2019 Water Column Monitoring Results

Massachusetts Water Resources Authority
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Environmental Quality Report 2020-08

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA), as part of its National Pollutant Discharge Elimination System (NPDES) permit for the Deer Island Treatment Plant, is required to monitor water quality in Massachusetts and Cape Cod Bays. This report documents the results of water column monitoring during 2019. 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 U.S. Environmental Protection Agency (EPA), and (3) determine whether thresholds of the Contingency Plan[1] attached to the permit have been exceeded.

The only Contingency Plan water column threshold exceeded in 2019 was the *Alexandrium* nuisance species Caution Level threshold (**Table i**). The 2019 *Alexandrium* bloom, which appeared to originate in the Gulf of Maine, was comparable to the large 2005 and 2008 blooms in magnitude and duration. Meteorological and oceanographic conditions during May through July, were conducive for transporting offshore *Alexandrium* populations into Massachusetts Bay via surface currents and sustaining the bloom. Initially, paralytic shellfish poisoning (PSP) toxicity was low or not detected as *Alexandrium* abundances increased into the thousands of cells L^{-1} in late May and early June. It was not until June 18 that PSP toxicity increased to >80 µg/100g along the South Shore and Massachusetts Division of Marine Fisheries (MA DMF) issued a shellfishing closure the next day. The shellfishing closure was lifted on July 19.

Table i. Contingency Plan threshold values and 2019 results for water-column monitoring.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2019
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: 7.18 SW Basin: 7.35
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 81.2% SW Basin: 79.0%
Bottom water DO rate of decline (mg L^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.011
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	92
	Winter/spring	>199	--	50	112
	Summer	>89	--	51	57
	Autumn	>239	--	90	132
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	18
	Summer	>43,100	--	14,635	598
	Autumn	>27,500	--	10,500	523
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	24,342

[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

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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 2019 monitoring confirmed that the treated wastewater discharge from the bay outfall influenced the local area within ~10 kilometers (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 2019 are as follows.

- The most notable physical oceanographic events in 2019 were a moderate Nor'easter in mid-May, strong seasonal stratification from May into September, and an unprecedented hypoxia/anoxia event in Cape Cod Bay in late September/early October.
- River flow, particularly from the Charles River between January and March, was higher than normal. The spring freshet of the Merrimack River was one of the strongest of the 1992-2019 monitoring period.
- The mid-May Nor'easter was not very intense but caused relatively strong near-surface currents into the bay from offshore. The low-salinity surface waters associated with the strong spring freshet enhanced stratification resulted in the upper water column being more "slippery" against deeper waters. Several more pulses of current occurred through mid-June, without a clear association with wind events.
- Stratification was strong in May and into June due to fresher surface waters and remained strong throughout the summer due to warmer surface water temperatures in late June and July.
- Bay nutrient concentrations were consistent with those observed since the outfall was diverted offshore in 2000. The most notable differences in 2019 were higher ammonium (NH_4), nitrate (NO_3) and phosphate (PO_4) concentrations in the nearfield during the summer months. Anomalously strong stratification, with high concentrations below the pycnocline (and depleted in the surface waters) contributed to the increase.
- As in other years since outfall start up, NH_4 concentrations 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, elevated NH_4 concentrations were observed up to about 10 km south of the outfall.
- Overall, chlorophyll concentrations were moderate. Elevated chlorophyll levels were observed in February, April, and late May in Massachusetts Bay, February to April in Cape Cod Bay, and in late May and August in Boston Harbor, while elevated levels were seen across the monitoring area during a large dinoflagellate bloom in September. Chlorophyll concentrations in the nearfield were below Contingency Plan thresholds.
- Bottom water dissolved oxygen (DO) concentration minima were also moderate over most of Massachusetts Bay in 2019 and higher than Contingency Plan thresholds. A mixing event in July caused bottom water DO to increase. After the mixing event, bottom water DO concentrations for the rest of the year in Massachusetts Bay remained close to long-term averages.
- Cape Cod Bay showed a similar summer increase in bottom water DO in July, but concentrations then decreased to low levels of 4 to 5 milligrams per liter (mg L^{-1}) by late August and early September. Hypoxic to anoxic conditions were observed by others in southern Cape Cod Bay near Barnstable Harbor in late September and early October, leading to mortality of bottom fish and lobsters in traps deployed in the area.
- The water column at the relatively shallow Cape Cod Bay stations typically become well mixed by early September, but weather conditions in 2019 were such that the fall mixing was delayed into October. The combination of a dinoflagellate bloom in August/September, and the prolonged strong stratification that isolated a thin bottom water layer, contributed to the hypoxic bottom-water DO in Cape Cod Bay.
- Annual total phytoplankton abundance in the nearfield was low in 2019 and ranked 23rd for the 28-year monitoring program. This was in part due to not observing a strong bay-wide winter/spring diatom or *Phaeocystis* bloom. Satellite imagery and nutrient depletion suggest a diatom bloom occurred prior to the April survey. This is consistent with the weak diatom bloom dominated by *Thalassiosira* and *Detonula* observed on the April survey in Massachusetts Bay.

Dinoflagellates were relatively abundant (3rd out of 28 years) largely due to a late summer-autumn bloom of *Karenia mikimotoi*. The 2019 phytoplankton abundance levels and community composition were similar to that observed in the past four years (2015-2018).

- A major, prolonged *Alexandrium catenella* bloom occurred in the bay from May to July 2019 with maximum abundances of >10,000 cells L^{-1}. The 2019 *Alexandrium* bloom was comparable in both magnitude and duration to the 2005 and 2008 bloom events. Elevated *Alexandrium* counts (>100 cells L^{-1}) were first observed on the mid-May survey triggering the *Alexandrium* Rapid Response Study (ARRS) surveys. The bloom continued over the course of seven ARRS surveys and two more regular water column surveys before ending in late July 2019. Meteorological and environmental conditions were conducive for transporting offshore *Alexandrium* populations into Massachusetts Bay and sustaining the bloom. Neither the timing nor geographic progression of the bloom suggested any influence of the Massachusetts Bay outfall.
- A large *Karenia mikimotoi* bloom occurred in Massachusetts Bay and Cape Cod Bay during August and September. The bloom was most intense in Boston Harbor, and for a brief period in September resulted in discolored harbor water. *K. mikimotoi* is a recent phenomenon in Massachusetts Bay, having been observed for the first time in 2017 from August to October, and then in 2018 during May and from August to October, and in 2019 during May and from July to October. *Karenia* population increases have been reported by others elsewhere in the northeast during the same period, suggesting regional processes have been responsible for the recent blooms in Massachusetts Bay and Cape Cod Bay.
- Seasonal patterns of zooplankton abundance were normal, with increases from winter lows to spring and summer peaks, followed by fall declines. At most of the locations in Massachusetts Bay, total zooplankton abundances were above the long-term median and often above the upper 75th percentile for the 28-year monitoring program. The zooplankton was usually dominated by typically-recorded taxa, including copepod nauplii and copepod adults and copepodites. Peak zooplankton abundances in 2019 were slightly lower than those seen from 2016 to 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. Zooplankton abundance declined during 2019 while total phytoplankton increased slightly, suggesting a possible change in phytoplankton-zooplankton dynamics, unrelated to the outfall, in Massachusetts Bay.

LIST OF ACRONYMS

AMP	Ambient Monitoring Plan
ARRS	*Alexandrium* Rapid Response Study
BACI	Before-After Control-Impact
BHWQM	Boston Harbor Water Quality Monitoring
CCS	Center for Coastal Studies
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorous
DISi	Dissolved inorganic silica
DO	Dissolved oxygen
EM&MS	Environmental Monitoring and Management System
EPA	U.S. Environmental Protection Agency
MA DMF	Massachusetts Division of Marine Fisheries
MDS	Multidimensional scaling
MGD	Million gallons per day
MODIS	Moderate-resolution Imaging Spectroradiometer
MWRA	Massachusetts Water Resources Authority
NA	Not analyzed/not applicable
NACWA	National Association of Clean Water Agencies
NDBC	National Data Buoy Center
NERACOOS	Northeastern Regional Association of Coastal and Ocean Observing Systems
NH_4	Ammonium
NO_3	Nitrate
NO_{3+2}	Nitrate plus Nitrite
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
OMSAP	Outfall Monitoring Science Advisory Panel
PO_4	Phosphate
POC	Particulate organic carbon
PSP	Paralytic shellfish poisoning
PSU	Practical salinity unit
QAPP	Quality Assurance Project Plan
SEIS	Supplemental environmental impact statement
SiO_4	Silicate

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 U.S. 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 2019, when wastewater has been discharged from the bay outfall and not into the harbor. The 2019 data complete 19 years of monitoring since operation of the bay outfall began and 28 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), based on the scientific understanding gained since monitoring started in 1992. The monitoring now focuses on the stations potentially affected by the discharge, and reference stations in Massachusetts Bay. During 2019, as required by the AMP, nine one-day surveys were undertaken (**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 three Cape Cod Bay stations in the same timeframe, extending the spatial extent of the monitoring. Seven additional surveys were conducted from May to July 2019 as part of an *Alexandrium* Rapid Response Study (ARRS) triggered by elevated abundances of this toxic species (Libby et al. 2013); those dates are listed in **Table 1-2**.

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 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

This annual report summarizes the 2019 water column monitoring results, examines conditions over the seasonal cycles during 2019, and compares these conditions with patterns seen during previous years. The water column monitoring is focused on observations potentially attributable to changes to inputs of nutrients and organic matter to the system. The report also compares bottom-water dissolved oxygen concentrations, percent saturation, and rate of decline; phytoplankton biomass measured as chlorophyll-a; and nuisance phytoplankton species abundance relative to Contingency Plan Warning and Caution thresholds (see **Table i**; MWRA 2001)

Table 1-2. Water column surveys for 2019.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN191	February 5	February 5	February 6
WN192	March 20	March 20	March 21
WN193	April 11	April 11	April 5
WN194	May 16	May 16	
AF191	May 22		
AF192	May 30		
WN195	June 6	June 7	June 12
AF193	June 12		
AF194	June 19		
AF195	June 27		
AF196	July 10		
WN196	July 17	July 19	July 22
AF197	July 31		
WN197	August 21	August 20	August 19
WN198	September 4	September 3	September 10
WN199	October 30	October 30	October 24

WN = the nine surveys undertaken each year; AF = ARRS surveys; Only harbor monitoring surveys undertaken within one week of the WN surveys, have been included in this report.

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. 2018a). 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 micron (µm) phytoplankton species abundance in one sample, the marine mammal observations, and any deviations from the survey plan. A single survey report was prepared for the 2019 ARRS surveys. 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 2019 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 eleven 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 [DO]) collected within 7 days (**Table 1-2**) of an AMP survey are included in this report. During the seven ARRS surveys in 2019, up to 19 sampling locations were visited during each survey (**Figure 1-2**) including all of the AMP survey stations except N21. The ARRS surveys provide data on in situ parameters, dissolved inorganic nutrients, and *Alexandrium* abundances. Marine mammal observers were present on all AMP surveys in Massachusetts Bay during 2019. Marine mammal 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 2019 seasonal chlorophyll or DO 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, 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 in the report are the non-tidal currents, isolated from tidal variations by application of a low-pass (33-hour cutoff Butterworth) filter to the raw current data.

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 2019. 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.

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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

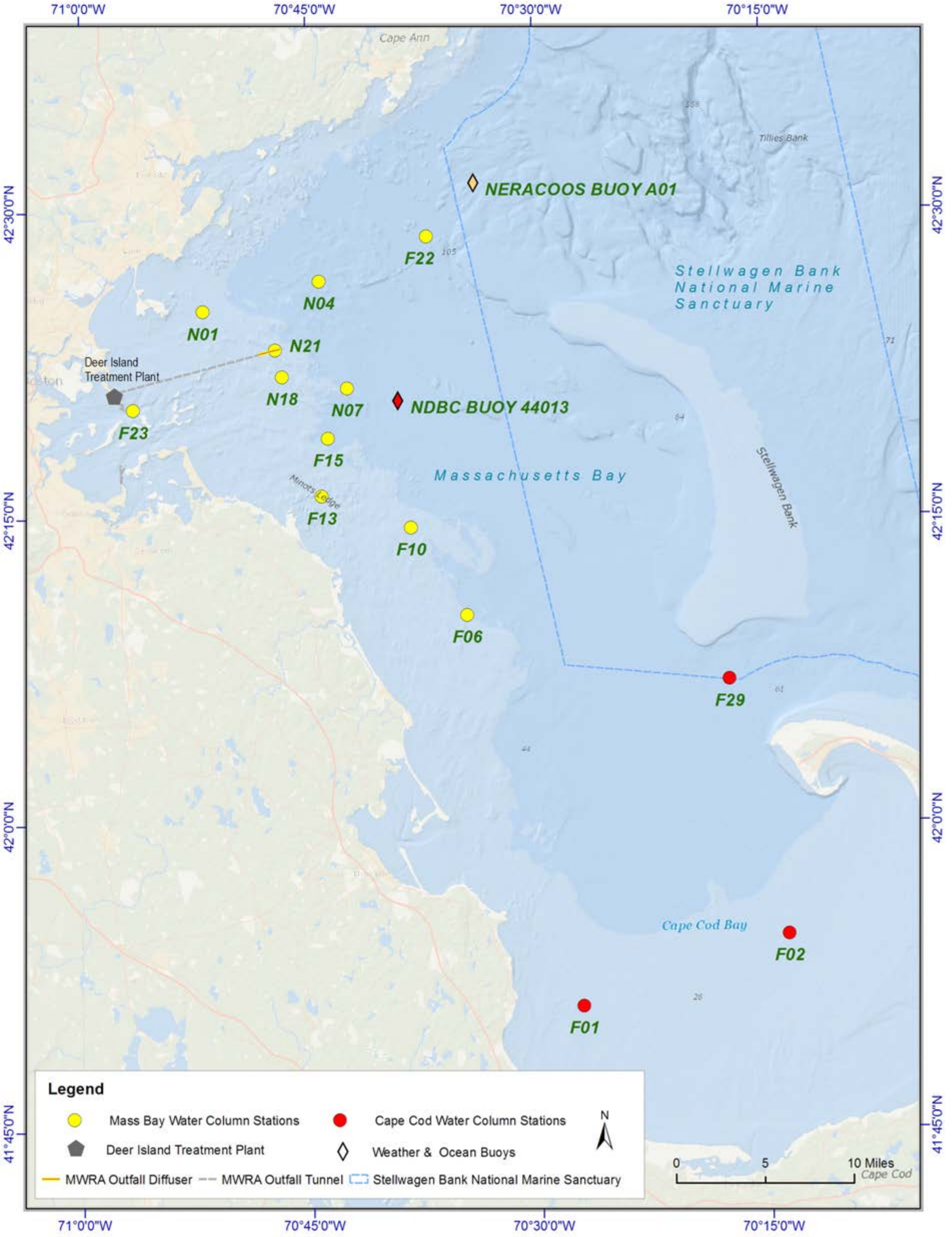

Figure 1-1. **Water column monitoring locations.**

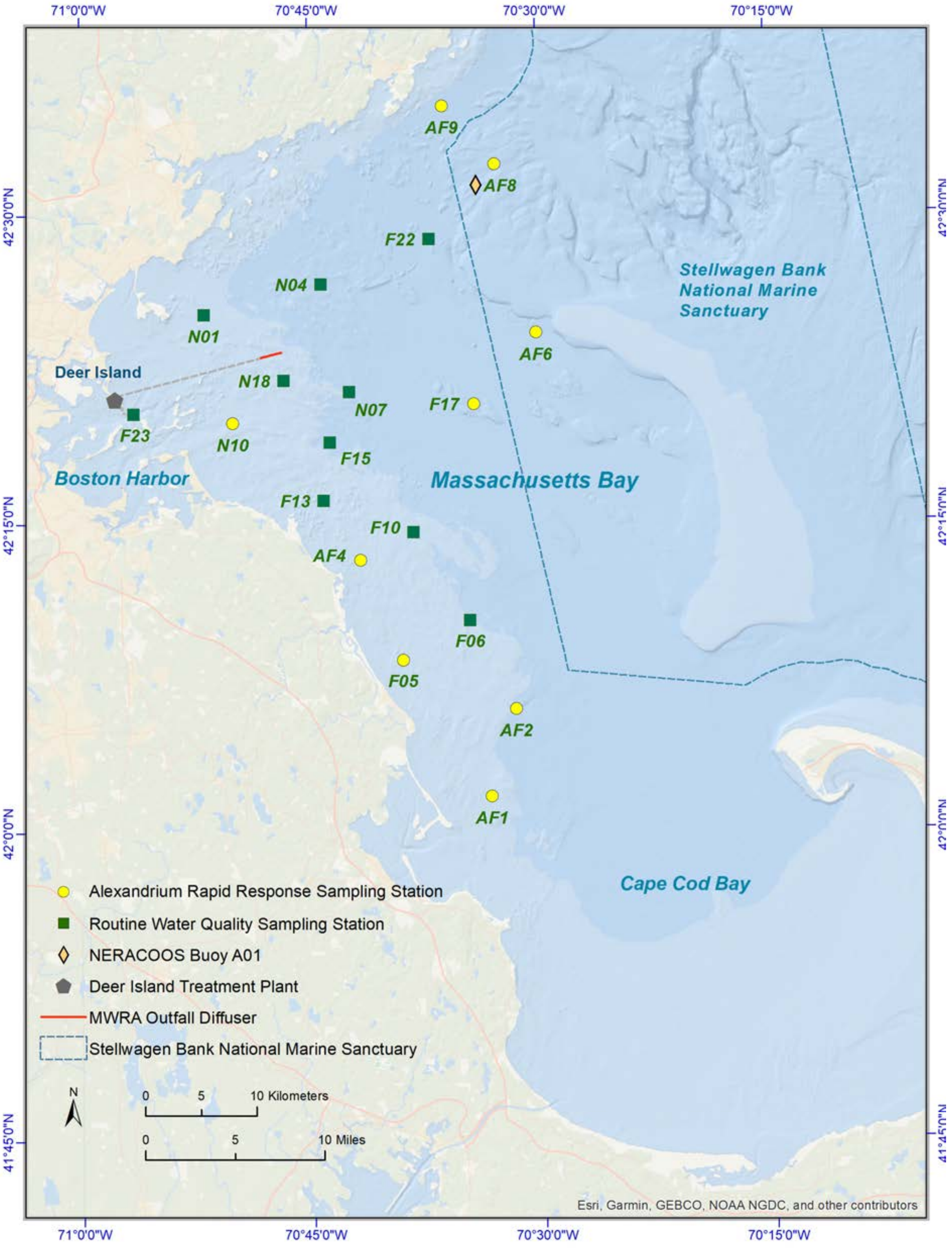

Figure 1-2. ***Alexandrium*** **Rapid Response Study monitoring locations.**

2 2019 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 meters (m) deep, where cells have access to both adequate light and nutrients; 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 28-year dataset (1992-2019). The major features and differences in 2019 are described below.

2.2 PHYSICAL CONDITIONS

Surface water temperatures were close to average from January to June 2019 at Buoy 44013, about 10 km southeast of the outfall (**Figure 2-1**). At nearfield station N18, where both surface and bottom water temperature data are available, water temperatures at both depths began the year near the historic median levels and stayed close to them into June (**Figure 2-2**). Salinity was also at median values from February through April 2019, but then declined sharply in May.

Charles River flows from January through early May 2019 were higher than in many years (**Figure 2-3**). The 2019 spring freshet of the Merrimack River was one of the strongest of the monitoring period, cresting in late April at more than 1,000 cubic meters per second ($m^3 s^{-1}$). There was a corresponding decrease in surface salinity in Massachusetts Bay observed in May at stations F22 and N18 with surface salinity reaching a historic low (**Figure 2-2**). The low salinity signal persisted through July with surface salinity values in the nearfield in the lower 25th percentile of historic value until August. Continued input of low salinity waters from the western Gulf of Maine, as indicated by Buoy A01 measurements, contributed to these extended lowered salinities (**Figure 2-4**).

A Nor'easter storm mid-May caused an increase in currents into the bay and lower salinity waters being observed down to 20 m deep at Buoy A01 (**Figure 2-4**). This event resulted in strong near-surface currents providing a conduit for transport of *Alexandrium* cells from the western Gulf of Maine into Massachusetts Bay. The low-salinity surface waters associated with the strong spring freshet made the upper water-column more "slippery" during May, explaining the relatively strong response of the near-surface currents. Several more pulses of surface current occurred through mid-June that were not clearly associated with wind events. These pulses continued to bring water from the Gulf of Maine into the bay.

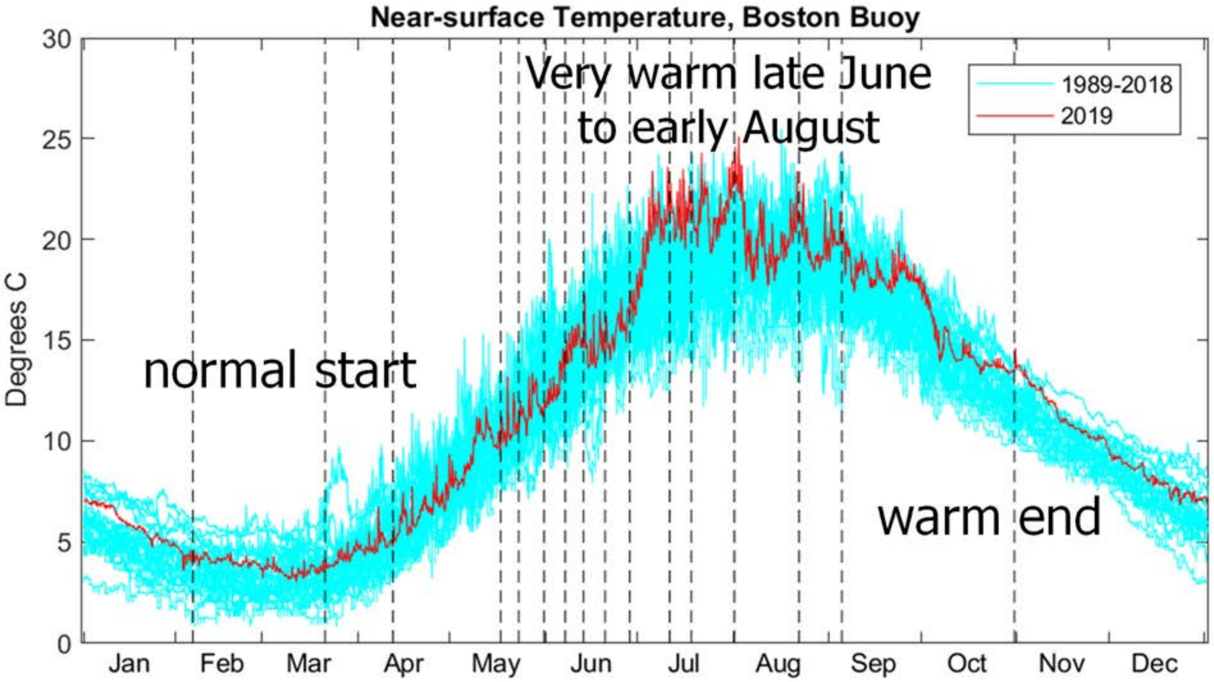

Figure 2-1. Comparison of 2019 (solid red line) surface water temperature (°C) at Buoy 44013 ("Boston Buoy") in the vicinity of the nearfield with 1989-2018 (cyan lines). The vertical dashed lines are when the 16 surveys were conducted in 2019.

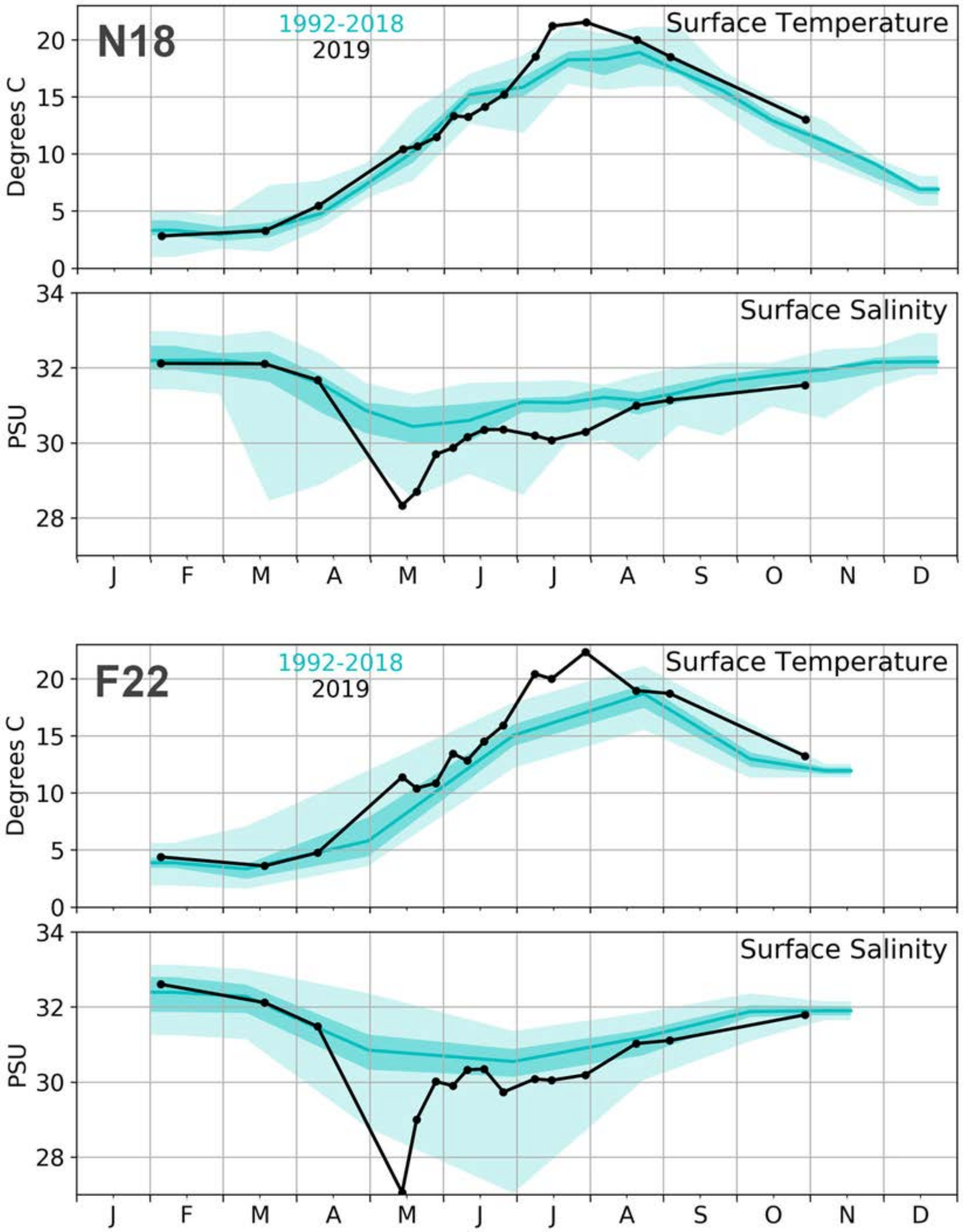

Figure 2-2. **Comparison of 2019 surface water temperature (°C) and salinity (practical salinity unit [PSU]) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years.** 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

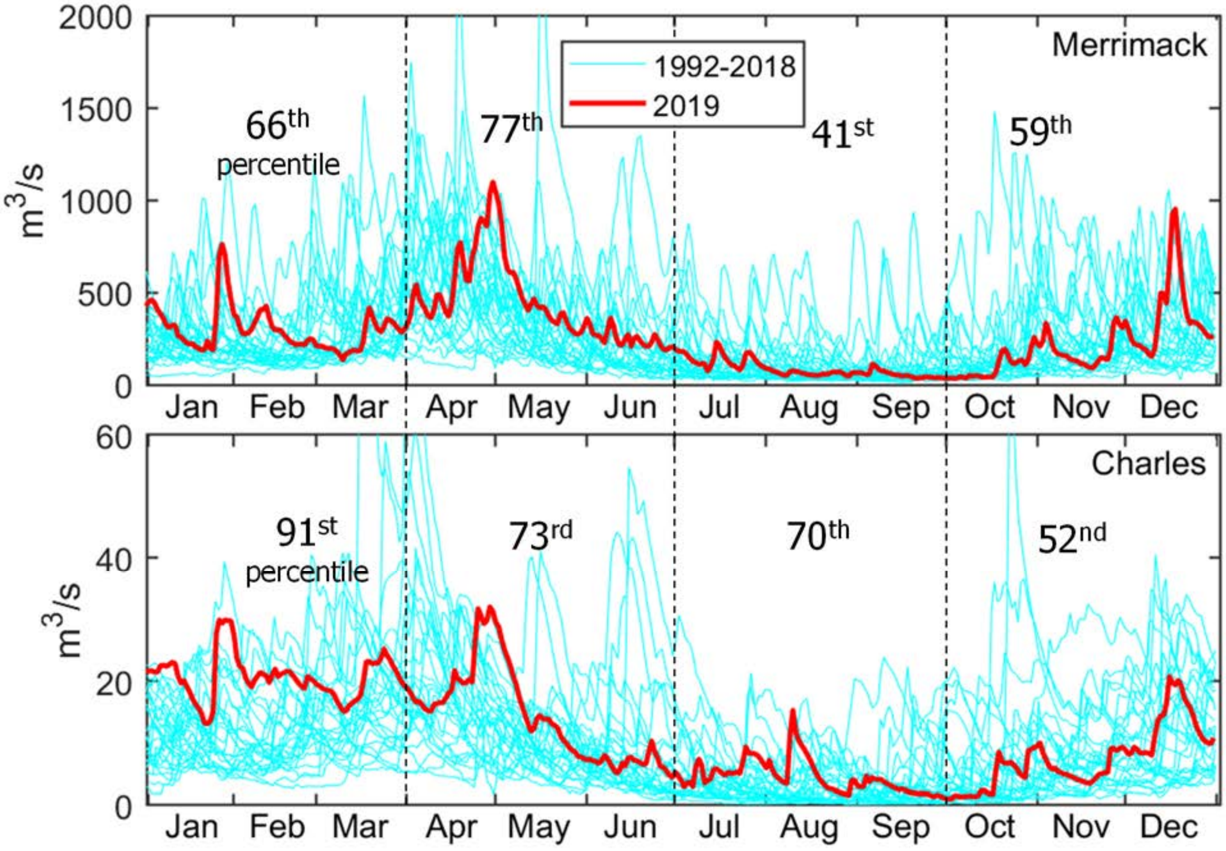

Figure 2-3. Comparison of 2019 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2018 (light blue lines). The percentiles shown represent 2019 flow, compared to the entire 28-year record, during each quarter of the year.

The spring freshet and low salinity waters entering Massachusetts Bay from April through June contributed to the onset and intensification of stratification across the bay (**Figure 2-5**). By mid-May, the water column was strongly stratified reaching maxima Δ sigma-T for the monitoring program. Stratification decreased slightly into June but remained in the upper quartile of historic values. By late June and into July, surface water temperatures increased sharply while bottom temperatures remained close to the long-term median (**Figures 2-1 and 2-2**). The high surface water temperatures resulted in increased stratification in the bay in July (**Figure 2-5**). The water column in Massachusetts Bay was more strongly stratified over most of the summer of 2019 than long-term average conditions.

The summer 2019 surface water temperatures were the highest recorded of the monitoring period, reaching 22 C° at the end of July and remaining higher than normal for the rest of the measurement period (**Figure 2-2**). The record-high near-surface temperatures cannot be explained only by air temperature because the air temperature was not abnormally high. It may be explained in part by weak upwelling during July (**Figure 2-6**), but there may also be a regional influence of generally warmer surface waters in the Gulf of Maine. The long-term trend of air and water temperature (**Figure 2-7**) shows that both have long-term warming trends, but the warming trend of the surface water temperature is more pronounced than that of the air temperature. This difference may be due to regional rather than local influences on the water temperature.

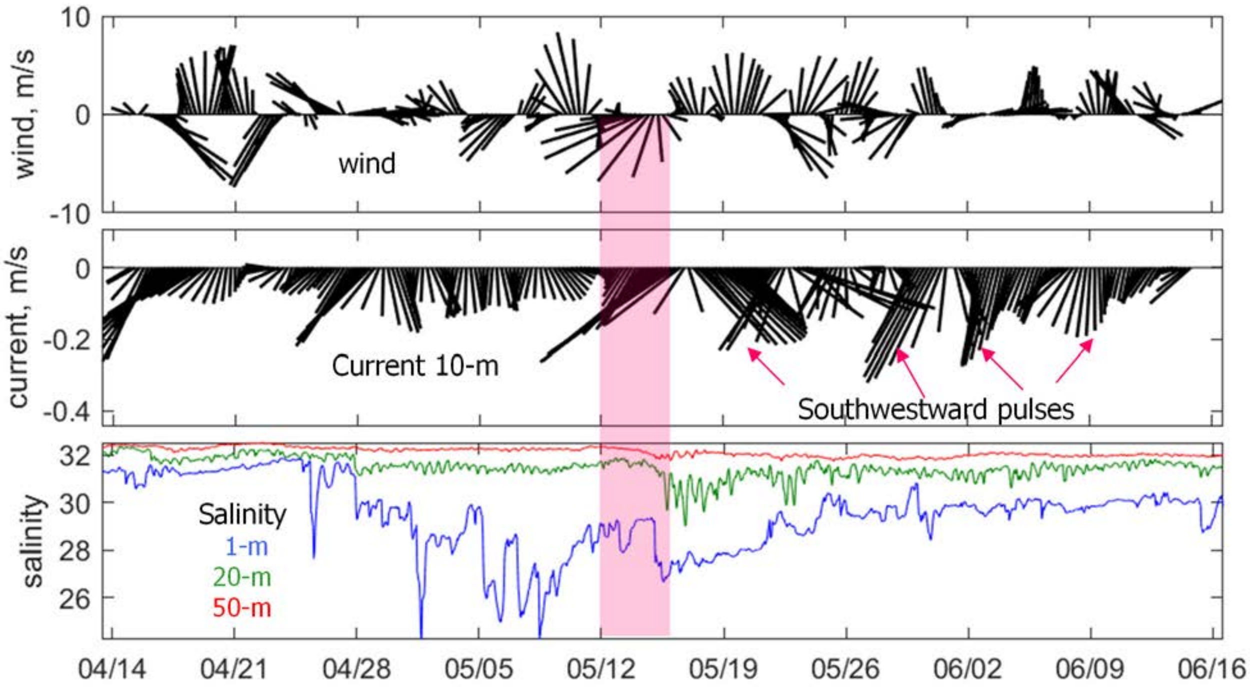

Figure 2-4. **Buoy A01 time series observations in April – June 2019.** Top: surface wind strength (m/s) and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: currents (m/s) at 10 m depth. Bottom: salinity (PSU). The vertical rectangle highlights the winds and currents during the Nor'easter in mid-May. Intermittent southeastward current pulses are also highlighted.

The water column in Massachusetts Bay remained strongly stratified into September before decreasing in October (**Figure 2-5**). The shallower inshore stations were well mixed in October, but at the deeper offshore stations seasonal stratifications persisted until after the late October survey. For example, at station F22 the pycnocline was observed at 40 m and a Δ sigma-T > 1 between surface and bottom waters in late October. Buoy A01 data indicate the water column did not become well mixed in these deeper waters until mid-November. The strongly negative upwelling index in November and December is indicative of a stormy fall (**Figure 2-6**), which contributed to the mixing of the water column and a return to well-mixed winter conditions.

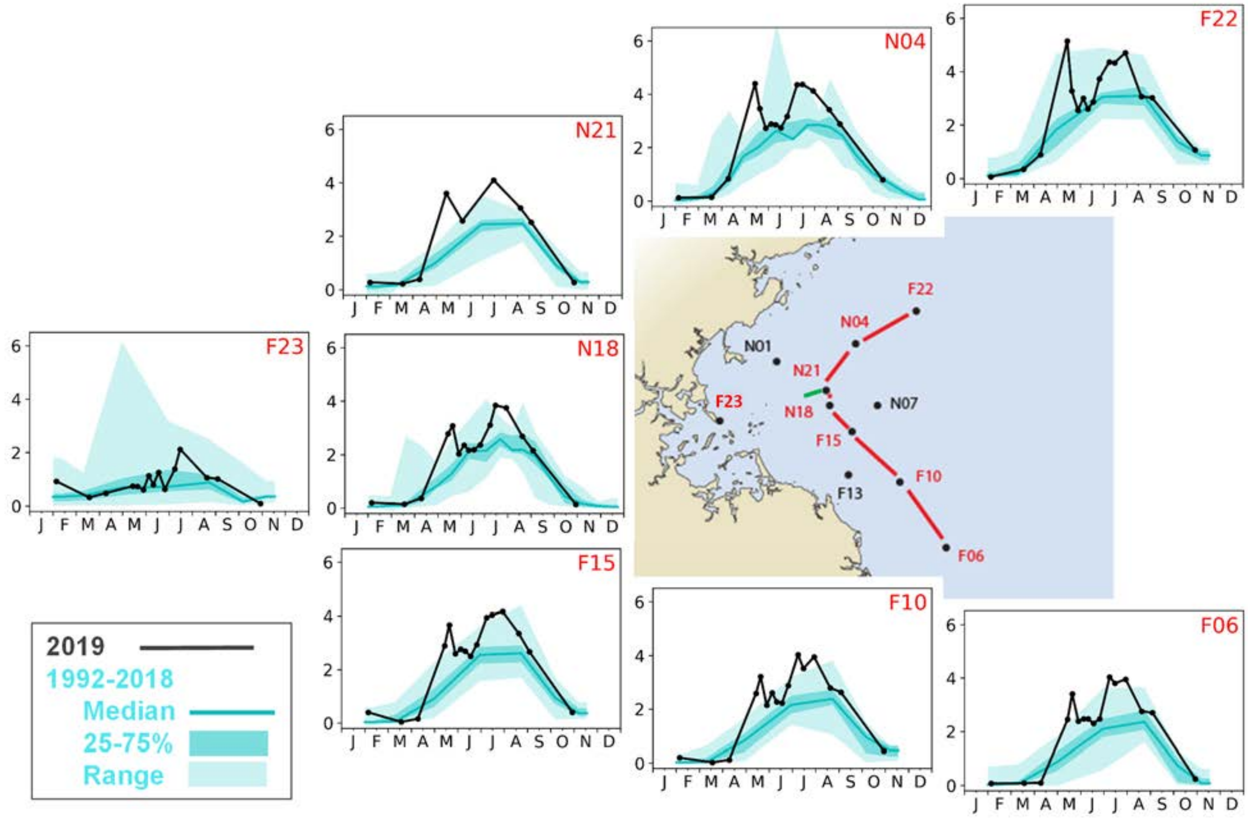

Figure 2-5. Stratification (Δ sigma-T; kg m^{-3}) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

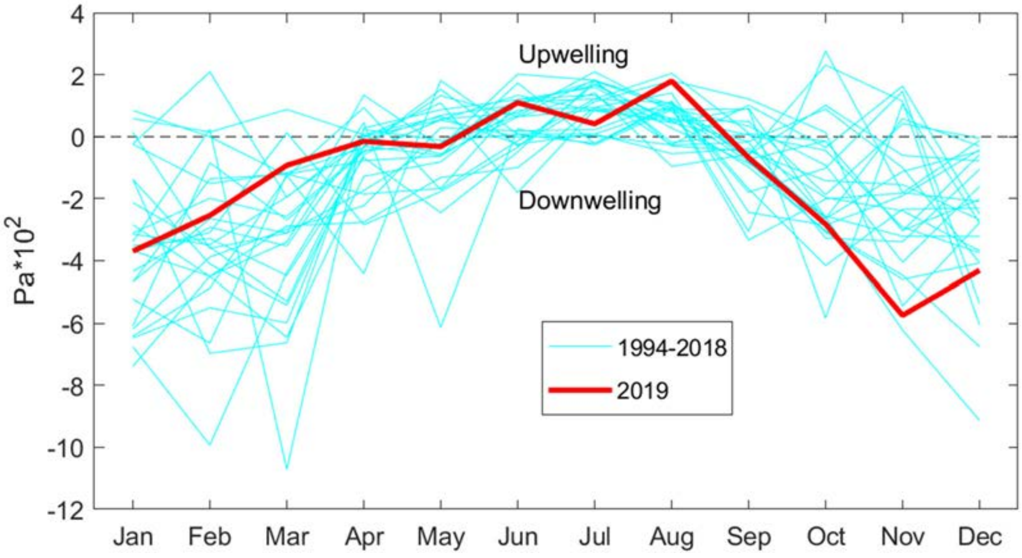

Figure 2-6. Average wind stress (Pascals) at Buoy 44013. 2019 results are in red. Results from 1994–2018 are in cyan. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

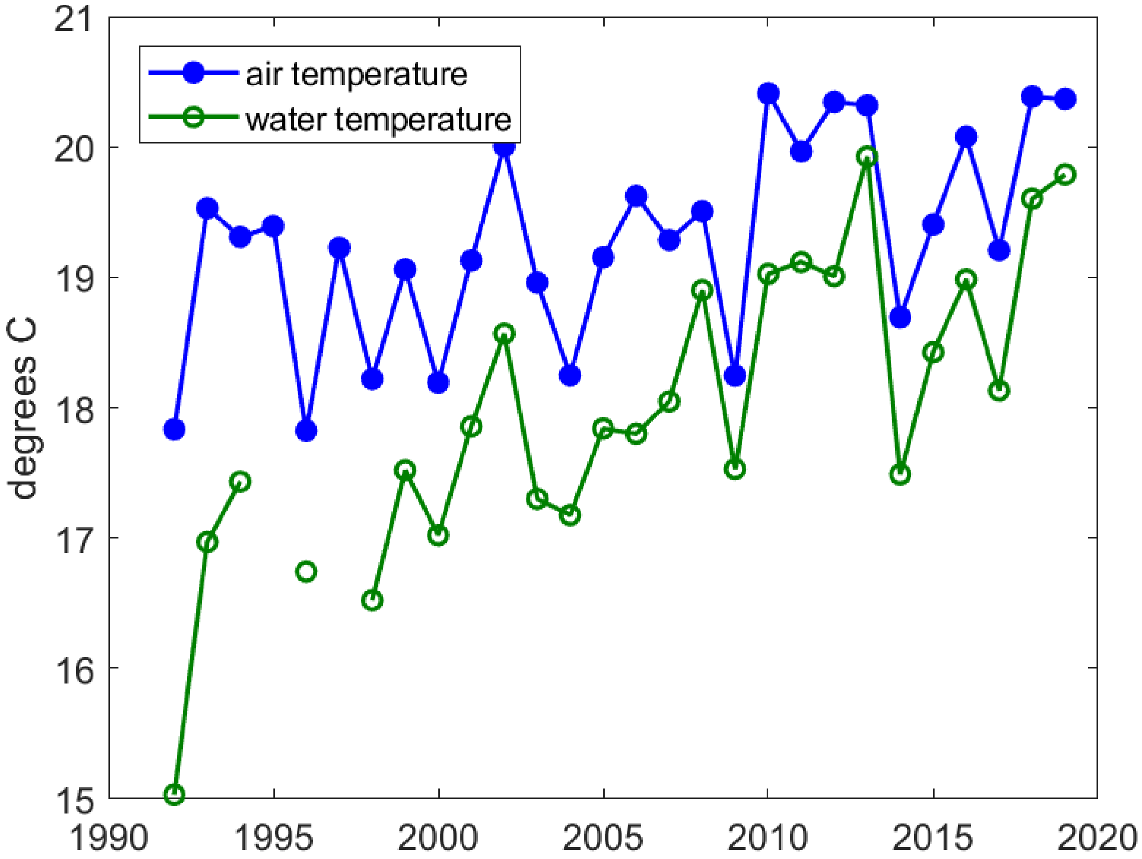

Figure 2-7. **Comparison of average mid-June to mid-August air and surface water temperature (°C) at Buoy 44013 in the vicinity of the nearfield from 1992-2019.**

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

This section documents nutrient (N, P and Si) concentrations and phytoplankton biomass in the bay during 2019. It also quantifies the spatial extent of the outfall's nutrient and chlorophyll biomass signals in the bay. Additional information related to the outfall signal is provided in Section 3.1

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 the Gulf of Maine as well as phytoplankton uptake. Concentrations are elevated from February into April, relatively low from May into August or September, and then increase into November-December. Observations for NO_3, SiO_4 and PO_4 from station N18, located 1 km south of the outfall, are representative of the nearfield and Massachusetts Bay and exhibited this seasonal pattern, though during the summer months in 2019, concentrations were higher than typically observed (**Figure 2-8**; see dark shaded areas denoting the 25th to 75th percentile). Ammonium (NH_4) concentrations (**Figure 2-8**, upper right), which typically do not exhibit this seasonal pattern, were, during many of the summer months, also higher than in previous years.

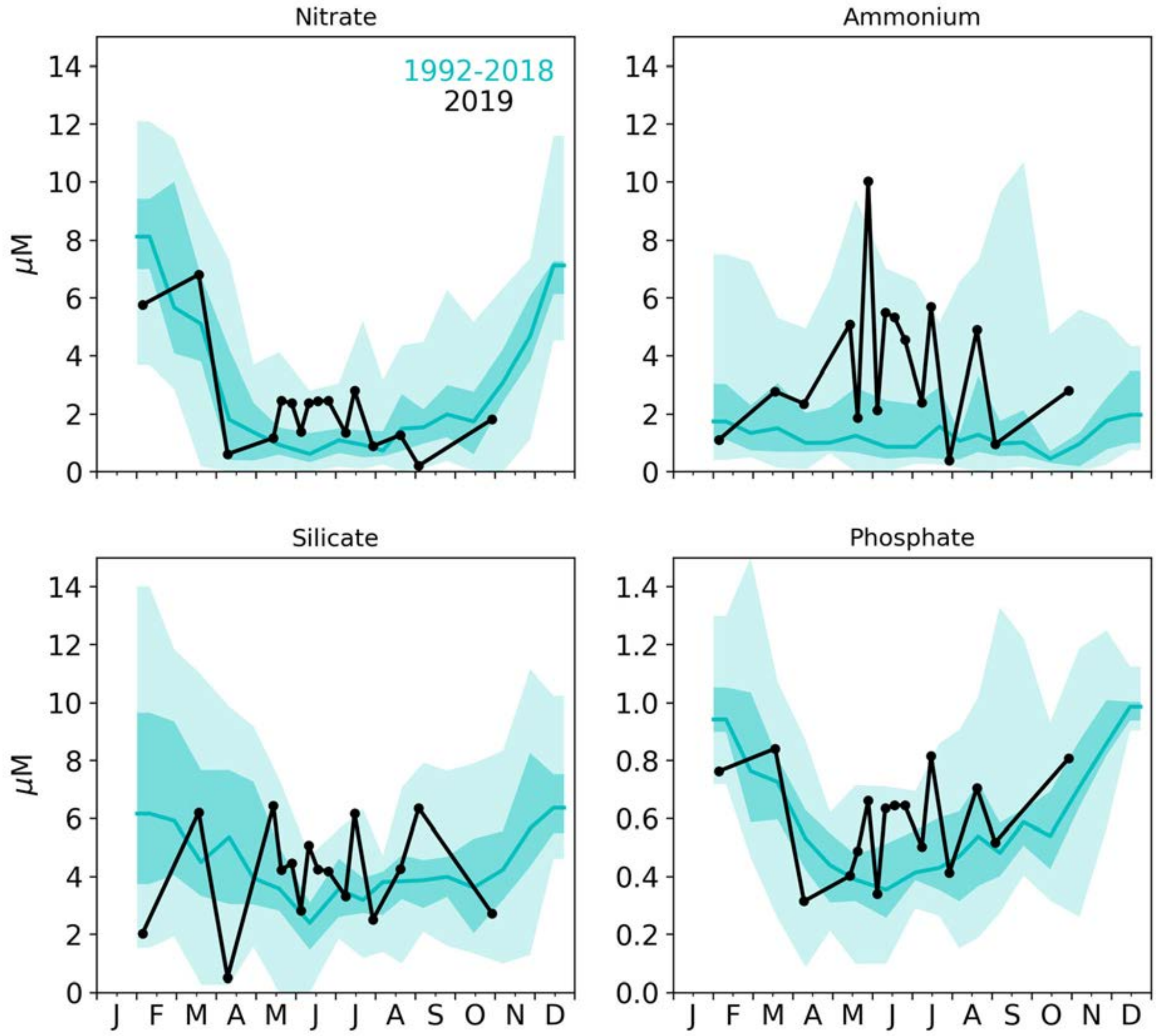

Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2019 compared to prior years. Note difference in scale for phosphate. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

In 2019, NO_3 concentrations were low to moderate with levels in February below the long-term median, and in March above the median (**Figure 2-8** and **Figure 2-9**). From March to April, NO_3 concentrations decreased sharply and were depleted in the shallower stations in Boston Harbor, nearfield and along the South Shore. SiO_4 concentrations were also lower suggesting that diatoms, which require SiO_4 for growth, likely bloomed in early April. During April 2019, the NO_3, SiO_4, and PO_4 concentrations were in the lower 25th percentile of historic values at the inshore Massachusetts Bay locations, while close to the median further offshore (**Figure 2-9**).

By May, nutrient levels had increased across all stations (**Figure 2-8** and **Figure 2-9**), coincident with fresher waters being transported into the bay from the Gulf of Maine (see **Figure 2-2** and **Figure 2-4**). By late May to August, nutrients were low to depleted in the surface waters, but were available below the pycnocline in higher concentrations than typically observed during summer stratified conditions. The high concentrations at depth resulted in elevated station average concentrations within or above the upper quartile observed historically (**Figure 2-8** and **Figure 2-9**). This was the case for all four dissolved inorganic nutrients (NH_4, NO_3, SiO_4 and PO_4), and was likely the result of the strong stratification isolating nutrients at depth.

Summer nutrient concentration minima were observed in late July, but by August, levels had increased again. Upwelling conducive winds (see **Figure 2-6**) likely brought deeper offshore bottom water nutrients into shallower inshore waters, causing nutrient concentrations below the pycnocline to increase. From August to September, all nutrients except SiO_4 decreased with NO_3 being depleted at shallow stations (**Figure 2-9**). This change coincided with a major bloom of dinoflagellates dominated by *Karenia mikimotoi*. By October, NO_3 levels had increased, but remained in the lower quartile of historic values and there was a sharp decrease in SiO_4 concentrations, caused by a centric diatom *Skeletonema* increase that occurred at the same time.

Episodic peaks in NH_4 attributable to MWRA effluent were observed in the nearfield (stations N18 and N21) and to the south at station F15, (**Figure 2-10**). At N18 and N21, May to September NH_4 concentrations were mostly above the long-term median, and often within or above the upper quartile of historic bay outfall values. Effluent NH_4 loading in 2019 was comparable to previous years.

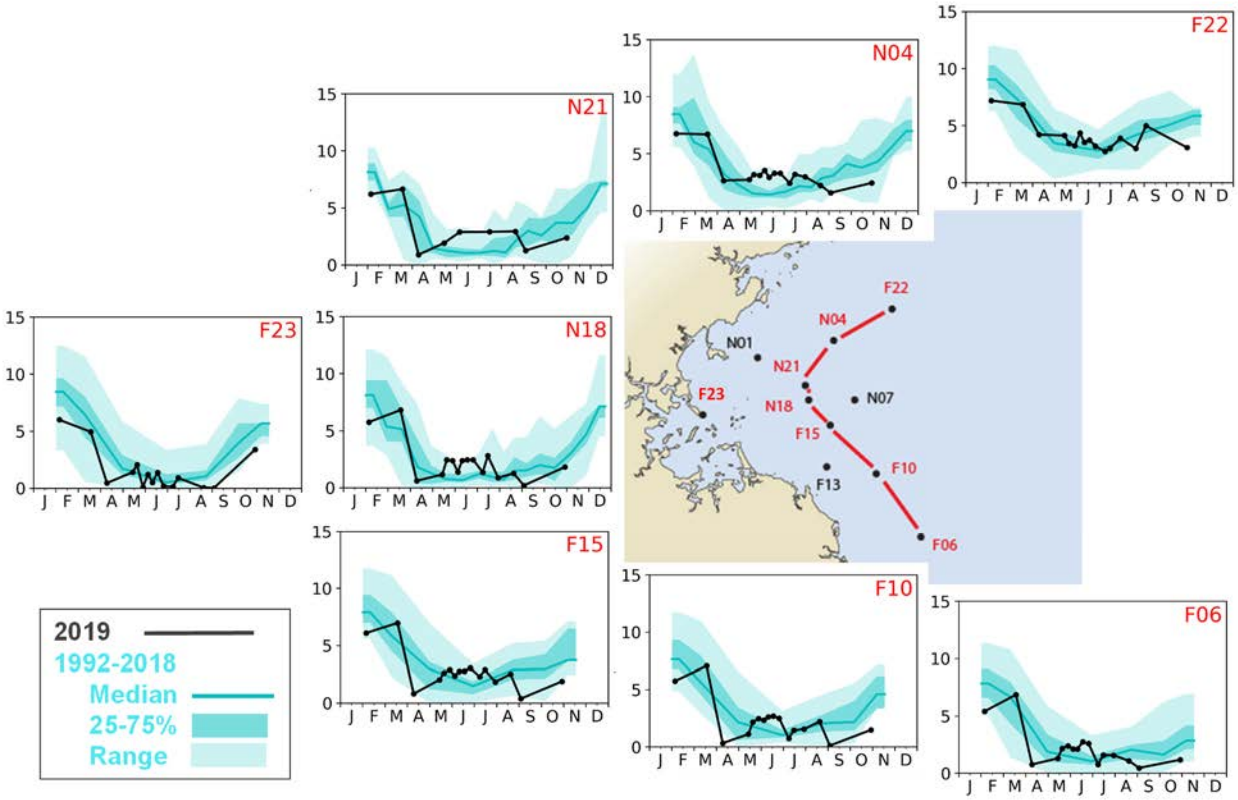

Figure 2-9. Depth-averaged NO_3 (µM) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

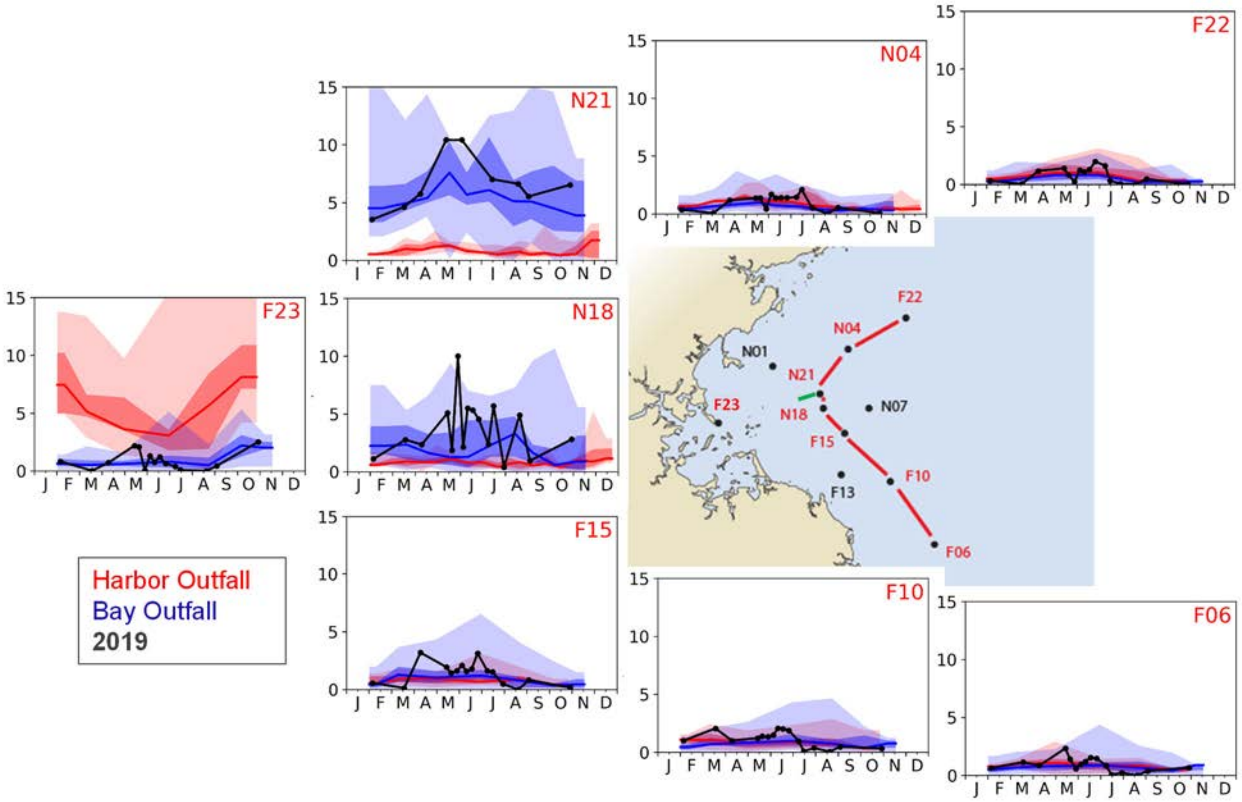

Figure 2-10. Depth-averaged NH_4 (µM) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2018) results are in blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

In 2019, as in other years since bay outfall startup, NH_4 concentrations at N21 and N18, and especially during summers at F15, were higher than during years effluent was discharged to the harbor rather than bay (**Figure 2-10**). Summer 2019 NH_4 concentrations at these three locations, because of the more intense stratification during summer 2019, were greater than during other bay discharge years. NH_4 concentrations at Boston Harbor station F23 in 2019, again as in other post-discharge years, were much lower than during the pre-2000 years the wastewater was discharged directly to the harbor.

As can be seen in **Figure 2-10, and Figure 2-11** and **Figure 2-12,** in 2019, as in other years since the bay outfall became operational, the NH_4 signal from the effluent discharge plume was observed within 10 to 20 km of the outfall . In March, when the water column was vertically well mixed, the NH_4 plume signature was most pronounced in the nearfield surface waters, but levels >2 µM were also observed about 20 km south at station F10 (**Figure 2-11**). During the July 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 (>8 µM) were also seen to the northeast of the outfall at station N04 and slightly lower levels (2-4 µM) were observed 10 km south of the outfall at station F15 (**Figure 2-12**). During the stratified July survey, NO_3 concentrations (2 to 6 µM) were elevated below the pycnocline with higher concentrations (6-8 µM) in the deeper bottom waters at the west-east transect, and a very sharp, sub-surface chlorophyll maxima was observed near the pycnocline with values reaching >6 µg L^{-1} at station N04 (**Figure 2-13**).

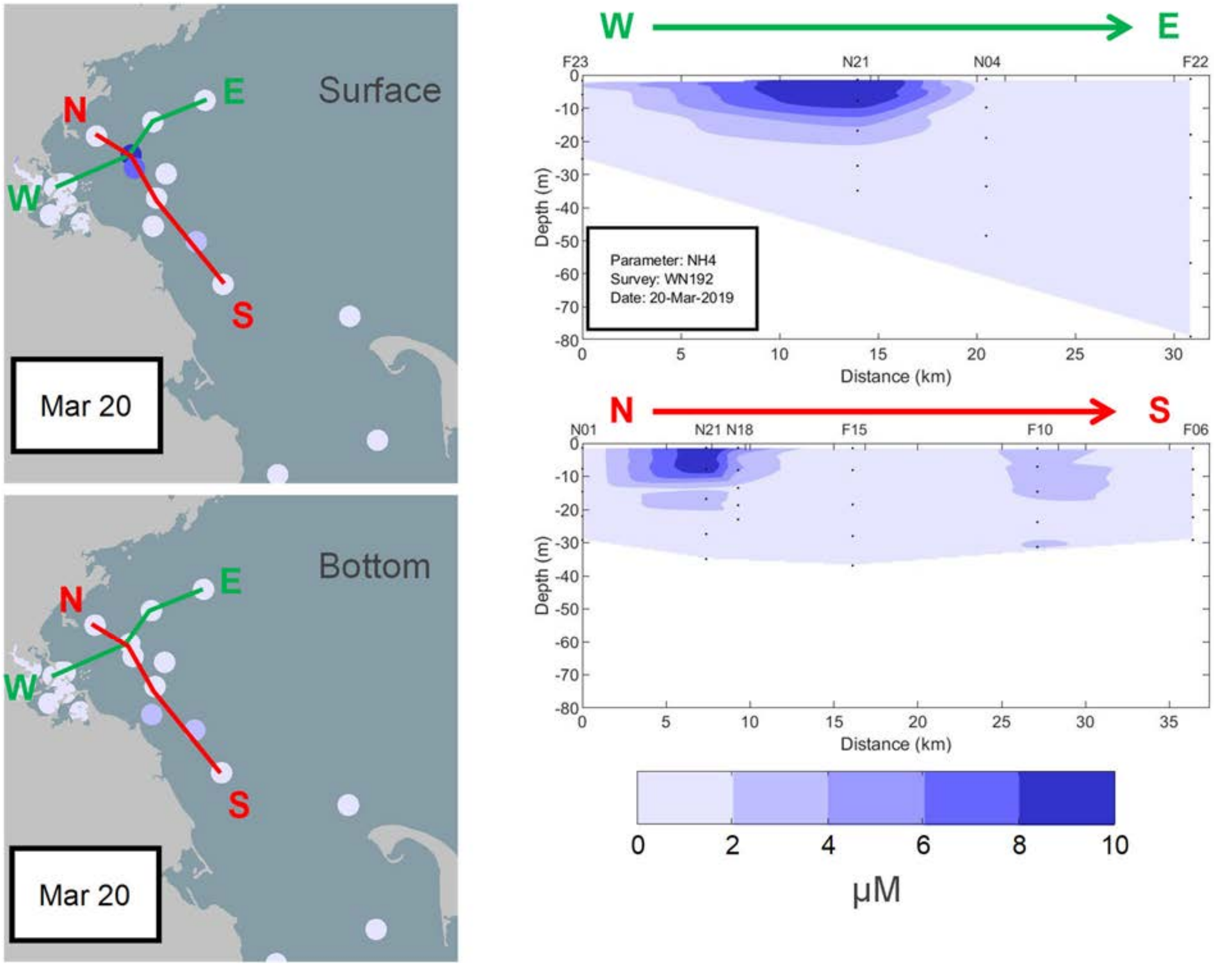

Figure 2-11. (Left) Surface- and bottom-water NH$_4$ on March 20, 2019 during unstratified conditions. (Right) Cross-sections of water column concentrations along transects connecting selected stations. Small black dots in the plots at right indicate the sampling depths for nutrients.

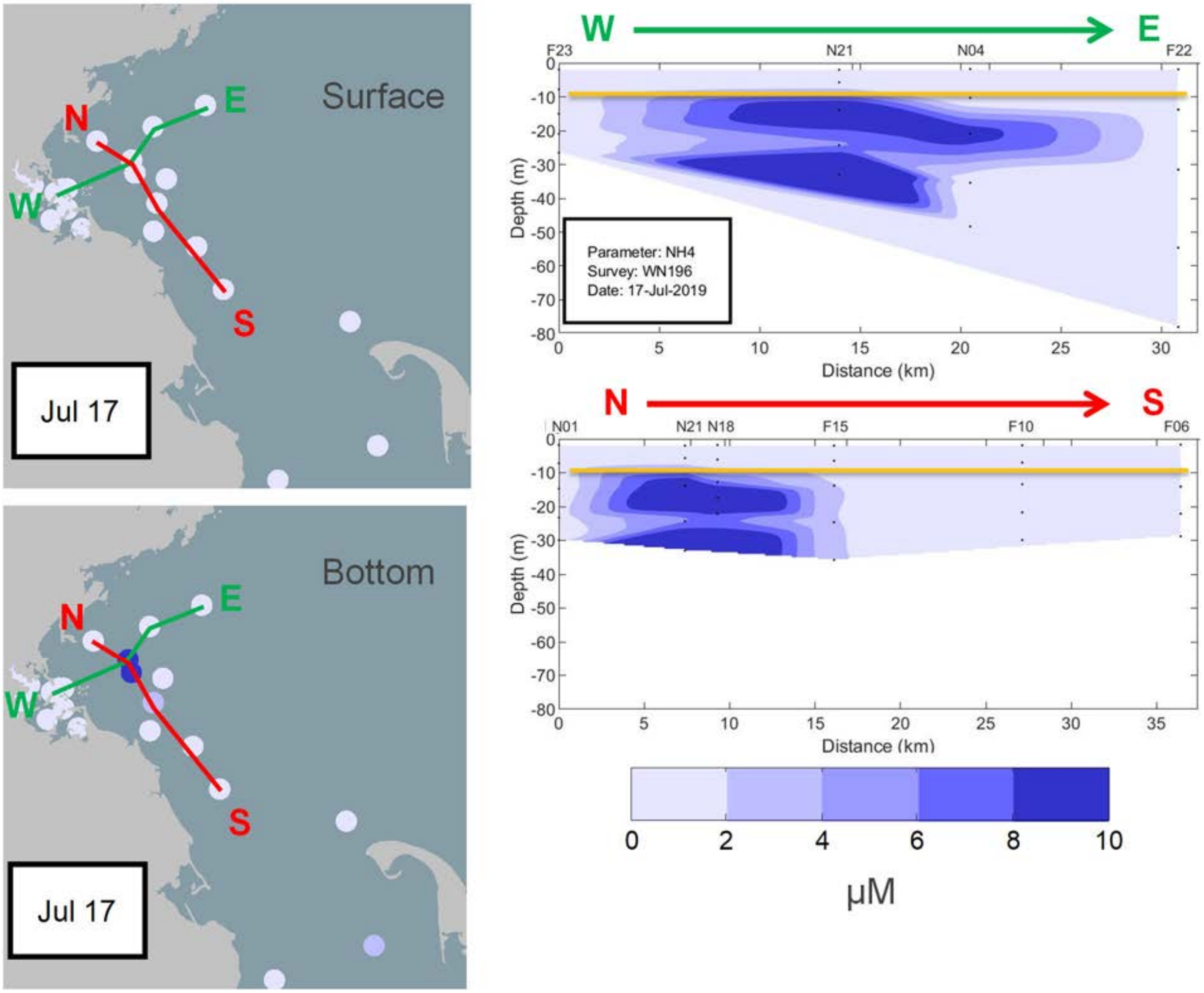

Figure 2-12. Surface- and bottom-water NH_4 on July 17, 2019 during stratified conditions. Presented as Figure 2-11, with orange line in frames at right indicating the approximate depth of the pycnocline.

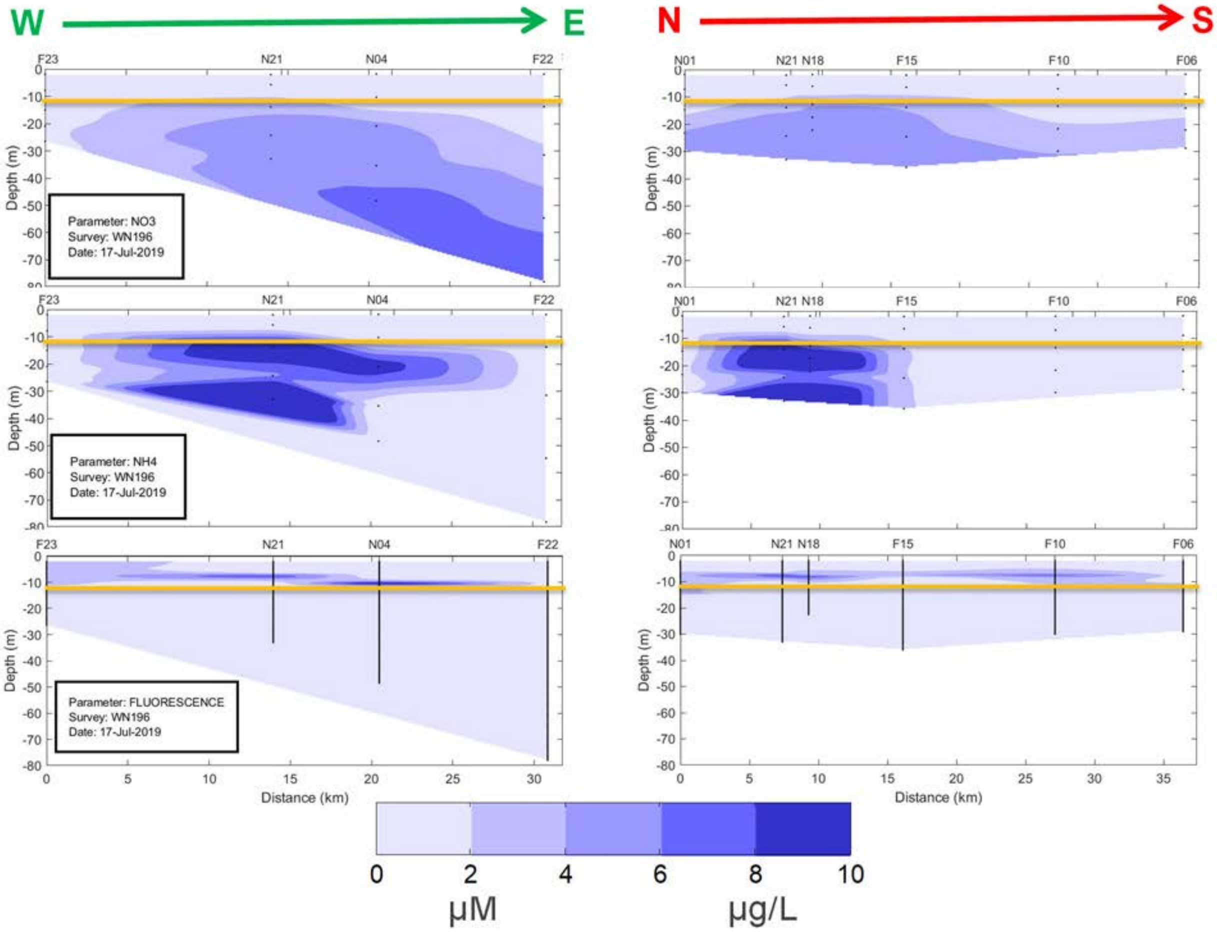

Figure 2-13. Nitrate (top; µM), ammonium (middle; µM), and chlorophyll from fluorescence (bottom; µg L^{-1}) concentrations during the stratified July 2019 survey along the east-west (left column) and north-south (right column) transects shown in Figure 2-12. Dots (nutrients) and lines (fluorescence) 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**. These seasonal peaks were observed during the 2019 surveys, though the timing of the peaks varied across the region, plus at most stations, large summer peaks were also observed. The highest areal chlorophyll levels for the year were observed during the February, April, and late May surveys in Massachusetts Bay, February to April in Cape Cod Bay, and in late May and August in Boston Harbor. Chlorophyll was also elevated across much of the monitoring area during a large dinoflagellate bloom in September (**Figure 2-15**).

Unlike the past few years, MODIS satellite imagery showed relatively low chlorophyll levels through January 2019 before increasing in early February (**Figure 2-16**). Although phytoplankton abundances were low in winter/spring 2019, February chlorophyll in northern Massachusetts Bay was elevated and in the upper quartile compared to historic data (**Figure 2-14**). By March, chlorophyll had decreased dramatically throughout Massachusetts Bay, but were elevated in Cape Cod Bay. In late March, surface chlorophyll fluorescence at Buoy A01 showed a large increase (**Figure 2-17**), and then during the April survey, increased chlorophyll was seen at most stations (**Figure 2-15**). Total phytoplankton abundances were relatively low in April, but large decreases in NO_3 and SiO_4 from March to April, and *Thalassiosira* and *Detonula* diatom species were dominant during the April survey, together suggest there was a diatom bloom prior to the April survey.

Chlorophyll concentrations decreased by mid-May. Observation of elevated *Alexandrium* abundances initiated a series of seven additional ARRS surveys during the summer providing nearly weekly observations until late July (**Figure 2-14**). During this period chlorophyll was highly variable and reached annual maxima in Boston Harbor and at many Massachusetts Bay stations in late May at or above historic maxima. The late May increase in chlorophyll was seen throughout the bay (**Figure 2-15**). Normally only *Alexandrium* cells are counted during ARRS surveys, however, preserved samples from the May 30 survey were available and examined. The samples from stations across the bay (AF8, N18, F23 and F06; see **Figure 1-2**) were dominated by a mixed diatom assemblage of *Guinardia delicatula*, *Thalassiosira* and *Chaetoceros*. Chlorophyll levels decreased by June and remained close to the historical median through July.

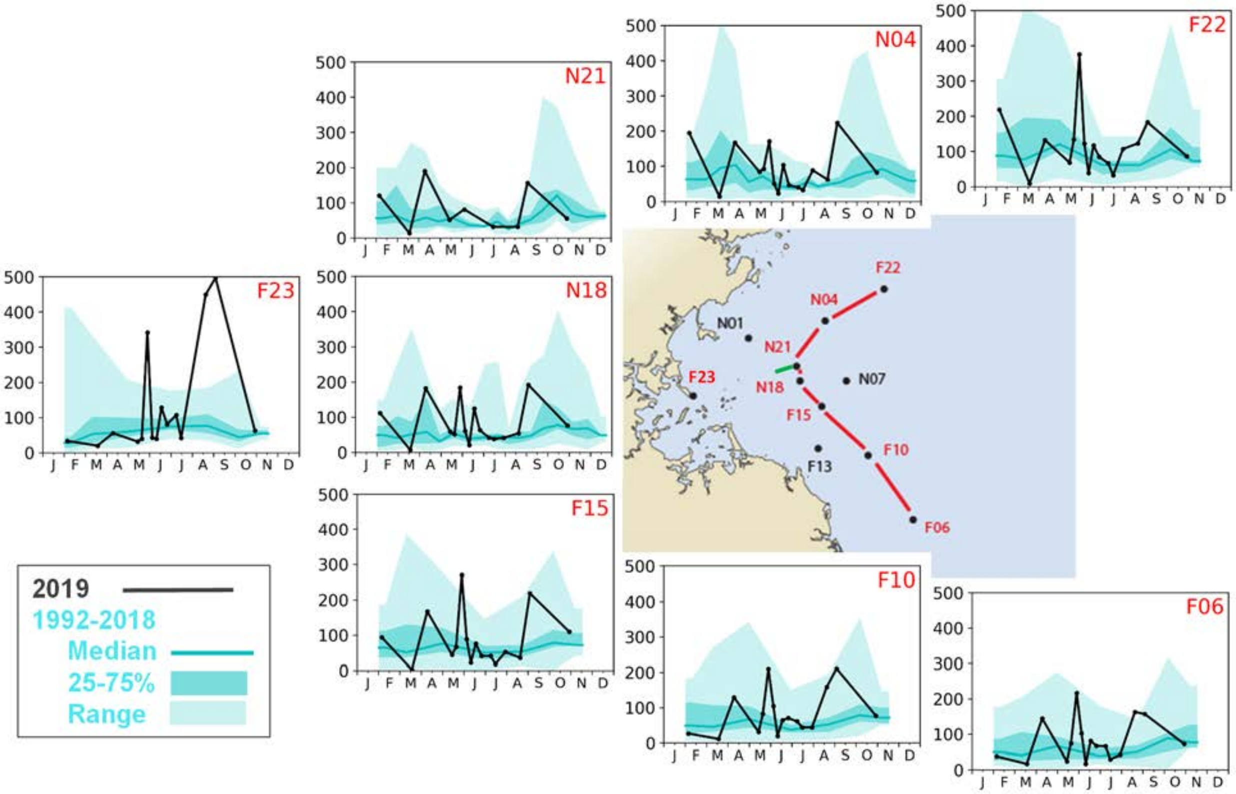

Figure 2-14. Areal chlorophyll from fluorescence (milligram per meter squared [mg m^{-2}]) at representative stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

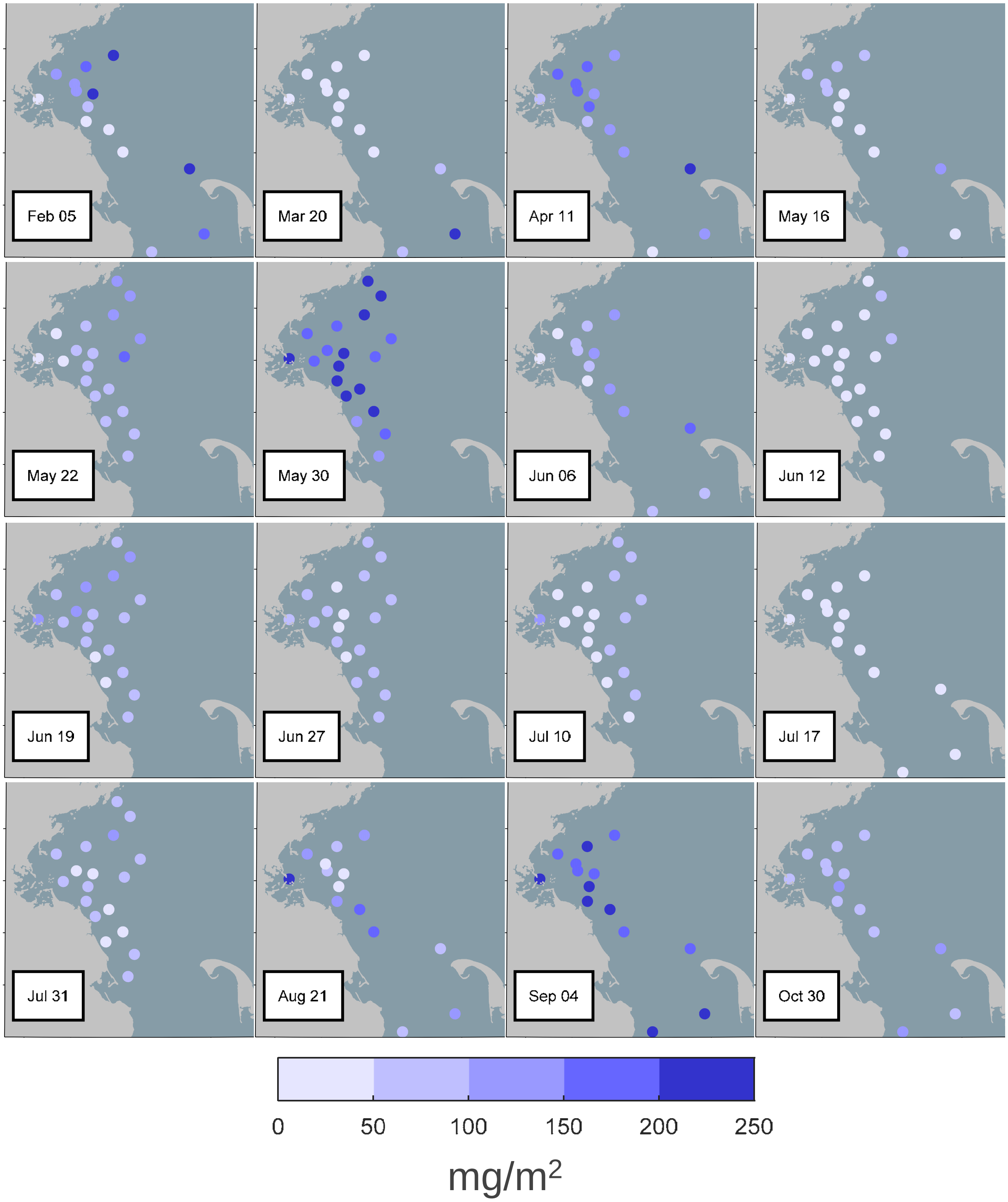

Figure 2-15. Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2019.

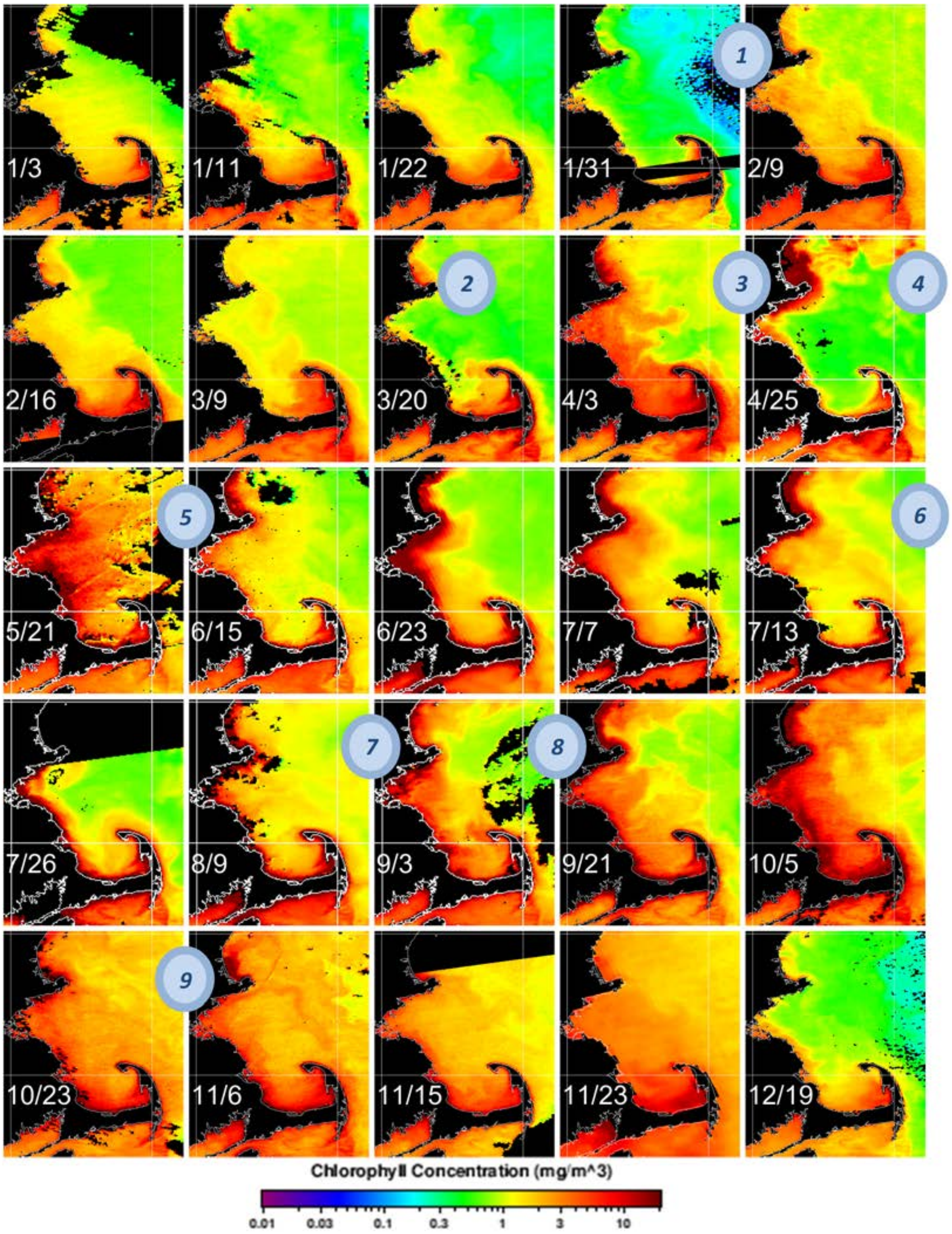

Figure 2-16. Satellite (MODIS) imagery-based estimates of surface chlorophyll concentrations (mg m^{-3}) in 2019. Black areas over water indicate missing data due to clouds.

Highlights and specific blooms:

1st row – low to moderate chlorophyll levels in January increasing in February;
2nd row – decreasing in March with an apparent bloom in early April prior to survey WN193 dominated by *Detonula* and *Thalassiosira* in April;
3rd row – variable chlorophyll from May thru July, with high levels in late May;
4th row – high late summer chlorophyll – nearshore in August and throughout the bays in September (dinoflagellate bloom – 10-40% *Karenia mikimotoi*); and
5th row – elevated chlorophyll levels in October and November before decreasing in December.

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 2 which was the same day as the 3/20 image).

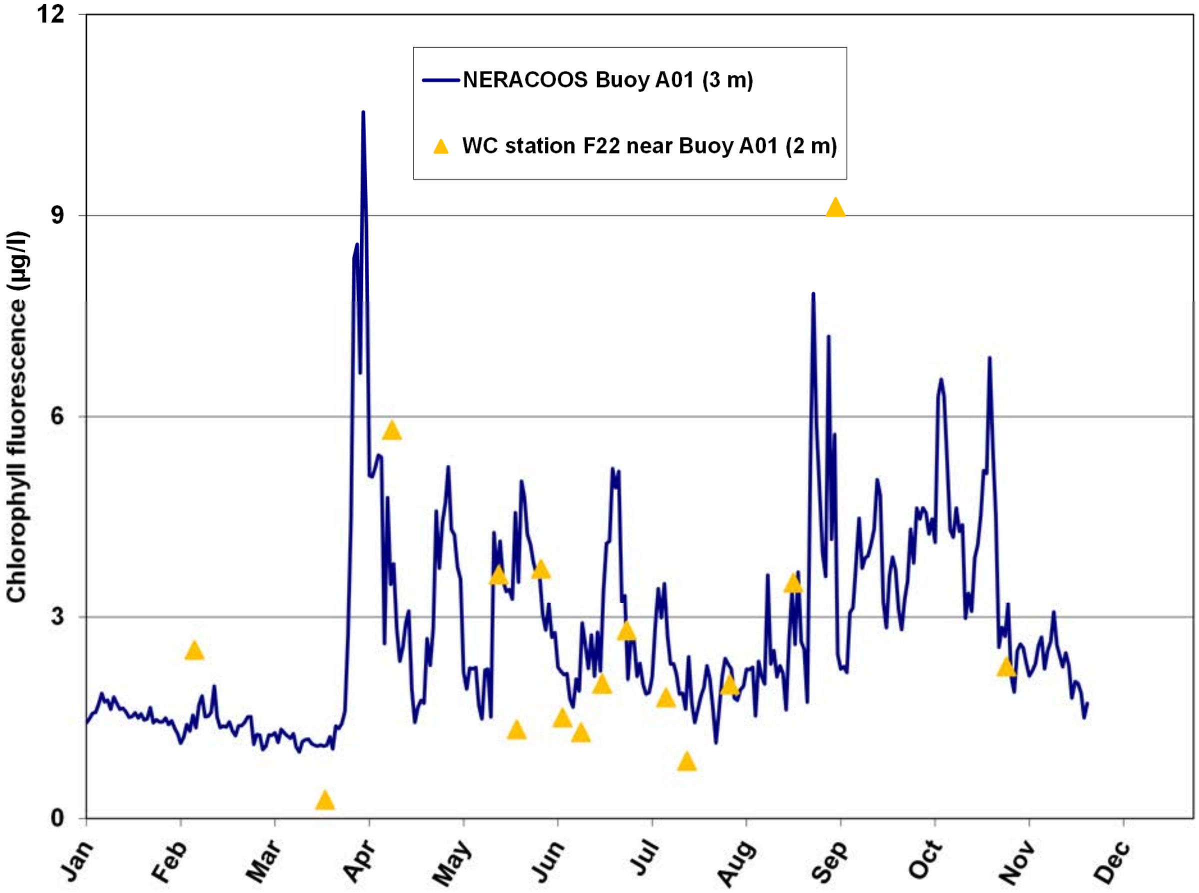

Figure 2-17. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (blue line) and water samples at nearby water column (WC) station F22 (yellow symbols). The buoy values are daily medians.

A late summer dinoflagellate bloom dominated by *K. mikimotoi* led to very high chlorophyll at the Boston Harbor station in both August and September that were more than double the maxima observed previously (**Figure 2-14**). In August high chlorophyll levels caused by *K. mikimotoi* were also observed in southern Massachusetts Bay. By September, the bloom extended over most Massachusetts Bay, with chlorophyll levels comparable to historic maxima. Both MODIS imagery and Buoy A01 data indicate chlorophyll was elevated throughout Massachusetts and Cape Cod Bays in surface waters from late August until late October (**Figure 2-16** and **Figure 2-17**). Survey observations in October were close to the long-term median and had also decreased at Buoy A01. MODIS imagery showed elevated chlorophyll through November and low levels by mid-December 2019.

Even though relatively high chlorophyll levels were observed in the nearfield during the February, April, late May and September surveys, the seasonal and annual average values in 2019 were moderate. They were higher than baseline seasonal averages, but well below the Contingency Plan threshold levels (see **Table i**).

2.4 BOTTOM WATER DISSOLVED OXYGEN

Typically, bottom water DO declines at a relatively constant rate in Massachusetts and Cape Cod Bays from winter/spring maxima to September or October annual minima, but in recent years mixing events have been observed that punctuated this seasonal decline. This was the case in 2019 when a downwelling favorable wind event in late July caused mixing, re-ventilated the bottom waters, and increased DO by about 0.5-1 mg L^{-1} over most of the bay (**Figure 2-18**). Bottom water DO concentrations began the year at close to median levels before decreasing to lower levels often in the lower historic quartile from May to July. In late July, after the mixing event, bottom water DO levels increased to more typical levels and stayed close to long-term averages for the rest of the year in Massachusetts Bay. The influence of late fall mixing events is evident in Buoy A01 DO data from 51 m with a return of DO to winter levels in mid-November (**Figure 2-19**).

Cape Cod Bay had a summer DO increase in July, similar to Massachusetts Bay, but then decreased to low levels of 4 to 5 mg L^{-1} by late August and early September (**Figure 2-20**). Bottom DO during the August and September surveys at F02 was the lowest seen since monitoring started. Further inshore, in late September and early October, others reported hypoxic to anoxic conditions, which led to fish and lobster mortality in bottom traps. Around October 4th, sensors deployed by the Massachusetts Division of Marine Fisheries (MA DMF) showed DO dropping to zero at their southernmost sensor, and hypoxic conditions at their other sensors (**Figure 2-21**). Strong northerly winds on October 5 mixed down to the bottom at the shallower stations, increasing bottom water DO levels and ending the anoxic event. By the time MWRA's CCB stations (F01 and F02) were sampled in late October, bottom water DO in Cape Cod Bay had increased to 7-8 mg L^{-1} (**Figure 2-20**).

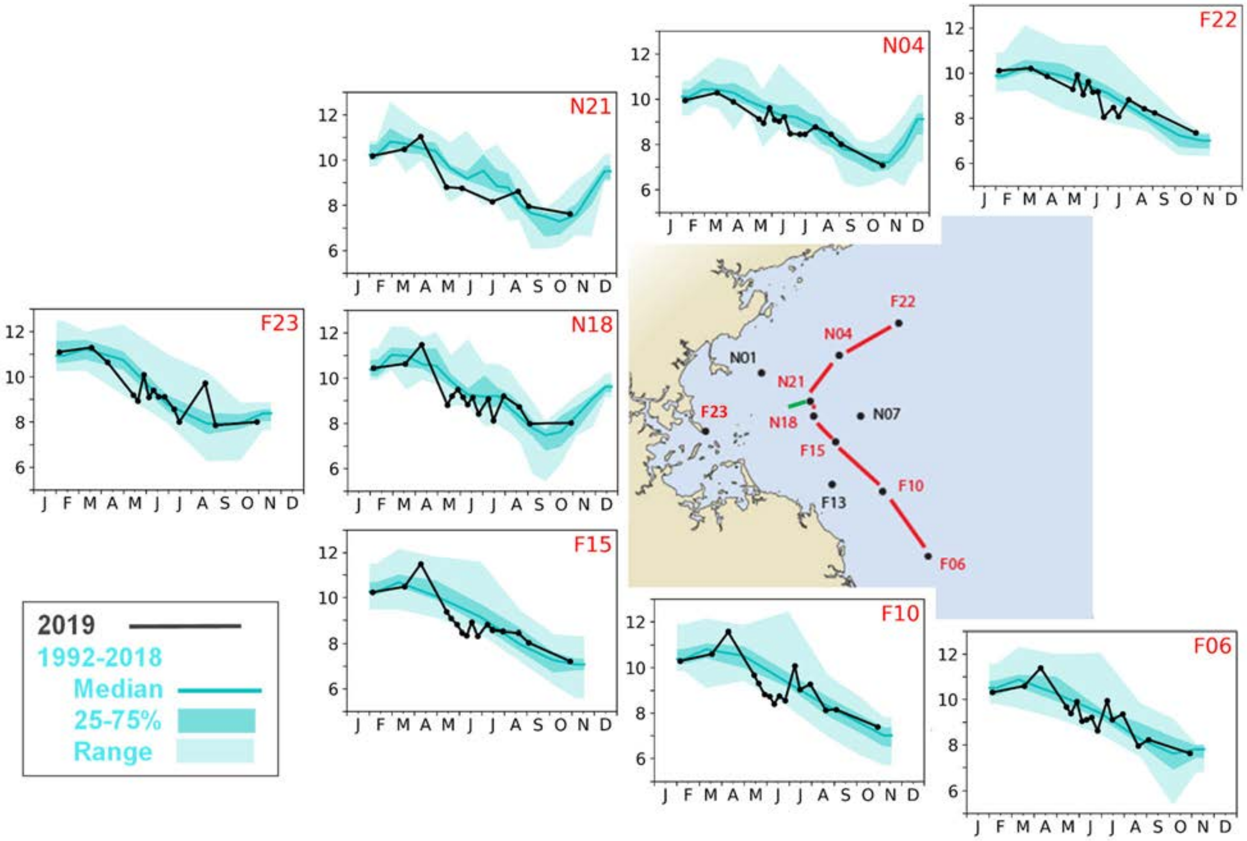

Figure 2-18. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

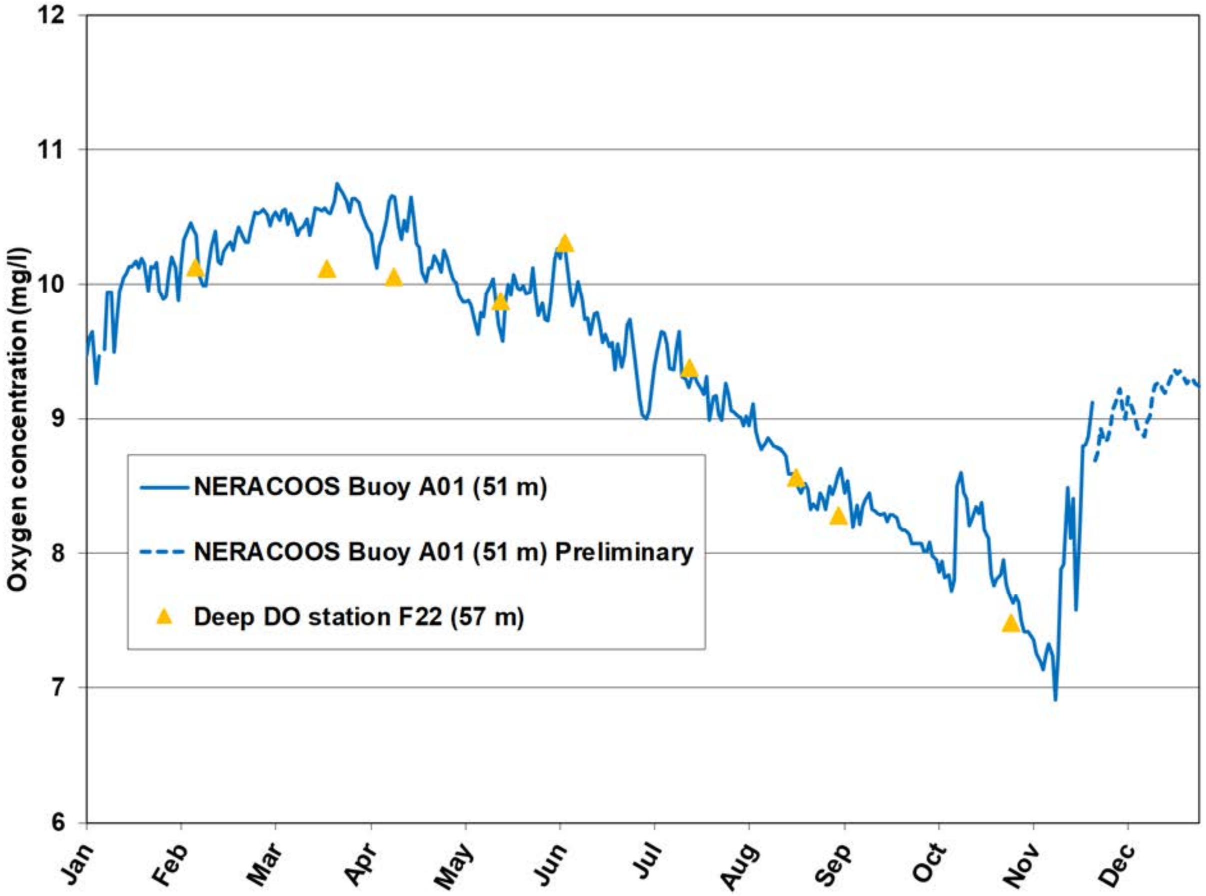

Figure 2-19. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (51 m) and at the deep sampling depth (~57 m) at station F22 in 2019. The buoy values are daily means.

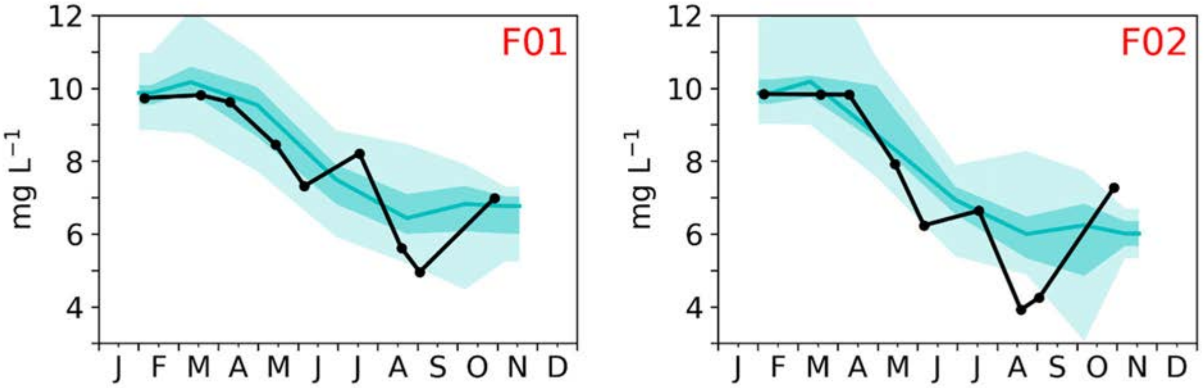

Figure 2-20. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

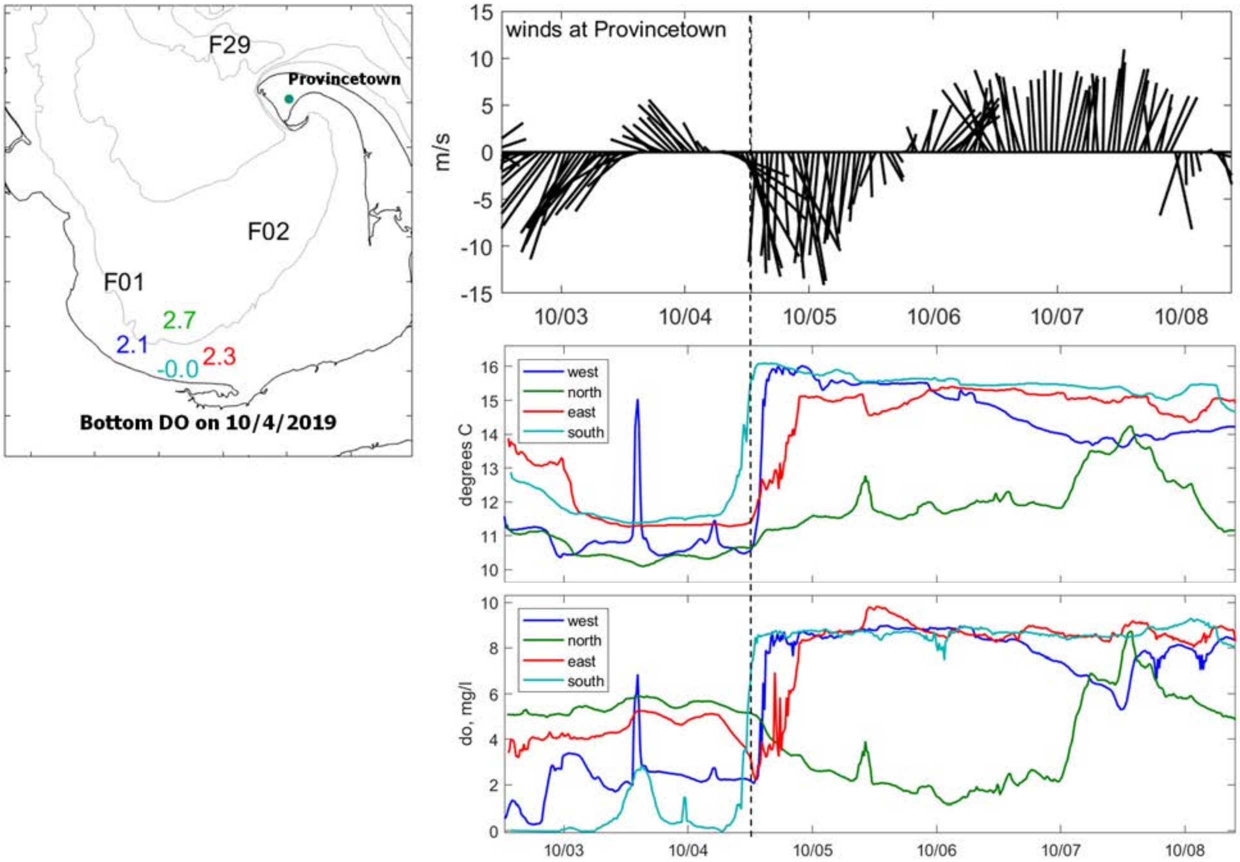

Figure 2-21. Data characterizing the hypoxic/anoxic DO event in Cape Cod Bay in October 2019. Top left – map showing MWRA stations F01, F02, and F29 in relation to the four bottom water monitoring locations MA DMF established to assess the low DO event. Top right - surface wind strength and direction in Provincetown (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: bottom temperature. Bottom: DO concentration. The vertical line highlights the deep mixing of the water column October 4th. Data courtesy of Tracy Pugh, MA DMF.

A combination of factors were responsible for the low DO in Cape Cod Bay in 2019. The relatively shallow CCB stations typically become well mixed by September, but in 2019 mixing was delayed. The combination of a large dinoflagellate bloom in August/September providing a source of biomass, and strong stratification that isolated a thin bottom layer in 2019, contributed to the unusually low DO levels. At MWRA's two CCB stations in 2019 DO concentrations were lower than usual, but considerably higher than the anoxic/hypoxic conditions observed by MA DMF at their near-shore stations in early October. At F02 in 2019, bottom water DO levels were comparable to those observed in October 2013, when similar strong stratification was observed in Cape Cod Bay.

2.5 PHYTOPLANKTON ABUNDANCE

Overall, total phytoplankton abundance measured in 2019 was low compared to the range of 1992-2018 observations (**Table 2-1** and **Figure 2-22**). Total phytoplankton abundance in the nearfield in 2019 (0.79 million cells L^{-1}) was 61% of the long-term mean level (1.31 million cells L^{-1}) and ranked 23rd for the 28-year monitoring program (**Table 2-1**). The relatively low 2019 total phytoplankton abundance was in part due to the lack of large winter-spring diatom or *Phaeocystis* blooms during the monitoring surveys. However, based on buoy data, satellite imagery and nutrient depletion data, a diatom bloom likely occurred in Massachusetts Bay between the March and April surveys. Another factor was reduced microflagellate abundance in 2019 relative to long-term mean levels. The annual mean 2019 nearfield microflagellate abundance (0.48 million cells L^{-1}) was significantly less than the long-term mean abundance (0.63 million cells L^{-1}).

A large, prolonged bloom of *Alexandrium catenella* was observed from May through July 2019, and dinoflagellates were relatively abundant during 2019 (3rd rank of 28 years) largely because of a late summer-autumn *Karenia mikimotoi* bloom Phytoplankton abundance and community composition during 2019 were similar to the past four years (2015-2018).

Table 2-1. Comparison of 2019 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	1992-2018 (cells L^{-1})	2019 (cells L^{-1})	2019 Rank (out of 28)	p value	Significant Change
CENTRIC DIATOM	248,604	107,283	23rd	0.1310	
Chaetoceros	31,433	3,026	20th	0.2264	
Dactyliosolen fragilissimus	49,523	5,631	21st	0.3420	
Skeletonema spp. complex	43,147	11,052	17th	0.2959	
Thalassiosira	32,755	12,635	17th	0.6361	
CRYPTOPHYTES	122,639	79,487	22nd	0.0369	decrease
DINOFLAGELLATES	57,420	87,898	3rd	0.0319	increase
Ceratium	1,843	2,949	10th	0.1105	
Dinophysis	296	2,574	1st	0.0001	increase
Prorocentrum	5,485	3,061	13th	0.4472	
MICROFLAGELLATES	627,601	480,714	20th	0.0137	decrease
MICROZOOPLANKTON (2011-2018)	4,925	6,786	2nd	0.0002	increase
PENNATE DIATOM	52,565	23,382	11th	0.7283	
Pseudo-nitzschia	6,993	9,676	8th	0.7972	
Phaeocystis pouchetii	185,696	1,228	21st	0.2863	
TOTAL PHYTOPLANKTON	1,307,967	791,574	23rd	0.0158	decrease

Differences between values were assessed using the Mann-Whitney non-parametric statistical hypothesis test; p values of ≤ 0.05 are noted. These are exploratory analyses involving multiple comparisons. Determination of significant changes is complicated by multiple comparison issues and corrections for the associated errors are considered beyond the scope of the analyses.

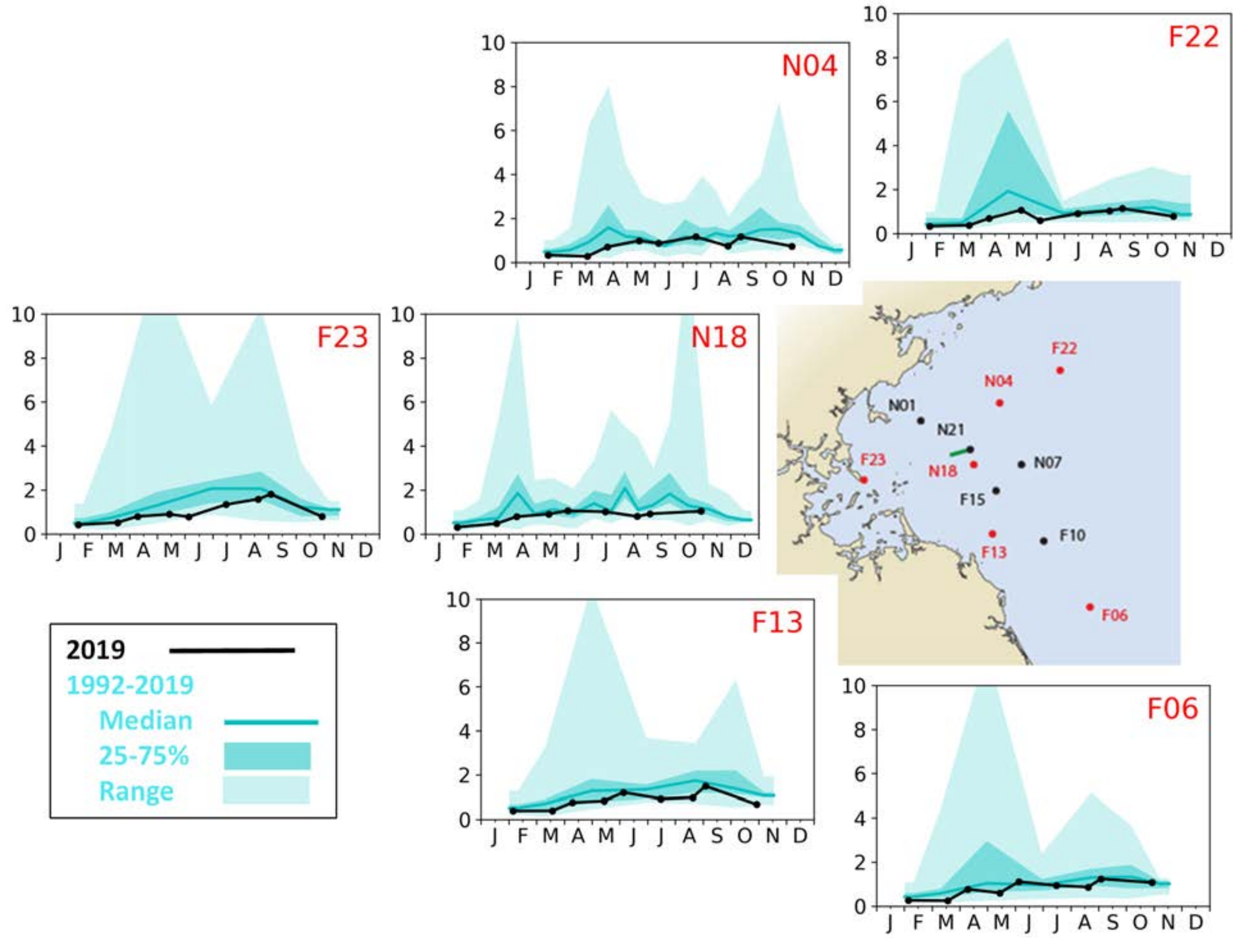

Figure 2-22. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2019 compared to prior years. 2019 results are in black. Results from 1992-2018 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The map insert highlights stations (shown in red) where an extended plankton dataset is available, which is presented here and in subsequent phytoplankton and zooplankton figures.

Elevated chlorophyll was observed in both February and April 2019 (see **Figure 2-14**). MODIS and Buoy A01 data both indicated concentrations increased in late March and early April. February through April 2019 total phytoplankton abundance, however, was at the low end of the range of previous observations (**Figure 2-22**). Centric diatom abundances peaked at 0.2-0.4 million cells L^{-1} in April dominated by *Thalassiosira* and *Detonula confervacea*, but overall diatom abundances were very low in 2019. Total phytoplankton abundance peaked in Massachusetts Bay in September but remained well below 2 million cells L^{-1} and close to the long-term median, contributing to the low overall abundances in 2019.

Phaeocystis pouchetii was present at very low abundance levels during the spring of 2019. A maximum of ~13,000 *Phaeocystis* cells L^{-1} was observed during February of 2019 in the nearfield area. Companion sampling by CCS indicated that *Phaeocystis* achieved an abundance of ~40,000 cells L^{-1} during April 2019 in Cape Cod Bay. For comparison, tens of millions of cells per liter may be found during a large *Phaeocystis* bloom in Massachusetts Bay and Cape Cod Bay. Low *Phaeocystis* abundance during 2019 and during six of the last seven years has contributed to a long-term decline in total phytoplankton abundance.

Centric diatom abundance was low during 2019 with abundances peaking at 0.1 to 0.4 million cells L^{-1} in April during a minor winter-spring diatom "bloom". Centric diatom abundance was at the low end of previous observations through the winter-spring and summer of 2019. Summer increases in several diatoms (*Dactyliosolen fragilissimus*, *Skeletonema spp.* and *Guinardia fragilissima*) that are often observed in nearshore areas of Massachusetts Bay were not observed during 2019. The small winter-spring bloom and the lack of summer diatom blooms resulted in a reduced 2019 mean nearfield diatom abundance (rank 23 of 28 years; **Table 2-1**).

Mean nearfield pennate diatom abundance during 2019 (23,382 cells L^{-1}) was approximately 44% of the long-term mean level (52,565 cells L^{-1}) equivalent to an 11th rank of 28 years. However, *Pseudo-nitzschia* abundance was moderately elevated during 2019 compared to the long-term mean level. *Pseudo-nitzschia* is a genus of potentially toxigenic pennate diatoms that can cause amnesiac shellfish poisoning (ASP). Most *Pseudo-nitzschia* cells observed during 2019 were narrow, *P. delicatissima* type cells which generally have low biotoxin production potential. Abundances of the *Pseudo-nitzschia* species likely to cause ASP (i.e., *Pseudo-nitzschia pungens)* and are grouped for Contingency Plan threshold testing were very low with seasonal means in the nearfield of <600 cells L^{-1} and well below threshold values (see **Table i**). No ASP shellfish closures were required in the region during 2019.

Dinoflagellate abundance was above long-term mean levels in Boston Harbor and Massachusetts Bay from May/June through September 2019 (**Figure 2-23**). The 2019 dinoflagellate annual cycle featured an April-May period dominated by small dinoflagellates (*Gymnodinum* spp. <20 µm, *Heterocapsa triquetra*, *Heterocapsa rotundata*), high abundances of *Alexandrium* in June and July, and a larger summer (July to September) peak in dinoflagellate abundance dominated by larger forms (*Ceratium* spp., *Dinophysis* spp., *Karenia mikimotoi*). *Ceratium* spp. and *Dinophysis* spp. abundances peaked in July and the 2019 annual means for both were above long-term levels. *Dinophysis* spp. abundance during 2019 was nearly 10 times the long-term nearfield mean level, with 2019 ranking number 1 (= most abundant) of 28 years of monitoring (**Table 2-1**). *Dinophysis* spp. abundance was elevated due to a bloom of *Dinophysis norvegica* (max abundance of 58,000 cells L^{-1}) during July 2019. It is of note that this species has been associated with a novel toxin in the diarrhetic shellfish toxin family (personal communication Jon Deeds, Food and Drug Administration). In August and September, dinoflagellate abundances were at or well above long-term maximum levels with levels in Boston Harbor more than double historic maxima (**Figure 2-23**). This was due to a bay-wide bloom of *K. mikimotoi*. The elevated dinoflagellate abundance observed during 2019 resulted in 2019 being the third rank of 28 years for dinoflagellate abundance (**Table 2-1**).

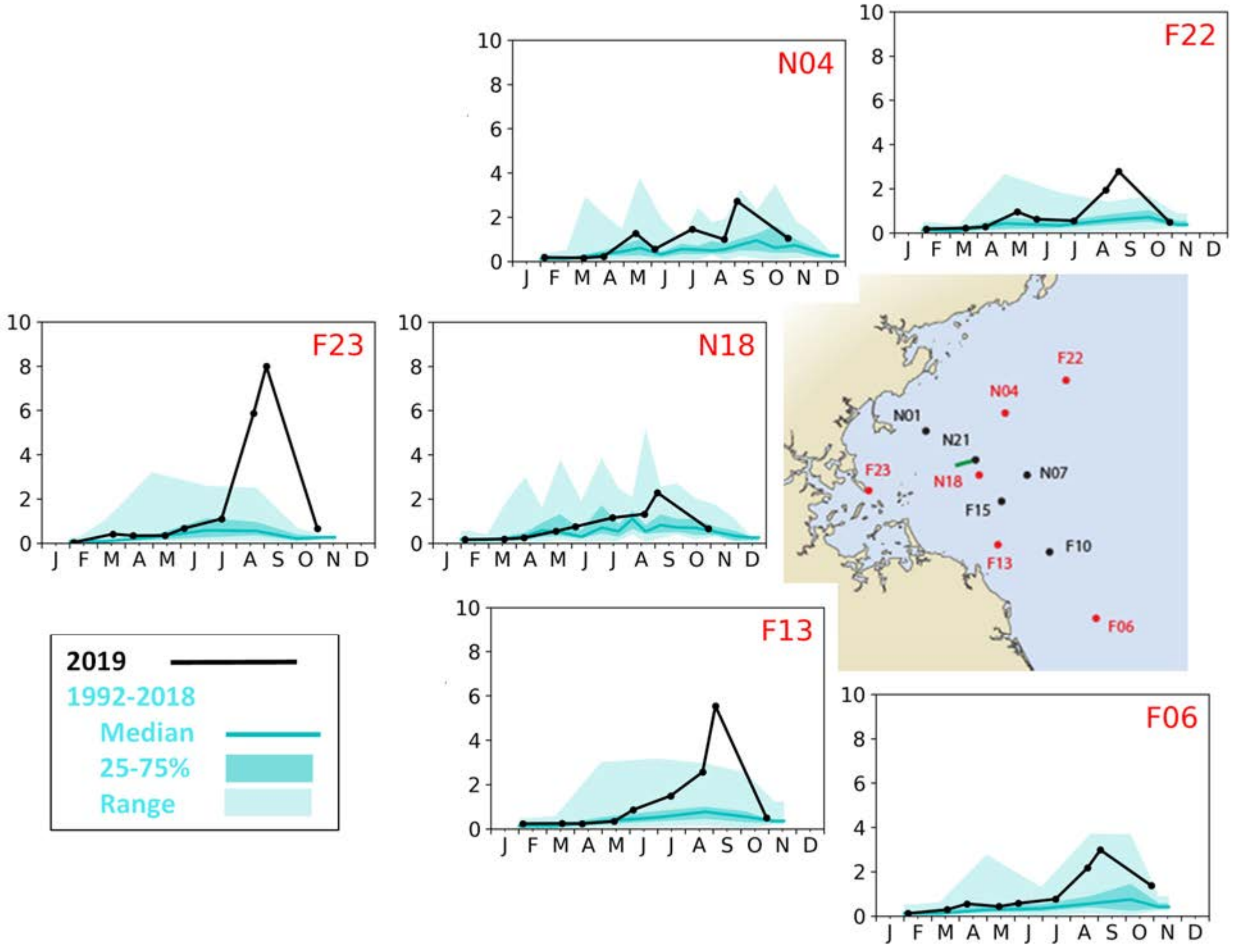

Figure 2-23. Dinoflagellate abundance (100,000 cells L^{-1}) at selected stations in 2019 compared to prior years. 2019 results are in black. Results from 1992-2018 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Alexandrium catenella

A major, prolonged *Alexandrium catenella* (formerly *A. fundyense*) bloom in Massachusetts Bay in 2019 was comparable to the large blooms observed in 2005 and 2008 (**Figure 2-24**). Very low abundances were seen in the bay during the April survey and in early May there were indications that a bloom had started in the Gulf of Maine. New Hampshire Department of Environmental Services (NHDES, personal communication Chris Nash) began to see detectable levels of PSP toxicity in early May and by May 9 saw a dramatic increase in toxicity at stations in Hampton (inshore) and Star Island (offshore) to 82 and 328 µg/100 g, respectively. Persistent winds out of the northeast prior to the May AMP survey led to strong onshore currents (down to 10 m depth) bringing western Gulf of Maine waters into Massachusetts Bay (see **Figure 2-4**). During the May 16 survey, *Alexandrium* cells were observed at all 10 stations sampled at abundances of 1 to 171 cells L^{-1} (**Table 2-2**). The maximum was from surface water at station F22 and triggered the ARRS surveys (>100 cells L^{-1}), which were conducted weekly over the ensuing two months.

Table 2-2. Summary of *Alexandrium* abundance for water column and ARRS surveys in April-July 2019.

Event Id	Date	# samples collected	# samples with *Alexandrium*	# *Alexandrium* cells/L			MAX value station (depth)
				MEAN	MIN	MAX	
WN193	April 11	20	5	0.3	0	2	Multiple
WN194	May 16	20	20	27	1	171	F22 (2 m)
AF191	May 22	43	40	74	0	413	N07 (10 m)
AF192	May 30	43	43	220	1	1,177	N07 (11 m)
WN195	June 6	24	24	631	4	1,852	F22 (2 m)
AF193	June 12	43	43	2,069	1	7,442	N01 (10 m)
AF194	June 19	43	43	2,180	4	16,080	AF6 (10 m)
AF195	June 27	43	43	1,771	2	14,636	F13 (10 m)
AF196	July 10	43	41	564	0	2,846	N07 (10 m)
WN196	July 17	24	24	3,074	22	24,342	N04 (10 m)
AF197	July 31	41	25	8	0	66	N10 (2 m)

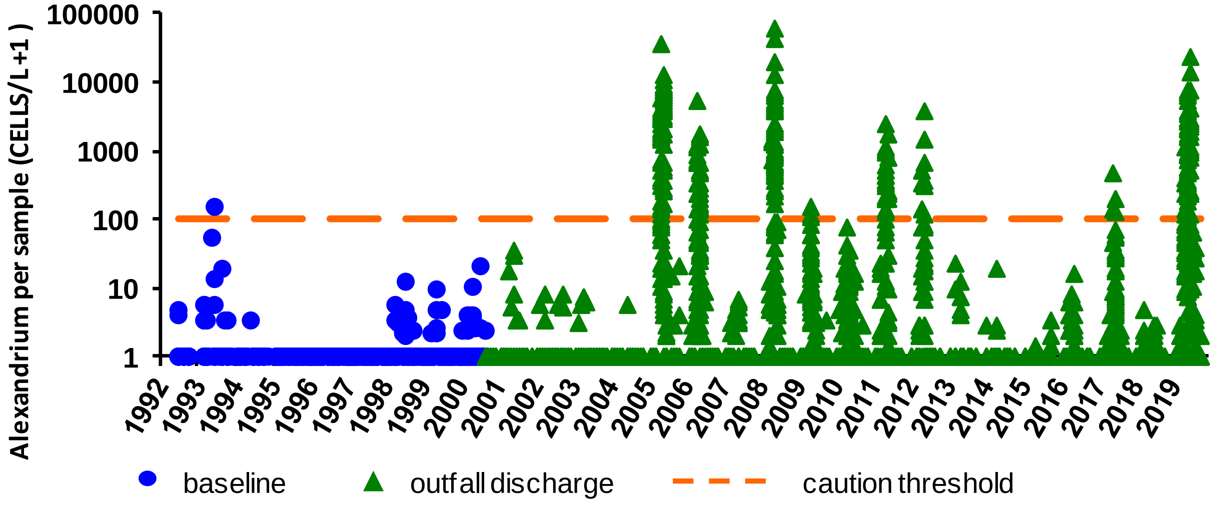

Figure 2-24. Nearfield *Alexandrium* abundance (cells L^{-1} +1) from 1992 to 2019. The dashed line represents the Contingency Plan caution threshold of 100 cells L^{-1}.

On the first ARRS survey (May 22), *Alexandrium* were observed in 40 of the 43 samples collected ranging from 0 to 413 cells L^{-1}. The maximum abundance was measured in the 10-m sample at station N07 and at >100 cells L^{-1} it triggered a Contingency Plan caution threshold exceedance. The higher counts (>100 cells L^{-1}) were found at stations south of Cape Ann (AF8, AF9 and F22), southeastern nearfield (N07), and further to the east within the Stellwagen Marine Sanctuary (**Figure 2-25**). The cell distributions during the first two surveys in May are indicative of the transport of *Alexandrium* into Massachusetts Bay from the Gulf of Maine and consistent with the winds, current, and salinity data for that period. MA DMF sampled stations within Massachusetts Bay (located along the South Shore) on May 20 and no PSP toxicity was detected within Massachusetts Bay.

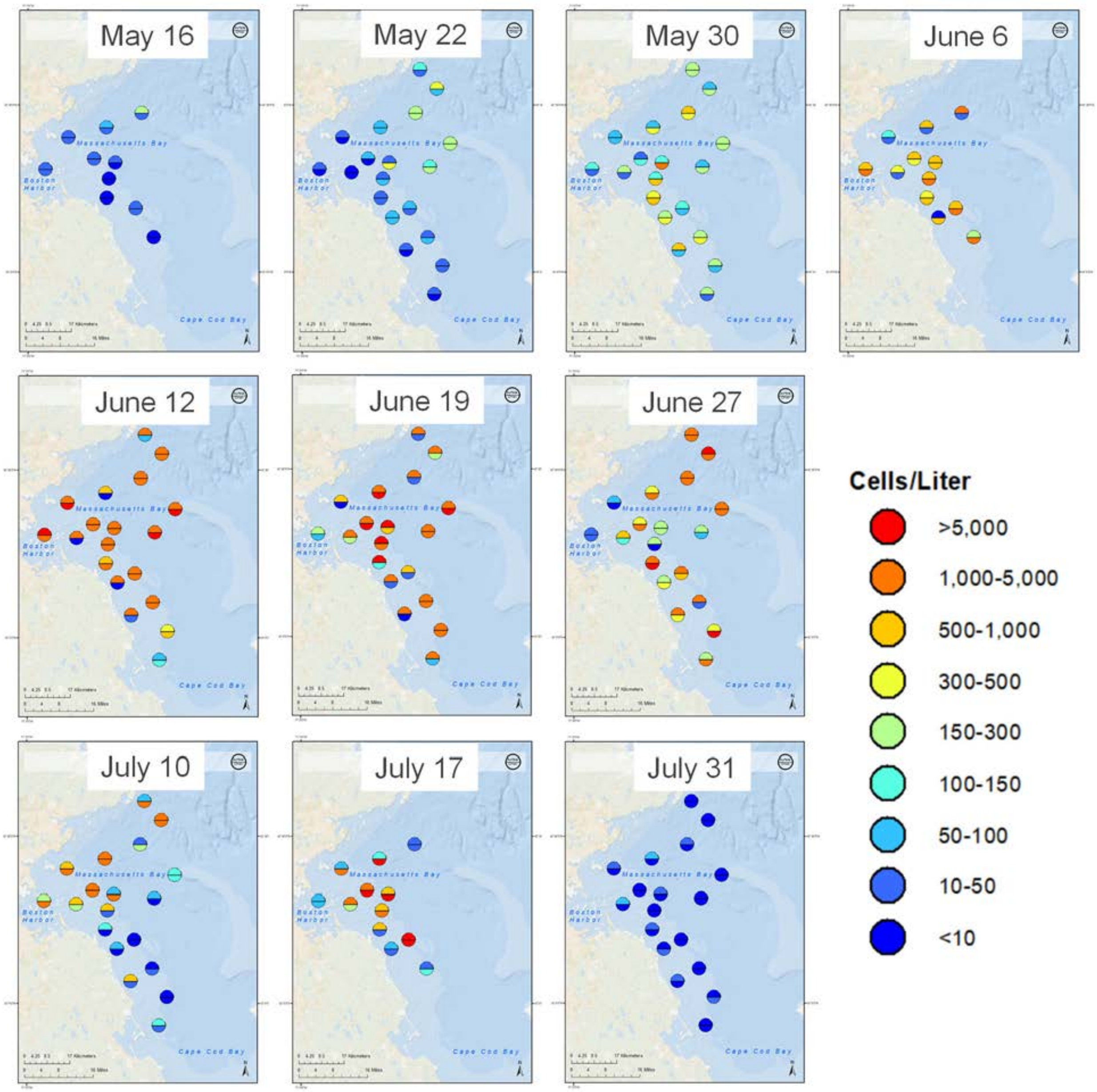

Figure 2-25. ***Alexandrium* abundance (cells L^{-1}) from surface and mid depth samples during the 2019 bloom.** The symbols show abundance for the surface in the upper half and from ~10 m in the bottom half of each symbol.

By late May, *Alexandrium* were observed in all 43 samples collected with counts ranging from 1 to 1,177 cells L^{-1} with high counts observed to the northeast as well as along the South Shore. On May 28, MA DMF had the first detectable levels of PSP toxicity (39-40 µg/100g) at stations within Massachusetts Bay (Cohasset, Scituate, and Marshfield stations). The *Alexandrium* bloom continued into June with a sharp increase in *Alexandrium* counts on June 12 with a maximum of 7,442 cells L^{-1} (**Table 2-2**). High counts (>1,000 cells L^{-1}) were observed in both surface and 10-m waters in 27 of the 43 samples at stations throughout all but the most southern stations in Massachusetts Bay (**Figure 2-25**). MA DMF sampled at the South Shore stations on June 10 and despite the high cell abundances continued to observe low PSP toxicity (42 to 50 µg/100 g) from Cohasset south to Plymouth (not detected in Sandwich). By June 18, PSP toxicity increased to 81 to 164 µg/100 g at Cohasset, Scituate, and Marshfield stations prompting MA DMF to close shellfishing areas from Boston to Plymouth on June 19. Both *Alexandrium* abundance across Massachusetts Bay and PSP toxicity continued to increase into late June.

By early July, *Alexandrium* counts and PSP toxicity along the South Shore had begun to decrease and it looked like the bloom was winding down (**Figure 2-25**). However, during the regular water column survey on July 17 *Alexandrium* counts had increased, reaching the highest survey mean and maximum observed during the 2019 bloom ranging from 22 to 24,342 cells L^{-1} (**Table 2-2**). High abundances (>1,000 cells L^{-1}) were observed in samples from the surface and subsurface chlorophyll-max depth in the nearfield and at stations about 6 to 8 miles offshore of the South Shore (stations F15 and F10). Lower abundances were observed at offshore station F22 and along the coast from Boston Harbor south to Marshfield. These lower *Alexandrium* abundances in nearshore waters were coincident with a decrease in PSP toxicity to 40-50 µg/100g along the South Shore. On July 19, MA DMF lifted the shellfishing closure from Boston to Plymouth. By late July, *Alexandrium* abundances were well below 100 cells L^{-1} and PSP toxicity was undetectable in Massachusetts Bay.

As noted above, water column stratification was strong in May due to fresher surface waters and remained strong throughout the summer due to warmer than typical surface water temperatures in June and July 2019 (**Figure 2-2**, **2-4**, and **2-5**). The inputs of fresher surface water in May and early June presumably carried *Alexandrium* into the bay and the availability of nutrients at the pycnocline likely supported the large, prolonged bloom. Indeed, 2019 was a year of elevated and prolonged PSP toxicity in western Maine and New Hampshire, so it is likely that *Alexandrium* cells were transported into Massachusetts on a sustained basis through the spring and early summer. Once in the bay, they could then use their vertical migration ability to take advantage of the high nutrient concentrations below the pycnocline.

NOAA modelers evaluated a number of potential factors (e.g., winds, oceanographic conditions, biomass, and nutrients) that may have contributed to the development and duration of the bloom (personal communication Yizhen Li, NOAA). The NOAA forecast model had captured the initiation of the bloom quite well when compared to survey observations in mid-May, but by late May and into June the model drastically underestimated abundances in Massachusetts Bay. NOAA modified the model to increase nutrient inputs to the system by resetting the nutrient climatology for May and June to the higher April levels. This increase resulted in a much better comparison between model and survey observations in Massachusetts Bay, suggesting higher nutrients contributed to the 2019 *Alexandrium* bloom magnitude and duration.

Karenia mikimotoi

The athecate dinoflagellate *Karenia mikimotoi* was first observed in the MWRA samples collected during August and September of 2017 with a maximum abundance of 337,800 cells L^{-1} (Libby et al. 2018b). This appears to have been a regional event, with *Karenia* at concentrations of ~800,000 cells L^{-1} in Salem Harbor, Massachusetts and at water-discoloring levels of millions of cells per liter in Casco Bay and Portland Harbor, Maine (Portland Press Herald, 2017[4]). *Karenia* was also observed in Massachusetts Bay during September 2018, but abundance levels were much lower (maximum level of ~ 4,000 cells L^{-1}). A much larger *Karenia* bloom was observed in Massachusetts Bay during August and September 2019 (**Figure 2-26**). The 2019 *Karenia* bloom was most intense in Boston Harbor (maximum of 850,000 cells L^{-1} at station F23). For a brief period during September 2019 elevated concentration of *Karenia* cells resulted in discolored water in Boston Harbor (Save the Harbor website, 2019[5]). *Karenia mikimotoi* appears to be increasing in persistence in Massachusetts Bay. It was present in 2017 from August to

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[4] https://www.pressherald.com/2017/09/26/casco-bay-algae-bloom-threatens-marine-life/

[5] http://blog.savetheharbor.org/2019/09/brown-algae-bloom.html

October, in 2018 during May and from August to October, and in 2019 during May and from July to October. A similar regional increase seems to be happening for the Gulf of Maine region as well.

The 2019 *Karenia mikimotoi* bloom was regional, with *Karenia* observed in Casco Bay (Portland Press Herald, Maine DMR) and in Massachusetts Bay from Salem Harbor (750,000 cells L^{-1} maximum August 2019: D. Borkman, personal observations) south to Cape Cod Bay (MWRA and CCS monitoring). The summer bloom appeared earliest (July-August) at Boston Harbor station F23 and the nearfield and then appeared to peak in September 2019 along the south shore (station F13) and in Cape Cod Bay. The highest 2019 *Karenia* concentrations were usually seen at the sub-surface chlorophyll maximum depth. *Karenia* maximum abundance ranged from approximately 850,000 cells L^{-1} in Boston Harbor, 665,000 cells L^{-1} in the nearfield, 792,000 cells L^{-1} along the south shore and 193,000 cells L^{-1} in Cape Cod Bay. Of note, regions of Cape Cod Bay experienced anoxia and invertebrate die-offs in late September/early October 2019 coincident with the *Karenia* bloom (see **Figure 2-21**). Ungrazed, senescent *Karenia* cells could have provided additional carbon to the bottom waters increasing biological oxygen demand and contributing to the hypoxia observed in shallow Cape Cod Bay in 2019. Anoxia, fish kills, and benthic mortalities are commonly associated with this species elsewhere in the world at higher abundances of 3 to 10 million cells L^{-1} (Gentien 1998, Turner et al. 1987, Li et al. 2019).

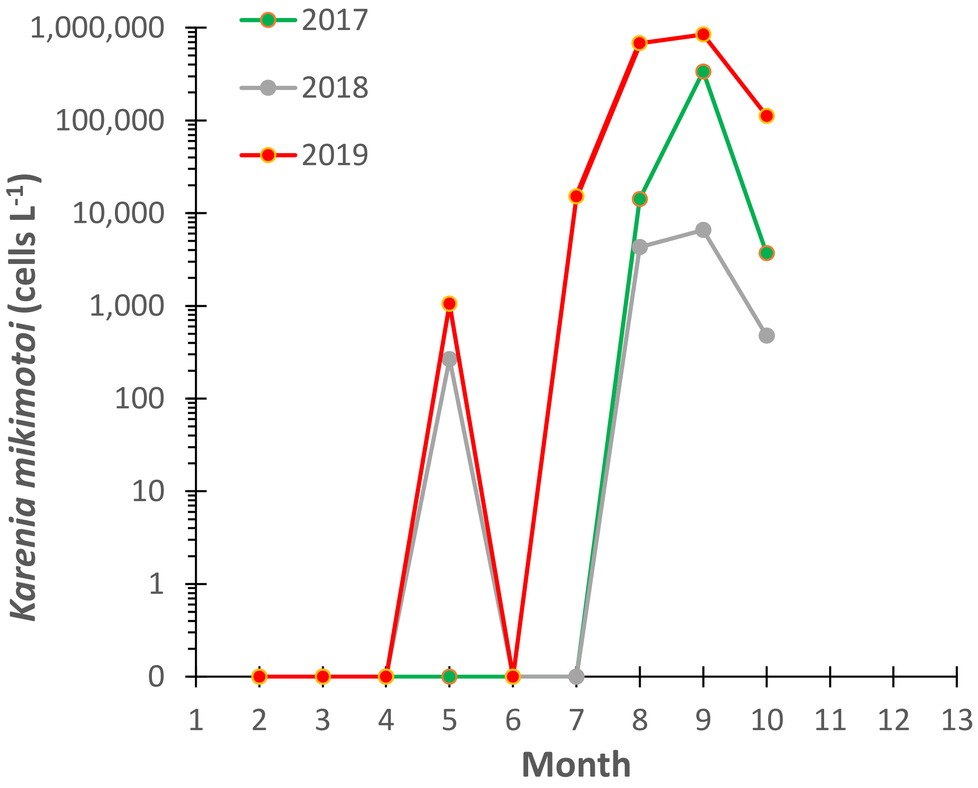

Figure 2-26. Survey maximum *Karenia mikimotoi* abundance (cells L^{-1}) in 2017, 2018, and 2019.

2.6 ZOOPLANKTON ABUNDANCE

Seasonal patterns of zooplankton abundance were typical, with increases from winter lows to spring and summer peaks, followed by fall declines. At most of the locations in Massachusetts Bay, total zooplankton abundances were above the long-term median and often higher than the upper 75th percentile for the 28-year monitoring program (**Figure 2-27**). In 2019, total zooplankton reached annual maxima in July at most stations. The zooplankton was usually dominated by typically-recorded taxa, including copepod nauplii and copepod adults and copepodites ("A+C"; **Figure 2-28**). Abundances of many dominant taxa were above the median or in the upper quartile for the 28-year monitoring program at many of the stations in Massachusetts Bay. Peak total zooplankton abundances in 2019 (~130,000 animals m^{-3}) were slightly lower than those seen in 2016, 2017, and 2018.

Peak abundance of copepod nauplii and copepod adults + copepodites at most stations were observed in May to July (**Figure 2-28**). The copepod A+C abundance was driven primarily by *Oithona similis* abundance which was close to or slightly above the long-term median for most of the year. There were typically low abundances of *Calanus finmarchicus* at all stations for most of the year except for March when abundances of >5,000 m^{-3} were observed over much of Massachusetts Bay with a maximum of 9,549 m^{-3} at station N18. These peak *Calanus* abundances were high compared to historic values for March, but overall were about <50% 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 (< 4,000 m^{-3}), mainly in Boston Harbor at station F23. However, a peak in *Acartia* spp. abundance of ~11,000 m^{-3} was observed at station N04 in May and a later maximum at station F23 of nearly 40,000 m^{-3} in September; both of these peaks were comparable to the long-term maximum at these stations. There were peaks in abundance of meroplankters and non-copepods in the upper quartile in 2019 (**Figure 2-29**). The annual maxima were of >20,000 m^{-3} observed in July and were comprised primarily of bivalve veligers plus the marine cladoceran *Evadne nordmanni*. The highest abundance of these non-copepods (40,756 m^{-3}) was observed at station N18. The July peaks in meroplankters and non-copepods were a major contributor to the annual maxima in total zooplankton observed at most stations in July (**Figure 2-27**).

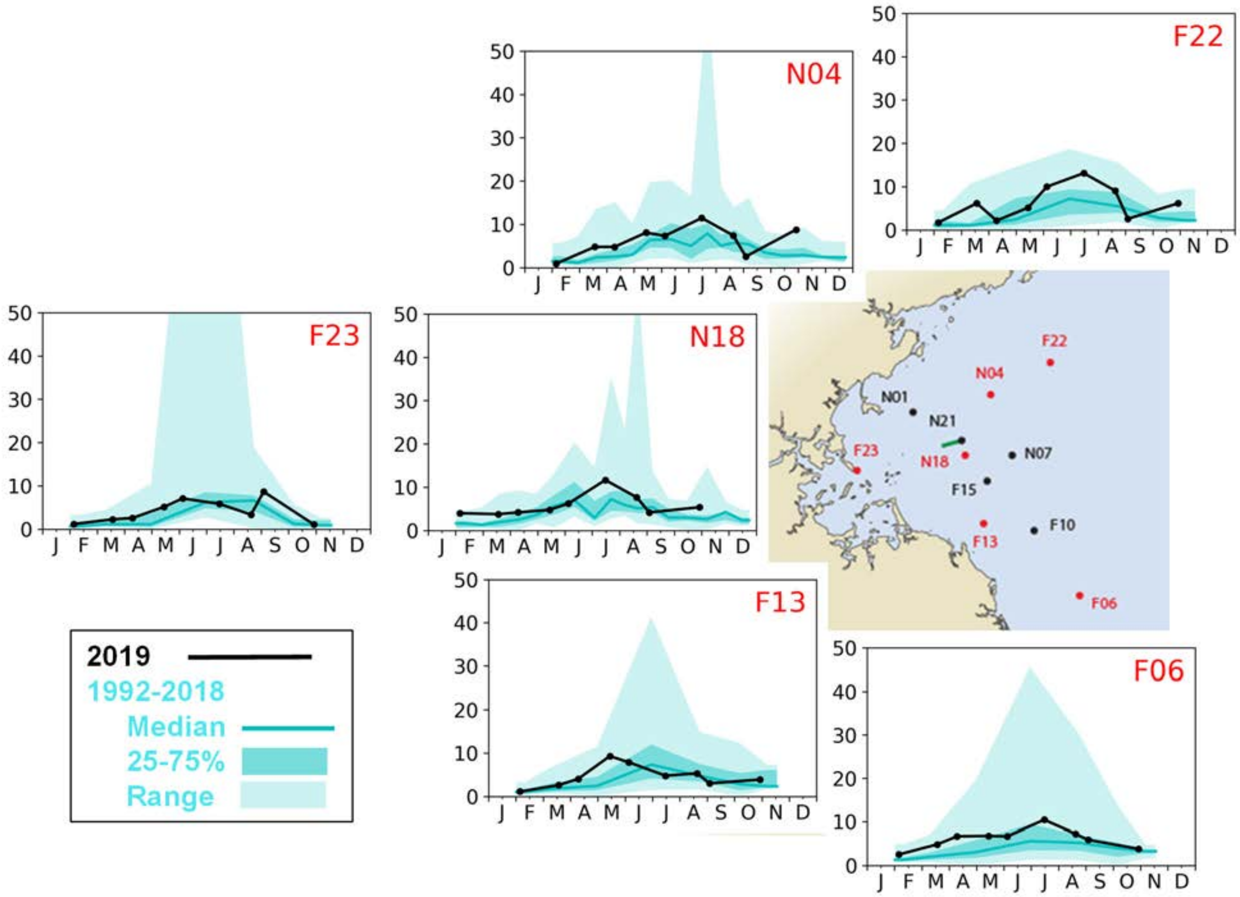

Figure 2-27. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992–2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans 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}.

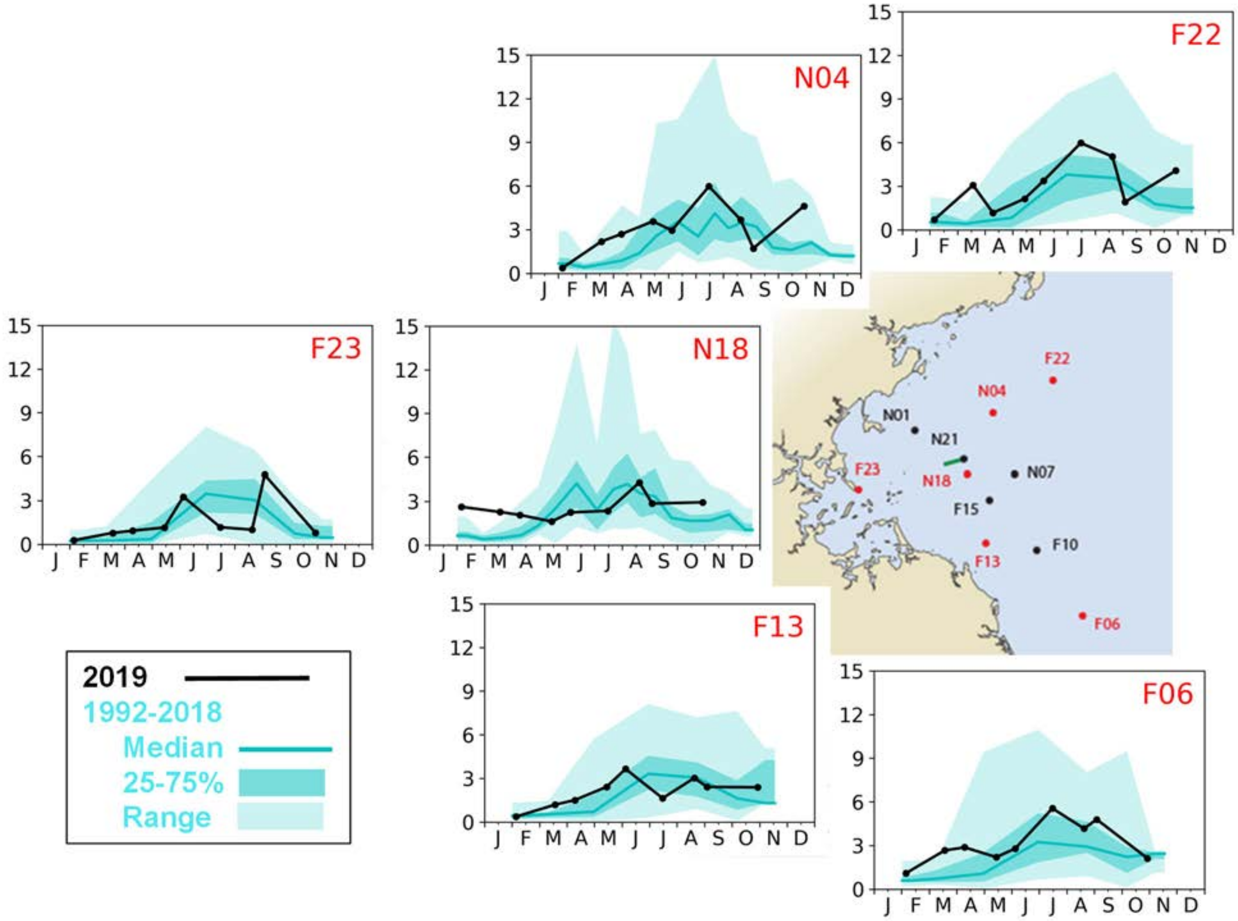

Figure 2-28. Copepod A+C abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992-2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

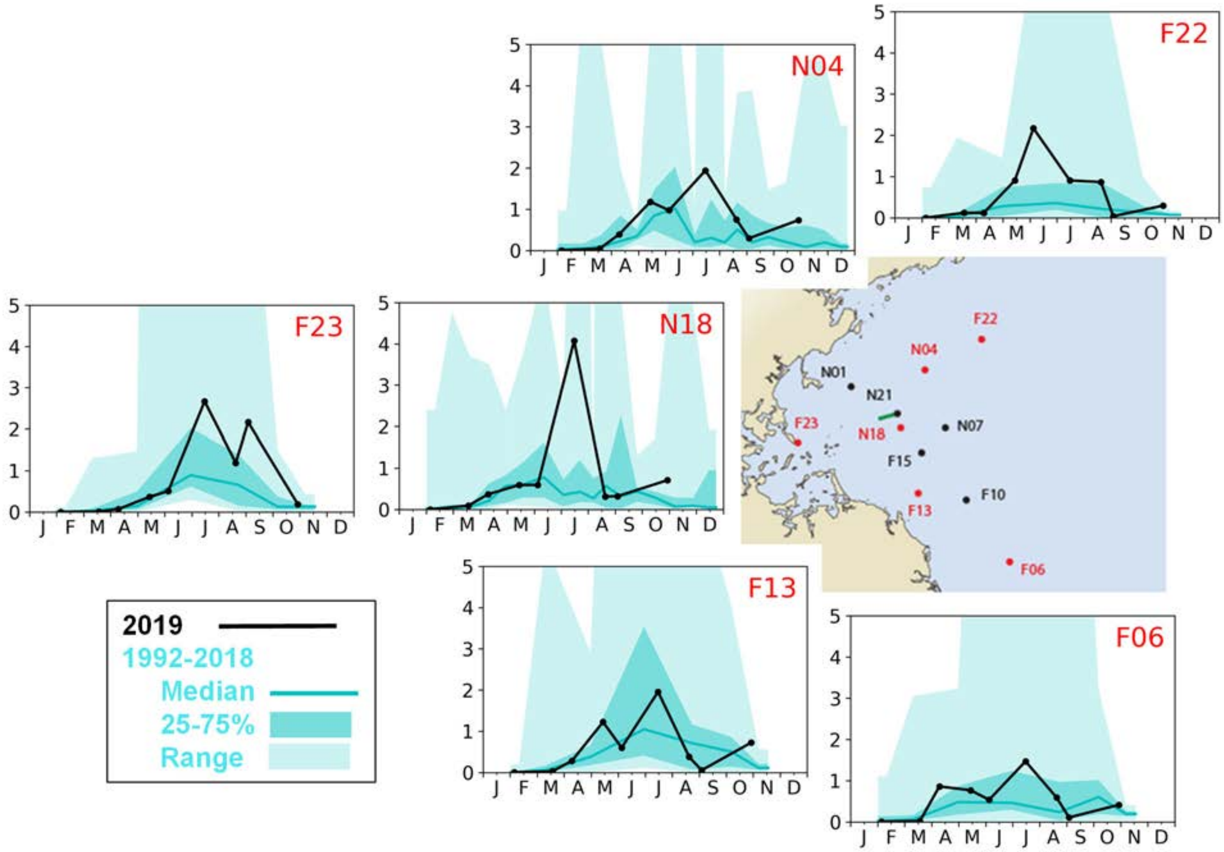

Figure 2-29. Meroplankton and other non-copepod abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2019 compared to prior years. 2019 results are in black. Results from 1992-2018 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. The majority of the values off scale are due to extraordinarily high bivalve veliger abundances in 2015.

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 2019, one finback whale (*Balaenoptera physalus*), one humpback whale (*Megaptera novaeangliae),* and one minke whale (*Balaenoptera acutorostrata*) were observed during the water column surveys in Massachusetts Bay (**Table 2-3** and **Figure 2-30**). No North Atlantic right whales were sighted during 2019 surveys. Several other marine mammals including 21 harbor seals (*Phoca vitulina*) and more than one hundred Atlantic white-sided dolphin (*Lagenorhynchus acutus)* were also observed. Although not sighted during MWRA survey cruises, one juvenile humpback whale was spotted while feeding at the mouth of Boston Harbor in early August.

MWRA has revised its outfall ambient monitoring plan in 2004 and 2011 (MWRA 2004, 2010) to reduce both the number of annual surveys and the monitoring stations sampled during each survey through each revision, and the prime whale habitats of Stellwagen Bank and Cape Cod Bay are no longer included in MWRA's marine mammal observations. To provide qualitative information of relative whale abundance through years, whale observations that occurred during surveys before 2011 and within the areas covered by the current monitoring plan in Boston Harbor and Massachusetts Bay (see **Figure 1-1**) were identified. The results are summarized in **Table 2-3** and **Figure 2-30**, 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 2-3. Number of whale sightings from 1998 to 2019.

Whale species	Total number of sightings (1998-2010)	Range of sightings per year (1998-2010)	2011	2012	2013	2014	2015	2016	2017	2018	2019
Finback	11	0-4	1	0	0	0	0	0	0	1	1
Humpback	4	0-1	0	2	0	0	0	0	0	0	1
Minke	30	0-6	4	0	0	2	0	3	3	4	1
North Atlantic Right	0	0-0	0	2	4	0	0	2	8	0	0
Unidentified	15	0-2	0	3	1	1	0	0	4	2	4

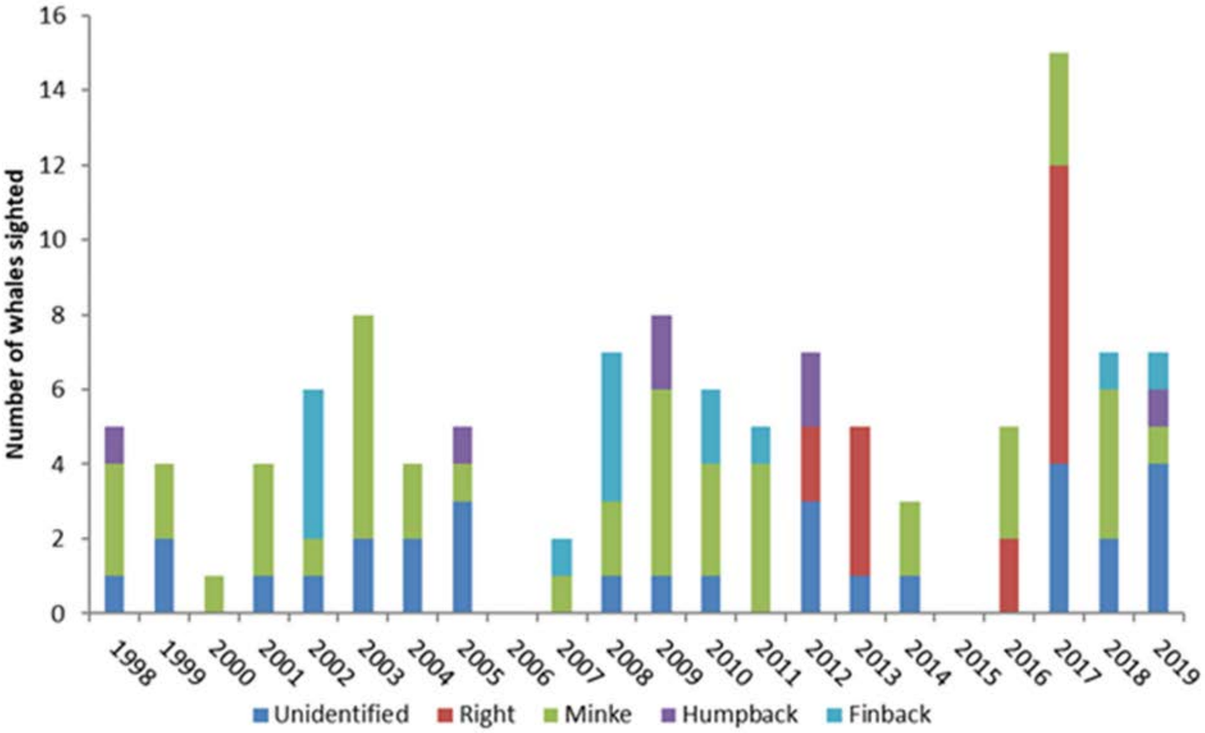

Figure 2-30. Number of whale sightings and whale species sighted in current survey areas (1998 – 2019).

3 ANALYSIS OF THE LONG-TERM MONITORING DATASET

3.1 OUTFALL NUTRIENT SIGNATURE IN MASSACHUSETTS BAY

The 2019 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. 2009) demonstrated that the annual cycle for NO_3 and SiO_4 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 stations 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. In this section, these findings are reexamined.

An examination of nutrient concentration and phytoplankton biomass gradients was undertaken to quantify the outfall's nutrient signal more fully in Massachusetts Bay. The analysis was conducted on data averaged for 2011-2019, the nine most recent years the outfall has been in operation, and also the nine years for which all 11 stations were sampled the same nine times per year with the full suite of parameters measured at each station. Boston Harbor station F23 was not included in this analysis, because conditions at this location are driven more by harbor than bay processes.

The 2011-2019 depth-averaged total nitrogen (N), dissolved inorganic nitrogen (DIN = NH_4 and NO_{3+2}) and NH_4 concentrations were all highest at station N21 located over the outfall (**Figure 3-1**). The proportion of the total N contributed by DIN, and of DIN contributed by NH_4, were also highest at this location. Total N, DIN and NH_4 concentrations all declined in an exponential manner with distance from the outfall, achieving background levels at 7.5 to 10 km. NH_4 was the only nutrient to exhibit significantly higher concentrations beyond the nearfield with mean-depth averaged levels 0.45 µM higher at station F15 compared to background Massachusetts Bay levels. Exponential decay plots yielded r^2 values > 0.77 for all three N fractions. At N21, depth-averaged NO_{3+2} concentrations were no greater than at more distal stations. Note that this analysis has shown that NH_4 increases are confined within 7.5-10 km of the outfall on a long-term average basis. However, as documented in previous reporting on individual years, elevated NH_4 concentrations can occur for short durations in localized areas as far as 10-20 km from the outfall.

Total phosphorus (P) and dissolved inorganic phosphorus (DIP) concentrations were also highest at N21 (**Figure 3-1**). Concentrations of both fractions declined in an exponential manner from the outfall. The rates of attenuation were more rapid for P than for N, with concentrations approaching background at N18. Dissolved inorganic Si (DISi = SiO_4) concentrations, like NO_{3+2}, exhibited no spatial gradient with distance from outfall.

Depth-averaged total N: total P, DIN: DIP and DIN: DISi ratios also declined exponentially with distance from the outfall (**Figure 3-1**). Total N:total P ratios declined from values greater than the Redfield N:P ratio (16:1; Redfield 1958) at stations N21 and N18, to values approximating Redfield ratio at stations N01 and N07. DIN:DIP ratios decreased more rapidly from the outfall than did total N:total P. Aggregated DIN:DIP ratios at all stations fell well below the Redfield ratio. DIN:DISi ratios declined from values above the Redfield ratio for N:Si (1.7:1) at stations N21 and N18, to levels approximating the Redfield ratio further afield. Exponential decay plots yielded r^2 values between 0.70 and 0.91 for all three sets of ratios.

Chlorophyll and particulate organic carbon (POC) concentrations exhibited greater temporal availability at each of the stations than did nutrient concentrations (**Figure 3-2**). Depth-averaged chlorophyll and POC concentrations at the 10 stations showed no relationship with distance from outfall. Station F22 is a deep offshore station south of Cape Ann, possibly accounting for the low chlorophyll and POC at this location.

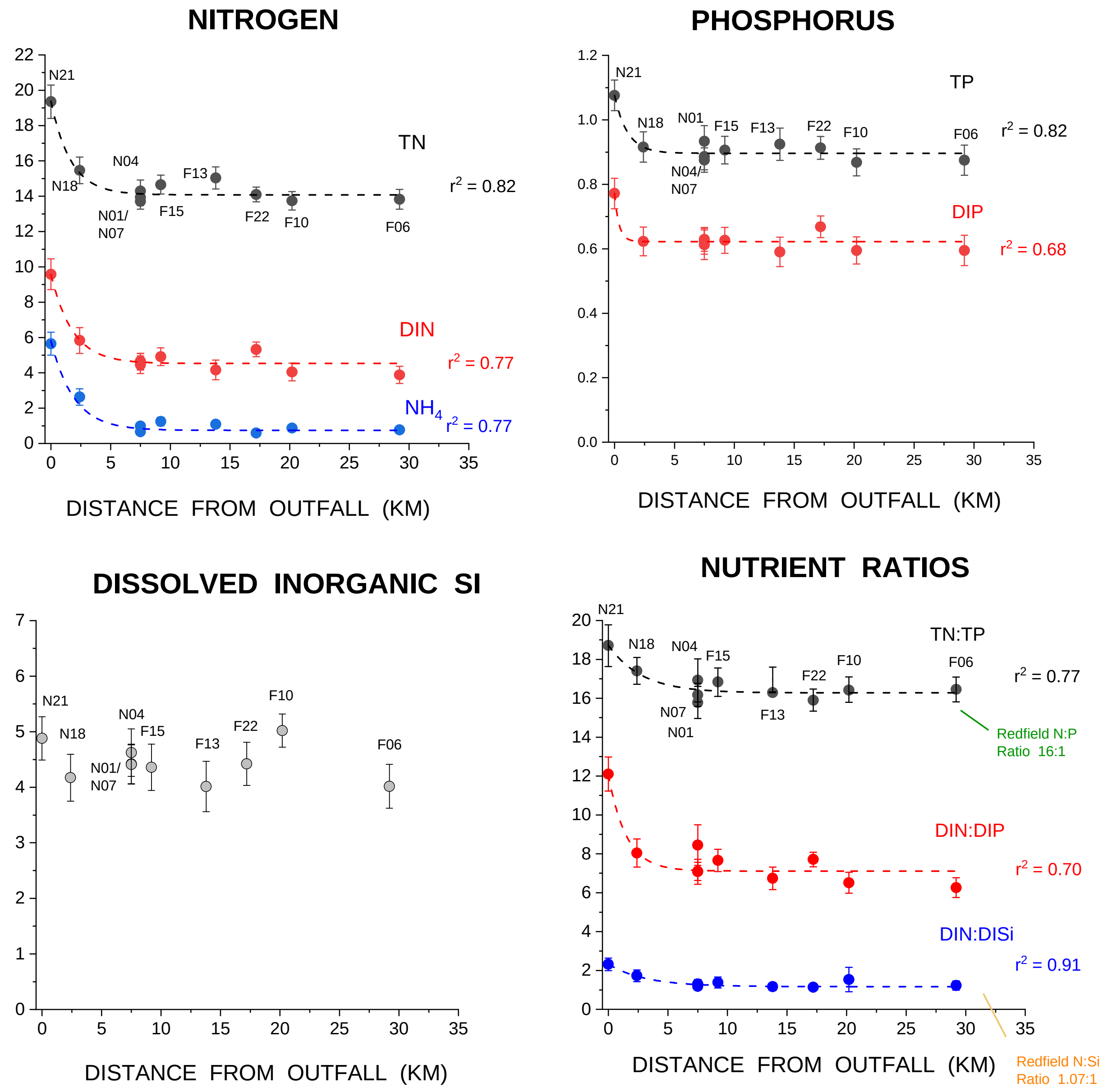

Figure 3-1. Depth-averaged nutrient concentrations (μM) and molar ratios with distance from the outfall. Error bars are 95% CL. Data are averaged for 2011-2019.

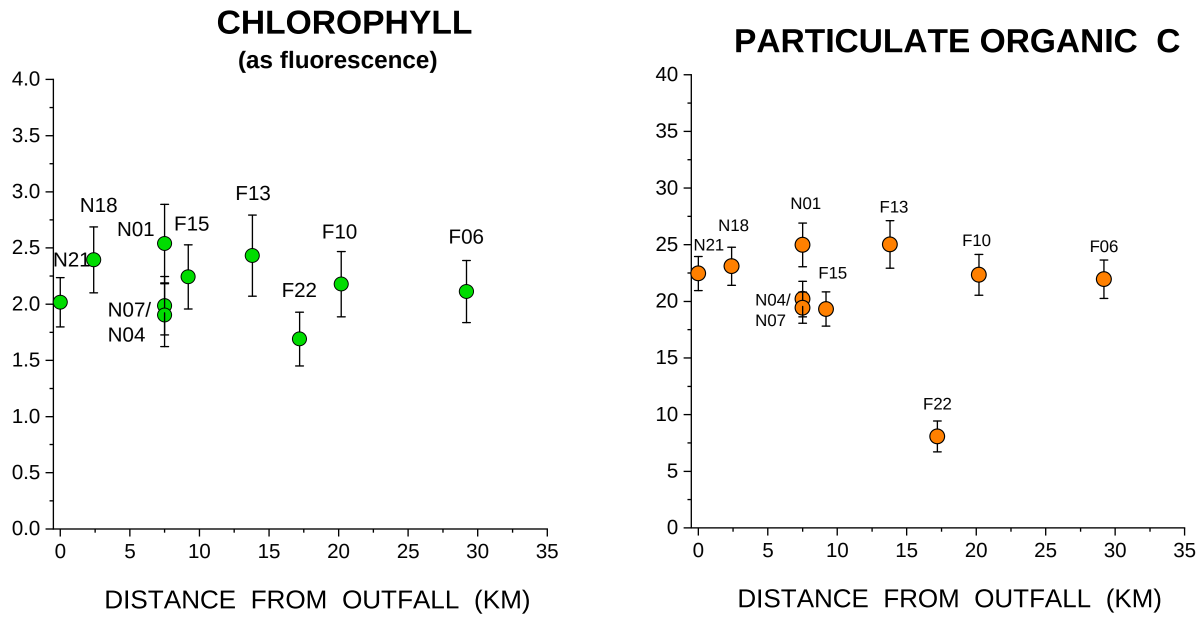

Figure 3-2. Depth-averaged chlorophyll fluorescence (µg L^{-1}) and particulate organic carbon concentrations (µM) with distance from the outfall. Error bars are 95% CL. Data are averaged for 2011-2019.

This gradient study of depth-averaged nutrient and phytoplankton biomass data for 2011-2019 confirmed earlier studies that demonstrated the signature from the outfall is localized (e.g., Libby et al. 2009, 2019). Depth-averaged concentrations of total N, DIN, NH4, total P and DIP, and molar total N:total P, DIN:DIP and DIN:DISi ratios all declined rapidly with distance from outfall with all, except NH_4, achieving background well within the margins of the nearfield. NH_4 concentrations reached background levels within ~10 km of the bay outfall. The total N and DIN, and in turn total N:total P, DIN:DIP and DIN:DISi ratio decreases were all driven largely by a rapid NH_4 decline within the nearfield. Aggregated NO_{3+2}, SiO_4, chlorophyll, and POC concentrations were no greater in the vicinity of the outfall than at stations outside the nearfield.

Despite differences in methodology and in the periods examined, these results are consistent with the "Before-After Control-Impact" (BACI) regression analysis reported by Libby et al. (2009). The analysis was undertaken on NH_4, NO_3, SiO_4, chlorophyll, and POC data from 1995-2007. The purpose of the BACI analysis was to determine any temporal change in the spatial differences between the inner nearfield region and three control regions defined by distance from the outfall. The only significant difference in response between the four regions was an increase in NH_4 in the inner nearfield. The NH_4 increase was evident during each of the three MWRA-defined threshold seasons of winter/spring (February-April), summer (May-August), and fall (September-December).

3.2 LONG-TERM VARIABILITY IN PLANKTON

Compared to the phytoplankton levels observed during the 1990s and early 2000s, phytoplankton abundance in the Massachusetts Bay nearfield area has been declining since 2008 (**Figure 3-3**). 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}; **Table 2-1**). Decreased abundance of several important phytoplankton groups (microflagellates, *Phaeocystis*, centric diatoms) have contributed to the overall decline.

Abundance of microflagellates, which are the most abundant phytoplankton numerically in the MWRA monitoring area, 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. Increased grazing by microzooplankton, that have increased, likely contributed to this decrease. In 2019, microzooplankton abundance (6,786 individuals L^{-1}) that was approximately one and a half times the 2011 to 2018 average level (4,925 individuals L^{-1}; **Table 2-1**).

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 seven 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 3-3**). For the nearfield, 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, with no summer diatom bloom observed in 2019. The net result has been a long-term decline in centric diatom abundance.

Although the mechanisms are not well known, phytoplankton abundance and community composition in the Massachusetts Bay nearfield area have had three main phases during 1992 to 2019. A multivariate ordination technique was used to visualize the similarity of monitoring years (1992 to 2019) in terms of phytoplankton species composition and abundance. Observations from the top 10 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 multidimensional scaling [MDS]) to construct a non-dimensional scaling diagram of phytoplankton years (**Figure 3-4**). In this diagram, years that are near each other had more similar species composition and abundance than 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.
- The most recent years 2013 to 2019 (cluster at center of plot) reduced or absent *Phaeocystis* abundance (except in 2014), reduced winter/spring diatom abundance and reduced total phytoplankton abundance.

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 3-5**]), which suggests zooplankton grazing is a mechanism at least partially responsible. Of note, zooplankton abundance leveled off in 2018 and declined during 2019 while total phytoplankton had a slight upturn which suggests a possible change may be occurring in phytoplankton-zooplankton dynamics in Massachusetts Bay.

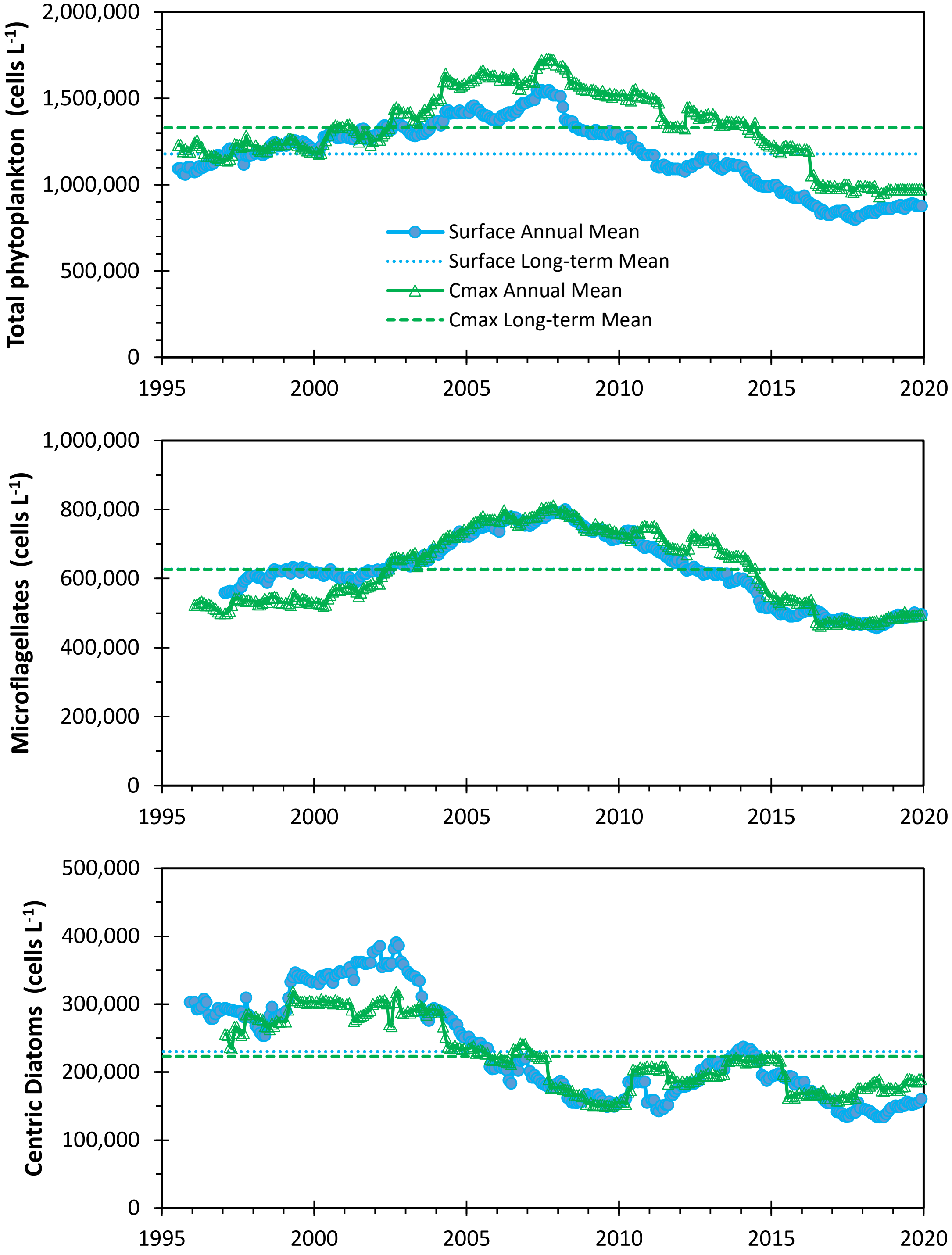

Figure 3-3. Estimated long-term (1992-2019) abundance levels of phytoplankton groups in the nearfield region (stations N04 and N16/N18) derived from time series analysis. Each panel shows the de-seasonalized annual mean abundance at the surface (blue) and at the chlorophyll maximum depth (green) during 1992-2019. Horizontal dashed lines are 1992-2019 mean levels. Panels show total phytoplankton (top panel), microflagellates (middle panel), and centric diatoms (bottom panel). Monthly de-seasonalized abundance estimates have been smoothed with a 15% smoothing window equivalent to the ~48 months preceding the sample date.

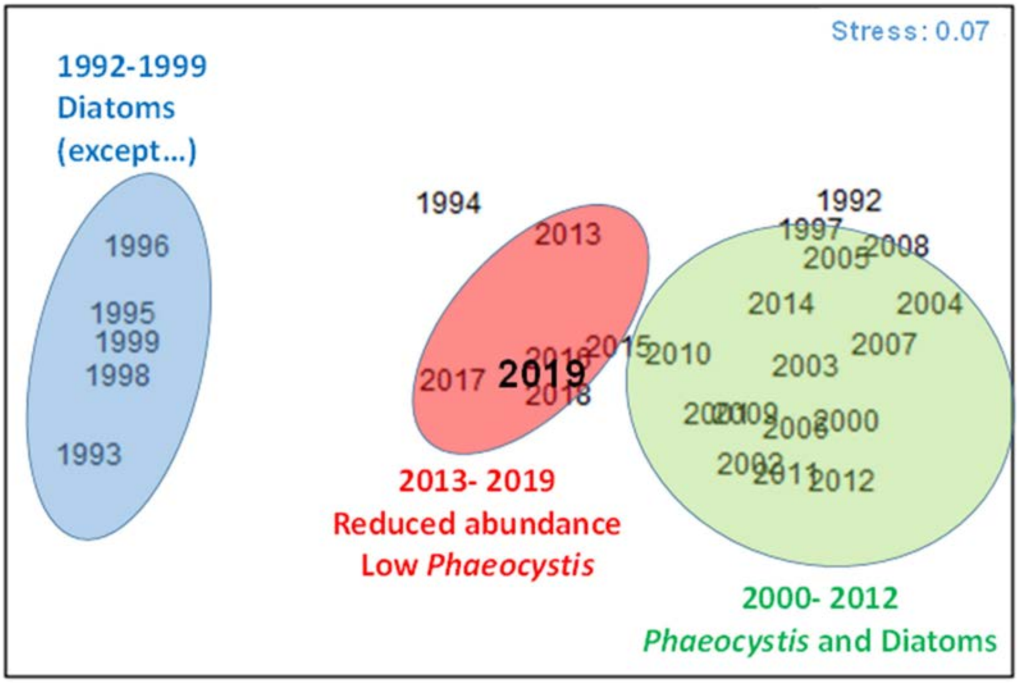

Figure 3-4. MDS plot of nearfield phytoplankton years in terms of phytoplankton community composition and abundance from 1992-2019. Based on the top 10 taxa, log x+1 transformed data, Bray-Curtis similarity index. A stress of 0.07, a metric for goodness of fit or statistical strength of the differences between the years, is considered "good".

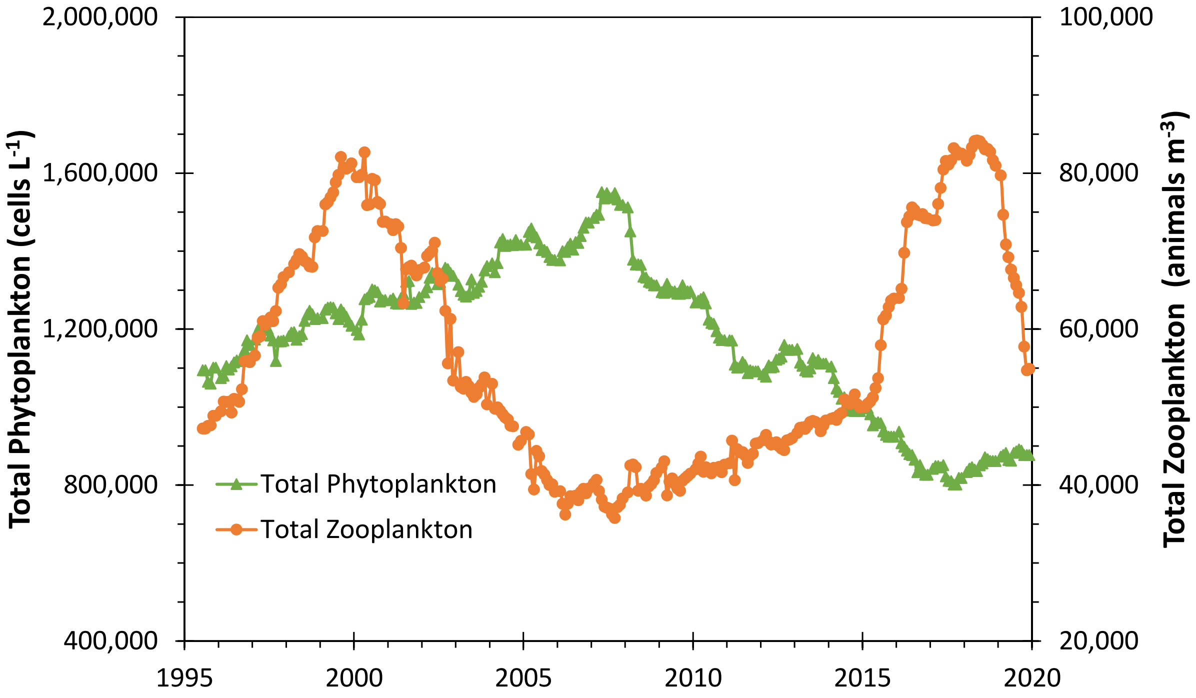

Figure 3-5. Estimated long-term (1995-2019) abundance levels of total phytoplankton (green) and total zooplankton (orange) abundance in the nearfield (stations N04 and N16/N18) derived from time series analysis. Data lines based on 15% smoothing windows (~4 years).

4 SUMMARY

The most notable physical oceanographic events in 2019 were the Nor'easter in mid-May, strong stratification conditions, and the hypoxia/anoxia event in nearshore, shallow waters of Cape Cod Bay. Overall, river flow was generally higher than normal, particularly the Charles River between January and March. The spring freshet of the Merrimack River in late April and early May was one of the strongest of the monitoring period (**Figure 2-3**). The mid-May Nor'easter was not very intense, but low-salinity surface waters associated with the strong spring freshet made the upper water-column more "slippery" against deeper waters, leading to a relatively strong response of the near-surface currents transporting Gulf of Maine waters into Massachusetts Bay (**Figure 2-4**). Several more pulses of surface current into the bay occurred through mid-June, which were not clearly associated with wind events.

Water column stratification was strong in May and early June due to fresher surface waters and remained strong throughout the summer due to warmer surface water temperatures in late June and July 2019 (**Figure 2-5**). A moderate Nor'easter in late July resulted in enough mixing to bring increased bottom water DO levels up by 0.5 to 1 mg L^{-1}. Stratification persisted into the fall in both Massachusetts Bay (November) and Cape Cod Bay (October). The strength and persistence of seasonal stratification was one of the primary factors in the hypoxic/anoxic event in Cape Cod Bay.

Nutrient concentrations in Massachusetts and Cape Cod Bays were generally consistent with typical seasonal patterns, with naturally elevated NO_3, SiO_4 and PO_4 concentrations in winter/spring, decreases during the summer months and then increases in October (**Figure 2-8**). The most notable differences were the higher concentrations below the pycnocline during the summer months for all dissolved inorganic nutrients, due to strong stratification isolating nutrients at depth. Station average nutrient concentrations varied over the summer but were high and within or above the upper quartile observed historically (**Figure 2-8** and **Figure 2-9**). As in previous years, compared to the other three nutrients, the NH_4 concentrations during 2019 were more variable from survey to survey and were highest during stratified summer conditions (**Figure 2-10**). The high concentrations of NH_4 and other nutrients observed in the nearfield during the summer were primarily due to anomalously strong stratification and high concentrations below the pycnocline.

The 2019 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**). During both winter (unstratified) and summer (stratified) conditions, elevated NH_4 concentrations were observed up to 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 2019 (**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).

A gradient study of depth-averaged nutrient and phytoplankton biomass data for 2011-2019 confirmed earlier studies that demonstrated the signature from the outfall is localized (e.g., Libby et al. 2009, 2019). Depth-averaged concentrations of nitrogen and phosphorous nutrients and nutrient ratios declined rapidly with distance from outfall and, except for NH_4, reached background levels well within the margins of the nearfield, typically less than 5 km from the outfall (**Figure 3-1**). NH_4 concentrations reached background levels with ~10 km of the bay outfall. Aggregated NO_{3+2}, SiO_4, chlorophyll, and POC concentrations were no greater in the vicinity of the outfall than at stations outside the nearfield. Despite differences in methodology and in the periods examined, these results are consistent with a BACI regression analysis reported by Libby et al. (2009).

There were no major winter/spring diatom or *Phaeocystis* blooms observed in Massachusetts Bay in 2019, but buoy data, satellite imagery and nutrient depletion suggest a diatom bloom occurred in between the March and April surveys. Typical spring and fall peaks were observed in 2019, but the timing of them varied across the region, while large peaks were observed at most stations in summer (**Figure 2-14**). Highest chlorophyll levels for the year were observed in February, April, and late May surveys in Massachusetts Bay, February to April in Cape Cod Bay, and in late May and August in Boston Harbor, while a large dinoflagellate bloom caused elevated levels across the monitoring area in September (**Figure 2-15**). Even though relatively high chlorophyll levels were observed in the nearfield, the seasonal and annual average values in 2019 were moderate, higher than baseline seasonal averages, but well below the Contingency Plan threshold levels (see **Table i**).

Bottom water DO concentration minima were moderate over most of Massachusetts Bay in 2019 and higher than Contingency Plan thresholds. Bottom water DO levels would have been lower if not for a July mixing event that raised concentrations (**Figure 2-18**). After the mixing event, bottom water DO concentrations remained close to long-term averages for the rest of the year in Massachusetts Bay and higher than Contingency Plan thresholds (see **Table i**). Cape Cod Bay showed a similar summer increase in bottom water DO concentrations in July, but then concentrations decreased to low levels of 4 to 5 mg L^{-1} by late August and early September. Hypoxic to anoxic conditions were observed in southern Cape Cod Bay near Barnstable Harbor in late September and early October leading to mortality of bottom fish and lobsters in the area. The relatively shallow Cape Cod Bay stations typically become well mixed earlier by September, but in 2019 mixing was delayed into October (**Figure 2-21**). A dinoflagellate bloom in August/September and strong stratification isolating a thin bottom layer, together contributed to the low DO levels observed nearshore by others in 2019.

Annual total phytoplankton abundance in the nearfield was low in 2019 compared to the range of 1992-2018 observations, ranking 23rd for the 28-year monitoring program (**Table 2-1** and **Figure 2-22**). This was in part due to not observing a strong bay-wide winter/spring diatom or *Phaeocystis* bloom during the monitoring surveys. There was a large, prolonged bloom of *Alexandrium catenella* from May through July 2019 and dinoflagellates were relatively abundant (3rd rank of 28 years) largely due to a late summer-autumn bloom of *Karenia mikimotoi*. The 2019 phytoplankton abundance levels and community composition were similar to the past four years (2015-2018).

The 2019 *Alexandrium* bloom was relatively large and comparable in both magnitude (abundances >10,000 cells L^{-1}) and duration to historically large blooms in 2005 and 2008. Elevated *Alexandrium* counts (>100 cells L^{-1}) were first observed in the mid-May survey triggering the ARRS surveys. The bloom continued over the course of seven ARRS surveys and two more regular water column surveys before ending in late July 2019 (**Table 2-2** and **Figure 2-25**). PSP toxicity led to a month long shellfishing closure in Massachusetts Bay from June 19 to July 19, 2019. The inputs of fresher surface water in May (and into June) brought *Alexandrium* into the bay. Regional and environmental conditions in Massachusetts Bay were conducive for the bloom to be larger and more prolonged than in many other years. Neither the timing nor geographic progression of the bloom suggested any influence of the Massachusetts Bay outfall.

Karenia mikimotoi bloomed in Massachusetts Bay and Cape Cod Bay during August and September 2019. The bloom was most intense in Boston Harbor, where for a brief period in September the *Karenia* populations were sufficient to discolor the water. *Karenia mikimotoi* appears to be increasing in persistence in Massachusetts Bay. Similar *K. mikimotoi* population increases have been reported elsewhere in the northeast, suggesting that regional processes have been responsible for the *Karenia* increases in Massachusetts Bay and Cape Cod Bay. *K. mikimotoi* is known to have a history of ‘invasions’ into new waters, and is characterized as a harmful species (Gentien 1998). Toxins from *K. mikimotoi* are not well-understood (Yamasaki et al. 2004) and no direct negative impacts on human health are known. *Karenia* has been implicated in anoxia, fish kills and benthic mortalities in other parts of the world, but at much higher concentrations (3-10 million cells L^{-1}) than the < 850,000 cells L^{-1} that were seen in Massachusetts Bay (Turner et al. 1987, Li et al. 2019).

Seasonal patterns of zooplankton abundance were typical in 2019, with increases from winter lows to spring and summer peaks, followed by fall declines. At most of the locations in Massachusetts Bay, total zooplankton abundances were above the long-term median and often above the 75th percentile for the 28-year monitoring program (**Figure 2-27**). The zooplankton was usually dominated by typically-recorded taxa, including copepod nauplii and copepod adults and copepodites. Peak zooplankton abundances in 2019 were slightly lower than those seen in 2016 to 2018, but remain elevated over the long-term levels observed since 1992 (**Figure 3-5**).

Massachusetts Bay and Boston Harbor phytoplankton and zooplankton have undergone long-term (decadal) changes since monitoring started in 1992 (**Figure 3-3** and **Figure 3-5**). The mechanisms are not fully known but appear to be regional and unrelated to the outfall. Phytoplankton abundance and community composition in the Massachusetts Bay nearfield area has had three main phases during 1992 to 2019 (**Figure 3-4**). 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 2019, 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. In recent years, the declining total phytoplankton trend has been simultaneous with a period of increasing zooplankton abundance (both copepods and microzooplankton **Figure 3-5**), which suggests zooplankton grazing is at least partially responsible. The trend in zooplankton abundance leveled off in 2018 and declined in 2019, while total phytoplankton had a slight upturn suggesting a possible change in phytoplankton-zooplankton dynamics in Massachusetts Bay.

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