2022 Water Column Monitoring Results

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Environmental Quality Department
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Cover Photo: CTD-Rosette set for deployment to collect samples at station F23 off Deer Island.
Credit: Scott Libby, Battelle on the October 2022 MWRA survey WN229.

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2022 Water Column Monitoring Results

Submitted to

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Environmental Quality Report 2023-11

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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. MWRA implemented a long-term monitoring program to assess the environmental impacts of the MWRA discharge, which in 2000 was diverted from Boston Harbor to Massachusetts Bay. This report documents the results of 2022 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 2022, the COVID-19 pandemic had a limited impact on the level of sampling conducted in February. As in 2020 and 2021, 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 2022 with exceedances observed for the *Alexandrium* and dissolved oxygen (DO) thresholds (**Table i**). Three additional *Alexandrium* Rapid Response Study (ARRS) surveys were conducted in July 2022.

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 2022 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 2022:

Physical Conditions

- The most notable physical oceanographic characteristics of 2022 were the very dry summer and fall, warm and higher salinity waters for most of the year, and persistent upwelling favorable winds over most of the summer.
- River flow was relatively high in the winter, but decreased by May and from June to October flows were close to historic minima for the 31-year monitoring program.
- Water temperatures were high compared to historical levels for most of 2022, except in July during a period of persistent upwelling.
- Surface salinity was close to the long-term median for the first half of the year before increasing to abnormally high levels in June and July and remained elevated through the fall. Bottom-water salinity was near or above historical highs over most of the year.
- The occurrence of warmer temperatures and higher salinity has been correlated to low DO during previous years and this continued to be the case in 2022 with bottom water DO levels exceeding Contingency Plan thresholds in the nearfield and Stellwagen Basin in summer and fall 2022 (**Table i**).

[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.

Table i. Contingency Plan threshold values and 2022 results for water-column monitoring. Seven exceedances occurred, with the highest level of exceedance indicated in red.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2022
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: 5.85 SW Basin: 6.08
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 66.6% SW Basin: 65.4%
Bottom water DO rate of decline (mg L^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.027
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	53
	Winter/spring	>199	--	50	66
	Summer	>89	--	51	43
	Autumn	>239	--	90	51
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	502
	Summer	>43,100	--	14,635	5,770
	Autumn	>27,500	--	10,500	1,280
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	10,180

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

- Winds followed a typical annual pattern, with several storm systems producing strong winds from the northeast (known as Nor'easters) during the winter/spring. Persistent upwelling-favorable winds out of the south were observed from late June to early July. Strong fall winds/storms were not consistently seen until mid-November delaying the fall overturn of the water column in the deeper waters for Massachusetts Bay.

Nutrients and Phytoplankton Biomass

- Massachusetts Bay nutrient concentrations were consistent with those observed since the outfall was diverted offshore. In 2022, concentrations were relatively low in February and March due to the winter/spring diatom bloom and changes in nitrate and silicate concentrations from March to May suggested a *Phaeocystis* bloom may have occurred between the monthly MWRA surveys. Surface water concentrations of these nutrients were depleted from May into summer. Upwelling led to a sharp increase in nutrient concentrations in late July bringing both ambient and effluent derived nutrients closer to the survey layer. Nutrients were low in the fall consistent with the moderate fall diatom bloom observed across the bays.
- As in other years since outfall startup, compared to the baseline years 1992-2000, the 2022 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. Spatial variability of the effluent plume signal due to prevailing currents was evident with elevated ammonium observed about 30 km to the south in June, confined to the nearfield in July, and several kilometers to the northeast at station N04 in August.

- 2022 chlorophyll concentrations were low to moderate. Elevated areal chlorophyll levels were observed from March to June and October in Cape Cod Bay and during the March and October surveys in Massachusetts Bay. These results coincided with the winter/spring *Skeletonema* bloom and minor mixed assemblages of centric diatom bloom in the fall.
- Overall, seasonal and annual average chlorophyll threshold values in 2022 were relatively low, comparable to baseline seasonal averages and generally less than half the Contingency Plan thresholds (**Table i**). Only during the winter/spring diatom bloom were results well above the baseline mean.

Bottom Water Dissolved Oxygen

- Bottom water DO concentrations were low and below historical minima at many stations in 2022. Unlike recent years, there were no major mixing events over the summer and bottom water DO decreased from March to September/October. The 2022 rate of DO depletion in the nearfield did not exceed the Contingency Plan threshold but it was the highest rate observed since 1998.
- The warm temperatures, high salinities, and lack of mixing events or storms in 2022 were conducive to achieving low bottom water DO in Massachusetts and Cape Cod Bays and resulted in Contingency Plan exceedances for both the nearfield and Stellwagen Basin in 2022 (**Table i**).
- The lowest DO concentration (<3 mg L^{-1}) observed over the 1992-2022 monitoring program was measured in the bottom waters at Cape Cod Bay station F02 in September 2022. However, DO in shallow, nearshore Cape Cod Bay waters did not reach the hypoxic levels in 2022 that were reported in 2019 and 2020 by other Cape Cod Bay focused monitoring programs.
- Increased water temperatures and stratification resulting from regional changes in long-term summer wind patterns have been identified as a primary factor in the 2019 and 2020 hypoxic DO events in Cape Cod Bay (Scully et al. 2022). However, in 2022, the return to upwelling-favorable conditions, weaker stratification, and deeper thermocline led to earlier mixing in the shallow, nearshore Cape Cod Bay waters alleviating any potential hypoxia in these waters. These same factors likely contributed to the low DO observed further offshore at station F02 as a deeper thermocline would have resulted in a thinner bottom water layer thereby concentrating the impact of respiration on bottom water DO levels.

Phytoplankton and Zooplankton

- A large *Alexandrium catenella* bloom was observed in Massachusetts Bay in late June and July. This species of *Alexandrium* is typically associated with "red tide" in New England. Elevated *Alexandrium* abundances and paralytic shellfish poisoning (PSP) toxicity were observed in New Hampshire and north of Cape Ann by late May. The first detectable PSP toxicity levels were observed along the South Shore on June 22 which led to a shellfishing closure for Massachusetts Bay and triggered the 2022 ARRS (Libby et al. 2013).
- *Alexandrium* abundances peaked in late June with a maximum of 10,180 cells L^{-1} in the surface waters at station N10 off Hull. Other high counts of >1,000 cells L^{-1} were observed from the north at station F22, to western nearfield stations, and further south to stations along the South Shore. These high abundances were observed less than a week after PSP toxicity was first detected within Massachusetts Bay. Three additional ARRS surveys were conducted in July with decreasing abundances each successive survey until the bloom ended in late July. The timing of the bloom was similar to that observed during the recent blooms in 2019 and 2021 with high abundances not observed until the late June survey. As in 2019 and previous years, the pattern was consistent with the transport of bloom cells from northern waters into the bay.
- 2022 total phytoplankton abundances were mostly at or above long-term levels. This was due to a winter/spring bloom of *Skeletonema* spp. and *Pseudo-nitzschia* spp., a *Prorocentrum* bloom in May, and a mixed centric diatom bloom during October 2022. Total phytoplankton levels in the

nearfield during 2022 were about 1.5 times higher than the abundances observed during the previous three years (2019-2021) and may signal a change from the low abundance observed in the bay since the early 2000s.

- Dinoflagellates are the only phytoplankton functional group that has been increasing in abundance in recent years; this has primarily been due to the presence of *Karenia mikimotoi* (Libby et al. 2022). However, in 2022, *Karenia* abundance was relatively low compared to 2019 and 2020 levels; the elevated dinoflagellate abundances were due in large part to a bloom of *Prorocentrum cordatum* and elevated *Tripos* spp. abundance. The *Prorocentrum* bloom was the largest observed in Massachusetts Bay during the past 31 years of monitoring.
- Zooplankton taxa, seasonal patterns, and abundances in 2022 were generally similar to those of most previous years with increases from February lows through to summer peaks, followed by fall declines. However, peaks in total zooplankton abundance in July were due to high abundances of radiolarians similar to the past two years. 2020 was the first time radiolarians had been recorded in the sampling program. Doliolids, which are warm-water planktonic tunicates, were recorded for the first time in the MWRA sampling area in October 2022. The presence of the radiolarians and doliolids suggest intrusions of water from offshore in the Gulf of Maine, which is consistent with the comparatively warm waters recorded for 2022 in Massachusetts Bay.

LIST OF ACRONYMS

°C	degrees Celsius
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
l	liter
m	meter
mg	milligram
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, sewage was discharged to Boston Harbor, which used to be one of the most polluted 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 to the harbor. For this report, the outfall discharge period extends from September 6, 2000 through 2022, when wastewater has been discharged from the bay outfall and not into the harbor. The 2022 data complete 22 years of monitoring since operation of the bay outfall began and 31 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) has been periodically revised to focus on stations potentially affected by the discharge, as well as reference stations elsewhere in Massachusetts Bay (MWRA, 2021). The AMP currently calls for nine one-day water column surveys to be conducted each year (**Table 1-2**). Due to elevated COVID-19 cases, the first survey of 2022 was 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 during the previous two years, 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 March 2022, the field team was back to the full complement of six for the remainder of the year.

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 2022 as part of an *Alexandrium* Rapid Response Study (ARRS) triggered by detectable levels of paralytic shellfish poisoning (PSP) toxicity along the South Shore and high abundances of this toxic species (Libby et al. 2013); those dates are listed in **Table 1-2** (denoted as Survey AF22#).

This annual report summarizes the 2022 water column monitoring results, examines conditions over the seasonal cycle during 2022, 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 2022.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN221	February 10	February 7	February 15
WN222	March 23	March 23	March 23
WN223	April 13	April 13	
WN224	May 13	May 13	
WN225	June 28	June 28	June 27
AF221	July 6	n/a	
AF222	July 13	n/a	
AF223	July 20	n/a	
WN226	July 26	July 26	July 27
WN227	August 23	August 23	August 24
WN228	September 20	September 20	September 15
WN229	October 18	October 21	October 13

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 2022 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 2022 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, except N21 which is directly over the outfall. The Massachusetts Bay stations were sampled during one-day surveys; typically, within two days of those dates the three Cape Cod Bay stations were sampled by CCS. The February and October 2022 surveys were conducted three days apart due to sea conditions. 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, and reports on these separately.[2] MWRA collects samples at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally a 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 2022, 19 sampling locations were visited during each survey (**Figure 1-2**) including all the AMP survey stations except N21. The ARRS surveys provide data on in situ parameters, dissolved inorganic nutrients, and *Alexandrium* abundances. In 2022, a marine mammal observer was not present on the February AMP survey 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 2022 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 2022. 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

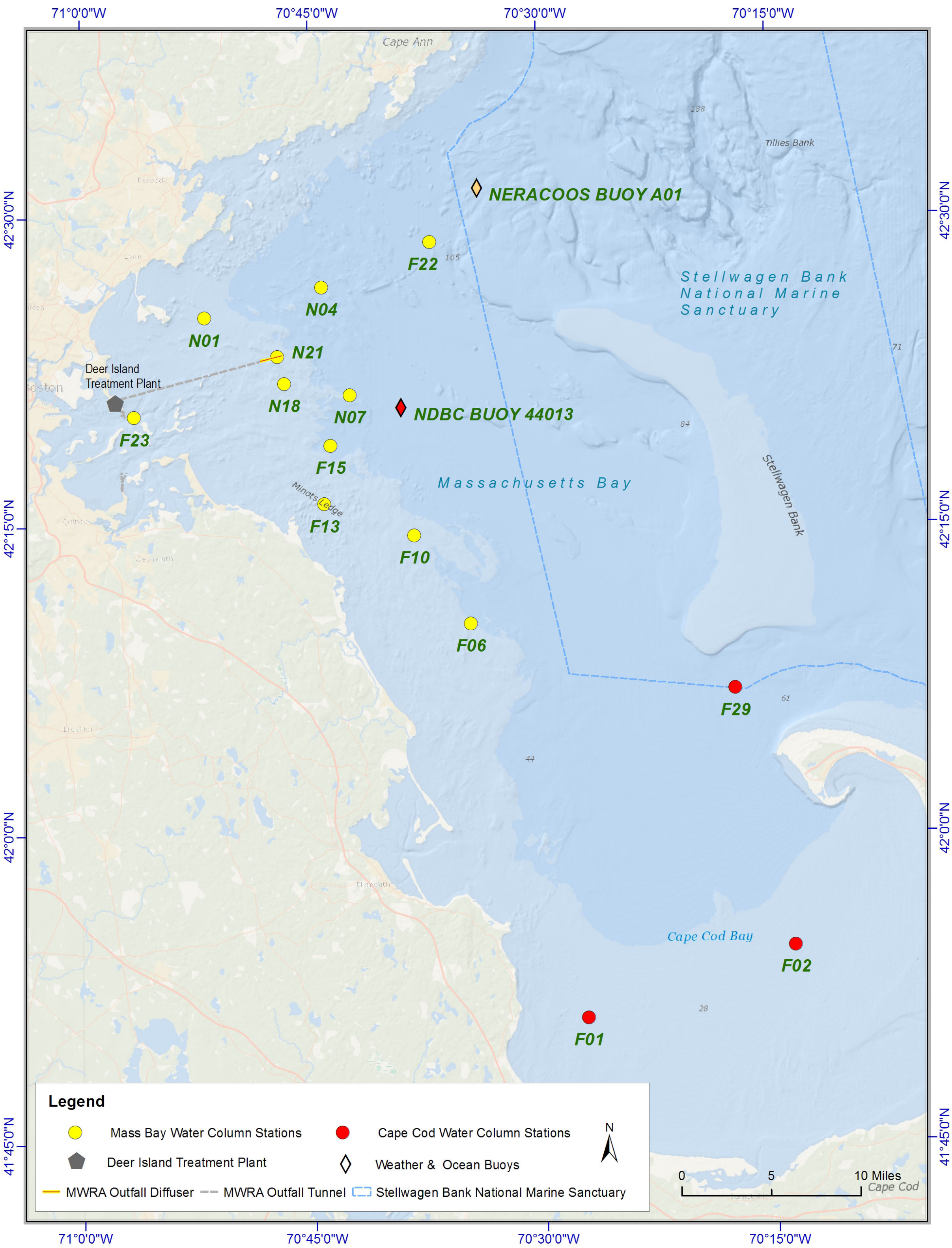

Figure 1-1. Water column monitoring locations.

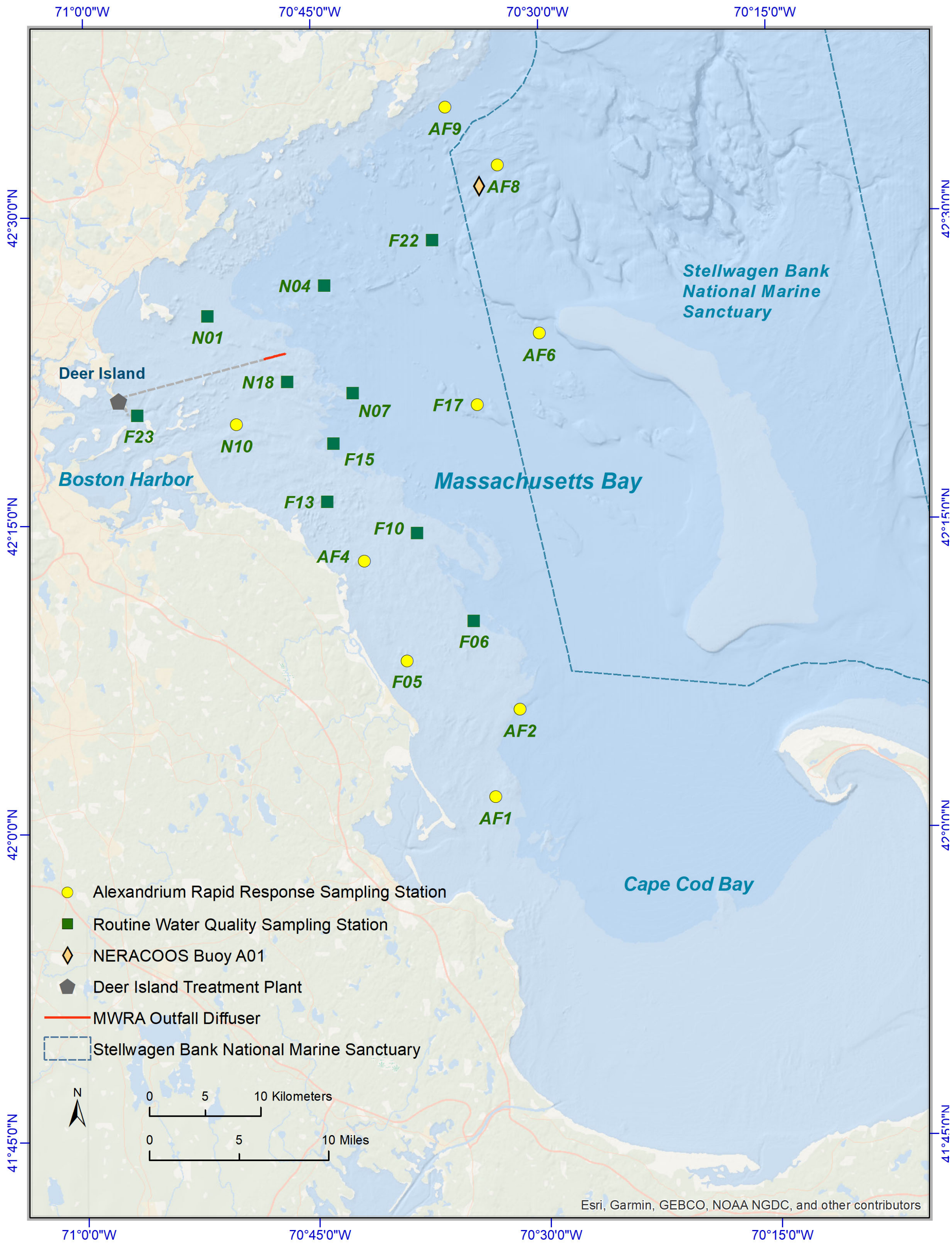

Figure 1-2. ***Alexandrium*** **Rapid Response Study monitoring locations.**

2 2022 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. Each year specific details of the cycle can differ spatially across the bay system and temporally 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. This bloom typically occurs in March or April, but the intensity of the bloom can vary greatly, as can its timing. 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 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 from 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 31-year dataset (1992-2022). The major features and differences observed in 2022 are described below.

2.2 PHYSICAL CONDITIONS

To provide an overview of physical conditions in Massachusetts Bay in 2022, stations N18 and F22 are discussed. These are representative of the nearfield and waters entering Massachusetts Bay from the north, respectively. Surface water temperatures were warm compared to historical levels at station N18 from March to June before decreasing below the long-term minima in late July due to upwelling (**Figure 2-1**). Surface water temperatures increased sharply from late July to late August and remained in the upper quartile of historic levels for the rest of the year. This trend was observed across the bays as similarly high temperatures were seen at station F22 farther offshore in winter/spring, decreasing closer to historic median levels in July before increasing close to maximum levels observed at the station from August to October. Bottom water temperatures were consistently in the upper quartile or above historical maxima at both stations N18 and F22 from February to October 2022 with a slight decrease at station N18 during the July upwelling events. Air temperatures were close to average in 2022 at NERACOOS buoy A01.

Surface salinity was near the long-term median in February and March, decreased in April, and increased in May 2022. Salinity was anomalously high at historic maxima in June and July and remained elevated through September 2022 (**Figure 2-2**). During the summer and fall, both surface and bottom salinity were near or above historical maxima in the nearfield and in the surface waters at station F22. The bottom waters at station F22 remained close to the long-term median over most of the year until reaching a historic maximum in October. In the winter and early spring, Merrimack and Charles River flows were relatively high and consistent with the typical surface salinities observed at stations N18 and F22. However, by May, river flows had decreased sharply and were very low compared to historic levels from June through October (**Figure 2-3**) and low river flow continued to be observed into December. The low river flow in summer and fall 2022 was reflected in surface and bottom salinity in Massachusetts Bay. Warmer, more saline bottom waters such as those observed in summer/fall 2022 have lower DO concentrations and are also associated with longer residence times in the bay which likely contribute to even lower DO concentrations (Geyer et al. 2002).

Wind speeds and directions were typical in early 2022, with several storm systems producing strong northeast winds (known as Nor'easters) during the winter/spring (**Figure 2-4**). 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. In late April and early May, strong northeasterly winds were observed, but, unlike some past years, an *Alexandrium* bloom was not occurring in the Gulf of Maine to be transported into the bay. By late May, upwelling-favorable winds out of the south became more dominant and were persistent over the summer from late June to early August (**Figure 2-4**). There was a large wind/storm event in early October, but the majority of the strong winds that lead to mixing and the fall overturn of the water column were not seen consistently until mid-November.

The impact of the summer wind events was evident in the upwelling index which is the monthly average of the north-south component of wind stress (**Figure 2-5**). A positive index indicates more wind from the south, which favors upwelling and cooling of both surface and bottom waters. The index showed moderate upwelling in June and strong upwelling in July, equal to the strongest that has been observed during the 31-year monitoring program. August showed weak upwelling and switched to net downwelling in September. The weak or negative upwelling index corresponds to the warmer waters observed during the late summer (**Figure 2-1**).

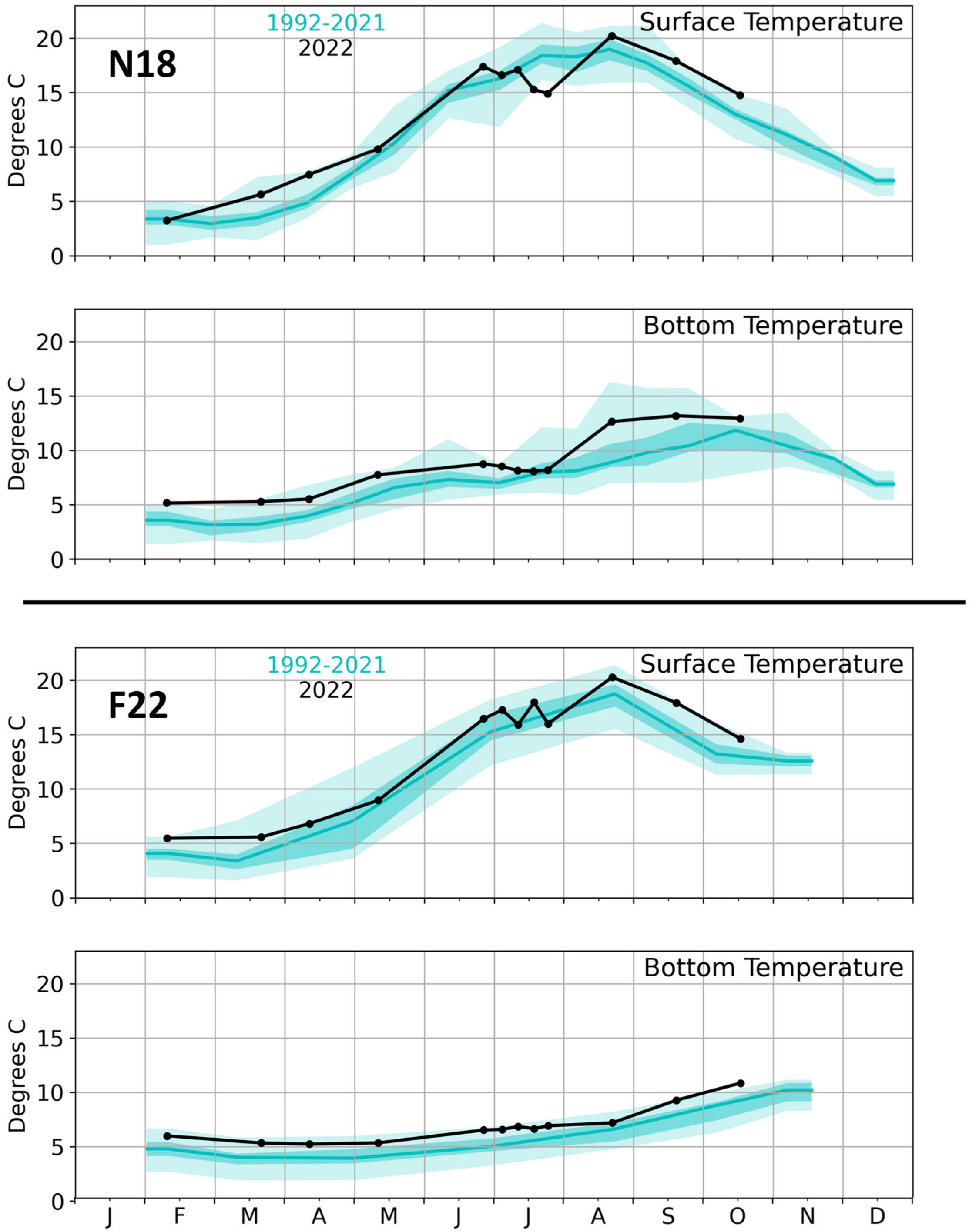

Figure 2-1. Comparison of 2022 surface and near bottom water temperature (°C) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2021 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

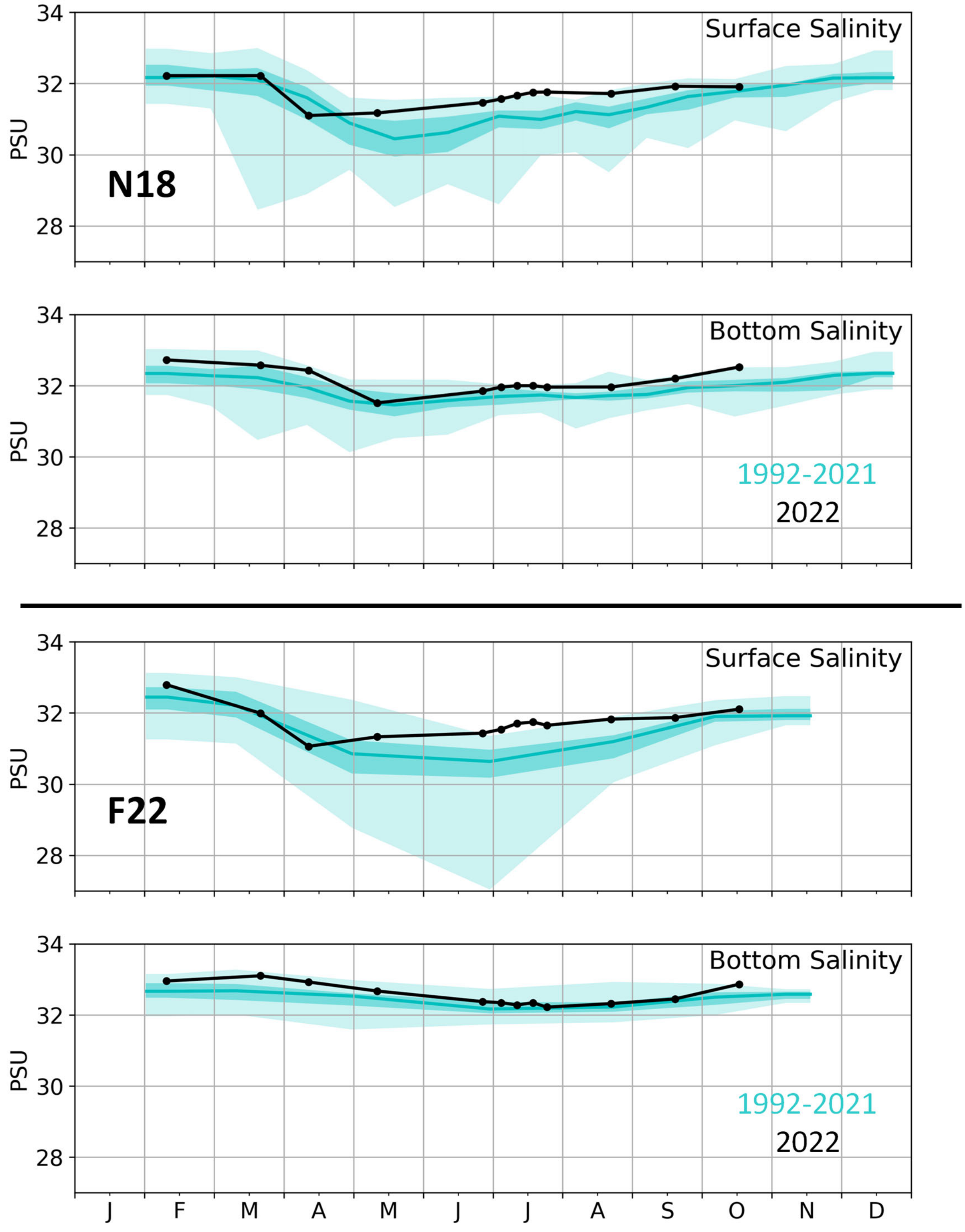

Figure 2-2. Comparison of 2022 surface and near bottom water salinity (PSU) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

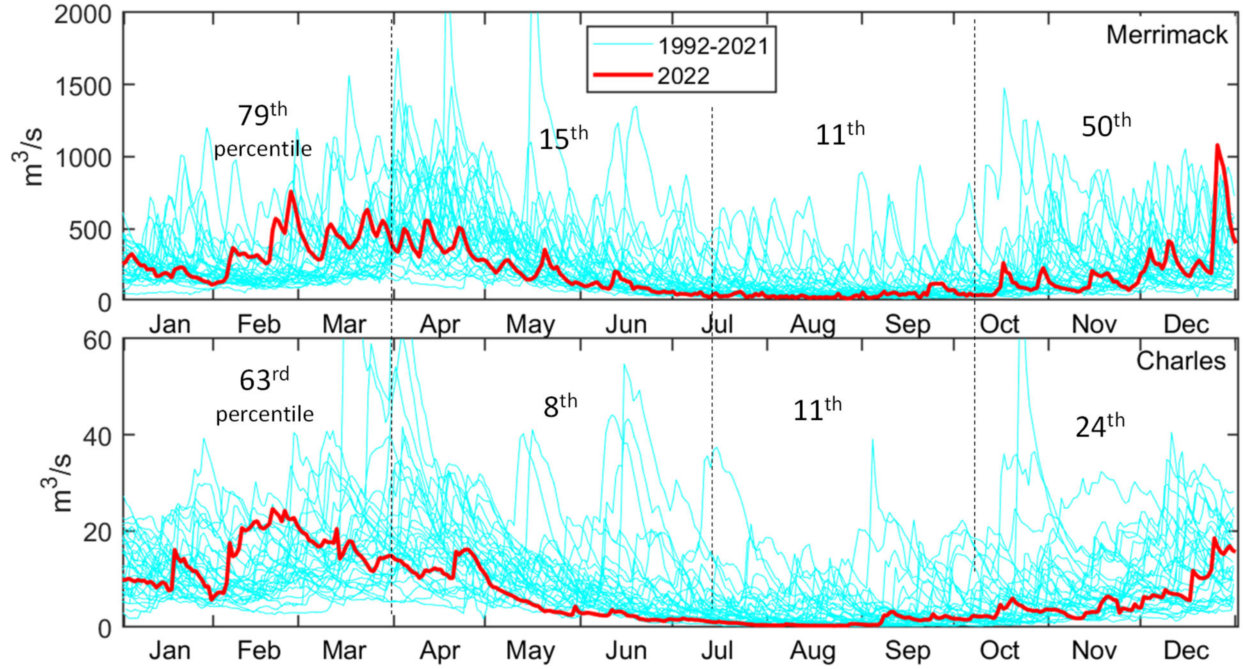

Figure 2-3. Comparison of 2022 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2021 (light blue lines). The percentiles represent 2022 flow, compared to the entire 31-year record, during each quarter of the year.

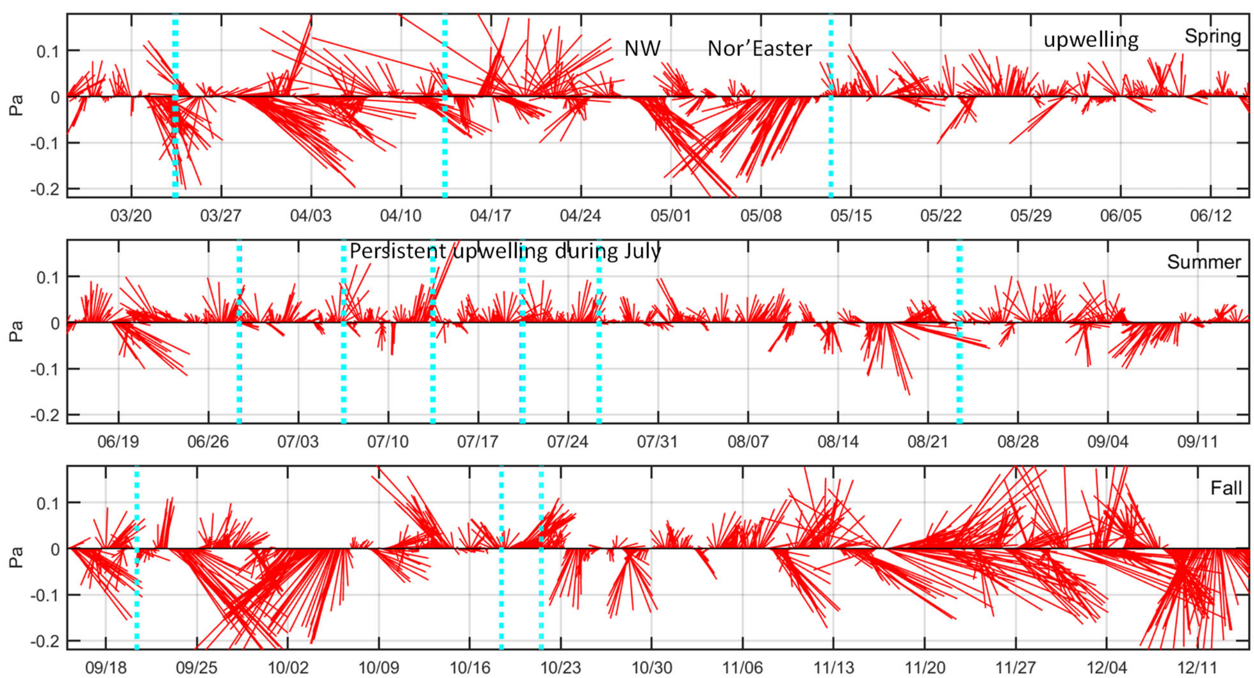

Figure 2-4. NERACOOS Buoy A01 time series observations of surface wind stress (Pa) and direction in 2022. The lines represent wind flow in the direction away from the origin line; northward up and eastward to the right. Vertical blue dotted lines represent survey dates (Note the CCS WN29 survey was delayed until 10/21 due to sea conditions).

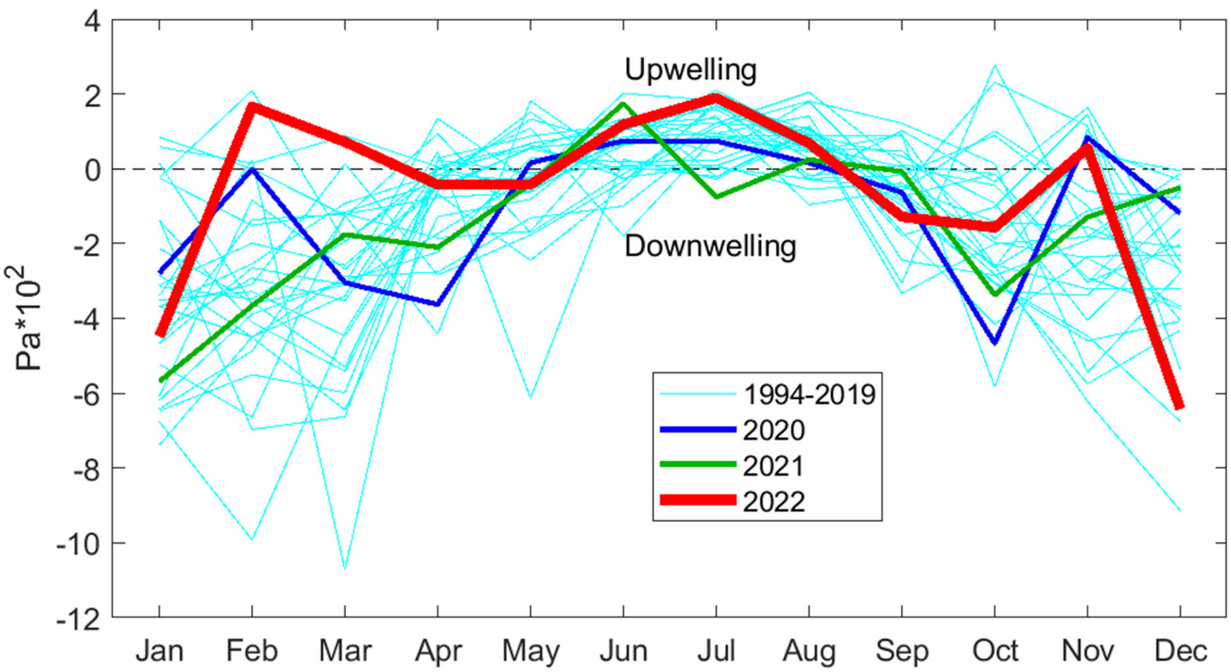

Figure 2-5. Upwelling index (100 x Northward component of wind stress; Pascals) at NOAA Buoy 44013. 2022 results are in red, 2021 in green and 2020 in blue. Results from 1994–2019 in cyan. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

Stratification in Massachusetts Bay was close to the long-term median in February and March, increased sharply in April, and a decrease of similar magnitude was seen in May 2022 (**Figure 2-6**). The April and May changes were especially evident in the nearfield and likely associated with impacts of river flow on surface salinity with lower surface salinity in April and higher in May. By June, stratification was close to the historic median across the bay but decreased in July in association with the upwelling favorable conditions and cooling of the surface waters (see **Figure 2-1**). In August, once upwelling had weakened, stratification increased and remained near historical median until October when stratification was close to or above historical maxima due to the lack of major storms in the fall of 2022. The persistence of stratified conditions into late October was a factor in the low bottom water DO levels observed in 2022. The impact of stratification on bottom water DO concentrations is described in detail in Section 2.4.

The long-term time series of summertime air and water temperature based on the NOAA buoy shows surface waters warming more rapidly than air temperatures (approximately 1 degree Celsius [°C] per decade). However, the long-term trend of increasing summertime water temperatures eased in 2022 due to the presence of cooler waters associated with the persistent late June to early August upwelling-favorable winds (**Figure 2-7**). Interestingly, the summer-average water temperature showed cooler conditions, even though the summer air temperatures were relatively high.

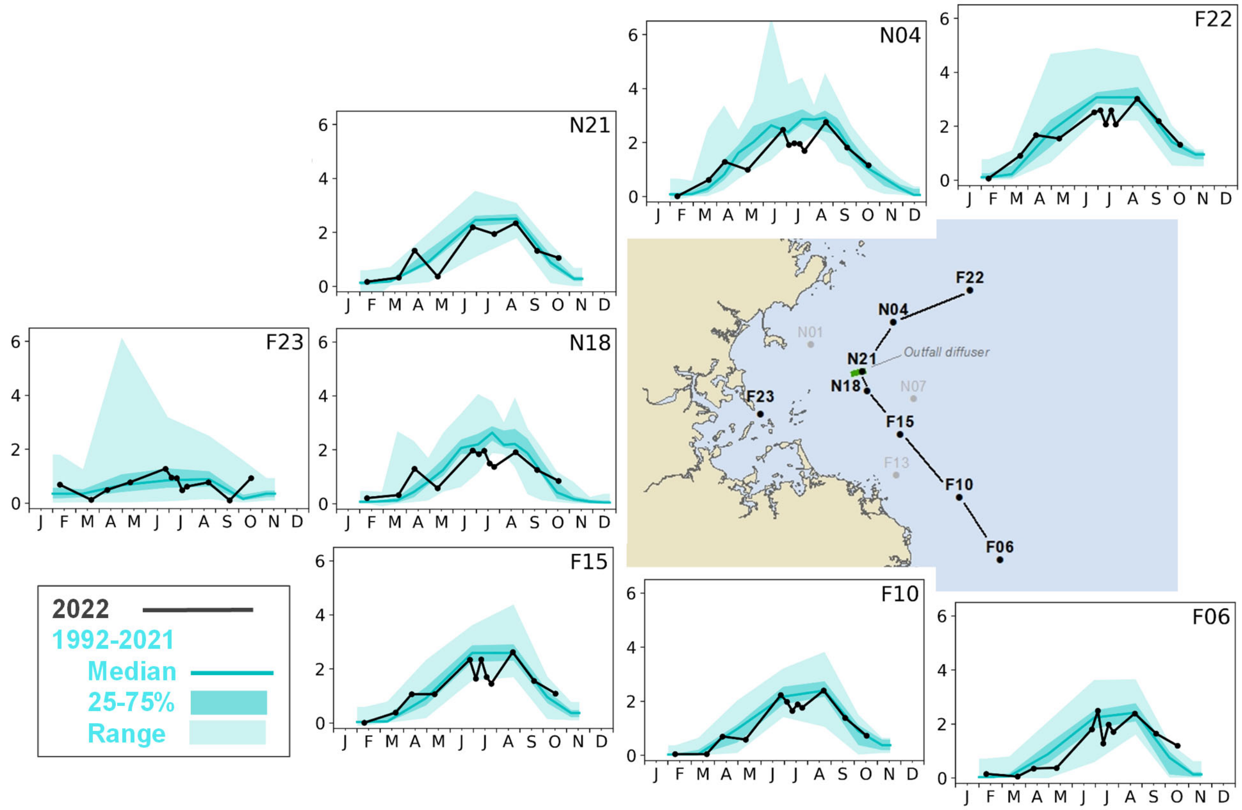

Figure 2-6. Stratification (Δ sigma-t; kg m^{-3}) at selected stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

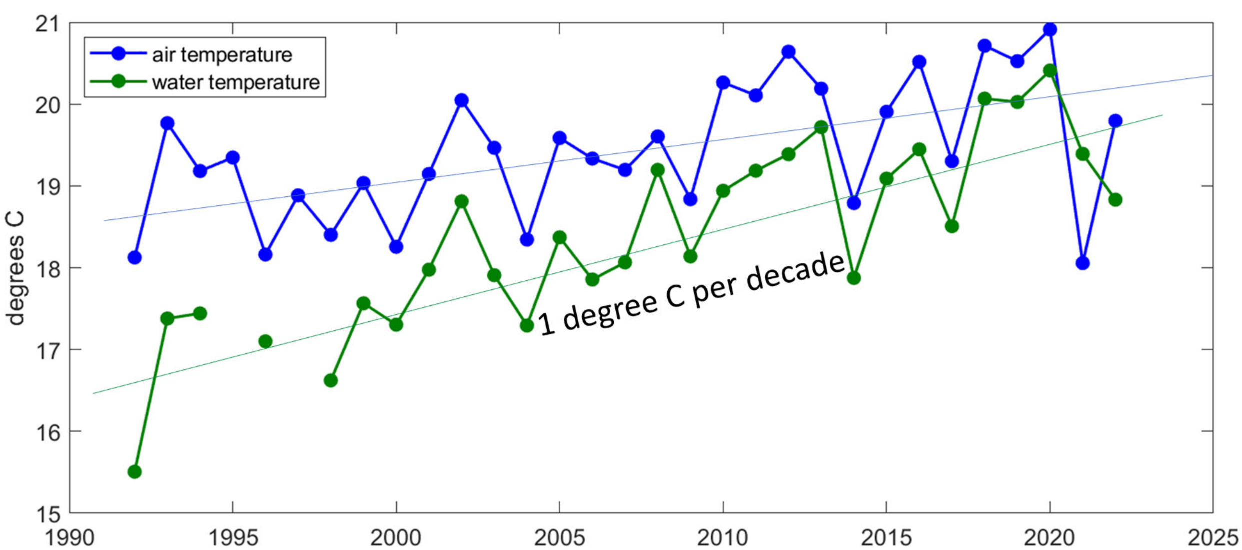

Figure 2-7. Comparison of average mid-June to mid-August air and surface water temperature (°C) at Buoy 44013 in Massachusetts Bay from 1992-2022. Missing segments of the water temperature line represent gaps in the record.

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

This section documents dissolved inorganic nutrient concentrations and phytoplankton biomass in the bay during 2022. 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 2022 with some interesting departures from the trends which are discussed below (**Figure 2-8**). Ammonium (NH_4) (**Figure 2-8**, upper right) does not exhibit this seasonal pattern in the bay, and was quite variable in 2022 with a maximum well above the historical range in late July (**Figure 2-8**, upper right).

Nutrient concentrations were relatively low in February 2022. Nitrate concentrations were in the lower quartile or below the historical minima and SiO_4 levels were nearly depleted and the lowest observed historically (**Figure 2-8**). Ammonium and phosphate concentrations at station N18 were higher in February and typically exhibited an outfall effluent signal of elevated concentrations over most of the year. Silicate concentrations remained very low in March with decreases in the other nutrients from February to March consistent with the large winter/spring diatom bloom observed. Chlorophyll levels peaked at most stations in Massachusetts Bay during the March survey with concentrations into the upper quartile nearshore with especially high levels observed along the South Shore reaching historical maxima (see **Figure 2-16**).

From March to April, NO_3 concentrations continued to decrease at station N18 and throughout Massachusetts Bay (**Figure 2-9**) while SiO_4 increased to levels approaching the historical median. This change and the ratio of nitrogen to silica observed over this period is consistent with the presence of *Phaeocystis* though the chlorophyll levels during the April survey were relatively low as were the *Phaeocystis* abundances. Nutrient concentrations increased from April to May with NO_3 concentrations close to the historical median and SiO_4 levels at or above the median (**Figure 2-8**). Although the increase in chlorophyll levels from April to May was minor, there was a large dinoflagellate bloom observed in May. MODIS imagery and NERACOOS Buoy A01 fluorescence data are often useful in filling the information gaps between surveys. High chlorophyll levels were seen in these remote sensing data prior to and after the March survey consistent with the winter/spring diatom that was observed (see **Figures 2-17** and **2-18**, respectively). The elevated chlorophyll fluorescence at the buoy increased and continued into early April but had decreased by mid-April which could be associated with a possible *Phaeocystis* bloom suggested by the change in nitrogen and silica ratio. Elevated fluorescence levels were also seen in late April and early May.

Survey mean nutrient levels remained close to the historical median from May through most of July before increasing slightly in late July in association with prolonged period of upwelling favorable winds (**Figure 2-8** and **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 (see **Figure 2-12** and **Figure 2-13**). The impact of upwelling on nutrient availability is suggested by the shallowing of the nitracline, where nitrate concentrations increase above the depleted surface layer, at N18 in late June and July. Station mean nutrient concentrations varied over the summer but were typically close to the historical median. A sharp increase in all nutrient concentrations was observed at station N18 during the late July survey suggesting a combined influence of both upwelled and effluent derived nutrients (**Figure 2-8**). Overall, there was considerable variability in NH_4 and PO_4 levels, which both peaked at station N18 in late July. Ammonium concentrations have been more variable over the course of the summer in the nearfield since the bay outfall came online in 2000, as expected (**Figure 2-10**).

There was a sharp decline in nutrient concentrations from late July to late August, NO_3 was nearly depleted at the shallow, inshore stations and close to historical minima while slightly higher concentrations were seen at the deeper offshore stations near historical median levels (**Figure 2-9**). Nitrate levels increased slightly in September and October, while SiO_4 levels remained low consistent with the fall diatom bloom observed across Massachusetts Bay.

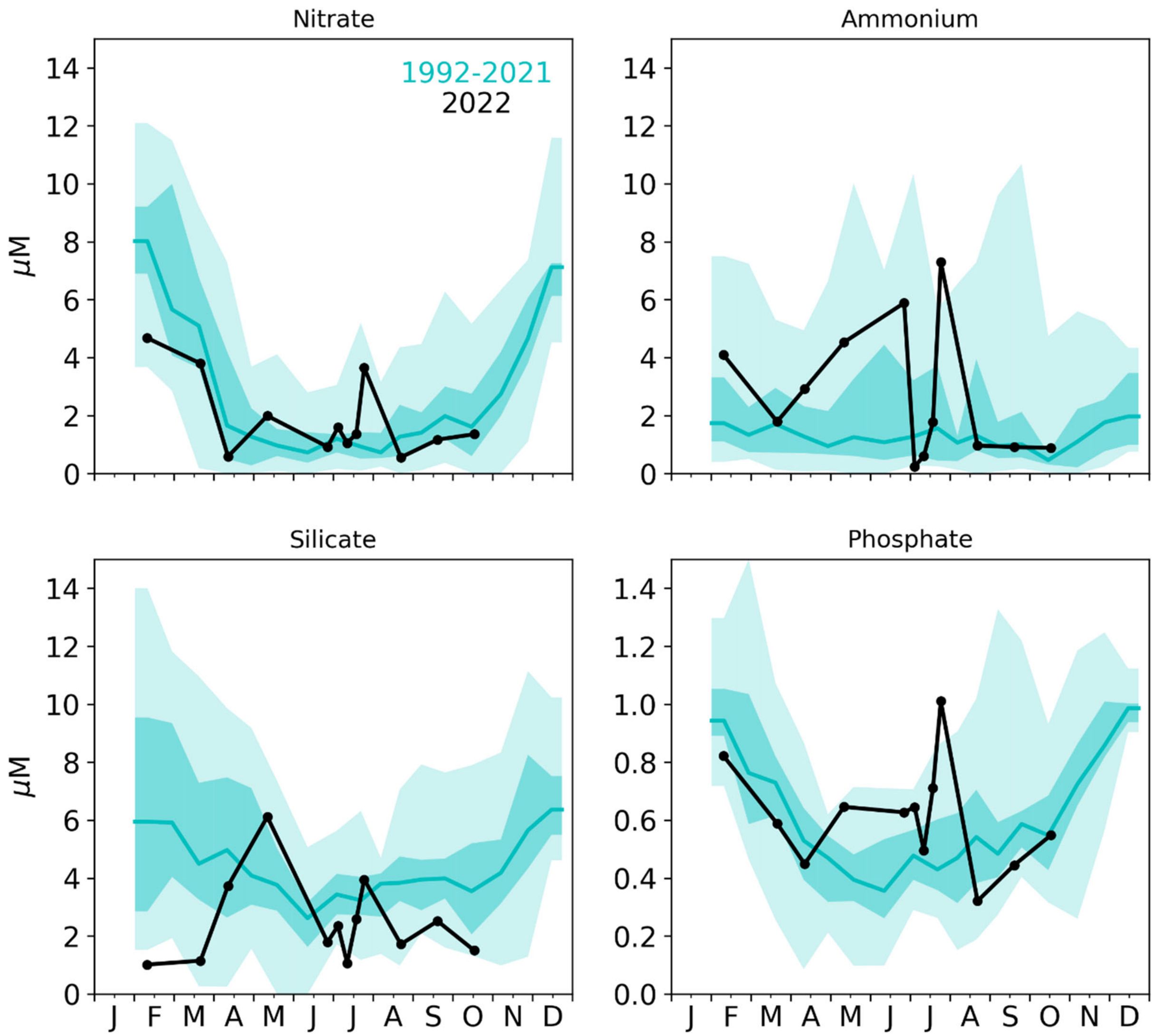

Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2022 compared to prior years. Note difference in scale for phosphate. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

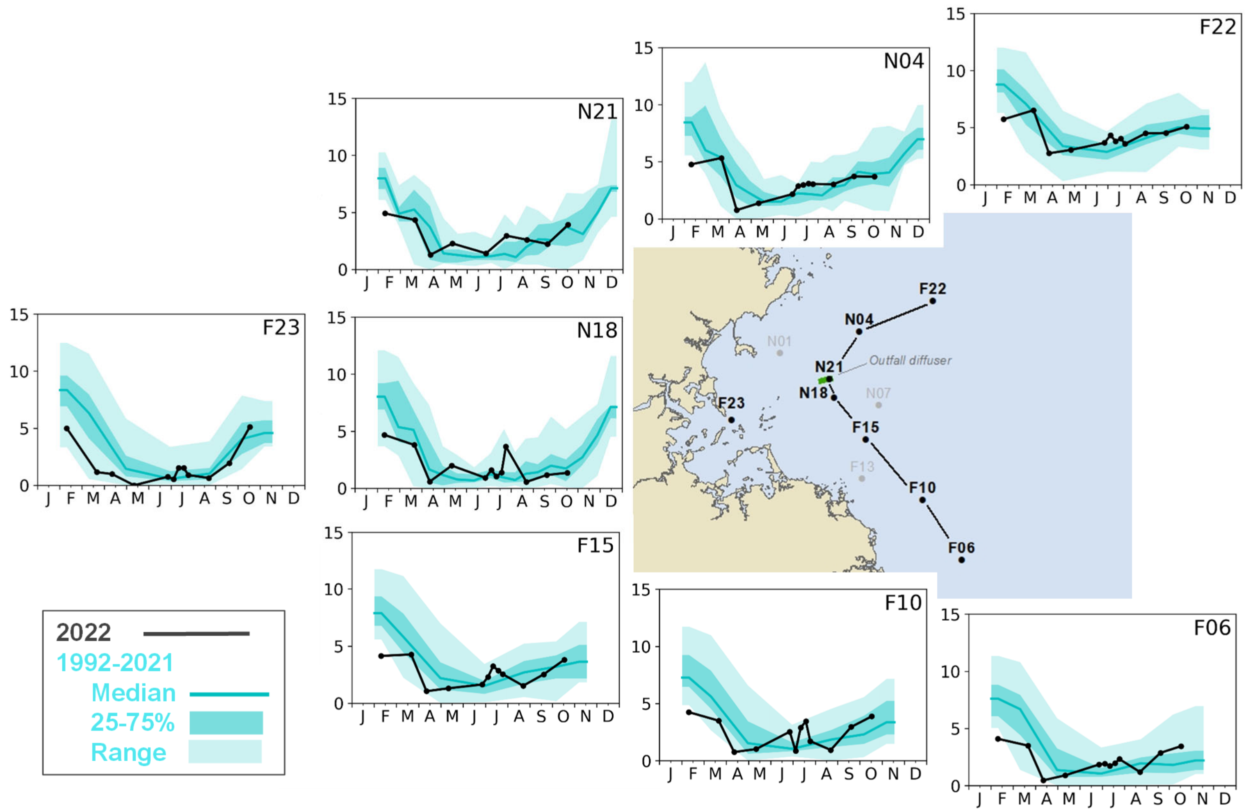

Figure 2-9. Depth-averaged nitrate (µM) at selected stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

As in other years since bay outfall startup, NH_4 concentrations at stations N21 and N18 were higher than during years effluent was discharged to Boston Harbor (**Figure 2-10**). Ammonium concentrations were quite variable at stations N18 and N21 in 2022. This is highlighted at station N21 with NH_4 concentrations in the upper quartile or higher for most of the year and then dropping to the lower range of values in July. This drop in NH_4 concentrations at station N21 coincided with a large increase to the maximum concentration observed at station N18 for the year. Such large differences in NH_4 concentrations between these two stations and the survey-to-survey variability observed is due to the location of the effluent plume during sampling and where the samples were collected along the mixing zones associated with the plume. Elevated NH_4 concentrations were also observed in June at stations F15 and F10 and even as far south at station F06 nearly 30 km south of the outfall (**Figure 2-10**). These NH_4 concentrations at southern stations were above historical medians but within historical maxima and are not observed consistently year to year. A record high NH_4 concentration for the 31-year monitoring program of ~5 micromolar (µM) was observed at station N04 in late August which highlights the variability in the location of the effluent plume due to prevailing currents. Ammonium concentrations at Boston Harbor station F23 in 2022, again as in other post-discharge years, were much lower than during the years the wastewater was discharged directly to the harbor.

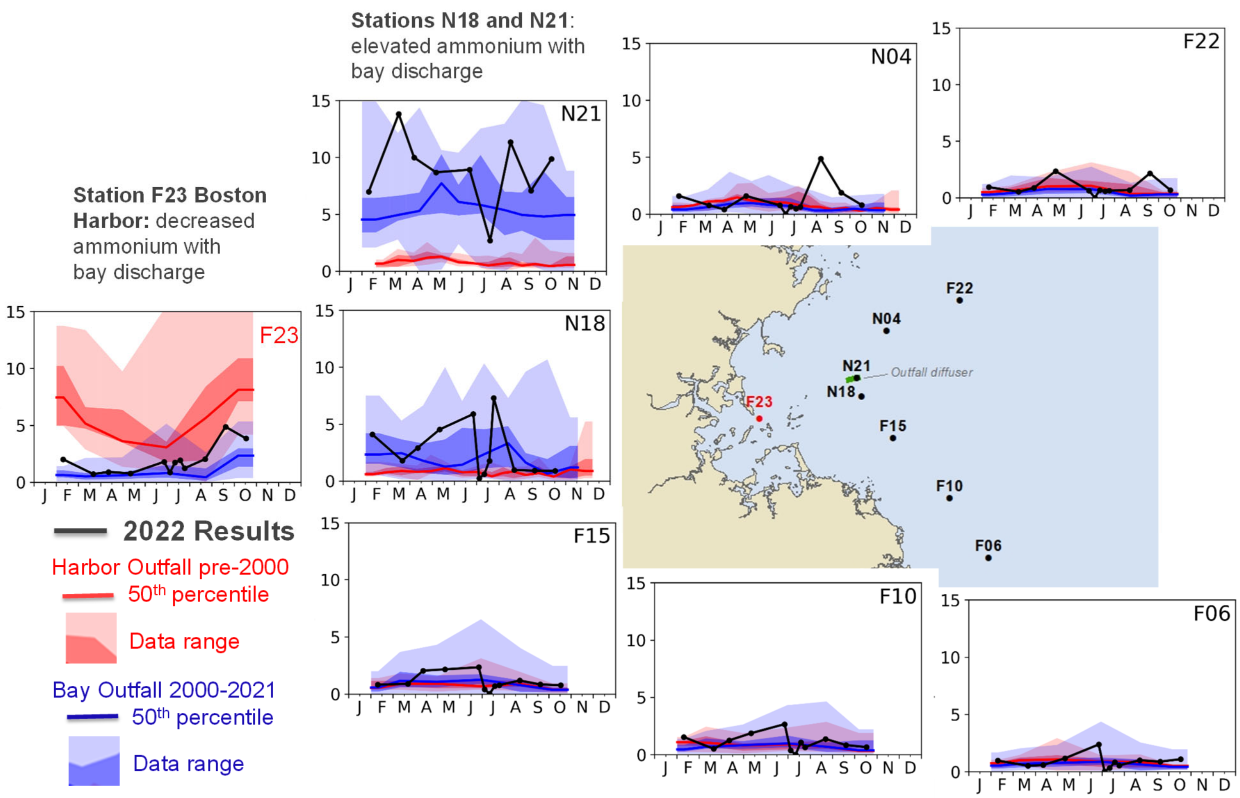

Figure 2-10. Depth-averaged ammonium (NH_4) (µM) at selected stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2021) results are in blue. For baseline and post-diversion: line is 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**, increases in NH_4 above background conditions were observed in late June 2022 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 and at stations N21 and N18 (**Figure 2-11**). During the June and July surveys, 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. In June, elevated NH_4 concentrations >4 µM were also observed in the bottom waters at stations 10 to 30 km south of the outfall (**Figure 2-12**). However, in July, the high NH_4 concentrations associated with the effluent plume were confined to the nearfield stations N18 and N21 highlighting the influence of prevailing currents on the distribution of the NH_4 associated with the plume. It should be noted that 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 in June (**Figure 2-14**). In July, upwelling favorable conditions led to a combination of both elevated NH_4 (effluent plume) and NO_3 (ambient bottom water) concentrations at the pycnocline in the nearfield. This nutrient availability likely contributed to phytoplankton growth as demonstrated by elevated sub-surface chlorophyll maximum concentrations (**Figure 2-14**).

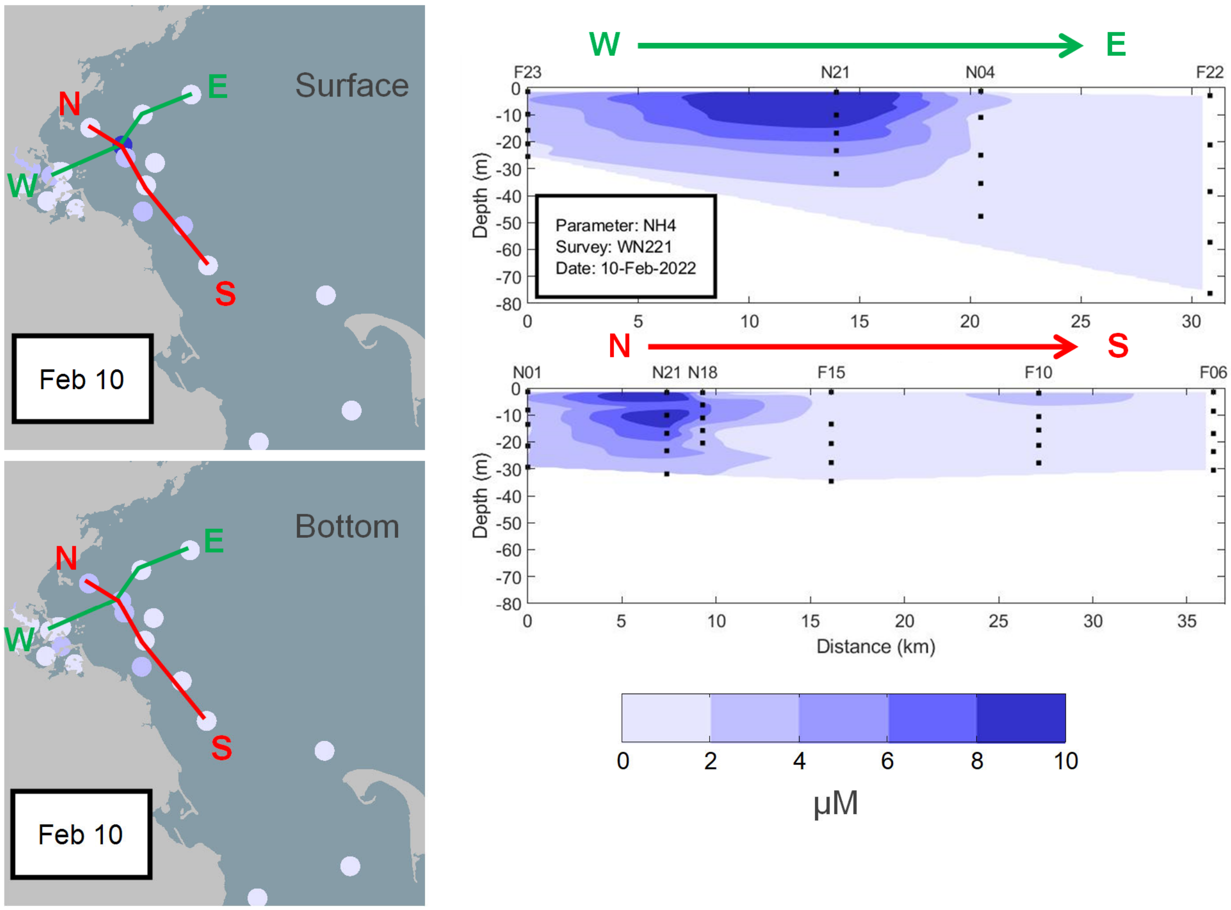

Figure 2-11. (Left) Surface and bottom water ammonium (NH_4) on February 10, 2022 during unstratified conditions. (Right) Cross-sections of water column concentrations along transects connecting selected stations. Small black dots in the plots at right indicate the sampling depths for nutrients.

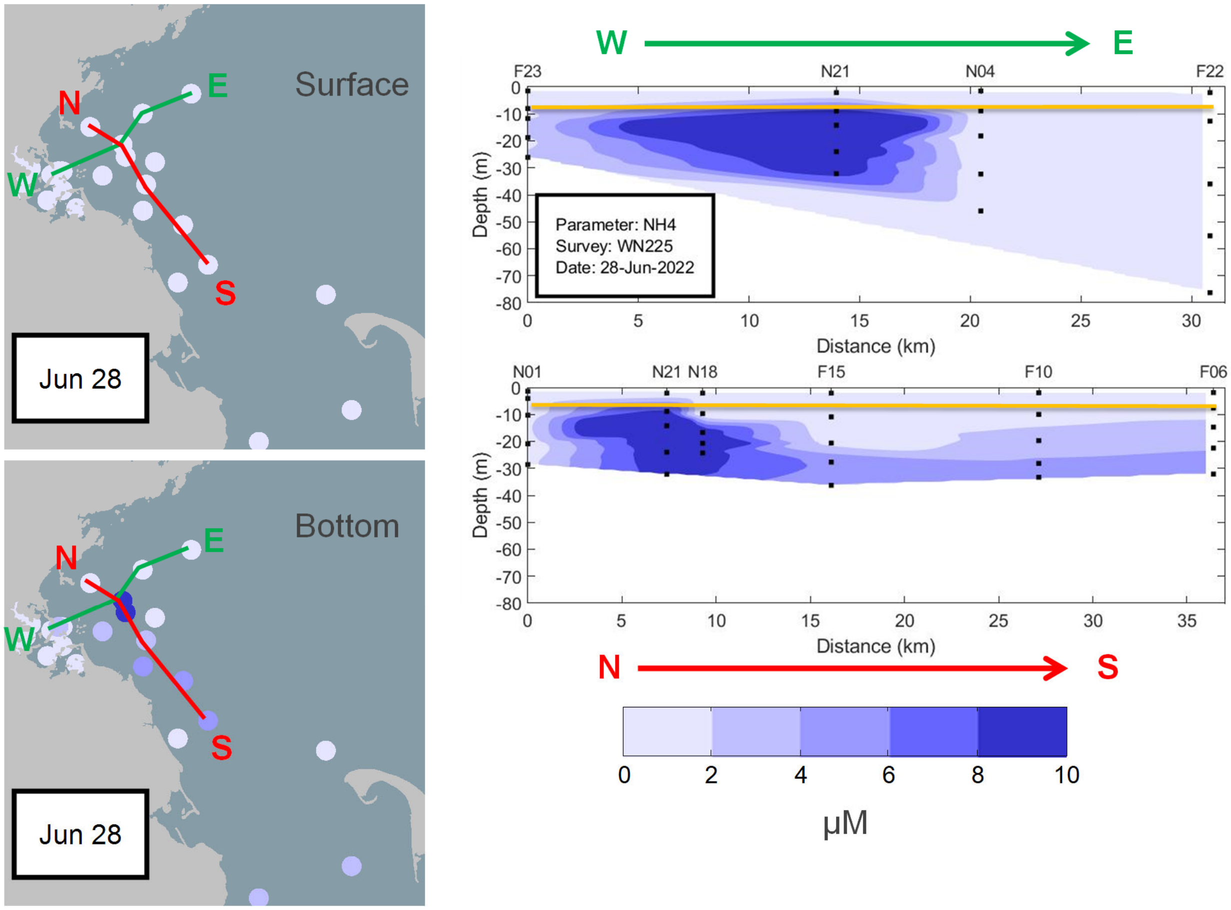

Figure 2-12. Surface and bottom water ammonium (NH_4) on June 28, 2022 during stratified conditions. Presented as Figure 2-11, with orange line in frames at right indicating the approximate depth of the pycnocline.

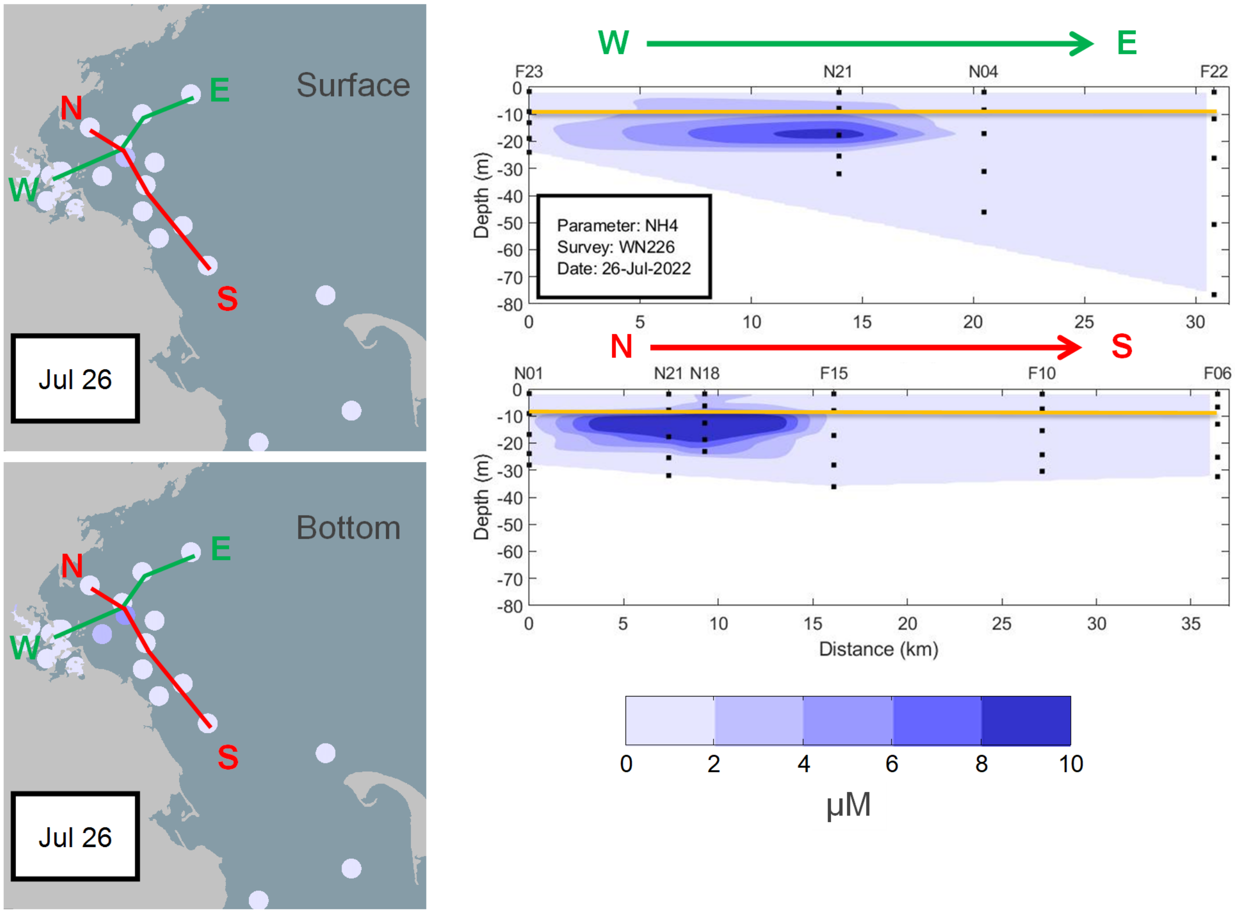

Figure 2-13. Surface and bottom water ammonium (NH_4) on July 26, 2022 during stratified conditions. Presented as Figure 2-11, with orange line in frames at right indicating the approximate depth of the pycnocline.

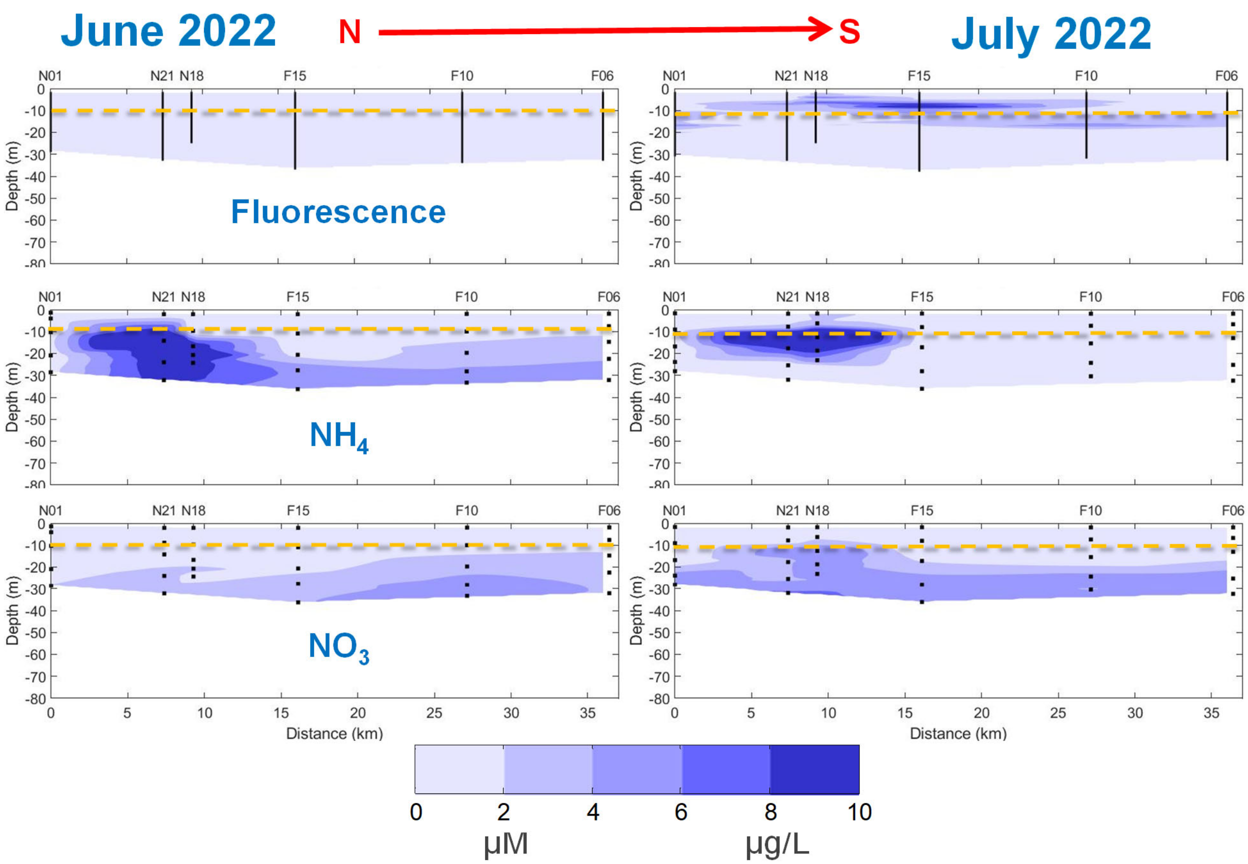

Figure 2-14. Chlorophyll from fluorescence (top; µg L^{-1}), ammonium (middle; µM), and nitrate (bottom; µM) during the stratified June (left) and July (right) 2022 survey along the north-south transects shown in Figure 2-12 and Figure 2-13. Dots (nutrients) and lines (fluorescence) indicate the sampling 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 2-15**. These seasonal peaks were observed again during the 2022 surveys with a large peak in March associated with the winter/spring diatom bloom and a smaller peak in October in conjunction with the fall diatom bloom. High areal chlorophyll was observed from March to June and October in Cape Cod Bay and during the March and October surveys in Massachusetts Bay (**Figure 2-16**). Overall, seasonal and annual average chlorophyll values in 2022 were relatively low, comparable to baseline seasonal averages in summer and fall and less than half the Contingency Plan threshold levels (**Table i**). The 2022 winter/spring seasonal nearfield mean of 66 milligram (mg) m^{-2} was higher than the baseline average of 50 mg m^{-2}.

MODIS imagery showed moderate chlorophyll in January and lower levels in mid-February to early March 2022 (**Figure 2-17)** consistent with the concentrations observed at the offshore Massachusetts Bay and the Cape Cod stations during the first survey (**Figure 2-16**). Preliminary data from Buoy A01 showed low chlorophyll fluorescence in the surface waters from January until late March (**Figure 2-18**). By late March, chlorophyll levels increased in both MODIS imagery and Buoy A01 data.

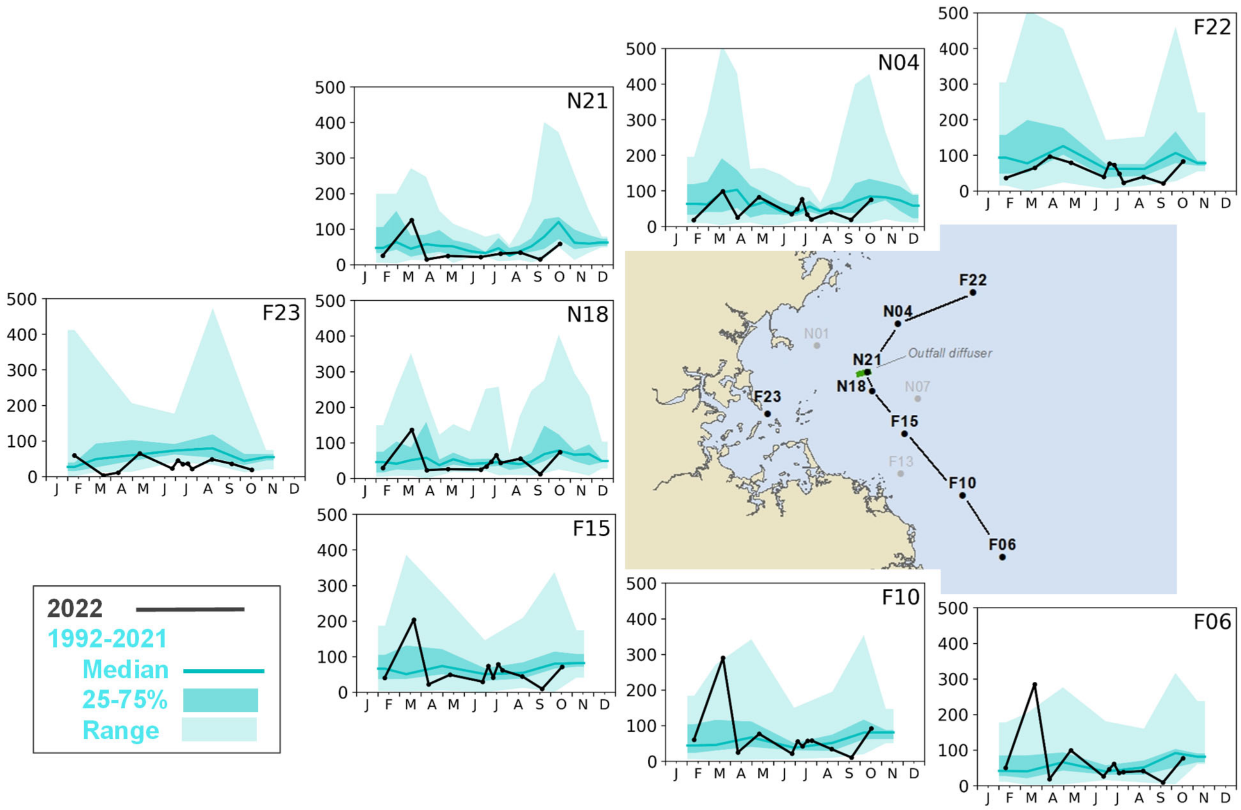

Figure 2-15. Areal chlorophyll from fluorescence (milligram per meter squared [mg m^{-2}]) at representative stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

High chlorophyll was also observed during the late March survey at most stations in Massachusetts Bay with concentrations into the upper quartile nearshore with especially high levels observed along the South Shore reaching historical maxima (**Figure 2-15**). MODIS imagery and Buoy A01 fluorescence data are often useful in filling the information gaps between surveys. High chlorophyll levels were seen in these remote sensing data prior to and after the March survey consistent with the winter/spring diatom that was observed (**Figure 2-17** and **Figure 2-18**). Chlorophyll fluorescence at the buoy increased and continued into early April which could be associated with a possible *Phaeocystis* bloom suggested by the change in nitrogen and silica ratio observed from the March to April surveys. April and May survey measurements of chlorophyll were quite low in Massachusetts Bay with higher concentrations observed in Cape Cod Bay (**Figure 2-16**). MODIS imagery and buoy observations suggest an increase in chlorophyll between these two surveys in Massachusetts Bay with even higher concentrations in Cape Cod Bay.

Chlorophyll remained low in Massachusetts Bay in June with higher concentrations observed in Cape Cod Bay (**Figure 2-16**). Areal chlorophyll remained close to the long-term median over the course of the four surveys conducted in July, but there was a slight increase from late June into July at most stations (**Figure 2-15**). This corresponds to elevated nutrients and cooler waters during this period of persistent upwelling favorable conditions observed. By late August and early September, chlorophyll throughout Boston Harbor and Massachusetts Bay had decreased below the historic median with September levels approaching historic minima at many stations. There was an increase in chlorophyll levels in October coincident with a fall diatom bloom in the bays. Boston Harbor chlorophyll levels were low for most of 2022 with survey minima observed during most of the surveys.

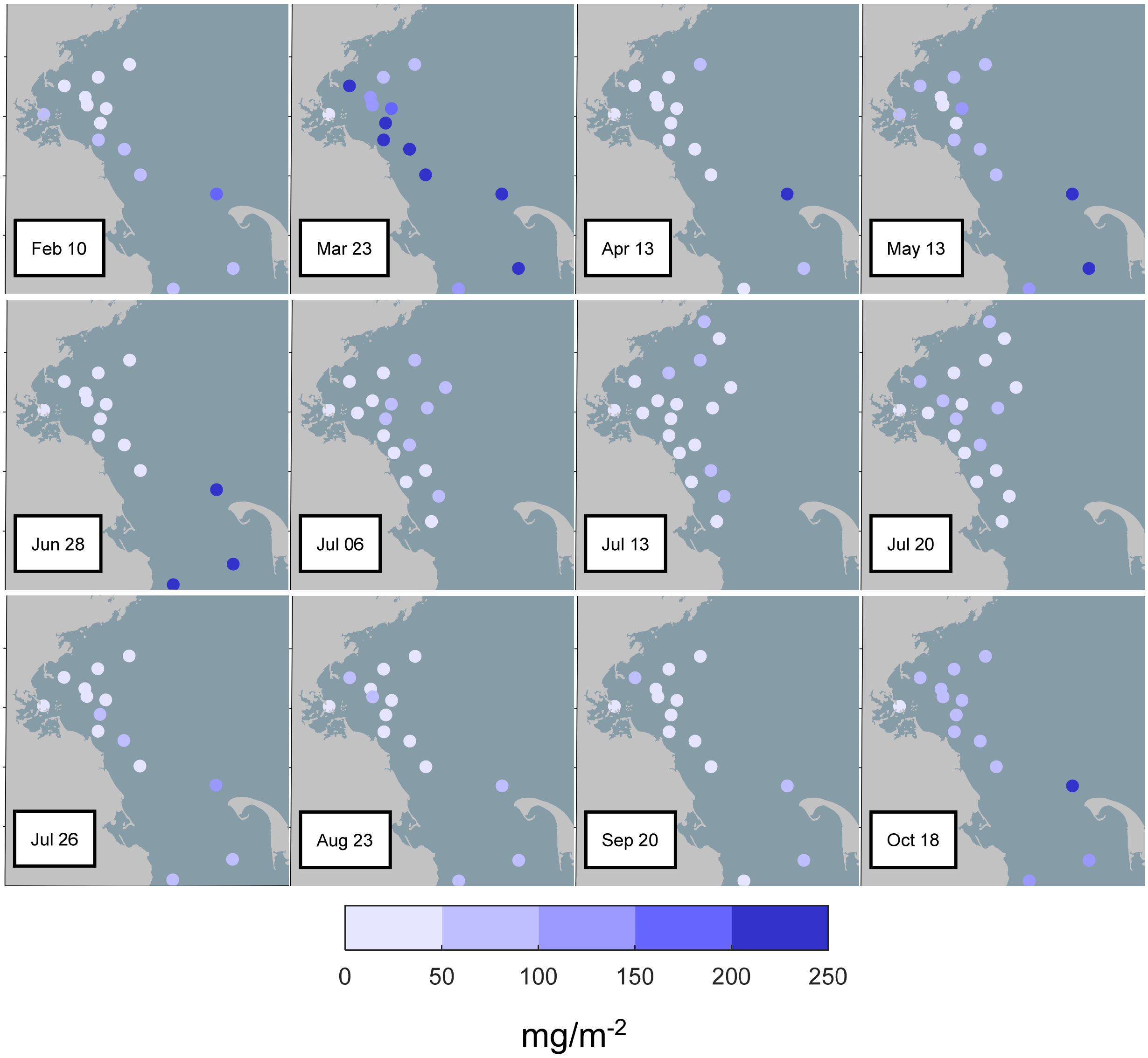

Figure 2-16. Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2022.

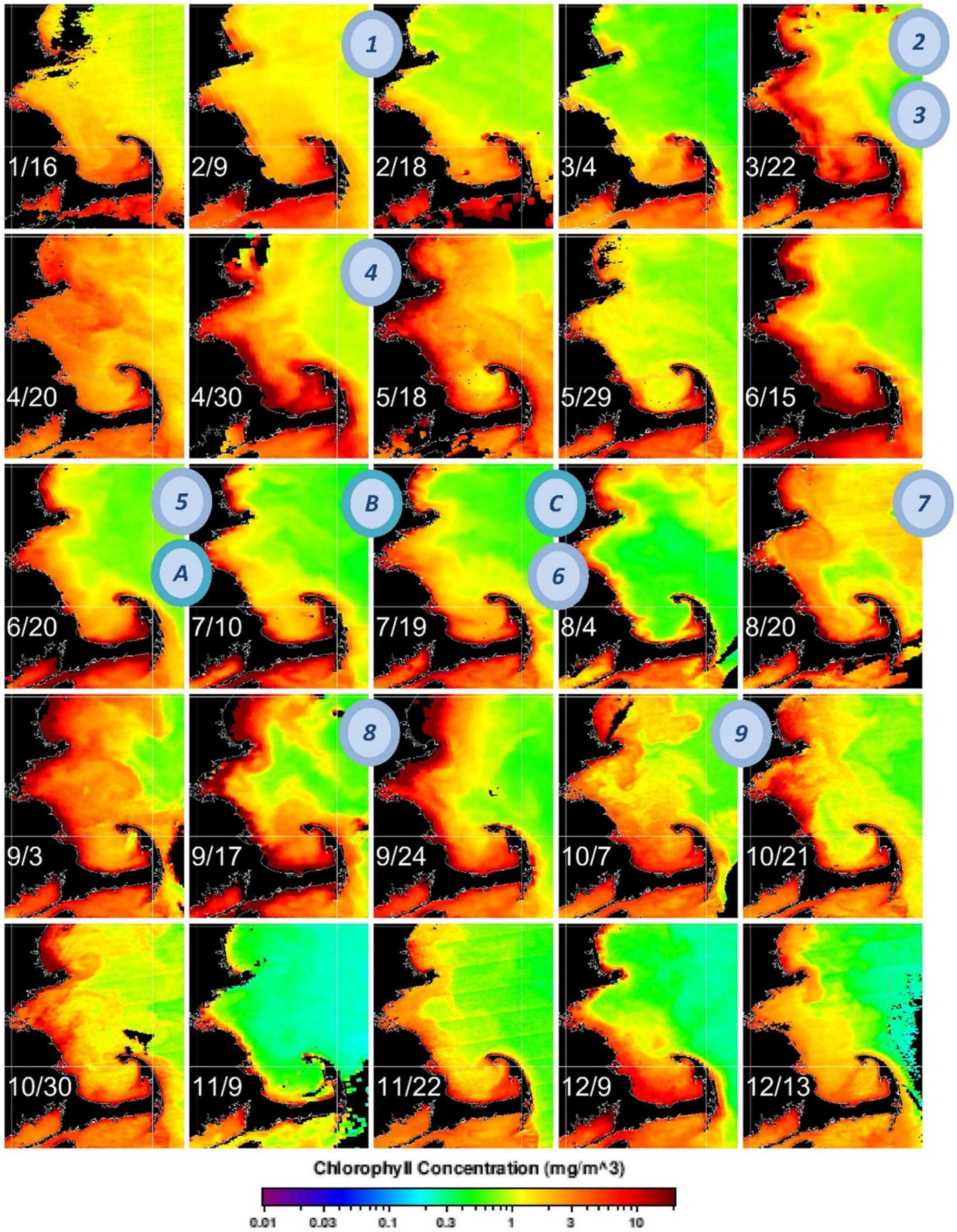

Figure 2-17. Satellite (MODIS) imagery-based estimates of surface chlorophyll concentrations (mg m^{-3}) in 2022. Black areas over water indicate missing data due to clouds.

Highlights and specific blooms:

1st row – moderate chlorophyll in January through early February, lower mid-February and early March, increasing by mid-March and into April (consistent with winter/Spring diatom bloom);

2nd row –apparent 'bloom' in May – no *Phaeocystis* bloom observed, but high abundance of dinoflagellates then decrease in late May and June;

3rd row – remained relatively low from June through August with higher levels near shore – limited MODIS imagery available over this period which corresponded to the *Alexandrium* bloom rapid response surveys;

4th row –levels increased early September and remained elevated through end of October with a fall diatom bloom; and

5th row – chlorophyll remained elevated in late October, decreased in November, and increasing in December.

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) and letters represent the three ARRS surveys.

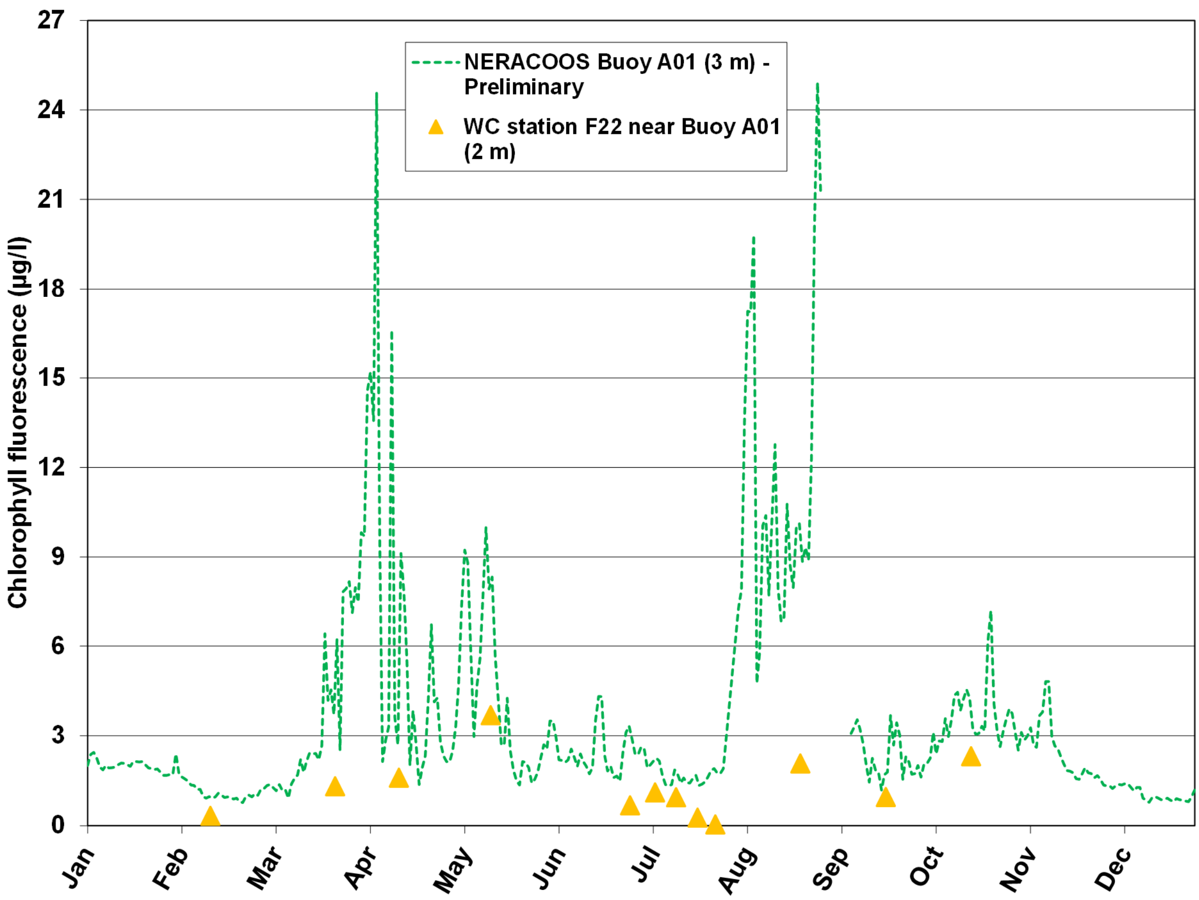

Figure 2-18. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (dashed green line) and water samples at nearby water column (WC) station F22 (yellow symbols) in 2022.

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. In 2022, the lack of strong summer storms or mixing events led to a steady decline in bottom water DO levels from March to September/October (**Figure 2-19** and **Figure 2-20**). The 2022 rate of DO depletion in the nearfield did not exceed the Contingency Plan threshold of 0.037 mg L^{-1} d^{-1} (**Table i**), but at 0.027 mg L^{-1} d^{-1} it is the highest rate observed since 1998 and resulted in low DO levels in Massachusetts and Cape Cod Bays in 2022.

The spring and summer of 2022 was very dry with low river flows leading to consistently high salinities (see **Figure 2-2** and **Figure 2-3**). Surface and bottom water temperatures, though cool in July due to upwelling, were some of the warmest observed in August and September (**Figure 2-1**) and there were no large mixing events or storms. All of these conditions are conducive to achieving low bottom water DO concentrations in the late summer to fall and resulted in Contingency Plan exceedances for both the nearfield and Stellwagen Basin in 2022 (**Table i**).

The steady decline in bottom water DO from March to September/October 2022 was observed across the monitoring area and at NERACOOS Buoy A01 (**Figure 2-19** and **Figure 2-21**). DO minima of ~6 mg per liter (L^{-1}) were reached in September at the shallower stations and in October at the deeper, offshore stations in Massachusetts Bay. In deeper waters, DO levels continued to decline into November. At NERACOOS Buoy A01, the water column had mixed down to 20-m depth by late September, however, it remained stratified down to 50-m depth until late November with DO levels reaching a minimum of ~5.5 mg L^{-1} (**Figure 2-21**). Very low DO levels were also observed at stations in Cape Cod Bay with a minimum of <3 mgL^{-1} in early September 2022 well below the historical minima (**Figure 2-22**). This is the lowest DO observed during the 1992-2022 monitoring program.

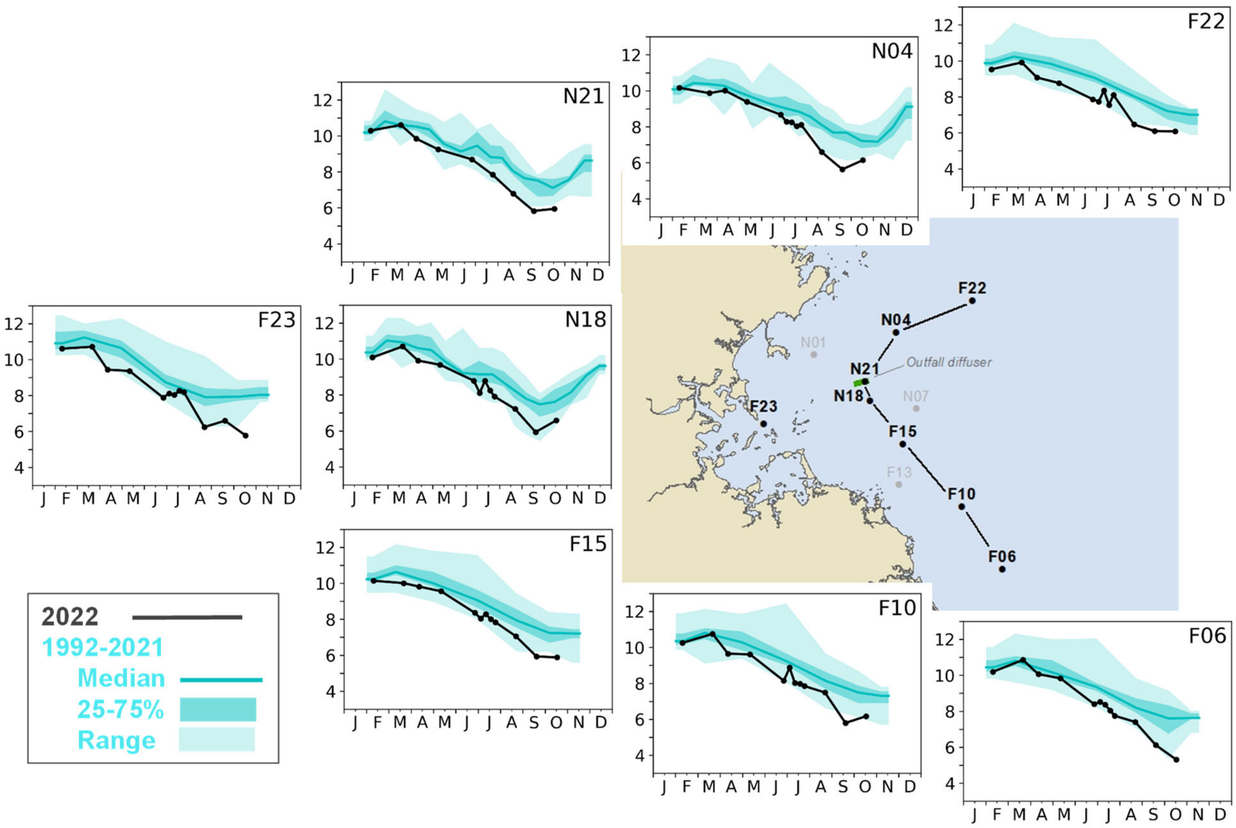

Figure 2-19. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

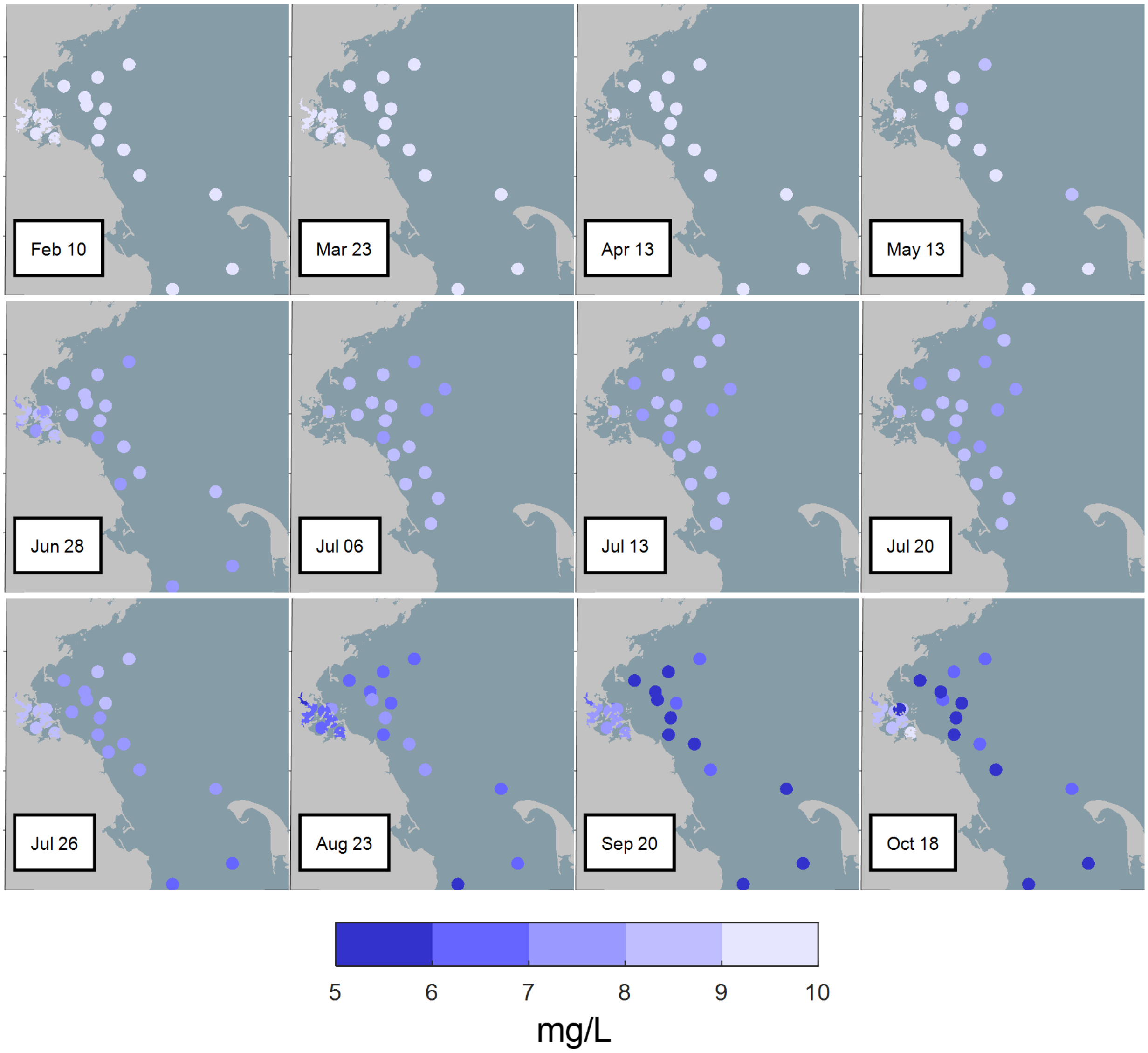

Figure 2-20. Bottom water dissolved oxygen concentration (mg L^{-1}) by station in Boston Harbor, Massachusetts Bay, and Cape Cod Bay in 2022.

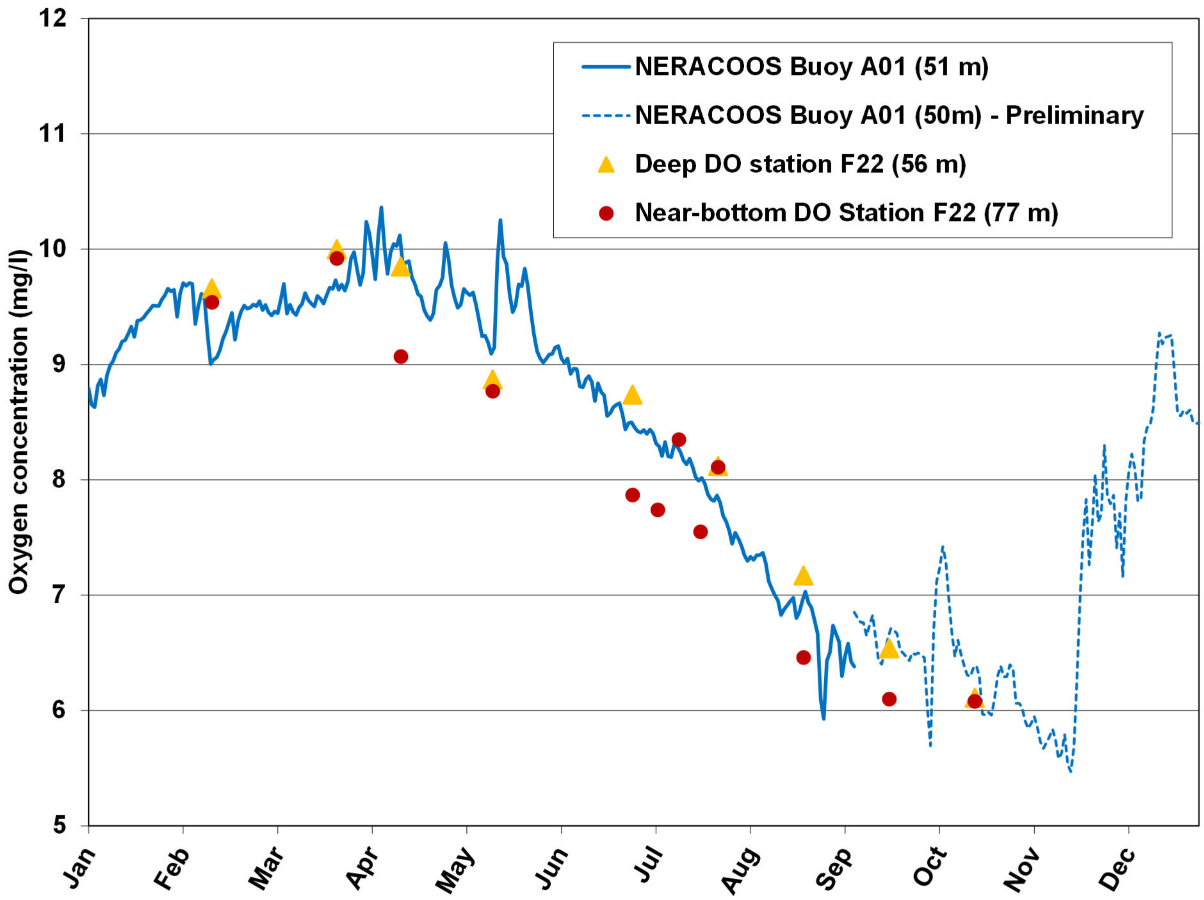

Figure 2-21. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (51 m) and at the deep and near bottom sampling depths (~56 and ~77 m) at station F22 in 2022. The buoy values are daily means.

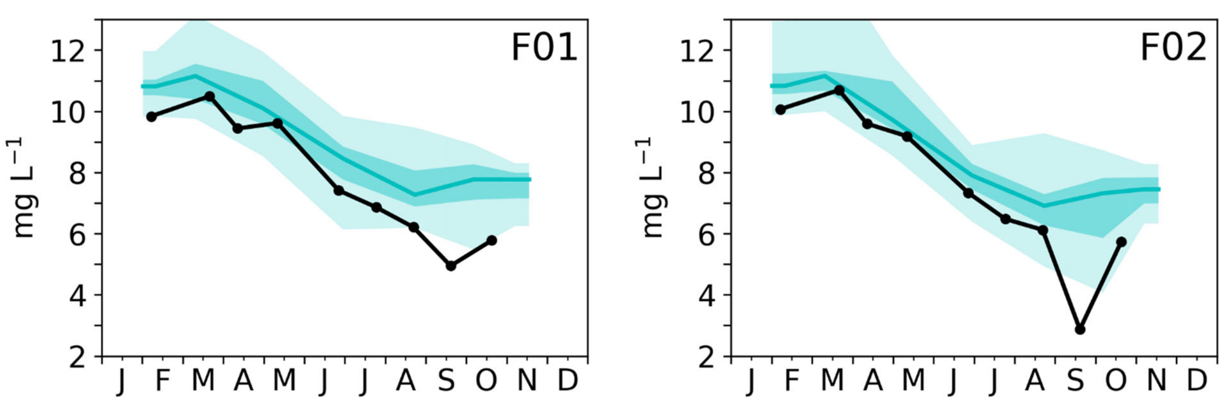

Figure 2-22. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2020 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.5 PHYTOPLANKTON ABUNDANCE

Overall, total phytoplankton measured in 2022 was mostly at or above long-term levels (**Figure 2-23**). This was primarily driven by a *Skeletonema* spp. and *Pseudo-nitzschia* spp. bloom in March 2022 (elevated during both February and March in Boston Harbor), a *Prorocentrum* bloom in May 2022, and a mixed centric diatom bloom during October 2022. Total phytoplankton levels at station N18 averaged 1,127,147 cell L^{-1} during 2022 compared to levels of 710,602 cells L^{-1} observed during the previous three years (2019-2021). This represents a 1.6-fold and significant increase and resulted in 2022 nearfield total phytoplankton being the 18th ranked in abundance of 31 years monitored (**Table 2-1**). Elevated 2022 total phytoplankton abundance is evident as an uptick in the long-term deseasonalized trend, with total phytoplankton abundance recently trending upward during 2021-2022 after over a decade of declines and low levels (**Figure 2-24**).

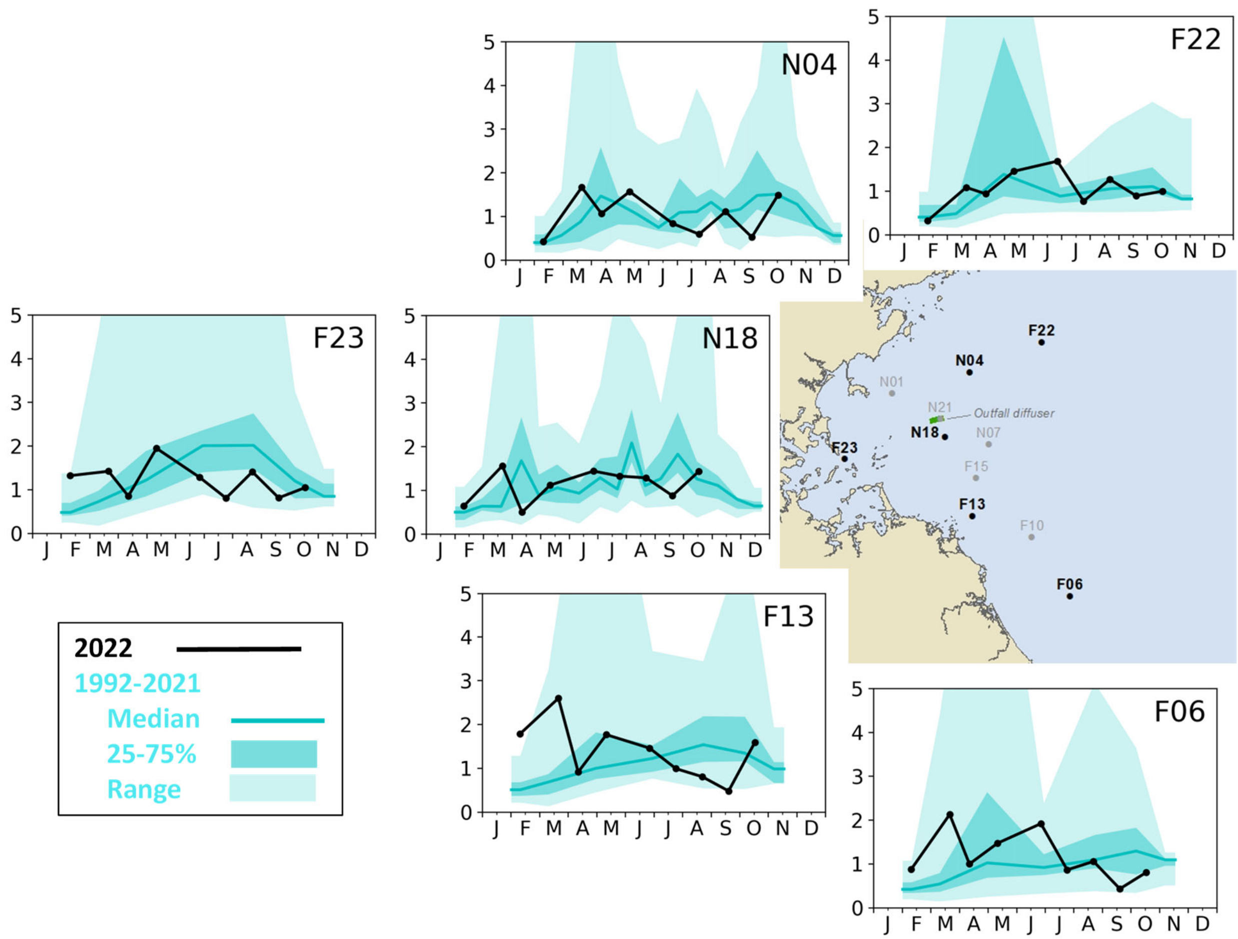

Figure 2-23. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2022 compared to prior years. 2022 results are in black. Results from 1992-2021 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The map insert highlights stations shown here and in subsequent phytoplankton and zooplankton figures, where an extended plankton dataset is available.

Table 2-1. 2022 annual mean nearfield phytoplankton abundance (cells L^{-1}) ranked for 1992-2022 period and compared to 2019-2021 abundances for major groups and species. Data are from the surface and chlorophyll maximum sampling depths at stations N16/N18. Significant differences compared to 2019-2021 means highlighted in blue.

Group	2022 Rank (out of 31 years)	2022 (cells L^{-1})	2019-2021 (cells L^{-1})	p value[1]
CENTRIC DIATOM	17th	179,678	73,702	0.0266
Chaetoceros	15th	9,029	3,519	0.1529
Dactyliosolen fragilissimus	28th	160	3,046	0.1433
Skeletonema spp. complex	2nd	91,296	7,187	0.0007
Thalassiosira	18th	13,818	11,260	0.9375
MICROFLAGELLATES	12th	687,950	432,599	0.0002
Phaeocystis pouchetii	20th	4,350	36,409	0.5036
CRYPTOPHYTES	25th	78,010	58,930	0.2121
DINOFLAGELLATES	3rd	96,417	75,743	0.6232
Ceratium	11th	2,704	1,428	0.5532
Dinophysis	22nd	398	706	0.9236
Prorocentrum	1st	50,856	4,906	0.0105
PENNATE DIATOM	6th	59,545	16,371	0.1322
Pseudo-nitzschia	1st	54,461	9,201	0.0211
TOTAL PHYTOPLANKTON	18th	1,127,147	721,601	0.0001

[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.

Centric diatom abundance was well above normal in the nearfield during the winter/spring of 2022 (**Figure 2-25**). First quarter centric diatom abundance at station N18 was four times the long-term mean and was the second highest first quarter centric diatom abundance observed during 31 years of monitoring. The majority of this increase was due to a February-March 2022 bloom of *Skeletonema*. The winter-spring *Skeletonema* bloom was followed by low centric diatom abundance near the historical median during the summer and fall. Abundances increased in October due to a minor fall bloom of a mixed diatom assemblage of *Leptocylindrus danicus*, *Skeletonema*, and *Thalassiosira*. *Chaetoceros* spp. and *Thalassiosira* spp. had near average abundance levels during 2022, which represents an increase compared to the low levels of these genera observed during 2019-2021. The centric diatom annual mean abundance of 179,678 cells L^{-1} at station N18 represents a 2.5-fold increase compared to levels observed during 2019-2021. Overall, the annual mean centric diatom abundance was close to the long-term average and ranked 17th of 31 years (**Table i**).

Phaeocystis abundances were very low in Massachusetts Bay from February to April 2022. The maximum *Phaeocystis* abundance of only ~91,000 cells L^{-1} was observed at station F22 during the March 2022 survey. Note maximum *Phaeocystis* abundances of tens of millions of cells L^{-1} have been recorded in Massachusetts Bay during major bloom years. Historically, *Phaeocystis* is one of the dominant phytoplankton taxa in the bay and low to moderate *Phaeocystis* abundance observed during 2022 and during nine of the last ten years has contributed to the long-term decline in total phytoplankton abundance relative to the levels observed during the early 2000s.

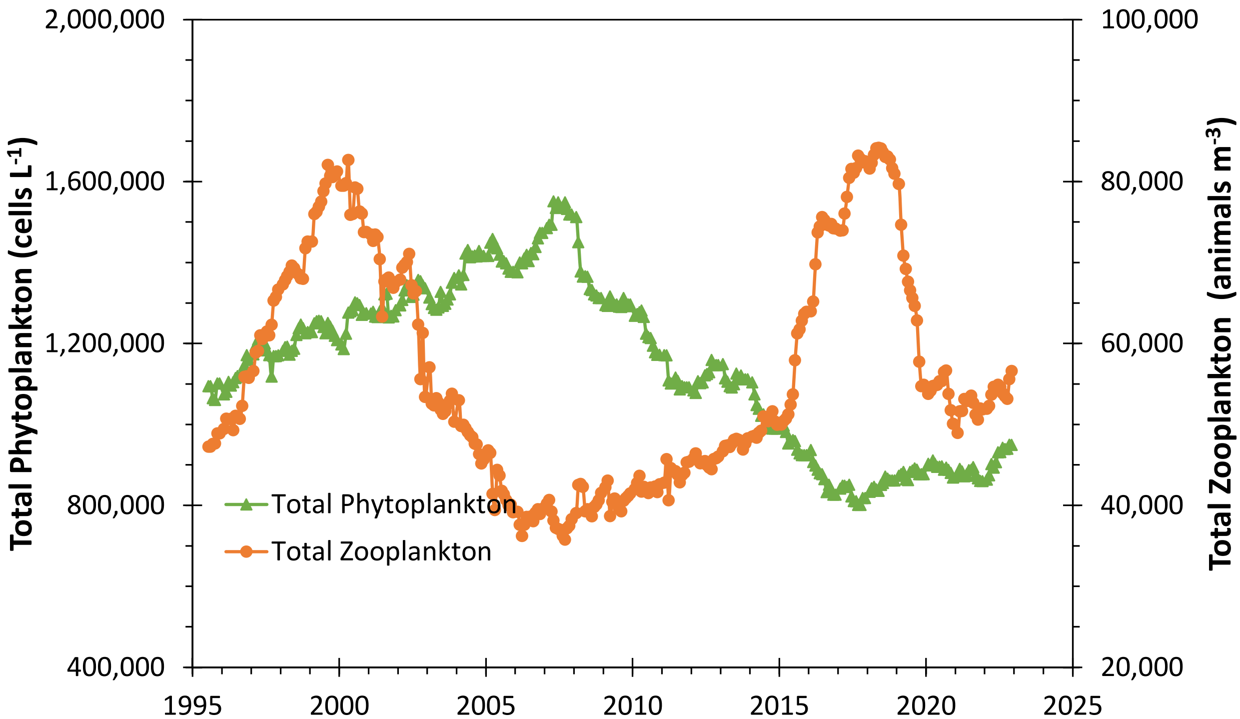

Figure 2-24. Estimated long-term (1995-2022) abundance levels of total phytoplankton (green) and total zooplankton (orange) abundance in the nearfield (stations N04 and N16/N18) derived from time series analysis. Data lines based on 15% smoothing windows (~4 years).

Microflagellates (spherical cells less than 10 µm diameter) are the most numerically abundant phytoplankton group in the Massachusetts Bay monitoring area, comprising ~61% of phytoplankton cells in 2022. Microflagellate abundance was near long-term mean levels for most of 2022, with the exception of May to June 2002 which had elevated microflagellate abundance at many stations (data not shown). Microflagellate abundance, relative to long-term mean levels, resulted in 2022 nearfield microflagellate abundance (687,950 cells L^{-1}) that was approximately 1.6-fold the level (432,599 cells L^{-1}) observed during 2019 to 2021 and ranked 12th of 31 years (**Table i**). This was a significant increase in microflagellate abundance in 2022 versus 2019-2021.

Mean nearfield pennate diatom abundance during 2022 (59,545 cells L^{-1}) was approximately 3.6 times that observed during 2019-2021 (16,371 cells L^{-1}) equivalent to 6th rank of 31 years (**Table i**). Most of this elevated pennate diatom abundance was due to a bloom of the potentially toxigenic genus *Pseudo-nitzschia* in March 2022. The March 2022 *Pseudo-nitzschia* bloom was confined to Massachusetts Bay, with elevated levels observed from near Cape Ann (station F22), the nearfield region, and south to station F13. A maximum abundance of 683,358 cells L^{-1} was observed at station F13 and four other Massachusetts Bay stations had *Pseudo-nitzschia* abundance of greater than 500,000 cells L^{-1}. Note that *Pseudo-nitzschia* was not elevated in Boston Harbor or at the three Cape Cod Bay stations in March 2022. Due to the March bloom, 2022 had the greatest (#1 rank) mean annual *Pseudo-nitzschia* abundance (54,461 cells L^{-1}) recorded in Massachusetts Bay during 1992-2022 (**Table i**). The vast majority of *Pseudo-nitzschia* cells observed during the March bloom were 'narrow' cells (< 3 µm transverse axis) consistent with the *P. delicatissima* group. Massachusetts Division of Marine Fisheries (MA DMF) shellfish monitoring programs did not detect domoic acid in Massachusetts Bay waters and there were no shellfish amnesic shellfish poisoning (ASP) closures associated with the March 2022 *Pseudo-nitzschia* bloom.

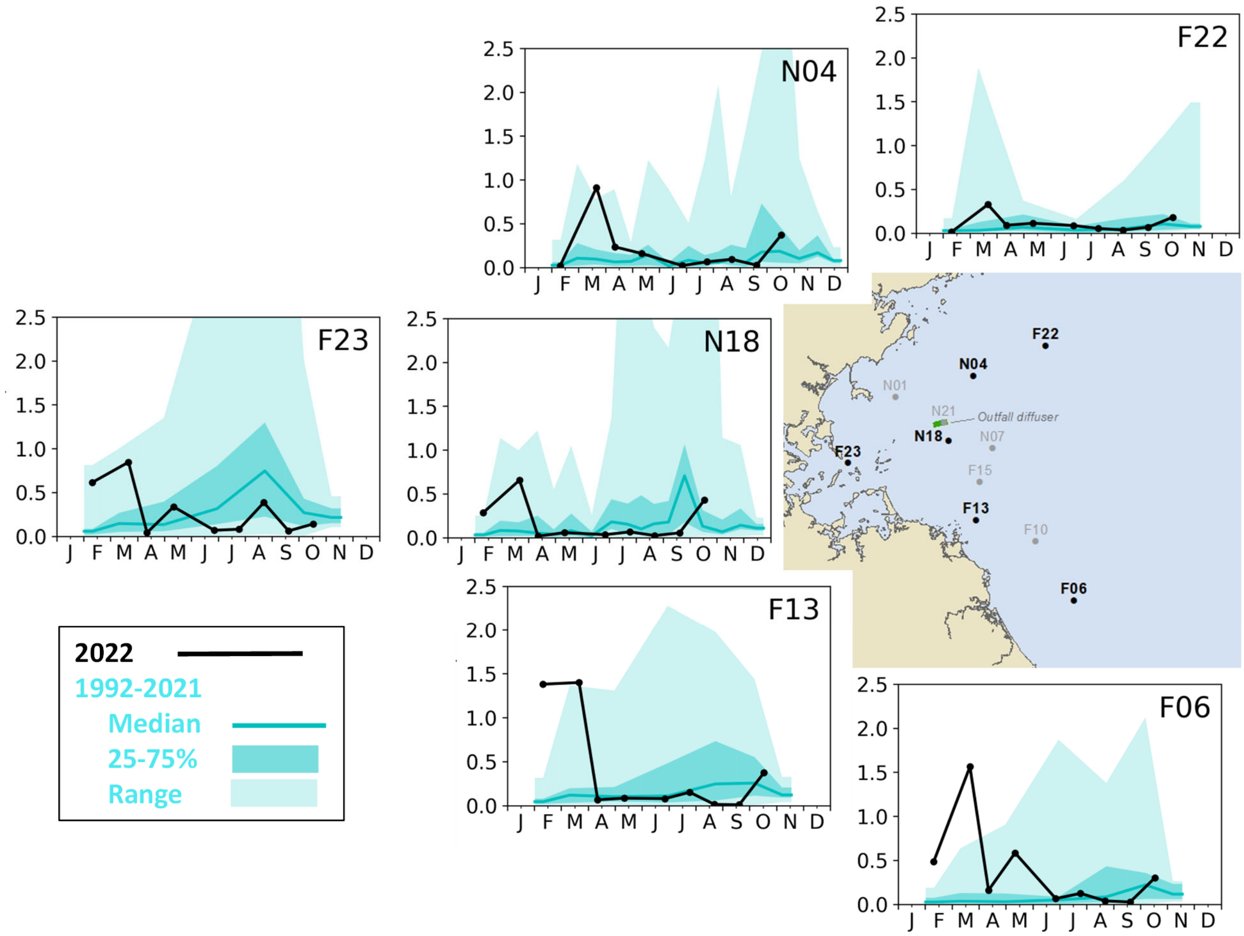

Figure 2-25. Centric diatom abundance (millions of cells L^{-1}) at selected stations in 2022 compared to prior years. 2022 results are in black. Results from 1992-2021 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Overall, dinoflagellates were more abundant than the long-term average in the nearfield during 2022 ranking 3rd of 31 years (**Table i**). Dinoflagellate abundances were close to the historical median in Massachusetts Bay for much of the year, but a large bloom was observed in May with numbers well above historical maxima and remained elevated in June and July at many stations (**Figure 2-26**). This was due in large part to a bloom of *Prorocentrum cordatum* (former name *P. minimum*) in May 2022, elevated *Tripos* spp. abundance, and moderate *Karenia mikimotoi* abundance during 2022. *Tripos* is the current valid name for marine *Ceratium* species.

A regional *Prorocentrum* bloom, reaching a maximum of 526,500 cells L^{-1}, was observed in Massachusetts Bay during May 2022. The bloom was comprised mainly (90%) of *P. cordatum*, but *P. micans* and *P. triestinum* were also present. The May bloom was present at all Massachusetts Bay stations at levels of greater than 200,000 cells L^{-1} but was not observed at Cape Cod Bay stations. This is the largest *Prorocentrum* bloom observed in Massachusetts Bay during the past 31 years of monitoring and 2022 was the 1st ranked of 31 years with regard to *Prorocentrum* abundance (**Table i**). *Prorocentrum* has been increasing in the bay in recent years and the mean *Prorocentrum* level observed during 2022 was more than 10-fold greater than the *Prorocentrum* abundance observed during 2019-2021.

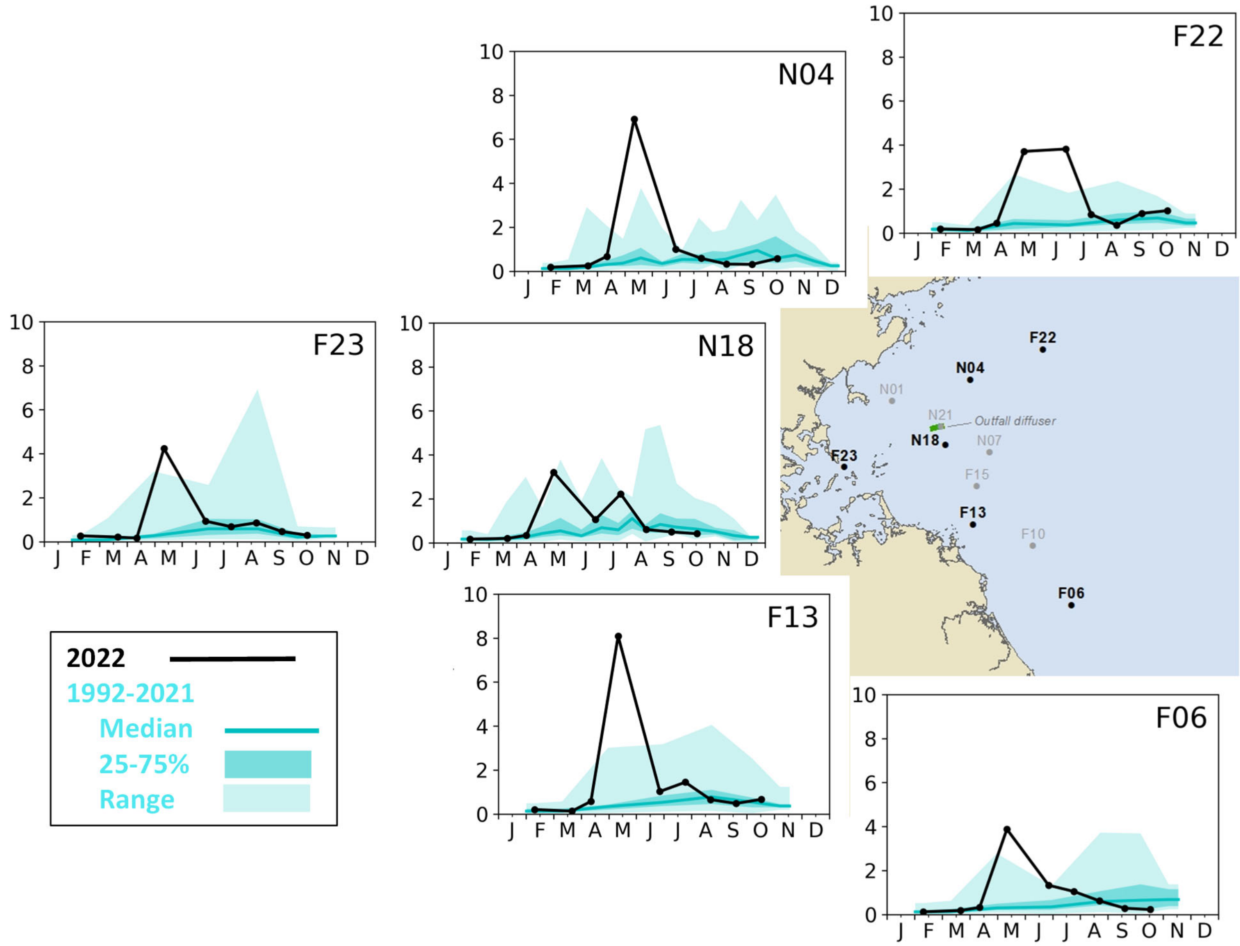

Figure 2-26. Dinoflagellate abundance (100,000 cells L^{-1}) at selected stations in 2022 compared to prior years. 2022 results are in black. Results from 1992-2021 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

A large *Alexandrium catenella* bloom was observed in June and July 2022 and is described in more detail below. *Tripos* was relatively abundant in the bay during 2022 with summer and early autumn abundance near or above the envelope of previous observations. Annual mean 2022 *Tripos* abundance was 2,704 cells L^{-1} at station N18 which was 11th ranked of 31 years. It is perhaps noteworthy that these relatively high abundances preceded a massive *Tripos muelleri* bloom throughout Massachusetts Bay and the Gulf of Maine in the subsequent year (2023).

Karenia mikimotoi was present in Massachusetts Bay during 2022, continuing the trend of recent years. It was observed in 56% of samples (down from 84% in 2020) and reached a maximum abundance of 277,576 cells L^{-1} during 2022. This was a marked decrease in maximum *Karenia* abundance from levels of 850,000 to 900,000 cells L^{-1} observed during 2019 and 2020. *K. mikimotoi* abundance of approximately one million cells L^{-1} is a threshold for inimical effects (Li et al. 2019). *K. mikimotoi* abundance approached those levels during 2019 and 2020 and were associated with hypoxia and benthic mortalities in Cape Cod Bay (Scully et al. 2022). *K. mikimotoi* has been observed every year since first appearing in 2017 and now appears to be an established member of the regional phytoplankton flora.

2022 broke a pattern of declining Massachusetts Bay phytoplankton abundance that was observed during 2008-2021 (**Figure 2-24**). Elevated abundance of *Skeletonema* (February and March), *Prorocentrum*

(May), *Ceratium* (summer), and *Chaetoceros* (late summer, autumn) all contributed to the 2022 increase. The 2022 *Skeletonema*-dominated winter spring bloom was the largest seen in the bay since 1999. The pattern of blooms observed during 2022 was largely regional, with each bloom being observed in all regions of Massachusetts Bay.

A graphical comparison of total phytoplankton trends at stations N18 (near the MWRA outfall) and N04 (~7 km away, and generally removed from the outfall's influence) suggests that phytoplankton patterns in the nearfield have followed similar trajectories and no distinct outfall effect on phytoplankton abundance is evident (**Figure 2-27**). These simultaneous and synchronous patterns suggest that regional drivers (weather, oceanographic variation, zooplankton abundance) are important determinants of phytoplankton patterns regionally and that these drivers take precedence over local drivers such as changes in nutrient input. Further, the dramatic increase in phytoplankton abundance and increased number of blooms across several taxa this year (diatoms, dinoflagellates; **Table i**) suggest that a change in regional oceanographic drivers may have occurred during 2022.

2022 *Alexandrium catenella* Bloom

A large *Alexandrium catenella (*hereafter *Alexandrium)* bloom was observed in Massachusetts Bay in 2022 comparable to the large blooms in the bay in 2005, 2008, 2019, and 2021 (**Figure 2-28**). Nearfield *Alexandrium* abundance peaked on June 28 at 10,180 cell L^{-1} well above the Contingency Plan threshold (**Table 2-2** and **Figure 2-29**).

The initiation and progression of the bloom was similar to that observed during the recent blooms in 2019 and 2021, with high abundances not observed until the late June survey. *Alexandrium* abundances were low in Massachusetts Bay and the western Gulf of Maine from February to May. New Hampshire Department of Environmental Services (NH DES) first detected PSP toxicity mid-May with increasing *Alexandrium* abundances also observed. Peak *Alexandrium* abundances (>1,000 cells L^{-1}) and elevated PSP toxicity were observed at the NH DES stations the week of June 12. PSP toxicity was not detected by the MA DMF until late May at stations north of Gloucester. PSP toxicity increased by mid-June and MA DMF issued a shellfishing closure for all bivalves from Gloucester to the New Hampshire border on June 16. On June 22, MA DMF reported the first detectable PSP toxicity levels at its Cohasset and Marshfield sites in Massachusetts Bay (>40 µg/100 gram) and issued a closure for blue mussels from Gloucester south to Plymouth. By June 27, PSP toxicity levels had increased along the South Shore and the closure was updated to all bivalve shellfish.

The presence of detectable PSP toxicity at these South Shore stations triggered the 2022 ARRS (Libby et al. 2013). Two additional stations along the South Shore (F05 and N10) were added to the late June regular water column survey to expand the spatial coverage of *Alexandrium* sampling as the first ARRS sampling of 2022. Very high *Alexandrium* abundances were observed during the June 28 survey with a maximum of 10,180 cells L^{-1} in the surface waters at station N10 off Hull (**Figure 2-30** and **Table 2-2**). Other high counts of >1,000 cells L^{-1} were observed from the north at station F22, to western nearfield stations, and further south to stations along the South Shore. These high abundances were observed less than a week after PSP toxicity was first detected within Massachusetts Bay and were well above the 100 cells L^{-1} Contingency Plan threshold.

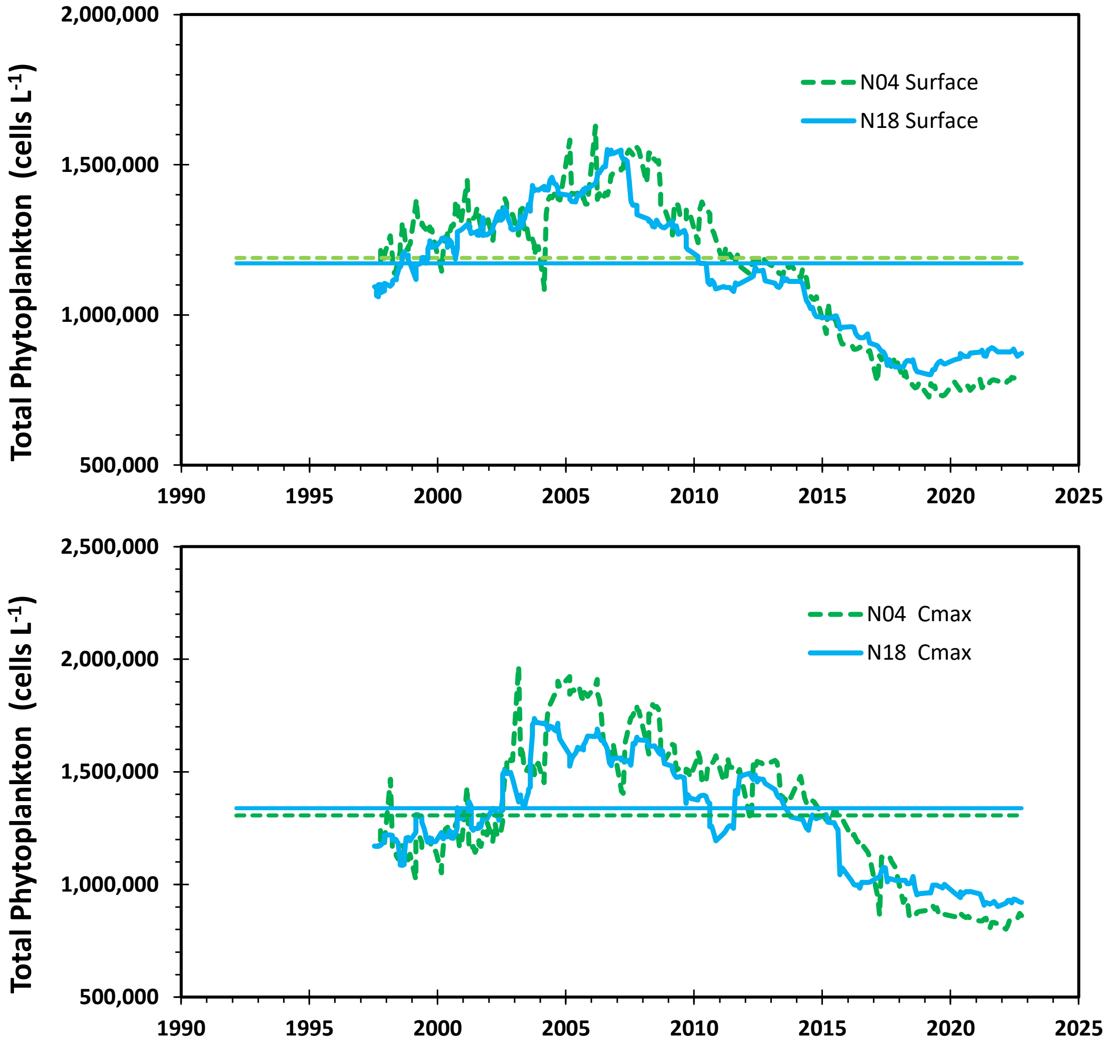

Figure 2-27. Estimated long-term (1992-2022) abundances of total phytoplankton at nearfield stations N04 (green/dashed) and N16/N18 (blue/solid) for surface and chla-max samples derived from time series analysis. Each panel shows the deseasonalized annual mean abundance at the surface (top) and at the chlorophyll maximum depth (bottom) during 1992-2022. Horizontal lines are 1992-2022 mean abundances. Monthly deseasonalized abundance estimates have been smoothed with a 15% smoothing window equivalent to the ~48 months preceding the sample date.

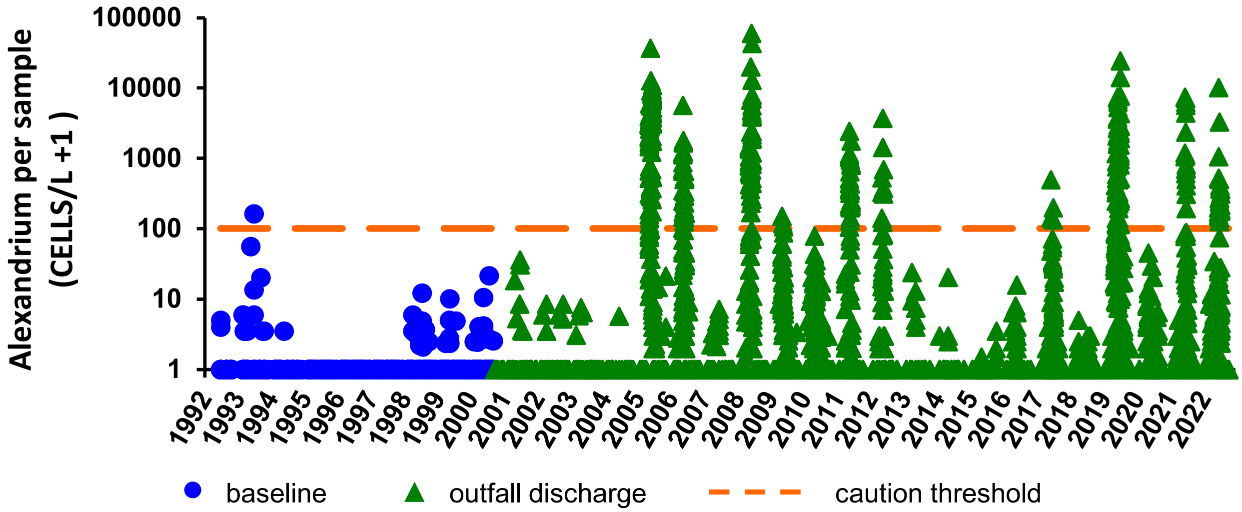

Figure 2-28. Nearfield *Alexandrium* abundance (cells L^{-1} +1) from 1992 to 2022. The dashed line represents the Contingency Plan caution threshold of 100 cells L^{-1}.

Table 2-2. *Alexandrium* abundance for water column and ARRS surveys in May-July 2022.

Event Id	Date	# samples collected	# samples with *Alexandrium*	# *Alexandrium* cells/L			MAX value station (depth)
				MEAN	MIN	MAX	
WN224	May 13	20	15	5	0	34	N04 (7 m)
WN225	June 28	24	24	1,247	3	10,180	N10 (2 m)
AF221	July 6	39	30	166	0	3,290	N01(10 m)
AF222	July 13	43	23	43	0	449	F23 (2 m)
AF223	July 20	43	36	50	0	359	N01 (10 m)
WN226	July 26	24	19	4	0	12	F23 (2 m)

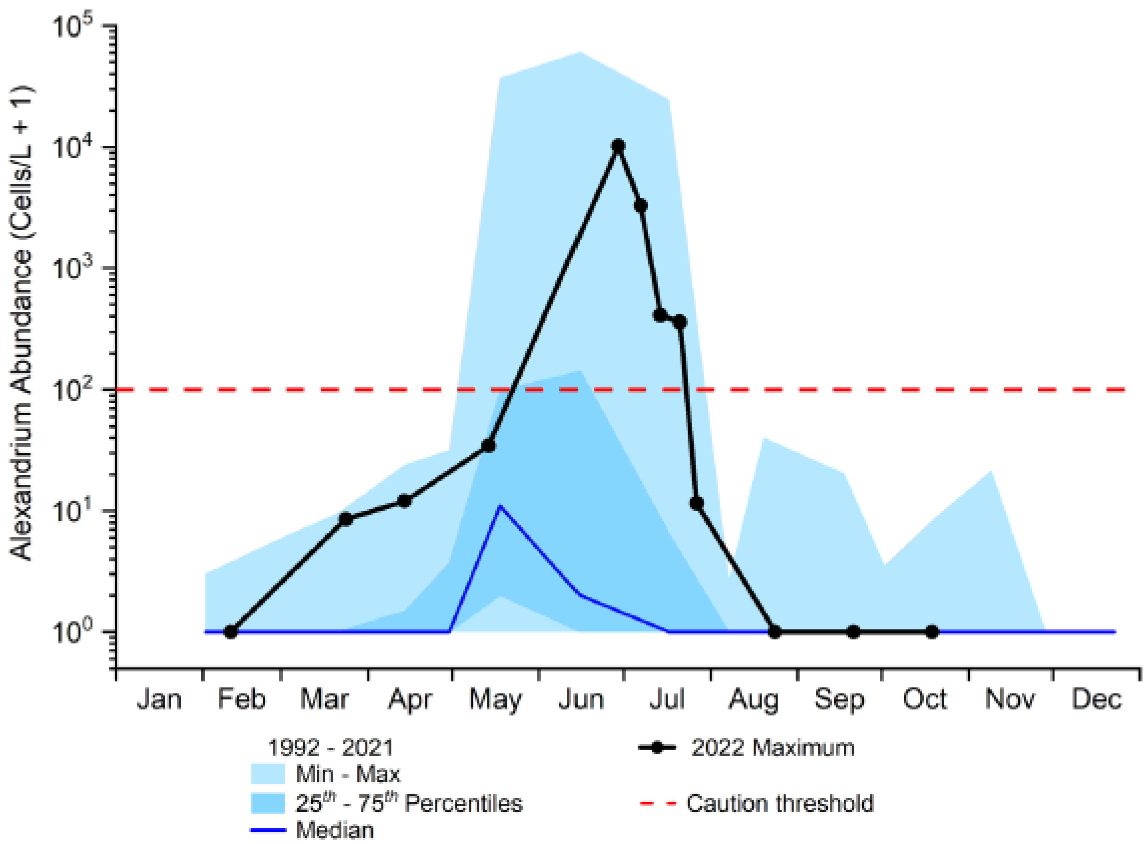

Figure 2-29. Nearfield sample abundance of *Alexandrium* in 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

By early July, *Alexandrium* were observed in most samples, but abundances had decreased, with only one sample having an abundance of >1,000 cells L^{-1} and 10 others with 111 to 576 cells L^{-1} (**Figure 2-30**). The maximum of 3,290 cells L^{-1} was observed at station N01 and the other elevated counts were observed in western Massachusetts Bay within the nearfield area, Boston Harbor, and along the South Shore. By mid-July, *Alexandrium* abundances had decreased substantially over most of the bay with only four samples having an abundance of >100 cells L^{-1} and just two other others >50 cells L^{-1}. All elevated cell counts were observed within the nearshore waters of Boston Harbor, western nearfield area, and along the South Shore near Minot Light (**Figure 2-30**). There was little change in the overall abundance of *Alexandrium* from July 13 to July 20 and only eight of the samples had an abundance of >100 cells L^{-1} (139-359 cells L^{-1}). The distribution of the elevated counts, however, changed from the inshore waters near Boston Harbor to a range of stations from south of Cape Ann (stations AF9 and F22), into the nearfield (stations N01, N04, and N18), and to station F15 south of the nearfield. By late July, *Alexandrium* were present at very low abundances (0 to 12 cells L^{-1}) consistent with MA DMF reporting no detectable PSP toxicity in Massachusetts Bay lifting the remaining shellfishing closures on July 25 and signaling the end of the 2022 *Alexandrium* bloom and the ARRS.

Summarizing, a significant *Alexandrium* bloom occurred within Massachusetts Bay in 2022, sufficient to cause dangerous levels of shellfish toxicity and thus harvesting closures by MA DMF. Given that the trend in toxin detection along the coast began in New Hampshire, followed by the MA north shore, and then Massachusetts Bay stations, it is reasonable to conclude that this was a population transported into the bay from the north. It is not possible to determine whether this population benefited from outfall nutrients given the relatively short duration of the bloom and the relatively low cell abundances.

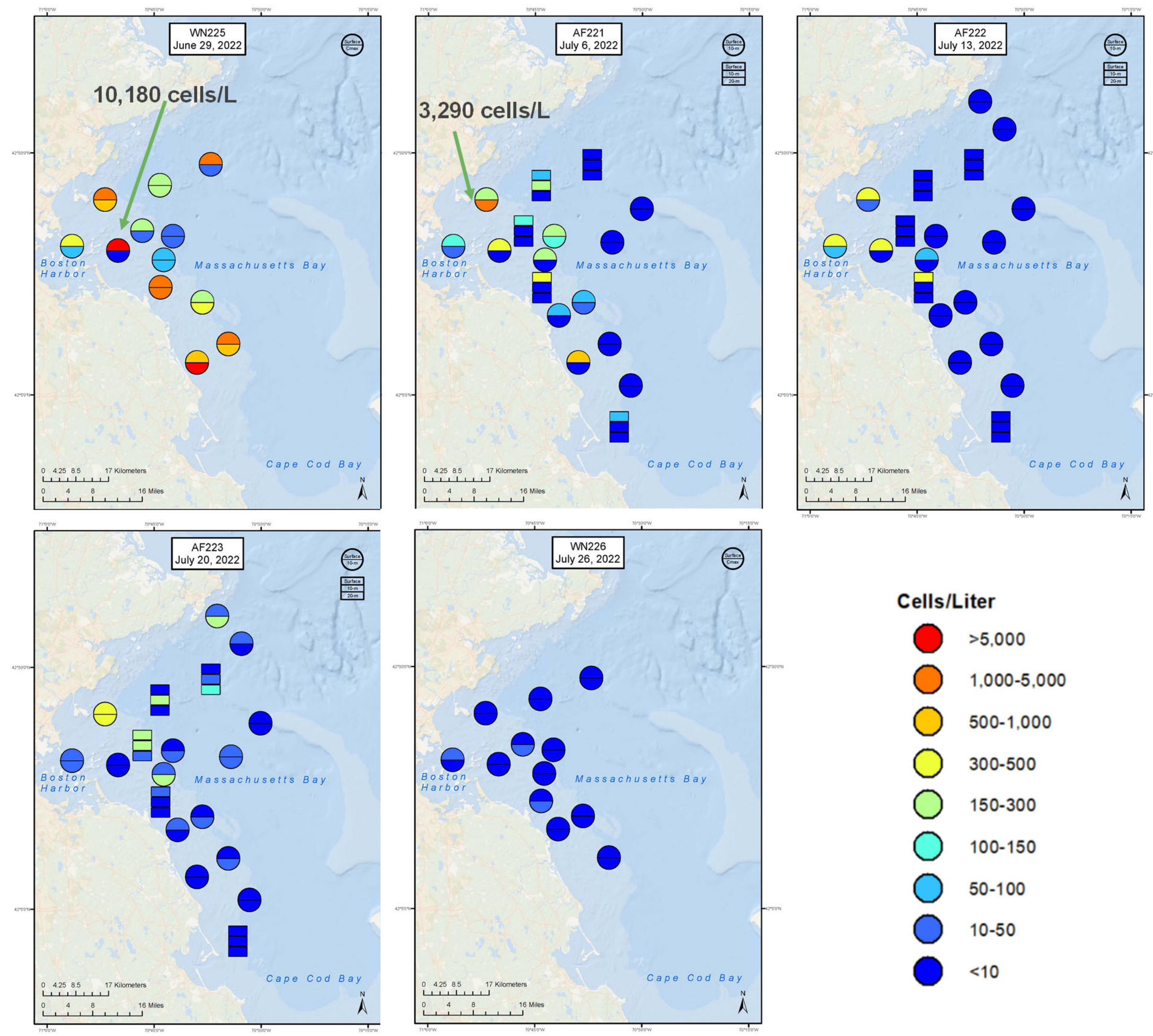

Figure 2-30. ***Alexandrium* abundance (cells L^{-1}) from June and July 2022 surveys.** Symbols show abundance for the surface in the upper half and from ~10 m in the bottom half of each symbol.

2.6 ZOOPLANKTON ABUNDANCE

Zooplankton taxa, seasonal patterns, and abundances in 2022 were generally similar to those observed during the previous years of the monitoring program (**Figure 2-31**). The main differences were the presence of two warm-water taxa of radiolarians and doliolids in July and October 2022, respectively.

Seasonal patterns of total zooplankton abundance were typical, with increases from winter lows through to spring and summer peaks, followed by fall declines (**Figure 2-31**). Barnacle nauplii were high in February and March, particularly in Boston Harbor. There were elevated abundances at offshore station F22 dominated by copepod nauplii in March and copepod adults + copepodites in March and July. Abundances of total zooplankton and copepod adults + copepodites reached historical maxima at station F22 (**Figure 2-32**) and were composed mainly of copepod adults + copepodites of *Oithona similis*. The larger copepod *Calanus finmarchicus* was mainly present in April at offshore stations with abundances of 3,000 to 5,000 individuals m^{-3} (not shown). As usual, estuarine copepods of the genus *Acartia* were found mainly in Boston Harbor and had lower abundance than in most previous years (not shown).

Total zooplankton abundance peaked at many Massachusetts Bay stations in July 2022 and were dominated by high abundances of radiolarians (**Figure 2-31**) similar to peaks observed in August/September 2020 and July/November 2021. Radiolarians had not been observed in the monitoring program prior to 2020 but have now appeared for three years in a row. Doliolids, which are warm-water planktonic tunicates, were recorded for the first time in the MWRA sampling area in October 2022. The presence of the radiolarians and doliolids suggests intrusions of offshore Gulf of Maine waters, which is consistent with the comparatively warm waters recorded for 2022 in Massachusetts Bay.

There had been a sustained trend of increasing abundance of total zooplankton from 2006 through 2017 that was driven by increases in copepod adults and copepodites (Libby et al. 2019). Zooplankton and copepod abundances leveled off in 2018 and began decreasing. The data from 2022 seem to indicate a slight increase in total zooplankton abundance coincident with an increase in total phytoplankton (see **Figure 2-27**).

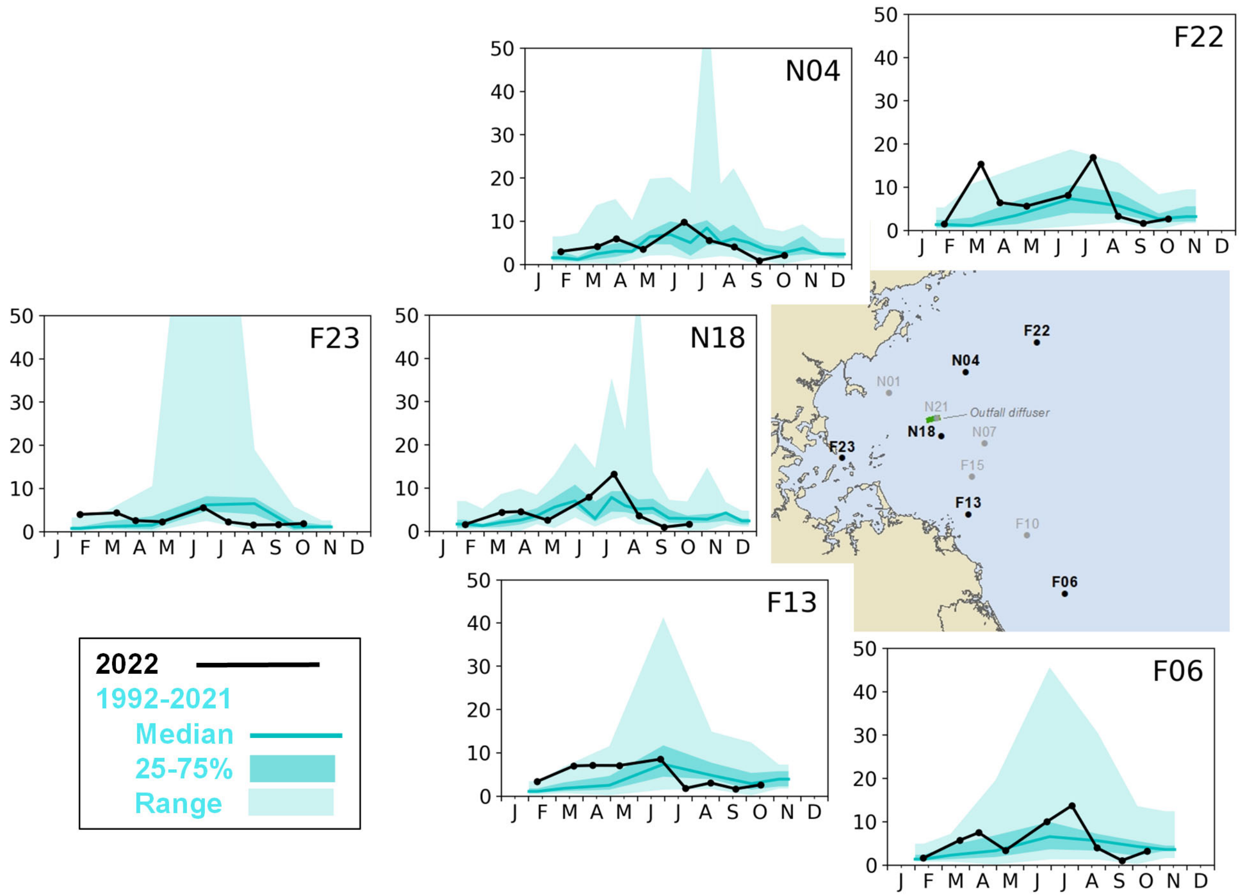

Figure 2-31. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans 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}.

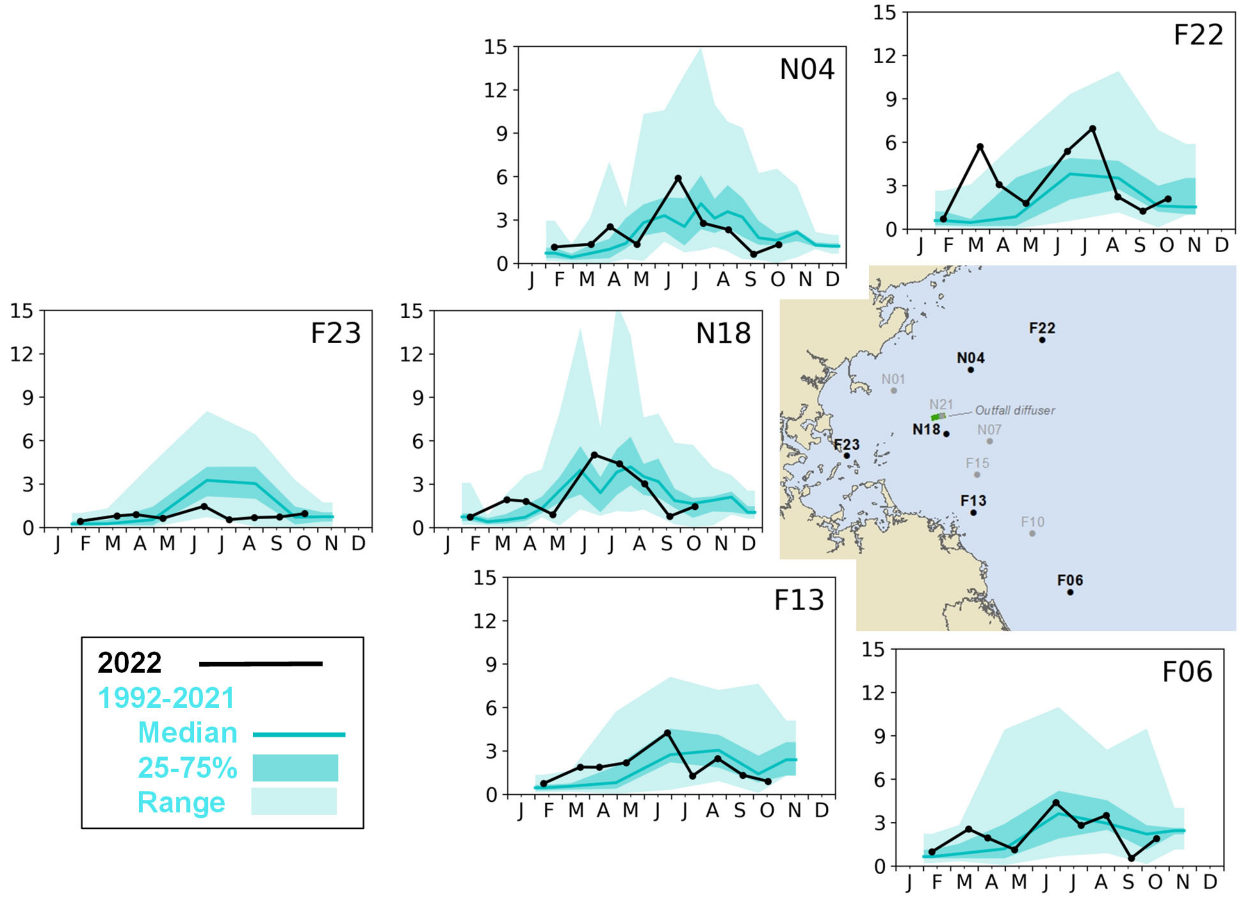

Figure 2-32. Total copepod adults and copepodites (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.7 MARINE MAMMAL OBSERVATIONS

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 2022, the marine mammal observer was not onboard for the February 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 this survey. 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 2-33**.

In 2022, five North Atlantic right whales (*Eubalaena glacialis*), one humpback whale (*Megaptera novaeangliae),* one minke whale (*Balaenoptera acutorostrata*), one unidentified toothed whale, one unidentified baleen whale, and one unidentified whale were observed during the MWRA surveys in Massachusetts Bay (**Table 2-3** and **Figure 2-33**). Other marine mammal sightings included 17 harbor seals (*Phoca vitulina*), one harbor porpoise (*Phocoena phocaena*), and six Atlantic white-sided dolphins (*Lagenorhynchus acutus)*. During the ARRS survey AF223 conducted on July 20, a large pod (50-75 individuals) of Atlantic wide-sided dolphins was observed while transiting to the west of the Stellwagen Bank National Marine Sanctuary.

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. Decreases in the number of whale sightings after 2010 are due to reduction of the number and frequency of surveys as well as monitoring stations, and not evidence of a decline in whale populations. These results are summarized in **Table 2-3** and the 2022 results are shown geographically in **Figure 2-33**. 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 2022.

Note that the numbers in this table may not match tables in previous reports, which only reported sightings within the nearfield area of the MWRA outfall.

Year	Finback whale	Humpback whale	North Atlantic right whale	Fin or Sei whale	Minke whale	Pilot whale	Unidentified baleen whale	Unidentified toothed whale	Unidentified whale	Year Totals
1998		5	3		7		5		3	23
1999	27	12	2		4		9		5	59
2000	5	22			3	21	11		2	64
2001		4	11		4		3			22
2002	6	9	2		1		2		1	21
2003	1	3			6		4			14
2004	3		3		2				3	11
2005	1	5			17		9		1	33
2006	9	32	1		7		1		4	54
2007	1	7	1		4		1		3	17
2008	5	9	13	1	5		10			43
2009	1	12	1		10		10		4	38
2010	4	9	4		9	1	6	1		34
2011	1				5					6
2012		4	2		1				1	8
2013			4						1	5
2014					2		1			3
2016			2		3					5
2017		2	8		4		3		1	18
2018	1				4		2			7
2019	1	1			1		2	1		6
2020		2	1		4					7
2021	1	2	5		3				2	13
2022		1	5		1		1	1	1	10
Species Totals	**67**	**141**	**68**	**1**	**107**	**22**	**80**	**3**	**32**	**521**

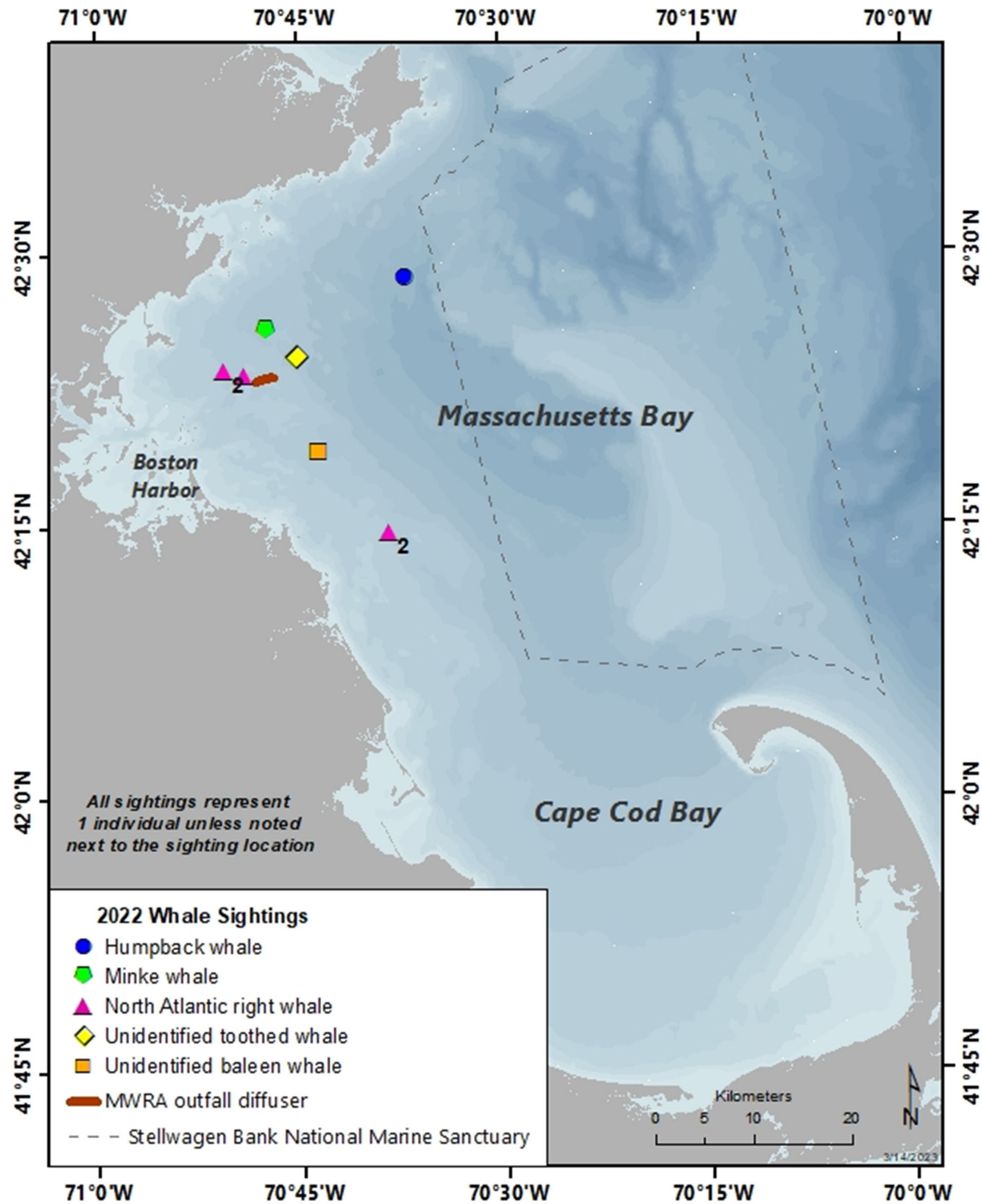

Figure 2-33. Locations and number of whale sightings and whale species sighted during the 2022 surveys.

3 ANALYSIS OF THE LONG-TERM MONITORING DATASET

3.1 SKELETONEMA

As noted in Section 2.5, there had been a long-term declining trend in total phytoplankton in Massachusetts Bay that seems to have leveled off in recent years and showed a slight increase in 2022 (**Figure 2-24**). The increase in 2022 was primarily due to higher abundances of centric diatoms. *Skeletonema* abundance was unusually high in February and March 2022 (**Figure 3-1**), exceeding historical levels at several stations. This *Skeletonema* bloom was regional, with *Skeletonema* abundance of greater than 1 million cells L^{-1} recorded at multiple stations in the nearfield (N01, N04, N07) and farfield (F06, F10, F13, F15, F23) of Massachusetts Bay. The maximum *Skeletonema* abundance of 2,530,757 cells L^{-1} was recorded in the surface waters at station F10 in March 2022. The *Skeletonema* bloom was much less abundant in Cape Cod Bay, with maximum abundance of 162,428 cells L^{-1} at station F01 in March 2022. Due to the large winter-spring bloom, 2022 was 1st rank in Boston Harbor and 2nd highest at station N18 of the 31 years of monitoring in *Skeletonema* abundance.

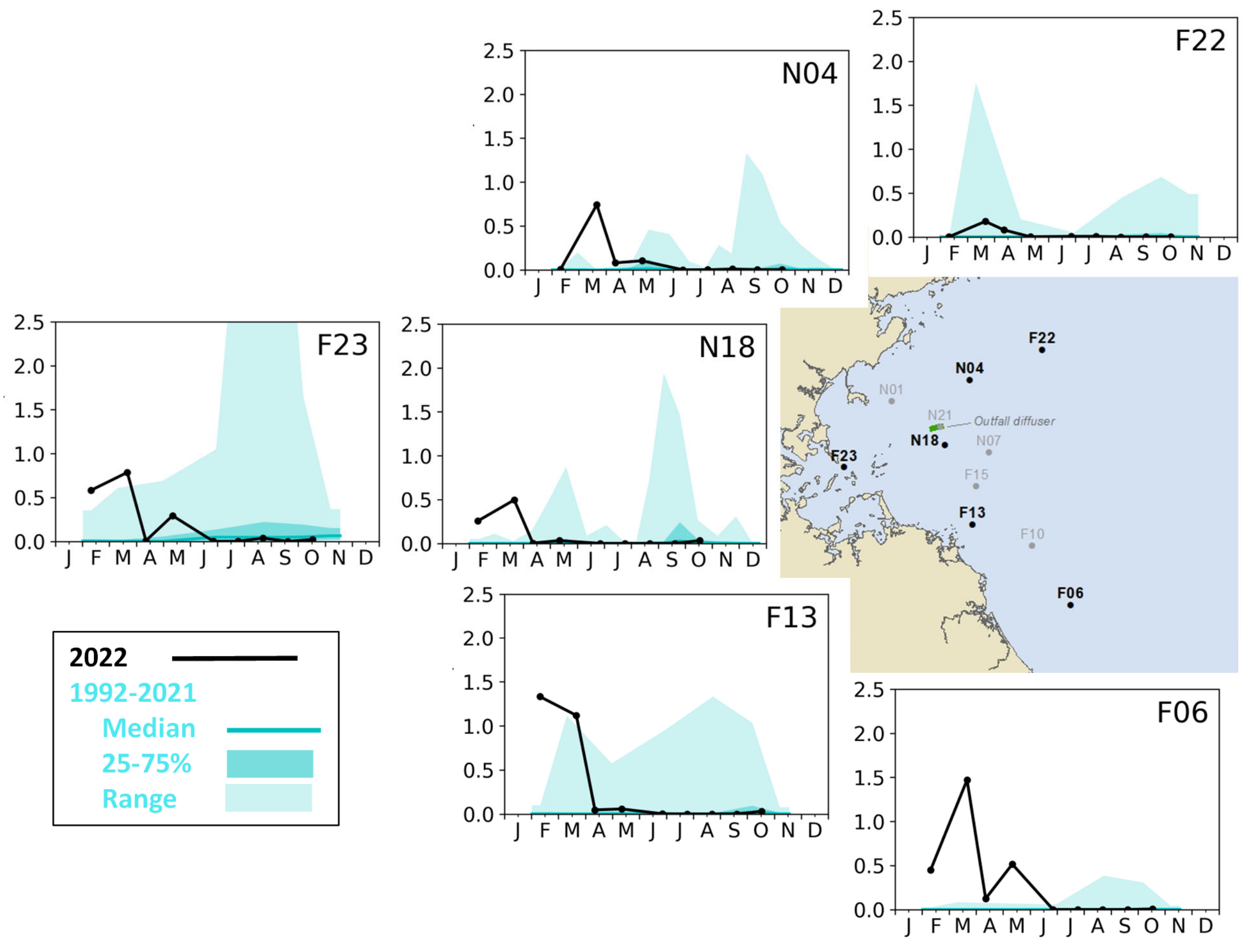

Figure 3-1. *Skeletonema* abundance (millions of cells L^{-1}) at selected stations in 2022 compared to prior years. 2022 results are in black. Results from 1992-2021 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

The 2022 *Skeletonema* annual cycle, with a large, dominant winter-spring bloom and a reduced summer bloom, is a markedly different pattern than seen in Massachusetts Bay during the 1990s. During that interval, the *Skeletonema* annual cycle was bimodal with peaks in abundance during May and October (**Figure 3-2**). The *Skeletonema* annual cycle thus far in the 2020s, largely due to elevated abundance in 2022, has been dominated by a large winter-spring bloom and a reduced, or absent, summer-fall bloom.

Skeletonema spp. are morphologically similar, and the taxa formerly known as *Skeletonema costatum* contains several molecularly distinct species (Kooistra et al. 2008). Further, these formerly unidentified cryptic *Skeletonema* spp. have distinct temperature and other environmental preferences for maximum growth (Canesi and Rynearson, 2016). In Narragansett Bay, shifts in the *Skeletonema* annual cycle have been associated with winter warming (Borkman and Smayda, 2009a) and variation in ocean currents (the Gulf Stream; Borkman and Smayda, 2009b). Dominance of the winter-spring bloom by *Skeletonema* has not been observed previously during 1992-2022 monitoring and may be indicative of similar changes in winter conditions in Massachusetts Bay. This is consistent with the warmer temperatures that have been observed in the bay as discussed in Section 2.1.

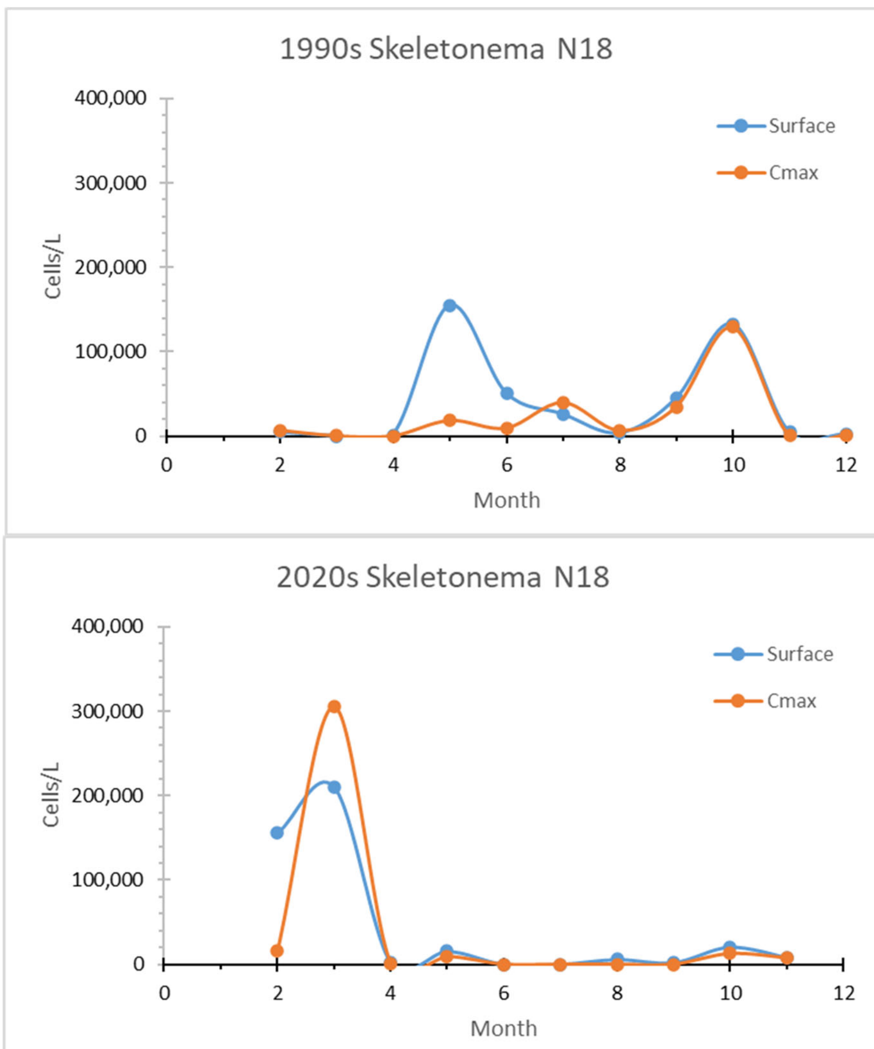

Figure 3-2. ***Skeletonema*** **abundance (cells L^{-1}) from MWRA monitoring stations in 1990s (1992-1999) and 2020s (2020-2022).** "CMAX" is the depth of the chlorophyll maximum, typically about 10-20 m deep.

3.2 DISSOLVED OXYGEN TRENDS

As noted in Section 2.4, bottom water DO concentrations were low in Massachusetts Bay in 2022 and exceeded the Contingency Plan thresholds for DO concentration and percent saturation in the nearfield and Stellwagen Basin (**Table i**). In recent years the seasonal decline in bottom water DO has been punctuated by mixing events, but in 2022, the lack of strong summer storms or mixing events led to a steady decline in bottom water DO levels from March to September/October leading to a DO depletion rate of 0.027 mg L^{-1} d^{-1}. This is the highest rate observed since 1998 and resulted in low DO levels in Massachusetts and Cape Cod Bays in 2022. In the nearfield, bottom water DO concentrations of 5.85 mg L^{-1} were observed in both September and October 2022 exceeding the warning level threshold of 6.05 mg L^{-1}. At Stellwagen Basin station F22, bottom water DO percent saturation levels in August (66%) and September (65.4%) were below the warning level threshold (67.2%) and DO concentrations were below the caution level threshold (6.23 mg L^{-1}) in both September (6.10 mg L^{-1}) and October (6.08 mg L^{-1}; **Figure 3-3**).

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 3-4**). Historically, the model was relatively good at predicting bottom water DO, but in recent years the model has predicted much lower concentrations than observed. For 2022, the model predicted low DO based on both higher temperatures and higher salinity in the bottom waters and was consistent with the bottom water DO observations. The large errors seen in the regression model in the period from 2015 to 2021 may be due to changes in wind patterns. The winds in 2022 were more consistent with earlier years having frequent upwelling favorable winds out of the south, which may explain the more consistent model prediction in 2022.

The lowest bottom water DO concentrations in Cape Cod Bay for the monitoring program were observed in 2013 and 2022. The temperature, salinity and DO anomalies for 2013 and 2022 were compared, to try to determine if unusually warm temperature or salinity may have contributed to the low DO observed in 2022. During 2013, the low DO may be explained by the pronounced temperature anomaly of 4.9 °C above the long-term mean (**Figure 3-5**). For 2022, the temperature anomaly was also large with waters warmer than the mean by +3.6 degrees and there was an accompanying salinity anomaly of +0.5 PSU (**Figure 3-6**), which is large relative to the typical variability of bottom water salinity. The pronounced DO minimum observed in Cape Cod Bay in 2022 is consistent with the water property anomalies.

Fortunately, unlike 2019 and 2020, there were no observations of hypoxic to anoxic conditions in shallow, nearshore Cape Cod Bay waters. Scully et al. (2022) cited a number of factors contributing to the hypoxic conditions observed in 2019 and 2020 including a shift in prevailing winds leading to less upwelling and a deeper thermocline (thus thinner bottom water layer) plus the high biomass associated with *Karenia* blooms in both years. Conversely, in 2022, the return to upwelling favorable conditions, weaker stratification, and deeper thermocline led to earlier mixing in the shallow, nearshore Cape Cod Bay waters where hypoxia had been observed in 2019 and 2020. These factors as noted above may have contributed to the low bottom water concentrations (<3 mg L^{-1}) observed further offshore at Cape Cod Bay station F02 as a deeper thermocline would have resulted in a thinner bottom water layer at this station thereby concentrating the impact of respiration on bottom water DO levels.

Vertical profiles from station F02 during the September 20, 2022 survey shows a strong, deep thermocline, which corresponds to the level at which DO sharply decreases (**Figure 3-7**). The chlorophyll fluorescence (middle panel) showed only modest biomass at this time compared to the much higher chlorophyll observed during the *Karenia* blooms in 2019 and 2020. There was no large *Karenia* bloom in 2022, but elevated high chlorophyll levels were observed in Cape Cod Bay over much of the year (see **Figure 2-16**) providing a substantial source of biomass for decomposition contributing to the low DO levels observed.

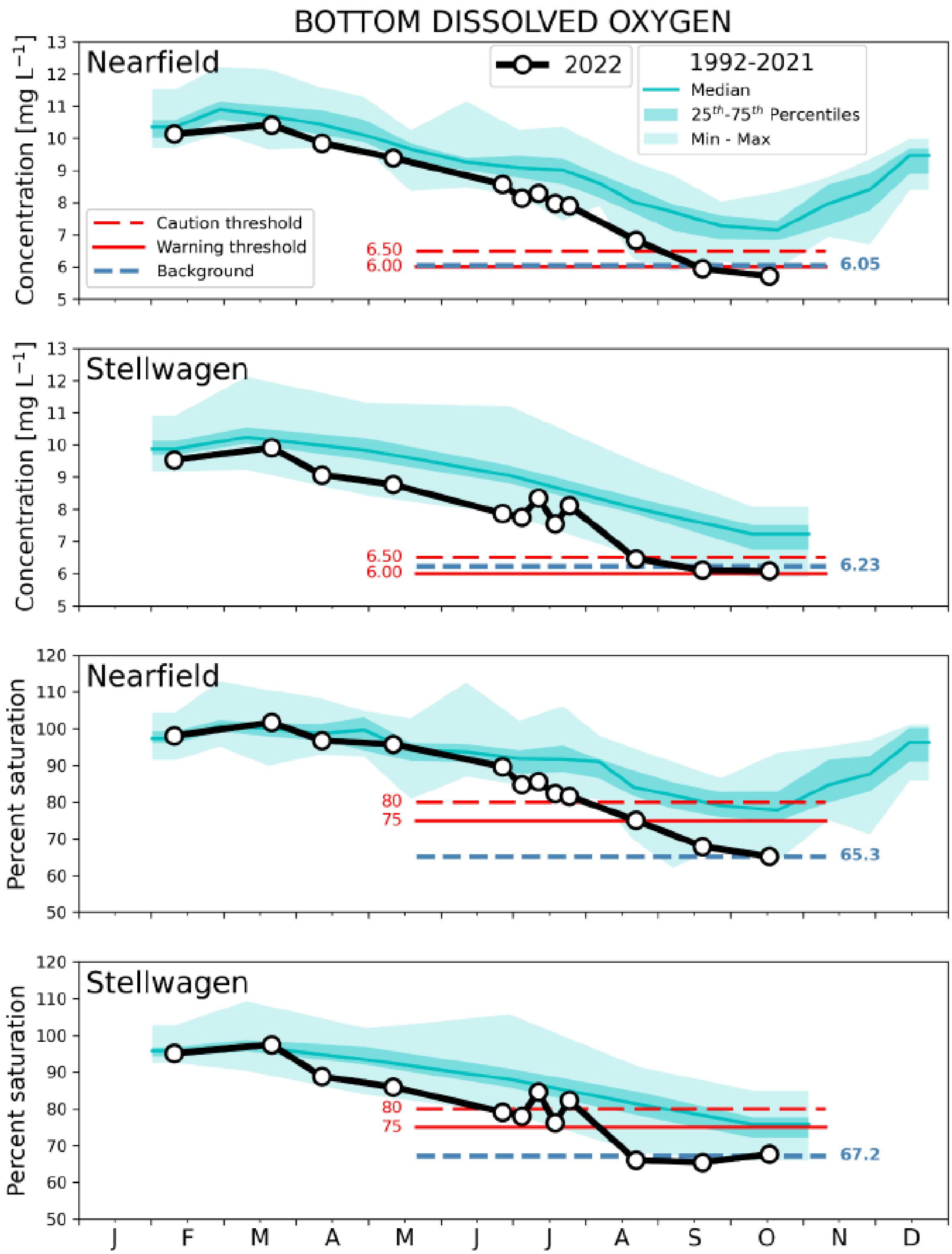

Figure 3-3. Survey bottom water dissolved oxygen concentration (mg L^{-1}) and percent saturation in the Nearfield and Stellwagen Basin versus Contingency Plan Thresholds for 2022 compared to prior years. 2022 results are in black. Results from 1992–2021 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

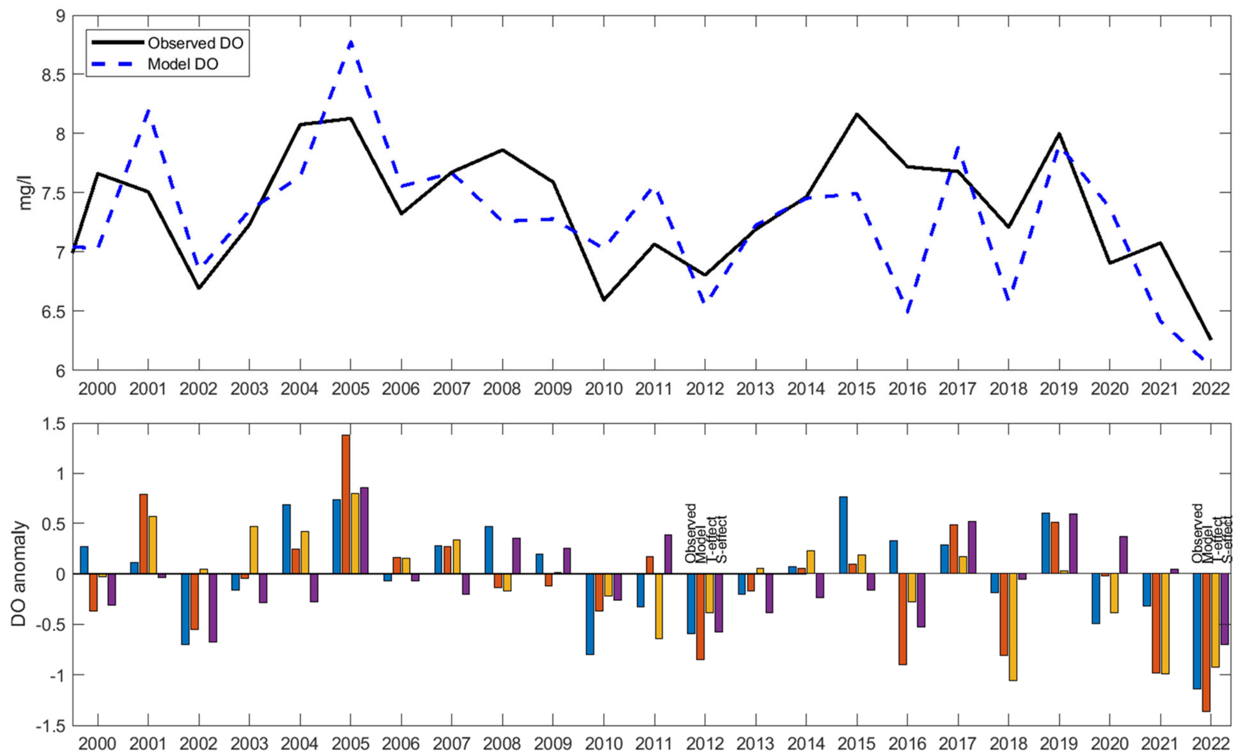

Figure 3-4. Average near-bottom dissolved oxygen in the nearfield during September-October, compared with linear regression model based on temperature and salinity variation (upper panel). Bar plot showing the individual contributions due to temperature and salinity for each of the years (lower panel).

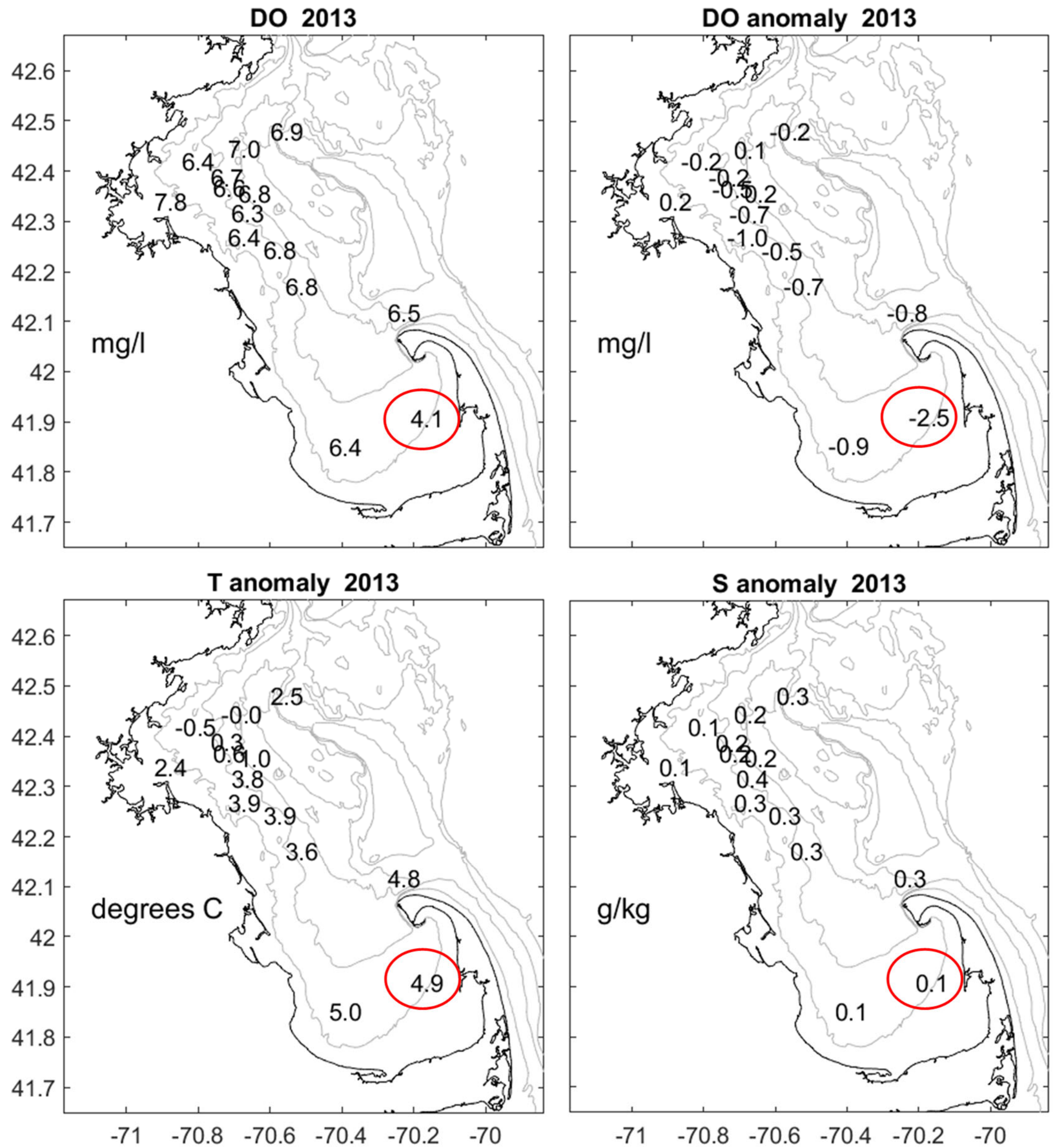

Figure 3-5. Bottom water DO concentration and anomalies for DO, temperature and salinity for 2013 versus the long-term means. The results at station F02 in eastern Cape Cod Bay are circled to highlight the large anomalies with low DO and high temperature and salinity.

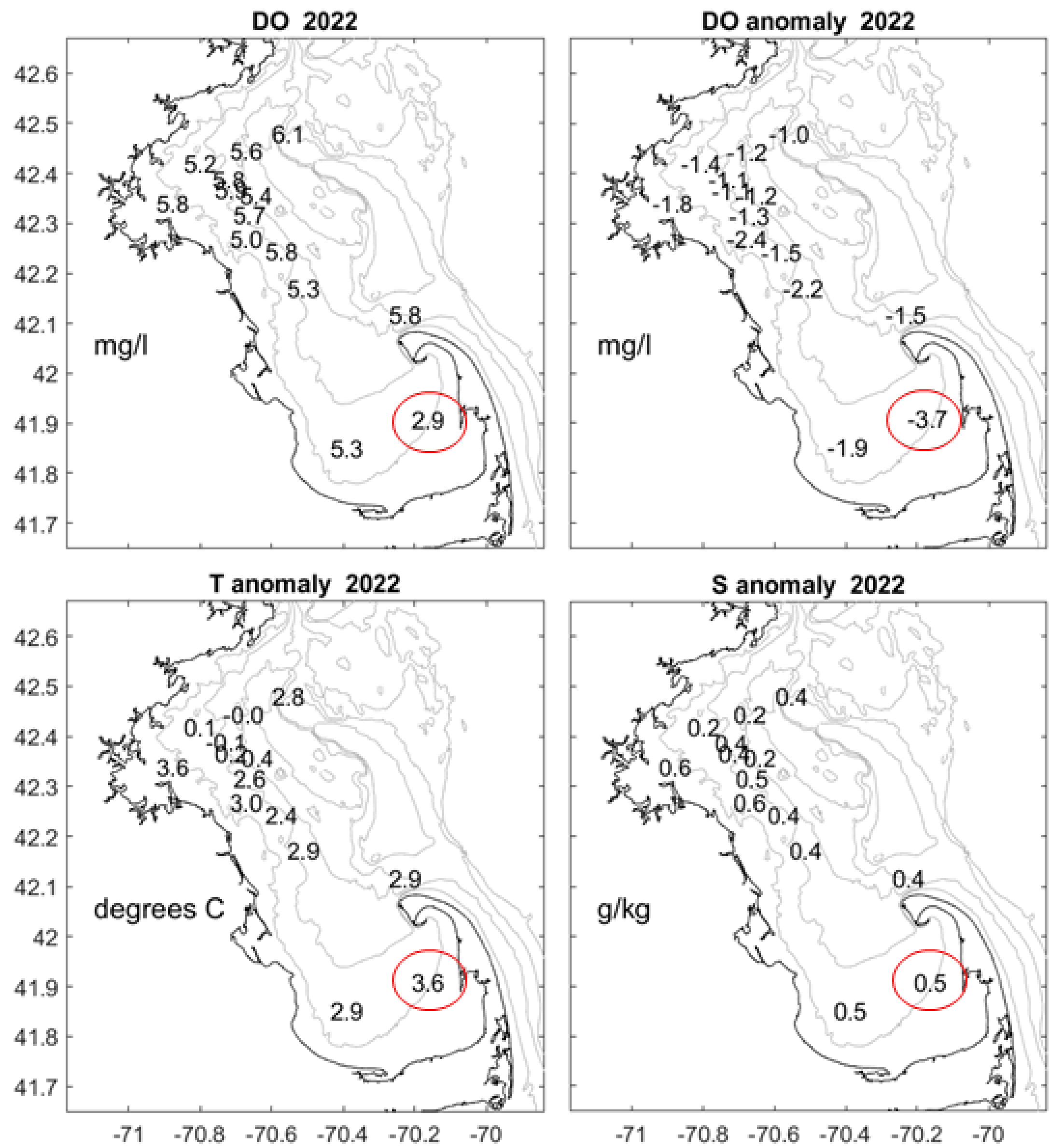

Figure 3-6. Bottom water DO concentration and anomalies for DO, temperature and salinity for 2022 versus the long-term means. The results at station F02 in eastern Cape Cod Bay are circled to highlight the large anomalies with low DO and high temperature and salinity.

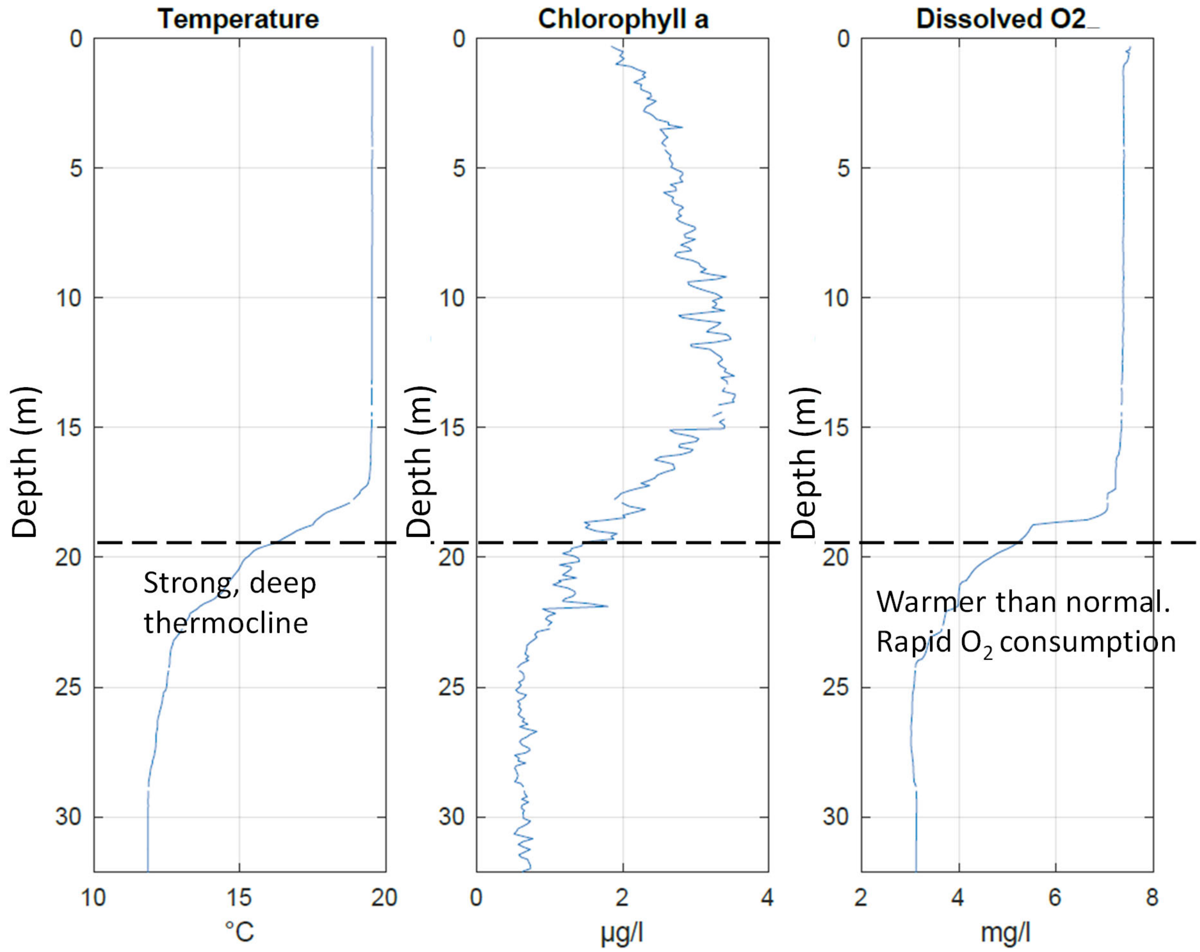

Figure 3-7. Vertical profiles of temperature (°C), chlorophyll (µg L^{-1}), and dissolved oxygen (mg L^{-1}) at station F02 on September 20, 2022.

4 SUMMARY

The most notable physical oceanographic characteristics of 2022 were the very dry summer and fall, warm and higher salinity waters for most of the year, and persistent upwelling favorable winds from late June to early August. River flow was relatively high in the winter, but decreased by May and from June to October flows were close to historic minima for the 31-year monitoring program (**Figure 2-3**). Surface water temperatures were high compared to historical levels from February to October 2022, except during July when persistent upwelling favorable winds led to lower surface temperatures which reached historical minima in the nearfield in late July (**Figure 2-1**).

Bottom water temperatures were consistently in the upper quartile or above historical maxima from February to October 2022. Surface salinity was close to the long-term median for the first half of the year before increasing to anomalously high levels in June and July and remained elevated through the fall (**Figure 2-2**). Bottom water salinity was near or above historical maxima over most of the year. The occurrence of warmer temperatures and higher salinity have been correlated to low DO during previous years and this continued to be the case in 2022.

The long-term time series of summertime air and water temperature shows that surface waters are warming more rapidly than air temperatures, at a rate of approximately 1 °C per decade (**Figure 2-7**). 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. However, the long-term trend of increasing summertime water temperatures eased in 2022 due to the presence of cooler waters associated with the persistent late June to early August upwelling favorable winds.

Stratification in Massachusetts Bay was close to the long-term median for most of 2022 with variability in April and May associated with changes in surface water salinity likely associated with coincident changes in river flow and with historically low stratification in July due to the strong upwelling favorable conditions and cooling of the surface waters (**Figure 2-6**). In August, once upwelling had weakened, stratification increased and remained near historical median until October when stratification was close to or above historical maxima due to the lack of major storms in the fall of 2022. The persistence of stratified conditions into late October was another factor in the low bottom water DO levels observed in 2022.

Nutrient concentrations in Massachusetts and Cape Cod Bays were generally consistent with typical seasonal patterns, with naturally elevated nitrate (NO_3), silicate (SiO_4) and phosphate (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 2022 were relatively low nutrient concentrations in February with SiO_4 levels nearly depleted and at historically low levels in the nearfield. Silicate concentrations remained very low in March with decreases in the other nutrients from February to March consistent with the large winter/spring diatom bloom and high chlorophyll levels observed at most stations in Massachusetts Bay during the March survey (**Figure 2-16**).

A sharp decrease in NO_3 and the NO_3 to SiO_4 ratio from March to April and May was suggestive of a *Phaeocystis* bloom between surveys, as observed chlorophyll levels and *Phaeocystis* abundances remained low. In general, low nutrient concentrations were observed from May into summer, with intermittent peaks in NH_4 and PO_4. The impact of upwelling on nutrients was evident with a sharp increase in all nutrient concentrations observed in the nearfield during the late July survey and suggesting a combined influence of upwelled ambient and effluent derived nutrients (**Figure 2-8**). Nutrients were low in the fall consistent with the moderate fall diatom bloom observed across the bays.

As typically observed, the bay outfall effluent plume was characterized by elevated ammonium (NH_4) concentrations. The 2022 NH_4 concentrations were similar to those 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 generally unchanged in the rest of Massachusetts and Cape Cod

Bays (**Figure 2-10**). However, concentrations were quite variable at stations N18 and N21 in 2022 with very high NH_4 concentrations at station N21 for most of the year except in July when they dropped sharply. This drop in NH_4 concentrations at station N21 coincided with a large increase to the maximum concentration observed at station N18 for the year. Such large differences in NH_4 concentrations between these two stations and the survey-to-survey variability observed is due to the variable location of the effluent plume during sampling and where the samples are collected along the mixing zones associated with the plume. Elevated NH_4 concentrations were also observed in June at stations F15 and F10 and even as far south at station F06 nearly 30 km south of the outfall (**Figure 2-10**). High NH_4 concentrations at these stations have been observed previously but are not common. A record high NH_4 concentration for the 31-year monitoring program of ~5 µM was observed at station N04 in late August which highlights the variability in the location of the effluent plume due to prevailing currents and intensity of upwelling favorable conditions.

Ammonium concentrations at Boston Harbor station F23 in 2022, as in other post-discharge years, were much lower than during the years 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, 2022 chlorophyll concentrations were low to moderate. Elevated areal chlorophyll was observed in Massachusetts Bay during March associated with the winter/spring diatom bloom and a smaller peak in October in conjunction with the fall diatom bloom (**Figure 2-15)**. Chlorophyll was higher in Cape Cod Bay with elevated levels observed from March to June and October (**Figure 2-16**). Overall, seasonal and annual average chlorophyll values in 2022 were relatively low, comparable to baseline seasonal averages in summer and fall and less than half the Contingency Plan threshold levels (**Table i**). The large centric diatom bloom in March contributed to a moderate winter/spring seasonal nearfield mean of 66 mg m^{-2} for 2022 which was higher than the baseline average of 50 mg m^{-2}.

Typically, bottom water DO declines at a relatively constant rate from winter/spring to fall in Massachusetts Bay. In recent years mixing events have been observed that punctuated this seasonal decline, but in 2022, the lack of strong summer storms or mixing events led to a steeper, uninterrupted decline in bottom water DO levels from March to September/October (**Figure 2-19**). As noted above, 2022 was characterized by warmer, more saline waters, physical characteristics that are correlated with low bottom water concentrations (**Figure 3-4**).

The 2022 rate of DO depletion in the nearfield did not exceed the Contingency Plan threshold but it was the highest rate observed since 1998. This resulted in Contingency Plan exceedances of DO concentration and percent saturation thresholds in both the nearfield and Stellwagen Basin (**Figure 3-3**). In the nearfield, bottom water DO concentrations of 5.85 mg L^{-1} were observed in both September and October 2022 exceeding the warning level threshold of 6.05 mg L^{-1}. At Stellwagen Basin station F22, bottom water DO percent saturation levels in August (66%) and September (65.4%) were below the warning level threshold (67.2%) and DO concentrations were below the caution level threshold (6.23 mg L^{-1}) in both September (6.10 mg L^{-1}) and October (6.08 mg L^{-1}).

Fortunately, unlike 2019 and 2020, there were no observations of hypoxic to anoxic conditions in shallow, nearshore Cape Cod Bay waters. Scully et al. (2022) cited a number of factors contributing to the hypoxic conditions observed in 2019 and 2020 including a shift in prevailing winds leading to less upwelling and a deeper thermocline (thus thinner bottom water layer) and high biomass associated with *Karenia* blooms in both years. Conversely, in 2002, the return to upwelling favorable conditions and weaker stratification and deeper thermocline led to earlier mixing in the shallow, nearshore Cape Cod Bay waters where hypoxia had been observed in 2019 and 2020. These factors may also have contributed to the low bottom water concentrations (<3 mg L^{-1}) observed further offshore at Cape Cod Bay station F02 (**Figure 2-22**) as a deeper thermocline would have resulted in a thinner bottom water layer thereby concentrating the impact of respiration on bottom water DO levels. There were no large *Karenia* blooms in 2022, but elevated phytoplankton abundances were observed in Cape Cod Bay over much of the year providing a substantial source of biomass for decomposition.

Annual total phytoplankton measured in 2022 was mostly at or above long-term levels (**Figure 2-23**). This was primarily driven by a *Skeletonema* spp. and *Pseudo-nitzschia* spp. bloom in March 2022, a *Prorocentrum* bloom in May 2022, and a mixed centric diatom bloom during October 2022. Total phytoplankton levels in the nearfield during 2022 were about 1.5 times higher than the abundances observed during the previous three years (2019-2021). This was a significant increase and resulted in 2022 nearfield total phytoplankton being the 18th ranked in abundance of 31 years monitored (**Table 2-1**).

Centric diatom abundance was well above normal in the nearfield during the winter/spring of 2022 (**Figure 2-25**). The majority of this increase was due to a February-March 2022 bloom of *Skeletonema* spp.. Centric diatom abundances were also elevated in October due to a minor fall bloom of a mixed diatom assemblage of *Leptocylindrus danicus*, *Skeletonema* spp., and *Thalassiosira* spp.. Overall, the annual mean centric diatom abundance was close to the long-term average and ranked 17th of 31 years (**Table i**). Mean nearfield pennate diatom abundance during 2022 was also elevated and ranked 6th of 31 years (**Table i**). This was primarily driven by a bloom of the potentially toxigenic genus *Pseudo-nitzschia* in March 2022. The March 2022 *Pseudo-nitzschia* bloom reached abundances of >500,000 cells L^{-1} at stations in Massachusetts Bay. Due to the March bloom, 2022 had the highest mean annual *Pseudo-nitzschia* abundance recorded in Massachusetts Bay during the 1992-2022 monitoring program. The vast majority of *Pseudo-nitzschia* cells observed during the March bloom were 'narrow' cells (< 3 µm transverse axis) consistent with the *P. delicatissima* group which are not toxic. MA DMF shellfish monitoring programs did not detect domoic acid in Massachusetts Bay waters and there were no shellfish ASP closures associated with the March 2022 *Pseudo-nitzschia* bloom.

Dinoflagellates are the only phytoplankton functional group that appears to be increasing in recent years, primarily due to the presence of *Karenia* (Libby et al. 2022). However, in 2022, *Karenia* abundance was relatively low compared to 2019 and 2020 levels. The elevated dinoflagellate abundances were due in large part to a bloom of *Prorocentrum cordatum* (former name *P. minimum*) in May 2022, elevated *Tripos* spp. abundance, (former name *Ceratium*) and moderate *Karenia mikimotoi* abundance during 2022. The *Prorocentrum* bloom was observed throughout Massachusetts Bay at levels of greater than 200,000 cells L^{-1} (a maximum of 526,500 cells L^{-1}) but was not observed at Cape Cod Bay stations. This is the largest *Prorocentrum* bloom observed in the bay during the past 31 years of monitoring and 2022 was the 1st ranked of 31 years with regard to *Prorocentrum* abundance (**Table 2-1**).

A large *Alexandrium catenella* bloom was observed in Massachusetts Bay in 2022, comparable to the large blooms in the bay in 2005, 2008, 2019, and 2021 (**Figure 2-28**). Increases in *Alexandrium* abundances and PSP toxicity were first observed in New Hampshire in mid-May and by late May MA DMF detected PSP at stations north of Cape Ann. By mid-June, *Alexandrium* abundances (>1,000 cells L^{-1}) and elevated PSP toxicity were observed at the NH DES stations and MA DMF reported the first detectable PSP toxicity levels along the South Shore on June 22, which led to a blue mussel closure for Massachusetts Bay and triggered the 2022 ARRS (Libby et al. 2013). Very high *Alexandrium* abundances were observed during the June 28 survey with a maximum of 10,180 cells L^{-1} in the surface waters at station N10 off Hull (**Figure 2-30** and **Table 2-2**).

Other high counts of >1,000 cells L^{-1} were observed from the north at station F22, to western nearfield stations, and further south to stations along the South Shore. These high abundances were observed less than a week after PSP toxicity was first detected within Massachusetts Bay. Three additional ARRS surveys were conducted in July with decreasing abundances in each successive survey, though they remained above the 100 cells L^{-1} contingency threshold and ARRS trigger level. By late July, *Alexandrium* was present at very low abundances indicating the end of the bloom, consistent with MA DMF reporting no detectable PSP toxicity in Massachusetts Bay and lifting the remaining shellfishing closures on July 25. The initiation and progression of the bloom was similar to that observed during the recent blooms in 2019 and 2021 with high abundances not observed until the late June survey, and a pattern consistent with the transport of bloom cells from northern waters into the bay.

Zooplankton taxa, seasonal patterns, and abundances in 2022 were generally similar to those of most previous years (**Figure 2-31**). 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 were due to high abundances of radiolarians similar to the past two years. 2020 was the first time radiolarians had been recorded in the sampling program. Doliolids, which are warm-water planktonic tunicates, were recorded for the first time in the MWRA sampling area in October 2022. The presence of the radiolarians and doliolids suggests intrusions of offshore Gulf of Maine waters into Massachusetts Bay, which is consistent with the comparatively warm waters recorded for 2022 in 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 2022 suggest numbers may be increasing again.

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