low Merrimack River flow from April to June, a weak spring freshet. There were periods of upwelling-favorable, southwesterly winds in June/July that led to cooler surface waters offshore at Buoy A01 and station F22 (**Figure 2-7**). This was not evident in the nearfield, perhaps due to the southwesterly wind direction being more favorable to upwelling in the northern rather than central part of Massachusetts Bay. The late summer Nor'easter resulted in cooling surface waters at the offshore stations and warming of waters at depth; bottom temperatures at nearfield station N18 in August were higher than the 1992-2017 maximum.

Nutrient concentrations in Massachusetts and Cape Cod Bays followed typical seasonal patterns, with naturally elevated NO_3, SiO_4 and PO_4 concentrations from February to April, low concentrations through August or September, and then increases in October (**Figure 2-8**). As in previous years, compared to the other three nutrients, the NH_4 concentrations during 2018 were more variable from survey to survey and did not show a seasonal pattern. In 2018, NH_4 concentrations were mostly typical and within the range observed post-diversion: compared to baseline, they were lower in Boston Harbor, higher in the outfall nearfield, and unchanged in the rest of Massachusetts and Cape Cod Bays (**Figure 2-10**). Concentrations near the outfall at stations N18 and N21 were generally within the range of values observed post-diversion, while moderately elevated concentrations were observed during some months at station F15 which is about 10 km south of the outfall. 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 2018 (**Figure 2-11** and **Figure 2-12**). The NH_4 signature, when evident, was confined within 10 km of the outfall during both well-mixed and stratified conditions, consistent with 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 the model predictions (Taylor 2016; Libby et al. 2007).

There were no strong bay-wide winter/spring diatom or *Phaeocystis* blooms observed in Massachusetts Bay during the 2018 monitoring surveys. This contributed to annual-mean chlorophyll concentrations that were relatively low (**Figure 2-14**). Elevated chlorophyll concentrations were observed offshore in northeastern Massachusetts Bay and in Cape Cod Bay in April and October 2018 (**Figure 2-15**). In April they were associated with a minor bloom of centric diatoms *Skeletonema* and *Rhizosolenia* in northeastern Massachusetts Bay and a *Phaeocystis* bloom in Cape Cod Bay. In October they were associated with a fall *Skeletonema* bloom over most of Massachusetts and Cape Cod Bays. Chlorophyll concentrations in the nearfield met Contingency Plan thresholds.

Bottom-water DO concentrations in 2018 showed the typical decline from winter/spring maxima to September or October annual minima. In 2018, as during the last two years, the seasonal decline was punctuated by upwelling events that increased bottom water DO levels in June (**Figure 2-19**). The late summer Nor'easter increased DO levels down to 50 m at Buoy A01 (**Figure 2-21**). These upwelling and mixing events kept bottom water DO concentration minima to moderate levels over most of Massachusetts Bay in 2018 and higher than Contingency Plan thresholds.

Annual total phytoplankton abundance measured during the 2018 MWRA surveys was low and ranked 23rd for the 27-year monitoring program (**Table 2-1**). The low 2018 total phytoplankton abundance was in part due to the lack of a strong bay-wide winter/spring diatom or *Phaeocystis* bloom. As observed the last few years there was an April diatom bloom dominated by *Skeletonema* in northeastern Massachusetts Bay (**Figure 2-24**). The large diatom *Rhizosolenia* was also abundant at these stations. There was a *Phaeocystis* bloom in Cape Cod Bay in April with moderate abundances (~2.5 million cells L^{-1}). In October 2018, the autumn diatom bloom was again dominated by *Skeletonema* spp. in Boston Harbor and Massachusetts Bay. The dinoflagellate *Prorocentrum* peaked in abundance (up to 15,000 cells L^{-1}) in October 2018. Elevated abundance of *Prorocentrum* spp., especially elevated *P. micans* abundance, during the late autumn (October-November) has occurred more commonly in Massachusetts Bay in recent years.

There were no issues with nuisance or potentially toxic algae in Massachusetts Bay in 2018. A *Phaeocystis* bloom was observed in Cape Cod Bay, but only low abundances were seen in Massachusetts Bay. *Alexandrium* were essentially absent from the bays in 2018 with counts <10 cells L^{-1} (**Figure 2-25**) and no PSP shellfish closures were required in Massachusetts Bay in 2018. *Pseudo-nitzschia* abundance was also low during 2018 with an annual mean only 25% as high as the long-term mean of 8,465 cells L^{-1}. The dinoflagellate *Karenia mikimotoi* was observed in September 2018, but at abundances about 100 times lower than observed in 2017. Prior to 2017, *K. mikimotoi* had not been observed in the previous 25 years of MWRA monitoring. It is known to have a history of 'invasions' into new waters. Toxins from *K. mikimotoi* are not well-understood (Yamasaki et al., 2004) and no direct negative impacts on human health are known.

2018 zooplankton abundances were higher than the long-term average for the program, as in many recent years. During 2018, copepod nauplii and adults were in the upper 75th percentile of past years' ranges, with peak abundances at most stations in May or July, and a secondary peak in later summer (**Figure 2-27**). Copepod abundance was driven primarily by *Oithona similis*, which had abundances near or above the historic range at many stations in Massachusetts Bay in May 2018 (**Figure 2-28**). Abundances of *Calanus finmarchicus* were typical of past years at all stations except for higher levels approaching 10,000 m^{-3} at stations south of the outfall (F13 and N04) in April. These peak *Calanus* abundances were high compared to historic values but were about 25% of the peak abundances observed in the bay in 2017 (20,000 to 40,000 cells L^{-1}). Overall, 2018 zooplankton abundances were comparable to 2017 and remain elevated over the long-term levels observed since 1992 (**Figure 3-4**).

Massachusetts Bay and Boston Harbor phytoplankton and zooplankton have undergone long-term (decadal) changes since monitoring started in 1992 (**Figure 3-1** and **Figure 3-3**). The mechanisms are not fully known but appear to be regional and not related to the outfall. Phytoplankton abundance and community composition in the Massachusetts Bay nearfield area has had three main phases during 1992 to 2018 (**Figure 3-2**). From 1992 to 1999 total abundances were relatively high and centric diatom blooms dominated, with the exception that 1994 had lower abundance, and *Phaeocystis* was important in 1992 and 1997. From 2000 to 2012, the phytoplankton community was characterized by large *Phaeocystis* blooms in the spring, and summer-fall diatom blooms. From 2013 to 2018, total phytoplankton abundance has been low due to reduced levels of *Phaeocystis* (except in 2014) and diatoms.

A combination of bottom-up (nutrients), oceanographic (currents, water mass composition) and top-down (grazing) processes likely determine long-term phytoplankton patterns in Massachusetts Bay. The past 10 years of declining total phytoplankton trend have been simultaneous with a period of increasing zooplankton abundance (both copepods and microzooplankton, **Figure 3-3**), which suggests zooplankton grazing is at least partially responsible.

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