2020 Water Column Monitoring Results

Massachusetts Water Resources Authority
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TABLE OF CONTENTS

FIGURES

TABLES

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 2020. The term "water column" denotes monitoring focused on water conditions (not sediments, fish, or shellfish) extending vertically from the ocean surface to the seafloor. 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 COVID-19 pandemic in 2020 required changes throughout the state, and the country. MWRA's monitoring was impacted as a result, but steps were taken to ensure the program was continued with minimal impacts and to allow for on-going testing of Contingency Plan thresholds. Massachusetts Bay sampling in March could not be conducted. However, researchers from the Center for Coastal Studies were able to conduct sampling at the Cape Cod Bay Stations on March 28. The April survey was postponed, occurring in early May in both Massachusetts Bay and Cape Cod Bay. Battelle worked with Woods Hole Oceanographic Institution (WHOI) to develop COVID-19 mitigation protocols including masking and social distancing for conducting surveys on the *R/V Tioga*. To meet the social distancing guidelines, the scientific field team was reduced from six to three staff, which required a commensurate reduction in sampling. In discussions with MWRA, field staff focused on collecting samples directly related to Contingency Plan thresholds including in situ oceanographic parameters, dissolved inorganic nutrients, chlorophyll, and phytoplankton samples (whole water community analyses and *Alexandrium* counts). In August, it was possible to include a fourth scientist on surveys, allowing for particulate carbon/nitrogen and zooplankton sample collection to resume.

No water column Contingency Plan thresholds tested in 2020 were exceeded (**Table i**). Due to the COVID-19 pandemic and resulting disruption in monitoring, three thresholds were not tested: the winter/spring and annual thresholds for chlorophyll, and the winter/spring threshold for *Pseudo-nitzschia pungens*.

Monitoring in 2020 confirmed that the treated wastewater discharge from the bay outfall influenced the local area persistently within about 8 km of the outfall, and up to 10 to 20 km away on an intermittent basis spatially and temporally, nearly exclusively as increased ammonium concentrations. This is the same as in previous years, and consistent with earlier predictions from calibrated eutrophication-hydrodynamic models. Noteworthy observations made in the bays during 2020 are as follows.

- The most notable physical oceanographic events were unusually warm surface waters during the summer, relatively abrupt increases in oxygen during June, and a hypoxic event in Cape Cod Bay in September, similar to the 2019 event.
- River flow was lower than normal, there was no large spring freshet, and the summertime period was indicative of moderate drought conditions for the Merrimack River discharge.
- Variable winds over the summer resulted in periods of relatively weak upwelling interrupted by mixing events.

[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.

Table i. Contingency Plan threshold values and 2020 results for water-column monitoring.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2020
Bottom water DO[a] concentration (mg L^{-1})	Survey Mean June-October	<6.5[b]	<6.0[b]	Nearfield[c]: 6.05 SW[d] Basin: 6.23	Nearfield: 6.69 SW Basin: 7.14
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 73.1% SW Basin: 74.3%
Bottom water DO rate of decline (mg L^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.018
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	NV[e]
	Winter/spring	>199	--	50	NV
	Summer	>89	--	51	54
	Autumn	>239	--	90	102
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	NV
	Summer	>43,100	--	14,635	366
	Autumn	>27,500	--	10,500	1,150
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	45

[a]DO = dissolved oxygen [b]Unless background lower
[c]Stations within about 8 km of the outfall are referred to as "nearfield" and those further away are "farfield"
[d]SW = Stellwagen [e]NV = no value (no March/April data due to COVID-19)

- Stratification was close to the long-term median from February to June, peaked in July driven by very warm surface waters, and reached record levels in late July.
- Summer average water temperature was the warmest over the 29-year period of observations. The long-term trend shows summer surface water temperature is increasing more rapidly than air temperature.
- A driving factor for increased surface water temperature may be a change in the mean direction of summertime winds in Massachusetts Bay from a predominantly southerly direction to a southeasterly direction over the last 20 years. Southeasterly winds do not result in coastal upwelling of cold water, whereas southerly, and even more so southwesterly, winds lead to stronger upwelling and cooler surface water temperatures.
- Bay nutrient concentrations were consistent with those observed since the outfall was diverted offshore in 2000. The most notable observations in 2020 were relatively high nutrient concentrations in February, sharp decreases in nitrate (NO_3) to silicate (SiO_4) ratio in May indicative of a *Phaeocystis* bloom, and depleted surface water concentrations from May through August.
- As in other years since outfall start up, compared to the baseline years 1992-2000, the 2020 ammonium (NH_4) concentrations during both winter (unstratified) and summer (stratified) conditions were lower in Boston Harbor, higher in the outfall nearfield and vicinity (within about 10 to 20 km of the outfall), and unchanged further away.
- Overall, chlorophyll concentrations were moderate. High chlorophyll levels were observed during surveys in February in Cape Cod Bay, early May in Massachusetts Bay, and August and September across much of the monitoring area during a large dinoflagellate bloom.

- Satellite imagery and mooring measurements of fluorescence helped fill in gaps in winter/spring sampling caused by the cancellation of the March survey and postponement of the April survey until early May due to the COVID-19 pandemic. The remote sensing data showed a large increase in chlorophyll fluorescence in late February/early March likely due to a winter/spring diatom bloom, and also from mid-April to early May due to a *Phaeocystis* bloom that was still present when the early May survey was conducted.
- Bottom water dissolved oxygen (DO) concentration minima in late summer/early fall were moderate over most of Massachusetts Bay and higher than Contingency Plan thresholds. Bottom water DO concentrations were relatively low from February to June with May and June levels at or below historic minima at many stations. DO concentrations increased by ~1 mg L^{-1} from June to July, but the physical processes driving this change were not as clear as in past years when downwelling favorable winds or mixing events have been observed.
- At the Cape Cod Bay monitoring stations there was a similar summer increase in bottom water DO in July, but concentrations then decreased to low levels of 4.7 to 5.3 mg L^{-1} by late August.
- For the second year in a row, hypoxic conditions (DO < 2 mg L^{-1}) were observed by other researchers in shallow, nearshore bottom waters of southwestern Cape Cod Bay. Hypoxic bottom water DO concentrations were observed along a transect off Sandwich, Massachusetts (MA) from late August to mid-September before increasing to >6 mg L^{-1} on September 24. The combination of a large dinoflagellate bloom in August/September as a source of biomass, strong stratification, and a thin bottom layer are thought to have contributed to these low DO levels in Cape Cod Bay.
- Total phytoplankton abundance in the nearfield was consistently below the historic median. From May to October, total phytoplankton abundance was often within the lower quartile of long-term levels or below the minima. This was due to very low abundances of the usually numerically dominant microflagellates and centric diatoms over the summer and fall. In general, 2020 phytoplankton results continue the trend of relatively low abundance in the Massachusetts Bay, due to natural variability, observed since the early 2000s.
- Dinoflagellates were the only phytoplankton functional group displaying above long-term mean abundance levels during 2020, primarily due to a bloom of *Karenia mikimotoi* during August and September 2020.
- *Karenia mikimotoi*, first observed in Massachusetts Bay during 2017, appears to now be a regular component of bay phytoplankton, with abundance maxima of near 1 million cells L^{-1} observed during both 2019 and 2020. *Karenia* is a harmful algal bloom species that can cause anoxia and extensive mortality of benthic animals at high concentrations. *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.
- *Alexandrium catenella* abundances were generally low in Massachusetts Bay and the western Gulf of Maine. Elevated abundances (>100 cell L^{-1}) were observed at a few farfield stations along the South Shore in mid to late June. This triggered Alexandrium Rapid Response Study (ARRS) surveys, two of which were completed (in late June and early July), with the maximum sampled abundance 2,123 cell L^{-1}. Nearfield *Alexandrium* abundances remained low and below the Contingency Plan threshold. MA DMF did not detect any paralytic shellfish poisoning (PSP) toxicity in Massachusetts Bay in 2020.
- Due to COVID-19 protocols zooplankton were only collected in February and August to October. Zooplankton taxa, seasonal patterns and abundances over these months were generally similar to those of most previous years. However, in August and continuing into September, there was a substantial and unprecedented abundance of radiolarians throughout most of the sampling area.

LIST OF ACRONYMS

AMP	Ambient Monitoring Plan
ARRS	*Alexandrium* Rapid Response Study
ASP	Amnesiac shellfish poisoning
BHWQM	Boston Harbor Water Quality Monitoring
CCS	Center for Coastal Studies
DO	Dissolved oxygen
EM&MS	Environmental Monitoring and Management System
EPA	U.S. Environmental Protection Agency
MA DMF	Massachusetts Division of Marine Fisheries
MA DEP	Massachusetts Department of Environmental Protection
MODIS	Moderate-resolution Imaging Spectroradiometer
MWRA	Massachusetts Water Resources Authority
NERACOOS	Northeastern Regional Association of Coastal and Ocean Observing Systems
NH DES	New Hampshire Department of Environmental Services
NH_4	Ammonium
NO_3	Nitrate
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
PO_4	Phosphate
PSP	Paralytic shellfish poisoning
QAPP	Quality Assurance Project Plan
SiO_4	Silicate
WHOI	Woods Hole Oceanographic Institution
WMCC	Western Maine Coastal current

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 major revisions MWRA 2004, 2010). During the baseline period, from 1992 to September 5, 2000, Deer Island and/or Nut Island wastewater discharges were released directly within the harbor. The outfall discharge period extends from September 6, 2000 through 2020, when wastewater has been discharged from the bay outfall and not into the harbor. The 2020 data complete 20 years of monitoring since operation of the bay outfall began and 29 years of monitoring since the program began in 1992. **Table 1-1** shows the timeline of major upgrades to the MWRA wastewater treatment system.

Table 1-1. Major upgrades to the MWRA treatment system.

Date	Upgrade
December 1991	Sludge discharges ended
January 1995	New primary plant online
December 1995	Disinfection facilities completed
August 1997	Secondary treatment begins to be phased in
July 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 tunnel from Deer Island to Fore River in operation
2005	Improved removal of total suspended solids (TSS), etc. due to more stable process
2010	Major repairs and upgrades to primary and secondary clarifiers

Based on the scientific understanding gained since monitoring started in 1992, MWRA's Effluent Outfall Ambient Monitoring Plan (AMP) was revised to focus on stations potentially affected by the discharge, and reference stations in Massachusetts Bay (MWRA, 2010). The AMP calls for nine one-day water column surveys to be conducted each year. Unfortunately, in 2020, the COVID-19 pandemic resulted in cancelation of the March survey in Massachusetts Bay and postponement of the April survey until early May (**Table 1-2**). The surveys were modified to meet COVID-19 mitigation protocols established by Woods Hole Oceanographic Institution (WHOI) for conducting field work on the *R/V Tioga*. To meet the social distancing guidelines, the Battelle scientific field team was reduced from six to three staff, which required a commensurate reduction in sampling. After MWRA notified EPA and Massachusetts Department of Environmental Protection (MA DEP), sample collection was modified to focus on measurements directly related to Contingency Plan thresholds including in situ oceanographic parameters, dissolved inorganic nutrients, chlorophyll, and phytoplankton samples (whole water community analyses and *Alexandrium* counts). In August, a fourth scientist was able to be added to the surveys allowing for sampling of particulate carbon/nitrogen and zooplankton to resume.

The monitoring 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. Two additional surveys were conducted in late June and early July 2020 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**.

This annual report summarizes the 2020 water column monitoring results, examines conditions over the seasonal cycle during 2020, 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 (DO) 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 (**Table i**; MWRA 2001).

Table 1-2. Water column surveys for 2020.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN201	February 11	February11	February 5
WN202	*	March 28**	
WN203	May 4**	May 4**	
WN204	May 18	May 17	
WN205	June 16	June 16	June 23
AF201	June 25	n/a	
AF202	July 9	n/a	
WN206	July 14	July 16	
WN207	August 19	August 19	August 17
WN208	September 2	August 31	September 2
WN209	October 20	October 19	October 21

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.
* Cancelled due to COVID-19. **Delayed due to COVID-19.

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. 2021). 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 2020 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 2021) all sampling locations (**Figure 1-1**) are visited during each of the nine planned surveys per year; the 2020 sampling dates are shown in **Table 1-2**. Five stations are sampled in the nearfield (N01, N04, N07, N18, and N21) and nine stations in the farfield (F01, F02, F06, F10, F13, F15, F22, F23, and F29). The 11 stations in Massachusetts Bay are sampled for a comprehensive suite of water quality parameters, including plankton, at all stations except N21 directly over the outfall. The Massachusetts Bay stations were sampled during one-day surveys; within two days of those dates the three Cape Cod Bay stations were sampled by CCS. Nutrient data from these three Cape Cod Bay stations are included in this report. CCS also has an ongoing water quality monitoring program at eight other stations in Cape Cod Bay.[2] MWRA collects samples at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally biweekly frequency.[3] The BHWQM data (nutrient and DO) collected within 7 days (**Table 1-2**) of an AMP survey are included in this report. During the two ARRS surveys in 2020, 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. In 2020, a marine mammal observer was only present on the February AMP survey in Massachusetts Bay due to COVID-19 mitigation protocols limiting survey staffing on the surveys conducted from May to October. However, the field team and *R/V Tioga* crew did watch for marine mammals and noted all observations. Marine mammal observations made by field staff on the AMP, 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 2020 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 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. The cancellation of the March AMP survey in Massachusetts Bay and postponement of the April survey until early May resulted in no results being available for comparison to thresholds for winter/spring and annual chlorophyll and winter/spring *Pseudo-nitzschia*. 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 2020. 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.com/harbor/graphic/harbor_sampling_locations_detail.jpg

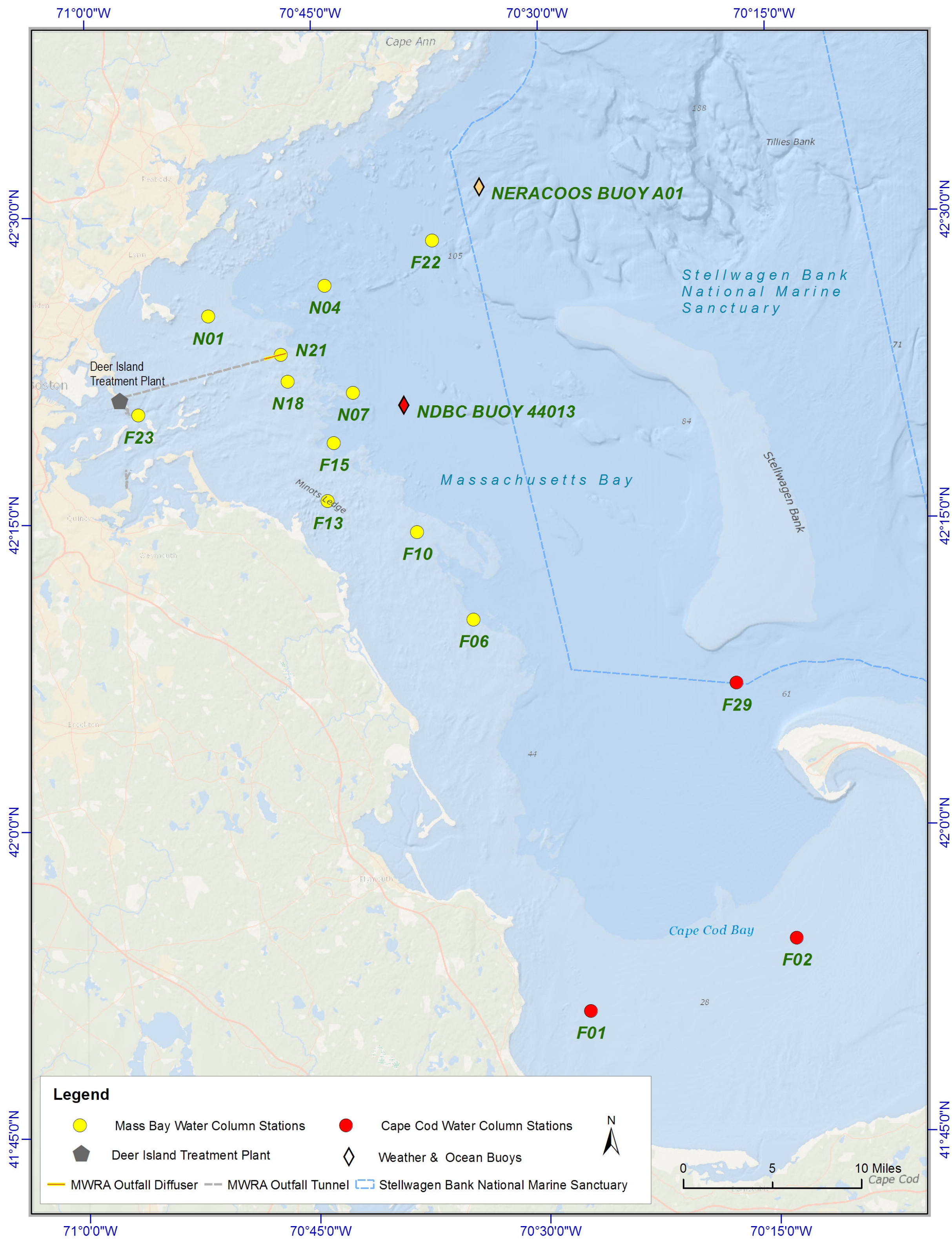

Figure 1-1. Water column monitoring locations.

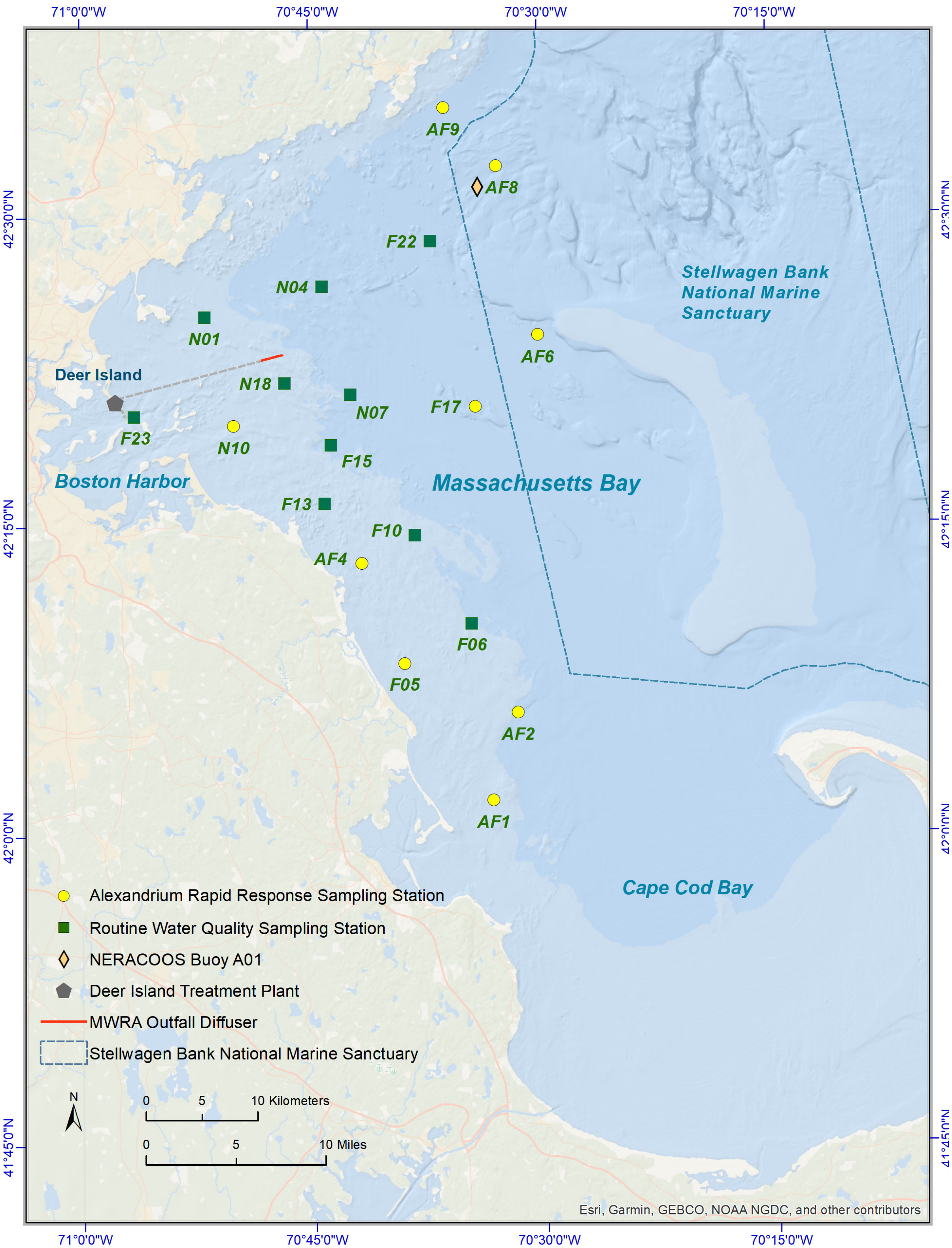

Figure 1-2. ***Alexandrium* Rapid Response Study monitoring locations.**

2 2020 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 and due to interannual variability.

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 (PSP), 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 29-year dataset (1992-2020). In 2020, the COVID-19 pandemic led to changes in the monitoring program impacting the timing of the surveys and limiting the breadth of samples collected (e.g., no zooplankton data from March through July). Remote sensing data sources supplemented the loss of March/April 2020 data and adding staff for the August to October surveys provided an opportunity to resume zooplankton sampling. The major features and differences observed in 2020 are described below.

2.2 PHYSICAL CONDITIONS

Air temperatures were warmer than average and surface water temperatures were close to maximum from January through March 2020 compared to the previous 31 years 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 historic median levels and stayed close to them into June (**Figure 2-2**). This was also the case for surface water at station F22 south of Cape Ann, but the deep bottom waters at this station were warmer than normal, in the upper quartile of historic temperatures from February to June 2020.

Merrimack and Charles River flows were slightly lower than normal in 2020 (**Figure 2-3**). January through March were slightly higher than normal for the Merrimack, but it had no large spring freshet in 2020 and the summertime period was indicative of moderate drought conditions. This was a departure from the previous two years which had relatively high flows (Libby et al. 2019 and 2020). Massachusetts Bay surface-water salinity (not shown) was slightly higher than average in 2020, consistent with the low river flows. Station average salinity values were close to or above historic median values for each of the 2020 surveys.

Winds showed the typical annual pattern, with strong winds in the winter, spring and fall and generally weaker winds during the summer. Waves (not shown) also had a typical annual pattern but with several notable wave events in March and April having wave heights exceeding 5 m. There was a strong Nor'easter in mid-April, but no strong northeasterlies during May, a time period when *Alexandrium* could be transported into Massachusetts Bay from the Gulf of Maine if present in offshore waters. Variable winds were observed over June and July with periods of persistent, weak upwelling interrupted by downwelling events, and strong upwelling in early August that abruptly cooled the surface water (**Figure 2-4**). An August Nor'easter also led to downwelling/vertical mixing cooling surface waters.

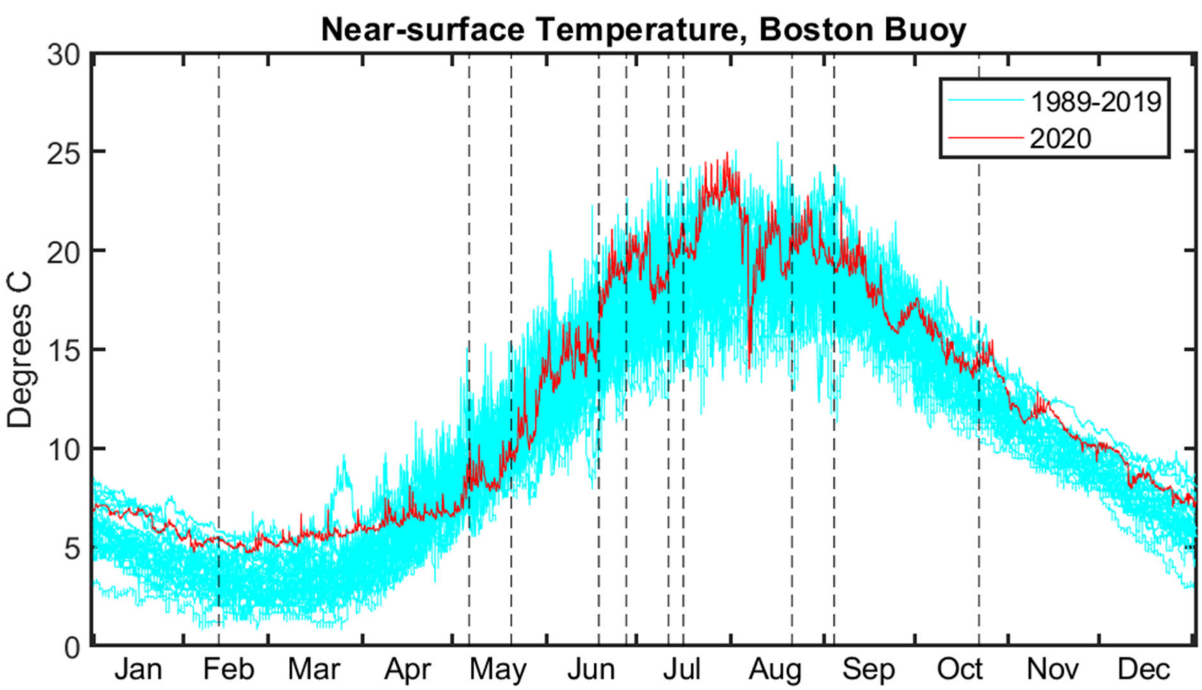

Figure 2-1. Comparison of 2020 (solid red line) surface water temperature (°C) at Buoy 44013 ("Boston Buoy") in the vicinity of the nearfield with 1989-2019 (cyan lines). The vertical dashed lines are when the 10 surveys were conducted in 2020.

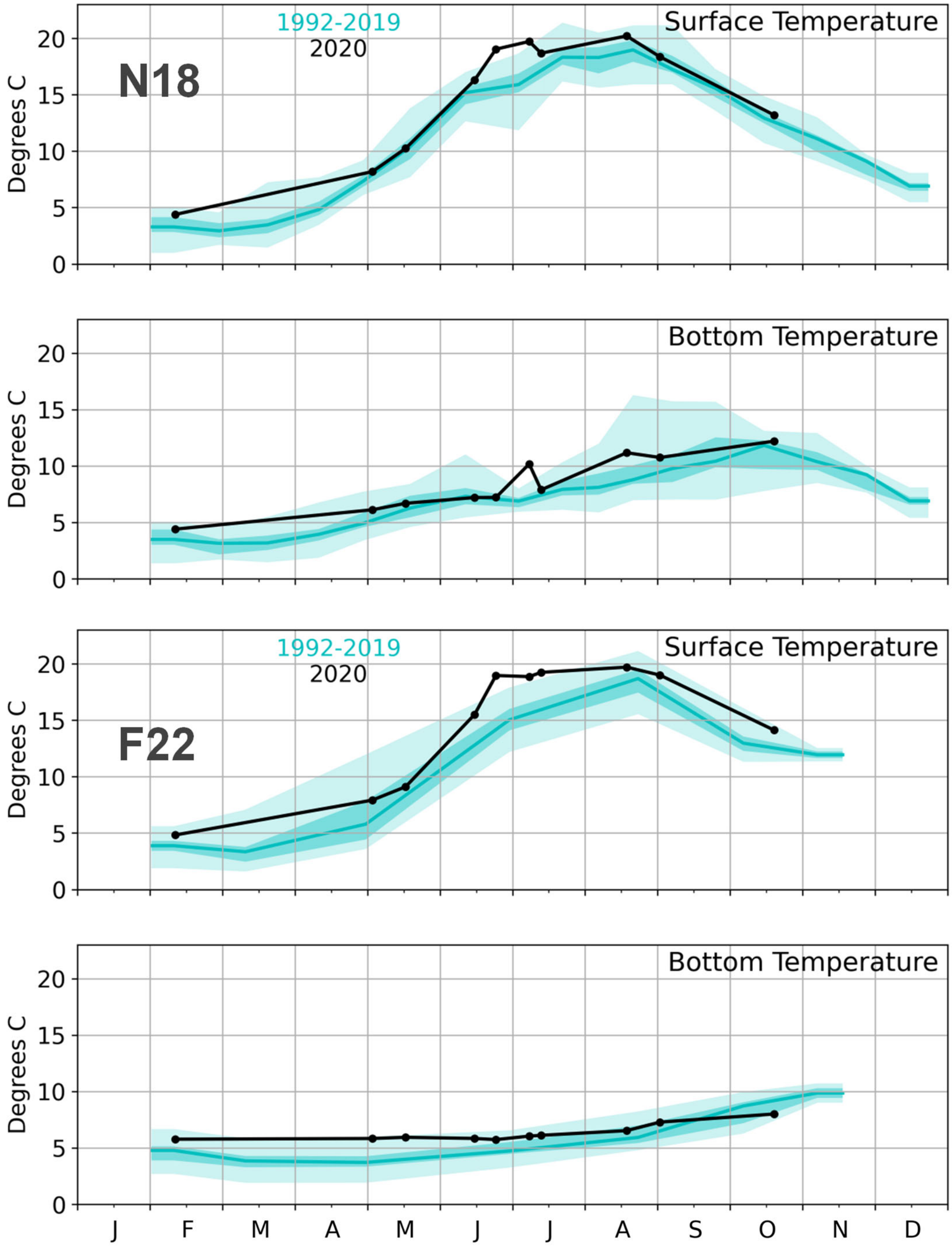

Figure 2-2. Comparison of 2020 surface and near bottom water temperature (°C) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

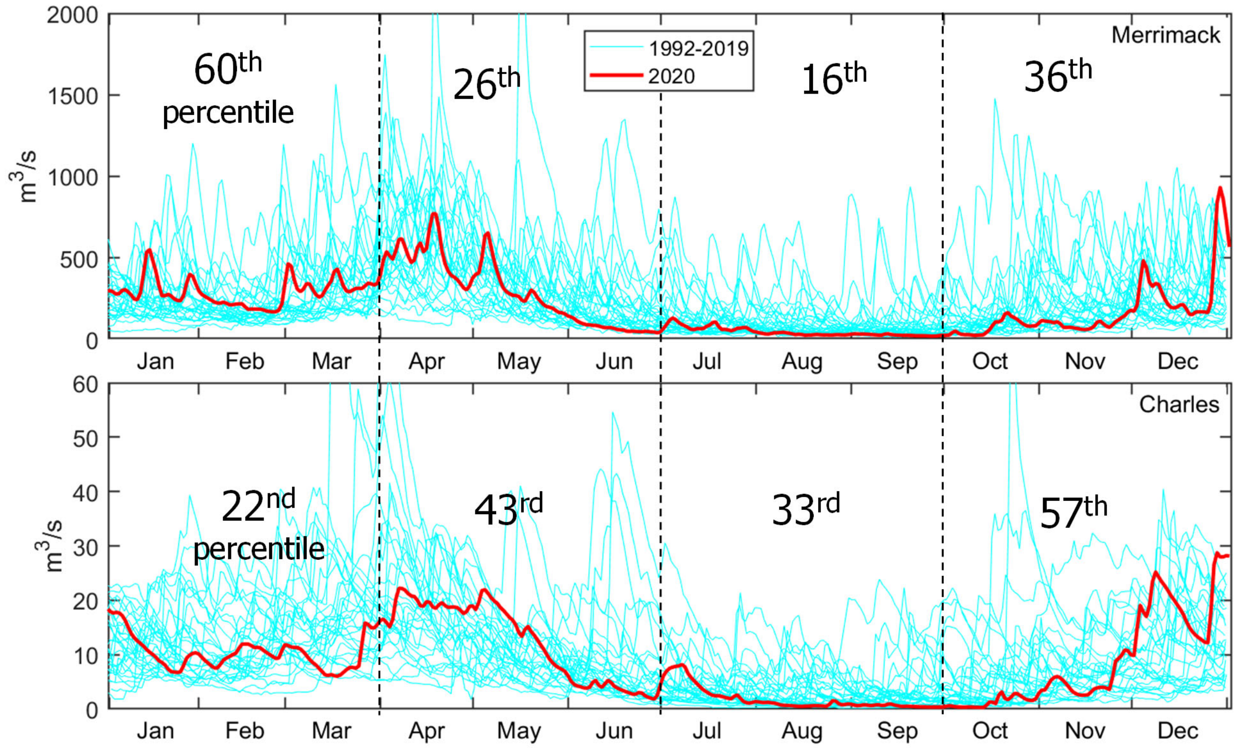

Figure 2-3. Comparison of 2020 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2019 (light blue lines). The percentiles represent 2020 flow, compared to the entire 29-year record, during each quarter of the year.

The mixing event in early July resulted in lower surface water temperatures and a commensurate increase in temperatures at 20 m at the NOAA buoy due to mixing of warm surface waters with deeper, cooler water (**Figure 2-4**). The impact on bottom water temperatures was observed at station N18 with an increase of 2°C on the early July survey to levels above the historic maxima (**Figure 2-2**). In August, upwelling events and the Nor'easter resulted in a sharp decrease in surface water temperatures. The timeseries of moored temperature measurements provides a look at the events that are not resolved by the bi-weekly to monthly shipboard sampling. Sharp rises in temperature at the NERACOOS buoy A01 20-m instrument are indicators of downwelling events including the mid-August Nor'easter (**Figure 2-4**).

Stratification in Massachusetts Bay was close to the long-term median from February to June (**Figure 2-5**). Stratification peaked within the upper quartile of the historical values in July driven by very warm surface waters which reached record levels in late July (**Figure 2-1**). Summer average water temperature shows that 2020 temperatures were the warmest over the 29-year period of observations, and the long-term trend shows that surface water temperature is increasing more rapidly than air temperature (**Figure 2-6**). This difference may be due to regional rather than local influences on the water temperature. Analysis performed by Malcolm Scully from WHOI (personal communication, April 2021) indicates that the mean direction of summertime winds in Massachusetts Bay has shifted from the southerly direction to the southeasterly direction over the last 20 years. This shift in winds may explain the general warming tendency, as southeasterly winds do not result in coastal upwelling of cold water, whereas southerly, and even more so southwesterly, winds lead to stronger upwelling and cooling of surface waters. The upwelling index was close to the long-term median in June and July 2020, but weaker upwelling was observed in August (**Figure 2-7**). Overall, intermittent downwelling/upwelling predominant winds, the Nor'easter in August, and the predominance of southeasterly winds resulted in relatively weak upwelling over the summer stratified period in 2020.

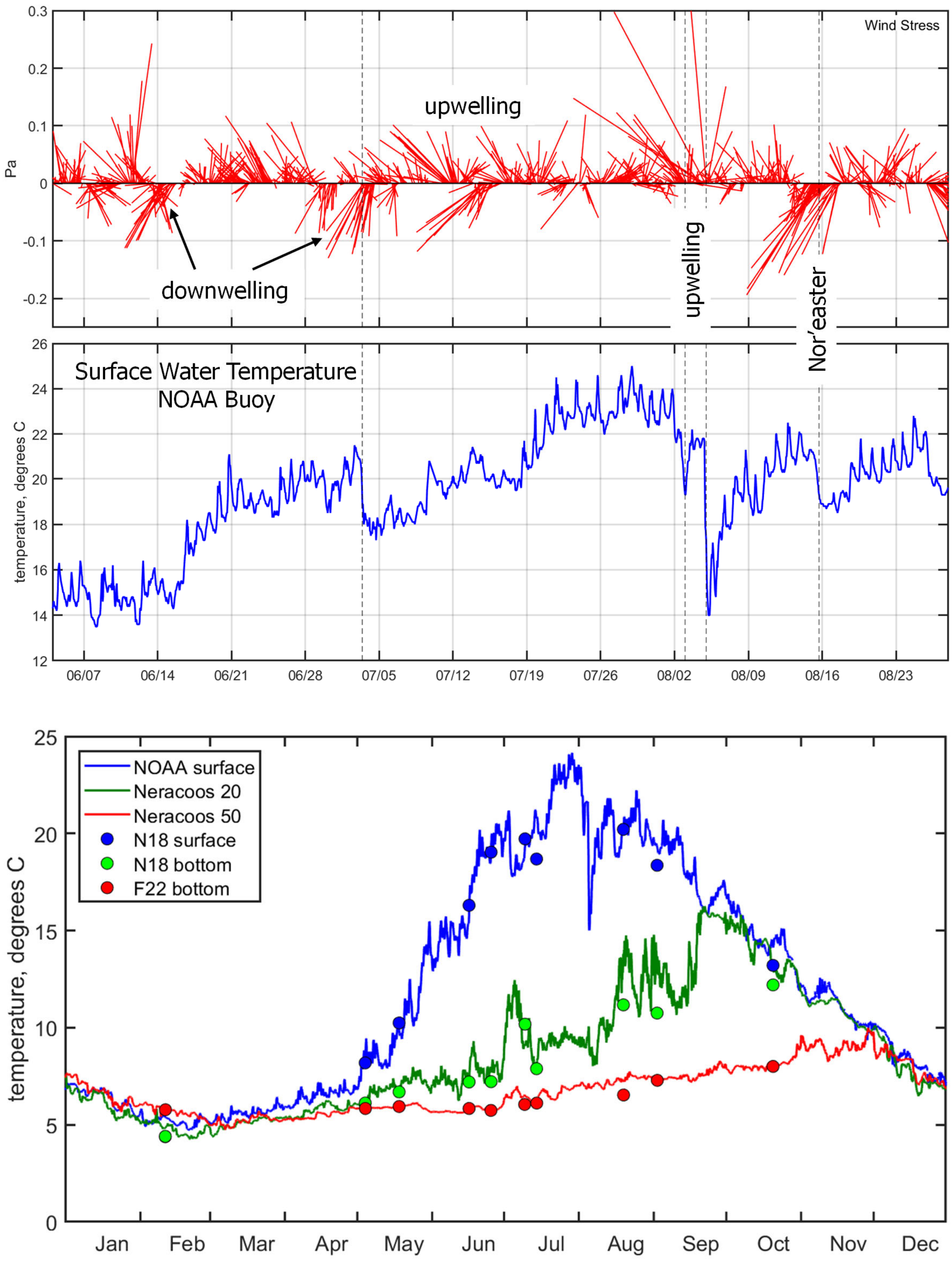

Figure 2-4. NOAA Buoy 44013 and NERACOOS Buoy A01 time series observations in 2020. Top: surface wind stress (Pa) and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right) and surface water temperature (°C) at Buoy 44013. Bottom: temperature (°C) at multiple depths at the buoys and nearby stations N18 and F22.

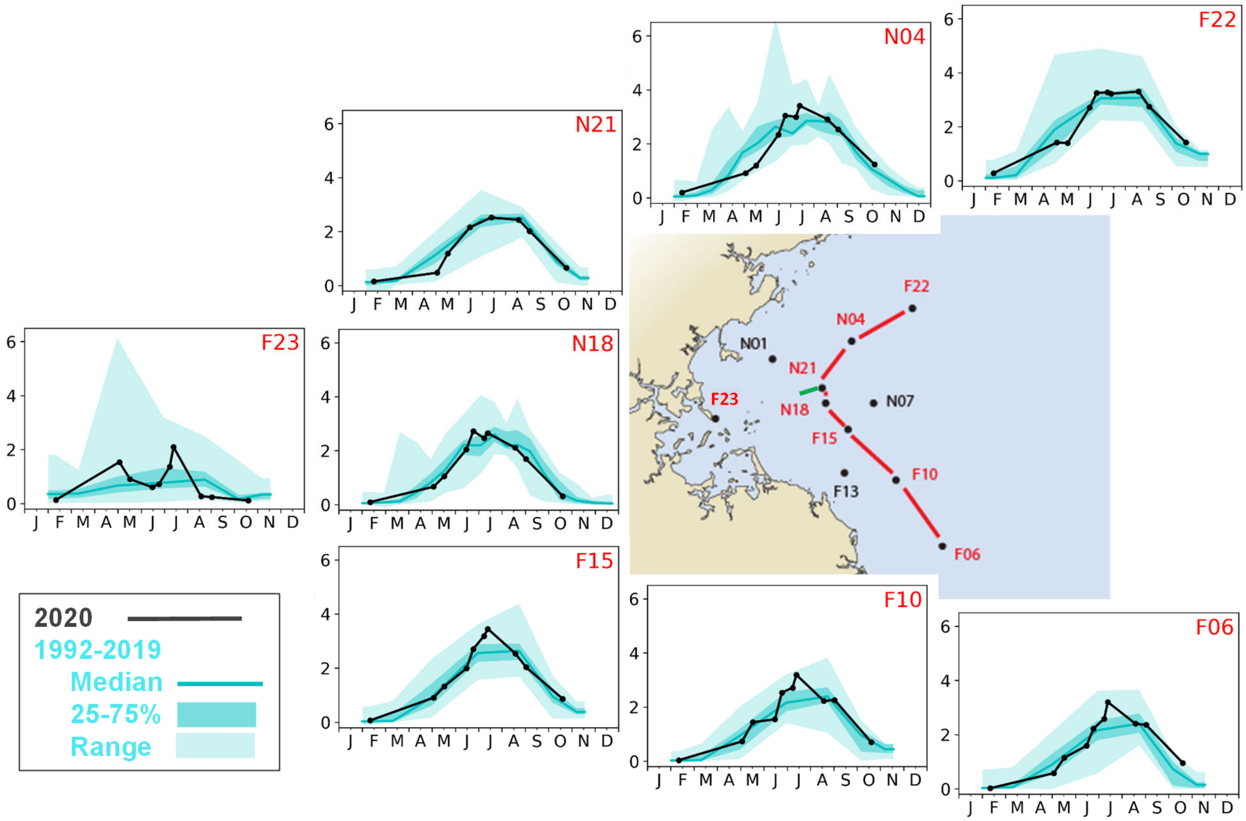

Figure 2-5. Stratification (Δ sigma-T; kg m^{-3}) at selected stations in Massachusetts Bay for 2020 compared to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Stratification in Massachusetts Bay remained strong in early September before decreasing in October (**Figure 2-5**). The shallower inshore stations were well mixed in October, but at the deeper offshore stations stratification persisted until after the late October survey. At Buoy A01, timeseries data clearly show the timing of destratification at the different depths, occurring at 20 m at the end of September, and at the 50-m depth in late November (**Figure 2-4**).

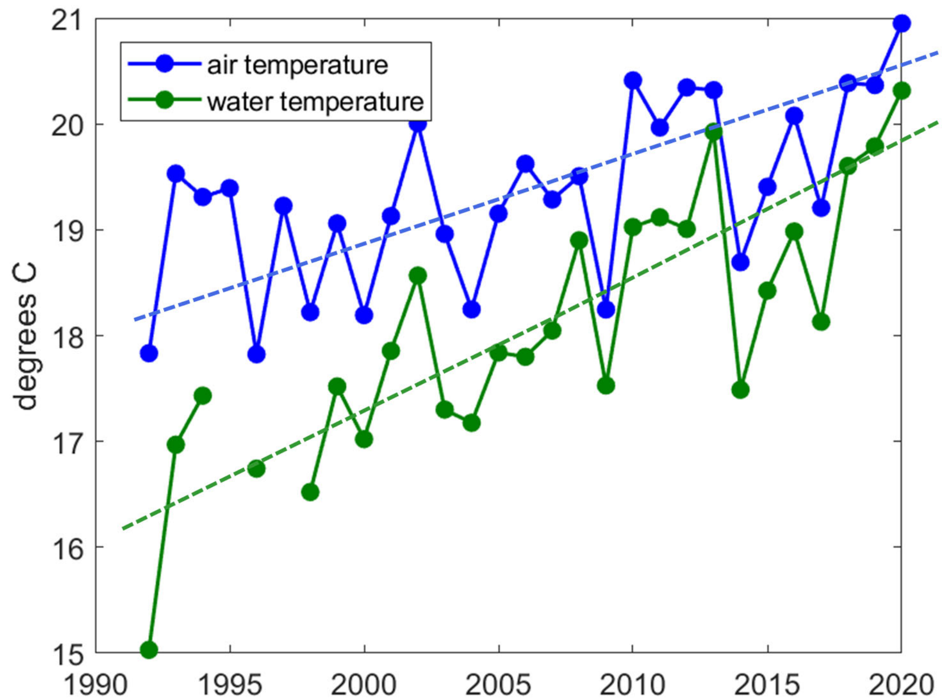

Figure 2-6. Comparison of average mid-June to mid-August air and surface water temperature (°C) at Buoy 44013 in the vicinity of the nearfield from 1992-2020.

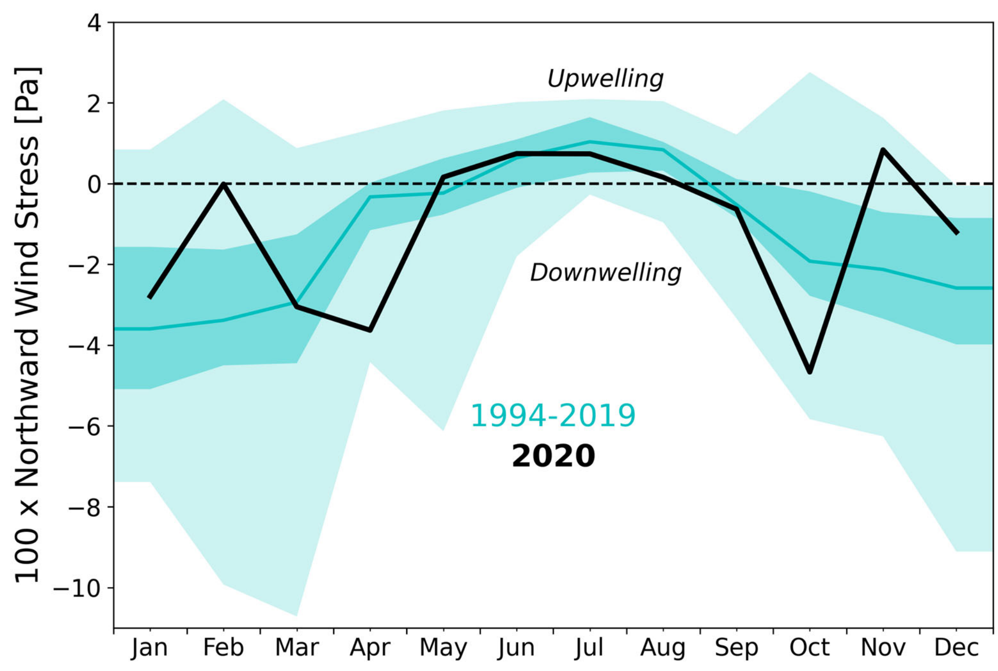

Figure 2-7. Upwelling index (100 x Northward component of wind stress; Pascals) at NOAA Buoy 44013. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

This section documents dissolved inorganic nutrient concentrations and phytoplankton biomass in the bay during 2020. It also quantifies the spatial extent of the outfall's nutrient and chlorophyll biomass signals.

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 cycles of nutrient inputs from rivers and the Gulf of Maine and phytoplankton uptake. Concentrations tend to be elevated from February into April, relatively low from May into August or September, and then increase into November-December. At station N18, located in the nearfield and 1 km south of the outfall, NO_3, SiO_4 and PO_4 all showed this basic seasonal pattern in 2020 (**Figure 2-8**). Ammonium (NH_4) (**Figure 2-8**, upper right), which typically does not exhibit this seasonal pattern at N18, was quite variable in 2020 with peaks in February, June, and September.

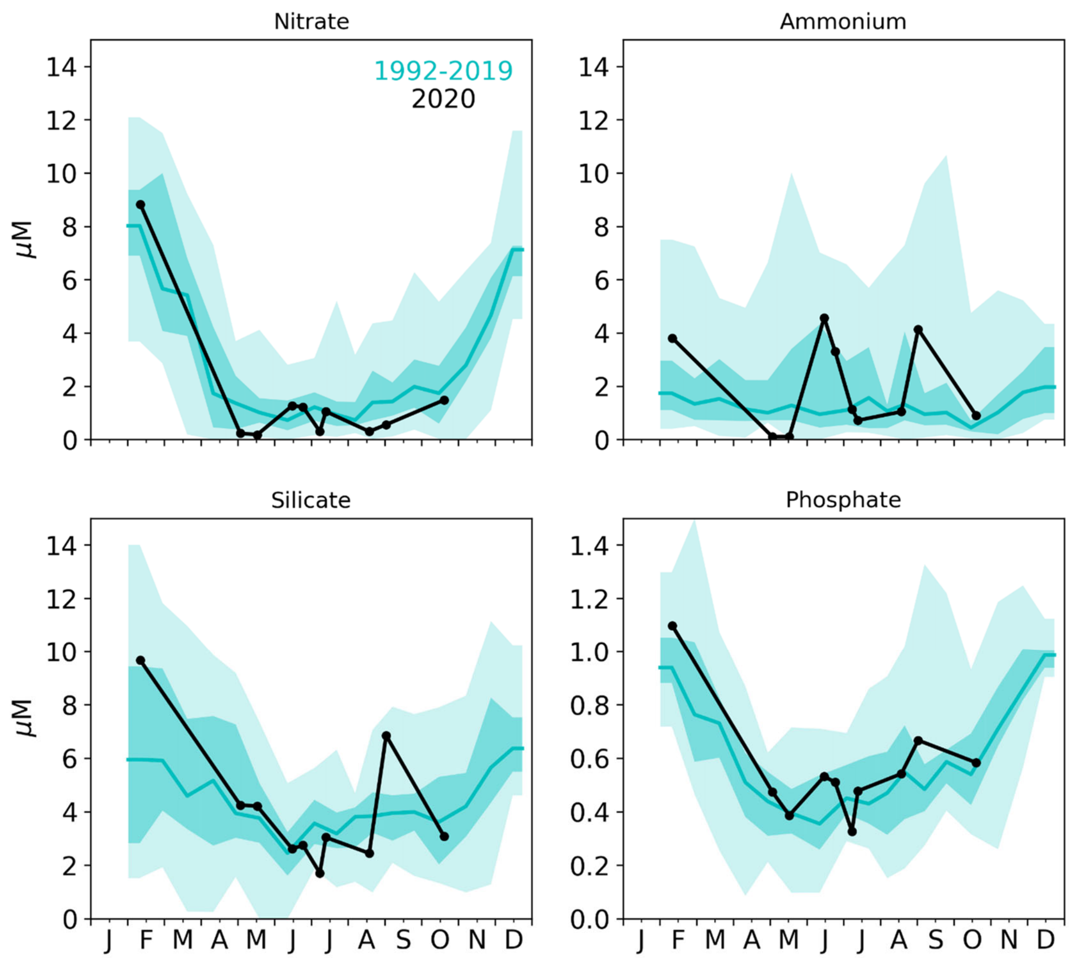

Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2020 compared to prior years. Note difference in scale for phosphate. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Nutrient concentrations in Massachusetts Bay as a whole were high in February 2020 with concentrations above the historic median and in the upper quartile of the historic range at many stations (**Figure 2-8** and **Figure 2-9**). The COVID-19 pandemic delayed sampling until early May by which time nitrogen (NO_3 and NH_4) concentrations were depleted throughout Massachusetts Bay. Levels of SiO_4 and PO_4 had decreased by ~50% since February but remained available in the water column at close to historic median levels (**Figure 2-8**). Low NO_3 relative to SiO_4 concentrations such as this are often associated with blooms of *Phaeocystis*, a phytoplankton that unlike diatoms, consumes NO_3 but not SiO_4.

Survey mean NO_3 levels remained depleted and near historic minima for the rest of May before increasing slightly in June and July (**Figure 2-9**). Overall, nutrients were low to depleted in the surface waters from May to August but were available below the pycnocline in higher concentrations as is typically observed during summer stratified conditions. Station average nutrient concentrations varied over the summer but were close to the historic median. Ammonium concentrations were more variable over the course of the summer in the nearfield as has been the case since the bay outfall came online in 2000 (**Figure 2-10**). In August and September, NO_3 was depleted at all but the deeper offshore stations (**Figure 2-9**), while SiO_4 levels increased from August to September (**Figure 2-8**). This change coincided with a major bloom of dinoflagellates dominated by *Karenia mikimotoi*. By October, NO_3 levels had increased close to historic median levels, but SiO_4 decreased at offshore Massachusetts Bay stations coincident with the increase in centric diatoms (see below) from September to October.

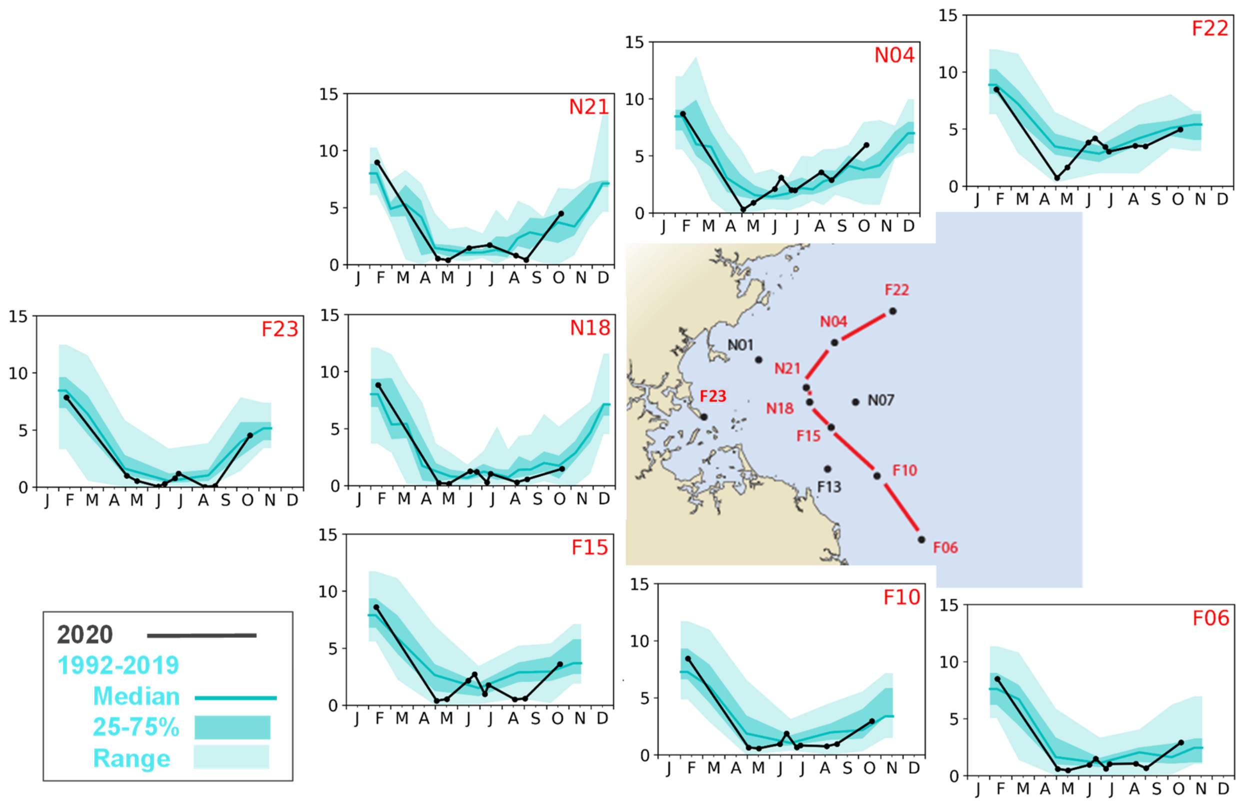

Figure 2-9. Depth-averaged NO_3 (µM) at selected stations in Massachusetts Bay for 2020 compared to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

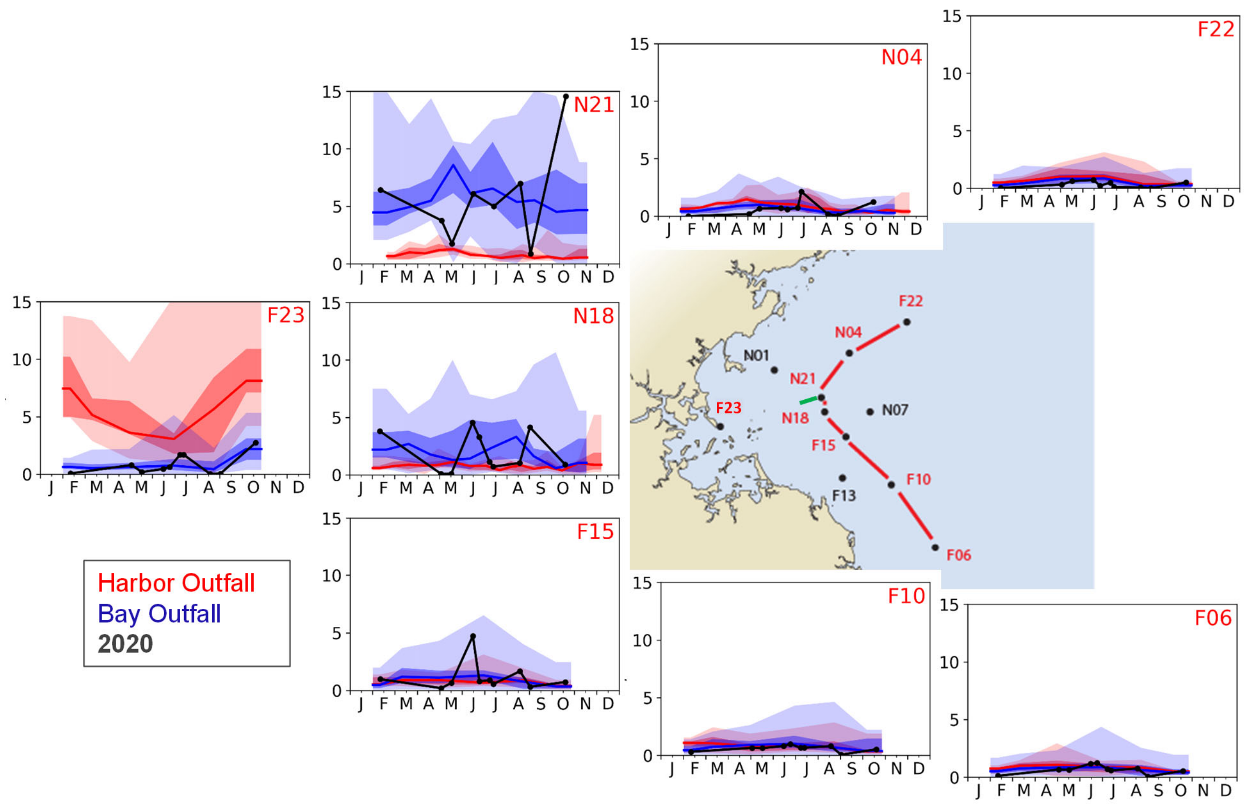

Figure 2-10. Depth-averaged NH_4 (µM) at selected stations in Massachusetts Bay for 2020 compared to prior years. 2020 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2019) results are in blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

As in other years since bay outfall startup, NH_4 concentrations at stations N21 and N18, and during summers at station F15, were higher than during years effluent was discharged to the harbor (**Figure 2-10**). In 2020, episodic peaks in NH_4 were observed at these three stations. At stations N18 and N21, there was a high degree of variability in NH_4 concentrations from nearly depleted in May to peaks in the upper quartile at station N18 in February, June, and September, while an annual maximum of nearly 15 µM was observed at station N21 in October. In mid-June, station average NH_4 concentrations of about 5 µM were observed at stations N21, N18, and F15. Ammonium concentrations at Boston Harbor station F23 in 2020, again as in other post-discharge years, were much lower than during the years the wastewater was discharged directly to the harbor.

As can be seen in **Figure 2-10**, in 2020, as in other years since the bay outfall became operational, the NH_4 signal from the effluent discharge plume was observed intermittently within 10 to 20 km of the outfall. In February, when the water column was vertically well mixed, the NH_4 plume signature was most pronounced in the nearfield surface waters (**Figure 2-11**). During the June survey, when the water column was vertically stratified with a pycnocline located at about 10 m, high NH_4 levels (>8 µM) were observed at or below the pycnocline at nearfield stations N21 and N18, and about 10 km south of the outfall at station F15 (**Figure 2-12**). During the stratified June survey, NO_3 concentrations (2 to 4 µM) were also elevated below the pycnocline with higher concentrations (4-8 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 >8 µg L^{-1} at station F15 (**Figure 2-13**).

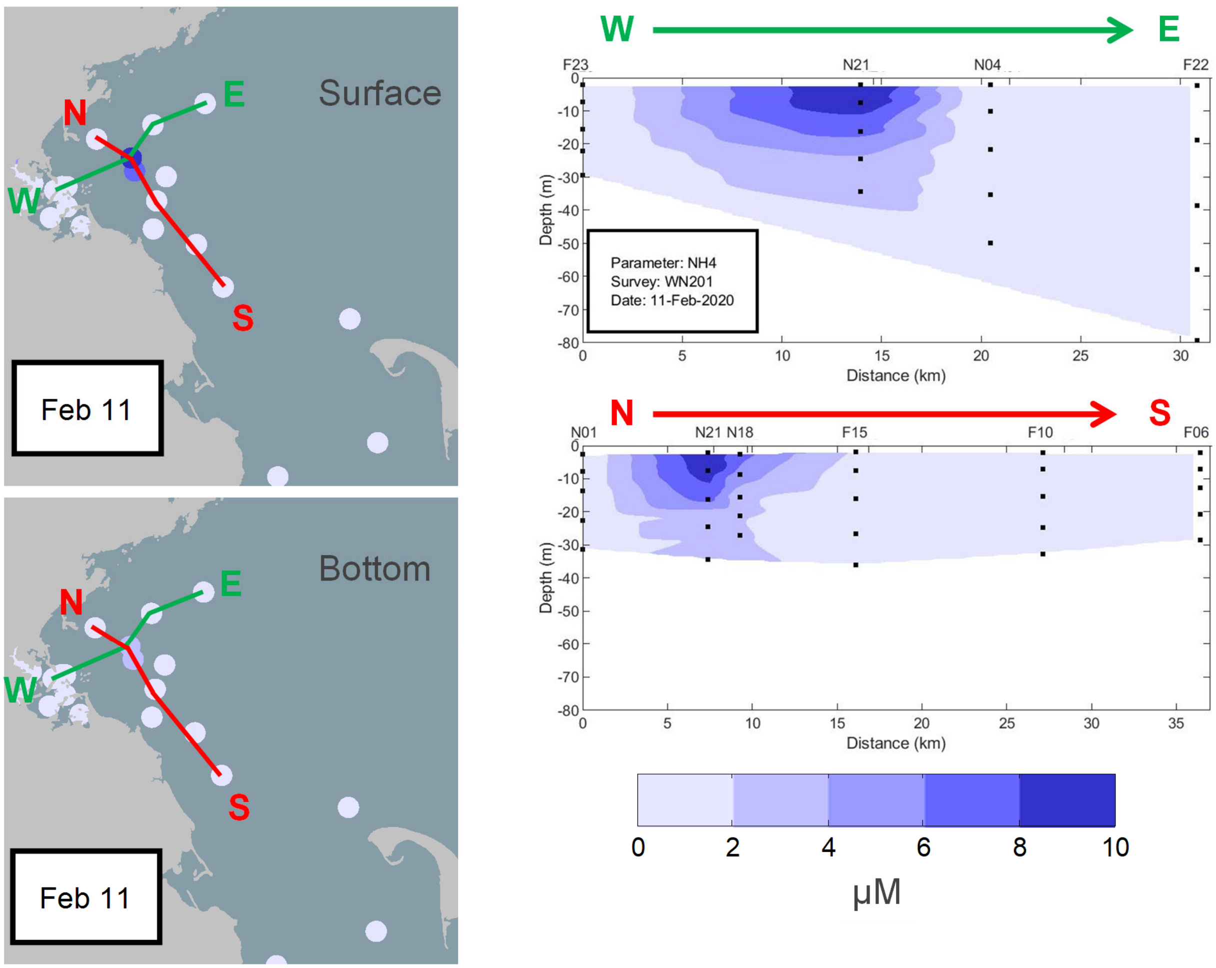

Figure 2-11. (Left) Surface and bottom water NH_4 on February 11, 2020 during unstratified conditions. (Right) Cross-sections of water column concentrations along transects connecting selected stations. Small black dots in the plots at right indicate the sampling depths for nutrients.

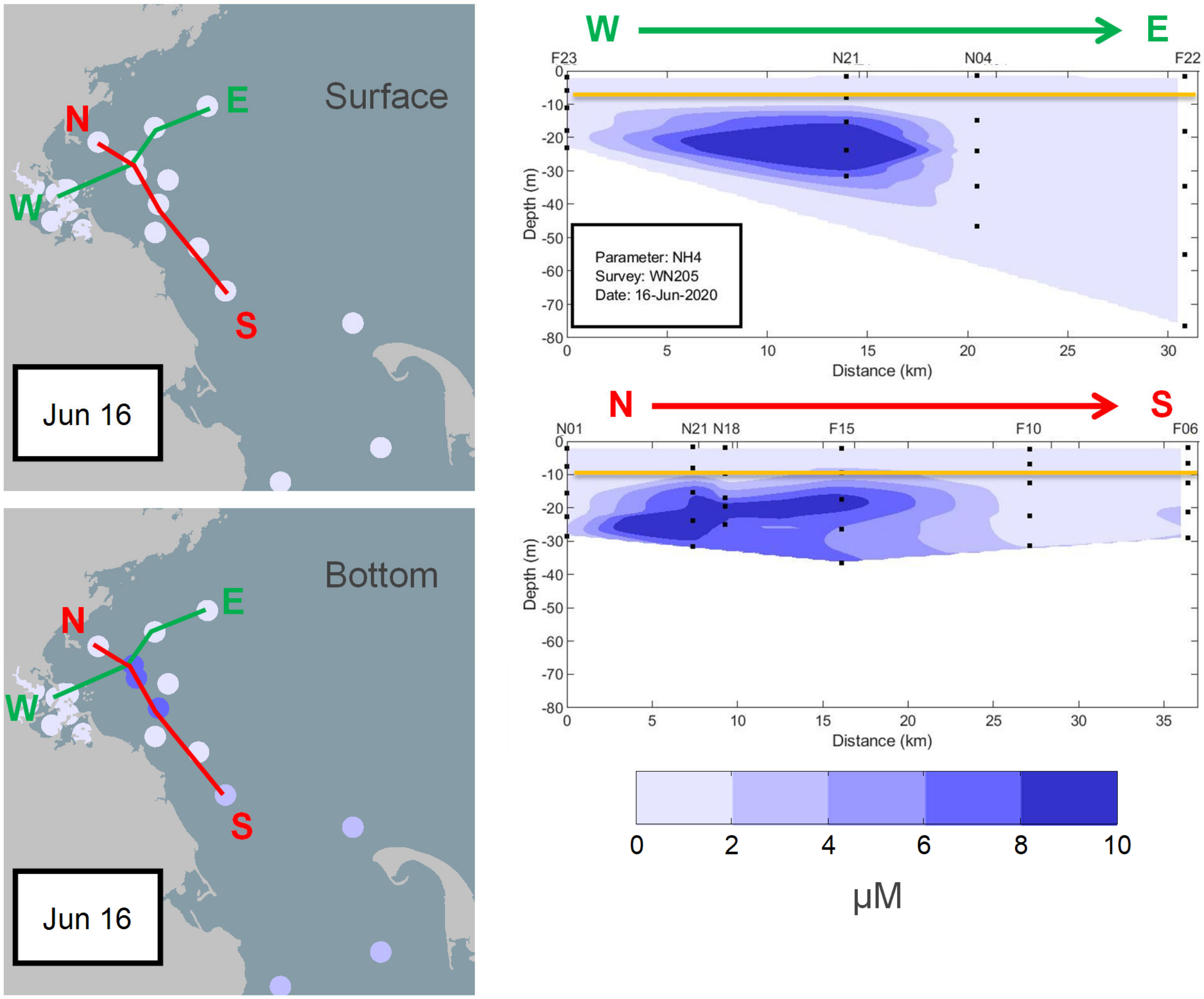

Figure 2-12. Surface and bottom water NH_4 on June 16, 2020 during stratified conditions. Presented as Figure 2-11, with orange line in frames at right indicating the approximate depth of the pycnocline.

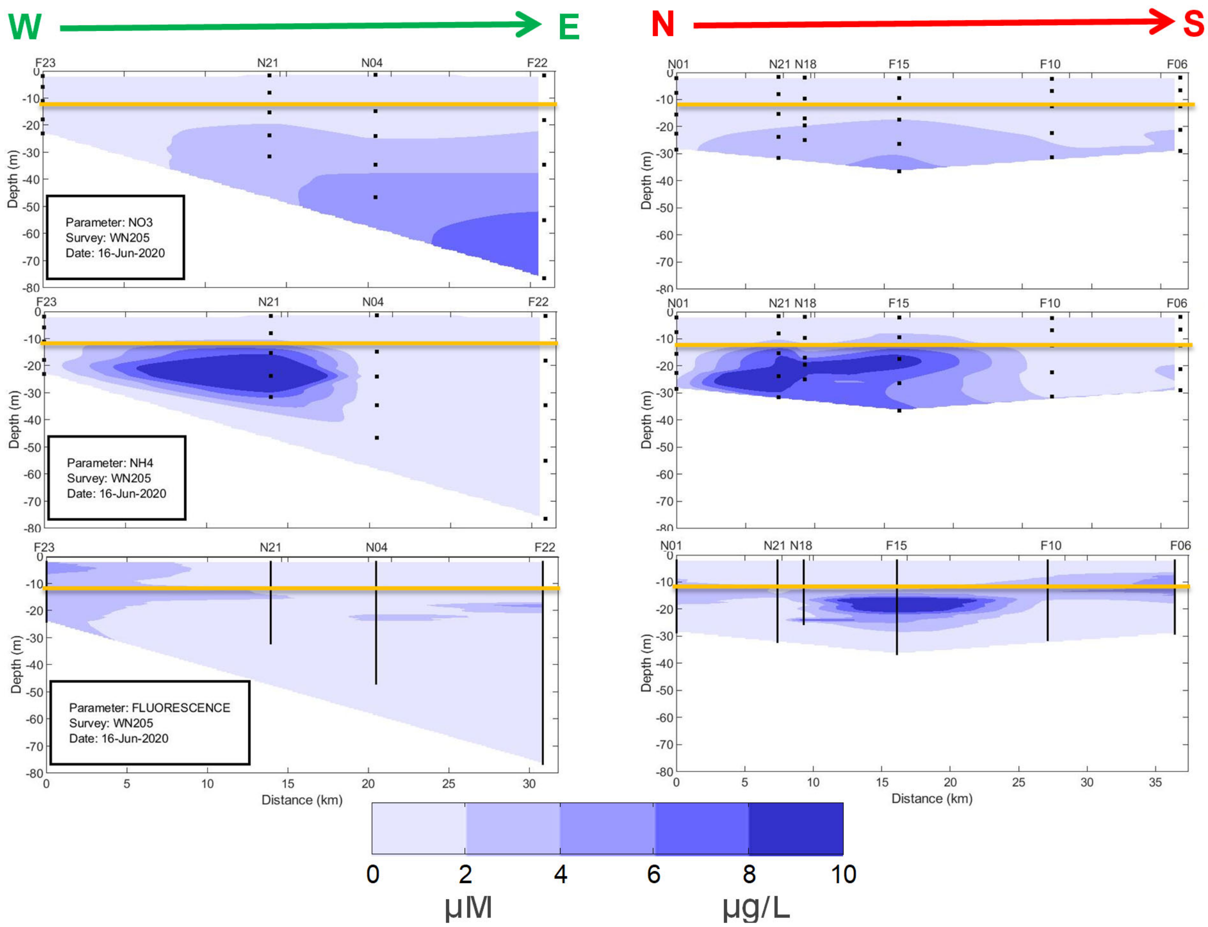

Figure 2-13. Nitrate (top; µM), ammonium (middle; µM), and chlorophyll from fluorescence (bottom; µg L^{-1}) during the stratified June 2020 survey along the east-west (left column) and north-south (right column) transects shown in Figure 2-12. Dots (nutrients) and lines (fluorescence) indicate the sampling 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 again during the 2020 surveys, though the timing of the peaks varied across the region. High areal chlorophyll levels were observed during the February survey in Cape Cod Bay, the early May survey in Massachusetts Bay, and in August and September across much of the monitoring area during a large dinoflagellate bloom (**Figure 2-15**).

MODIS imagery and NERACOOS Buoy A01 provided useful information on chlorophyll during the March-April period when, because of the COVID-19 pandemic, the shipboard surveys were cancelled/postponed. Both the satellite and the buoy observations showed a large increase in chlorophyll fluorescence in late February/early March that was likely associated with a winter/spring diatom bloom (**Figure 2-16** and **Figure 2-17**). High chlorophyll levels were also seen from mid-April to early May likely associated with the *Phaeocystis* bloom that was still present when the early May survey was conducted. Chlorophyll was elevated during the early May survey, with values at many stations in Massachusetts Bay in the upper quartile compared to historic data (**Figure 2-14**).

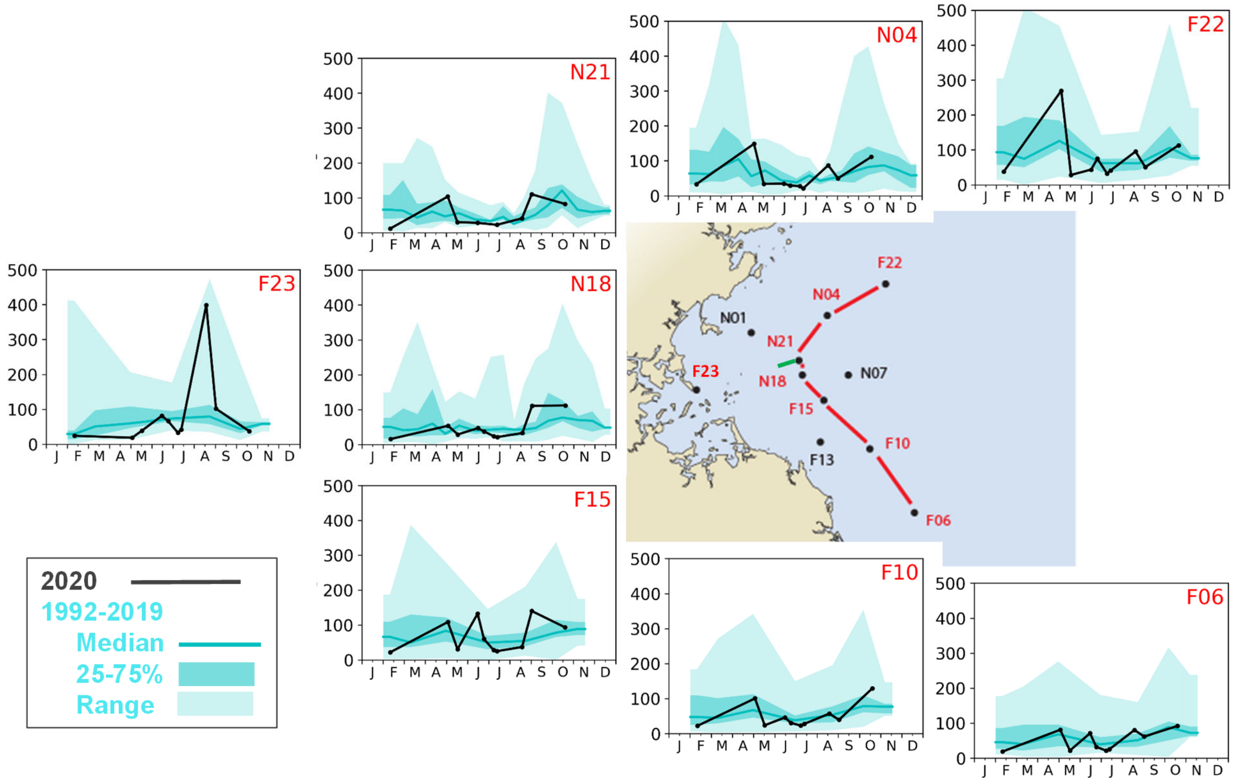

Figure 2-14. Areal chlorophyll from fluorescence (milligram per meter squared [mg m^{-2}]) at representative stations in Massachusetts Bay for 2020 compared to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Chlorophyll decreased by mid-May and remained low through July in both Massachusetts and Cape Cod Bays (**Figure 2-14** and **Figure 2-15**). By mid-August and early September, chlorophyll in Boston Harbor and nearshore stations had increased to the highest levels observed during 2020. In the harbor, areal chlorophyll reached levels comparable to those observed in August 2019 and about five times the historic median level for August (**Figure 2-14**). In Cape Cod Bay, chlorophyll levels remained high during both the August and September surveys (**Figure 2-15**). Dinoflagellates dominated by *Karenia mikimotoi* were responsible for the August/September increase. Chlorophyll at the offshore Massachusetts Bay stations increased from September to October: An increase in centric diatoms between these surveys (largely *Thalassiosira* and *Leptocylindrus*) were responsible for the increase. Based on the MODIS and buoy observations, chlorophyll was elevated in the bay after the October 20th survey, with elevated levels from early November to mid-December (**Figure 2-16** and **Figure 2-17**).

The seasonal summer and fall average chlorophyll values in 2020 were moderate, comparable to baseline seasonal averages and well below the Contingency Plan threshold levels (**Table i**). Due to the cancellation of the March survey and delay of the April survey to early May because of the COVID-19 pandemic, no calculations were made for winter/spring or annual chlorophyll averages for threshold comparisons.

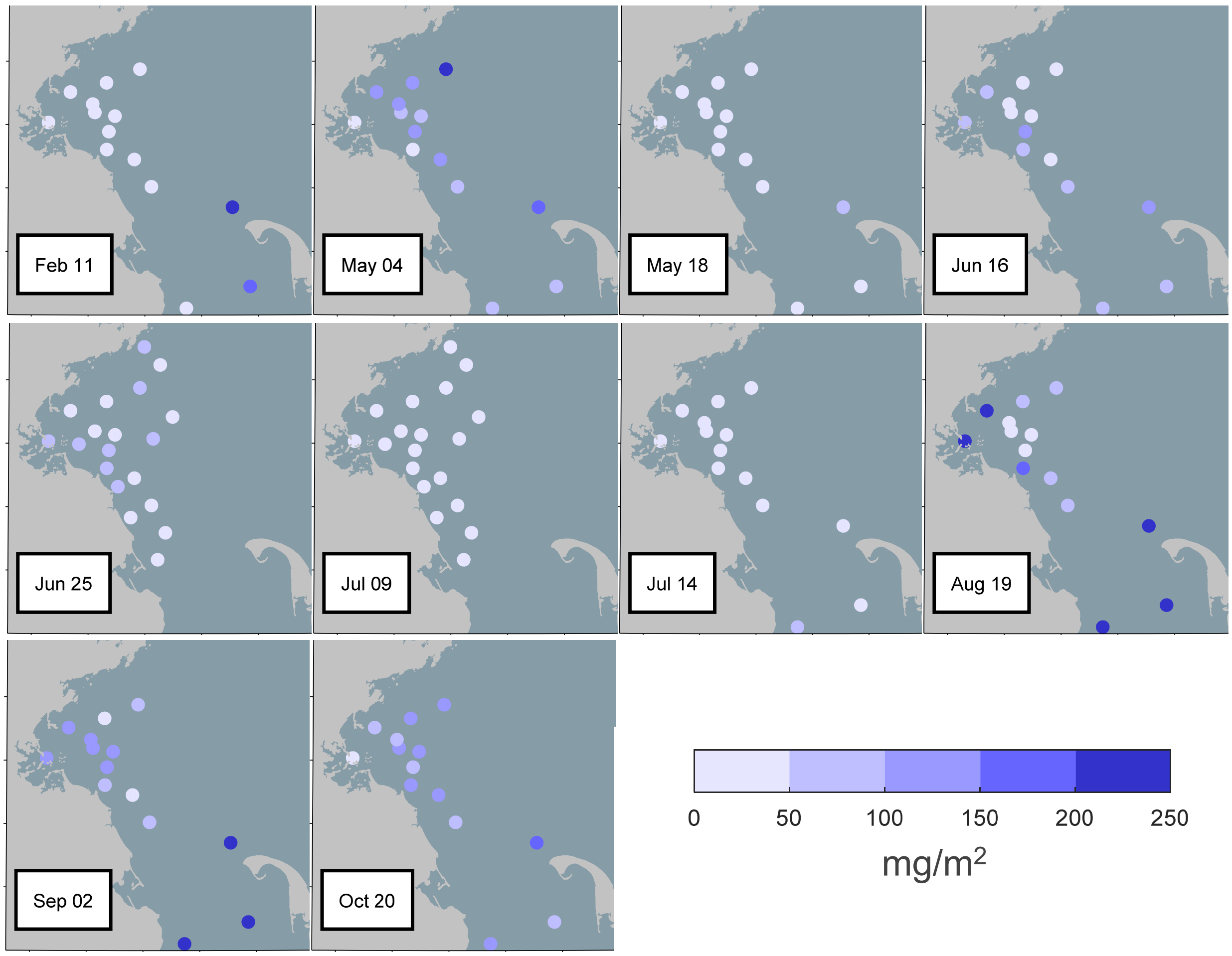

Figure 2-15. Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2020.

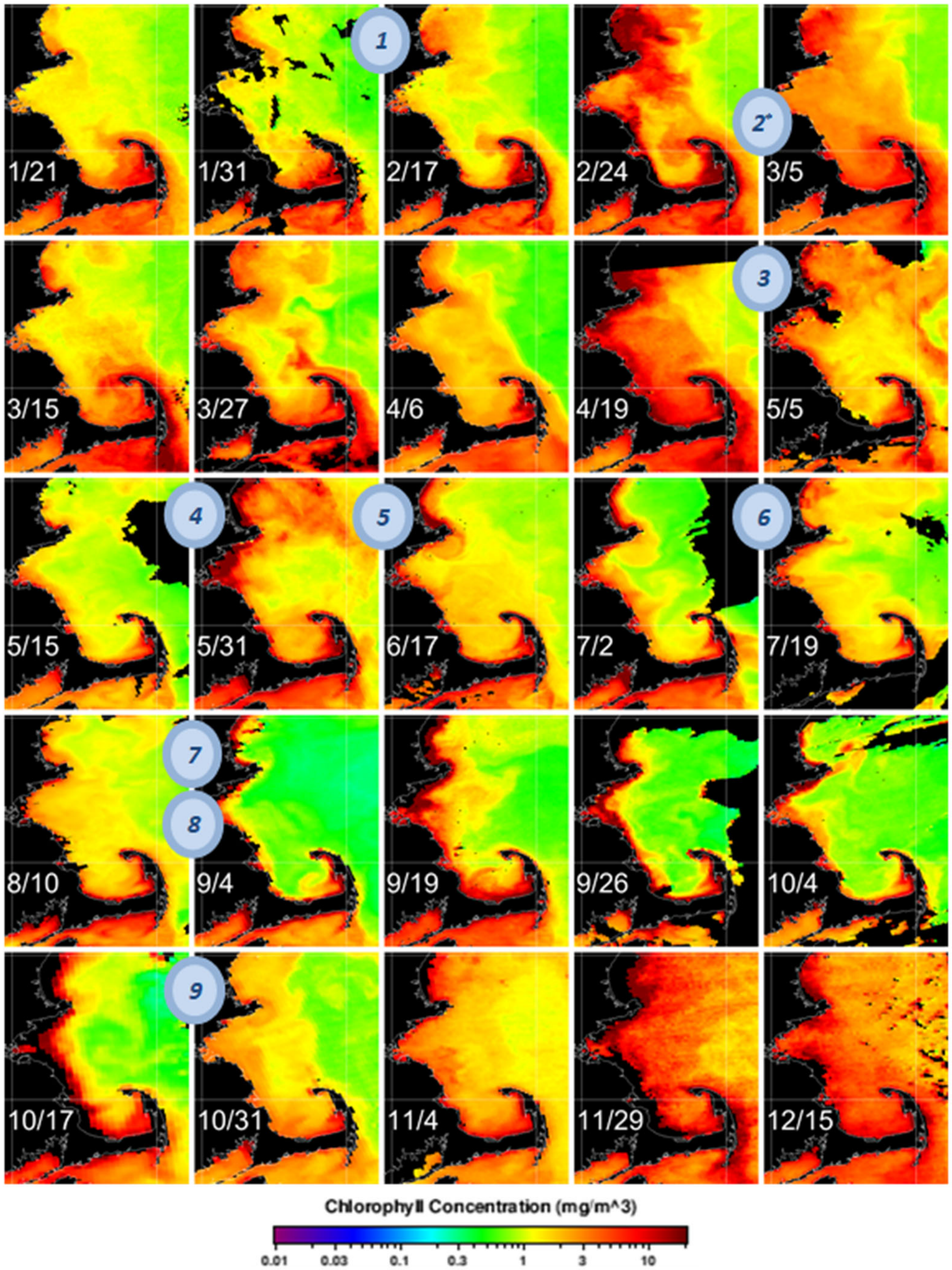

Figure 2-16. Satellite (MODIS) imagery-based estimates of surface chlorophyll concentrations (mg m^{-3}) in 2020. Black areas over water indicate missing data due to clouds.

Highlights and specific blooms:

1st row – low to moderate chlorophyll in January increasing in late February/early March (consistent with winter diatom bloom);

2nd row – decreasing after early March with an apparent bloom in April until early May, when *Phaeocystis* were observed;

3rd row – variable chlorophyll from May thru July, with high levels in late May;

4th row – high late summer chlorophyll – nearshore in August and September (*Karenia mikimotoi*); and

5th row – chlorophyll increased in late October and remained elevated into 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, survey 2* included only Cape Cod Bay stations).

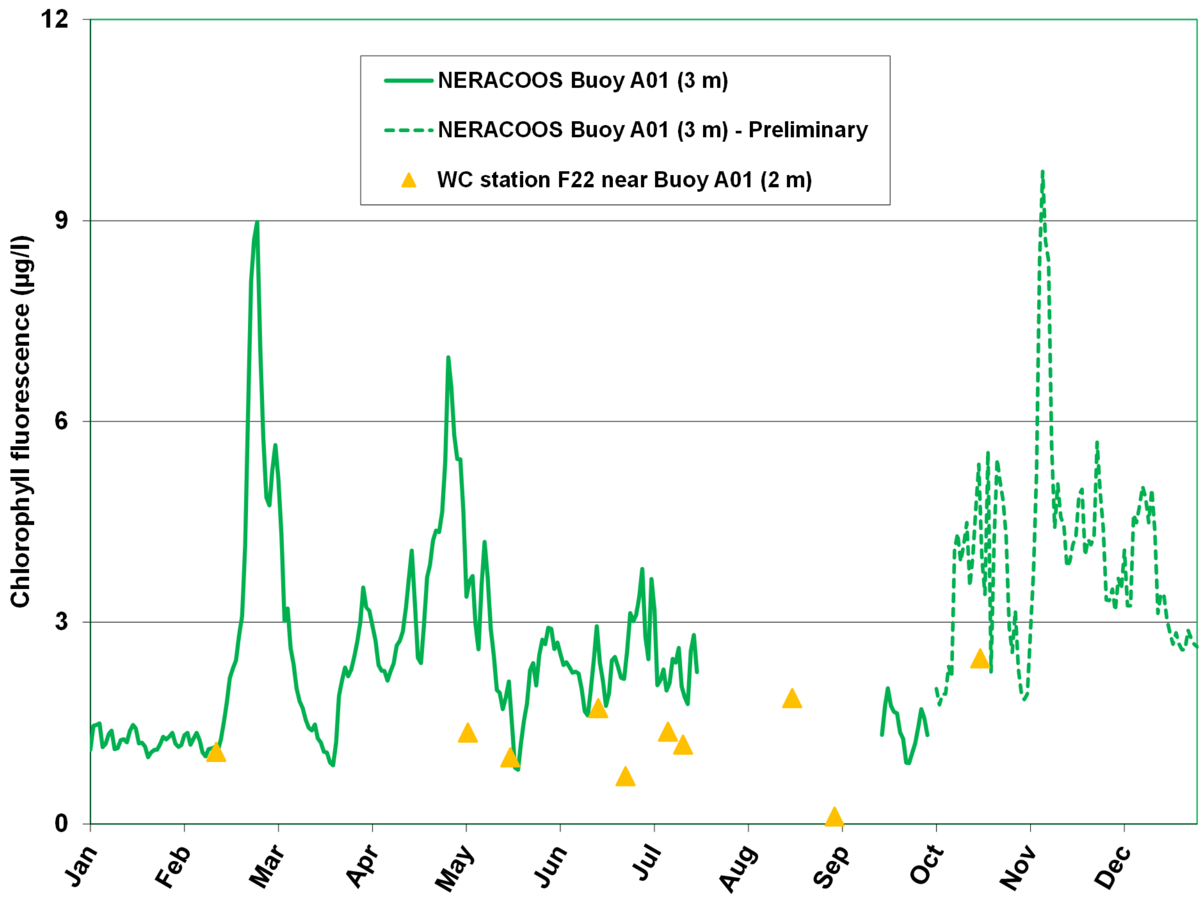

Figure 2-17. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (dashed green line) and water samples at nearby water column (WC) station F22 (yellow symbols) in 2020. The buoy values are daily medians from Collin Roesler and Sue Drapeau at Bowdoin College. The mid-July to mid-September data gap was due to a buoy communication error that developed during a deployment that was extended longer than normal due to COVID-related schedule disruptions.

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 again the case in 2020 with relatively low bottom water DO from February to June, with May and June levels at or below historic minima (**Figure 2-18** and **Figure 2-19**). Bottom water DO increased by ~1 mg L^{-1} from June to July at stations in Massachusetts Bay and Cape Cod Bay. The physical processes driving this change were not as clearly identifiable in association with specific downwelling favorable winds or mixing events as has been the case in past years. In June 2020, winds oscillated from downwelling to upwelling favorable, but appear not to have been strong enough to account for this large change in bottom water DO (**Figure 2-4**). The DO increase of ~0.5 mg L^{-1} from mid to late June was also captured by Buoy A01 (**Figure 2-20**).

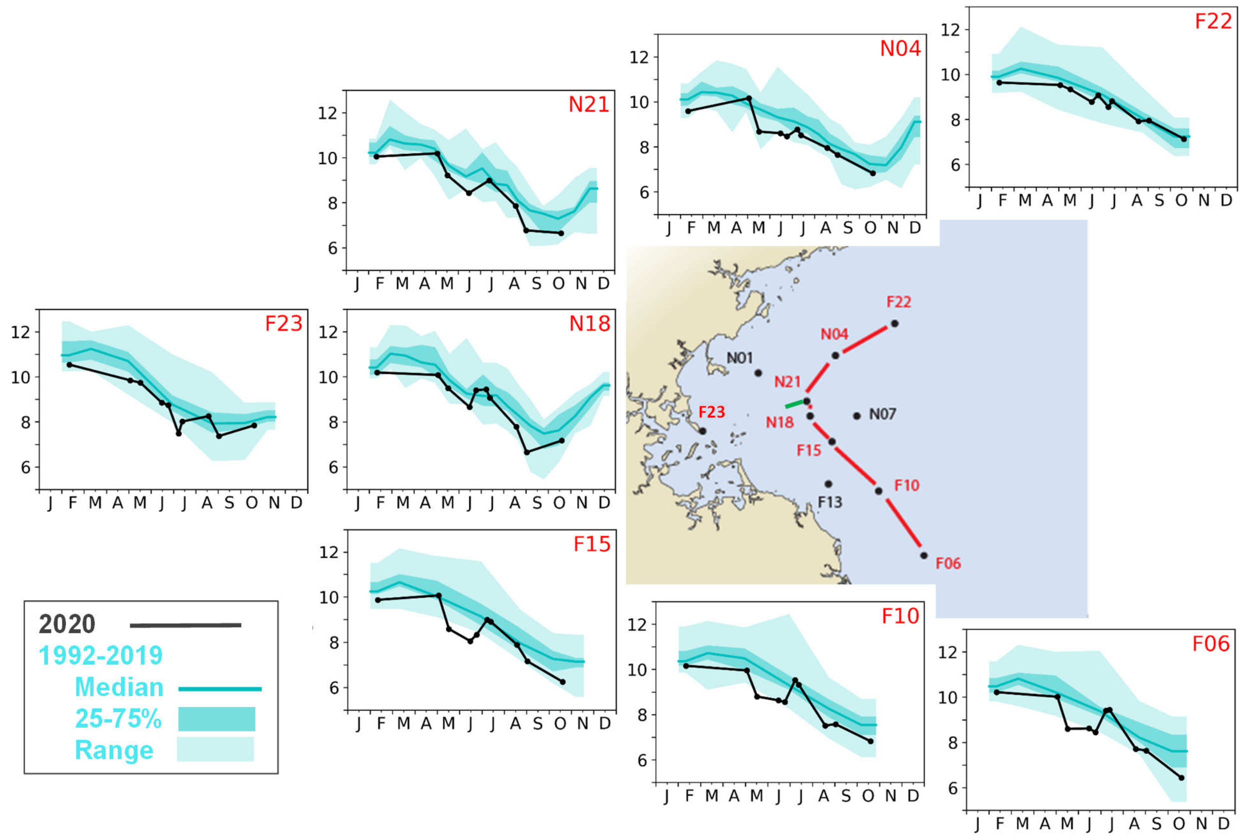

Figure 2-18. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2020 compared to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

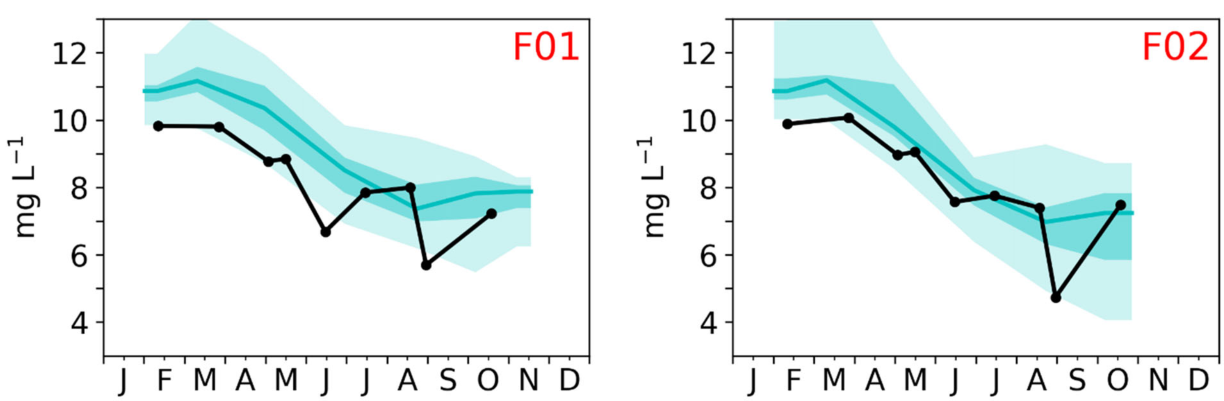

Figure 2-19. Survey bottom water DO concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2020 compared to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

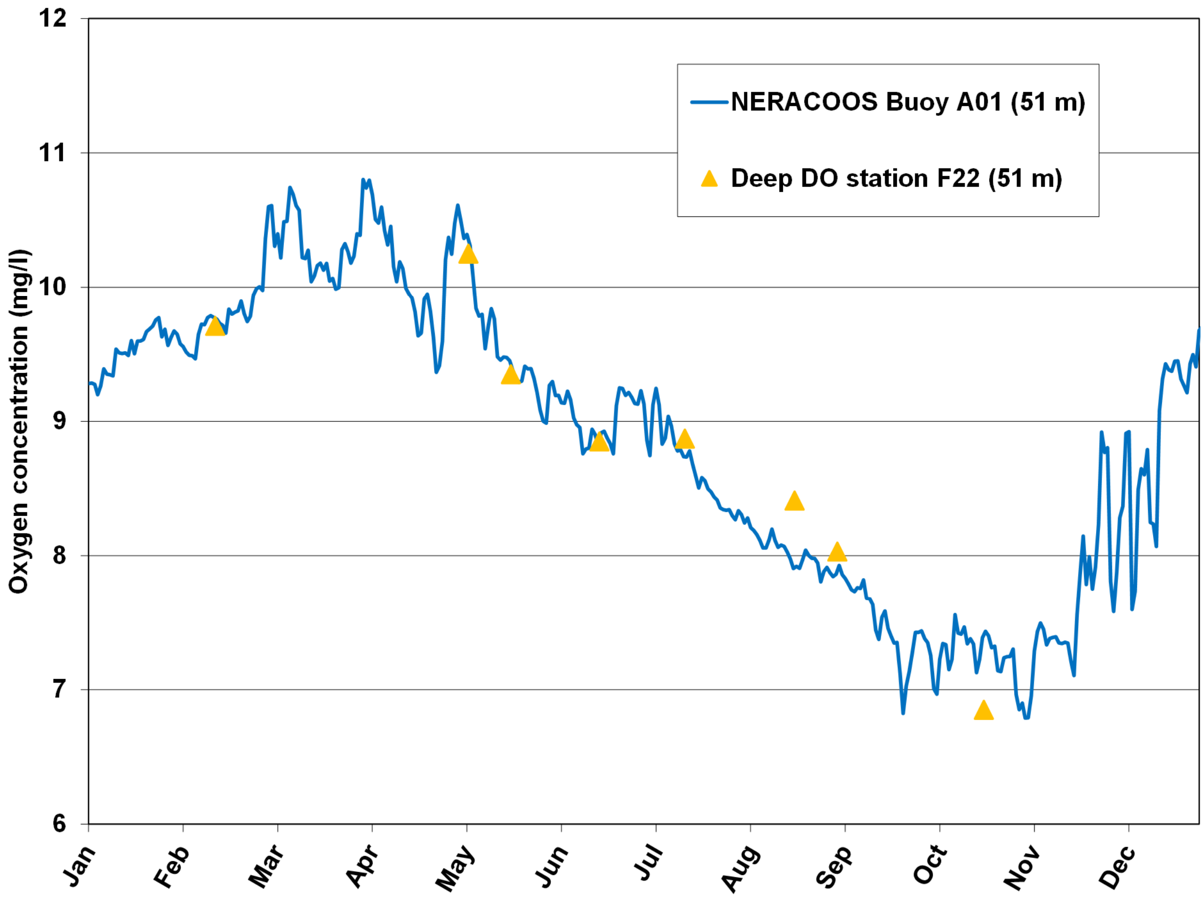

Figure 2-20. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (51 m) and at the deep sampling depth (~51 m) at station F22 in 2020. The buoy values are daily means.

The DO increase between June and July brought bottom water DO in the bays up to the historical median for July through mid-August. By late August and early September, bottom water DO had decreased, reaching annual minima of 6.5 to 7 mg L^{-1} in Boston Harbor and shallower Massachusetts stations, and 4.7 to 5.3 mg L^{-1} at the two Cape Cod Bay stations. At the offshore Massachusetts Bay stations, DO reached its annual minimum of 6.5 to 7 mg L^{-1} in October. The sharp increase in DO in mid-November, at the 50 m depth at Buoy A01, demonstrates the importance of mixing events in reaerating bay bottom waters in late fall (**Figure 2-20**).

In 2020, for the second year in a row, hypoxic conditions were observed in the shallow, nearshore bottom waters of southwestern Cape Cod Bay (Figure 2-21). An investigation of these conditions was undertaken by the Massachusetts Division of Marine Fisheries (MA DMF), CCS and WHOI. They documented hypoxic bottom water DO (<2 mg L^{-1}) along a transect off Sandwich, Massachusetts from August 31 to September 16, and then an increase to >6 mg L^{-1} on September 24 (**Figure 2-21**, upper panel). Unlike the 2019 event, no significant lobster mortality was reported in 2020. High chlorophyll values were observed during the hypoxia event (**Figure 2-21**, lower panel), suggesting the event was fueled by the oxygen demand of the high biomass of phytoplankton cells. Phytoplankton abundance at Cape Cod Bay station F01 was high with 1.7 million cells L^{-1} at the subsurface chlorophyll maximum of which nearly 0.8 million cells L^{-1} were *Karenia mikimotoi*. The combination of the large dinoflagellate bloom as a source of biomass, strong stratification, and a thin bottom layer are thought to have contributed to the low DO levels observed in Cape Cod Bay in late August to mid-September 2020.

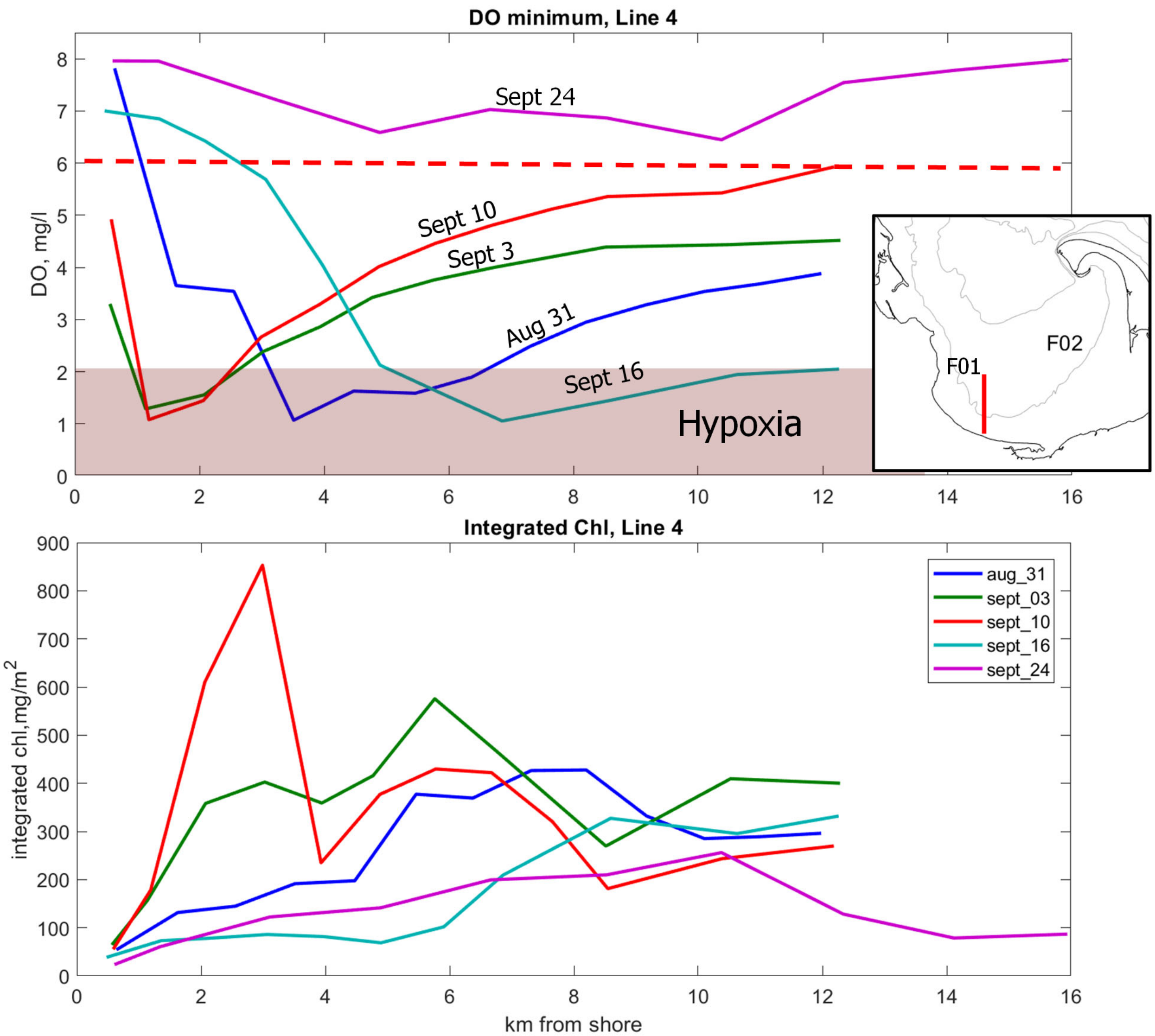

Figure 2-21. Observations characterizing the hypoxic event in Cape Cod Bay in August/September 2020. Inset map showing MWRA stations F01 and F02 in relation to the survey transect north of Sandwich, MA. Top panel – bottom water DO concentrations (mg L^{-1}) along MA DMF's sampling transect during five surveys undertaken from August 31 to September 24, 2020. Bottom panel – vertically integrated (areal) chlorophyll concentration (mg m^{-2}) on the same five dates along the same transect. Data courtesy of Tracy Pugh, MA DMF.

2.5 PHYTOPLANKTON ABUNDANCE

Overall, total phytoplankton abundance measured in 2020 was low compared to the range of 1992-2019 observations (**Figure 2-22**). Due to the impact of COVID-19 on the timing of monitoring surveys, long-term monthly averages for March and April were used in the calculation of the 2020 annual mean phytoplankton abundances shown in **Table 2-1**. The long-term averages used for March and April are consistent with the 2020 remote sensing chlorophyll images and buoy observations (**Figure 2-16** and **Figure 2-17**), which showed elevated chlorophyll during the period of missed sampling in early March (typically a winter-spring diatom bloom period) and April (often a *Phaeocystis* bloom period). Microflagellate and centric diatom abundance remained lower than the long-term mean during May to October 2020 (sampling not disrupted by COVID), continuing the trend of relatively low phytoplankton in the Massachusetts Bay nearfield observed since the early 2000s. Dinoflagellates were the only phytoplankton functional group displaying above long-term mean abundance levels during 2020 (**Figure 2-23**), primarily due to a bloom of *Karenia mikimotoi* during August and September 2020. *Karenia mikimotoi* first appeared in Massachusetts Bay in 2017, thought due to regional changes as it similarly appeared for the first time in other nearby waterbodies. It is classified as a harmful algal bloom species, although its toxins are not well characterized. At very high concentrations it can cause anoxia and extensive mortality of benthic animals. It appears to have become a regular component of Massachusetts Bay phytoplankton, with abundance maxima of near 1 million cells L^{-1} observed during both 2019 and 2020. Overall, phytoplankton abundance and community composition during 2020 were similar to the past five years (2015-2019).

The total phytoplankton annual average abundance in the nearfield for 2020 (856,783 cells L^{-1}) was only two thirds of the long-term mean level of 1,288,841 cells L^{-1} and ranked 22nd out of 29 years of the 1992-2020 monitoring program (**Table 2-1**). Total phytoplankton abundance was consistently below the historic median during the surveys conducted in 2020 (**Figure 2-22**). From May to October 2020, when sampling was not disrupted by COVID, total phytoplankton abundance was often within the lower quartile of long-term levels or below the minima, indicating 2020 was another low phytoplankton abundance year similar to the past several years.

Another factor contributing to the low total phytoplankton abundance was reduced microflagellate numbers in 2020 relative to the long-term mean levels. Microflagellates are typically the most abundant phytoplankton group in the Massachusetts Bay monitoring area, comprising ~60% of phytoplankton cells during 2020. Microflagellate abundance was near or slightly below long-term mean levels for most of 2020, with the exception of the late summer to autumn of 2020 when microflagellate abundance dropped rapidly to below long-term levels at most stations. The reduced microflagellate abundance, relative to long-term mean levels, resulted in 2020 nearfield microflagellate abundance (399,093 cells L^{-1}) that was significantly less than the long-term mean abundance of 622,161 cells L^{-1} (**Table 2-1**).

MODIS and Buoy A01 results both showed large increases in chlorophyll levels in late February/early March and late April/early May (**Figure 2-16** and **Figure 2-17**). Historically, these are the periods when the winter/spring diatoms and *Phaeocystis* blooms occur. *Phaeocystis pouchetii* was present at moderate abundance in samples collected in early May 2020. During the early May survey, in the Massachusetts Bay nearfield area a maximum of ~1.4 million *Phaeocystis* cells L^{-1} was observed and in Cape Cod Bay the maximum was ~40,000 cells L^{-1}. The remote sensing chlorophyll data suggest a larger *Phaeocystis* bloom may have occurred in the bays, but was not sampled due to COVID, in late April 2020. *Phaeocystis* is one of the dominant phytoplankton taxa in the bay and the low to moderate abundances observed during the 2020 surveys, and during seven of the last eight years, has contributed to a long-term decline in total phytoplankton abundance.

Centric diatom abundance was very low during 2020, with a mean nearfield level of only 59,974 cells L^{-1} compared to a long-term abundance of 243,370 cells L^{-1} (**Table 2-1**). Due to the pandemic, the monitoring surveys did not sample what was likely a winter/spring diatom bloom in late February/early

March, but once the regular sampling schedule was resumed, centric diatoms abundance remained low from May to October 2020. The usual summer increases in several diatoms (*Dactyliosolen fragilissimus, Skeletonema spp. and Guinardia fragilissima*) often observed in nearshore areas of Massachusetts Bay and Boston Harbor were not seen during 2020. The lack of summer diatom blooms resulted in 2020 having dramatically reduced annual mean nearfield diatom abundance compared to historic levels (ranking 27th out of 29 years; **Table 2-1**).

Mean nearfield pennate diatom abundance during 2020 (15,229 cells L^{-1}) was approximately 30% of the long-term mean level (51,484 cells L^{-1}). However, *Pseudo-nitzschia* abundance was ~10% above long-term mean levels during 2020. *Pseudo-nitzschia* is a genus of potentially toxigenic pennate diatoms that can cause amnesiac shellfish poisoning (ASP). Most *Pseudo-nitzschia* cells observed during 2020 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)*, grouped for Contingency Plan threshold testing, were low with seasonal means in the nearfield of <1,200 cells L^{-1} and well below threshold values (**Table i**). No ASP shellfish closures were required in the region during 2020.

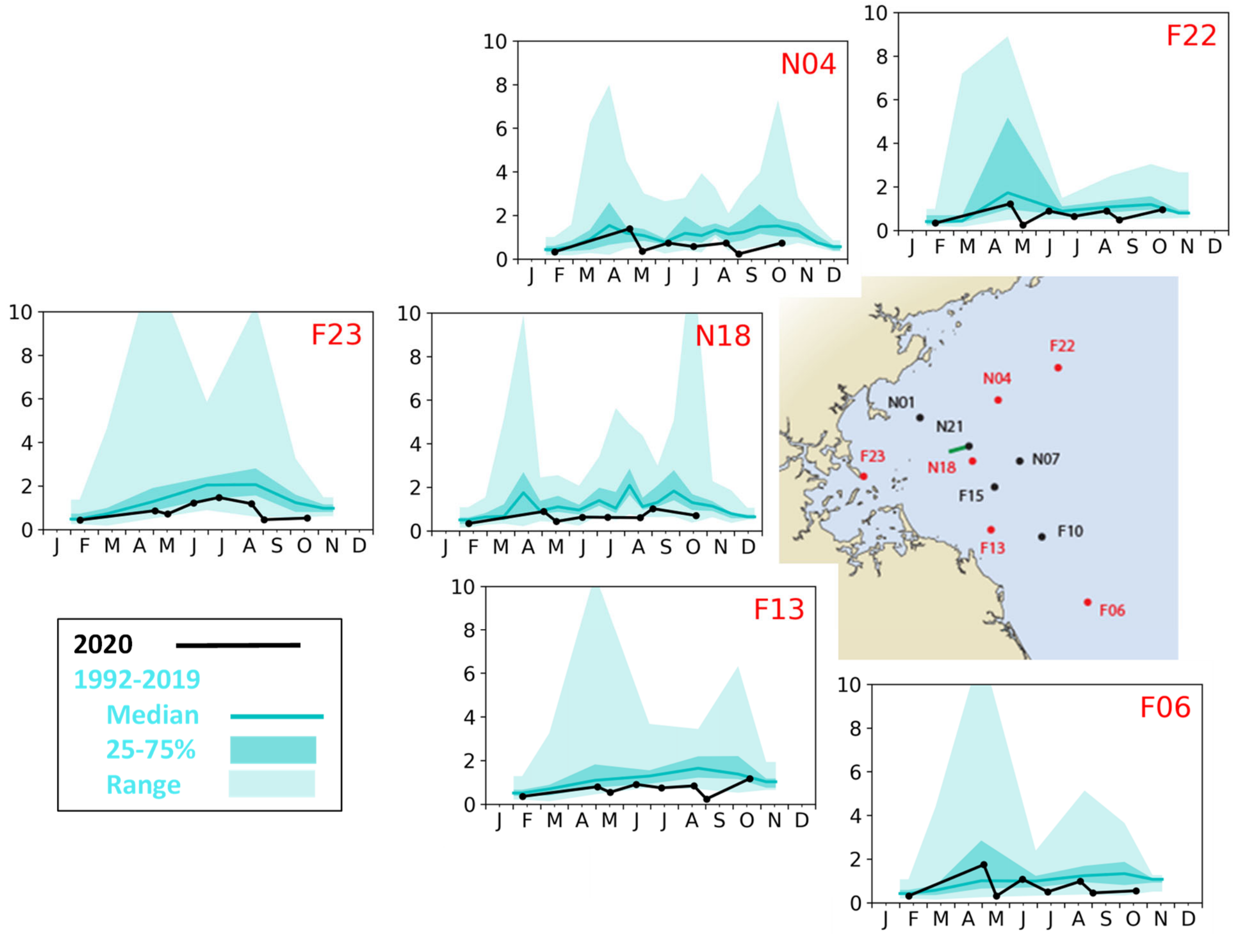

Figure 2-22. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2020 compared to prior years. 2020 results are in black. Results from 1992-2019 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The 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.

Table 2-1. Comparison of 2020 annual mean phytoplankton abundance (cells L^{-1}) in the nearfield 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. For the calculation of 2020 annual-mean abundances, long-term monthly mean values for March and April 1992-2019 (for microzooplankton, 2011-2019[2]) were used to fill COVID-related sampling gaps.

Group	1992-2019 (cells L^{-1})	2020 (cells L^{-1})	2020 Rank (out of 29)	p value	Significant Change[1]
CENTRIC DIATOM	243,370	59,974	27th	0.0410	decrease
Chaetoceros	30,381	14,996	13th	0.5065	
Dactyliosolen fragilissimus	47,897	544	25th	0.2762	
Skeletonema spp. complex	41,952	2,339	23rd	0.1719	
Thalassiosira	32,010	16,995	15th	0.6926	
CRYPTOPHYTES	121,040	54,391	26th	0.0008	decrease
DINOFLAGELLATES	58,549	64,801	11th	0.8028	
Ceratium	1,884	263	25th	0.0282	decrease
Dinophysis	381	140	18th	0.5856	
Prorocentrum	5,396	1,474	23rd	0.2051	
MICROFLAGELLATES	622,161	399,093	24th	0.0003	decrease
MICROZOOPLANKTON[2]	4,926	3,071	10th	0.0160	decrease
PENNATE DIATOM	51,484	15,229	19th	0.5381	
Pseudo-nitzschia	7,093	7,834	10th	0.9266	
Phaeocystis pouchetii	179,127	249,663	7th	0.7184	
TOTAL PHYTOPLANKTON	1,288,841	856,783	22nd	0.0277	decrease

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

2 Microzooplankton sampling methods changed after 2010. Results shown are based on 2011-2020 data.

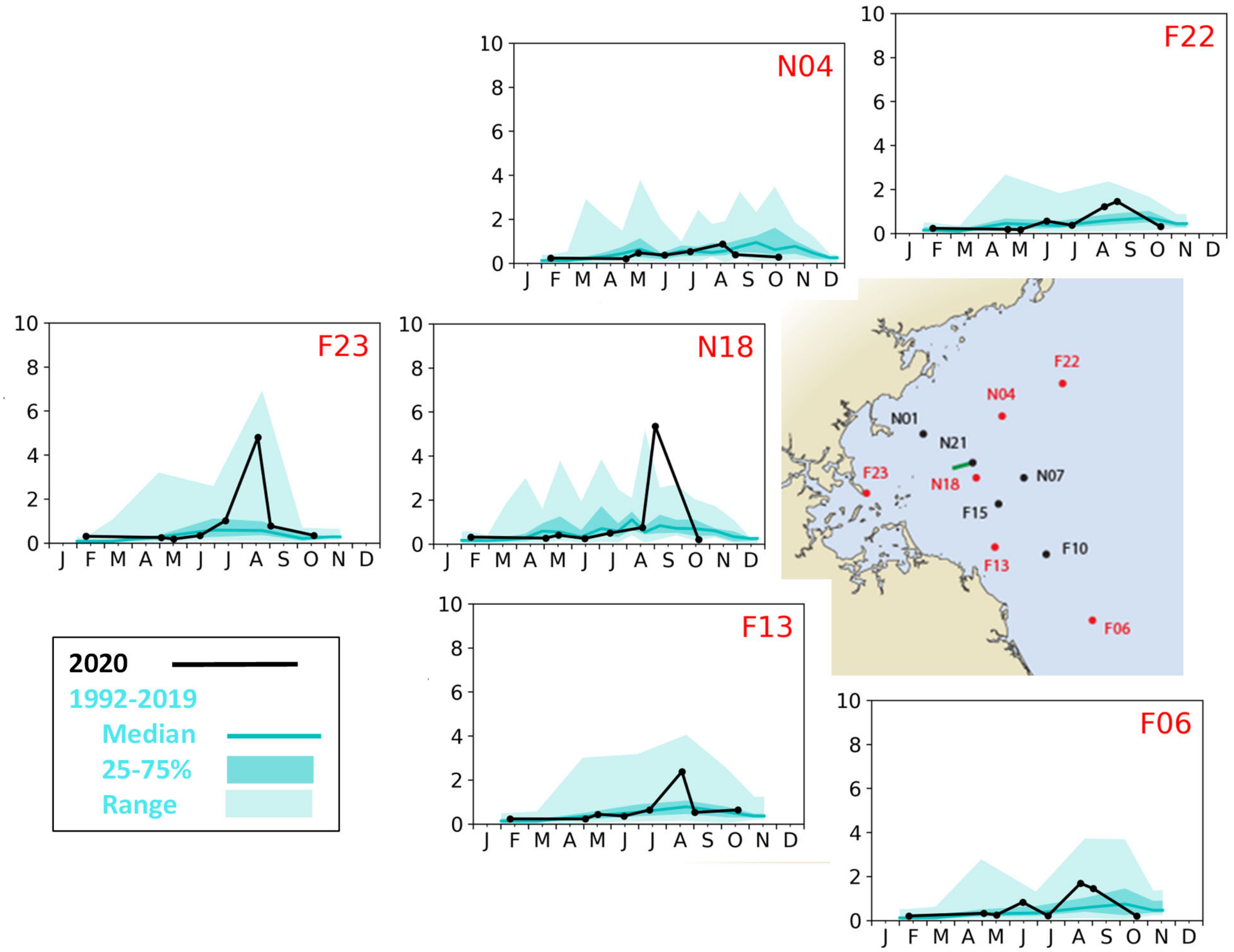

Figure 2-23. Dinoflagellate abundance (100,000 cells L^{-1}) at selected stations in 2020 compared to prior years. 2020 results are in black. Results from 1992-2019 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Dinoflagellate abundance was ~10% above long-term annual mean levels in the Massachusetts Bay nearfield during 2020, with a mean of 64,801 cells L^{-1} compared to a long-term mean of 58,549 cells L^{-1} (**Table 2-1**). Dinoflagellate abundance was close to the historic median from February to July 2020 and the spring to early summer period was dominated by small dinoflagellates (*Gymnodinum* spp. <20 µm, *Heterocapsa triquetra*, *Heterocapsa rotundata*). *Alexandrium catenella* abundances of >100 cells L^{-1} were observed at stations along the South Shore in June, but overall *Alexandrium* abundance was relatively low from April to July. *Ceratium*, typically a dominant component of the dinoflagellate community during the summer, were well below long-term levels, with a 2020 nearfield annual mean of only 14% compared to the long-term mean level (**Table 2-1**). In August and September 2020, dinoflagellate abundance peaked to levels within the upper quartile at many stations and reaching a maximum for the program at station N18 in early September (**Figure 2-23**). The summer peaks in dinoflagellate abundance were dominated by *Karenia mikimotoi*. *K. mikimotoi* were observed in Massachusetts Bay from February to October 2020 and blooms were observed in Boston Harbor, Massachusetts Bay, and Cape Cod Bay during August and early September 2020, with a maximum abundance of 879,087 cells L^{-1} at station N18, 15 m depth on September 2, 2020 **(Figure 2-24)**. The elevated dinoflagellate abundance observed during 2020 resulted in it being the 11th rank of 29 years for dinoflagellate abundance.

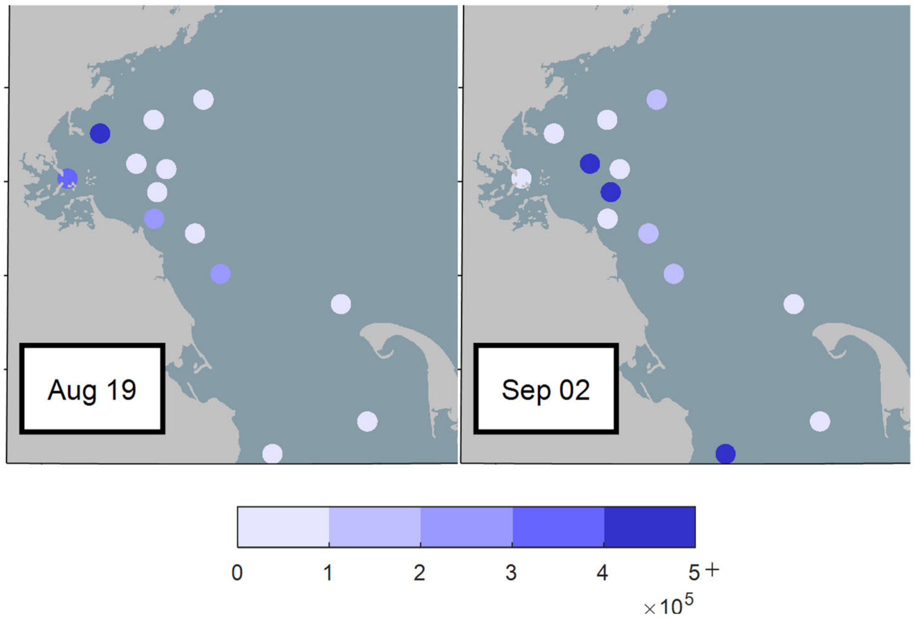

Figure 2-24. ***Karenia mikimotoi*** **abundance (100,000 cells L^{-1}) during the August and September 2020 surveys.**

Alexandrium catenella

During 2020, Massachusetts Bay did not experience a large *Alexandrium catenella* (formerly *A. fundyense*) bloom. In 2019, the bay experienced a large, prolonged bloom comparable to the large blooms in 2005 and 2008 (Libby et al. 2020). Subsequent sediment sampling in August (Massachusetts Bay) and October (Gulf of Maine) 2019 showed the numbers of cysts in Massachusetts Bay were elevated (**Figure 2-25**). The presence of these high numbers of cysts in the bay was surprising as after the extraordinary 2005 bloom very few cysts had been found in Massachusetts Bay (Anderson et al. 2014). It was unknown what the impact of these cysts would be on 2020 *Alexandrium*, and whether they might make possible a localized bloom being initiated in Massachusetts Bay rather than transported from offshore waters to the north.

Although the COVID-19 pandemic impacted the March and April water column surveys, New Hampshire Department of Environmental Services (NH DES) and MA DMF were able to sample PSP toxicity in April, and had non-detects for all stations from Portsmouth, New Hampshire south to the stations within Massachusetts Bay. In early May, NH DES reported *Alexandrium* counts of >100 cells L^{-1} at its offshore stations, but all PSP toxicity results from NH DES remained below detection limits. During the two May surveys, *Alexandrium* abundances were low in Massachusetts Bay (**Table 2-2**) and no PSP toxicity was detected by MA DMF in May 2020.

In mid-June, a sample from station F13 off Cohasset had an *Alexandrium* count of 127 cells L^{-1} which triggered the ARRS surveys. On June 25, during the first ARRS survey, high *Alexandrium* abundances were observed at station AF4 off Scituate with 2,123 cells L^{-1} and a few other stations along the South Shore had levels >100 cells L^{-1} (**Figure 2-26**). MA DMF at the time continued to report no detectable PSP toxicity at any of its South Shore stations. This apparent disconnect between high *Alexandrium* abundances and lack of PSP toxicity was likely due to the predominant offshore surface flow caused by multiple upwelling favorable periods of winds in June (**Figure 2-4**). By the second ARRS survey in early July, *Alexandrium* abundances were ≤20 cells L^{-1} and remained so for the rest of the year. *Alexandrium* abundances never exceeded 100 cells L^{-1} in the nearfield (46 cells L^{-1} maximum) so there was no exceedance of this Contingency Plan threshold in 2020 (**Table i** and **Figure 2-27**).

The source of *Alexandrium* cells within Massachusetts Bay could have been either from advection of populations from coastal waters of New Hampshire and western Maine, as has often been observed before, or from the localized germination of cysts observed in sediments within the bay south of Cape Ann in fall of 2019 (**Figure 2-25)**. In prior years, the latter has not been a concern, as *Alexandrium* cysts have typically been in very low abundance within the bay. Additional cyst sampling within the bay in future years will help to indicate whether such deposits are ephemeral in nature, or can be persistent through time, thereby establishing a third cyst seedbed in the region, augmenting the other two documented in the Bay of Fundy and offshore of Casco and Penobscot Bays (Anderson et al. 2014). Currently, WHOI researchers are processing and counting *Alexandrium* cysts from samples collected for MWRA's sediment survey in August 2021.

Table 2-2. *Alexandrium* abundance for water column and ARRS surveys in May-July 2020.

Event Id	Date	# samples collected	# samples with *Alexandrium*	# *Alexandrium* cells/L			MAX value station (depth)
				MEAN	MIN	MAX	
WN203	May 4	20	15	4	0	30	F13 (2 m)
WN204	May 18	20	19	8	0	45	N01 (2 m)
WN205	June 16	20	15	10	0	127	F13 (11 m)
AF201	June 25	43	27	61	0	2,123	AF4 (10 m)
AF202	July 9	42	9	1	0	20	N10 (2 m)
WN206	July 14	20	9	1	0	9	F22 (21 m)

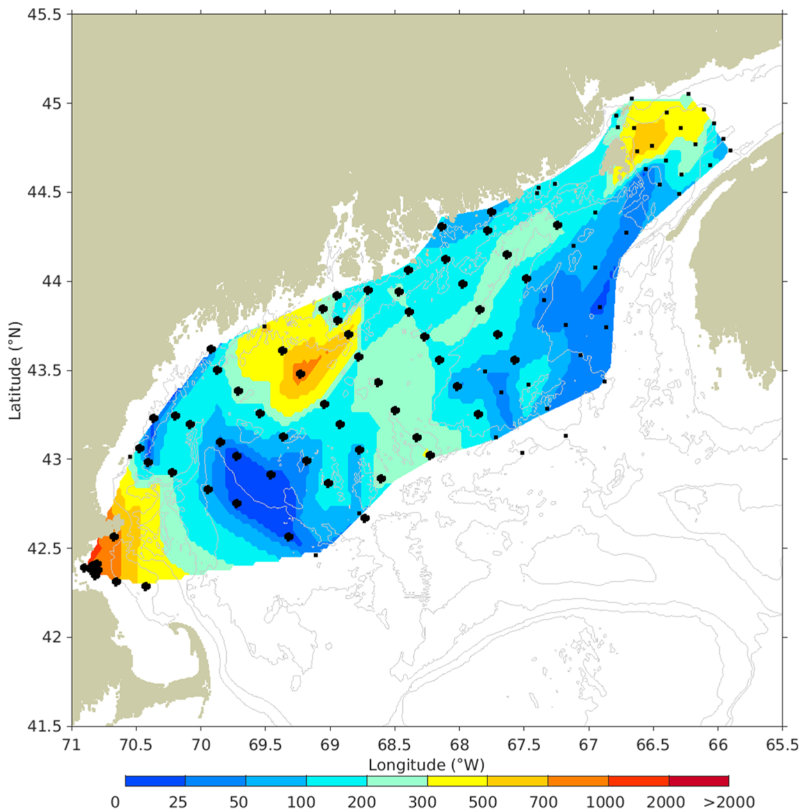

Figure 2-25. Fall 2019 *Alexandrium* cyst abundance (cysts cm^{-2}). Provided by Don Anderson, WHOI and Yizen Li, NOAA.

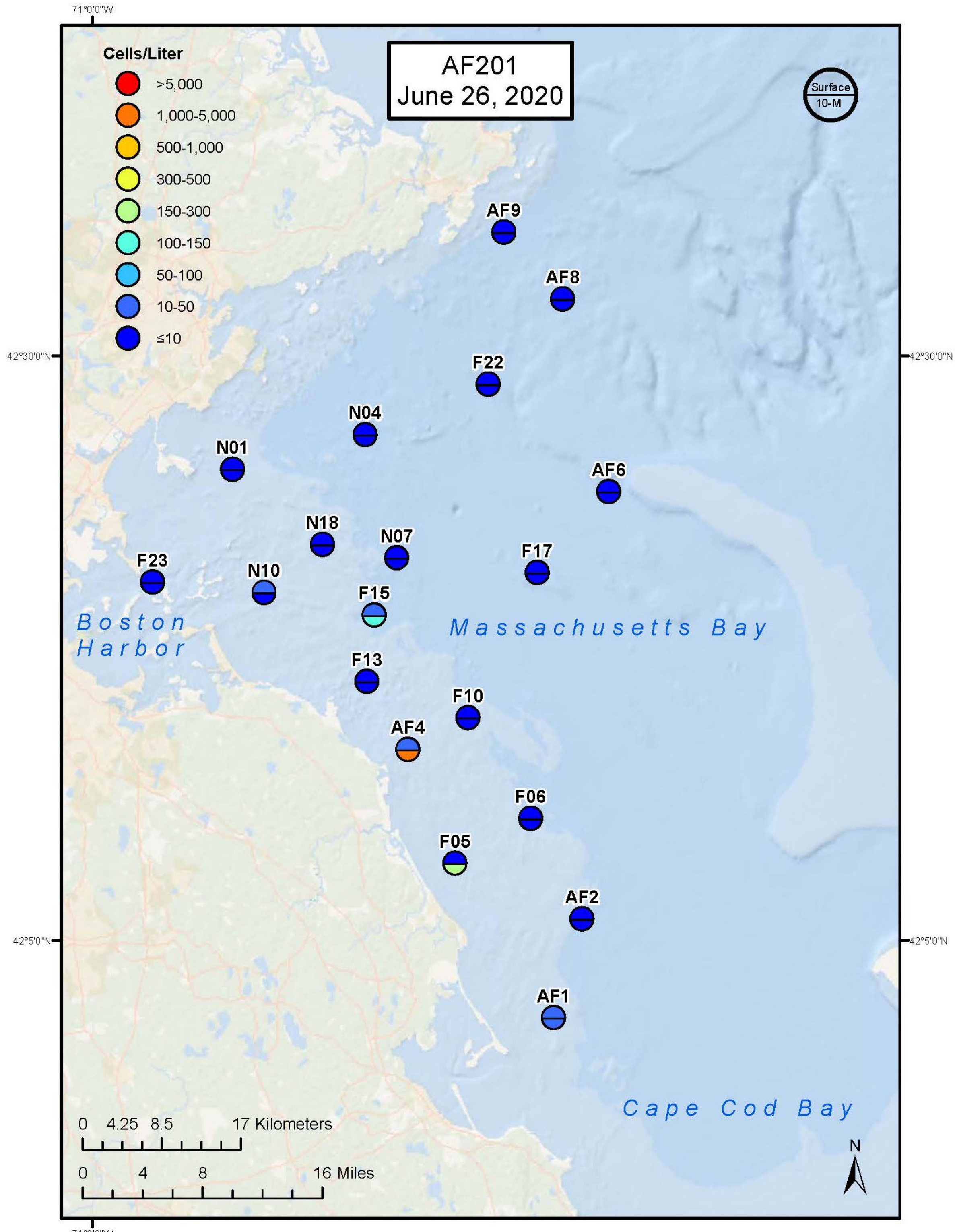

Figure 2-26. ***Alexandrium* abundance (cells L^{-1}) from ARRS survey AF201 on June 25, 2020.** Symbols show abundance for the surface in the upper half and from ~10 m in the bottom half of each symbol.

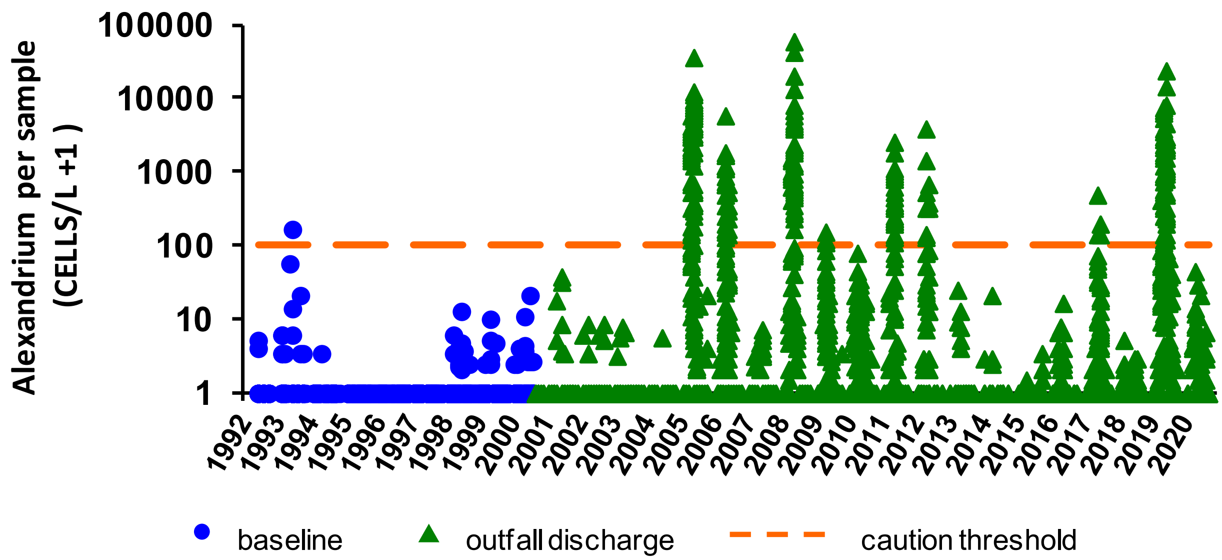

Figure 2-27. Nearfield *Alexandrium* abundance (cells L^{-1} +1) from 1992 to 2020. The dashed line represents the Contingency Plan caution threshold of 100 cells L^{-1}.

2.6 ZOOPLANKTON ABUNDANCE

Due to COVID-19 protocols and constraints on staffing, zooplankton were only collected in February, August, September, and October 2020. Zooplankton taxa and abundances in February and October were generally similar to those of most previous years. General seasonal patterns of abundance were typical, with increases from February lows through to summer peaks, followed by fall declines. However, in August, and continuing into September, there was a substantial and unprecedented abundance of radiolarians (unicellular protozoan animals) throughout most of the sampling area.

There were peaks in abundance of total zooplankton (dominated by radiolarians) that were within the upper quartile or above historic maxima in August and September 2020 (**Figure 2-28**). Radiolarians comprised about half of the category for “Other Zooplankton” (meaning non-copepod zooplankton) in August and September 2020 (**Figure 2-29**). Total copepod adults and copepodites also accounted for about half the total zooplankton in August and September, when their abundances were within the upper quartile observed over the program. Abundances of copepod adults + copepodites were dominated by *Oithona similis*. As is usually the case, adults plus copepodites of *Oithona similis* were the most abundant copepod taxa observed. The September abundance peak at Boston Harbor station F23 was driven by *Oithona*, veliger larvae of gastropods and bivalves, as well as the appendicularian *Oikopleura dioica*. Not counting radiolarians, the abundance peaks in September for non-copepod zooplankton were primarily due to high numbers of the marine cladocerans *Penilia avirostris* and *Evadne nordmanni.* Abundances at station F06 were elevated compared to the other stations due to the presence of abundant bivalve veliger larvae. The unusual August and September abundances of radiolarians and *Penilia avirostris*, both of which are typical of oligotrophic offshore waters, suggest a possible intrusion of offshore water into Massachusetts Bay.

There had been a sustained trend of increasing abundance of total zooplankton from 2006 through 2017 that was driven by increases in copepod adults and copepodites (Libby et al. 2019). Zooplankton abundances leveled off in 2018 and the limited data from 2020 are consistent with the zooplankton levels observed in 2018-2019.

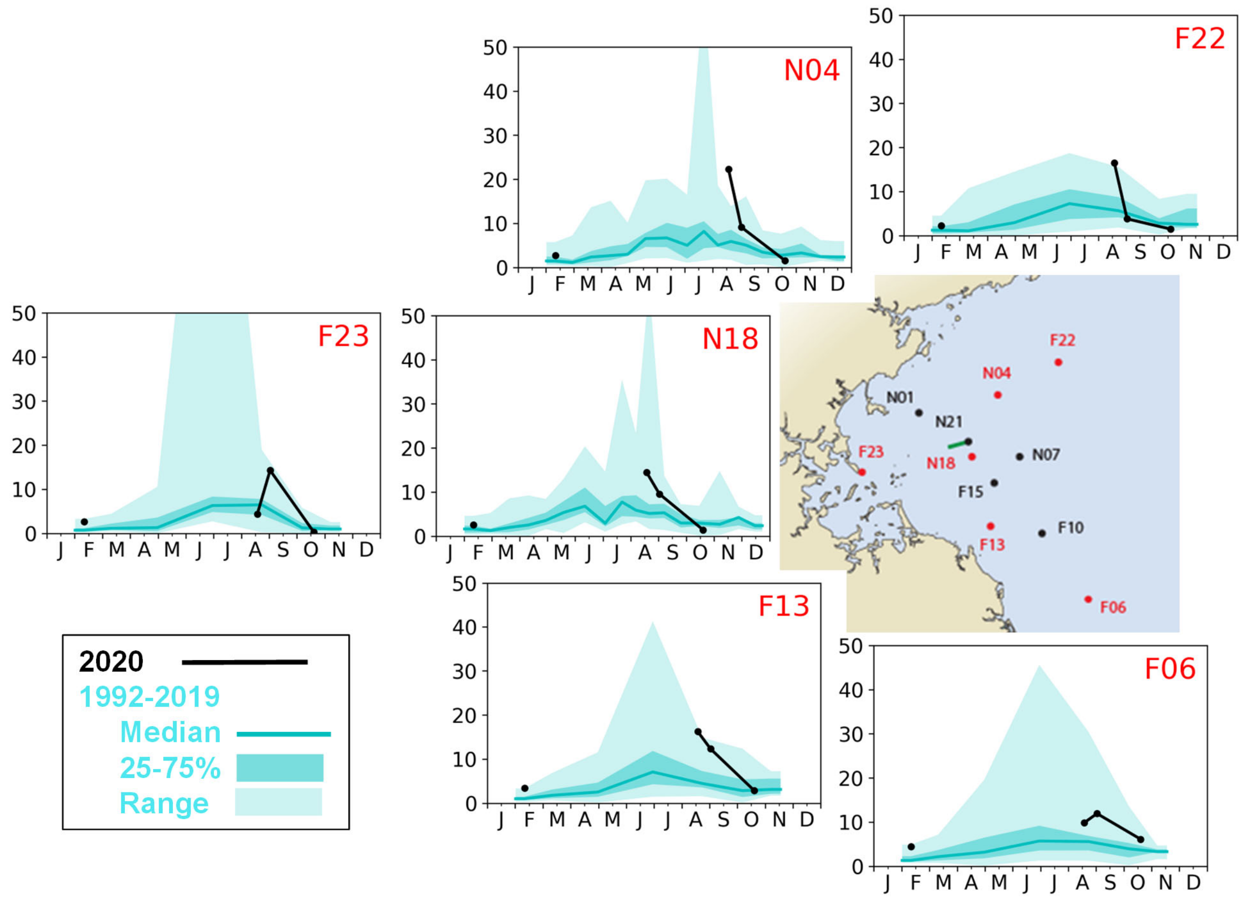

Figure 2-28. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2020 compared to prior years. 2020 results are in black. Results from 1992–2019 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans 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}.

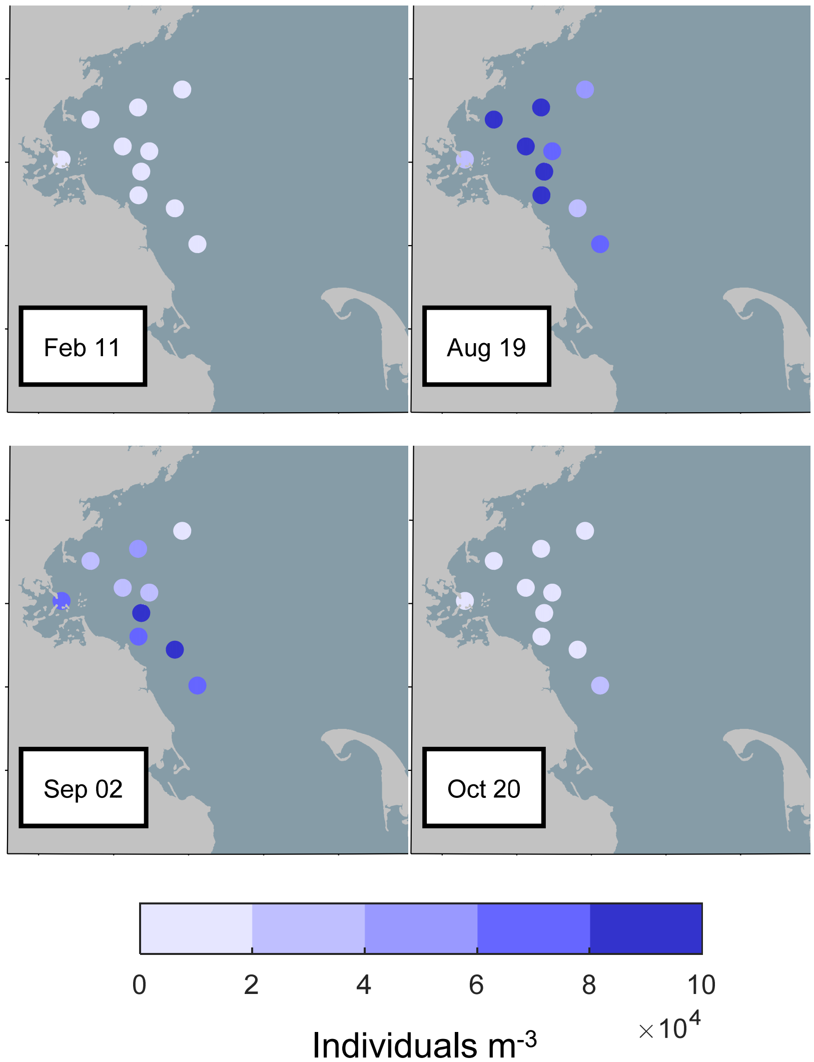

Figure 2-29. Meroplankton and other non-copepod abundance (10,000 individuals m^{-3}) during the four surveys sampled for zooplankton in Massachusetts Bay for 2020.

2.7 MARINE MAMMAL OBSERVATIONS

Observing 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 2020, due to COVID-19 protocols which reduced field staff, including the marine mammal observer, the only water column survey with a marine mammal observer on board the vessel was the February survey WN201. The captain and first mate on the *R/V Tioga* as well as the scientific team watched for marine mammals and noted any observations in the survey logbook. These data are included in **Table 2-3** and **Figure 2-30**.

In 2020, one North Atlantic right whale (*Eubalaena glacialis*), two humpback whales (*Megaptera novaeangliae),* and four minke whales (*Balaenoptera acutorostrata*) were observed during the water column and benthic surveys in Massachusetts Bay (**Table 2-3** and **Figure 2-30**). Several other marine mammals including three harbor seals (*Phoca vitulina*), one harbor porpoise (*Phocoena phocaena*), three Atlantic white-sided dolphins (*Lagenorhynchus acutus)* and five unidentified dolphins were also observed.

MWRA revised its outfall AMP 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 (**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, 2017 and 2020.

Table 2-3. Number of whale sightings from 1998 to 2020.

Whale species	Total number of sightings (1998-2010)	Range of sightings per year (1998-2010)	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Finback	11	0-4	1	0	0	0	0	0	0	1	1	0
Humpback	4	0-1	0	2	0	0	0	0	0	0	1	2
Minke	30	0-6	4	0	0	2	0	3	3	4	1	4
North Atlantic Right	0	0-0	0	2	4	0	0	2	8	0	0	1
Unidentified	15	0-2	0	3	1	1	0	0	4	2	4	0

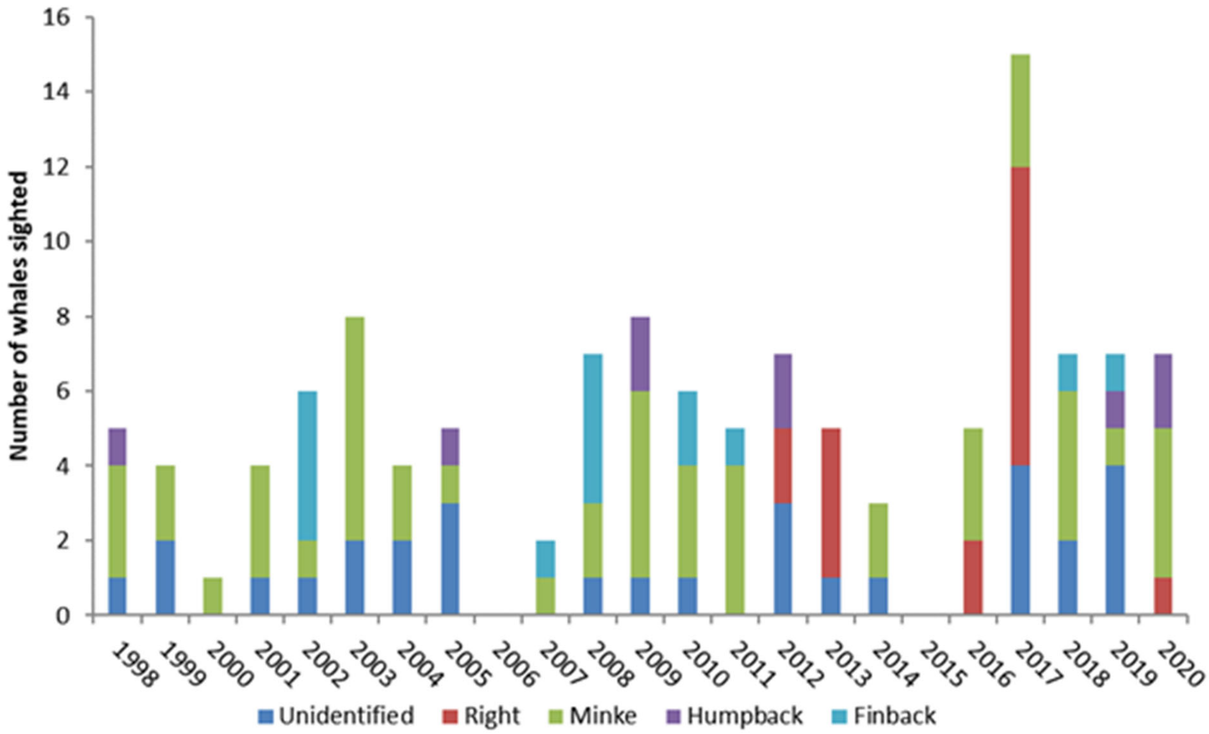

Figure 2-30. Number of whale sightings and whale species sighted in current survey areas (1998 – 2020).

3 ANALYSIS OF THE LONG-TERM MONITORING DATASET

3.1 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. 2018; **Figure 3-1**). 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[4]. *Karenia* was also observed in Massachusetts Bay during September 2018, but abundance levels were lower (maximum level of ~ 4,000 cells L^{-1}). A larger *Karenia* bloom was observed in Massachusetts Bay during August and September 2019. 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[5]. A large *Karenia* bloom was also observed in Boston Harbor and the Massachusetts Bay nearfield region during August and early September 2020, with a maximum abundance of 879,087 cells L^{-1} at station N18, 15 m depth on September 2, 2020 (**Figure 3-1**). *Karenia mikimotoi* appears to be persisting longer in Massachusetts Bay, increasing from an August to October (70 days) presence during 2017 to being present from February to October (252 days) during 2020.

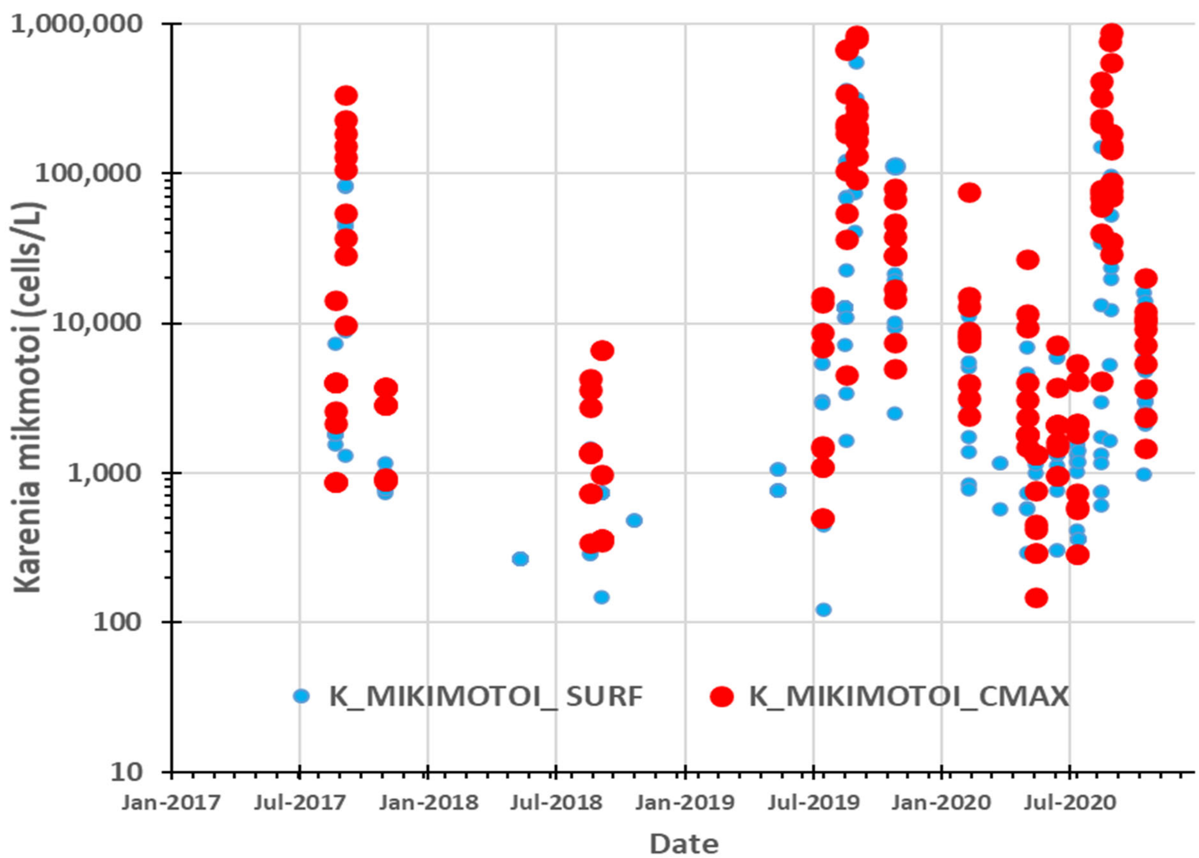

Figure 3-1. *Karenia mikimotoi* abundance (cells L^{-1}) in 2017-2020. "CMAX" is the depth of the chlorophyll maximum, typically about 10-20 m deep.

[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

The summer 2020 *Karenia* bloom was observed over the entire MWRA monitoring area south of Cape Ann, including Boston Harbor, the nearfield, and Cape Cod Bay (**Figure 2-24**). Maximum *Karenia* concentration approached one million cells L^{-1} in all regions except the northern offshore station F22 and station F29 off Race Point. Of note, regions of Cape Cod Bay experienced anoxia and invertebrate die-offs during September 2019 and hypoxia in September 2020, coincident with the *Karenia mikimotoi* blooms (Libby et al. 2020 and Section 2.4). *K. mikimotoi* contains 473 to 810 picograms of carbon per cell (Nielsen and Tonseth 1991) depending on physiological state. Scaling up to 850,000 *Karenia* cells L^{-1} (the approximate maximum observed in the region), this is equivalent to 0.04 to 0.07 milligrams of carbon per liter (40 to 69 milligrams carbon per m^3). *Karenia* abundance near the bottom during bloom senescence could be much higher. These ungrazed *Karenia* cells could provide added carbon, increase biological oxygen demand, and contribute to the hypoxia observed in shallow, nearshore bottom waters of southwestern Cape Cod Bay in late summer of 2019 and 2020. *Karenia* abundance in the bay has not reached levels that cause anoxia in other systems, but the combination of recently warming bottom waters, added oxygen demand from decaying *Karenia* cells, and thin bottom water layers may be pushing oxygen levels down in shallow regions of Cape Cod Bay.

The 2017 appearance of *Karenia mikimotoi* over a ~160 km stretch of coastline from Portland, Maine to Boston, Massachusetts at high abundance was unusual. Prior to 2017, *Karenia* was not observed in the previous 25 years of MWRA monitoring, and *K. mikimotoi* is not recorded as a member of the Gulf of Maine regional phytoplankton flora. Geographically, there is a record of *K. mikimotoi* as an identification from the Gulf of St. Lawrence (Dahl and Tangen 1993; Blasco et al. 1996), and in 2017 and 2019, major blooms of this species were responsible for benthic mortalities near Casco Bay, Maine[6]. *K. mikimotoi* has been characterized as an oceanic frontal zone and thin layer species that can be transported over long distances along frontal zones (Smayda 2002). Consistent with this, note that elevated cell counts were often observed in the chlorophyll maximum layer in offshore waters. *K. mikimotoi* also has a history of 'invasions' into new waters where it was not previously observed. For example, the phytoplankton flora of the North Sea had been studied for nearly a century before the novel appearance and establishment of *K. mikimotoi* in the North Sea in the 1960s (Partensky and Sourna 1986).

K. mikimotoi has been characterized as a harmful species (Gentien 1998), however toxins from this species are not well-characterized (Yamasaki et al. 2004), and negative effects of *K. mikimotoi* blooms have been limited to death of sessile shellfish and finfish, the latter located in confined environments such as fish farm pens (Turner et al. 1987). Anoxia, fish kills, and benthic mortalities are associated with this species in Maine and elsewhere in the world at abundances of 3 to 10 million cells L^{-1} (Gentien 1998, Turner et al. 1987, Li et al. 2019). With the observation of elevated *Karenia* and hypoxia in Cape Cod Bay during both 2019 and 2020, it appears that *Karenia* is having secondary negative ecosystem impacts, in the form of lowered DO, during the senescent period of the bloom. There is also a possibility that toxins are responsible for some of the observed mortalities of benthic organisms. It will be important to continue to monitor *Karenia* abundance in the region given the species potential for harmful impacts and the apparent establishment of *Karenia mikimotoi* as part of the regional phytoplankton flora.

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

3.2 STRATIFICATION AND CERATIUM

Ceratium species are typically one of the most abundant groups of dinoflagellates in the bays. To properly characterize and understand variability in bay phytoplankton community structure, it is important to understand factors controlling highly abundant species such as *Ceratium*. Previous analyses have identified a positive correlation between variation in stratification and variation in *Ceratium* spp. abundance from 1992 to 2007 (Hunt et al. 2010). This relationship is consistent with the ecology of *Ceratium* spp. which, in general, have a slow growth rate and require prolonged periods of stratification to achieve elevated abundance in the sub-surface, chlorophyll maximum layer near the pycnocline of stratified coastal systems (Cushing 1989).

Over the past two years a similar pattern was observed with high June 2019 *Ceratium* abundances associated with strong May 2019 stratification, while June 2020 *Ceratium* abundances were quite low and stratification in May 2020 was relatively weak. These factors and the previous findings by Hunt et al. (2010) led to a reexamination of the relationship between stratification and *Ceratium* for the 2008 to 2020 period. Unfortunately, there was no statistical relationship between stratification and *Ceratium* abundance for the 2008 to 2020 period ($r = 0.24$, $p = 0.4413$, **Figure 3-2**). What caused this shift from a significant positive correlation between stratification and *Ceratium* abundance during 1992 to 2007 to no statistical relationship is not known. The most likely factors are: 1) a change in *Ceratium* abundance estimation methods instituted in 2011 and 2) a post-2008 change in the physical oceanography of Massachusetts Bay.

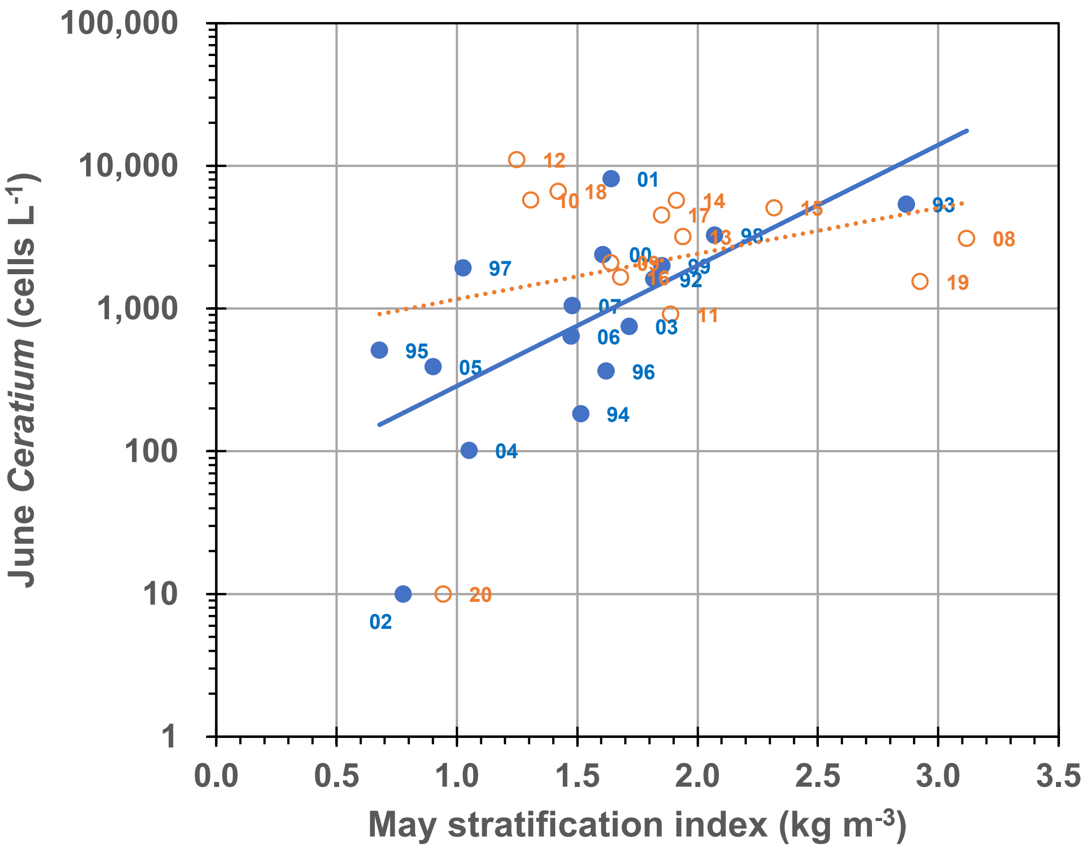

Figure 3-2. May stratification index (kg M^{-3}) vs. June *Ceratium* abundance (cells L^{-1}) for 1992-2007 (blue filled circles) and 2008-2020 (orange circles). The solid blue line represents the regression line for 1992-2007 data and the dashed orange line for 2008-2020.

During 1992 to 2010, *Ceratium* abundance was estimated using a dinoflagellate focused technique in which 4 liters of seawater was strained through a 20-µm screen. This resulted in a large number of *Ceratium* cells being observed in most samples, and a statistically robust estimate of *Ceratium* abundance. In 2011, the method used to estimate *Ceratium* abundance changed and abundances from 2011 to 2020 were derived from whole water phytoplankton counts, with lower numbers of cells observed under the microscope per sample counted. This resulted in *Ceratium* abundance estimates during 2011 to 2020 that were more variable and statistically less robust than those made for 1992 to 2007 (Hunt et al. 2010).

Oceanographic variability in Massachusetts Bay may also be a factor in explaining the post-2007 change in the stratification-*Ceratium* relationship. For example, oceanographic variability in the degree of Western Maine Coastal current (WMCC) intrusion into Massachusetts Bay has been identified as a primary driver of the stratification in the bay (McManus et al. 2014). A strong correlation between surface salinity, stratification and primary production was related to variation in intrusion of the WMCC into Massachusetts Bay, with a tendency of lower salinity, stronger stratification, and reduced production during the later years of the 2003 to 2010 time series (McManus et al. 2014). The 2008-2020 weakening of the previously identified (1992 to 2007) stratification-*Ceratium* relationship may be related to a change in the degree of WMCC intrusion into MA Bay during 2008 to 2020 versus that experienced during 1992 to 2007.

The change in the method used to estimate *Ceratium* abundance complicates interpretation of the results from 1992-2010 and 2011-2020. However, the 2019 and 2020 results are consistent with the findings of Hunt et al. (2010) with strong May stratification/high June *Ceratium* abundances in 2019 and weak May stratification/low June *Ceratium* abundance in 2020. These two years were also consistent with the findings of McManus et al. (2014) as the intrusion of lower salinity waters from the WMCC was especially pronounced in 2019 leading to strong stratification (Libby et al. 2020), while as noted in this report, during 2020 river flows were relatively low and surface water salinity was not indicative of a freshet or intrusion of lower salinity waters from the WMCC. The relative impact of stratification on the abundance of *Ceratium* and other dinoflagellates continues to be a focus of data analysis of this long-term phytoplankton dataset.

4 SUMMARY

The most notable physical oceanographic events in 2020 were unusually warm surface waters during the summer, relatively abrupt increases in oxygen during June, and a hypoxic event in Cape Cod Bay in September, similar to the hypoxic/anoxic event in the same region in 2019. Overall, river flow was lower than normal with near normal flow during the spring freshet and no large flow events (**Figure 2-3**). Over the summer months, river flows were especially low and indicative of moderate drought conditions for the Merrimack River discharge. Variable winds over the summer resulted in periods of relatively weak upwelling interrupted by strong downwelling/mixing events in early August, and a Nor'easter later in the month.

Water column stratification was close to the long-term median from February to June and peaked with record high levels in July. This was driven by very warm surface waters in late July. Summer average water temperature in 2020 was the warmest over the 29-year period of observations. The long-term trend shows summer surface water temperature is increasing more rapidly than air temperature (**Figure 2-6**). This difference is likely due to regional rather than local influences on the water temperature.

Analysis of wind data indicates the mean direction of summertime winds in Massachusetts Bay has shifted from the southerly direction to the southeasterly direction over the last 20 years (Personal communication Malcolm Scully WHOI, April 2021). The shift in winds may explain the general warming tendency, as southeasterly winds do not result in coastal upwelling of cold water, whereas southerly, and even more so southwesterly, winds lead to stronger cooling due to upwelling. Overall, intermittent downwelling/upwelling predominant winds, the Nor'easter in August, and the predominance of southeasterly winds resulted in relatively weak upwelling over the summer stratified period in 2020.

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 nutrient concentrations in February, sharp decreases in NO_3 and the NO_3 to SiO_4 ratio by May (indicative of a *Phaeocystis* bloom), and depleted surface water concentrations from May through August 2020. Station average nutrient concentrations varied over the summer but were typically close to the historic median (**Figure 2-8** and **Figure 2-9**). Ammonium concentrations in the nearfield during summer were variable, as has been the case since the bay outfall came online in 2000.

The 2020 NH_4 concentrations were mostly typical and within the range observed post-diversion: compared to the baseline period before operation of the outfall in the bay, they were lower in Boston Harbor, higher in the outfall nearfield and vicinity, and unchanged in the rest of Massachusetts and Cape Cod Bays (**Figure 2-10**). There was a high degree of variability in NH_4 concentrations in the nearfield from nearly depleted in May to peaks in the upper quartile in February, June, and September, while an annual maximum of nearly 15 µM was observed at station N21 in October. As has been the case since operation of the bay outfall began in 2000, in 2020 the NH_4 signal from the effluent discharge plume was observed consistently in the nearfield, and up to 10-20 km away on an intermittent basis spatially and temporally. In February, under well-mixed conditions, the NH_4 plume signature was most pronounced in the nearfield surface waters (**Figure 2-11**) and by June, when the water column was stratified, high NH_4 levels (>8 µM) were observed at or below the pycnocline at nearfield stations N21 and N18, and about 10 km south of the outfall at station F15 (**Figure 2-12**). These patterns in the NH_4 effluent plume are 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).

Overall, 2020 chlorophyll concentrations were moderate. High chlorophyll levels were observed during surveys in February in Cape Cod Bay, early May in Massachusetts Bay, and August and September across much of the monitoring area (**Figure 2-14** and **Figure 2-15**). MODIS and NERACOOS Buoy A01 fluorescence data (**Figure 2-16** and **Figure 2-17**) were used to help understand the winter/spring months not sampled due to COVID. Based on them, if there were no COVID-related sampling disruptions it is likely that higher winter/spring seasonal and annual chlorophyll concentrations would have been observed. A large increase in MODIS and buoy chlorophyll fluorescence in late February/early March suggests the occurrence of a winter/spring diatom bloom and another mid-April to early May was indicative of a large *Phaeocystis* bloom. During the early May survey, *Phaeocystis* abundances remained elevated and chlorophyll levels were high in Massachusetts Bay. The August and September peaks in chlorophyll were associated with the bloom of *Karenia mikimotoi* across Cape Cod and Massachusetts Bays (**Figure 2-15**). Chlorophyll concentrations in the nearfield were below Contingency Plan seasonal thresholds in summer and fall 2020 (**Table i**). Annual and winter/spring thresholds could not be calculated due to lack of March and April sampling due to the COVID-19 pandemic.

Bottom water DO concentration minima were moderate over most of Massachusetts Bay in 2020 and higher than Contingency Plan thresholds. Bottom water DO concentrations were relatively low from February to June (**Figure 2-18**). DO concentrations increased by ~1 mg L^{-1} from June to July, but the physical processes driving this change were not as clearly identifiable in association with specific downwelling favorable winds or mixing events as has been the case as in past years. In June 2020, winds oscillated from downwelling to upwelling favorable and did not appear to be strong enough to account for this large change in bottom water DO (**Figure 2-4**). By late August and early September, bottom water DO had decreased to annual minima of 6.5 to 7 mg L^{-1} in Boston Harbor and shallower Massachusetts stations. At deeper offshore Massachusetts Bay stations, annual minima of 6.5 to 7 mg L^{-1} were observed in October and Buoy A01 data indicated deep DO concentrations did not increase until mid-November (**Figure 2-20**).

Cape Cod Bay stations showed a similar summer increase in bottom water DO in July, but concentrations then decreased to low levels of 4.7 to 5.3 mg L^{-1} by late August (**Figure 2-19**). For the second year in a row, hypoxic conditions were observed by other researchers in southern Cape Cod Bay in 2020. Hypoxic bottom water DO concentrations were seen along a transect off Sandwich, Massachusetts from late August to mid-September before increasing to >6 mg L^{-1} on September 24 (**Figure 2-21**). As was the case in 2019, the combination of the large *Karenia mikimotoi* bloom in August/September 2020 as a source of biomass, strong stratification, and a thin bottom layer are thought to have contributed to these very low DO levels in Cape Cod Bay.

Annual total phytoplankton abundance in the nearfield was very low in 2020 and ranked 22nd for the 29-year monitoring program (**Table 2-1** and **Figure 2-22**). Total phytoplankton abundance was consistently below the historic median during the surveys conducted in 2020 (**Figure 2-22**). From May to October 2020, which followed the usual sampling schedule, total phytoplankton abundance was often within the lower quartile of long-term levels or below the minima. This was due to very low abundances of the usually numerically dominant microflagellates and centric diatoms over the summer and fall. In general, 2020 phytoplankton results continue the trend of relatively low phytoplankton in the Massachusetts Bay nearfield observed since the early 2000s.

Dinoflagellates were the only phytoplankton functional group displaying above long-term mean abundance levels during 2020 (**Table 2-1** and **Figure 2-23**): primarily due to a bloom of *Karenia mikimotoi* during August and September 2020 (**Figure 2-24**). *Karenia*, a harmful algal species, appears to have become a regular component of Massachusetts Bay phytoplankton, with abundance maxima of near 1 million cells L^{-1} observed during both 2019 and 2020. *Karenia* also appears to be becoming more persistent in Massachusetts Bay, increasing from an August to October (70 days) presence during 2017 to being present from February to October (252 days) during 2020. *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.

Regions of Cape Cod Bay experienced anoxia and invertebrate die-offs during September 2019 and hypoxia in September 2020, coincident with the *Karenia mikimotoi* blooms. The high *K. mikimotoi* biomass concentrated near the bottom during bloom senescence likely provided additional carbon, increased biological oxygen demand, and contributed to the hypoxia observed in shallow Cape Cod Bay. *Karenia* abundance in the bay has not reached levels that cause anoxia in other systems, but the combination of recently warming bottom waters, added oxygen demand from decaying *Karenia* cells, and thin bottom water layers may be pushing oxygen levels down in shallow regions of 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 seen thus far in Massachusetts Bay (Turner et al. 1987, Li et al. 2019).

In 2019, there was a major, prolonged *Alexandrium* bloom in Massachusetts Bay comparable to the large blooms observed in 2005 and 2008 (Libby et al. 2020). Sediment sampling in August 2019 showed elevated numbers of cysts in Massachusetts Bay (**Figure 2-25**), presumably a result of the prolonged bloom in the preceding months. The presence of these cysts in the bay was surprising and the impact on a 2020 *Alexandrium* bloom, or the possibility of a localized bloom being initiated in Massachusetts Bay rather than transported from offshore waters to the north, was unknown. Fortunately, *Alexandrium* abundances were generally low in Massachusetts Bay and the western Gulf of Maine in 2020. In mid-June, one sample off Cohasset had an *Alexandrium* count of 127 cells L^{-1} which triggered the first ARRS survey. Elevated *Alexandrium* abundances were observed during the first of two ARRS surveys along the South Shore with a maximum of 2,123 cells L^{-1} off Scituate (**Figure 2-26**). However, MA DMF did not observe any detectable PSP toxicity within Massachusetts Bay in 2020. This was likely due to a combination of the spatially and temporally limited extent of the elevated *Alexandrium* abundances and the occurrence of multiple upwelling favorable periods of winds in June (**Figure 2-4**) leading to predominantly offshore surface flow. *Alexandrium* abundances never exceeded 100 cells L^{-1} in the nearfield (46 cells L^{-1} maximum) so there was no exceedance of this Contingency Plan threshold in 2020 (**Table i** and **Figure 2-27**). It is not known whether the *Alexandrium* cells observed in Massachusetts Bay were the result of the typical advection of populations from the western Gulf of Maine, or from localized cyst germination within the bay. Plans are underway to sample Massachusetts Bay sediments for *Alexandrium* cysts going forward to help determine whether a cyst seedbed could be developing within the bay.

Zooplankton sampling was limited to four surveys in 2020 – February and August to October. Zooplankton taxa and abundances in February and October were generally similar to those of most previous years (**Figure 2-28**). General seasonal patterns of abundance were typical, with increases from February lows through to summer peaks, followed by fall declines. However, in August, and continuing into September, there was a substantial and unprecedented abundance of radiolarians (unicellular protozoan animals) throughout most of the sampling area. There had been a sustained trend of increasing abundance of total zooplankton from 2006 through 2017 that was driven by increases in copepod adults and copepodites (Libby et al. 2019). Zooplankton abundances leveled off in 2018 and the limited data from 2020 are consistent with the zooplankton levels observed in 2018-2019.

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