2021 Water Column Monitoring Results

Massachusetts Water Resources Authority
Environmental Quality Department
Report 2022-13

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Cover Photo: CTD-Rosette set for deployment to collect samples at several depths.
Credit: Alex Mansfield, Battelle on the February 2021 MWRA survey WN211.

2021 Water Column Monitoring Results

Submitted to

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Environmental Quality Report 2022-13

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA), as part of its National Pollutant Discharge Elimination System (NPDES) permit for the Deer Island Treatment Plant, is required to monitor water quality in Massachusetts and Cape Cod Bays. This report documents the results of 2021 water column monitoring, which focuses on water conditions (not sediments, fish, or shellfish) from the ocean surface to the seafloor. The monitoring is intended to evaluate whether the environmental impact of the treated sewage effluent discharged at the MWRA bay outfall meets the expectations of the Supplemental Environmental Impact Statement from the U.S. Environmental Protection Agency (EPA), and whether thresholds of the Contingency Plan[1] attached to the permit have been exceeded.

In 2021, the COVID-19 pandemic impacted the level of sampling conducted in February through May. As in 2020, 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) plus zooplankton. All Contingency Plan thresholds were able to be tested in 2021 with exceedances observed for the *Alexandrium* and dissolved oxygen thresholds (**Table i**). Three additional *Alexandrium* Rapid Response Study (ARRS) surveys were conducted in July 2021.

Table i. Contingency Plan threshold values and 2021 results for water-column monitoring. Three exceedances occurred, as indicated in red.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2021
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: 6.36 SW Basin: 5.89
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 71.3% SW Basin: 65.9%
Bottom water DO rate of decline (mg L^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.012
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	49
	Winter/spring	>199	--	50	62
	Summer	>89	--	51	43
	Autumn	>239	--	90	42
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	130
	Summer	>43,100	--	14,635	3,110
	Autumn	>27,500	--	10,500	94
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	7,386

[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 Basin monitoring station. The deepest monitoring location located ~16 km (10 mi) NE of the outfall and just outside the boundary of the Stellwagen Bank National Marine Sanctuary.

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[1] MWRA's discharge permit includes a Contingency Plan with thresholds that may indicate a need for action if exceeded. The thresholds are based on permit limits, state water quality standards, conditions during the 1992-2000 baseline monitoring period, 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.

Nitrogen, including the dissolved forms nitrate and ammonium, is the most important nutrient for phytoplankton growth in marine waters. Ammonium is the largest fraction of the total nitrogen in wastewater, making it a good effluent tracer. Monitoring in 2021 found elevated ammonium concentrations above baseline conditions frequently within 10 km (6 miles) of the outfall and intermittently both spatially and temporally up to 30 km (19 miles) from the outfall in the direction of prevailing background currents to the south. This is similar to previous years, and consistent with results from calibrated eutrophication-hydrodynamic models. Other noteworthy observations during 2021:

Physical Conditions

- The most notable physical oceanographic characteristics were a very wet summer, with frequent northeasterly wind events; unusually warm water, both surface and bottom; and a strong Nor'easter in October causing larger-than normal waves. Bottom water dissolved oxygen levels were lower than normal in the late summer, but perhaps not as low as they would have been without late summer mixing due to strong northeast winds.
- River flow was lower than normal during winter and spring, but July, August and September saw the highest flows of the 30-year monitoring program.
- Winds followed a typical annual pattern, with one notable event: strong winds in late October that drove extreme waves reaching significant wave heights of almost 9 meters (30 feet).
- Surface water temperature warmed to unusually high values during the late July and August surveys. Surface salinity started out high, but then dropped to below-average values due to the large summertime freshwater inputs.

Nutrients and Phytoplankton Biomass

- Massachusetts Bay nutrient concentrations were consistent with those observed since the outfall was diverted offshore. In 2021, concentrations were relatively high nutrient in February, changes in nitrate and silicate from February to March and April to May suggesting blooms may have occurred between the monthly MWRA surveys, depleted surface water concentrations from May into summer, with intermittent peaks in ammonium and phosphate.
- As in other years since outfall startup, compared to the baseline years 1992-2000, the 2021 ammonium concentrations during both winter (unstratified) and summer (stratified) conditions were lower in Boston Harbor, higher in the outfall nearfield, intermittently elevated within about 10 to 30 km of the outfall, and unchanged further afield.
- 2021 chlorophyll concentrations were low to moderate. Elevated areal chlorophyll levels were observed during the February, April, June, August, and September surveys in Cape Cod Bay and during the March and July surveys in Massachusetts Bay.
- Seasonal and annual average chlorophyll averages threshold values in 2021 were low, comparable to baseline seasonal averages and generally less than half the Contingency Plan thresholds (**Table i**).
- Satellite imagery and mooring measurements of fluorescence showed increases in chlorophyll in March and late April/May, which along with changes observed in nutrient concentrations suggest winter/spring diatom and *Phaeocystis* blooms occurred. Summer chlorophyll levels were low in Massachusetts Bay, but high chlorophyll concentrations were observed in Cape Cod Bay. in August and September 2021.

Bottom Water Dissolved Oxygen

- Bottom water dissolved oxygen (DO) concentrations were low and below historic minima at many stations by May 2021. Wind-driven mixing events in late May through July contributed to downwelling favorable conditions alleviating the decrease in bottom water DO concentrations in June and July. Strong stratification in late July and August contributed to a sharp decrease in bottom water DO concentrations in late August/early September in Massachusetts Bay.

- Low DO concentrations were observed at Stellwagen Basin station F22 in September and continued to decline in these deep waters into early November when they were the lowest seen at station F22 for the 30-year monitoring program exceeding Contingency Plan thresholds for DO concentration and percent saturation at Stellwagen Basin station F22 (**Table i**).
- Low DO was also observed in Cape Cod Bay but did not reach the hypoxic levels seen in 2019 and 2020. A Massachusetts Department of Marine Fisheries (MA DMF) led study measured a DO minimum of 2.3 mg L^{-1} off Wellfleet, MA on August 18, 2021, but the bottom waters were re-aerated by a late August northeast wind event and the remnants of Hurricane Ida in early September.
- Increased water temperatures and stratification resulting from regional changes in long-term summer wind patterns have been identified as a primary factor in the recent low DO events (Scully et al. 2022).

Phytoplankton and Zooplankton

- A large *Alexandrium catenella* bloom was observed in Massachusetts Bay in late June and July. Nearfield *Alexandrium* abundance peaked in June at 7,386 cell L^{-1} well above the Contingency Plan threshold (**Table i**) and triggered three ARRS surveys conducted in July. MA DMF did not detect any paralytic shellfish poisoning (PSP) toxicity in Massachusetts Bay until after the June survey with PSP toxicity first detected on June 28 at sites along the South Shore. High PSP toxicity was observed at MA DMF sites north of Cape Ann in early July resulting in shellfishing closures from the New Hampshire border south to Duxbury Bay, MA.
- 2021 total phytoplankton abundance was consistently low and often within the lower quartile or below the minima of long-term abundances. This was due to low abundances of centric diatoms, *Phaeocystis*, and the usually numerically dominant microflagellates. In general, 2021 phytoplankton results continue the trend of low abundance in Massachusetts Bay, due to natural variability, observed since the early 2000s.
- Dinoflagellates are the only phytoplankton functional group that appears to be increasing in recent years, primarily due to continued presence of *Karenia mikimotoi* that was first observed in Massachusetts Bay during 2017. *Karenia* abundance was lower in 2021 compared to 2019 and 2020, but as in 2020, it was present in the bays from February to November 2021. *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. These blooms have been identified as a contributing factor to hypoxic conditions observed in Cape Cod Bay in 2019 and 2020.
- Zooplankton taxa, seasonal patterns, and abundances in 2021 were generally similar to those of most previous years. Peaks in total zooplankton abundance in July and November were due to high abundances of radiolarians similar to 2020 observations, which was the first time radiolarians had been recorded in the sampling program. The high abundances of radiolarians suggest intrusions of water from offshore, which is consistent with frequent northeast wind events in July and the major storm in late November transporting offshore waters into the bay.

LIST OF ACRONYMS

µm	micrometer or micron
µM	micromolar concentration
AMP	Ambient Monitoring Plan
ARRS	*Alexandrium* Rapid Response Study
ASP	Amnesic 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
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

1 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) first started monitoring the Harbor and Bay in 1992, to assess baseline conditions before the Deer Island Treatment Plant started discharging treated effluent to Massachusetts Bay beginning in September 2000. Prior to that, inadequately treated sewage was discharged to Boston Harbor, which used to be one of the dirtiest urban water bodies in the United States. 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 changes within the system exceed 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 from Boston Harbor to Massachusetts Bay (MWRA 1991) and for the ‘outfall discharge’ period since the 2000 relocation (MWRA 1997; and major revisions MWRA 2004, 2010; most recent revision MWRA 2021). During the baseline period, from 1992 to September 5, 2000, Deer Island and/or Nut Island wastewater discharges were released directly within the harbor. For this report, the outfall discharge period extends from September 6, 2000 through 2021, when wastewater has been discharged from the bay outfall and not into the harbor. The 2021 data complete 21 years of monitoring since operation of the bay outfall began and 30 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, 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 (**Table 1-2**). Due to a winter rise in COVID-19 cases, the first four surveys of 2021 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 four staff, which required a commensurate reduction in sampling. As in 2020, the 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) plus sampling of particulate carbon/nitrogen and zooplankton. In May, a fifth member of the team, a marine mammal observer, was allowed to participate given the numerous right and humpback whales in the bays. By June, the field team was back to the full complement of six.

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. Three additional surveys were conducted in July 2021 as part of an *Alexandrium* Rapid Response Study (ARRS) triggered by elevated abundances of this toxic species (Libby et al. 2013a); those dates are listed in **Table 1-2**.

This annual report summarizes the 2021 water column monitoring results, examines conditions over the seasonal cycle during 2021, 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 tests Contingency Plan Warning and Caution thresholds (**Table i**; MWRA 2001) for bottom water dissolved oxygen (DO) concentrations, percent saturation, and rate of decline; phytoplankton biomass measured as chlorophyll-a; and nuisance phytoplankton species abundance.

Table 1-2. Water column surveys for 2021.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN211	February 9	February 9	February 4
WN212	March 31	March 23	April 6
WN213	April 14	April 14	
WN214	May 18	May 18	May 24
WN215	June 23	June 22	June 28
AF211	July 1	n/a	
AF212	July 8	n/a	
AF213	July 21	n/a	
WN216	July 27	July 27	July 28
WN217	August 25	August 25	August 26
WN218	September 8	September 7	September 7
WN219	November 2	November 2	November 2

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

1.1 DATA SOURCES

Details of field sampling procedures and equipment, sample handling and custody, sample processing and laboratory analysis, instrument performance specifications, and the program's data quality objectives are given in the Quality Assurance Project Plan (QAPP; Libby et al. 2021a). 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. An additional survey report was prepared for the 2021 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 2021 sampling dates are shown in **Table 1-2**. Stations within about 8 km of the outfall are referred to as “nearfield” and those further away are “farfield”. Five stations are sampled in the nearfield (N01, N04, N07, N18, and N21), six stations in the Massachusetts Bay farfield (F06, F10, F13, F15, F22, and F23), and three in the Cape Cod Bay farfield (F01, F02, and F29). The 11 stations in Massachusetts Bay (the nearfield and the Massachusetts Bay farfield) are sampled for a comprehensive suite of water quality parameters, including plankton, at all stations except N21 which is 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 three ARRS surveys in 2021, 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 2021, a marine mammal observer was not present on the AMP surveys from February to April in Massachusetts Bay due to COVID-19 mitigation protocols limiting survey staffing on the surveys. 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 2021 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 three four-month periods: winter/spring from January through April, summer from May through August, and fall from September through December. Comparisons of baseline and outfall discharge period data are made for a variety of parameters. The baseline period is February 1992 to September 5, 2000 and the outfall discharge period is September 6, 2000 through December 2021. 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

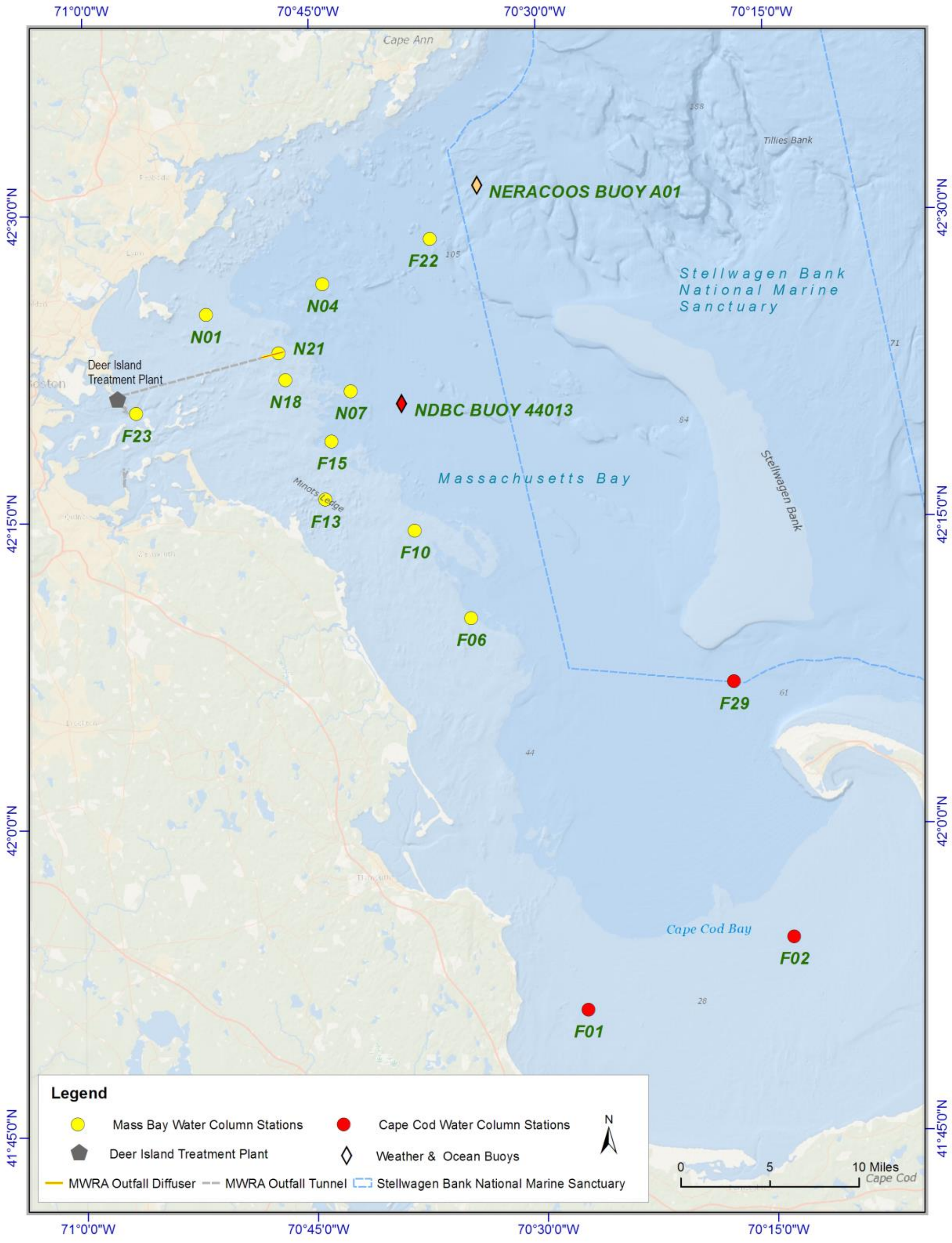

Figure 1-1. **Water column monitoring locations.**

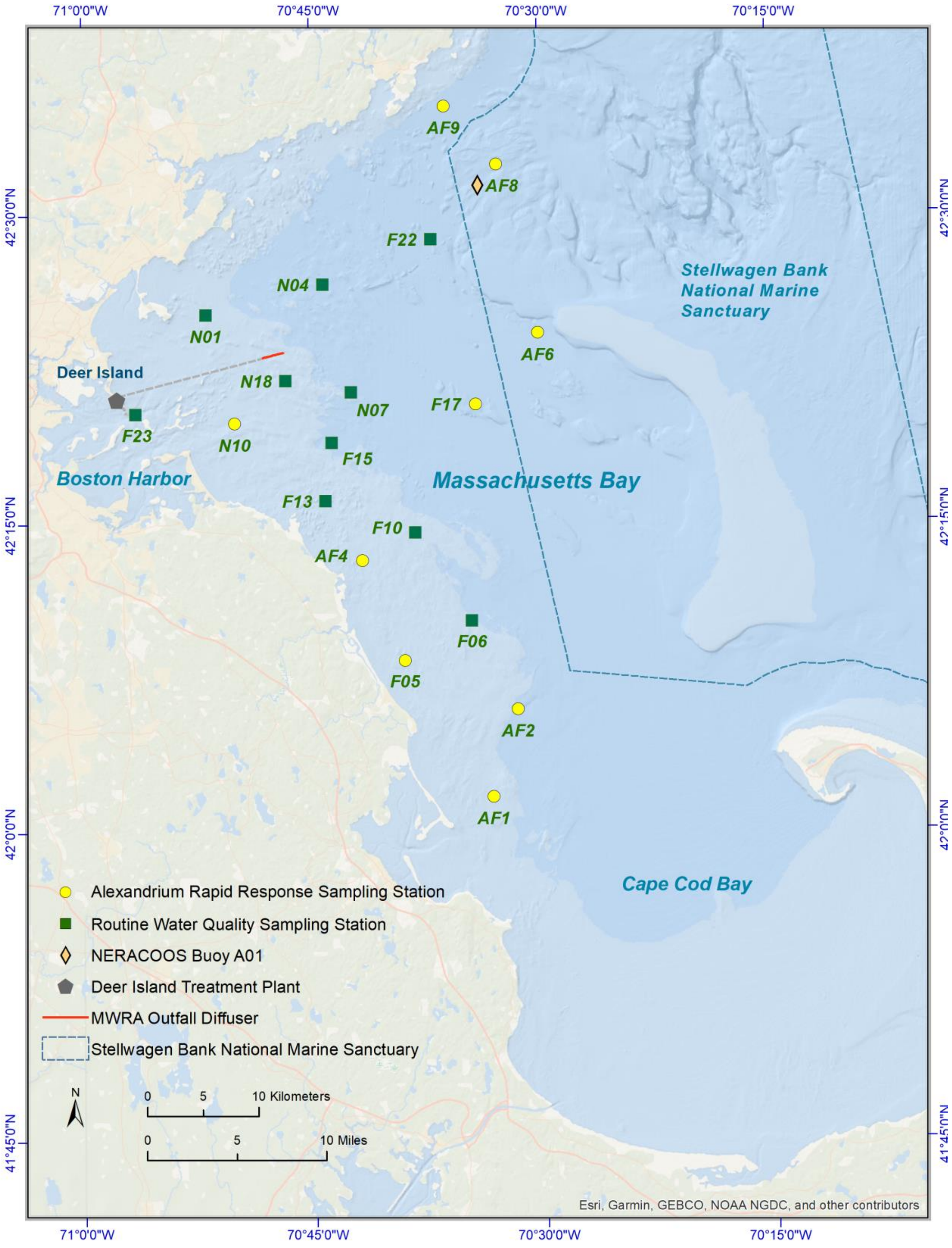

Figure 1-2. ***Alexandrium* Rapid Response Study monitoring locations.**

2 2021 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 and amounts of phytoplankton are typically moderate to low. Zooplankton counts are also typically 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 30-year dataset (1992-2021). The major features and differences observed in 2021 are described below.

2.2 PHYSICAL CONDITIONS

Air temperatures were slightly cooler than average in contrast to the warmer temperatures observed the past few years. Surface water temperatures were in the upper quartile compared to historical levels at station N18 from February to May before decreasing below the long-term median in June (**Figure 2-1**). Surface water temperatures remained close to the median in late June and early July before temperatures warmed to unusually high values during the late July and August surveys. This was a regional trend as similarly high February to May and late July August temperatures were also observed at station F22 farther offshore. Bottom water temperatures were consistently in the upper quartile or above historical maxima at both stations N18 and F22 from February to November 2021.

Surface salinity started out near the long-term median in February but was anomalously high from March through early July. During this period, both surface and bottom salinity were near or above historical maxima in the nearfield and station F22 (**Figure 2-2**). In July, surface salinity decreased sharply especially at station F22. Merrimack and Charles River flows were relatively low during winter and spring 2021, but an unusually wet summer period starting in July 2021 led to these low salinities. The July, August and September river flows were the highest observed over the 30-year monitoring program (**Figure 2-3**). Elevated river flow continued to be observed into the fall, due to a number of storms in the region, and is reflected in surface salinity below the historical median for the rest of 2021.

Wind speeds and directions were typical in early 2021, with a number of storm systems with strong northeast winds (known as Nor'easters) during the winter/spring. Strong northeasterlies result in strong near-surface currents and in the late spring often provide a conduit for the transport of surface waters and plankton such as *Alexandrium* from the Gulf of Maine into Massachusetts Bay. This may have been the case in late May 2021 when a period of strong northeasterly winds was observed. However, unlike past years, northeast wind events continued over much of the summer (**Figure 2-4**) and in late October strong winds led to extreme waves with significant wave heights of almost 9 m during a strong Nor'easter (data not shown). The response of surface waters to these northeast wind events is stronger when the water is stratified by the low-salinity water of the Merrimack River plume, and this was evident in July and August 2021 with currents transporting lower salinity waters into Massachusetts Bay. Northeast winds are not always associated with Nor'easters and may also be associated with smaller frontal systems or the remnants of tropical storms such as Hurricane Ida, which transited Massachusetts Bay in the beginning of September 2021.

The impact of the summer northeast wind events was evident in the upwelling index which is the monthly average of the north-south component of wind stress. A positive index indicates more wind from the south, which favors upwelling and cooling of both surface and bottom waters. The index showed strong upwelling conditions in June, but during July the index showed the strongest negative anomaly (i.e., downwelling-favorable) that has been observed over the 30-year monitoring program (**Figure 2-5**). August and September continued to show weak or absent upwelling conditions. The weak or negative upwelling index corresponds to the occurrence of multiple northeast wind events through the summer months. It also helps explain the warm waters observed during the late summer (**Figure 2-1**).

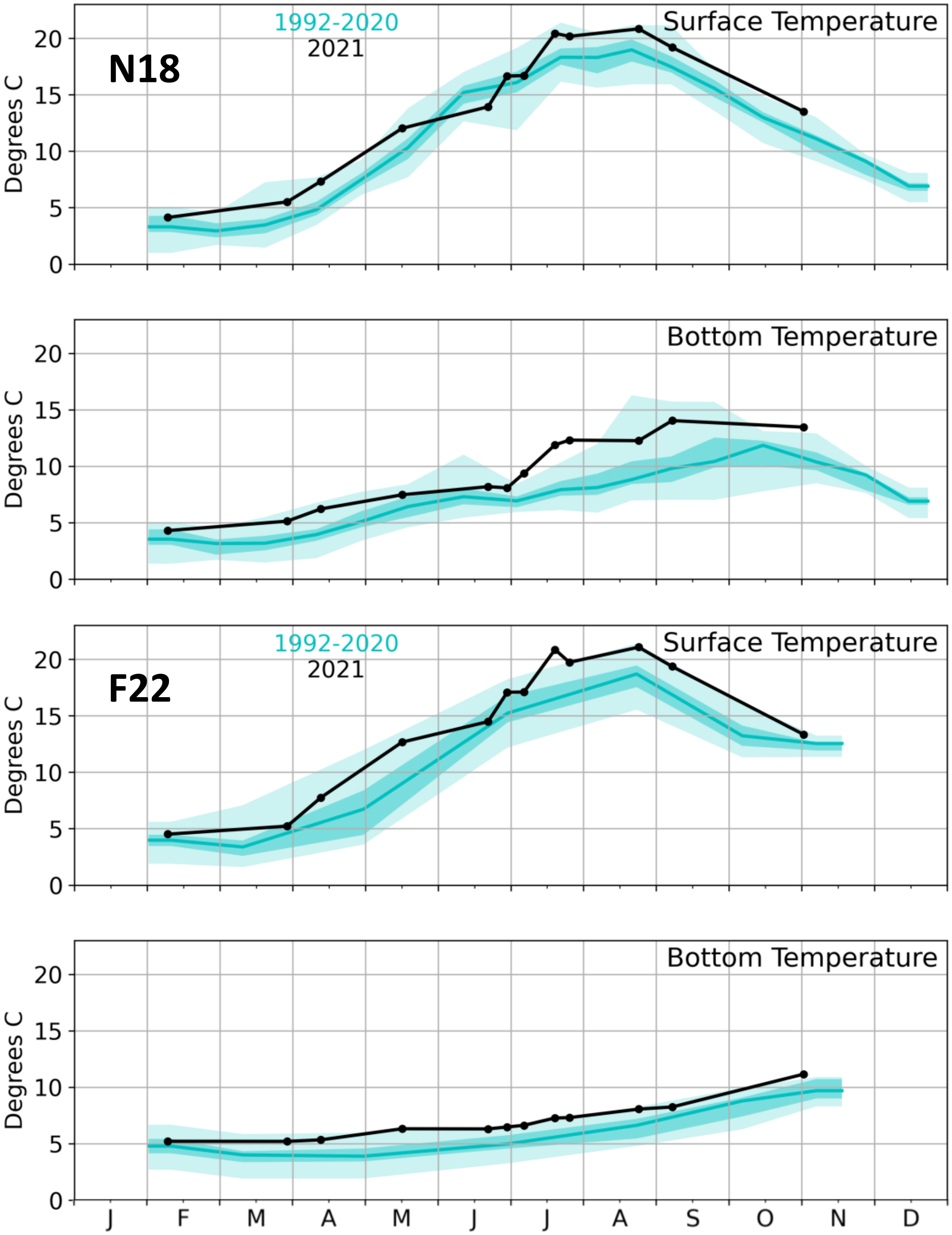

Figure 2-1. Comparison of 2021 surface and near bottom water temperature (°C) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

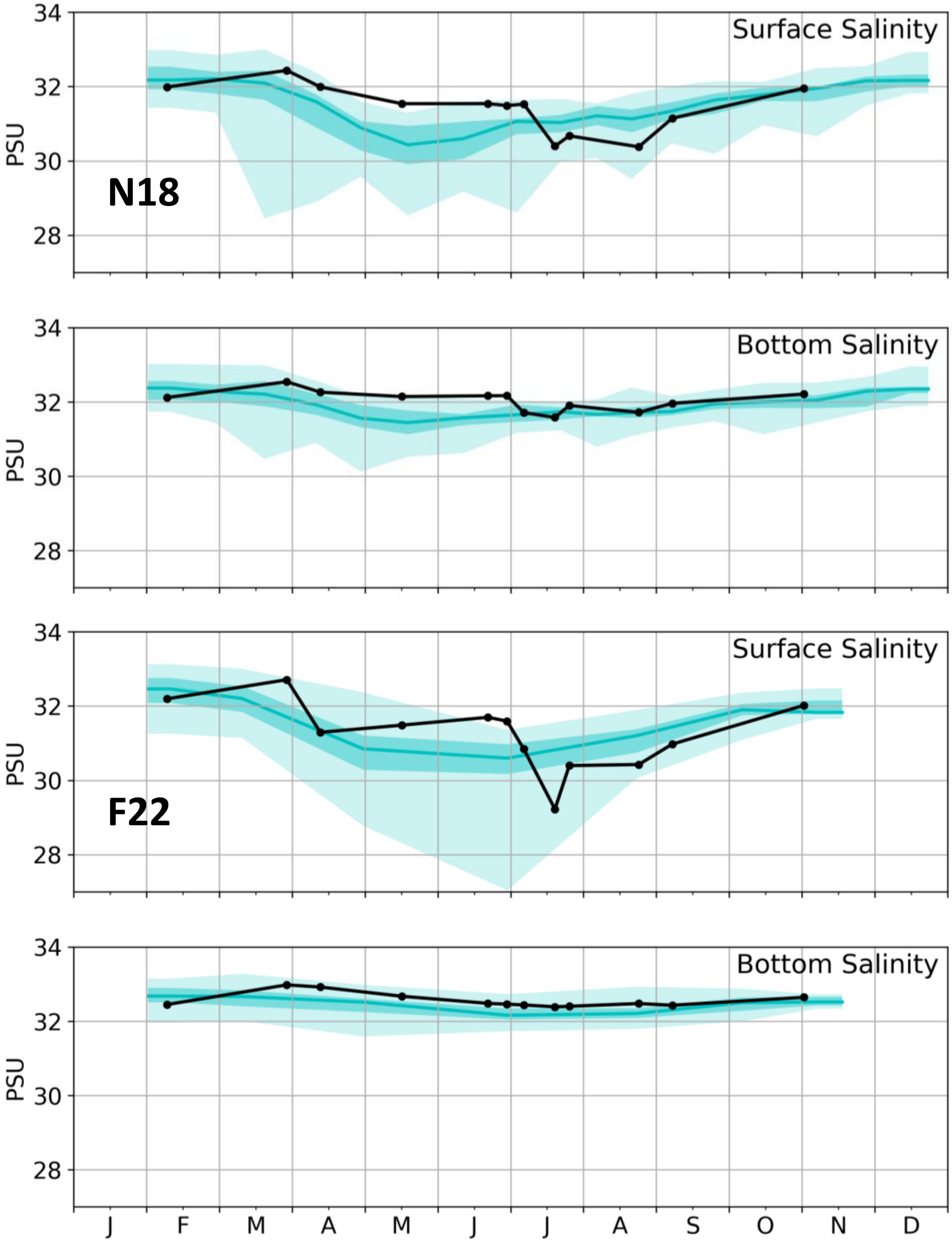

Figure 2-2. Comparison of 2021 surface and near bottom water salinity (PSU) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

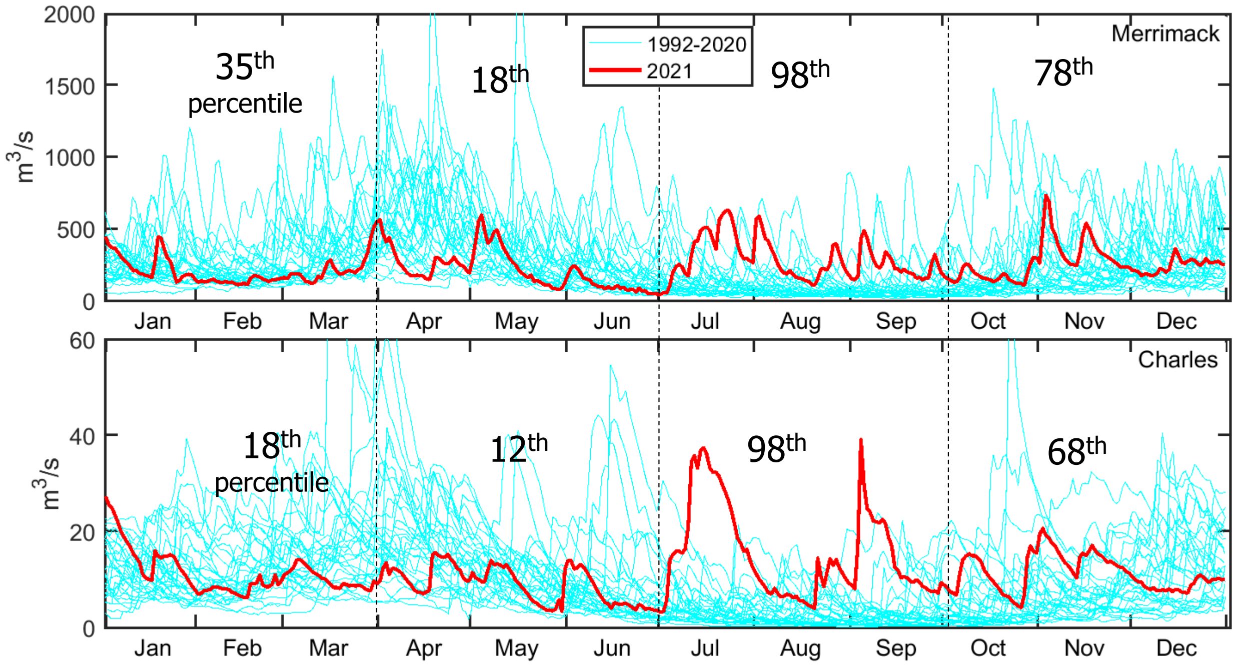

Figure 2-3. **Comparison of 2021 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2020 (light blue lines).** The percentiles represent 2021 flow, compared to the entire 30-year record, during each quarter of the year.

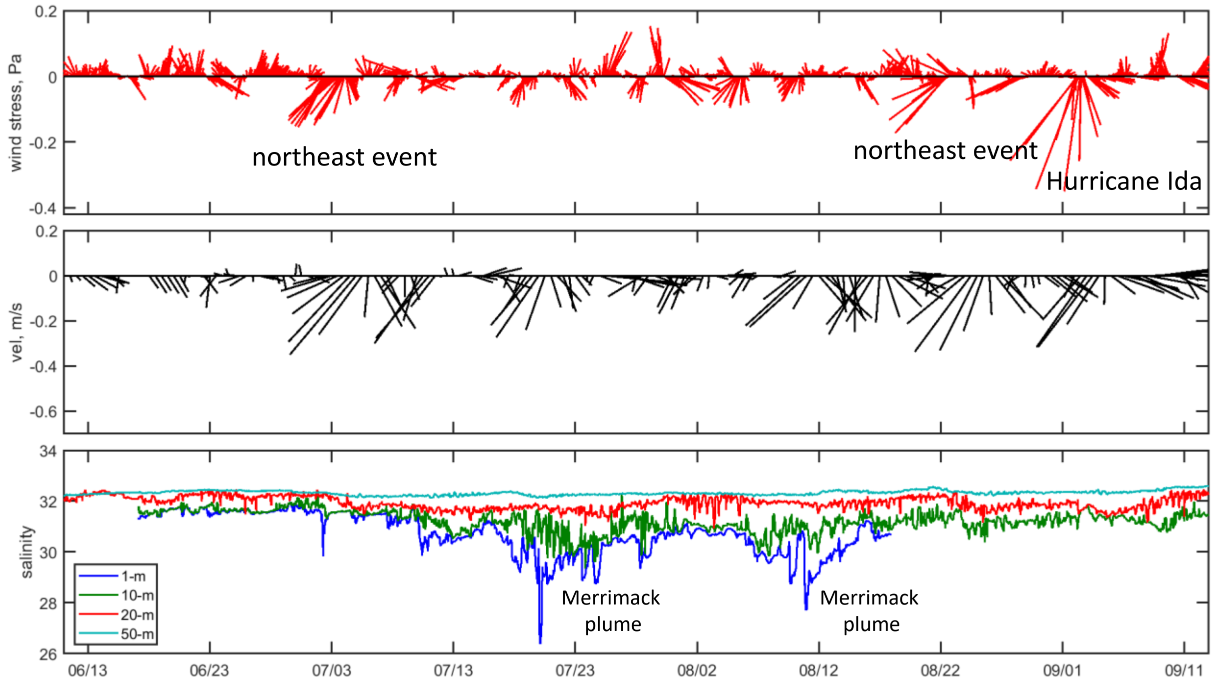

Figure 2-4. **NERACOOS Buoy A01 time series observations in summer 2021.** Top: surface wind stress (Pa) and direction (lines represent wind flow in the direction away from the origin line; northward up and eastward to the right). Middle: surface current speed and direction. Bottom: salinity (PSU) at multiple depths at the buoy.

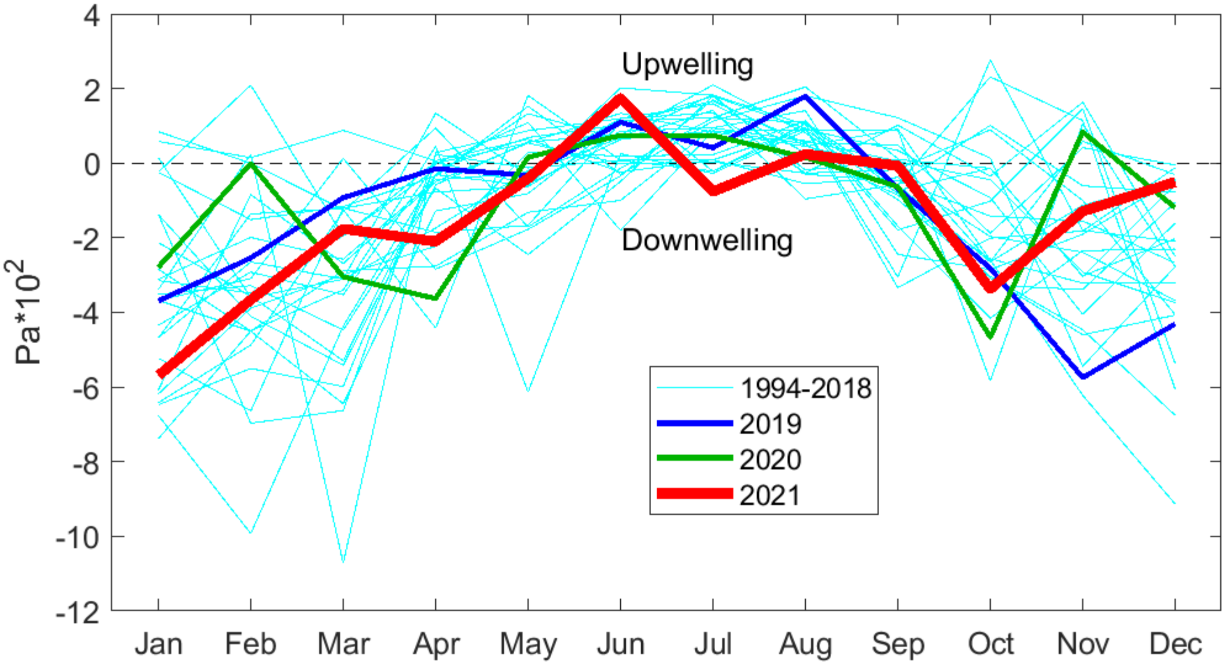

Figure 2-5. Upwelling index (100 x Northward component of wind stress; Pascals) at NOAA Buoy 44013. 2021 results are in red, 2020 in green and 2019 in blue. Results from 1994–2018 in cyan. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

Stratification in Massachusetts Bay was close to the long-term median from February to May 2021 (**Figure 2-6**). A combination of cooler, more saline surface waters and relatively warm, saline bottom waters led to historically low stratification in June. The influx of fresher, warmer surface waters in late June and into July led to a sharp increase in stratification with long-term maxima across the bay in late July and August. Stratification remained strong in early September before decreasing in November (**Figure 2-6**). The major Nor'easter in late October mixed the water column at all but the deepest waters in Massachusetts Bay. At station F22, the bottom waters remained cut off from the surface layer by stratification until after the early November survey. The impact of stratification and the intermittent northeast mixing events on bottom water DO concentrations is discussed in detail in Section 2.4.

The long-term trend of increasing summertime air and water temperatures eased in 2021 due to the cool northeasterly wind events (**Figure 2-7**). Interestingly, the summer-average water temperature also showed cooler conditions, even though the late-July and August water temperatures were unusually high, due to the unusually cool conditions in June and early July (**Figure 2-1**).

Although summer air and surface water temperatures decreased in 2021, the long-term trend shows that surface water temperature is increasing more rapidly than air temperature (**Figure 2-7**). This difference may be due to regional rather than local influences on the water temperature. Analysis performed by Scully et al. (2022) indicates that the mean direction of strong (>15 knots) summertime winds in Massachusetts Bay has shifted, from predominantly from the southwest to predominantly from the northeast over the last 20 years. This shift in winds may explain the general warming tendency, as northeast winds lead to downwelling and warming, opposite the upwelling and cooling due to southwest winds. The upwelling index was close to the long-term maxima in June 2021 (**Figure 2-5**) which may have contributed to the lower summer surface temperature at the Boston Buoy in 2021. However, the downwelling predominant winds in July and August 2021 did lead to an increase in surface water temperature at the buoy from early July through mid-August (**Figure 2-7**).

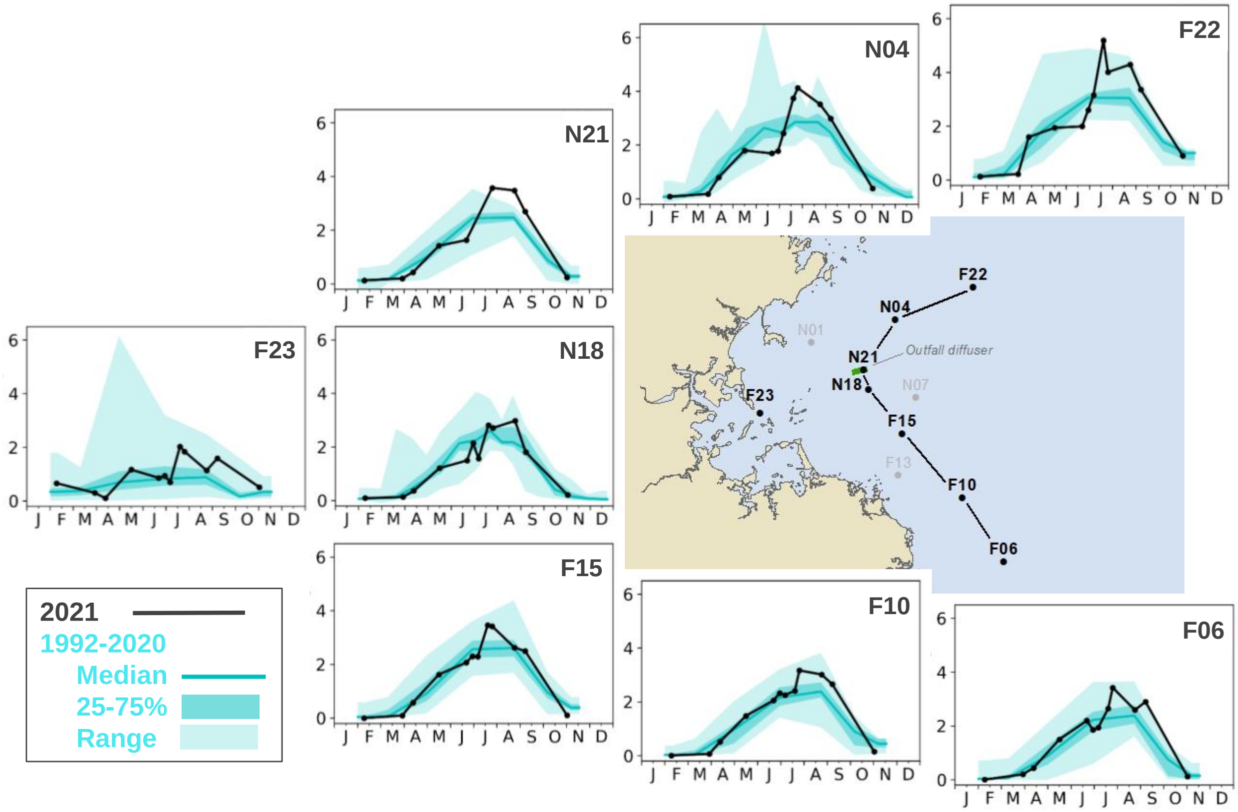

Figure 2-6. Stratification (Δ sigma-t; kg m^{-3}) at selected stations in Massachusetts Bay for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

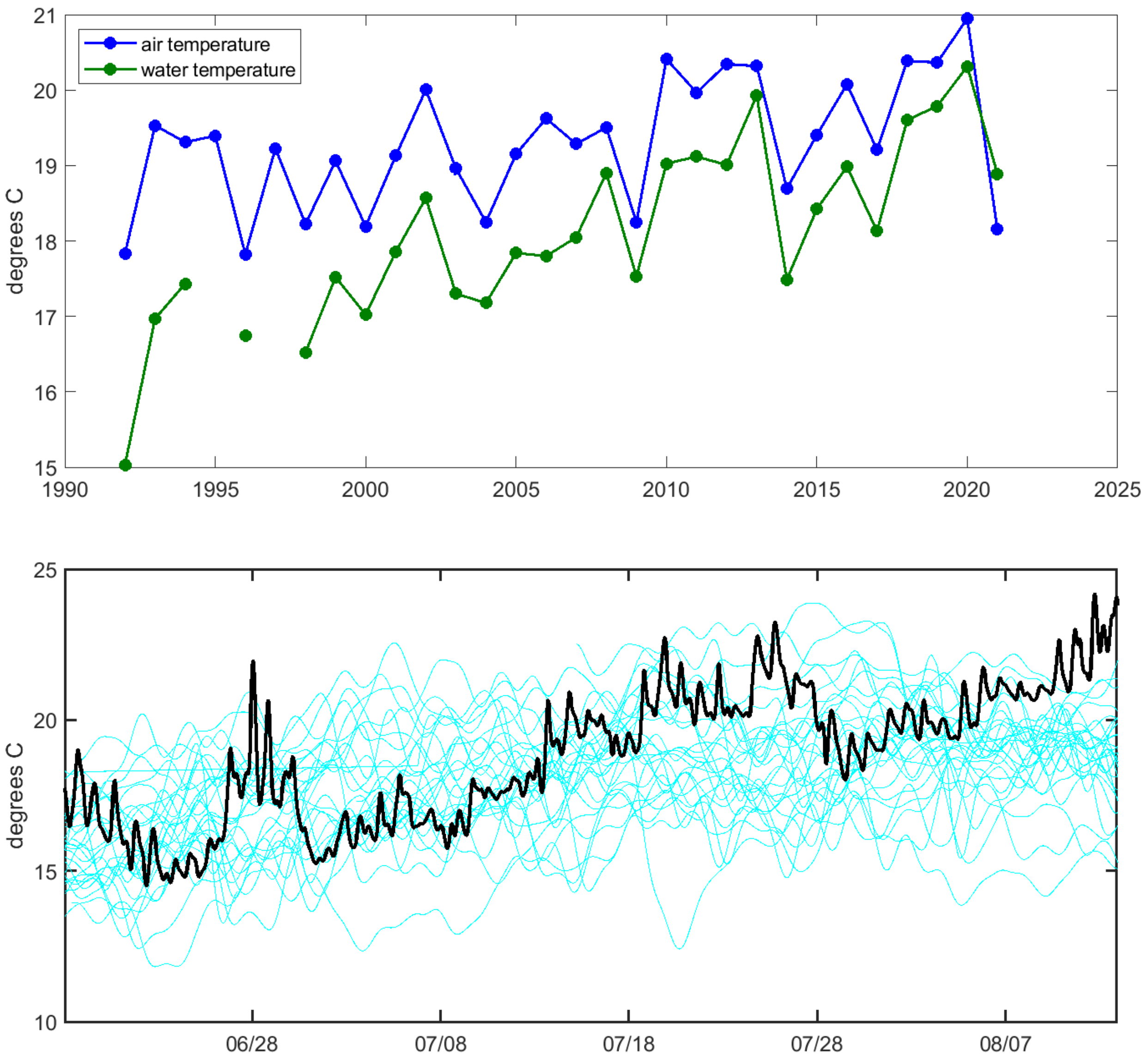

Figure 2-7. **Comparison of average mid-June to mid-August air and surface water temperature (°C) at Buoy 44013 in Massachusetts Bay from 1992-2021. Top: mid-June to mid-August averages. Missing segments of water temperature line represent gaps in the record. Bottom hourly water temperature 2021 in black and 1992-2020 in cyan.**

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

This section documents dissolved inorganic nutrient concentrations and phytoplankton biomass in the bay during 2021. 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. Depth-averaged concentrations tend to be elevated from February into April, relatively low from May into August or

September, and then increase into October and the winter. 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 2021 (**Figure 2-8**). Ammonium (NH_4) (**Figure 2-8**, upper right), which typically does not exhibit this seasonal pattern in the bay, was quite variable in 2021 with a maximum well above the historic range in early July (**Figure 2-8**, upper right).

Nutrient concentrations were seasonably high in February 2021 with concentrations close to the historic median for NO_3, NH_4 and PO_4 at station N18 and throughout Massachusetts Bay (**Figure 2-8** and **Figure 2-9**). However, concentrations of SiO_4 were in the lower quartile of the historic range in February and decreased close to long-term minima in March. The sharp decrease in SiO_4 was coincident with a similar decrease in NO_3 concentrations and suggests a diatom bloom likely occurred in February/March 2021 between the sampling surveys. Chlorophyll peaked at most stations in Massachusetts Bay during the March survey, with concentrations above the median and into the upper quartile compared to historic data, which is consistent with a bloom.

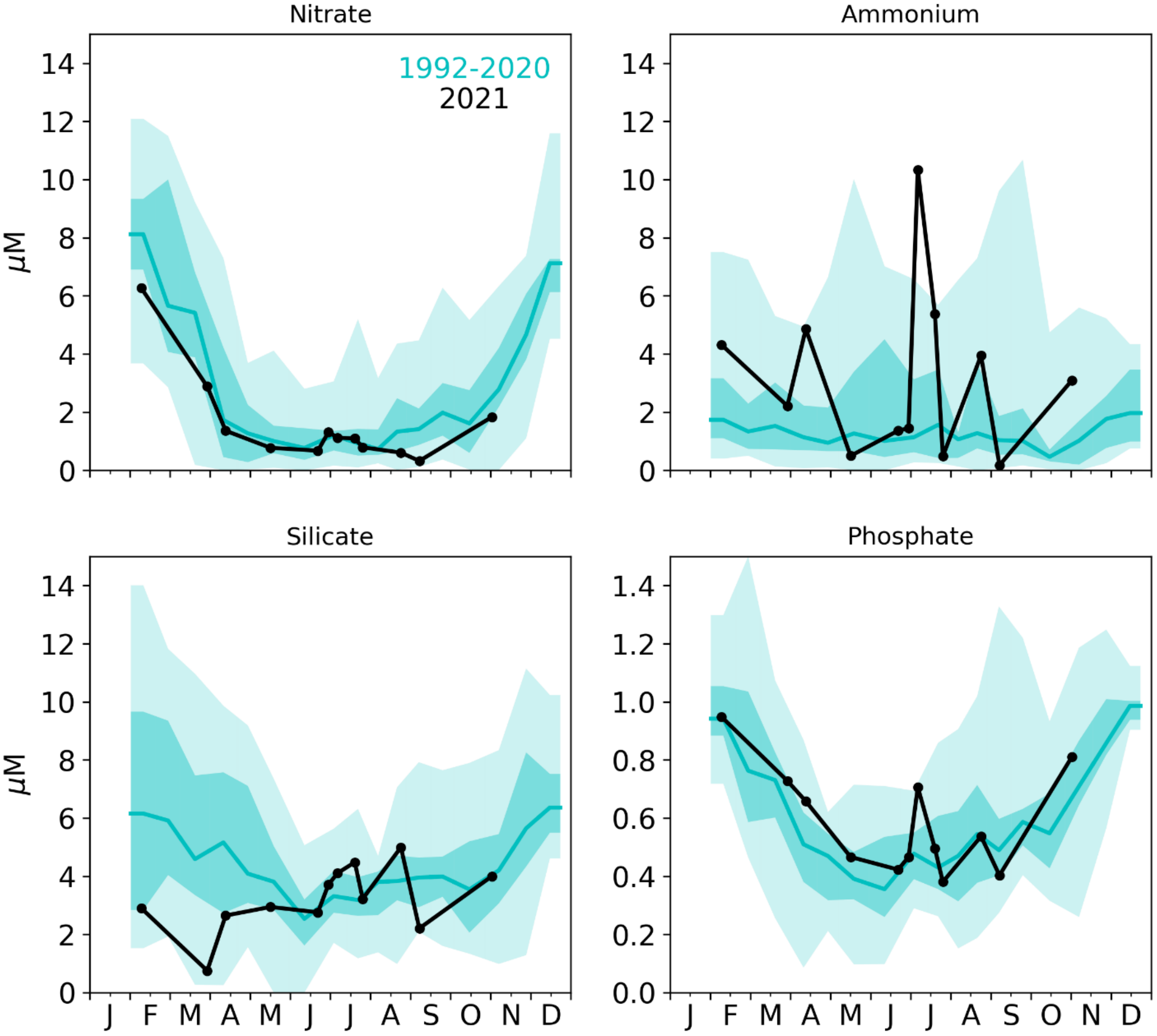

Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2021 compared to prior years. Note difference in scale for phosphate. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

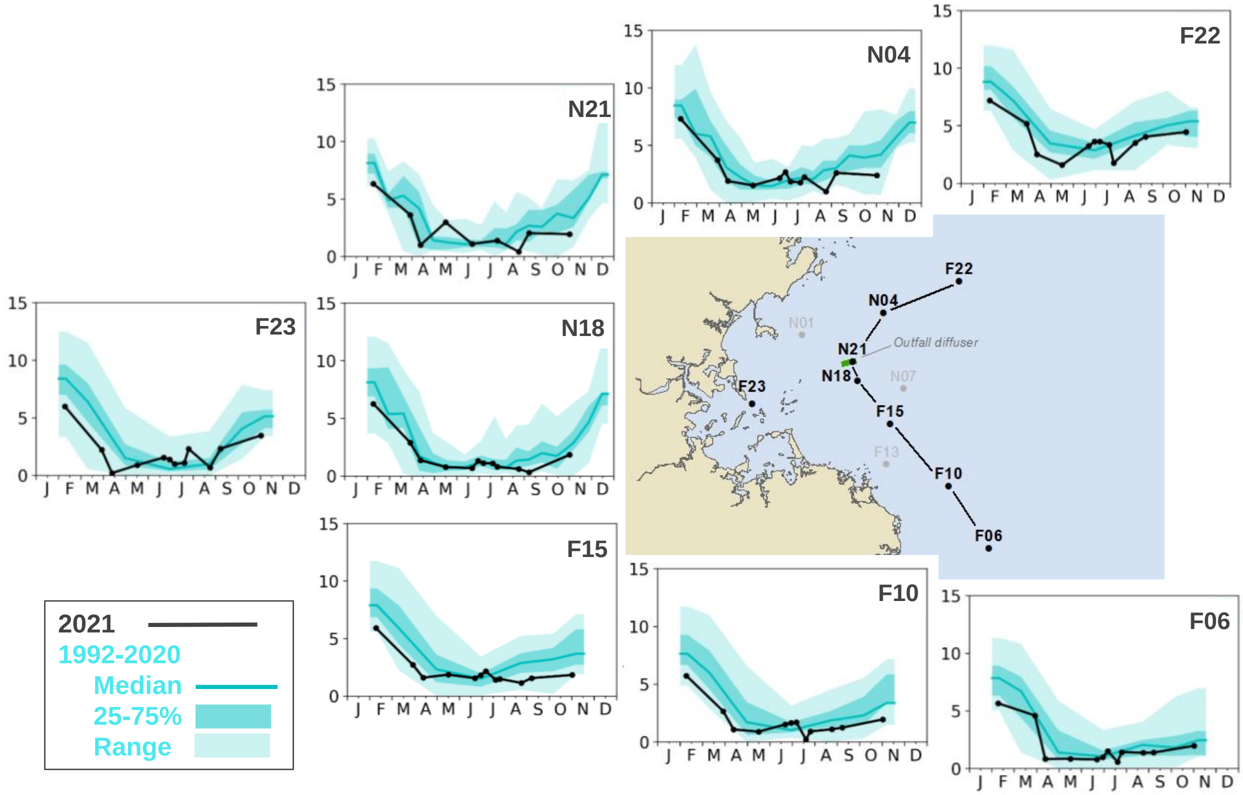

Figure 2-9. Depth-averaged nitrate (µM) at selected stations in Massachusetts Bay for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

From March to May, NO_3 concentrations continued to decrease at station N18 and throughout Massachusetts Bay, while SiO_4 increased to concentrations approaching the historical median at station N18 and higher at other stations in the bay (not shown). Both this change and the ratio of nitrogen to silica observed over this period are consistent with the presence of *Phaeocystis*, though the chlorophyll during the April and May surveys were relatively low as were the *Phaeocystis* abundances. MODIS imagery and NERACOOS Buoy A01 fluorescence data are useful in filling the information gaps between surveys. High chlorophyll was seen in both these auxiliary observations (see Figures 2-16 and 2-17, respectively) from mid-April to early May, which could be associated with the *Phaeocystis* bloom suggested by the change in the nitrogen to silica ratio.

Survey mean nutrient concentrations remained close to the historic median in May and June before increasing slightly in July in association with regional wind induced mixing events (see **Figure 2-4**). Overall, nutrients were low to depleted in the surface waters from May to August but were available below the pycnocline in higher concentrations as typically observed during summer stratified conditions (e.g., see **Figure 2-13**). Depth-averaged nutrient concentrations varied over the summer but NO_3 and SiO_4 were typically close to the historic median (**Figure 2-8**). However, there was considerable variability in NH_4 and PO_4 concentrations, which both peaked at station N18 in July. Ammonium concentrations have been more variable over the course of the summer in the nearfield since the bay outfall came online in 2000 (**Figure 2-10**). In August and September, NO_3 was depleted at the shallow, inshore stations, but began to increase at the deeper offshore stations (**Figure 2-9**), and by early November had increased to close to historic median concentrations across Massachusetts Bay.

As in other years since bay outfall startup, NH_4 concentrations at stations N21 and N18 were higher than during years effluent was discharged to Boston Harbor (**Figure 2-10**). At station N21, NH_4 concentrations were generally close to the long-term median except in April when they were nearly depleted. This is likely due to the effluent plume being advected away from that station by ambient currents during the survey, which is not unusual. At station N18, concentrations were more variable with peaks in the upper quartile during multiple months and with an annual maximum of about 10 µM observed in July well above the long-term maximum. Elevated NH_4 concentrations were also observed in June, July, and August 2021 at stations F15 and F10 and even as far south at station F06 nearly 30 km south of the outfall (**Figure 2-10**). These ammonium concentrations at southern stations were above historical medians but within historical maxima and are not observed consistently year-to-year. Ammonium concentrations at Boston Harbor station F23 in 2021, again as in other post-discharge years, were much lower than during the years the wastewater was discharged directly to the harbor.

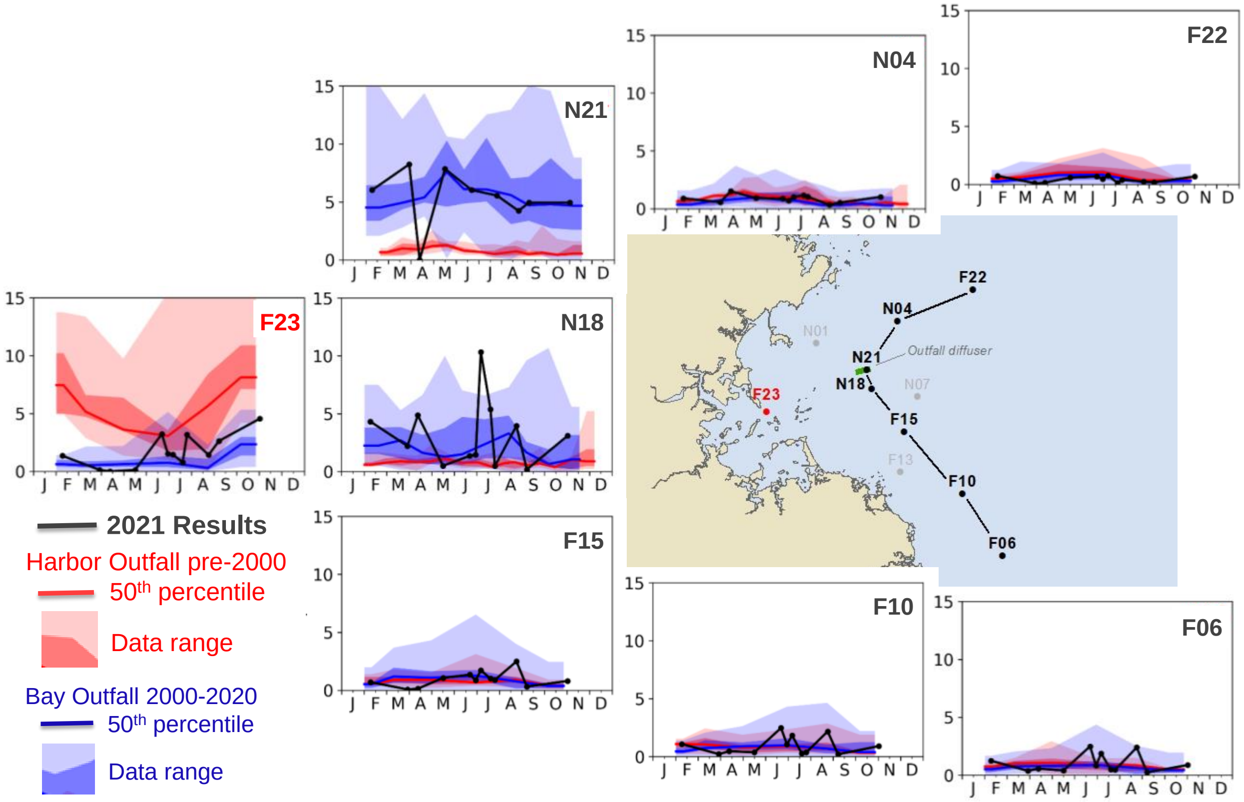

Figure 2-10. Depth-averaged ammonium (NH_4) (µM) at selected stations in Massachusetts Bay for 2021 compared to prior years. 2021 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2020) results are in blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

As can be seen in **Figure 2-10**, in 2021, increases in NH_4 above background conditions were observed intermittently up to 30 km from the outfall in the direction of prevailing background currents to the south. This is similar to other years since the bay outfall became operational in late 2000. 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 August survey, when the water column was vertically stratified with a pycnocline located at about 10 to 15 m, high NH_4 concentrations (>8 µM) were observed at or below the pycnocline at nearfield stations N21 and N18, and at concentrations >4 µM in the bottom waters at stations 10 to 30 km south of the outfall (**Figure 2-12**). During the stratified August survey, NO_3 concentrations were depleted in the surface waters and below the pycnocline with elevated concentrations (> 6 µM) only observed in deeper bottom waters along the west-east transect. Although elevated NH_4 concentrations were present at the pycnocline, sub-surface chlorophyll was low in the nearfield as well as at the farfield stations, where both NH_4 and NO_3 were low (**Figure 2-13**).

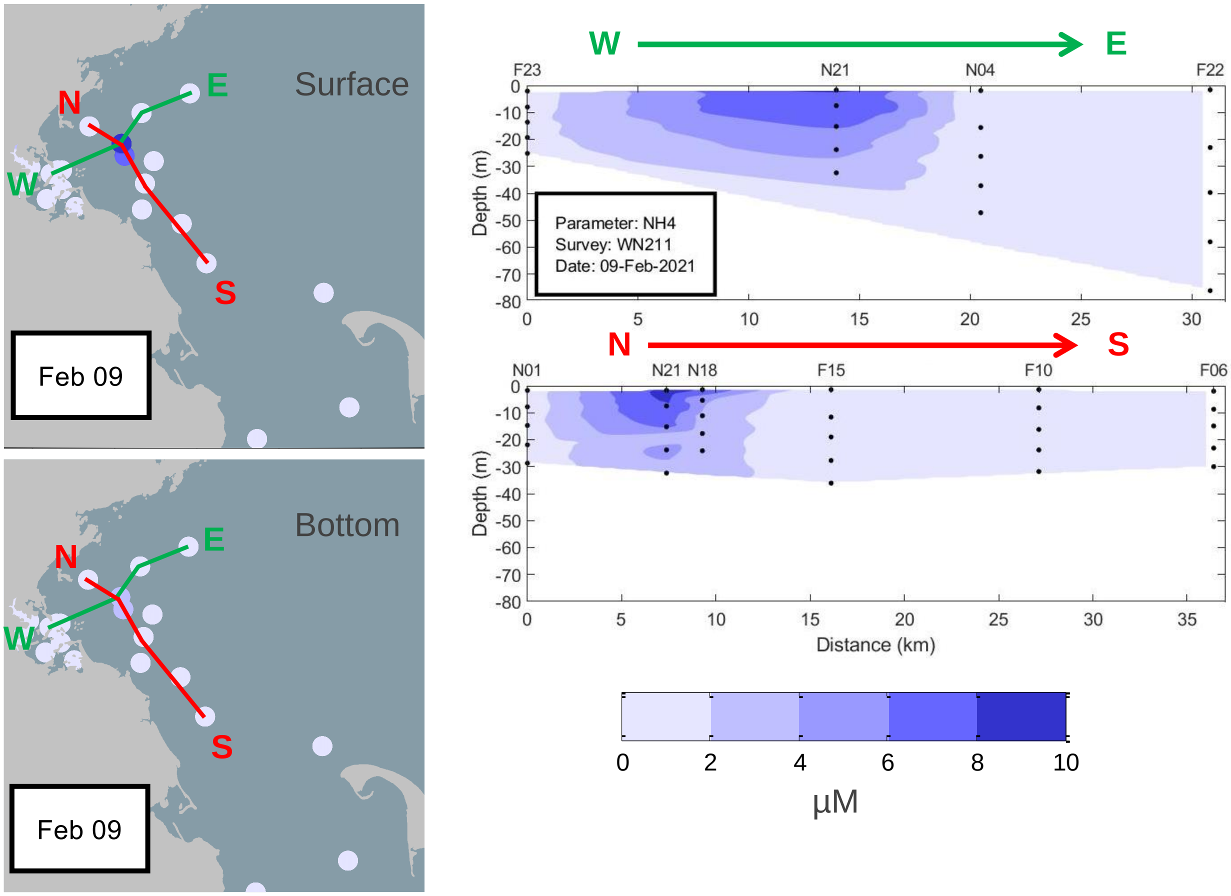

Figure 2-11. (Left) Surface and bottom water ammonium (NH_4) on February 09, 2021 during unstratified conditions. (Right) Cross-sections of water column concentrations along transects connecting selected stations. Small black dots in the plots at right indicate the sampling depths for nutrients.

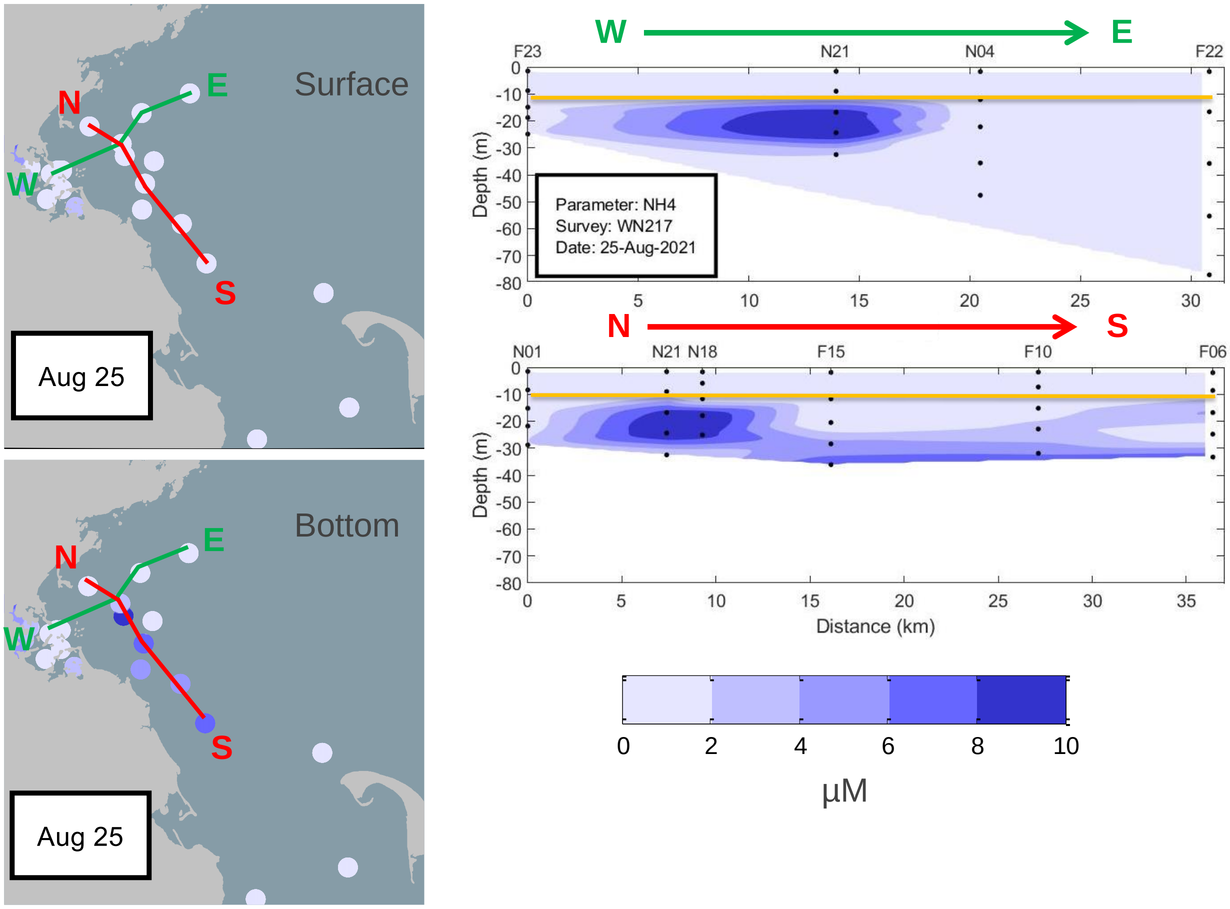

Figure 2-12. Surface and bottom water ammonium (NH$_4$) on August 25, 2021 during stratified conditions. Presented as Figure 2-11, with orange line in frames at right indicating the approximate depth of the pycnocline.

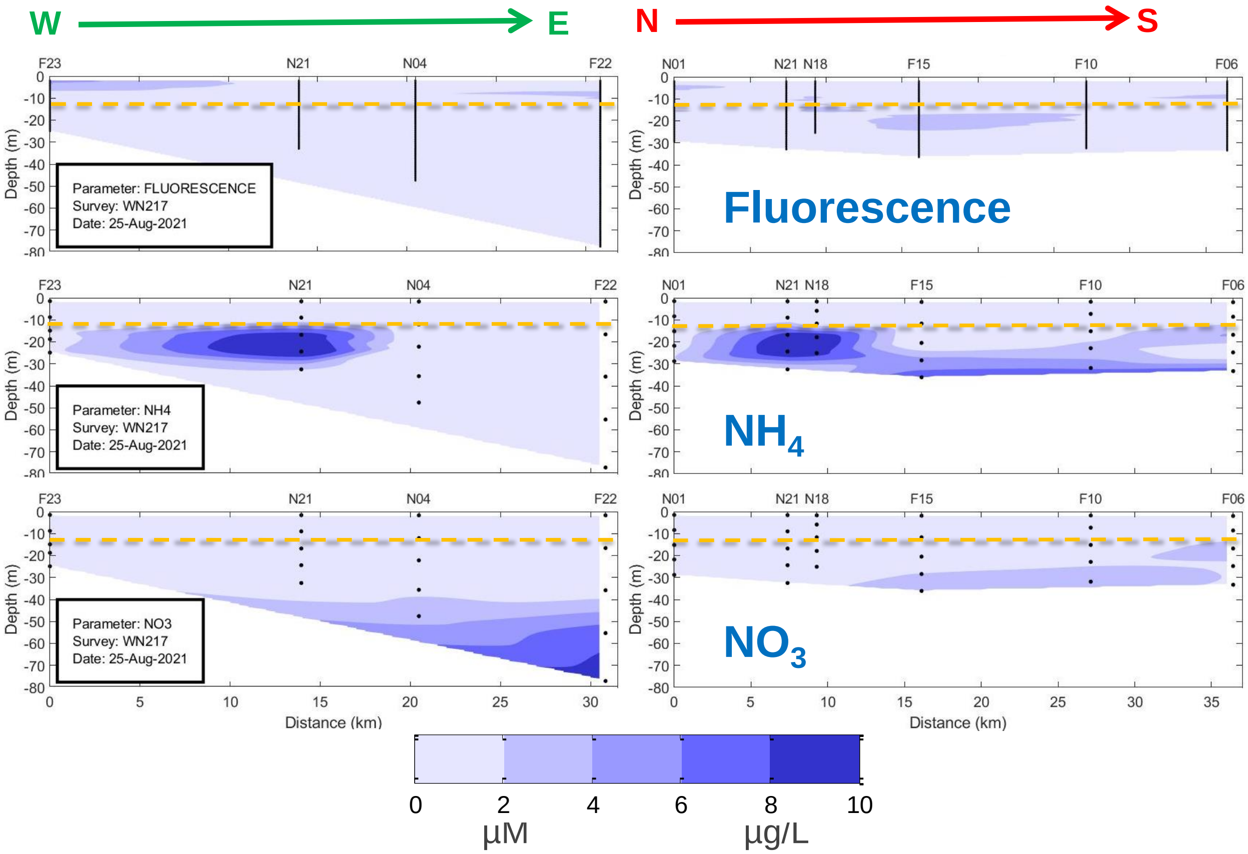

Figure 2-13. Chlorophyll from fluorescence (top; µg L^{-1}), ammonium (middle; µM), and nitrate (bottom; µM) during the stratified August 2021 survey along the east-west (left column) and north-south (right column) transects shown in Figure 2-12. Dots (nutrients) and lines (fluorescence) indicate the 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 2021 surveys, though the timing of the peaks varied across the region. High areal chlorophyll was observed during the February, April, June, August, and September surveys in Cape Cod Bay and during the March and July surveys in Massachusetts Bay (**Figure 2-15**). There was also an increase in areal chlorophyll seen in early November 2021. Overall, seasonal and annual average chlorophyll values in 2021 were low, comparable to baseline seasonal averages and less than half the Contingency Plan threshold levels (**Table i**).

MODIS imagery showed moderate chlorophyll in January and early February 2021 (**Figure 2-16)** consistent with the concentrations observed at the offshore Massachusetts Bay and the Cape Cod stations during the first survey (**Figure 2-15**). Preliminary data from Buoy A01 showed low chlorophyll fluorescence in the surface waters until March (**Figure 2-17**). It is unclear why there was a disconnect between the buoy and coincident survey and MODIS data.

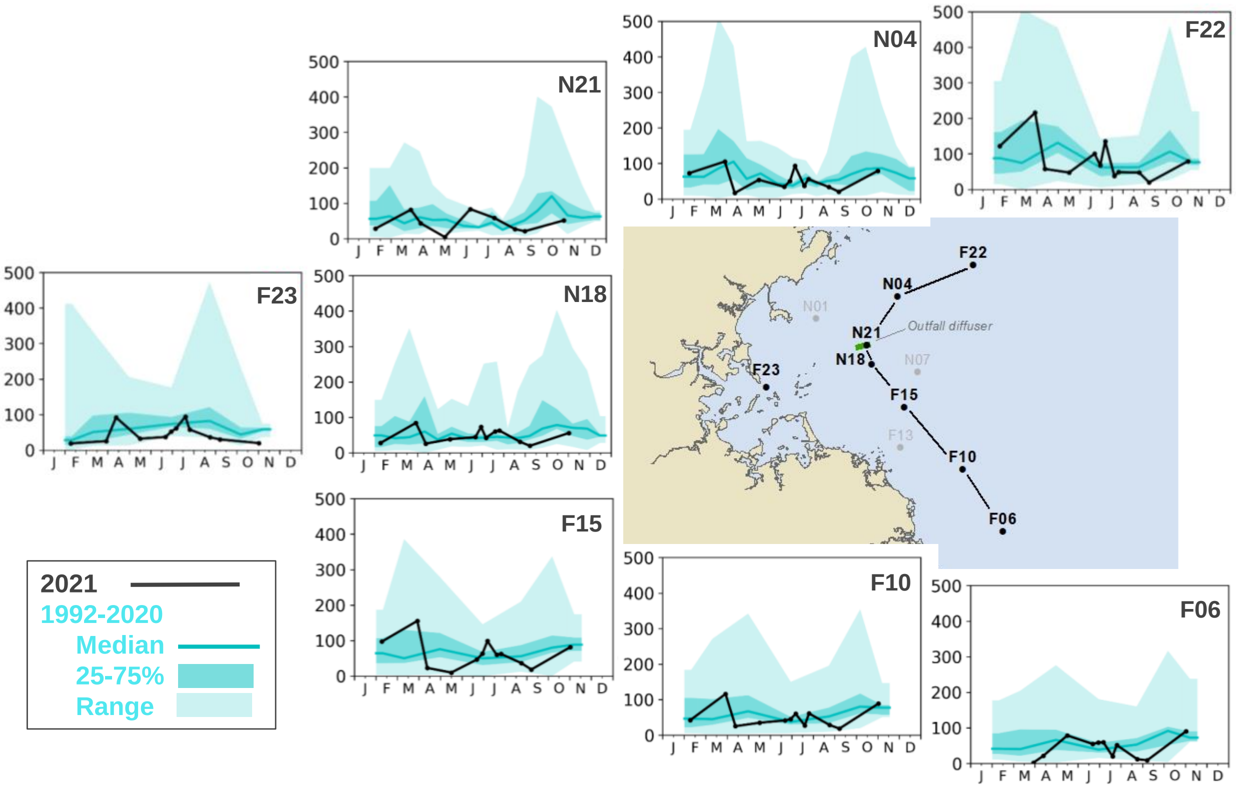

Figure 2-14. Areal chlorophyll from fluorescence (milligram per meter squared [mg m^{-2}]) at representative stations in Massachusetts Bay for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Both the satellite and the buoy observations showed increases in chlorophyll during March, likely associated with a winter/spring diatom bloom (**Figure 2-16** and **Figure 2-17**). High chlorophyll was also observed during the late March survey with concentrations reaching the upper quartile compared to historic data at many Massachusetts Bay stations (**Figure 2-14**). April and May survey measurements of chlorophyll were quite low in Massachusetts Bay with higher concentrations observed in Cape Cod Bay (**Figure 2-15**). MODIS imagery and buoy observations suggest an increase in chlorophyll between these two surveys and are consistent with a possible increase in *Phaeocystis* during this time period though phytoplankton data show only low to moderate levels of *Phaeocystis* in April.

Chlorophyll remained low in Massachusetts Bay in June with higher concentrations observed in Cape Cod Bay (**Figure 2-15**). Areal chlorophyll remained at or above the long-term median over the course of the four surveys conducted in July with a summer peak on July 8th at most of the stations (**Figure 2-14**). This corresponds to elevated nutrients and warmer, fresher waters that were observed during this survey. By mid-August and early September, chlorophyll in Boston Harbor and Massachusetts Bay had decreased to within the lower quartile of historic observations. Elevated concentrations were observed during these two surveys at the three Cape Cod Bay stations. MODIS imagery is consistent with these temporal and spatial trends with lower chlorophyll in Massachusetts Bay during this period and slightly higher concentrations seen in Cape Cod Bay (**Figure 2-16**). Chlorophyll at the offshore Massachusetts Bay stations increased from September to early November: This was likely the result of increased abundances of a mixed assemblage of dinoflagellates. Based on the MODIS and buoy observations, chlorophyll was elevated in the bay during certain periods of time after the November 2nd survey (**Figure 2-16** and **Figure 2-17**).

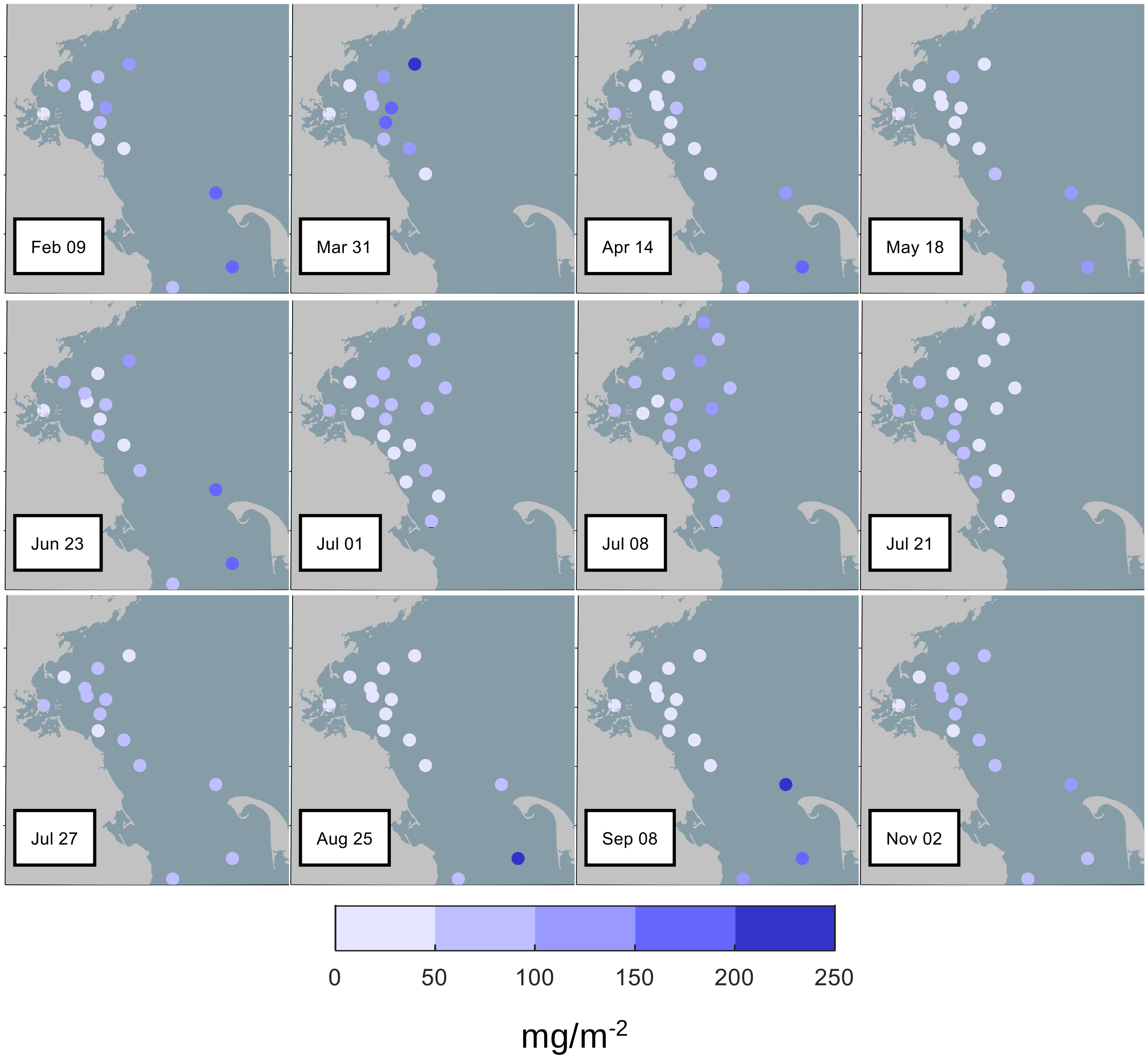

Figure 2-15. Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2021.

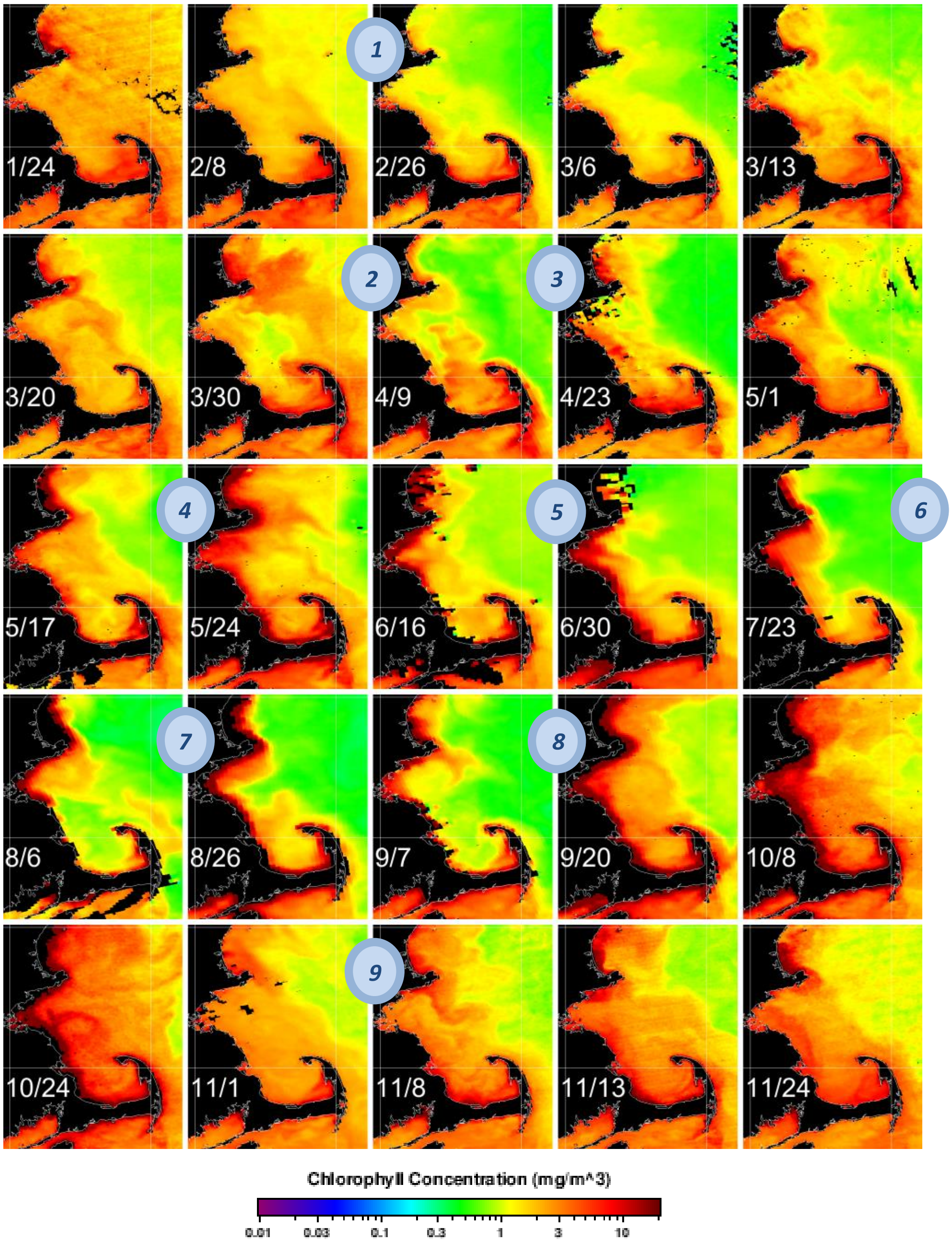

Figure 2-16. Satellite (MODIS) imagery-based estimates of surface chlorophyll concentrations (mg m^{-3}) in 2021. Black areas over water indicate missing data due to clouds.

Highlights and specific blooms:

1st row – moderate chlorophyll in January through mid-February, increasing by mid-March (consistent with winter diatom bloom);

2nd row – remaining elevated in through late March before decreasing in April, increasing again in early May (possible *Phaeocystis* bloom);

3rd row – remained elevated though May, and then variable June and July – limited MODIS imagery available over this period which corresponded to the *Alexandrium* bloom rapid response surveys;

4th row – low in August and early September, increasing in late September and October; and

5th row – chlorophyll continued to increase in late October (consistent with increase in dinoflagellates) and remained elevated into December (data not shown).

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

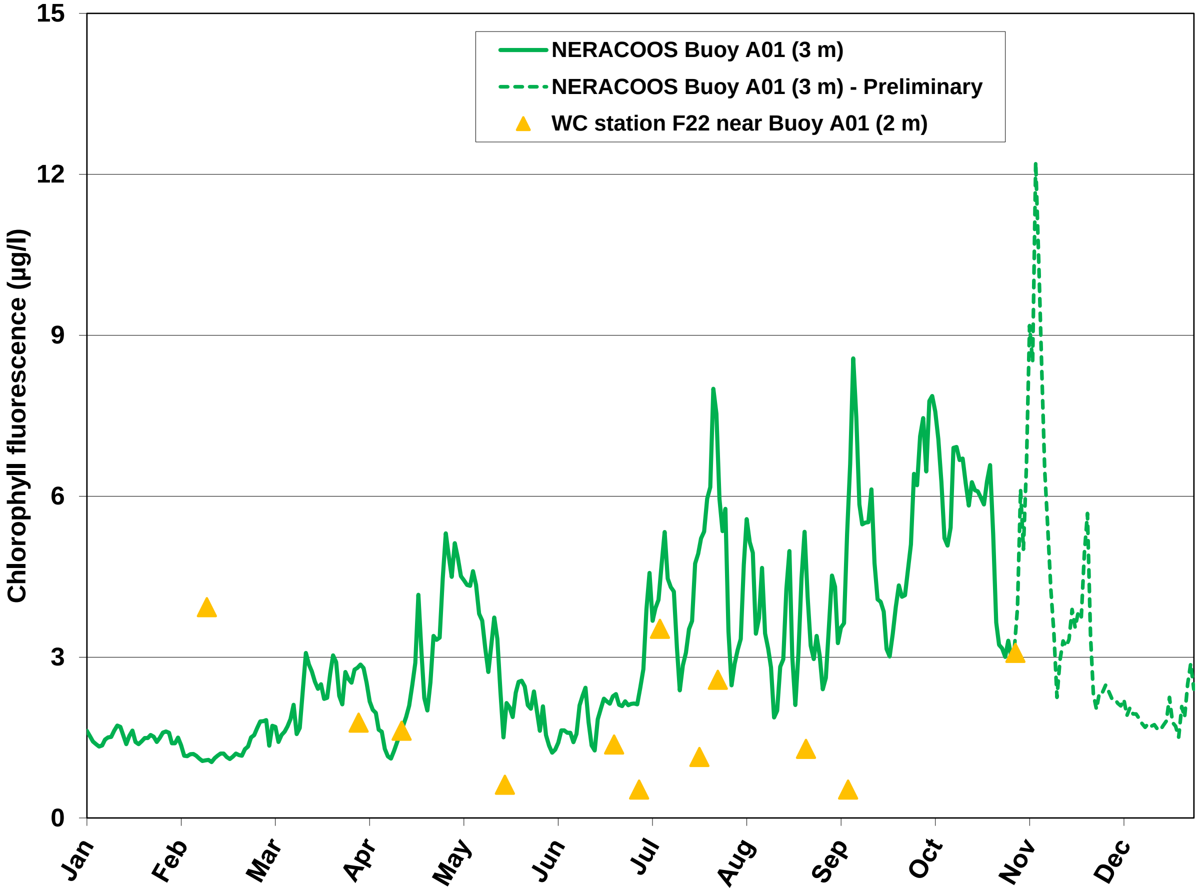

Figure 2-17. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (dashed green line) and water samples at nearby water column (WC) station F22 (yellow symbols) in 2021.

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 2021 with bottom water DO at many Massachusetts Bay stations at or below historic minima by May (**Figure 2-18**). Substantial northeast wind events in late May through July mixed the water column and contributed to downwelling favorable conditions in July (see **Figure 2-4** and **Figure 2-5**). This led to an increase, or pause in the seasonal decline, in bottom water DO concentrations in June, and concentrations remained relatively consistent into July in Massachusetts Bay. However, the storms also led to high precipitation and July river flows ranked among the highest of the monitoring period, causing a sharp increase in stratification in late July and August (**Figure 2-6**). With the strong stratification, bottom DO decreased sharply from mid-July to August, reaching annual minima at or below the historic range at the shallower Massachusetts Bay stations (**Figure 2-18**).

By September, bottom water DO had begun to increase at the inshore, shallow stations of Massachusetts Bay, but continued to decrease offshore. The contingency plan DO percent saturation threshold was exceeded at the deep, Stellwagen basin station F22 in September (66.3% versus 67.2%; **Table i** and **Figure 2-19**). Bottom water DO continued to decline at station F22 into early November, reaching the minima at this station measured over the 30-year monitoring program (**Figure 2-18**). The November DO concentration and percent saturation both exceeded the Contingency Plan thresholds for the Stellwagen Basin station F22, at 5.89 mg L^{-1} and 65.9%, respectively. The influence of late fall mixing events is evident in Buoy A01 DO data from 50 m, which showed DO decreasing until late October when a major Nor'easter storm mixed the water column down to below 50 m, with increased DO in the deep waters by the early November survey (**Figure 2-20**). However, the water column was not fully mixed at station F22 until after this survey and DO in the bottom water remained low in early November.

Low DO concentrations were also observed at the shallower stations in Cape Cod Bay (**Figure 2-21**). Bottom water DO concentrations at station F01 were below historic minima for May through July with an annual minimum of <5 mgL^{-1} measured in early September 2021. A Massachusetts Division of Marine Fisheries (MA DMF) study of DO in Cape Cod Bay showed concentrations <3 mg L^{-1} off Wellfleet on August 18, 2021, but a mixing event in late August kept concentrations from becoming hypoxic (<2 mg L^{-1}), in contrast to the hypoxia observed in 2019 and 2020 (Libby et al. 2021b). DO in Cape Cod Bay continued to increase after additional mixing associated with the passage of Hurricane Ida in early September. The low DO conditions observed in Cape Cod Bay are explored in more detail in Section 3.2.

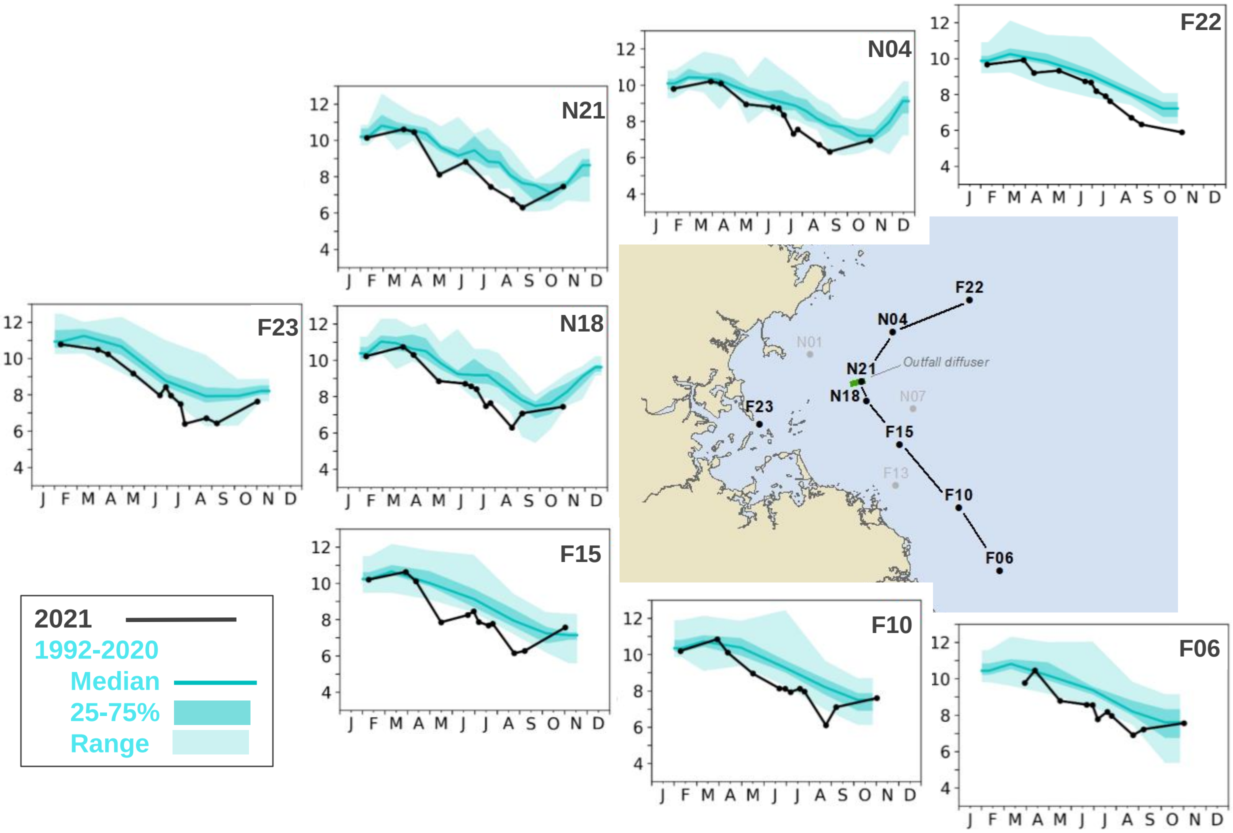

Figure 2-18. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

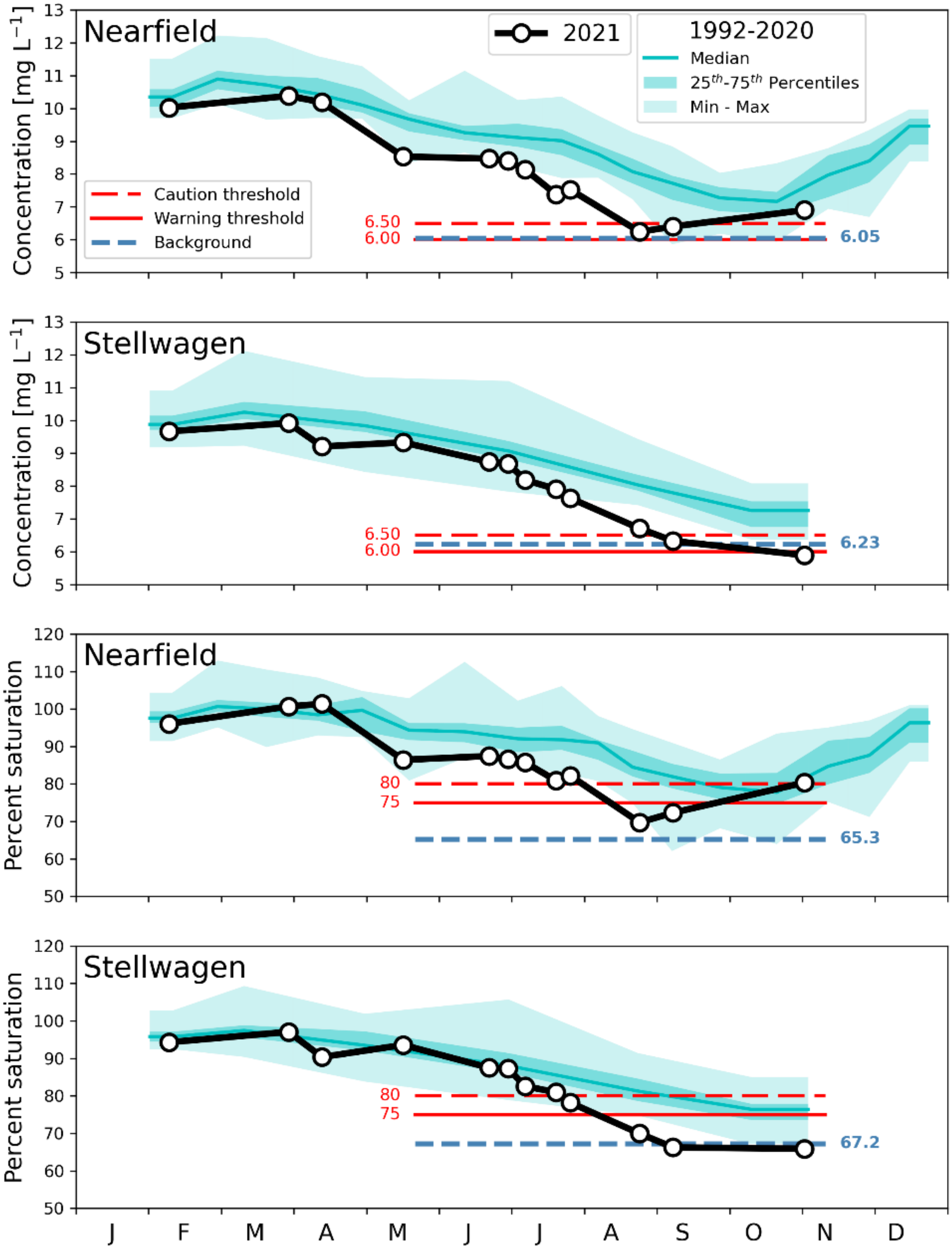

Figure 2-19. Survey bottom water dissolved oxygen concentration (mg L^{-1}) and percent saturation in the Nearfield and Stellwagen Basin versus Contingency Plan Thresholds for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

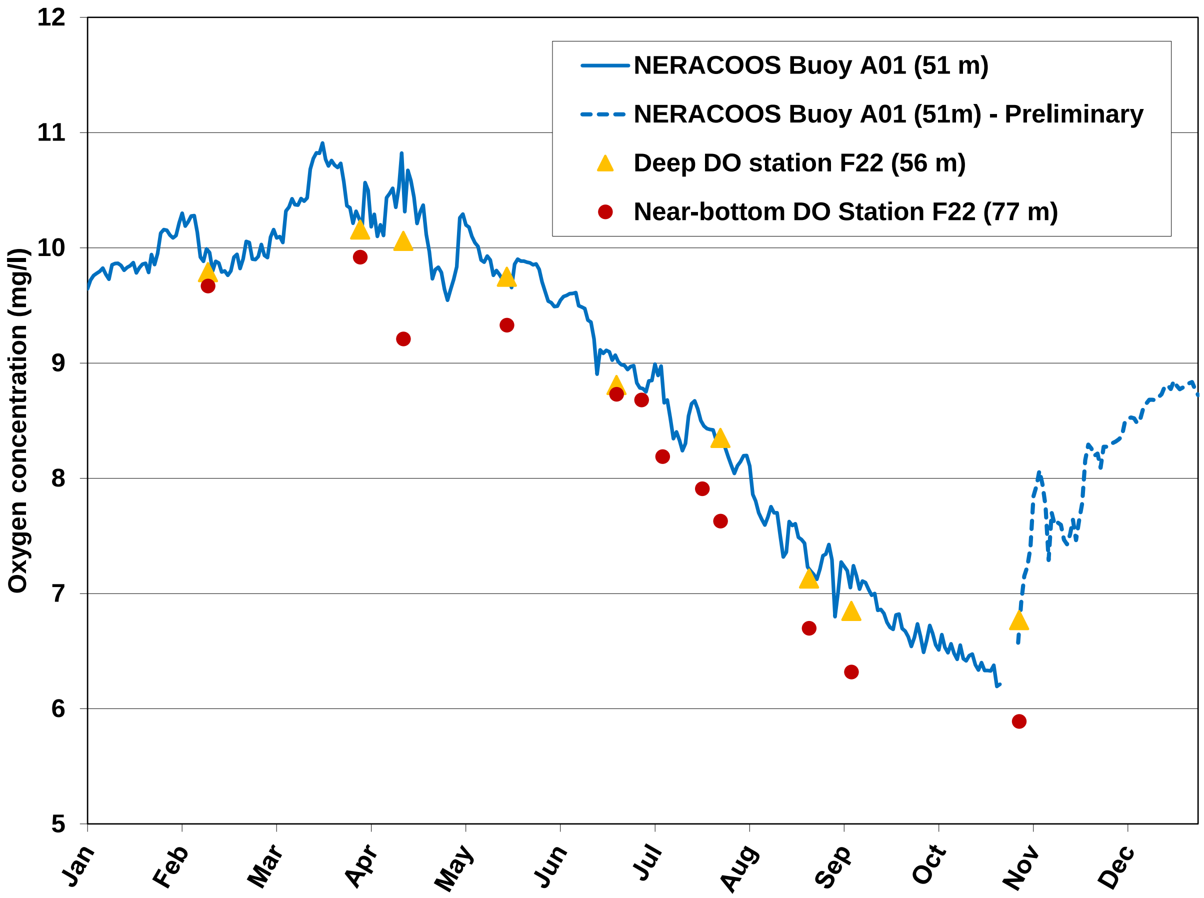

Figure 2-20. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (51 m) and at the deep and near bottom sampling depths (~56 and ~77 m) at station F22 in 2021. The buoy values are daily means.

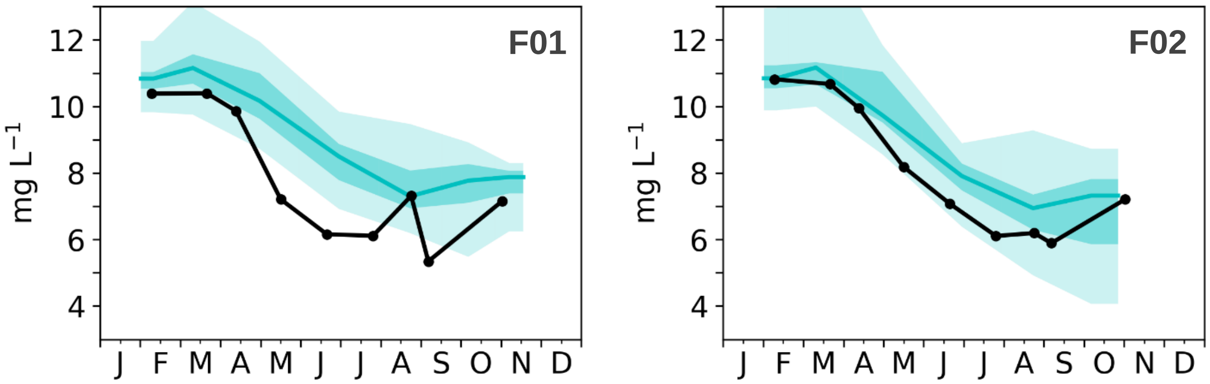

Figure 2-21. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.5 PHYTOPLANKTON ABUNDANCE

Overall, total phytoplankton measured in 2021 continued the recent trend, since the early 2000s, of low abundance compared to historic observations (**Figure 2-22** and **Table 2-1**). Microflagellate, centric diatom, and cryptophyte abundance remained well below the long-term mean. Phytoplankton abundance and community composition during 2021 were generally similar to the past five years (2015-2020).

The total phytoplankton annual average abundance in the nearfield for 2021 (691,169 cells L^{-1}) was only about half the long-term mean level of 1,334,277 cells L^{-1} and ranked 27th out of 30 years of the monitoring program (**Table 2-1**). Total phytoplankton abundance was consistently below the historic median during most of the surveys conducted in 2021 (**Figure 2-22**). Total phytoplankton abundance during 2015 to 2021 has been relatively stable at an annual mean level of approximately 800,000 cells L^{-1}. This abundance is nearly half the level of ~1.5 million cells L^{-1} observed during the early 2000s.

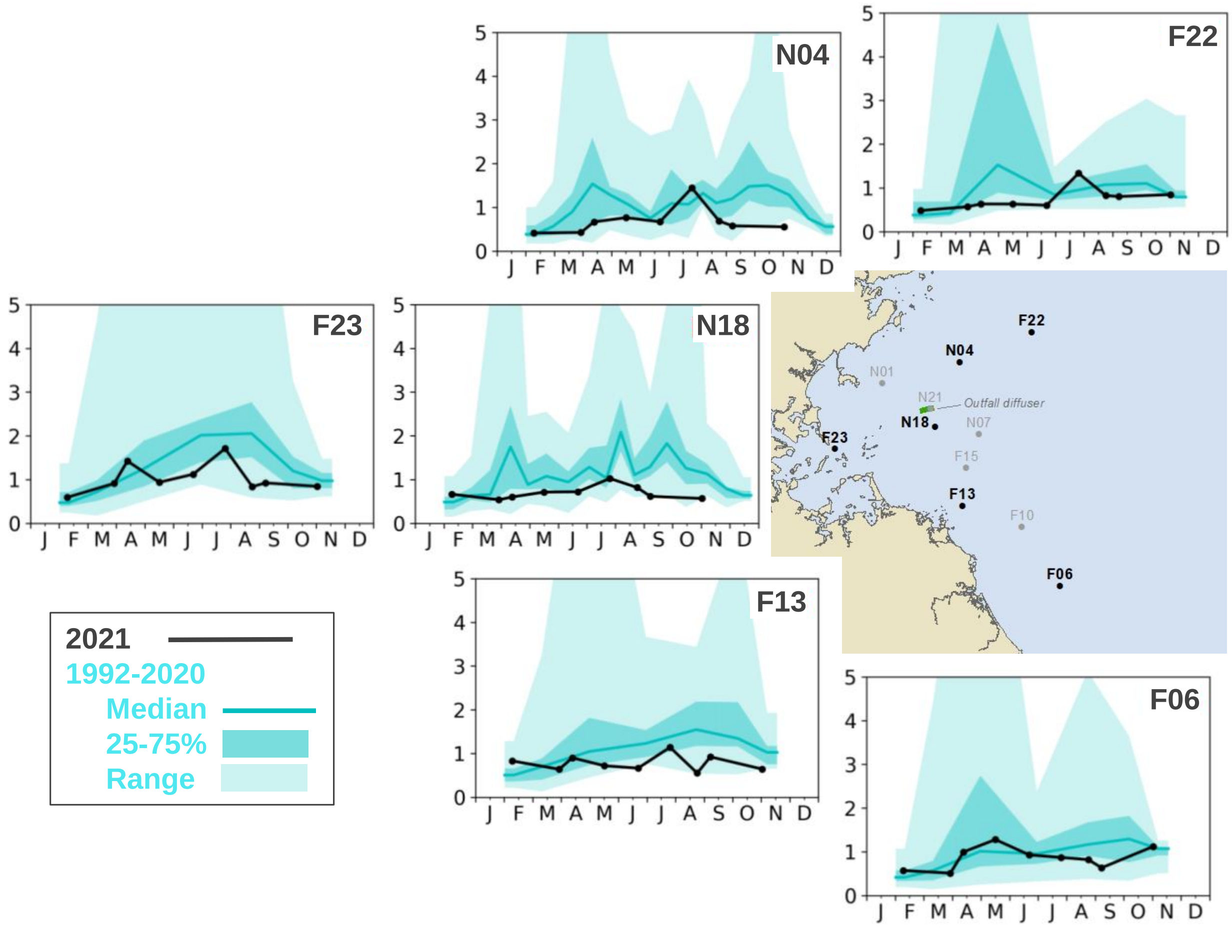

Figure 2-22. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2021 compared to prior years. 2021 results are in black. Results from 1992-2020 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The map insert highlights stations shown here and in subsequent phytoplankton and zooplankton figures, where an extended plankton dataset is available.

As has been the case since 2015, the low 2021 total phytoplankton abundance was primarily due to the lack of large winter/spring diatom and/or *Phaeocystis* blooms. Low phytoplankton abundances and relatively low chlorophyll concentrations were observed during the February to May 2021 surveys. However, MODIS and Buoy A01 results both showed increased chlorophyll 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, so they may have occurred in 2021 between the survey dates.

Centric diatom abundance during 2021 increased relative to that observed during 2020 but was still low, with a mean nearfield abundance of 71,026 cells L^{-1} only ~28% as high as the long-term mean abundance of 256,560 cells L^{-1} (**Table 2-1**). The 2021 centric diatom annual cycle was marked by moderate winter-spring and summer blooms (**Figure 2-23**). In March 2021, a *Thalassiosira* spp.-dominated diatom bloom was observed at coastal stations while *Skeletonema* spp. was dominant in Boston Harbor. In May, centric diatom abundance peaked with an annual maximum of >600,000 cells L^{-1} at station F06 with a mixed assemblage of diatoms (*Dactyliosolen fragilissimus*, *Guinardia delicatula*, *Leptocylindrus danicus*, and *Skeletonema* spp.). A moderate summer bloom was observed at harbor station F23 in July with nearly 600,000 cells L^{-1} that was dominated by *Leptocylindrus danicus*, and *Skeletonema* spp. The trend of reduced centric diatom abundance, noted since 2006, continued for the Massachusetts Bay nearfield region with 2021 abundance ranked 27th of 30 years.

Table 2-1. Comparison of 2021 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.

Group	**1992-2020** (cells L^{-1})	**2021** (cells L^{-1})	2021 Rank (out of 30)	p value	Significant Change[1]
CENTRIC DIATOM	256,560	71,026	27th	0.0723	
Chaetoceros	27,841	2,658	23rd	0.2324	
Dactyliosolen fragilissimus	53,057	2,423	24th	0.3257	
Skeletonema spp. complex	43,472	6,533	20th	0.2515	
Thalassiosira	34,241	14,054	15th	0.6696	
CRYPTOPHYTES	122,957	56,426	26th	0.0085	decrease
DINOFLAGELLATES	61,919	46,821	21st	0.2461	
Ceratium	1,754	1,167	15th	0.4212	
Dinophysis	347	128	21st	0.5872	
Prorocentrum	5,563	10,320	6th	0.1718	
MICROFLAGELLATES	661,735	491,997	19th	0.0283	decrease
PENNATE DIATOM	34,398	5,890	29th	0.3912	
Pseudo-nitzschia	8,319	1,578	22nd	0.2102	
Phaeocystis pouchetii	185,499	8,360	18th	0.3146	
TOTAL PHYTOPLANKTON	1,334,277	691,169	27th	0.0062	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.

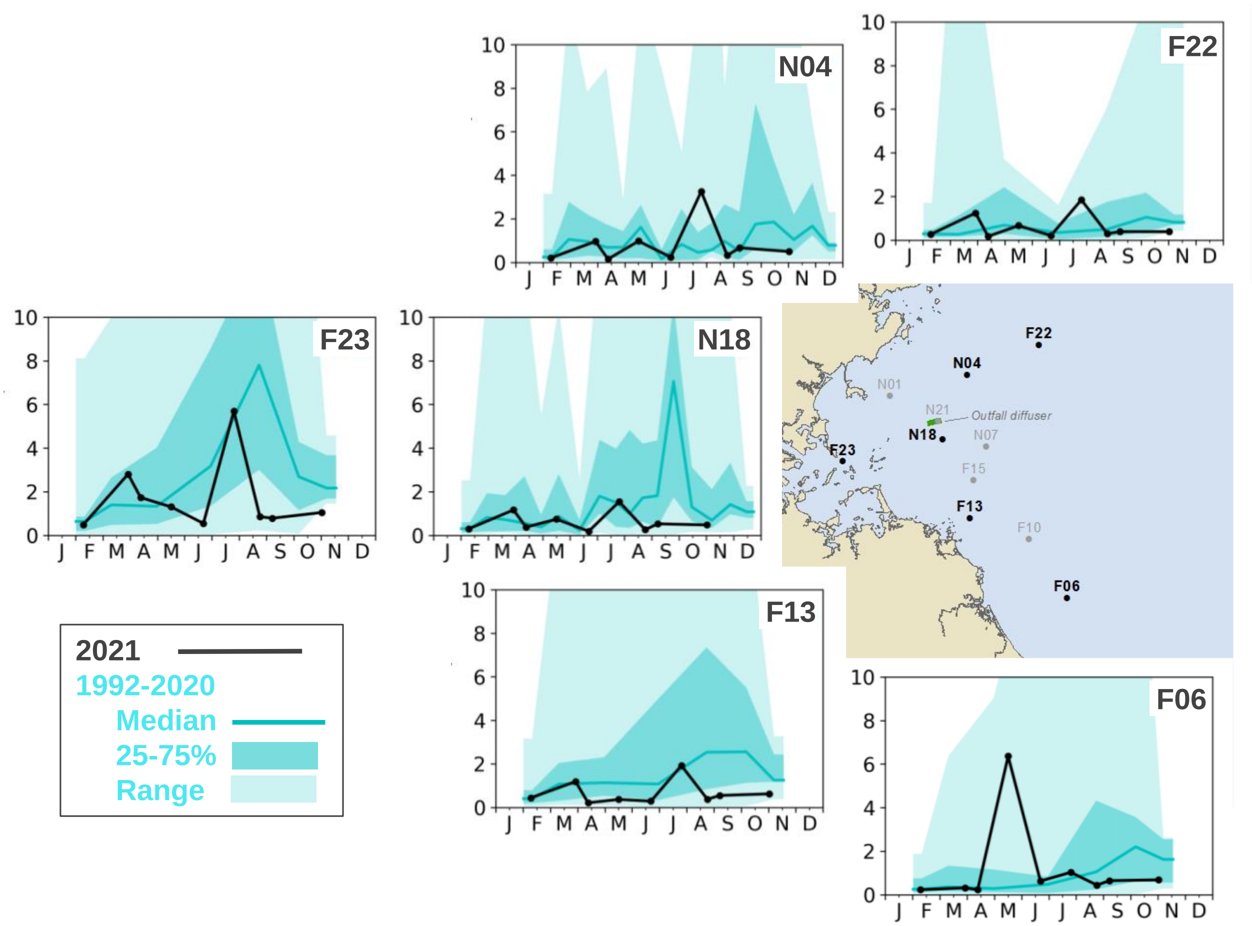

Figure 2-23. **Centric diatom abundance (100,000 cells L^{-1}) at selected stations in 2021 compared to prior years.** 2021 results are in black. Results from 1992-2020 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Phaeocystis pouchetii was present at low abundances in samples collected in 2021, with a maximum abundance of ~180,000 cells L^{-1} in Cape Cod Bay during the March survey. Note that maximum *Phaeocystis* concentrations of tens of millions of cells L^{-1} have been recorded in Massachusetts Bay during bloom years (Libby et al. 2013b). *Phaeocystis* is one of the dominant phytoplankton taxa in Massachusetts Bay and low to moderate *Phaeocystis* abundance observed during 2021 and during eight of the last nine years has contributed to the long-term decline in total phytoplankton abundance. Regression analysis indicates that approximately 45% of the long-term decline in total phytoplankton abundance since the early 2000s is due to reduced *Phaeocystis* abundance.

Another factor contributing to the low total phytoplankton abundance was reduced microflagellate numbers in 2021 relative to long-term means. Microflagellates are typically the most abundant phytoplankton group in the Massachusetts Bay monitoring area, comprising ~71% of phytoplankton cells during 2021. Microflagellate abundance was near or slightly below long-term medians for most of 2021. In 2021 nearfield microflagellate abundance (491,997 cells L^{-1}) was approximately 74% of the long-term mean of 661,735 cells L^{-1} (**Table 2-1**). Overall, 2021 had moderate microflagellate abundance relative to prior years as evidenced by its rank of 19 of the 30 years of monitoring.

Mean nearfield pennate diatom abundance during 2021 (5,890 cells L^{-1}) was approximately 17% of the long-term mean level (34,398 cells L^{-1}) ranking 29th of 30 years (**Table 2-1**). Reduced pennate diatom abundance during 2021 was driven by the relative low abundance of the potentially toxigenic genera *Pseudo-nitzschia* spp. and reduced abundance of *Thalassionema* spp. and *Asterionellopsis glacialis*. *Pseudo-nitzschia* is a genus of potentially toxigenic pennate diatoms that can cause amnesic shellfish poisoning (ASP). 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 <3,200 cells L^{-1} and well below threshold values (**Table i**). No ASP shellfish closures were required in the region during 2021.

Nearfield mean dinoflagellate abundance was 46,821 cells L^{-1}, or 76% of the long-term average of 61,919 cells L^{-1} (**Table 2-1**). Dinoflagellate abundance was close to the historic median from February to June 2021 (**Figure 2-24**) and dominated by small dinoflagellates (*Gymnodinum* spp. <20 µm, *Heterocapsa triquetra*, *Heterocapsa rotundata*). A large *Alexandrium catenella* bloom was observed in June and July 2021, which is discussed in more detail below. A late summer peak in dinoflagellate abundance was observed in August dominated by *Prorocentrum* spp. and *Karenia mikimotoi*. *Prorocentrum* spp. were more abundant than usual in 2021 with abundances in the upper quartile or above in May, July, and August (not shown); the 2021 nearfield mean abundance of 10,320 cells L^{-1} was nearly twice the long-term mean of 5,563 cells L^{-1} (**Table 2-1**). *Prorocentrum minimum* were dominant in the spring and elevated *Prorocentrum micans* abundances were observed during late summer. *Karenia* was not as abundant in Massachusetts Bay during 2021 compared to 2019 and 2020. A maximum abundance of 36,215 cells L^{-1} was recorded in the nearfield – a marked decrease from ~850,000 cells L^{-1} observed during 2019 and 2020. Although abundances vary widely, *Karenia* presence appears to be increasing in duration in Massachusetts Bay, from August to October during 2017 to being present from February to October/November during 2020 and 2021.

The pattern of reduced phytoplankton abundance relative to that observed in the early 2000s continued in Massachusetts Bay during 2021. Reduced phytoplankton abundance was driven by the lack of a *Phaeocystis* bloom and reduced centric diatom abundances. This trend has been observed in Boston Harbor and across Massachusetts Bay. The decline in Boston Harbor phytoplankton abundance evident in the early 2000s may be attributed to outfall relocation (Taylor 2013). Since that time, phytoplankton trends in the harbor, nearfield, and offshore regions of the bay have followed similar trajectories with respect to phytoplankton abundance. These simultaneous and synchronous patterns suggest that regional drivers (weather, oceanographic variation) are important determinants of phytoplankton patterns regionally and that these drivers take precedence over local drivers such as changes in nutrient input.

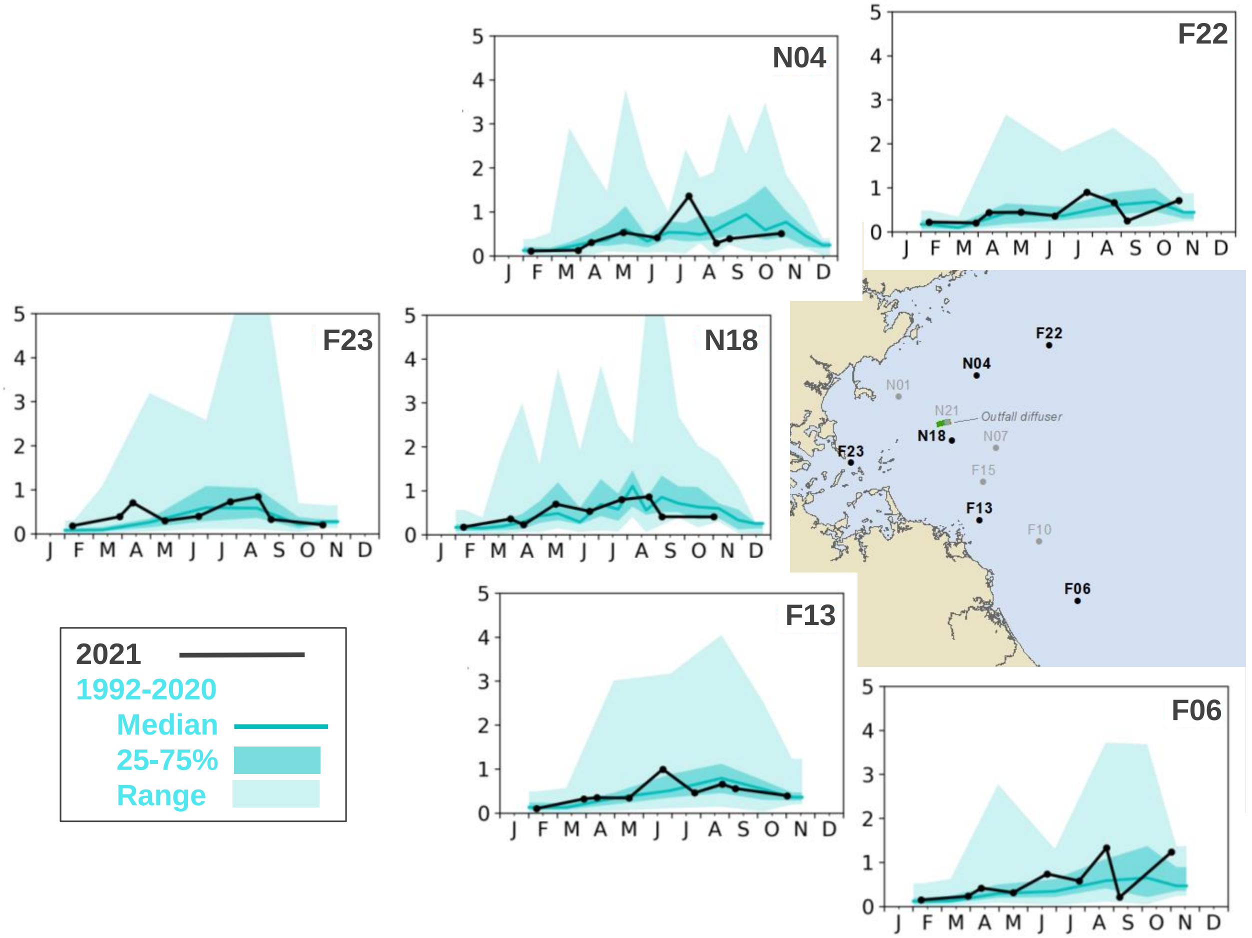

Figure 2-24. Dinoflagellate abundance (100,000 cells L^{-1}) at selected stations in 2021 compared to prior years. 2021 results are in black. Results from 1992-2020 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Alexandrium catenella

A large *Alexandrium catenella* (formerly *A. fundyense*) bloom was observed in Massachusetts Bay in 2021 comparable to the large blooms present in the bay in 2005, 2008, and 2019 (**Figure 2-25**). After the 2019 bloom, late summer/fall sediment sampling in Massachusetts Bay and Gulf of Maine showed high numbers of cysts in western Massachusetts Bay (Libby et al. 2021b). At that time, this was surprising because after the extraordinary 2005 bloom very few cysts had been seen in the bay (Anderson et al. 2014). It was unknown what the impact of these cysts would be on 2020 *Alexandrium*, and whether they might initiate localized blooms within Massachusetts Bay. The prevailing view has been that *Alexandrium* cells in the bay are transported there from established blooms from offshore waters to the north. In 2020, the *Alexandrium* bloom was minor and relatively short lived, but subsequent sediment monitoring in 2020 again showed elevated cyst abundances in western Massachusetts Bay (**Figure 2-26**). A review of cyst data from 2006 to 2018 suggests the area where the high cyst abundances were observed in the bay had not been sampled previously and areas in eastern Massachusetts Bay had only been sampled intermittently, suggesting the cyst bed may have been present prior to the 2019 observations. Regardless, it was present in fall 2019 and 2020 with different *Alexandrium* blooms in the subsequent years and the relationship between the cyst bed and Massachusetts Bay *Alexandrium* bloom characteristics continue to be part of ongoing research.

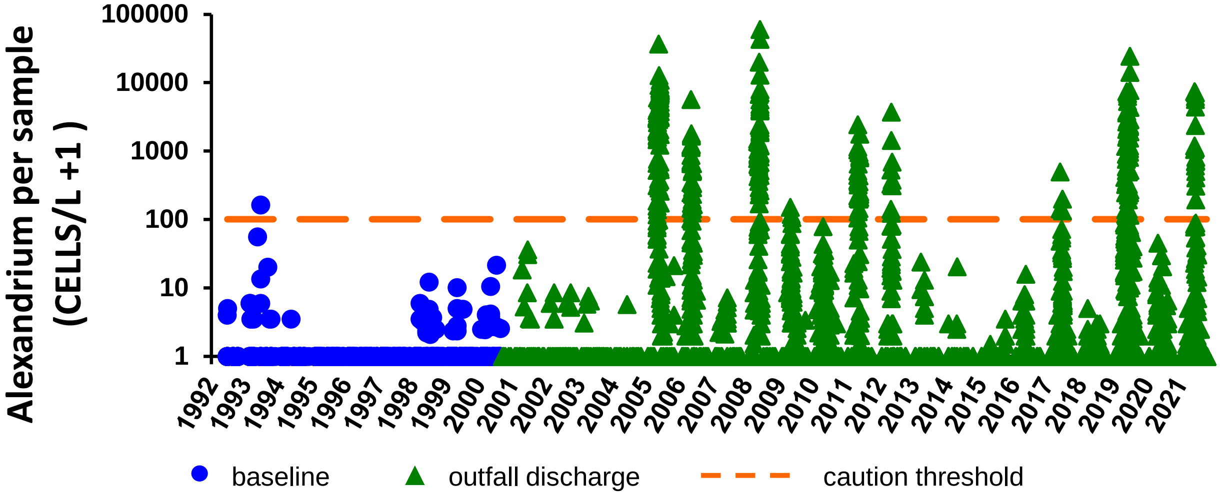

Figure 2-25. **Nearfield *Alexandrium* abundance (cells L^{-1} +1) from 1992 to 2021.** The dashed line represents the Contingency Plan caution threshold of 100 cells L^{-1}.

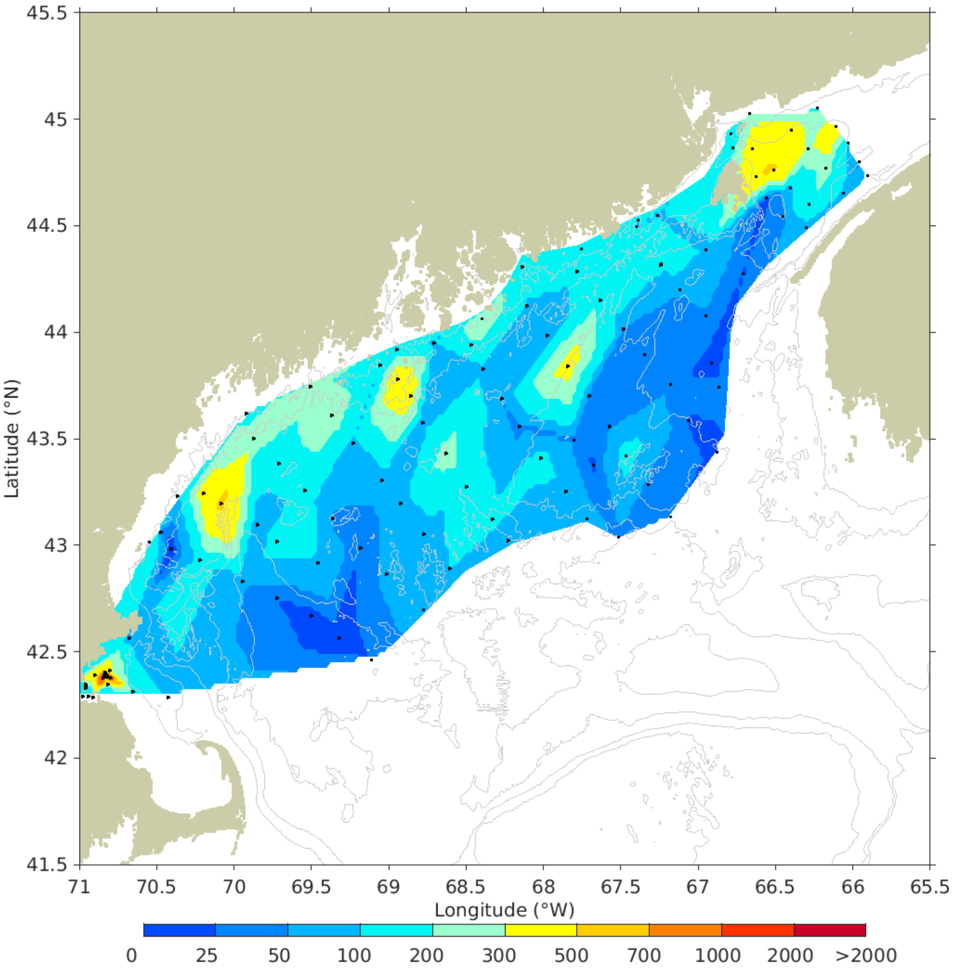

Figure 2-26. **Fall 2020 *Alexandrium* cyst abundance (cysts cm^{-2}).** Provided by Don Anderson, WHOI and Yizhen Li, NOAA.

In terms of bloom timing in 2021, *Alexandrium* abundances were low in Massachusetts Bay and the western Gulf of Maine from February to May and no PSP toxicity was detected by MA DMF until after the June survey. High *Alexandrium* abundances within the bay were first observed during the June survey with a maximum of 7,386 cells L^{-1} in surface waters at station N01 off Nahant and counts of >500 cells L^{-1} were observed at station N18 and along the South Shore (**Figure 2-27** and **Table 2-2**). *Alexandrium* abundances were well above the 100 cells L^{-1} Contingency Plan threshold and triggered Alexandrium Rapid Response (ARRS) surveys which were completed in July. Soon after the June survey, PSP toxicity was detected for the first time in Massachusetts along the South Shore at the Cohasset and Scituate MA DMF sites (48 µg/100 g tissue) on June 28, 2021. PSP toxicity was below detection limits (<40 µg/100 g) north of Cape Ann and at the other MA DMF sites in Massachusetts Bay.

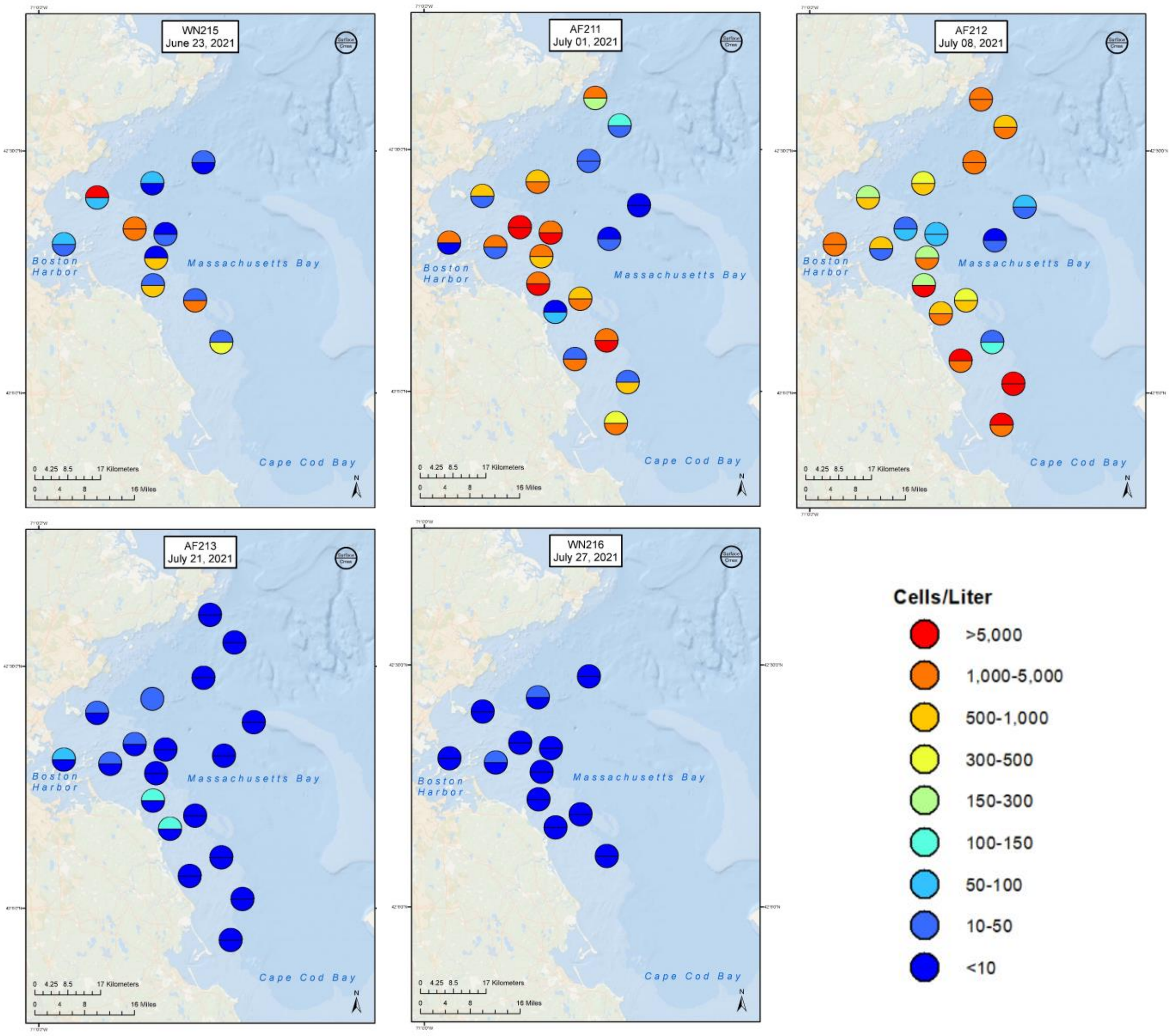

Figure 2-27. ***Alexandrium* abundance (cells L^{-1}) from June and July 2021 surveys.** Symbols show abundance for the surface in the upper half and from ~10 m in the bottom half of each symbol.

Table 2-2. *Alexandrium* abundance for water column and ARRS surveys in May-July 2021.

Event Id	Date	# samples collected	# samples with *Alexandrium*	# *Alexandrium* cells/L			MAX value station (depth)
				MEAN	MIN	MAX	
WN214	May 18	20	8	0.5	0	4	F23 (2 m)
WN215	June 23	20	20	653	3	7,386	N01 (2 m)
AF211	July 1	43	42	1,626	0	18,331	F06 (10 m)
AF212	July 8	43	43	1,609	7	6,491	AF2 (2 m)
AF213	July 21	43	23	10	0	142	F13 (2 m)
WN216	July 27	24	9	2.5	0	30	N04 (2 m)

By early July, *Alexandrium* abundances had increased to a maximum of 18,331 cells L^{-1} observed during the first ARRS survey at station F06 off Scituate (**Figure 2-27**). High abundances (>1,000 cells L^{-1}) were observed at stations across the monitoring area from Cape Ann to Duxbury including Boston Harbor. During the week of July 5, New Hampshire Department of Environmental Services (NH DES) reported an increase in *Alexandrium* abundance and the first detectable levels of PSP toxicity at Isle of Shoals off New Hampshire, which was the first clear indication of an *Alexandrium* bloom in the western Gulf of Maine "upstream" of Massachusetts Bay. During the July 8 ARRS survey, high abundances continued to be seen from Cape Ann to Duxbury with a maximum of 6,491 cells L^{-1} at station AF2 off Marshfield (**Figure 2-27**). Fortunately, MA DMF continued to report low, but detectable PSP toxicity within Massachusetts Bay and also at sites to the north of Cape Ann.

On July 12, 2021, MA DMF measured PSP toxicity levels of >200 µg/100 g at two sites north of Cape Ann and although PSP levels within Massachusetts Bay were below action levels (<80 µg/100 g) a shellfishing closure was issued from the New Hampshire border to Duxbury Bay on July 15. By July 21, *Alexandrium* abundances had decreased dramatically with most samples ≤55 cells L^{-1} and two samples just over 100 cells L^{-1} at stations off of Cohasset and Scituate (**Figure 2-27**). In late July, *Alexandrium* abundances were ≤30 cells L^{-1} and PSP was below detection limits in Massachusetts Bay. MA DMF lifted the shellfishing closure on July 30 – note that PSP toxicity never exceeded action levels within the bay in 2021, despite cell concentrations as much as an order of magnitude above levels thought to cause toxicity in the region (DM Anderson, personal communication). The disconnect between the very high *Alexandrium* abundances and low PSP toxicity in Massachusetts Bay is likely associated with prevailing winds and currents keeping the *Alexandrium* offshore and is the focus of ongoing data analyses. It is also possible that the strain of *Alexandrium* dominating within the bay was one of low intrinsic toxicity, but unfortunately there are no samples or cultures that could confirm or disprove this possibility.

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 first observed in sediments in western Massachusetts Bay in fall of 2019 and also summer/fall 2020 (**Figure 2-26)**. In prior years, the latter has not been a concern, as the data available showed very low *Alexandrium* cyst abundances within the bay, at least the eastern part of the bay that had been sampled. Additional cyst sampling in western Massachusetts Bay in future years will help to indicate whether deposits in that location are ephemeral in nature or can be persistent through time. There are two documented persistent cyst beds in the region, in the Bay of Fundy and offshore of Casco and Penobscot Bays (Anderson et al. 2014), and if there has been or is now a persistent cyst bed in Massachusetts Bay it would be the third. Currently, WHOI researchers are processing and counting *Alexandrium* cysts from samples collected for MWRA's sediment survey in August 2022 and a review of the 2005-2022 *Alexandrium* and ancillary data is underway to better understand bloom dynamics in Massachusetts Bay.

2.6 ZOOPLANKTON ABUNDANCE

Zooplankton taxa, seasonal patterns, and abundances in 2021 were generally similar to those observed during the previous years of the monitoring program (**Figure 2-28**). The main differences were the high abundances observed in July and November, which were due to meroplankton and other non-copepod plankton, over half of which were radiolarians (unicellular protozoan animals; **Figure 2-29**). The high abundances of radiolarians in July and November of 2021 were similar to high abundances of radiolarians observed in July and August of 2020, which was the first time radiolarians had been recorded in the sampling program (Libby et al. 2021b). These unusual high abundances of radiolarians suggest intrusions of water from offshore, which aligns with the comparably warm waters recorded for 2021 in the sampling area in July and is consistent with frequent northeast wind events in July and the major storm in late November transporting offshore waters into the bay (see Section 2.1).

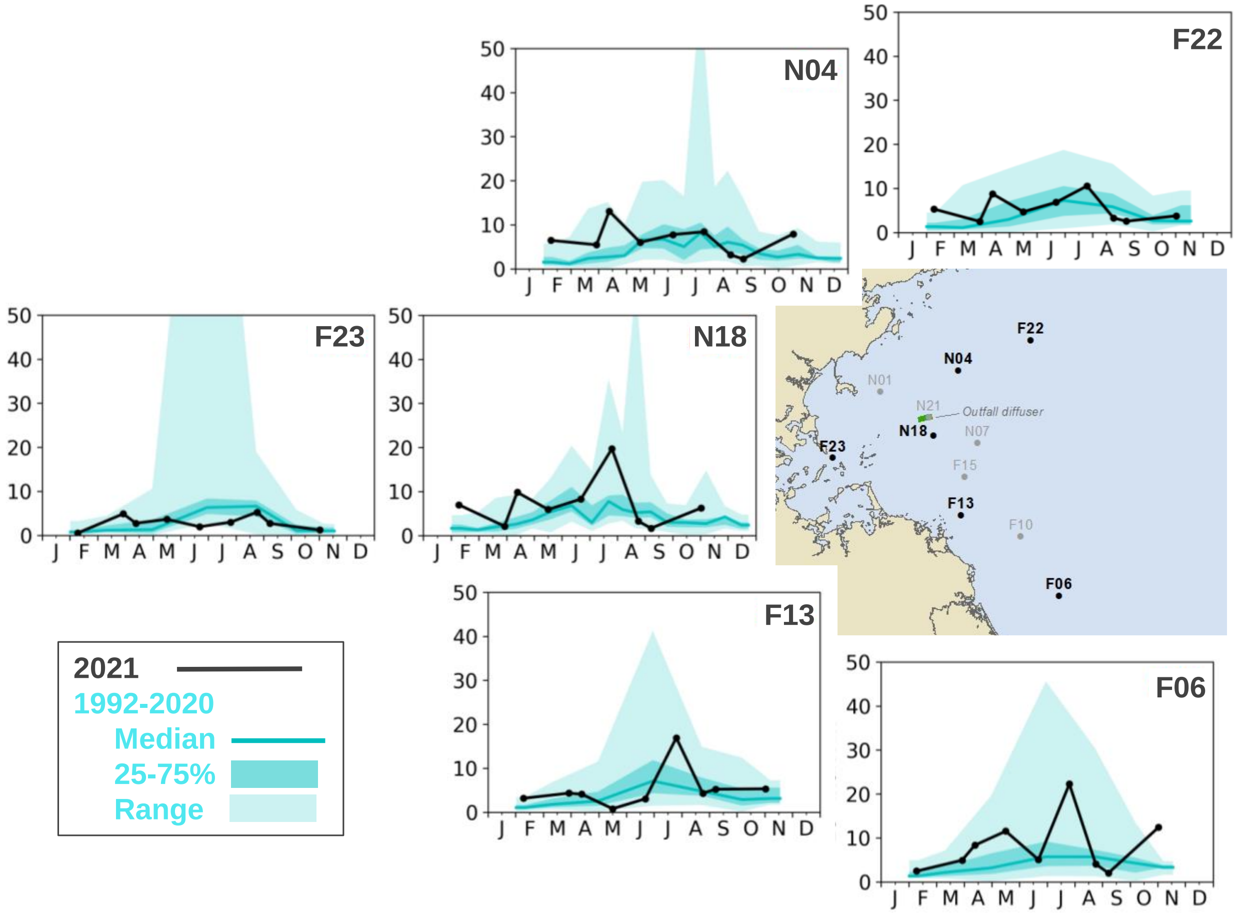

Figure 2-28. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2021 compared to prior years. 2021 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans 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}.

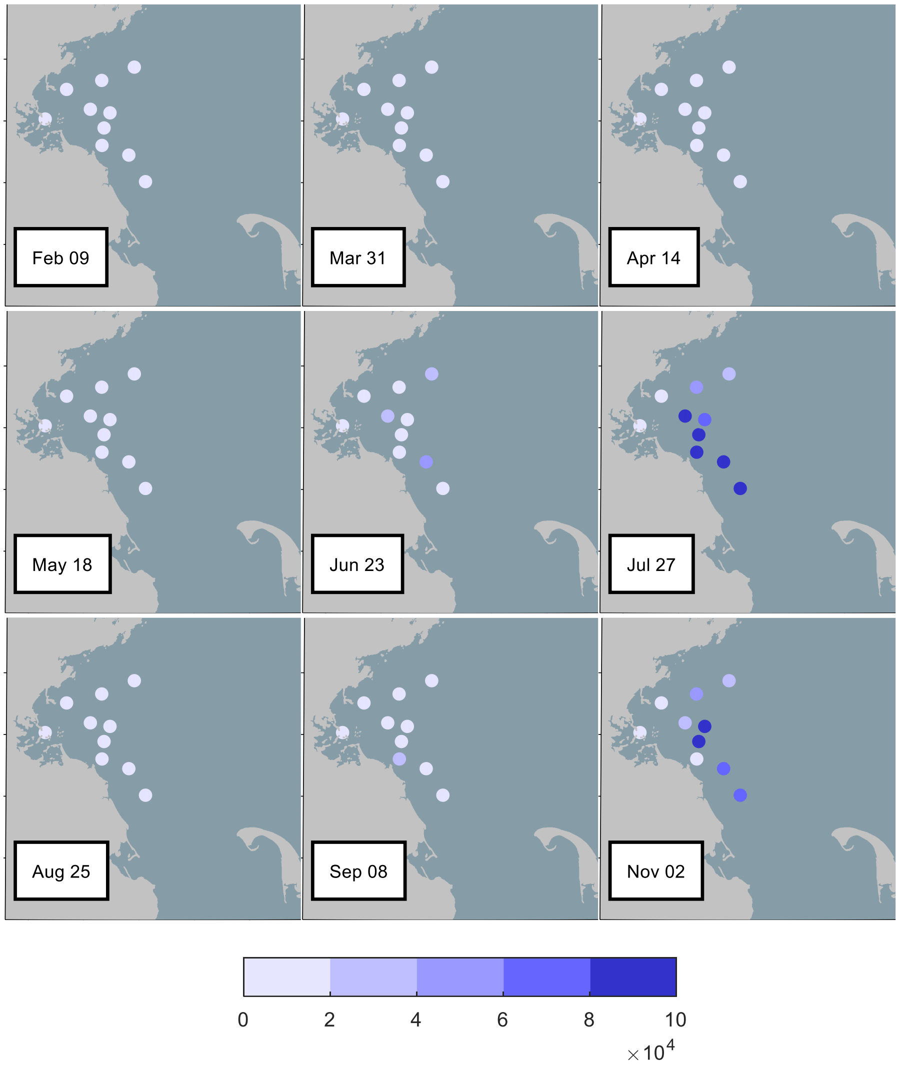

Figure 2-29. **Meroplankton and other non-copepod abundance (10,000 individuals m^{-3}) in Massachusetts Bay for 2021.**

Seasonal patterns of abundance of total zooplankton were typical, with increases from February lows through to summer peaks, followed by fall declines (**Figure 2-28**). There were peaks in abundance of both total zooplankton (dominated by radiolarians) and total copepod adults + copepodites (not shown) in April, May, and July or August. Abundances of copepod adults + copepodites were dominated by adults + copepodites of the small copepod *Oithona similis*. Copepod nauplii were unusually abundant early in the year, especially in April at stations N04 and N18 (not shown). Copepodites of the large copepod *Calanus finmarchicus* (not shown) were unusually abundant in April with abundances in the upper quartile at station N04 compared to historic abundances and reaching a new maximum of ~20,000 individuals m^{-3} at station F22.

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 and copepod abundances leveled off in 2018 and began decreasing. The data from 2021 are consistent with the trend in decreasing zooplankton abundances observed since 2018.

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 2021, the marine mammal observer was not onboard until the May survey due to COVID-19 protocols. 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 during these three surveys. Whale observations made by field staff on the routine water column surveys, ARRS and BHWQM surveys were documented and the data are included in **Table 2-3** and **Figure 2-30**.

In 2021, five North Atlantic right whales (*Eubalaena glacialis*), two humpback whales (*Megaptera novaeangliae),* three minke whales (*Balaenoptera acutorostrata*), one finback whale (*Balaenoptera physalus*), and two unidentified whales were observed during the MWRA surveys in Massachusetts Bay (**Table 2-3** and **Figure 2-30**). Several other marine mammals including one harbor seal (*Phoca vitulina*), three harbor porpoises (*Phocoena phocaena*), a pod of less than ten Atlantic white-sided dolphin (*Lagenorhynchus acutus)*, one unidentified seal, and two unidentified sharks 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, 2020, and 2021.

Table 2-3. Number of whale sightings from 1998 to 2021.

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	2021
Finback	11	0-4	1	0	0	0	0	0	0	1	1	0	1
Humpback	4	0-1	0	2	0	0	0	0	0	0	1	2	2
Minke	30	0-6	4	0	0	2	0	3	3	4	1	4	3
North Atlantic Right	0	0-0	0	2	4	0	0	2	8	0	0	1	5
Unidentified	15	0-2	0	3	1	1	0	0	4	2	4	0	2

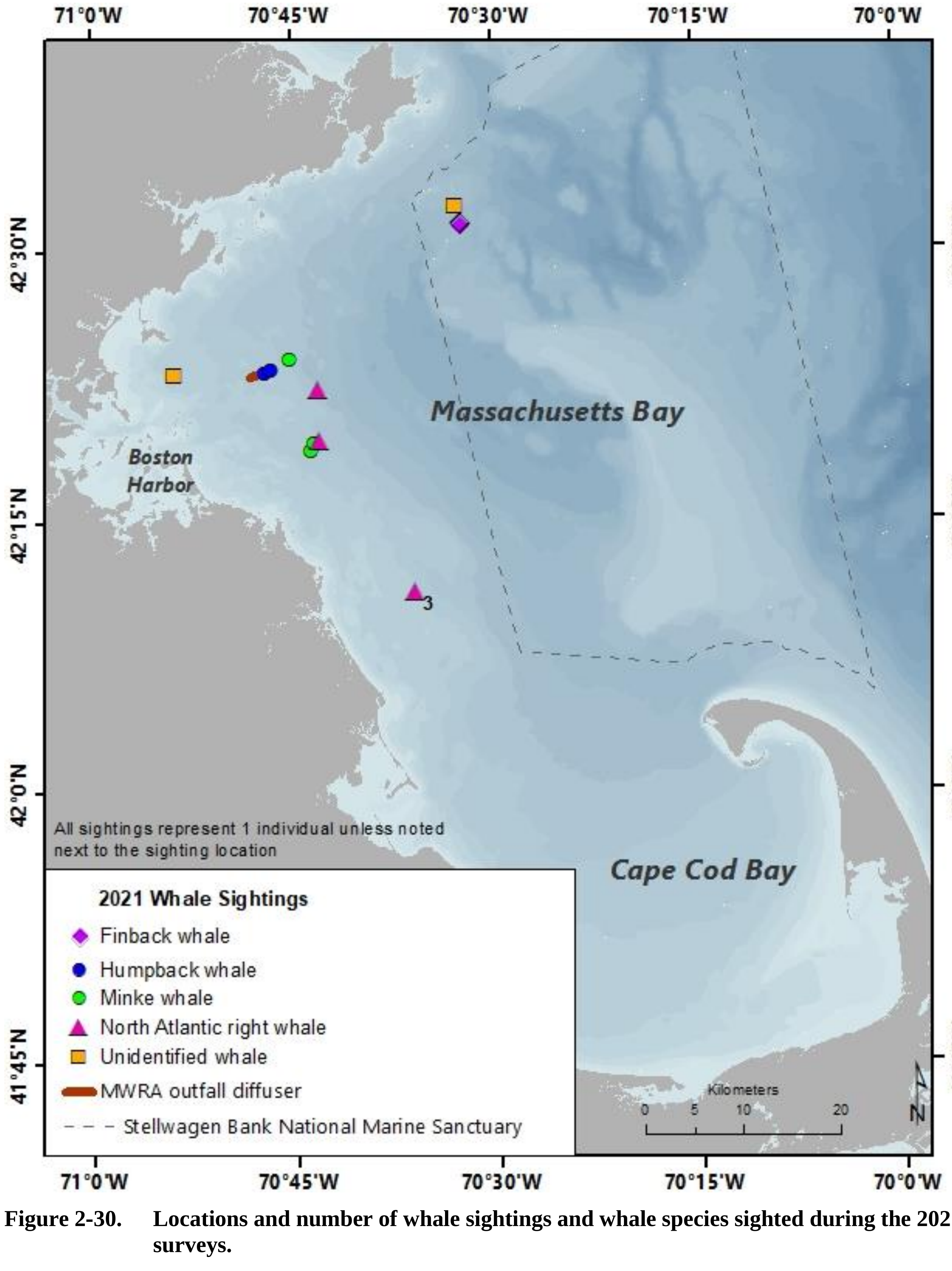

Figure 2-30. **Locations and number of whale sightings and whale species sighted during the 2021 surveys.**

3 ANALYSIS OF THE LONG-TERM MONITORING DATASET

3.1 KARENIA MIKIMOTOI: 2017-2021

As noted in Section 3.5, there has been a long-term declining trend in total phytoplankton and centric diatom abundance in Massachusetts Bay (**Figure 3-1**). The long-term trend in dinoflagellate abundance, however, has been increasing over the last few years and appears to be cyclical with an approximately 11-year period. The peaks in dinoflagellate abundance around 2000 and 2011 were driven by increased *Ceratium* abundance. The recent (2017-2020) increase in the cycle has been driven by the appearance and elevated abundance of a new dinoflagellate to the region, *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 3-2**). 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 concentrations of millions of cells L^{-1} in Casco Bay and Portland Harbor, Maine which resulted in benthic mortalities[4]. *Karenia* was also observed in Massachusetts Bay during September 2018, but abundances were lower (maximum level of ~ 4,000 cells L^{-1}). Larger *Karenia* blooms of nearly a million cells L^{-1} were observed in Massachusetts Bay during August and September of both 2019 and 2020.

The 2019 *Karenia* bloom was most intense in Boston Harbor (maximum of 850,000 cells L^{-1} at station F23; **Figure 3-2**) where for a brief period in September the high abundance of *Karenia* cells resulted in discolored water in the harbor[5]. 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. 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* blooms (Libby et al. 2021b; Scully et al. 2022).

Karenia was not as abundant in Massachusetts Bay during 2021 compared to 2019 and 2020. Maximum abundance for 2021 of 36,215 cells L^{-1} was recorded in the nearfield – a marked decrease from ~850,000 cells L^{-1} observed during 2019 and 2020. However, *Karenia* appears to be increasing in persistence in Massachusetts Bay, from about 70 days from August to October in 2017 to being present for the duration of MWRA monitoring from early February to late October/early November during 2020 and 2021 (**Figure 3-2**).

Karenia is adapted to maximize growth and population accumulation in areas having strong gradients such as frontal zones and pycnoclines (Li et al., 2019). For the 2017-2021 MWRA data, the average abundances of *Karenia* are four times higher for the chlorophyll maximum samples versus the surface samples and the maximum abundances are approximately 30 times higher in the samples collected at the chlorophyll maximum layer, often located within the pycnocline, when present. While there was reduced abundance during 2021 in the Massachusetts Bay region, targeted sampling at the pycnocline in Cape Cod Bay by CCS did identify *Karenia* at abundances of up to 1.3 million cells L^{-1} during August 2021. *Karenia* has now been observed in Massachusetts Bay and Cape Cod Bay for five consecutive years and appears to be present nearly year-round (**Figure 3-2**).

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

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

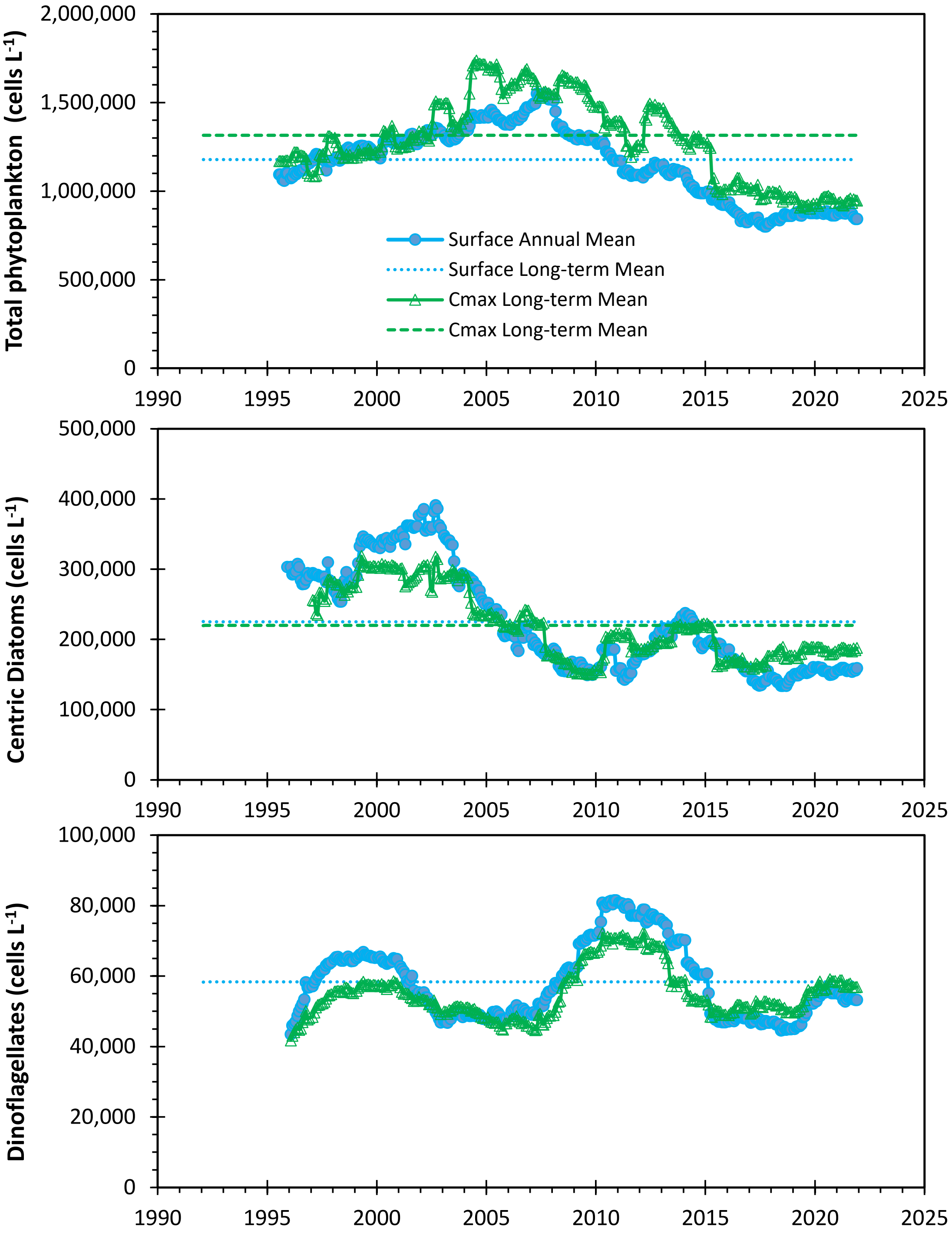

Figure 3-1. Estimated long-term (1992-2021) abundances of phytoplankton groups in the nearfield region (stations N04 and N16/N18) derived from time series analysis. Each panel shows the deseasonalized annual mean abundance at the surface (blue) and at the chlorophyll maximum depth (green) during 1992-2021. Horizontal dashed lines are 1992-2021 mean abundances. Panels show total phytoplankton (top panel), centric diatoms (middle panel), and dinoflagellates (bottom panel). Monthly deseasonalized abundance estimates have been smoothed with a 15% smoothing window equivalent to the ~48 months preceding the sample date.

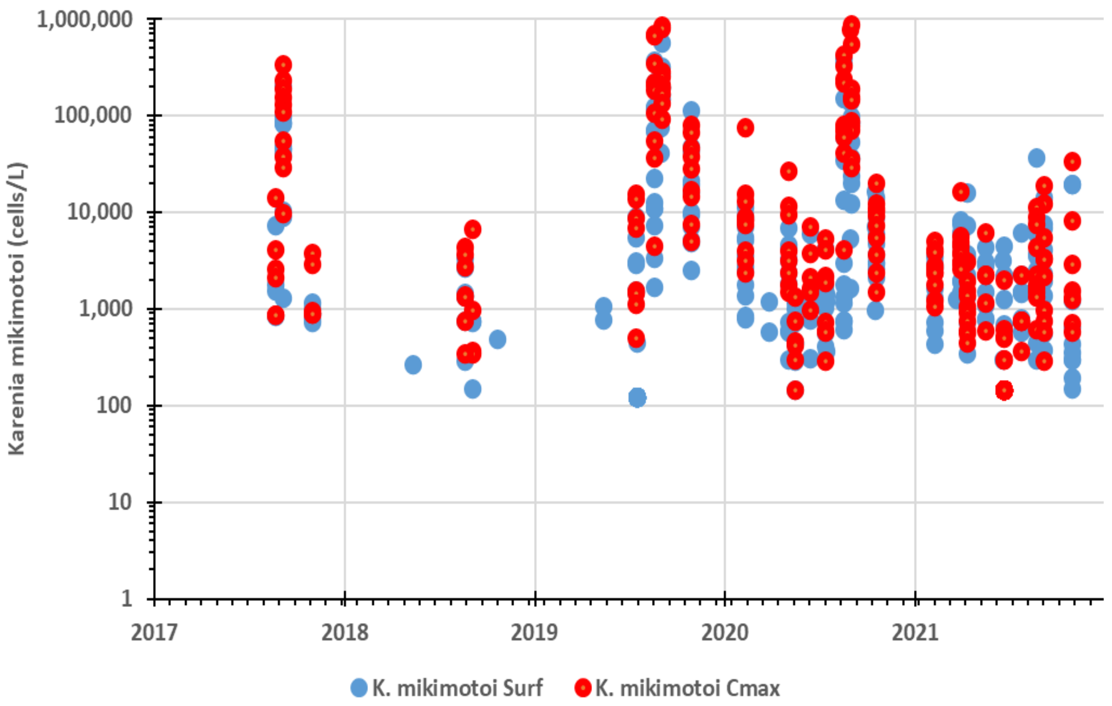

Figure 3-2. ***Karenia mikimotoi*** **abundance (cells L^{-1}) from MWRA monitoring stations in 2017-2021. "CMAX" is the depth of the chlorophyll maximum, typically about 10-20 m deep.**

Karenia mikimotoi has been described as a harmful species (Gentien 1998), however toxins from this species are not well-characterized (Yamasaki et al. 2004), and negative effects of *Karenia* 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). This species grows well in low-light conditions and thus can exploit light-limited environments (Li et al. 2019). It can vertically migrate at rapid rates, forming concentrated thin layers within the pycnocline, making abundance estimates more difficult. *Karenia* has low nutritional value, so it is often avoided by phytoplankton grazers. It also exhibits strong allelopathy (chemical warfare against co-occurring species; Riegman et al. 1996), which is likely an important mechanism allowing *Karenia* to reach high, often mono-specific cell densities.

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). The accumulation of *Karenia* blooms at the pycnocline and eventual decay in the bottom waters in shallow regions of Cape Cod Bay are contributing to hypoxia in Cape Cod Bay (Scully et al. 2022). 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* as part of the regional phytoplankton flora.

The appearance of *Karenia* in Massachusetts and Cape Cod Bays is regional phenomenon and its extended presence since 2017 is likely due to physical processes in the bays resulting in strong seasonal stratification. *Karenia* is particularly well suited to bloom effectively by exploiting low light, high nutrient conditions near the pycnocline. If there is a potential outfall effect on *Karenia*, if any, it would be expected to be observed in monitoring as locally higher abundances at or near to the outfall, which has not been observed in sampling to date.

3.2 DISSOLVED OXYGEN TRENDS

As noted in Section 3.5, bottom water DO concentrations were low in Massachusetts Bay in 2021 and exceedances of the Contingency Plan thresholds for DO concentration and percent saturation occurred in Stellwagen Basin (**Table i**). Fortunately, water column mixing events during summer months kept bottom water DO concentrations from reaching even lower concentrations in 2021. Early in the MWRA monitoring program, DO appeared to follow a pattern in which low DO in the deep waters of the nearfield was statistically associated with warm bottom waters and high salinity (Geyer et al. 2002). This observation was used to develop a regression model for bottom water DO based on water temperature and salinity (**Figure 3-3**). Historically, the model was relatively good at predicting bottom water DO, but in recent years the model has predicted much lower concentrations than observed. The conditions in 2021 again show that the actual DO was significantly higher than predicted by the model (**Figure 3-3**). In fact, the anomalously warm bottom temperatures (**Figure 2-1**) would have been expected to produce the lowest DO of the monitoring program.

This divergence in recent years appears to be due to the increasing importance of summertime mixing events. These events cause the DO to rebound before the seasonal destratification and appear to be due to regional rather than local influences on water temperature (Scully et al. 2022). Over the past 20 years, the mean direction of strong (>15 knots) summertime winds in Massachusetts Bay has shifted from predominantly out of the southwest to predominantly out of the northeast. This shift towards more northeast winds leads to less upwelling and more downwelling favorable conditions and mixing. This was clearly the case in summer 2021 (**Figure 2-4** and **Figure 2-5**).

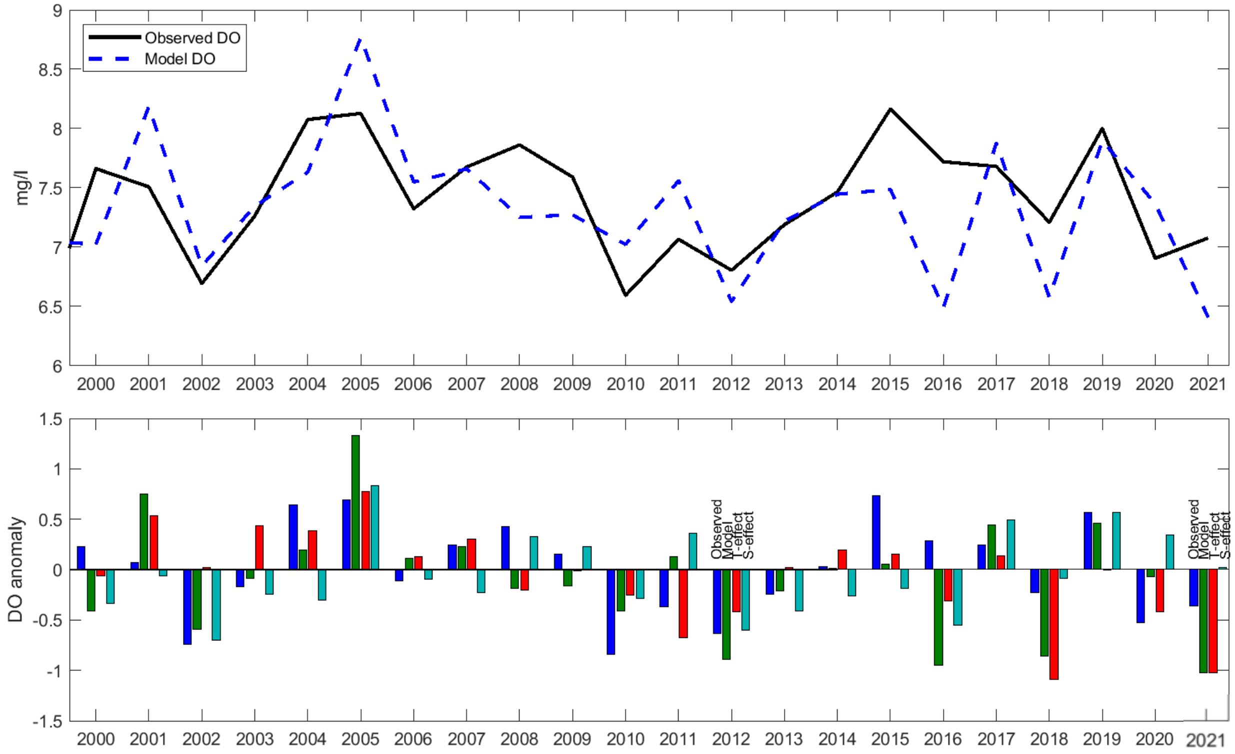

Figure 3-3. **Average near-bottom dissolved oxygen in the nearfield during September-October, compared with linear regression model based on temperature and salinity variation (upper panel). Bar plot showing the individual contributions due to temperature and salinity for each of the years (lower panel).**

The effect of mixing, or lack thereof, on bottom water DO has also been clear in Cape Cod Bay in recent years. In 2019, the shallow nearshore waters of Cape Cod Bay in the late summer became hypoxic and localized anoxic levels were reportedly associated with fish and lobster mortalities (Libby et al. 2020). These hypoxic/anoxic conditions were not alleviated until strong northerly winds mixed the water column in early October 2019. In 2020, hypoxic conditions were again observed in the shallow, nearshore bottom waters of southwestern Cape Cod Bay though anoxic levels were not reached, and no significant lobster mortality was reported (Libby et al. 2021b). An investigation by MA DMF, CCS and WHOI documented high chlorophyll and high abundances of phytoplankton, dominated by *Karenia*, in association with the 2020 hypoxia event. 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 concentrations observed in Cape Cod Bay in late August to mid-September 2020 (Scully et al. 2022).

These hypoxic/anoxic conditions were not caused by nutrient inputs from the Massachusetts Bay outfall. However, since the hypoxia event in 2019, MWRA and its monitoring team members from the CCS and WHOI have participated in studies to understand the causes of hypoxia and better protect the fish and lobster resources. In collaboration with the MA DMF, the Massachusetts Lobster Foundation sponsored a group of local lobstermen to aid in these studies, the Cape Cod Bay Study Fleet, providing them with oxygen probes to place in their traps to track bottom water DO conditions with near real-time measurements. In August 2021, the Cape Cod Bay Study Fleet probes detected declining DO concentrations at numerous sites. DO concentrations reached as low as 2.3 mg L^{-1} in eastern Cape Cod Bay on August 18 (**Figure 3-4**). An advisory notified lobstermen to check their traps regularly and consider removing some gear. However, conditions did not further decline; a mixing event on August 20 and Hurricane Ida in early September re-aerated the bottom waters, and no fish or shellfish mortalities were recorded.

Occurrence of hypoxia in Cape Cod Bay appears to be exacerbated by the presence of *Karenia mikimotoi*, the dinoflagellate that first appeared in the region in 2017. As noted in the previous section, *Karenia* is well-suited to exploit nutrient-rich, shallow bottom waters, such as are found in the Cape Cod Bay lobstering grounds. 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. The results from 2021 suggest that this condition may vary from year to year depending on the intensity of late summer mixing. *Karenia* abundance in the bay has not reached levels that cause anoxia in other systems (3 to 10 million cells L^{-1}; Gentien 1998, Turner et al. 1987, Li et al. 2019), but the combination of recently warming bottom waters, added oxygen demand from decaying *Karenia* cells, and thin bottom water layers may be pushing oxygen concentrations down in shallow regions of Cape Cod Bay (Scully et al. 2022).

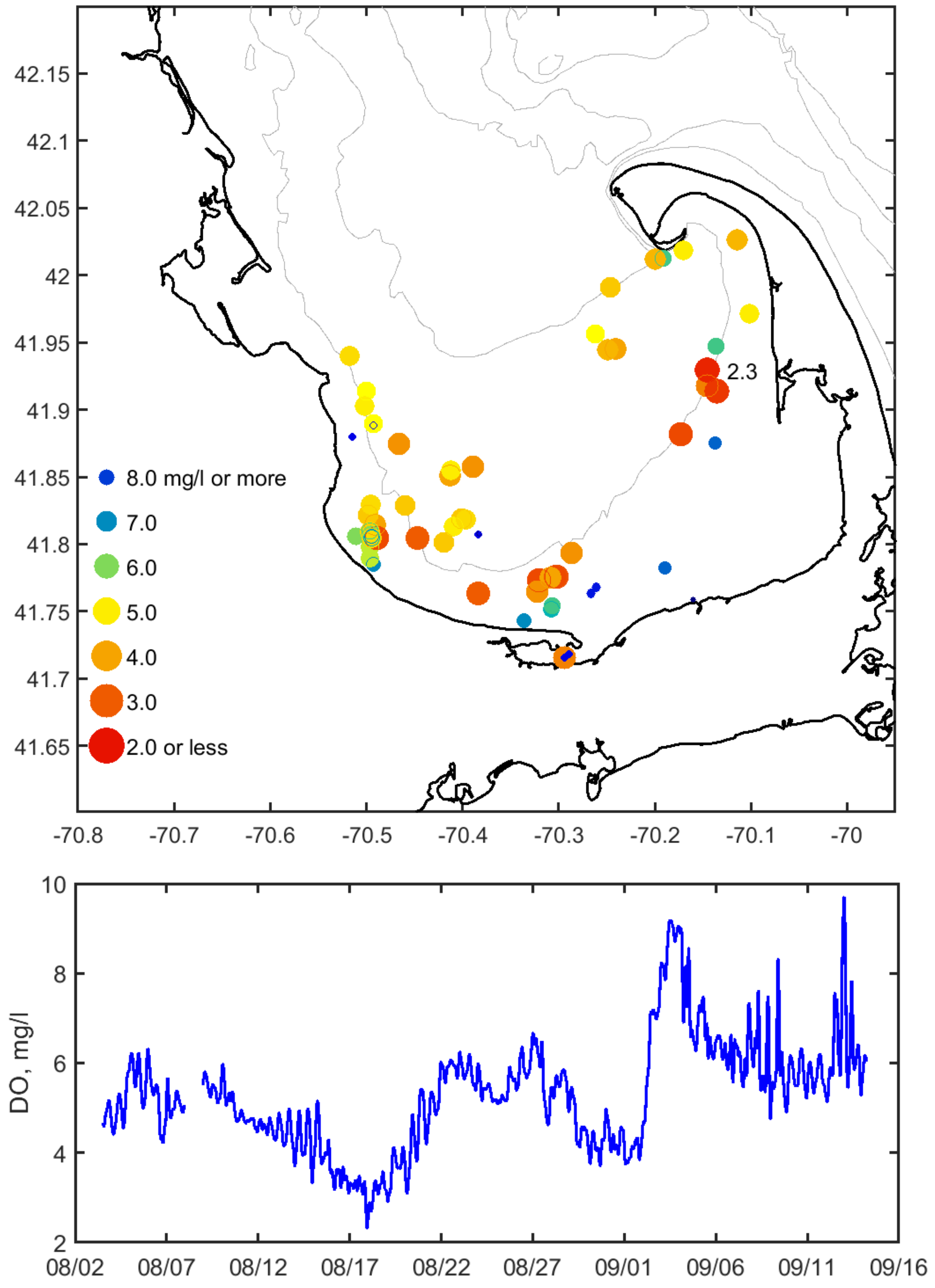

Figure 3-4. Cape Cod Bay Study Fleet dissolved oxygen (mg L^{-1}) data recorded on sensors deployed on lobster traps from July through October 2021. Top panel – DO minima from each lobster trap probe. Bottom panel - time series of hourly DO concentrations in the lobster trap off Wellfleet, MA where they 2.3 mg L^{-1} minimum was observed. Data courtesy of Tracy Pugh, MA DMF and the CCB Study Fleet.

4 SUMMARY

The most notable physical oceanographic characteristics of 2021 were a very wet summer, with frequent northeasterly wind events; unusually warm water, both surface and bottom; and a strong Nor'easter in October resulting in extreme waves with significant wave height of up to 9 m. Overall, river flow was lower than normal during the winter and spring, but the months of July, August and September saw the highest river flows of the 30-year monitoring program (**Figure 2-3**). Surface water temperature warmed to unusually high values during the late July and August surveys. Surface salinity started out anomalously high, but then dropped to below-average values due to the large summertime freshwater inputs. Wind speeds and directions were typical in early 2021, with a number of storm systems bringing strong northeast winds in the winter/spring. In contrast to a typical year, the northeast wind events continued over much of the summer (**Figure 2-4**). The impact of these summer northeast wind events was evident in the upwelling index which, after showing strong upwelling conditions during June, in July had its strongest negative anomaly (i.e., downwelling-favorable) observed over the 30-year monitoring program (**Figure 2-5**). August and September continued to show weak or absent upwelling conditions. The weak or negative upwelling index helps explain the warm waters observed during the late summer (**Figure 2-1**).

The long-term trend shows that surface water temperature is increasing more rapidly than air temperature (**Figure 2-7**). This difference is due to regional rather than local influences on the water temperature. Analysis performed by Scully et al. (2022) indicates strong summertime winds in Massachusetts Bay have shifted from predominantly southwest to northeast over the last 20 years. This shift helps explain the general warming tendency, as southwest winds lead to stronger upwelling and cooling of surface waters while northeast winds lead to downwelling, and warmer surface temperature as observed in July and August 2021.

Stratification in Massachusetts Bay was close to the long-term median from February to May 2021 (**Figure 2-6**). A combination of cooler, more saline surface waters and relatively warm, saline bottom waters led to stratification levels near historical minima in June. However, the influx of fresher, warmer surface waters in late June and into July led to a sharp increase in stratification leading to long-term maxima across the bay in late July and August contributing to the sharp decline in bottom water DO in late August/early September. The major Nor'easter in late October mixed the water column at all but the deepest waters in Massachusetts Bay. At station F22, the bottom waters remained isolated from the surface layer by stratification until after the early November survey.

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 the fall (**Figure 2-8**). The most notable observations in 2021 were relatively high nutrient concentrations in February, sharp decreases in NO_3 and SiO_4 from February to March (indicative of diatom bloom), decreases in NO_3 and the NO_3 to SiO_4 ratio from April to May (suggestive of a *Phaeocystis* bloom), and depleted surface water concentrations from May into summer, with intermittent peaks in NH_4 and PO_4.

The 2021 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**). In the nearfield, NH_4 concentrations varied with results at station N21 generally close to the long-term median except in April when they were nearly depleted (likely due to the effluent plume being advected away from that station by ambient currents during the survey, which is not unusual) while at station N18, concentrations were more variable with peaks in the upper quartile during multiple months and with an annual maximum of about 10 µM observed in July well above the long-term maximum. Elevated NH_4 concentrations were also observed in June, July, and August 2021 at stations F15 and F10 and even as far south at station F06 nearly 30 km south of the outfall, but were intermittent and within historic ranges (**Figure 2-10** and **Figure 2-13**). Ammonium concentrations at Boston Harbor station F23 in 2021, as in other post-discharge years, were much lower than during the years the wastewater was discharged directly to the harbor. These patterns 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, 2021 chlorophyll concentrations were low to moderate. Elevated areal chlorophyll was observed during the February, April, June, August, and September surveys in Cape Cod Bay and during the March and July surveys in Massachusetts Bay (**Figure 2-14** and **Figure 2-15**). Seasonal and annual chlorophyll averages in 2021 were low, comparable to baseline, and less than half the Contingency Plan levels (**Table i)**. MODIS and Buoy A01 chlorophyll (**Figure 2-16** and **Figure 2-17**) showed increases in March and late April/May, which along with changes observed in nutrient concentrations suggest winter/spring diatom and *Phaeocystis* blooms occurred between the monthly MWRA surveys. July increases in chlorophyll were coincident with increased mixing and nutrient availability. Late summer chlorophyll was low in Massachusetts Bay, but high concentrations were observed in Cape Cod Bay.

Bottom water DO concentration minima in late summer/early fall were lower than typical over most of Massachusetts Bay and exceeded Contingency Plan thresholds for DO concentration and percent saturation at the Stellwagen Basis station F22 (**Table i**). Bottom water DO concentrations were relatively low from February to April and were below historic minima at many stations by May 2021 (**Figure 2-18**). Substantial northeast wind events from late May through July mixed the water column, contributed to downwelling favorable conditions in July, and alleviated the decrease in bottom water DO concentrations, which remained relatively constant in June and July in Massachusetts Bay. A strongly stratified water column in late July and August contributed to a sharp decrease in bottom water DO concentrations by late August/early September in Massachusetts Bay. The contingency plan DO percent saturation threshold was exceeded at the deep, Stellwagen basin station F22 in September (66.3% versus 67.2%; **Table i** and **Figure 2-19**). Bottom water DO continued to decline at station F22 into early November reaching the lowest values measured at this station over the 30-year monitoring program (**Figure 2-18**). The November DO concentration and percent saturation both exceeded the Contingency Plan thresholds for the Stellwagen Basin station F22, at 5.89 mg L^{-1} and 65.9%, respectively. The influence of late fall mixing events was evident at Buoy A01, where DO decreased until late October when a major Nor'easter storm mixed the water column down to 50 m, but not deeper where bottom water DO remained low in early November (**Figure 2-20**).

Low DO was also observed in Cape Cod Bay with values below historic minima from May through July with an annual minimum of <5 mgL^{-1} measured at station F01 in early September 2021 (**Figure 2-21**). Mixing events in late August and the remnants of Hurricane Ida in early September re-aerated the Cape Cod Bay bottom waters and kept them from reaching the hypoxic levels seen in 2019 and 2020. In 2020 and 2021, MWRA and its monitoring team members from CCS and WHOI have participated in studies to understand the causes of hypoxia and better protect the fish and lobster resources. In collaboration with MA DMF, the Massachusetts Lobster Foundation provided a group of local lobstermen, the Cape Cod Bay Study Fleet, with oxygen probes to place in their traps and track bottom water DO conditions with near real-time measurements. The study detected declining DO concentrations at numerous sites in August 2021 with DO concentrations reaching a minimum of 2.3 mg L^{-1} in eastern Cape Cod Bay on August 18 (**Figure 3-4**). An advisory notified lobstermen to check their traps regularly and consider removing some gear. However, conditions did not further decline; a mixing event on August 20 and Hurricane Ida in early September re-aerated the bottom waters, and no fish or shellfish mortalities were recorded.

The occurrence of hypoxia in Cape Cod Bay appears to be caused by a combination of factors and exacerbated by the presence of *Karenia mikimotoi*, the dinoflagellate that first appeared in the region in 2017. *Karenia* is well-suited to exploit and bloom in nutrient-rich, shallow bottom waters, such as the Cape Cod Bay lobstering grounds. Senescing *Karenia* blooms may provide a source of added carbon, increasing biological oxygen demand, and contributing to the hypoxia observed in shallow, nearshore bottom waters of Cape Cod Bay. The results from 2021 suggest that this condition may vary from year to year depending on the intensity of late summer mixing. *Karenia* abundance in the bay has not reached concentrations as high as have been reported to 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 concentrations down in shallow regions of Cape Cod Bay (Scully et al. 2022).

Annual total phytoplankton abundance in the nearfield was very low in 2021 and ranked 27th for the 30-year monitoring program (**Table 2-1** and **Figure 2-22**). Total phytoplankton abundance was consistently below the historic median during most of the surveys conducted in 2021 (**Figure 2-22**). This was because winter/spring and fall blooms of centric diatoms or large *Phaeocystis* blooms either did not occur or were not captured by the monthly surveys in 2021. Overall, phytoplankton abundance and community composition during 2021 were similar to the past five years (2015-2020) and continue the trend of relatively low phytoplankton in the Massachusetts Bay nearfield observed since the early 2000s.

Dinoflagellates are the only phytoplankton functional group that appears to be increasing in recent years, primarily due to continued presence of *Karenia* (Libby et al. 2018; **Figure 3-2**). *Karenia* abundance was lower in 2021 compared to 2019 and 2020, but as in 2020, it was present in the bays from February to November 2021. *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. While there was reduced abundance during 2021 in the Massachusetts Bay region, targeted sampling at the pycnocline in Cape Cod Bay identified *Karenia* abundances of up to 1.3 million cells L^{-1} in August 2021. As noted above, these blooms have been identified as a contributing factor to hypoxic conditions observed in Cape Cod Bay in 2019 and 2020 (Scully et al. 2022).

A large *Alexandrium catenella* bloom was observed in Massachusetts Bay in 2021 comparable to the large blooms present in the bay in 2005, 2008, and 2019 (**Figure 2-25**). High *Alexandrium* abundances were first observed during the June 23 survey with a maximum of 7,386 cells L^{-1} at station N01 and abundances of >500 cells L^{-1} observed at station N18 and along the South Shore (**Figure 2-27** and **Table 2-2**). These abundances were well above the 100 cells L^{-1} Contingency Plan threshold and triggered ARRS surveys in July. Soon after the June survey, PSP toxicity was detected for the first time in Massachusetts along the South Shore at the Cohasset and Scituate MA DMF sites (48 µg/100 g tissue) on June 28, 2021. PSP toxicity was below detection limits (<40 µg/100 g) north of Cape Ann and at the other MA DMF sites in Massachusetts Bay.

Based on the data and understanding of the blooms through the early 2000s, the hypotheses of what an "outfall effect" might look like were focused on geographical indicators. If an *Alexandrium* bloom is more intense (abundance and higher toxicity) along the south shore than to the north, or if toxicity is observed earlier at stations along the south shore than at Gloucester, this pattern would be different than that historically observed and consequently suggestive of an outfall effect (Libby 2013a). These metrics were based on the "plume advection hypothesis" described by Franks and Anderson (1992) and revisited after the 2005 bloom by Anderson et al. (2005). In 2021, PSP toxicity was first detected at MA DMF sites along the South Shore, indicative of a different regional dynamic. However, PSP toxicity at the South Shore sites remained below 80 µg/100 g while toxicity north of Cape Ann reached levels >200 µg/100 g in July 2021 resulting in shellfishing closures from the New Hampshire border south to Duxbury, MA.

Our understanding of *Alexandrium* bloom dynamics in Massachusetts Bay is evolving based on recent observations of *Alexandrium* cysts in the western portion of the bay. In the late summer/fall of both 2019 and 2020, elevated cyst abundances were observed in western Massachusetts Bay (**Figure 2-26**). A review of cyst data from 2006 to 2018 shows this area had not been sampled previously, as areas in Massachusetts Bay had only been sampled intermittently and only in the eastern portions of the bay. This suggests that the cyst bed may have been present prior to the 2019 observations. In 2021, the initial inoculum of *Alexandrium* cells in Massachusetts Bay may have been either from advection of populations from coastal waters of New Hampshire and western Maine, as has often been observed before (Anderson et al. 2005), or from the localized germination of cysts from sediments in western Massachusetts Bay and Boston Harbor. Additional cyst sampling in western Massachusetts Bay in future years will help to indicate whether deposits in that location are ephemeral in nature or can be persistent through time. A review of the 2005-2022 *Alexandrium* and ancillary data is underway to better understand bloom dynamics in Massachusetts Bay and whether the MWRA outfall effluent discharge potentially has an impact on the initiation, duration, or magnitude of blooms.

Zooplankton taxa, seasonal patterns, and abundances in 2021 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, peaks in total zooplankton abundance in July and November were due to high abundances of radiolarians similar to 2020 observations, which was the first time radiolarians had been recorded in the sampling program. The high abundances of radiolarians suggest intrusions of water from offshore, which is consistent with frequent northeast wind events in July and the major storm in late November transporting offshore waters into the 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 data from 2021 are consistent with observations in 2018-2020.

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