2024 Water Column Monitoring Results

Massachusetts Water Resources Authority
Environmental Quality Department
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Cover Photo: View of Deer Island from station F23.
Credit: Scott Libby, Battelle on the October 2024 MWRA survey WN249.

2024 Water Column Monitoring Results

Submitted to

Massachusetts Water Resources Authority
Environmental Quality Department
33 Tafts Avenue
Boston, MA 02128
(617) 242-6000

Prepared by

P. Scott Libby[1]
David Borkman[2]
Rocky Geyer[3]
Jeff Turner[4]
Amy Costa[5]
Christopher Goodwin[6]
Jianjun Wang[6]

[1]Battelle
72 Main Street
Topsham, ME 04086

[2]University of Rhode Island
Narragansett, RI 02882

[3]Woods Hole Oceanographic Institution
Woods Hole, MA 02543

[4]University of Massachusetts Dartmouth
North Dartmouth, MA 02747

[5]Center for Coastal Studies
Provincetown, MA 02657

[6]Massachusetts Water Resources Authority
Boston, MA 02128

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Environmental Quality Report 2025-08

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA), as part of its National Pollutant Discharge Elimination System (NPDES) permit for the Deer Island Treatment Plant, is required to monitor water quality in Massachusetts and Cape Cod Bays. 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 2024 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. The Contingency Plan thresholds are designed to signal change from baseline conditions before wastewater diversion, not necessarily to indicate environmental degradation.

Overall, 2024 was an unremarkable year with typical seasonal patterns, water quality parameters close to long-term medians, no large phytoplankton or harmful algal blooms, and moderate bottom water dissolved oxygen (DO) levels. There were no exceedances of the water column thresholds for chlorophyll and bottom water DO concentrations or harmful algal bloom species *Alexandrium* and *Pseudo-nitzschia* (**Table i**).

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 2024 found elevated ammonium concentrations above baseline conditions frequently within 10 km (6 miles) of the outfall and intermittently both spatially and temporally up to 20 km (12 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 (Deltares 2025), despite a reported exceedance of the Contingency Plan threshold for effluent nitrogen loading in 2024[2]. Other noteworthy observations during 2024 include:

Physical Conditions

- The most notable physical oceanographic characteristics of 2024 were the unusually wet winter/spring and persistent upwelling favorable winds over most of the summer.
- River flows in the winter/spring of 2024 were the highest observed during the 33-year monitoring program and remained high into April before decreasing and being relatively dry for the remainder of the year.
- Surface and bottom water salinity reflected the wet winter/spring and high river flows with lower salinity values from February to May 2024.
- Persistent upwelling favorable winds in June and July resulted in decreased surface water temperatures and disrupted the seasonal decline in bottom water DO levels across most of Massachusetts and Cape Cod Bays.

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[1] MWRA's discharge permit includes a Contingency Plan with thresholds that may indicate a need for action if exceeded. The thresholds are based on permit limits, state water quality standards, conditions during the 1992-2000 baseline monitoring period, and expert judgment. "Caution-level" thresholds indicate a need for a closer look at the data to determine the reason for an observed change. "Warning-level" thresholds are a higher level of concern, for which the permit requires a series of steps to evaluate whether adverse effects occurred and, if so, whether they were related to the discharge. If exceedances were related to the discharge, MWRA might need to implement corrective action.

[2] https://www.mwra.com/media/file/20250117_tpx.pdf

Table i. Contingency Plan threshold values and 2024 results for water-column monitoring. There were no exceedances of the water column thresholds in 2024.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2024
Bottom water DO[a] concentration (mg L^{-1})	Survey Mean June-October	<6.5[b]	<6.0[b]	Nearfield[c]: 6.05 SW[d] Basin: 6.23	Nearfield: 6.24 SW Basin: 6.45
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 69.2% SW Basin: 68.7%
Bottom water DO rate of decline (mg L^{-1} d^{-1})	Seasonal June-October	>0.037	>0.049	0.024	0.023
Chlorophyll (nearfield mean, mg m^{-2})	Annual	>108	>144	72	61
	Winter/spring	>199	--	50	40
	Summer	>89	--	51	56
	Autumn	>239	--	90	102
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	73
	Summer	>43,100	--	14,635	28,200
	Autumn	>27,500	--	10,500	727
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	96

[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) northeast of the outfall and just outside the boundary of the Stellwagen Bank National Marine Sanctuary.

- The summer upwelling effect kept fall DO minima from reaching lower levels in 2024 and there were no exceedances of the DO Contingency Plan thresholds in the nearfield or Stellwagen Basin in 2024 (**Table i**).
- Winds followed typical patterns, with:
    - Storm systems producing intense winds from the northeast (known as Nor'easters) during the winter/spring.
    - Persistent upwelling-favorable winds out of the south observed in June and July.
    - Strong fall winds/storms in October mixed the water column at shallower, nearfield stations, but it wasn't until mid-November that the fall overturn of the water column occurred 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 2024, concentrations were relatively high in February. A sharp decline in silicate concentrations along with declines in nitrogen levels from February to March suggests there may have been a diatom bloom in the bay during the period between the two monthly MWRA surveys. Strong upwelling in June and July led to nutrient levels at or above historical long-term medians over the summer. In October, nutrient concentrations decreased to low levels coincident with an increase in chlorophyll levels and centric diatoms.
- As in other years since outfall startup, compared to the baseline years 1992-2000, the 2024 ammonium concentrations during both winter (unstratified) and summer (stratified) were lower in Boston Harbor, higher in the outfall nearfield, intermittently elevated from 10 to 20 km of the

outfall, and unchanged further afield. Spatial variability of the effluent plume signal due to prevailing currents was evident with variable and elevated ammonium observed within the nearfield, 10-20 km to the south in May and August, and several kilometers to the northeast at station N04 in July.

- 2024 chlorophyll levels were low for most of the year. Modest seasonal peaks were observed in March associated with a winter/spring diatom bloom that likely occurred between the two winter surveys and a larger peak in October observed in Massachusetts and Cape Cod Bays coincident with an increase in diatom abundances (not fall bloom levels). The increase in October was also observed at the Northeastern Regional Association of Ocean Observing Systems (NERACOOS) Buoy A01, with a prolonged period of high fluorescence readings in the surface water from late September until early November.
- Cape Cod Bay had a slightly different seasonal pattern than Massachusetts Bay with elevated chlorophyll concentrations in March and April, over the summer, and then again in October. These higher levels were increases in different centric diatom species each season.
- The low chlorophyll concentrations observed in 2024 led to Contingency Plan Threshold values for seasonal and annual nearfield chlorophyll well below caution levels and close to baseline means (**Table i**).

Bottom Water Dissolved Oxygen

- Bottom water DO concentrations were close to historical median levels in the winter/spring, before reaching surprisingly low concentrations in May in both Massachusetts and Cape Cod Bays. Strong upwelling-favorable conditions in June and July mitigated the decreases in bottom water DO concentrations in the bays, resulting in moderate levels in the late summer and fall.
- DO minima in Massachusetts Bay were moderate with levels ≥6.24 mg L^{-1} and ≥68.7% in October 2024 and no bottom water DO thresholds were exceeded in 2024 (see **Table i**). DO bottom water minima in Cape Cod Bay were above 6.5 mg L^{-1} and well above the hypoxic levels observed in recent years.
- Seasonal trends in bottom water DO levels in the nearfield and station F22 compared to NERACOOS Buoy A01 suggest variations in DO are regional, rather than local at the outfall site. Intense winds prior to the October survey mixed the water column deep enough to ventilate the bottom waters at station N18 near the outfall but not deep enough to cause significant ventilation at 50 m depth at NERACOOS Buoy A01 and station F22. Deep mixing did not occur until late November. This is typical of the fall mixing pattern in Massachusetts Bay, in which the shallow sites mix earlier than the deep sites.

Phytoplankton and Zooplankton

- Total phytoplankton abundances were near long-term mean levels with no exceptional blooms observed in Massachusetts Bay. This was due to low winter-spring diatom abundances, the lack of *Phaeocystis pouchetii*, and reduced dinoflagellate abundance (especially compared to 2023). Conditions were different in Cape Cod Bay which had higher abundances and a March-April 2024 bloom of *Guinardia delicatula* that was not observed in Massachusetts Bay. There were summer and autumn increases in the centric diatoms *Leptocylindrus minimus*, *Leptocylindrus danicus*, *Dactyliosolen fragilissimus*, and *Skeletonema* spp..
- There were no threshold exceedances for nuisance species in 2024 (**see Table i**). *Alexandrium* abundances were low and paralytic shellfish poisoning (PSP) toxicity was not detected in Massachusetts Bay. Abundances of *Pseudo-nitzschia* were well below threshold levels in the winter and fall and about half the summer threshold. There was a regional bloom of *Pseudo-*

nitzschia spp. in May 2024 that consisted primarily of narrow cell (< 3 um wide) forms (i.e., *Pseudo-nitzschia delicatissima*) and Massachusetts Division of Marine Fisheries (MA DMF) shellfish monitoring programs did not detect any domoic acid toxin during this bloom.

- Zooplankton taxa and abundances in 2024 were generally similar to those observed during previous years of the monitoring program, with abundances for total zooplankton close to the long-term median for most of the year. Seasonal patterns were atypical with small increases from winter lows to moderate spring and summer peaks at most stations and substantial increases in zooplankton abundance in October. The highest abundances observed in October were overwhelmingly dominated by radiolarians and were comparable to the historically high abundances observed during summer peaks of bivalve veliger larvae in previous years.
- Radiolarians are more oceanic and warmer water taxa than those typically observed in the MWRA sampling area. Radiolarians were first observed for the monitoring program in 2020 and have now been seen every year since. It may be that Massachusetts Bay is showing signs of warming associated with the northward extension of the Gulf Stream. The warming waters may be influencing changes in the species distribution and abundance in Massachusetts Bay and are important to consider when evaluating trends in many of the Massachusetts Bay monitoring parameters going forward.

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
EMMS	Environmental Monitoring and Management System
EPA	U.S. Environmental Protection Agency
HAB	harmful algal bloom
km	kilometer
l	liter
m	meter
mg	milligram
MA DMF	Massachusetts Division of Marine Fisheries
MODIS	Moderate-resolution Imaging Spectroradiometer
MWRA	Massachusetts Water Resources Authority
NDBC	National Data Buoy Center
NERACOOS	Northeastern Regional Association of Coastal and Ocean Observing Systems
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

1 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) started monitoring Boston Harbor and Massachusetts and Cape Cod Bays in 1992, to assess baseline conditions before the Deer Island Treatment Plant started discharging treated effluent to Massachusetts Bay 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 monitoring 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). For this report, the baseline period with Deer Island and/or Nut Island discharges to the harbor spans from 1992 to September 5, 2000, and the outfall discharge period extends from September 6, 2000 through 2024, when wastewater has been discharged from the bay outfall and not into the harbor. The 2024 data complete 24 years of monitoring since operation of the bay outfall began and 33 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**). 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. *Alexandrium* abundances were low in 2024 and no additional *Alexandrium* Rapid Response Study (ARRS; Libby et al. 2013) surveys were conducted. Separately from the AMP, MWRA conducts nutrient, chlorophyll, and bacteria monitoring at several stations in Boston Harbor.

This annual report summarizes the 2024 water column monitoring results, examines conditions over the seasonal cycle during 2024, 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 2024.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN241	February 8	February 8	February 8
WN242	March 20	March 20	March 27
WN243	April 9	April 9	April 9
WN244	May 14	May 13	May 14
WN245	June 18	June 16	June 25
WN246	July 24	July 24	July 23
WN247	August 21	August 18	August 22
WN248	September 4	September 4	September 11
WN249	October 17	October 22	October 22

WN = the nine surveys undertaken each year; 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. 2024). 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. Electronically gathered and laboratory-based analytical results are stored in the MWRA Environmental Monitoring and Management System (EMMS) database. The EMMS database undergoes extensive quality assurance and technical reviews. All data for this Water Column Summary Report have been obtained by export from the EMMS 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 2024 sampling dates are shown in **Table 1-2**. Stations within about 8 kilometers (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 in which the three Cape Cod Bay stations were sampled by CCS. The August and October surveys were conducted three and five days apart, respectively, due to sea conditions.

Nutrient data from the 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.[3] MWRA collects samples at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally a biweekly frequency.[4] The BHWQM data (nutrient and DO) collected within 7 days (**Table 1-2**) of an AMP survey are included in this report.

In addition to survey data, this report includes Moderate-resolution Imaging Spectroradiometer (MODIS) satellite observations provided by the National Aeronautics and Space Administration, and continuous monitoring data from both the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) Buoy 44013 and the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) Buoy A01. The satellite imagery provides information on regional-scale patterns, while the buoys sample multiple depths at a single location with high temporal frequency. Buoy 44013 is located ~10 km southeast of the outfall, near station N07; Buoy A01 is in the northwestern corner of Stellwagen Bank National Marine Sanctuary and ~5 km northeast of station F22 (**Figure 1-1**). The time series current observations from Buoy A01 presented and interpreted in the report are the non-tidal currents, isolated from tidal variations by application of a low-pass (33-hour cutoff Butterworth) filter to the raw current data.

The data are grouped by season for calculation of chlorophyll and *Pseudo-nitzschia* Contingency Plan thresholds. Seasons are defined as 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 2024. 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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[3] CCS station map and data available at http://www.capecodbay-monitor.org/

[4] BHWQM station map ("nutrient monitoring") at http://www.mwra.com/harbor/graphic/harbor_sampling_locations_detail.jpg

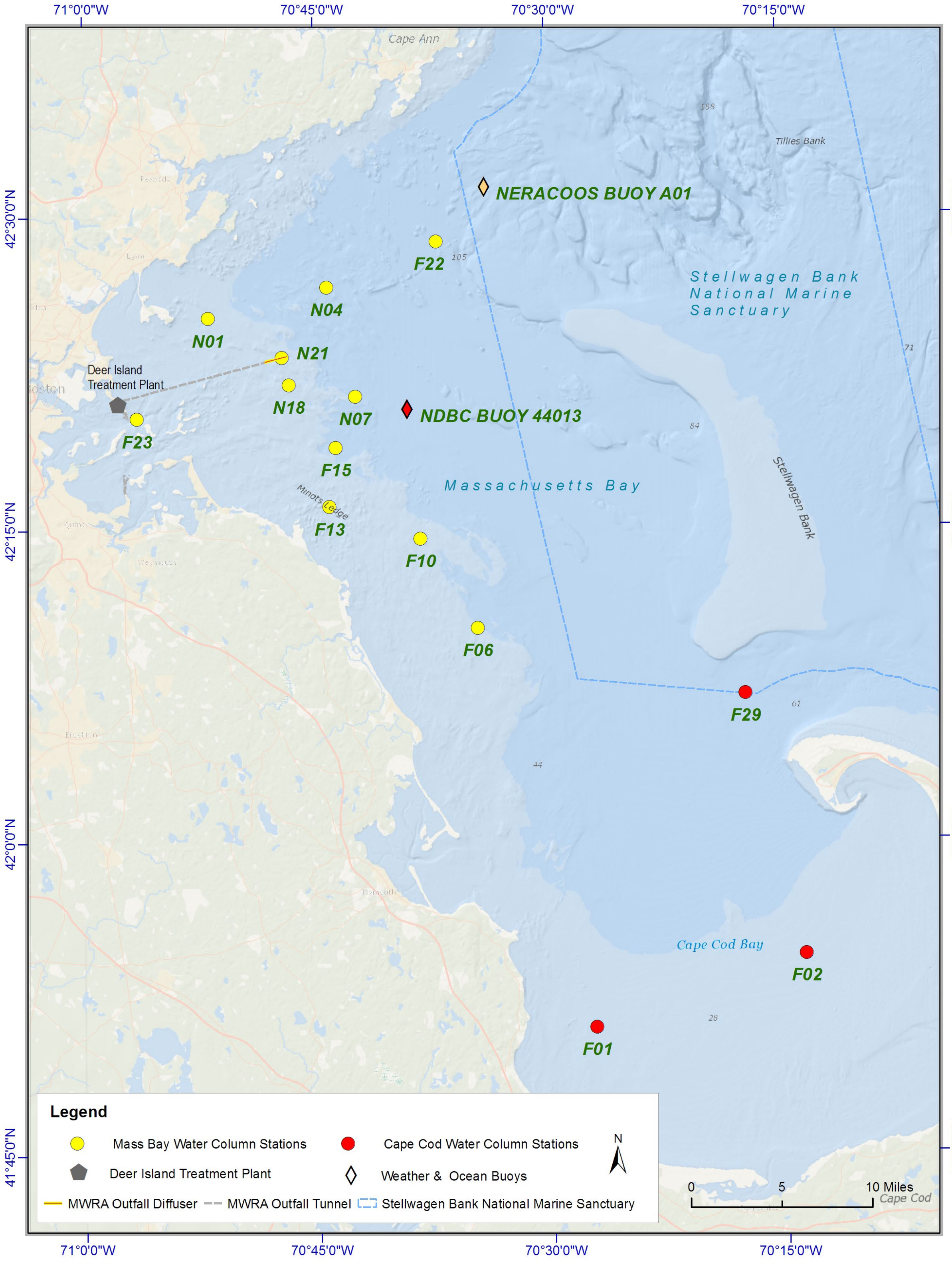


Figure 1-1. Water column monitoring locations.

2 2024 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 well as 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 July of certain years, *Alexandrium catenella*, the organism responsible for paralytic shellfish poisoning (PSP), is typically transported from the north into the bay by prevailing currents. 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. This deeper layer is 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 33-year dataset (1992-2024). The major features and differences observed in 2024 are described below.

2.2 PHYSICAL CONDITIONS

The most notable physical oceanographic condition in 2024 was the unusually wet winter which caused low salinities in Massachusetts Bay in winter/spring 2024. River flows in January to April were very high in both the Merrimac and Charles Rivers (**Figure 2-1**). Flows were the highest of the monitoring program during the first quarter of the year and remained elevated into April, but the remainder of the year was relatively dry. Over the 33-year period of the program, annual mean river flow remains variable and there are no long-term trends in the data.

To provide an overview of physical conditions in Massachusetts Bay in 2024, stations N18 and F22 are discussed. These stations are representative of the nearfield and of waters entering Massachusetts Bay from the north, respectively. The wet winter and high river flows were reflected in both surface and bottom water salinity below historical minima in February at both stations and remaining below or near the minima in March and April 2024 (**Figure 2-2**). Salinity values remained in the lower historical range in May and June before increasing in July in the surface waters. Both stations remained close to the long-term salinity median for the remainder of the year. Bottom water salinity at station N18 also increased in July and remained at the historical median. However, bottom water salinity at the deeper offshore station, F22, remained below or at the historical minima through October.

Surface water temperatures were at or above the long-term median at station N18 from February to June before decreasing below the long-term minima in late July due to upwelling (**Figure 2-3**). Surface water temperatures increased sharply from late July to late August and remained in the upper quartile of historical levels for the remainder of the year. This trend was muted at station F22 where temperatures were closer to historical median levels for most of the year. Bottom water temperatures were elevated above the historical median from February to April and then were close to the median for the remainder of the year. The main exception was higher bottom water temperatures at station N18 in October. Air temperatures were close to average in 2024 at NERACOOS buoy A01.

Wind speeds and directions were typical in 2024, with several storm systems producing strong northeast winds (known as nor'easters) during the winter/spring. Strong northeasterlies result in strong near-surface currents and in the late spring often provide a conduit for the transport of surface waters and plankton such as *Alexandrium* from the Gulf of Maine into Massachusetts Bay. In early April 2024, a strong nor'easter produced 8-m wave heights and transported lower salinity waters in the bay as evidenced during the April survey (**Figure 2-2**). Nor'easters in May and June resulted in surface currents of around 0.25 m/s (~ 20 km/day) at the NERACOOS buoy A01, providing a transport pathway from the western Gulf of Maine into Massachusetts Bay. If there had been *Alexandrium catenella* cells present in the western Gulf of Maine, they would have been brought into Massachusetts Bay, but this was not the case in 2024.

The impact of the summer wind events was noted in the surface water temperatures in July and evident in the upwelling favorable winds in June and July 2024 (**Figure 2-4**). The upwelling index is the monthly average of the north-south component of wind stress. A positive index indicates more wind from the south, which favors upwelling and cooling of both surface and bottom waters. The index showed strong upwelling in June and July, tapering off in August with weak upwelling and switched to downwelling in September (**Figure 2-5**). The negative upwelling index corresponds to the warmer waters observed in the nearfield during the late summer/fall of 2024 (**Figure 2-3**).

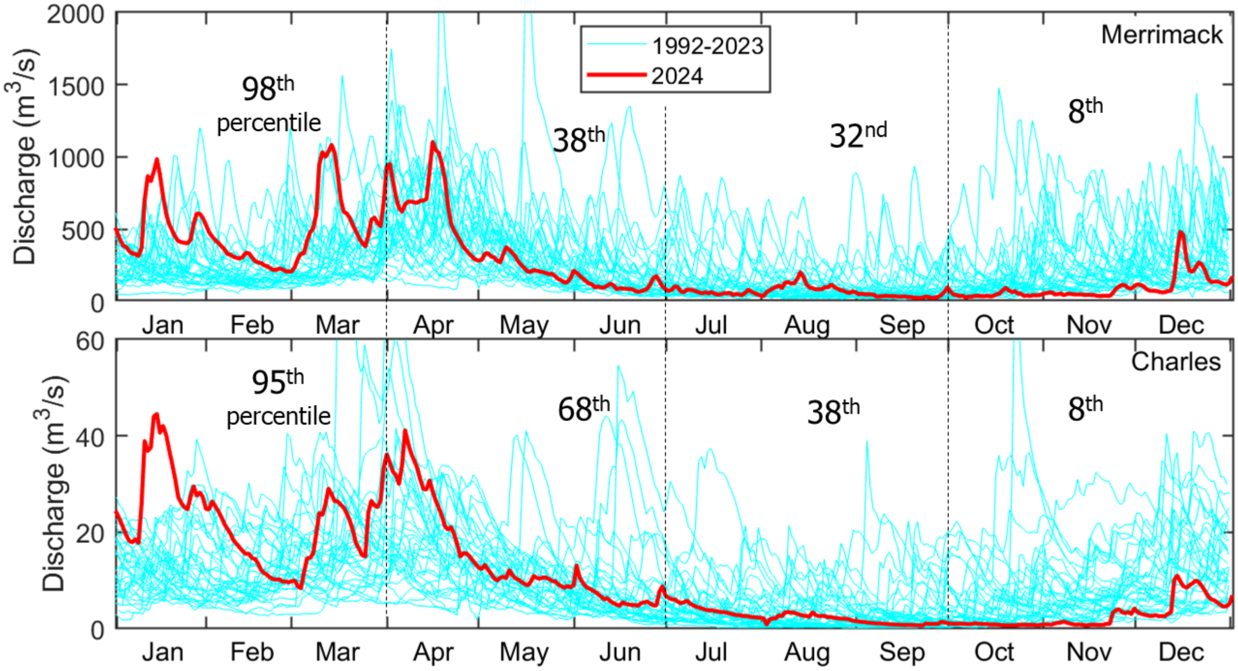


Figure 2-1. **Comparison of 2024 river flow (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2023 (light blue lines).** The percentiles represent 2024 flow, compared to the entire 33-year record, during each quarter of the year.

Stratification was close to the historical median from February to May, before weakening during mid-summer due to cold surface waters associated with upwelling (**Figure 2-6**). Stratification returned to historical median levels in August and September. The water column remained stratified in October at deeper, offshore station, but was well mixed at many of the shallower stations. A time series depiction of conditions at NERACOOS Buoy A01 in October and November 2024 illustrates the influence of wind-mixing events during the fall (**Figure 2-7**). The intense winds observed on October 12-14 resulted in a sharp drop in near-surface temperatures and a corresponding increase in density. This mixing event was deep enough to ventilate the bottom waters at station N18 near the outfall but not deep enough to cause significant ventilation at 50 m depth at NERACOOS Buoy A01 or nearby station F22 (**Figure 2-6** and **Figure 2-7**). Deep mixing did not occur until mid-November. This is typical of the fall mixing pattern, in which the shallow sites mix earlier than the deep sites.

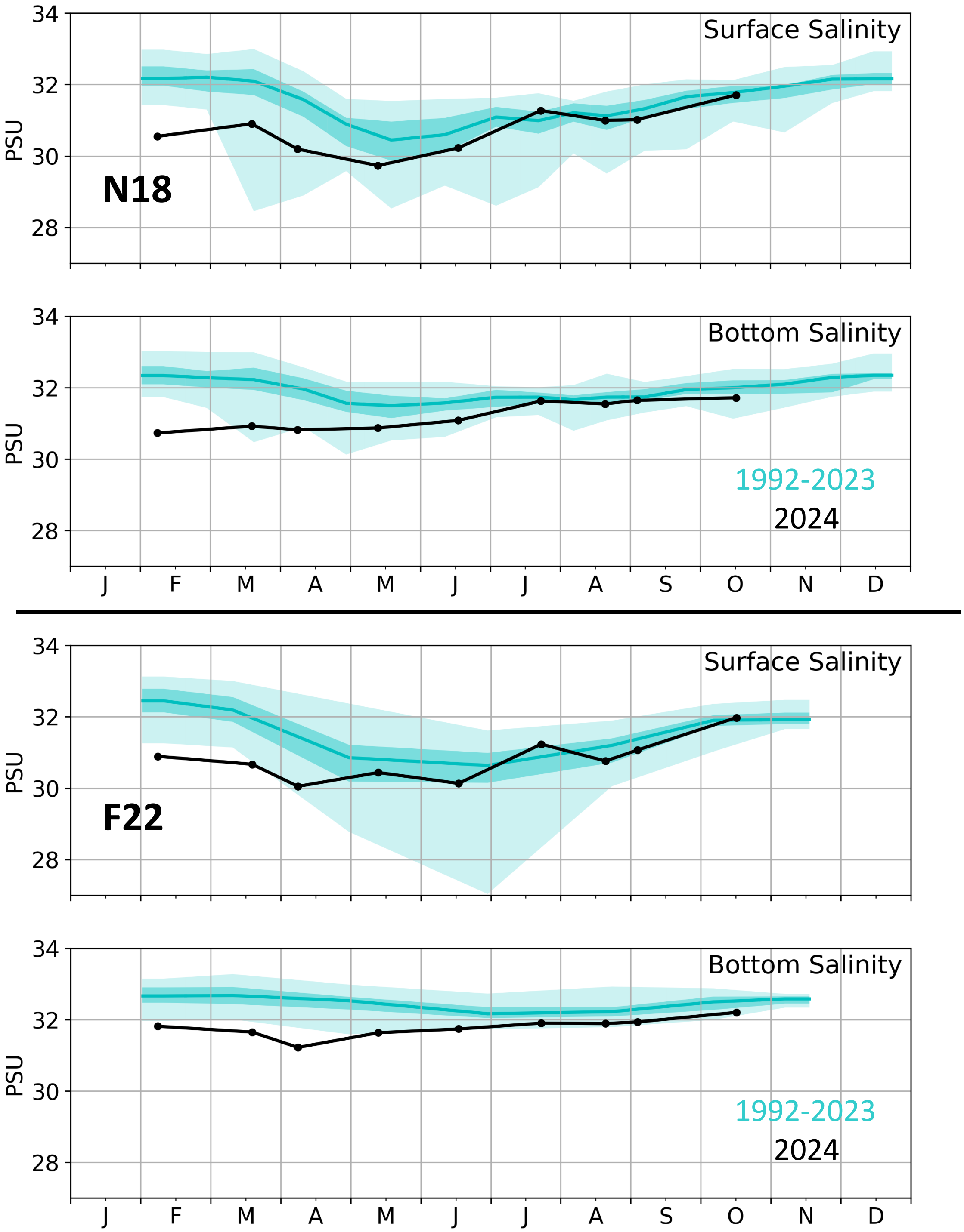


Figure 2-2. Comparison of 2024 surface and near bottom water salinity (PSU) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

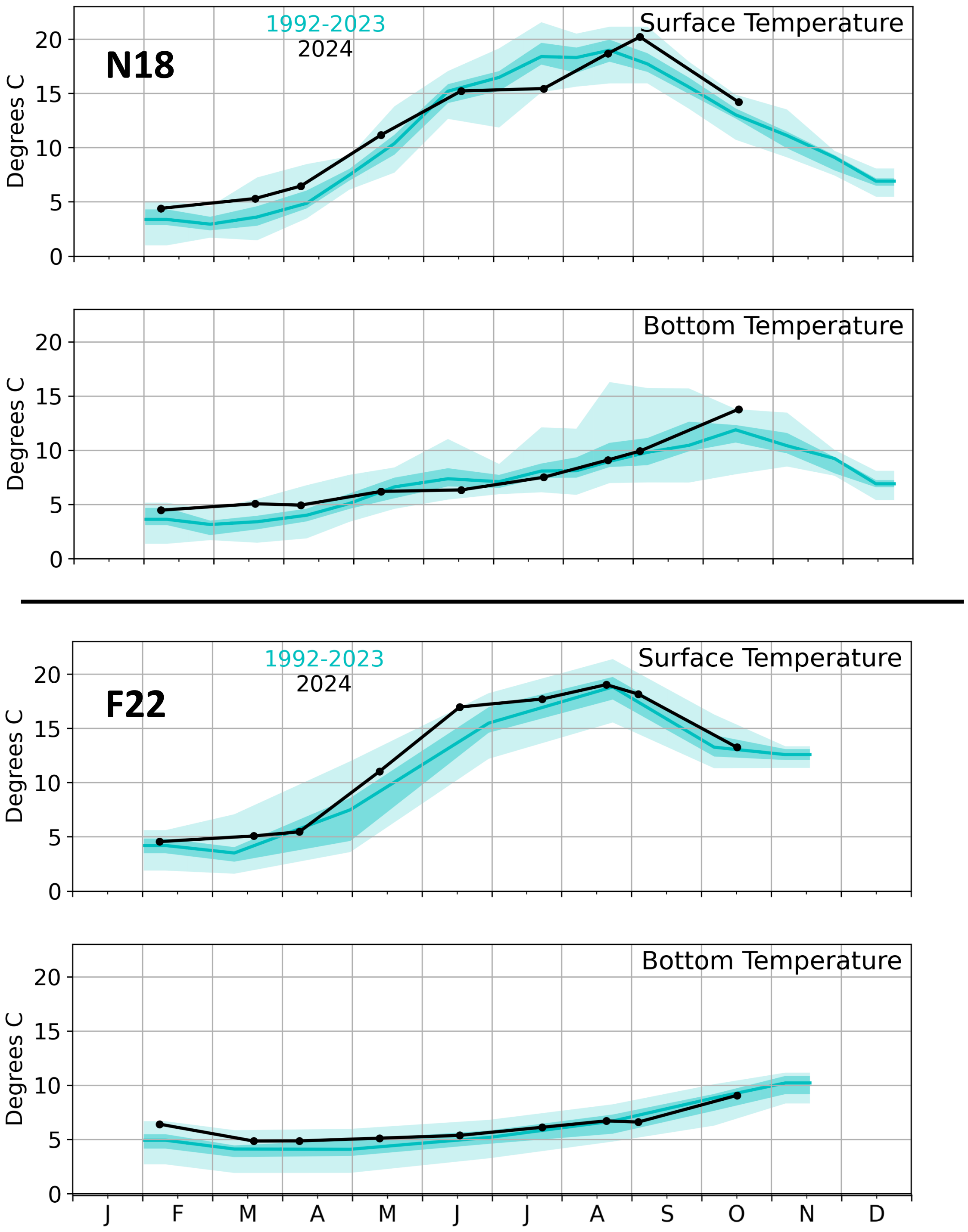


Figure 2-3. Comparison of 2024 surface and near bottom water temperature (°C) at nearfield station N18 (top) and farfield station F22 (bottom) relative to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

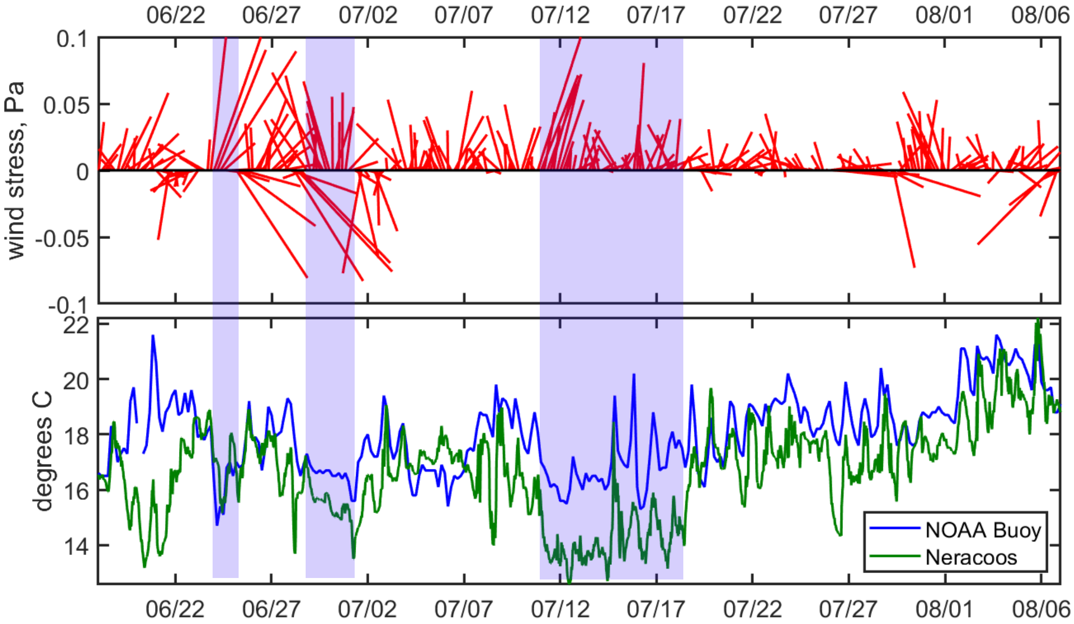


Figure 2-4. NERACOOS Buoy A01 and NOAA NDBC Bouy time series observations of surface wind stress (Pa) and direction and temperatures summer of 2024. The red lines represent winds in the direction away from the origin line; northward up and eastward to the right. Vertical blue blocks highlight cooling during upwelling events.

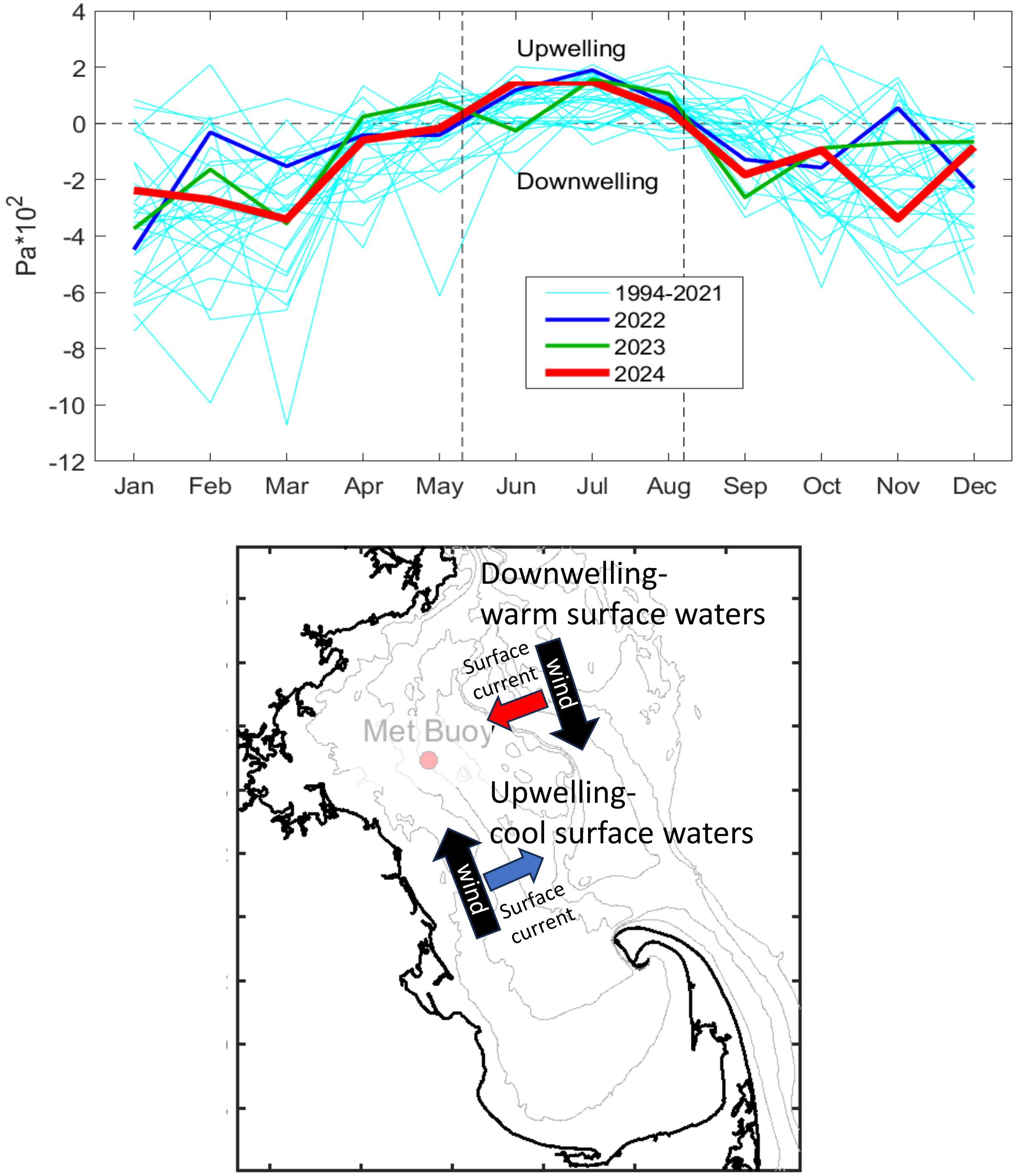


Figure 2-5. Upwelling index (100 x Northward component of wind stress; Pascals) at NOAA Buoy 44013. 2024 results are in red, 2023 in green and 2022 in blue. Results from 1994–2021 in cyan. As depicted in the bottom figure, positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

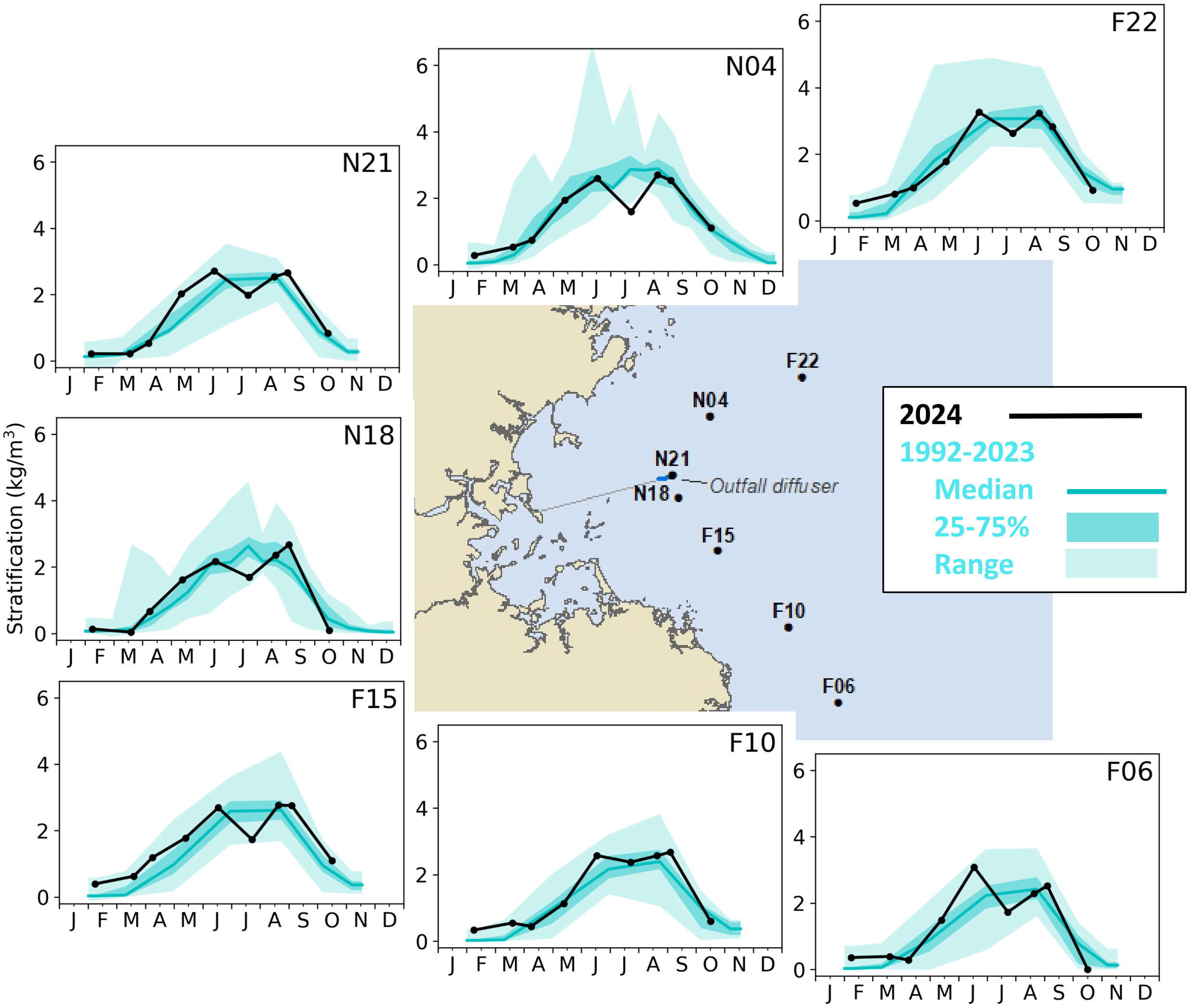


Figure 2-6. Stratification (Δ sigma-t; kg m^{-3}) at selected stations in Massachusetts Bay for 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

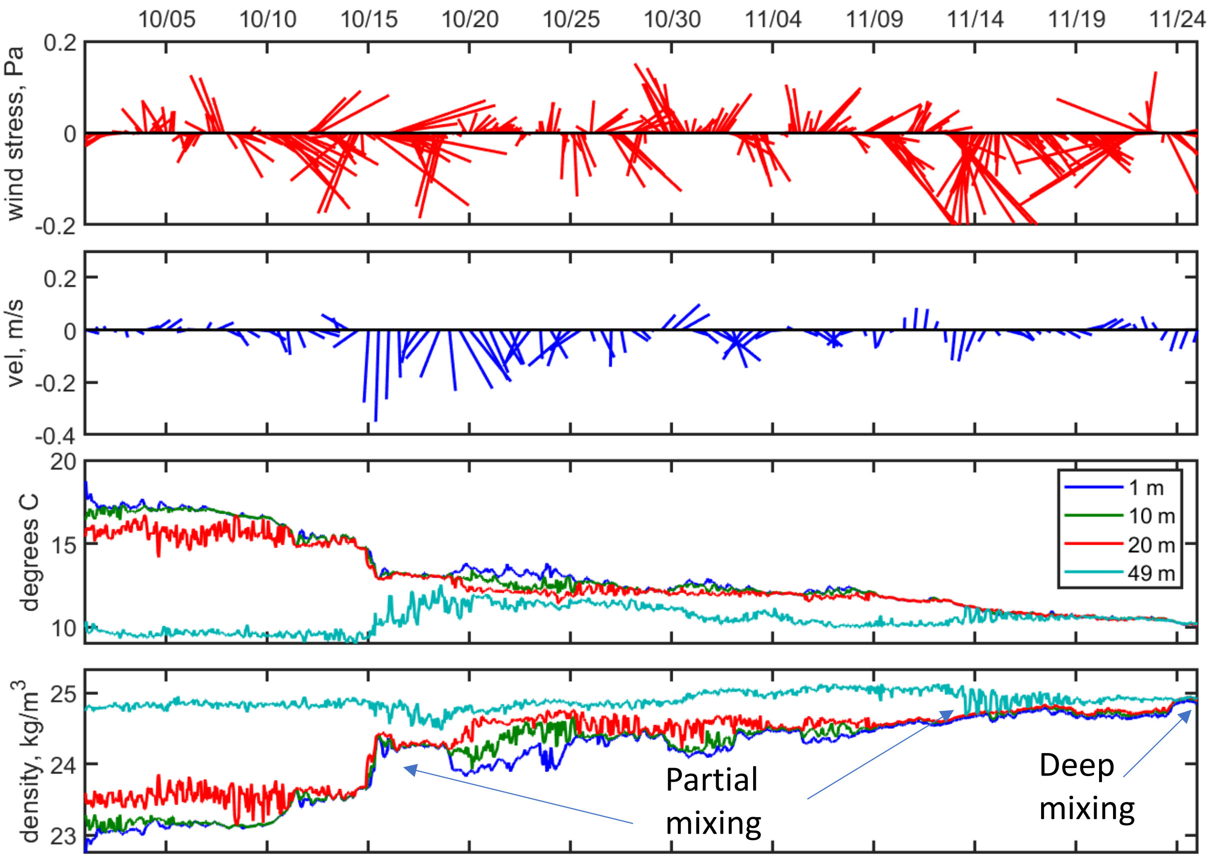


Figure 2-7. NERACOOS Buoy A01 time series observations of surface wind stress (Pa), surface current (m/s), temperature, and density October and November 2024. The red lines represent winds and the blue lines represent the direction of the currents from the origin line; northward up and eastward to the right.

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

This section documents dissolved inorganic nutrient concentrations and phytoplankton biomass in the bay during 2024. 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 and were close to long-term medians for most of 2024 with a few departures from the trends which are discussed below (**Figure 2-8**). Ammonium (NH_4) does not exhibit this seasonal pattern in the bay as seasonal changes are driven by increases in ambient levels in the summer associated with decomposition of biogenic material and recycling of nitrogen and the most notable NH_4 signal is associated with the effluent plume. Ammonium levels were quite variable in 2024 with a maximum well above the historical range in June (**Figure 2-8**, upper right).

Nitrate concentrations were at the historical median at most stations in February and March, while SiO_4 levels were high at the 75th percentile in February, before decreasing sharply into the lower 25th percentile in March (**Figure 2-8**). NH_4 and PO_4 concentrations at station N18 were above and close to the upper quartile in February, respectively, before decreasing in March. The sharp decline in SiO_4 concentrations from February to March suggests there may have been a diatom bloom in the bay during the period between these two surveys. This is also consistent with a slight increase in chlorophyll fluorescence observed at some stations in March (see **Figure 2-13**). MODIS imagery and NERACOOS Buoy A01 fluorescence data are often useful in filling the information gaps between surveys. Unfortunately, there was an issue with the buoy sensors, and no data were available until late summer. The MODIS imagery showed elevated fluorescence levels compared to the survey results for most of 2024.

From March to April, there was a sharp increase in nutrient concentrations at station N18 and throughout Massachusetts Bay from levels below the median in March to the upper quartile of long-term levels at most stations in April (**Figure 2-8**). NO_3 and PO_4 concentrations decreased from April to May but remained above long-term median levels across the bay, while SiO_4 concentrations decreased below the median in May (**Figure 2-8** and **Figure 2-9**). The variability in nutrients during the winter/spring 2024 was influenced by the high level of precipitation and river flows observed during this period (see **Figure 2-1**).

From May to August, NO_3 and SiO_4 concentrations remained slightly above the long-term median at station N18, while levels of NH_4 and PO_4 were much more variable due to the influence of the bay outfall. This was especially evident in June when maxima in both NH_4 and PO_4 station average concentrations were observed at station N18 (**Figure 2-8**). 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**). The elevated levels of all nutrients were also influenced by strong upwelling in June and July 2024, bringing near-bottom waters into the surface layer. By October, nutrient concentrations decreased to low levels, with concentrations in the lower quartile at many stations (**Figure 2-8** and **Figure 2-9**). This was concomitant with increases in areal chlorophyll levels across the bay in late summer and fall (see **Figure 2-13**). The increase in October was also observed at the NERACOOS Buoy A01, with a prolonged period of high fluorescence readings in the surface water from late September until early November (see **Figure 2-15**).

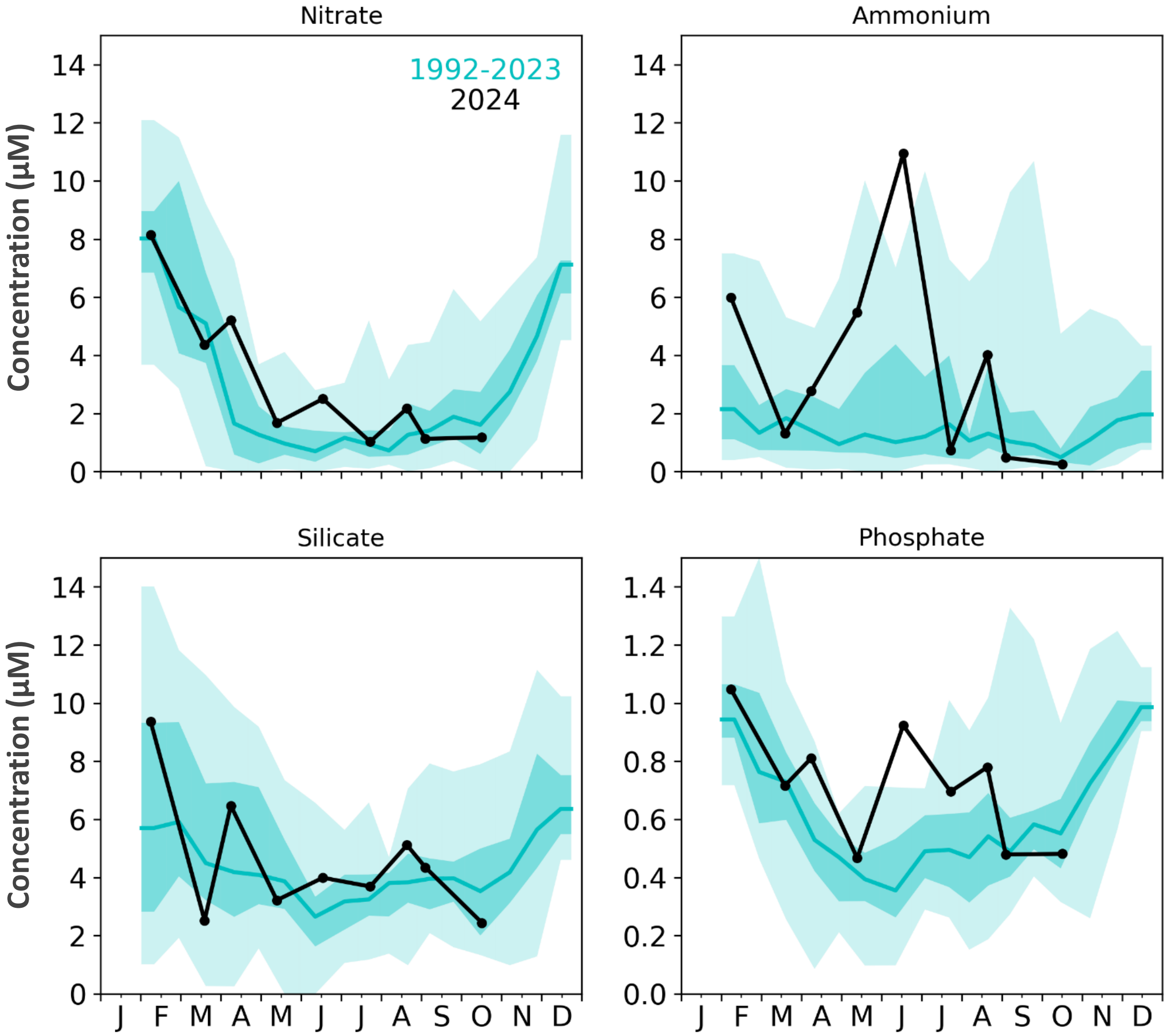


Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2024 compared to prior years. Note difference in scale for phosphate. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

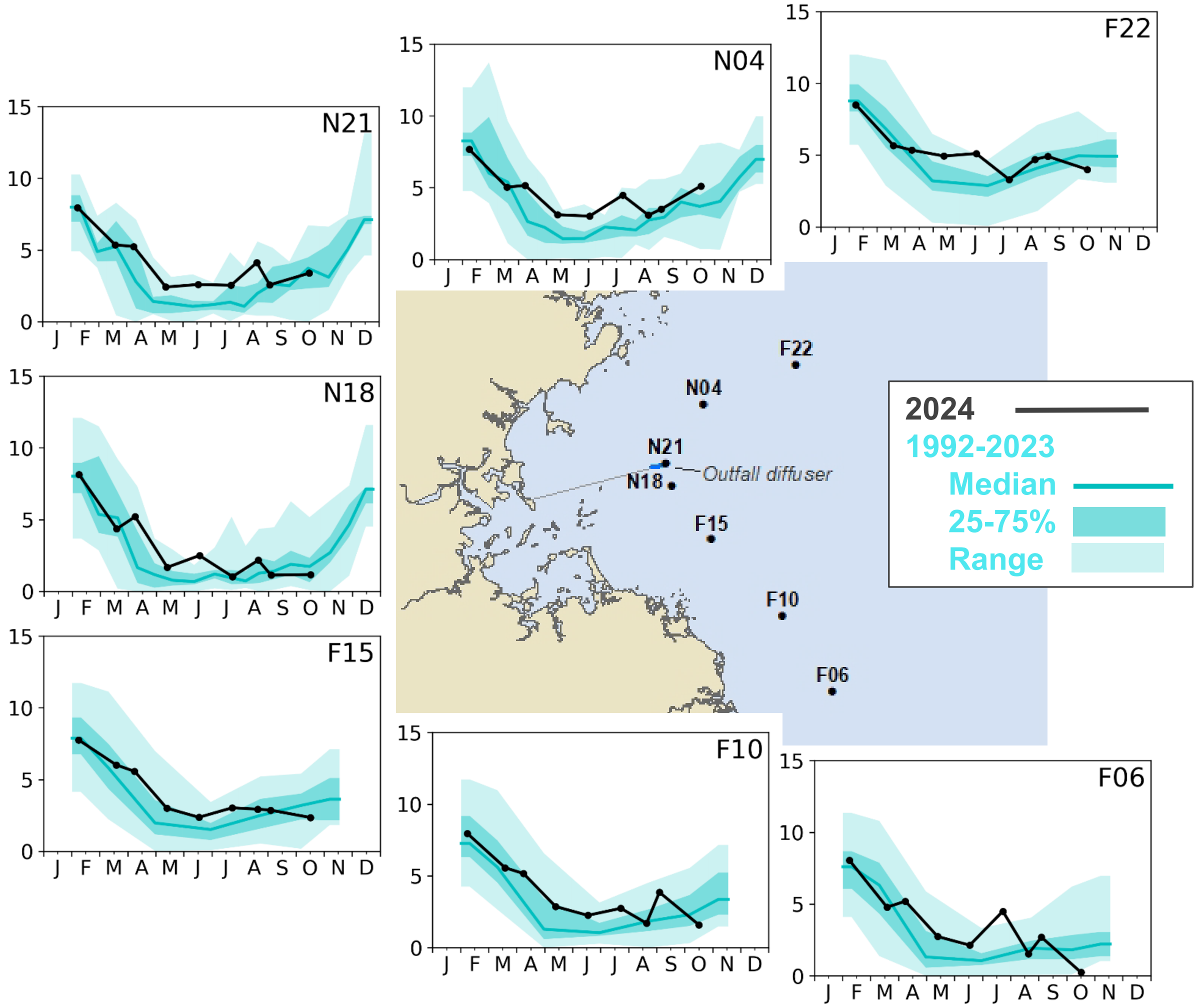
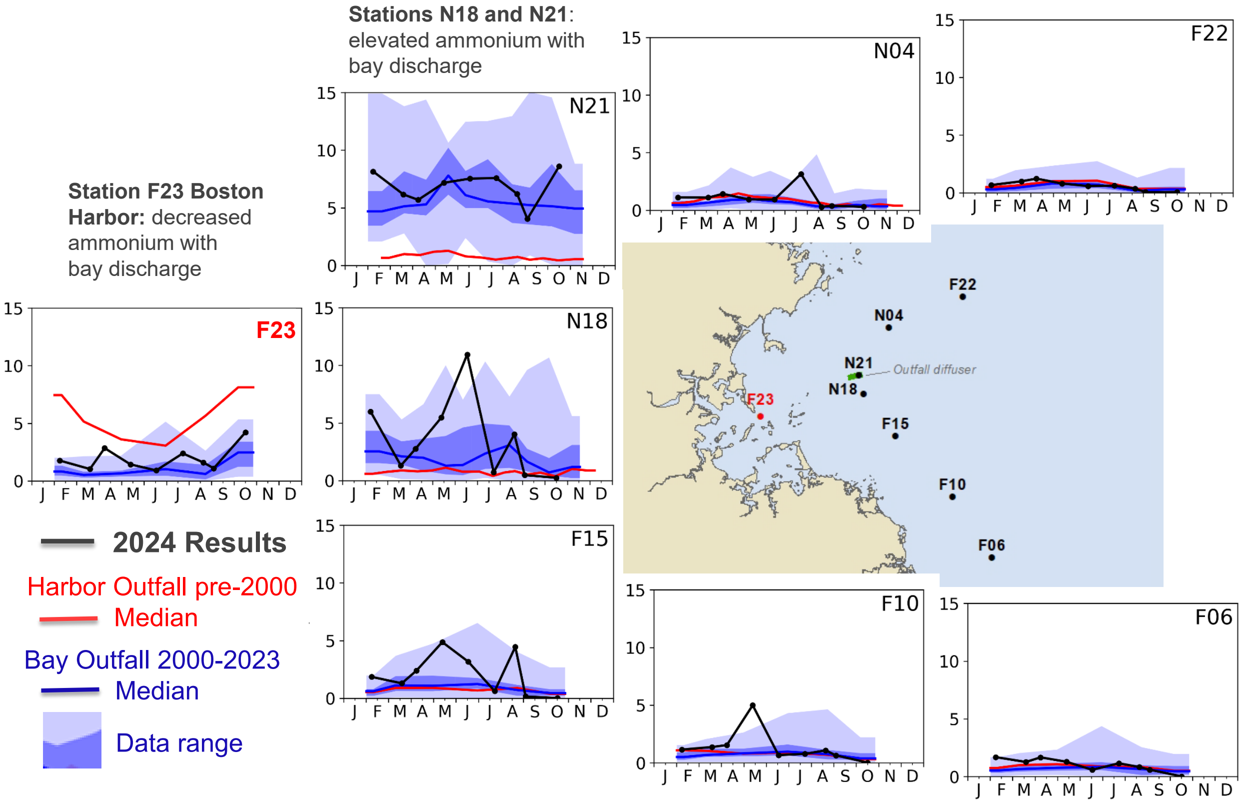


Figure 2-9. **Depth-averaged nitrate (µM) at selected stations in Massachusetts Bay for 2024 compared to prior years.** 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

As noted previously, NH_4 and PO_4 are highly variable in the nearfield (stations N18 and N21) due to elevated concentrations within the effluent plume compared to ambient levels. Each survey is a snapshot in time, and the location of the effluent plume changes based on current direction and magnitude, as well as stratification. The temporal variability is highlighted by the dramatic changes in average NH_4 concentrations at station N18 in 2024, with values close to minima in March, July, September and October but close to or above historical maxima in February, May, and June (**Figure 2-10**). Spatial variability in where the plume is transported is illustrated by the historically high NH_4 concentrations for the 33-year monitoring program of ~5 µM at stations 10-20 km to the south of the outfall at stations F15 and F10 in May and again at station F15 in August 2024. Additionally, in July 2024, when NH_4 concentrations were very low at station N18, they were elevated at station N04 to the northeast of the outfall. NH_4 levels at other Massachusetts Bay and Cape Cod Bay stations were low and consistent with post-diversion levels. Ammonium concentrations at Boston Harbor station F23 in 2024, again as in other post-discharge years, were much lower than during the years when wastewater was discharged directly to the harbor.



Stations N18 and N21: elevated ammonium with bay discharge

Station F23 Boston Harbor: decreased ammonium with bay discharge

Figure 2-10. Depth-averaged ammonium (NH_4; µM) at selected stations in Massachusetts Bay for 2024 compared to prior years. 2024 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2023) 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 May and August 2024 up to 20 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 May and August 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 and at station F15 10 km to the south (**Figure 2-12**). In May, elevated NH_4 concentrations (>8 µM) were also observed in shallower waters at station F10 which is 20 km south of the outfall. Note that the high NH_4 level at station F10 was associated with a shallower pycnocline at that station and NH_4 was lower in the surface water. Elevated concentrations of NO_3 were also observed below the pycnocline along these transects in May and August. However, the availability of NH_4 and NO_3 did not result in elevated fluorescence levels in May and a narrow sub-surface chlorophyll maximum with moderate concentrations was observed in August (**Figure 2-12**).

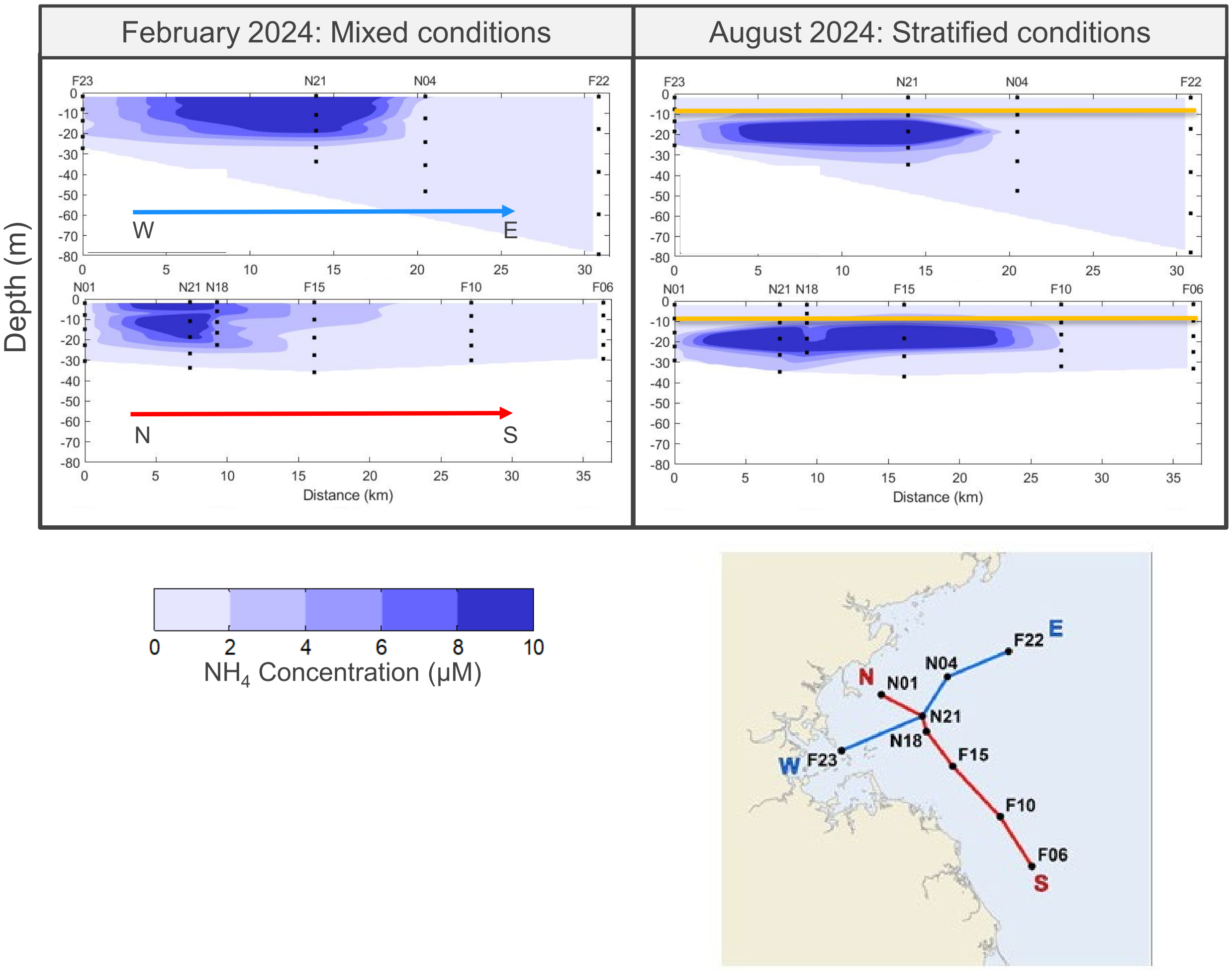


Figure 2-11. Cross-sections of water column ammonium (NH_4) concentrations along transects connecting selected stations in February and August 2024. Small black dots in the contour plots indicate the sampling depths for nutrients. The orange line is the approximate depth of the pycnocline during the August stratified conditions.

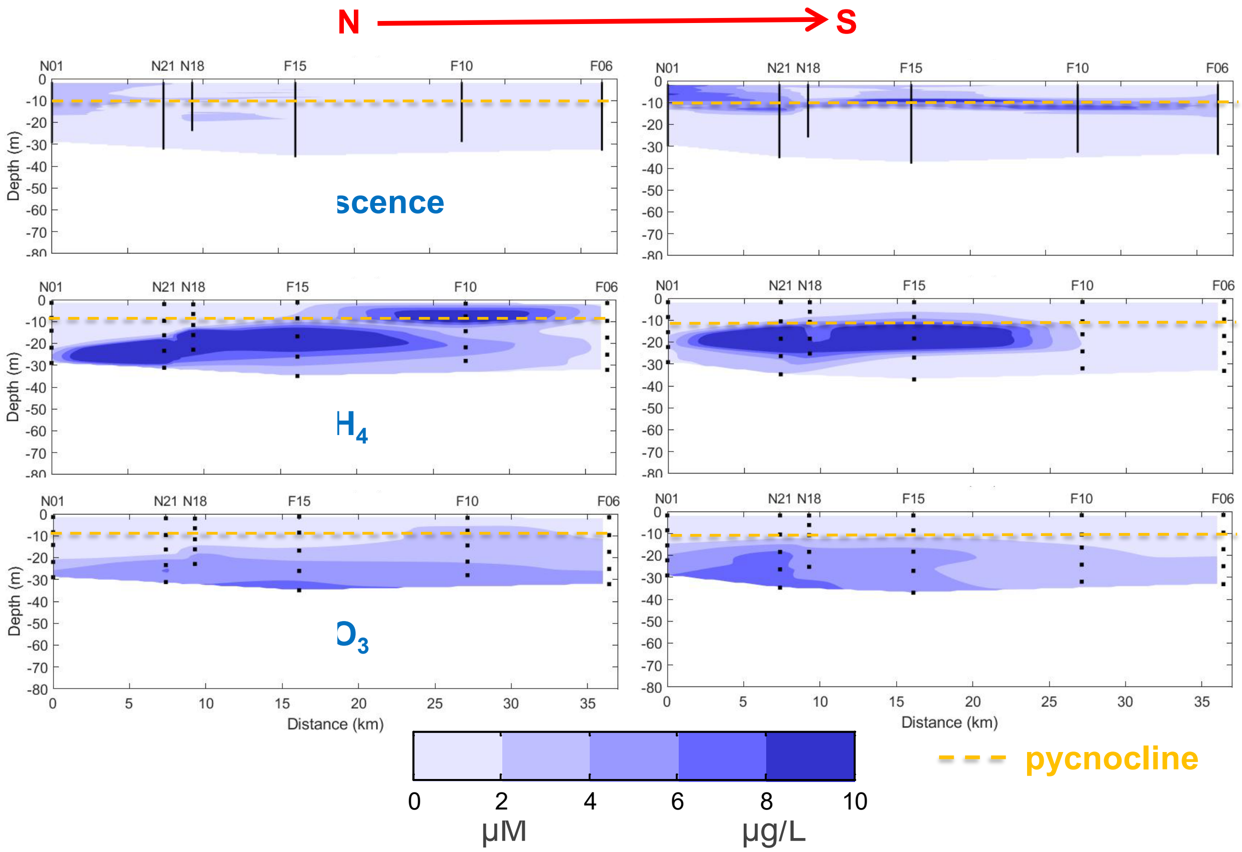


Figure 2-12. Chlorophyll from fluorescence (top; µg L^{-1}), ammonium (middle; µM), and nitrate (bottom; µM) during the stratified May (left) and August (right) 2024 survey along the north-south transects shown in Figure 2-11. Dots (nutrients) and lines (fluorescence) indicate the sampling depths and 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 during the fall, as seen in the historical results (shaded regions) in **Figure 2-13**. Modest seasonal peaks were observed during the 2024 surveys with a small peak in March. This peak was probably associated with a winter/spring diatom bloom that likely occurred between the two winter surveys. A larger peak in October across the bay coincided with a slight increase in diatom abundances.

Overall, 2024 chlorophyll levels were low and close to or below the historical median values for most of the year in Massachusetts Bay. Chlorophyll levels were low from February to August 2024, with a slight increase in March at some stations. During the summer, depleted surface nutrient concentrations and increases in nutrients at depth led to higher subsurface chlorophyll maximum levels near the pycnocline, as is typically observed in the bay (**Figure 2-12**). Chlorophyll levels increased in September and October at most of the Massachusetts Bay stations due to a mixed assemblage fall bloom (**Figure 2-14**). The increase in October was also observed at NERACOOS Buoy A01, with a prolonged period of high fluorescence readings in the surface water from late September until early November (**Figure 2-15**). Given the relatively low chlorophyll concentrations observed in the nearfield in 2024, Contingency Plan

Threshold values for seasonal and annual nearfield chlorophyll were all well below caution levels and close to baseline means (see **Table i**).

Cape Cod Bay had a slightly different seasonal pattern than seen in Massachusetts Bay during 2024 with elevated chlorophyll concentrations at stations F01 and F02 in March and April, over the summer, and then again in October. These higher levels were concomitant with higher abundances of a variety of centric diatoms during each season.

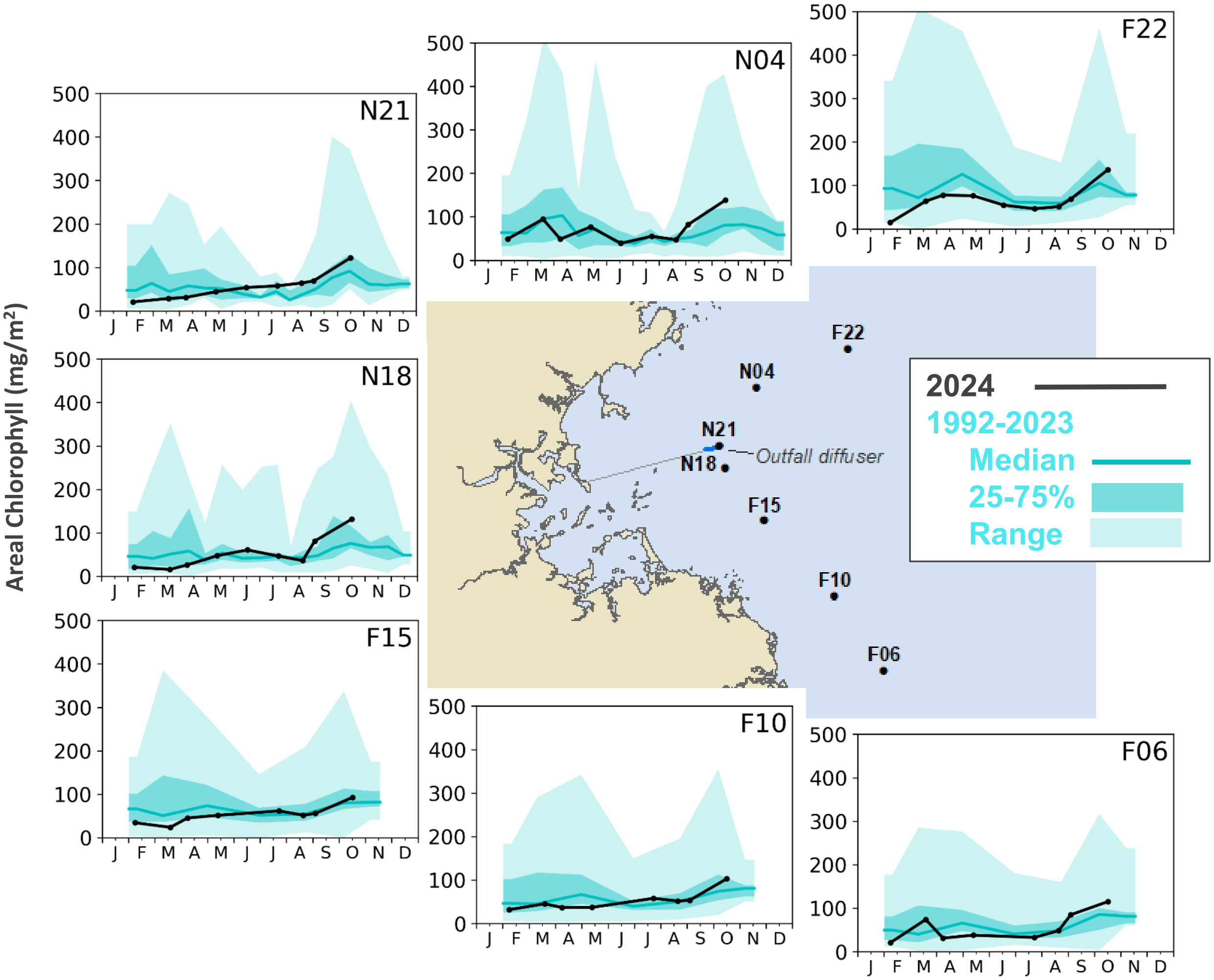


Figure 2-13. Areal chlorophyll from fluorescence (milligram per meter squared [mg m^{-2}]) at representative stations in Massachusetts Bay for 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

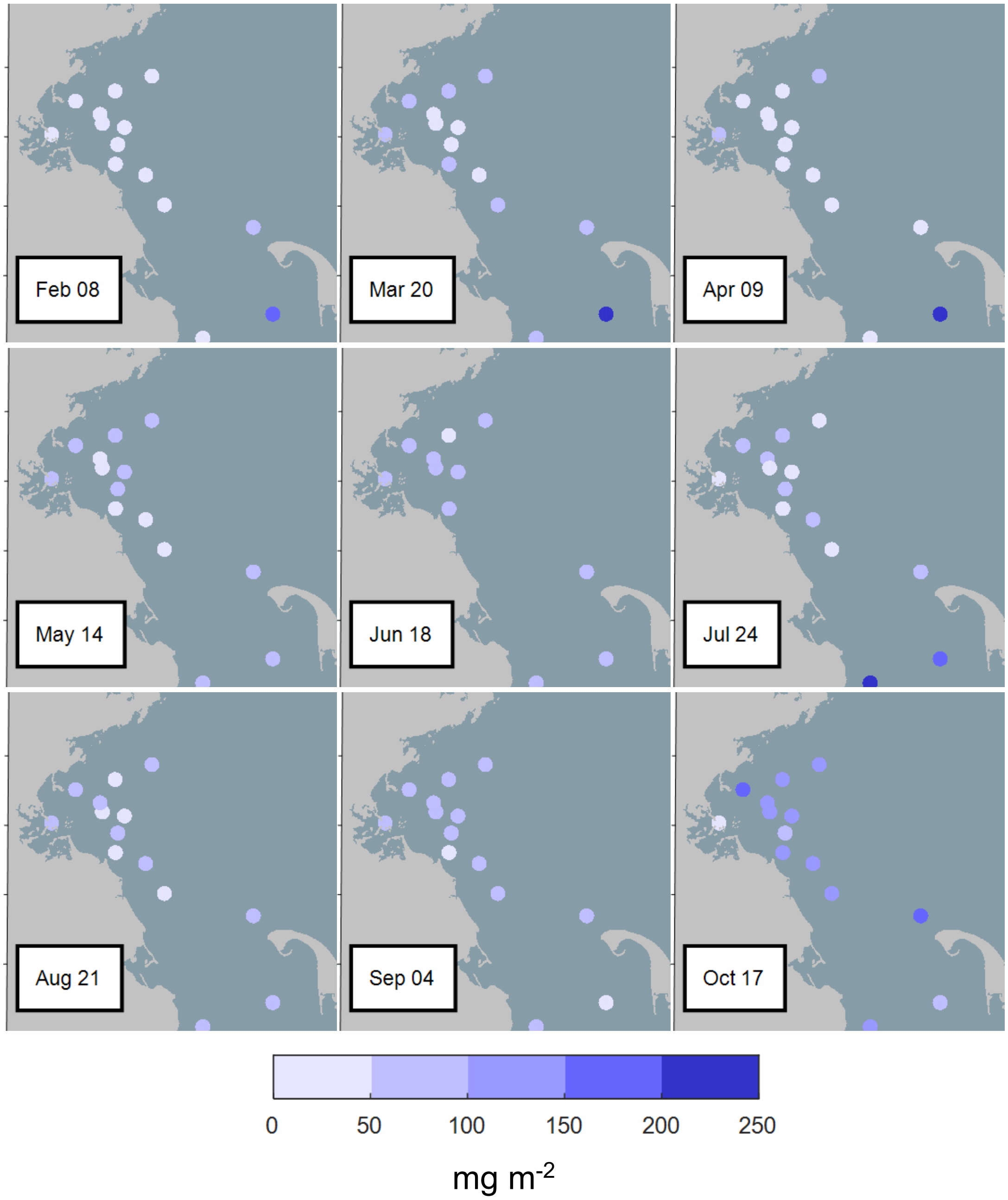


Figure 2-14. Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2024.

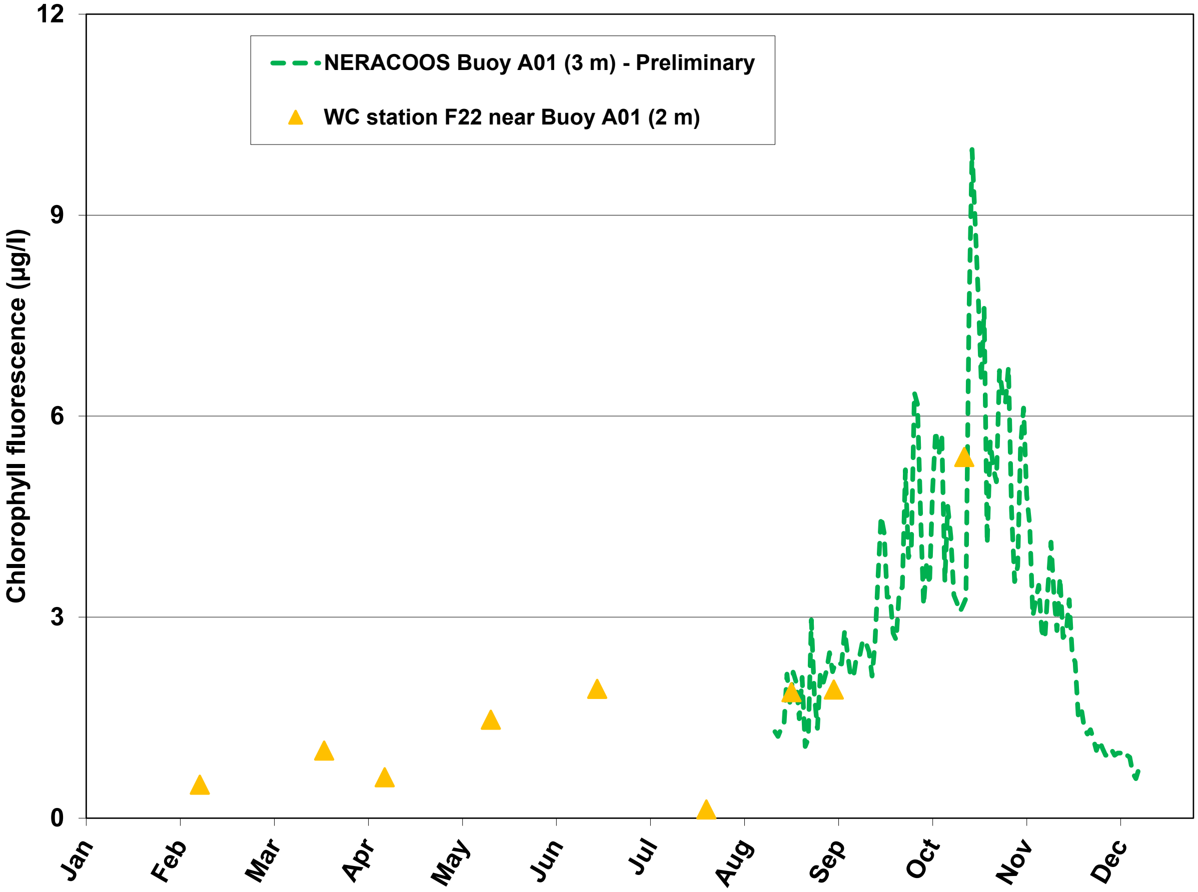


Figure 2-15. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (dashed green line) and water samples at nearby water column (WC) station F22 (yellow symbols) in 2024. The sensor failed in late 2023 through mid-August 2024; see Roesler 2025 for additional details.

2.4 BOTTOM WATER DISSOLVED OXYGEN

Typically, bottom water DO declines at a relatively constant rate in Massachusetts and Cape Cod Bays from winter/spring maxima to September or October annual minima, but in recent years mixing events have been observed that punctuated this seasonal decline. This was the case in 2024 with strong upwelling in June and July halting the decline midsummer before continuing into September/October (**Figure 2-16** and **Figure 2-17**). Bottom water DO levels were close to historical median levels at most stations during the February to April surveys, before reaching surprisingly low concentrations in May at many stations in both Massachusetts and Cape Cod Bays. Data from NERACOOS Buoy A01 suggest this may have been due to inflow of deep Gulf of Maine waters into the bay in April and May. Interestingly, the annual minima at station F01 was observed in June. Fortunately, strong upwelling-favorable conditions in June and July led to increases or leveling off of decreases in bottom water DO concentrations in the bays, averting seasonal decreases to lower levels in the late summer and fall. The 2024 annual DO minima in Massachusetts Bay were moderate with levels ≥6.25 mg L^{-1} observed in October (**Figure 2-16**). DO bottom water minima in Cape Cod Bay were above the long-term median from August to October 2024, remaining above 6.5 mg L^{-1} and well above the hypoxic levels observed in recent years (**Figure 2-17**). No bottom water DO thresholds were exceeded in 2024 (see **Table i**).

NERACOOS Buoy A01 data were only available from August to December 2024 but tracked survey data from station F22 very well. The DO data indicated that the water column started to mix to 50 m in mid-October after the final MWRA survey, but did not fully mix until mid-November (**Figure 2-18**). The observed decrease in DO at nearfield station N18 to the farfield station F22 and the NERACOOS Buoy A01 show that the variations of DO are regional, rather than local at the outfall site. As noted previously, the fall overturn of the water column in Massachusetts Bay is strongly influenced by storm wind-mixing events (see **Figure 2-7**). The intense winds prior to the October survey lowered near-surface temperatures. Additionally, the mixing event was deep enough to ventilate the bottom waters at station N18 near the outfall, but not deep enough to cause significant ventilation at 50 m depth at NERACOOS Buoy A01 (**Figure 2-18**). The deep mixing did not occur until late November. This is typical of the fall mixing pattern in Massachusetts Bay, in which the shallow sites mix earlier than the deep sites.

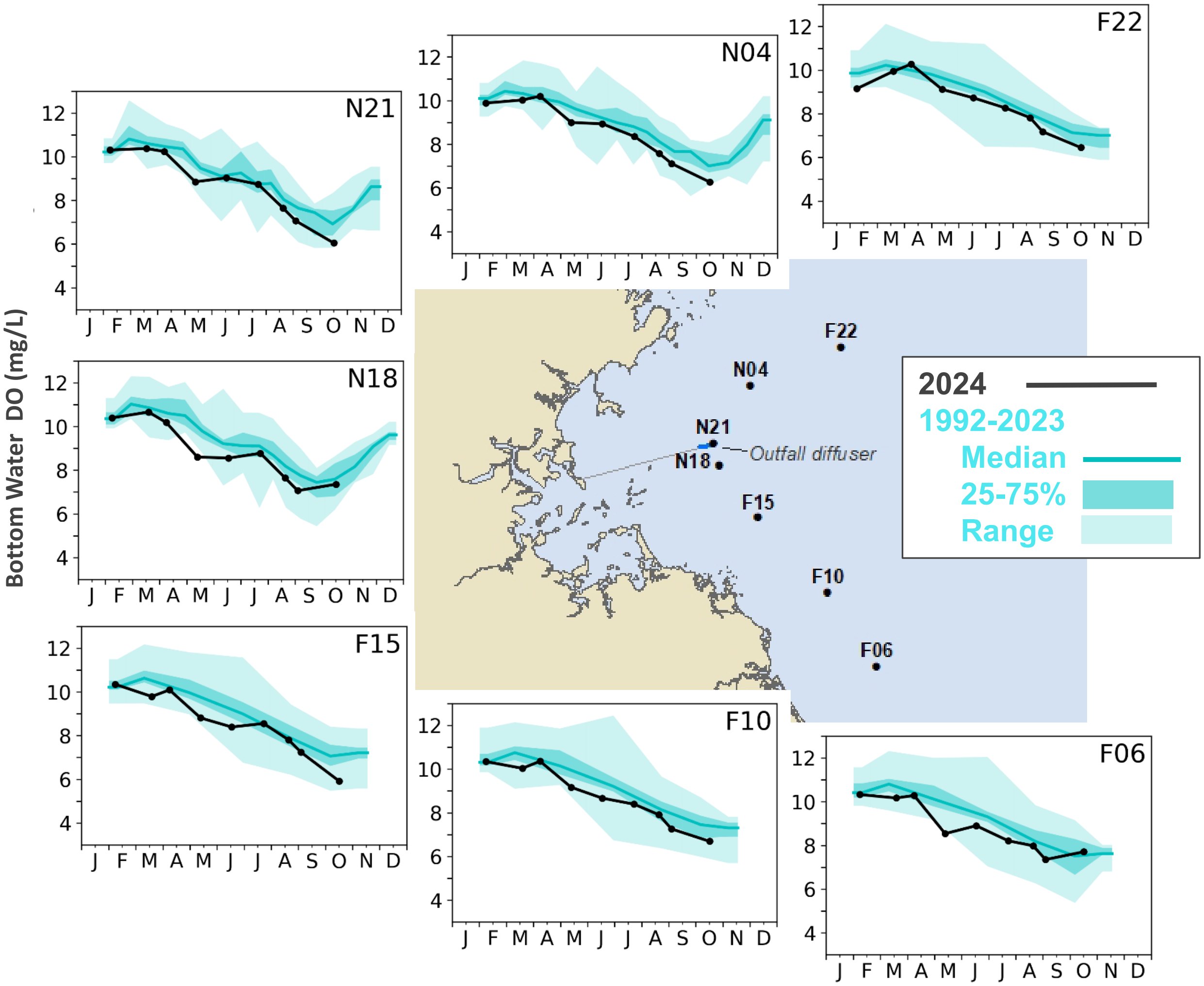


Figure 2-16. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

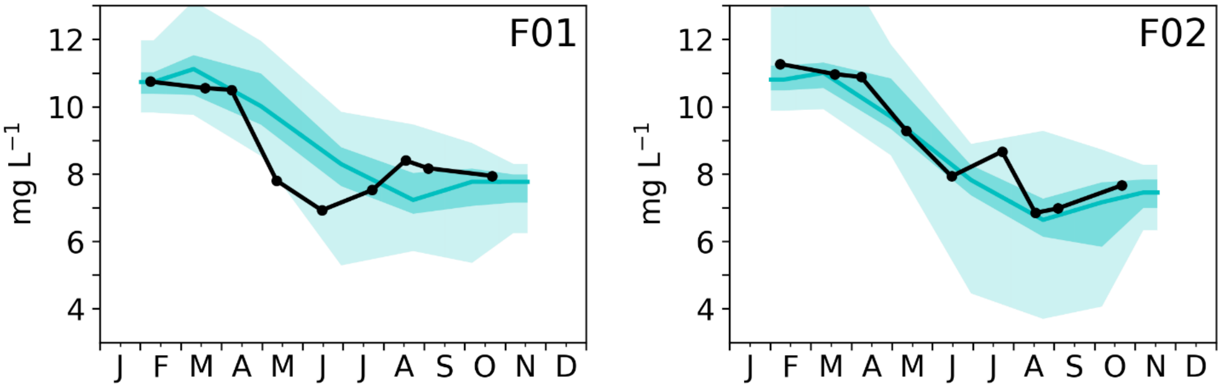


Figure 2-17. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

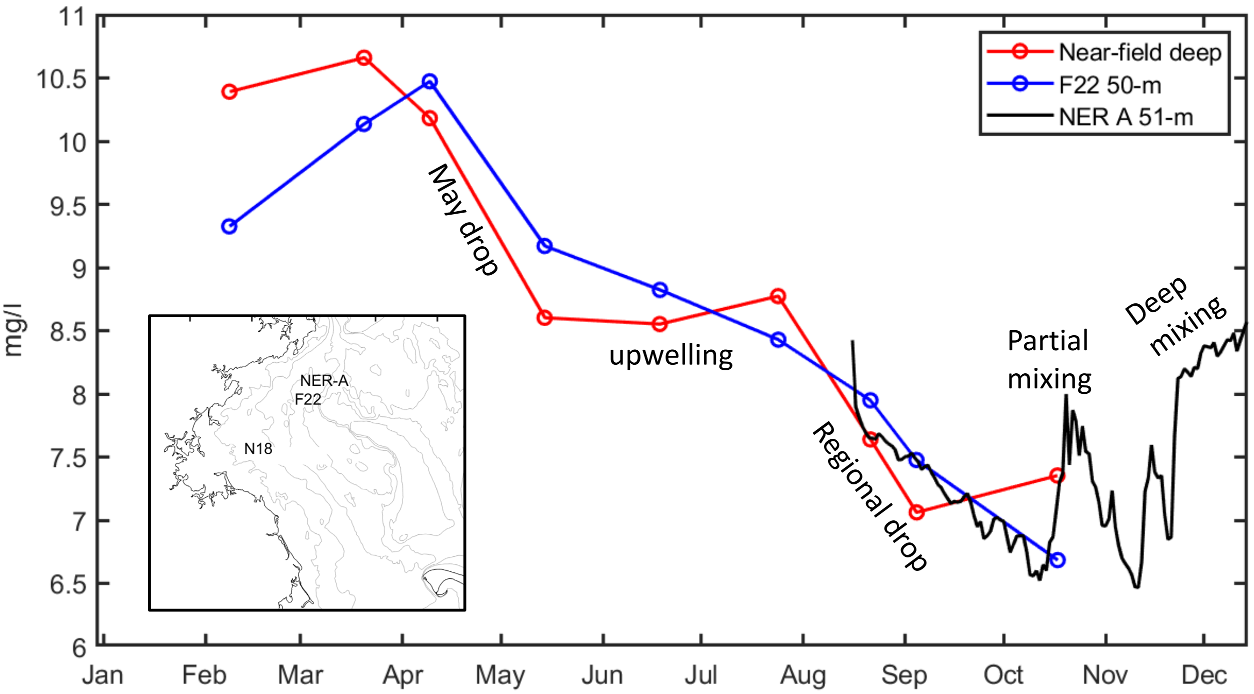


Figure 2-18. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (51 m; black) and at the deep bottom water at nearfield station N18 (red) and near bottom sampling depths (~50 m) at station F22 (blue) in 2024. The buoy values are daily means.

2.5 PHYTOPLANKTON ABUNDANCE

Overall, total phytoplankton measured in 2024 was near long-term mean levels with no exceptional blooms observed (**Figure 2-19**). This was partially driven by the lack of *Phaeocystis pouchetii*, reduced dinoflagellate abundance, and reduced winter-spring diatom abundance. Note that Cape Cod Bay had a March-April 2024 bloom of *Guinardia delicatula* that was not observed in Massachusetts Bay. Summer and autumn increases in the centric diatoms *Leptocylindrus minimus*, *Leptocylindrus danicus*, *Dactyliosolen fragilissimus*, and *Skeletonema* spp. resulted in a 2024 centric diatom abundance in the nearfield that was 76% greater than the 2019-2023 average. Microflagellate abundance, which is greatest during summer, was also elevated during 2024 compared to that seen in the prior 5 years.

2.5.1 2024 Phytoplankton Abundance

In 2024, total phytoplankton abundance in the nearfield ranked 20th of 33 years of monitoring, with an average concentration of 1.1 million cells L^{-1} in 2024 — a 32% increase compared to recent levels observed between 2019 and 2023 (**Table 2-1**). However, 2024 phytoplankton levels remained lower than those recorded during the first 20 years of monitoring (1992-2011) and slightly below those observed in 2023. This decrease is primarily due to the decline of *Phaeocystis pouchetii* over the past decade, as well as the absence of any significant bloom events (e.g., *Karenia mikimotoi, Tripos muelleri*) in 2024.

Centric diatom abundance was elevated relative to recent levels (2019-2023) in the nearfield during 2024 (**Table 2-1**). The 2024 centric diatom annual cycle featured near- to below-median levels in the winter-spring with abundances during February through April 2024 averaging 23,000 to 68,000 cells L^{-1} compared to average levels of 115,000 to 162,000 cells L^{-1} historically (1992-2023). However, in the summer centric diatom abundance was near or above long-term mean levels from May through August 2024. June 2024 centric diatom abundance in the nearfield (231,000 cells L^{-1}) was triple the historical mean level of 74,224 cells L^{-1}. This 2024 increase was largely due to elevated abundance of *Leptocylindrus danicus* and *Leptocylindrus minimus* **(Figure 2-20)**. *L. minimus* abundance in May and June 2024 was approximately 25 to 50 times higher compared to long-term mean May and June levels, respectively.

Centric diatom abundance in the nearfield during September 2024 was dominated by *Dactyliosolen fragilissimus* with a nearfield abundance of 155,000 cells L^{-1} that was 3.5-fold greater than the historical average (44,000 cells L^{-1}). In October, centric diatom were dominated by a mixed assemblage of *Skeletonema* spp. and *Leptocylindrus danicus*. The combination of reduced winter-spring diatoms and consecutive blooms of *L. minimus* and *L. danicus*, *Dactyliosolen fragilissima* and *Skeletonema* spp. during May through October 2024 gave the 2024 centric diatom annual cycle a summer-autumn peak rather than a winter-spring peak. Overall, the annual mean centric diatom abundance was below the long-term average and ranked 18th of 33 years (**Table 2-1**). The annual nearfield centric diatom abundance of 182,944 cells L^{-1} in 2024 was 76% higher compared to levels observed recently in 2019-2023.

Cape Cod Bay centric diatoms had a slightly different annual pattern than that seen in Massachusetts Bay during 2024. *Guinardia delicatula* was elevated to >250,000 cells L^{-1} in March and April at station F02; this was not observed in Massachusetts Bay samples. Similar to Massachusetts Bay, a bloom of *L. minimus* was observed in Cape Cod Bay during June (104,000 cells L^{-1} at station F01) and July (present at all stations at up to 175,000 cells L^{-1}). In September 2024, *Dactyliosolen fragilissimus* was elevated in Cape Cod Bay at 150,000 to 350,000 cells L^{-1}, similar to levels in Massachusetts Bay.

Table 2-1. 2024 annual mean nearfield phytoplankton abundance (cells L^{-1}) ranked for 1992-2024 period and compared to 2019-2023 abundances for major groups and species. Data are from the surface and chlorophyll maximum sampling depths at stations N16/N18. Significant differences compared to 2019-2023 means highlighted in green (increase) and red (decrease).

Group	**2024 Rank** (out of 33 years)	**2019-2023** (cells L^{-1})	**2024** (cells L^{-1})	**% change**	**p value**[1]
CENTRIC DIATOMS	18	104,130	182,944	+76%	0.007
Chaetoceros	17	5,043	5,701		0.097
Dactyliosolen fragilissimus	5	2,923	57,691		0.114
Skeletonema spp. complex	19	30,334	16,433		0.742
Thalassiosira	21	10,498	9,349		0.763
MICROFLAGELLATES	9	530,880	756,943	+43%	0.001
Phaeocystis pouchetii	27	16,673	0		0.238
CRYPTOPHYTES	22	67,396	81,555		0.551
DINOFLAGELLATES	27	78,269	41,559	-47%	0.003
Dinophysis	14	638	205		0.414
Prorocentrum	15	19,274	4,493	-77%	0.001
Tripos[2]	3	6,543	5,001		0.910
Tripos muelleri	14	5,289	254	-95%	0.046
PENNATE DIATOMS	12	22,642	23,659		0.064
Pseudo-nitzschia	7	13,289	13,307		0.929
TOTAL PHYTOPLANKTON	20	832,535	1,100,798	+32%	0.014

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

[2] *Tripos* includes all species in the genera – i.e., *Tripos muelleri*.

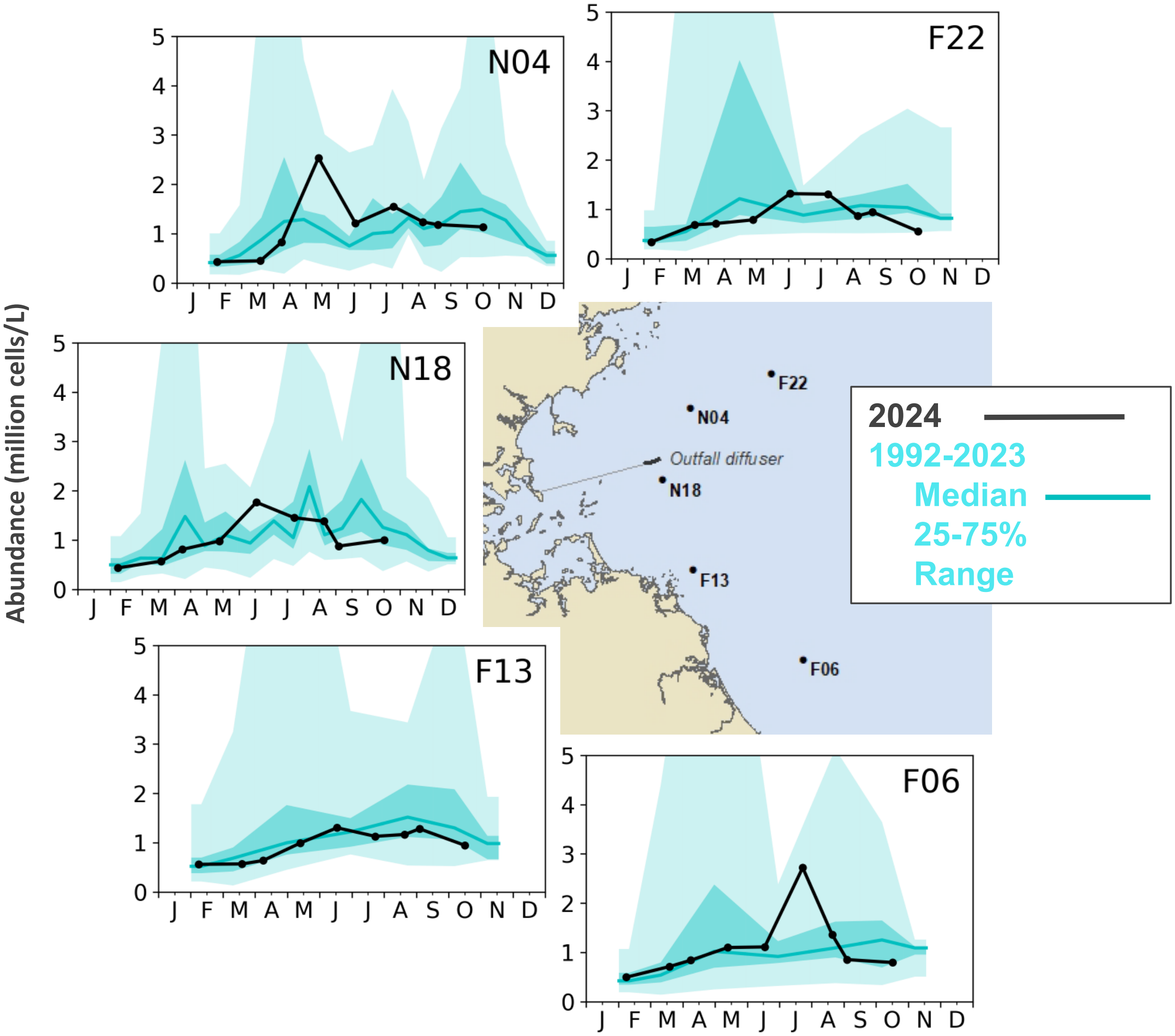
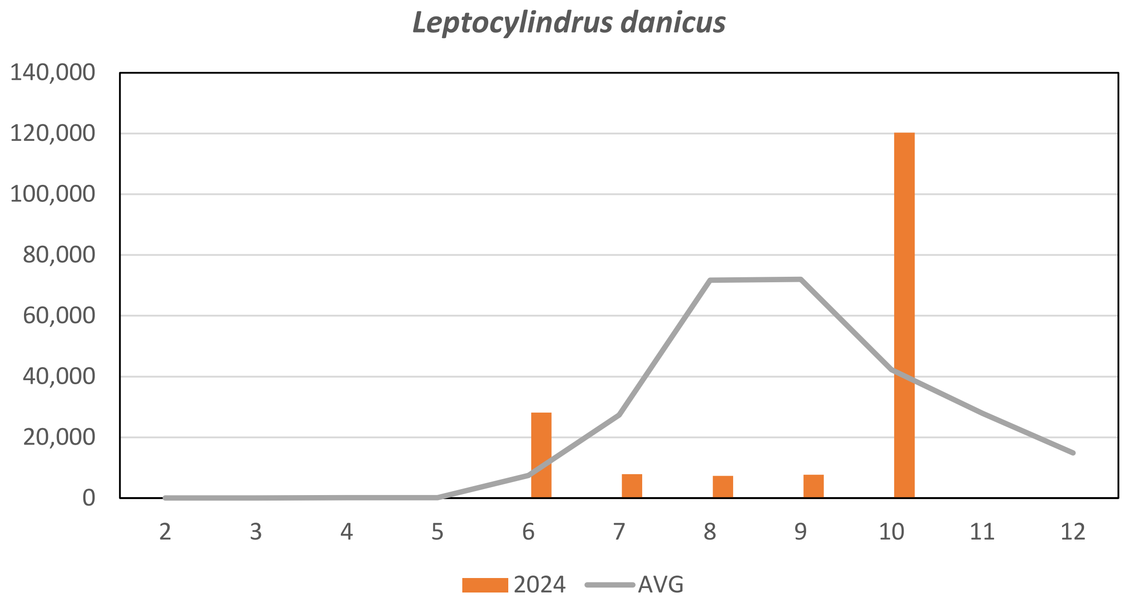


Figure 2-19. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2024 compared to prior years. 2024 results are in black. Results from 1992-2023 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The map insert highlights stations shown here and in subsequent phytoplankton and zooplankton figures, where an extended plankton dataset is available.



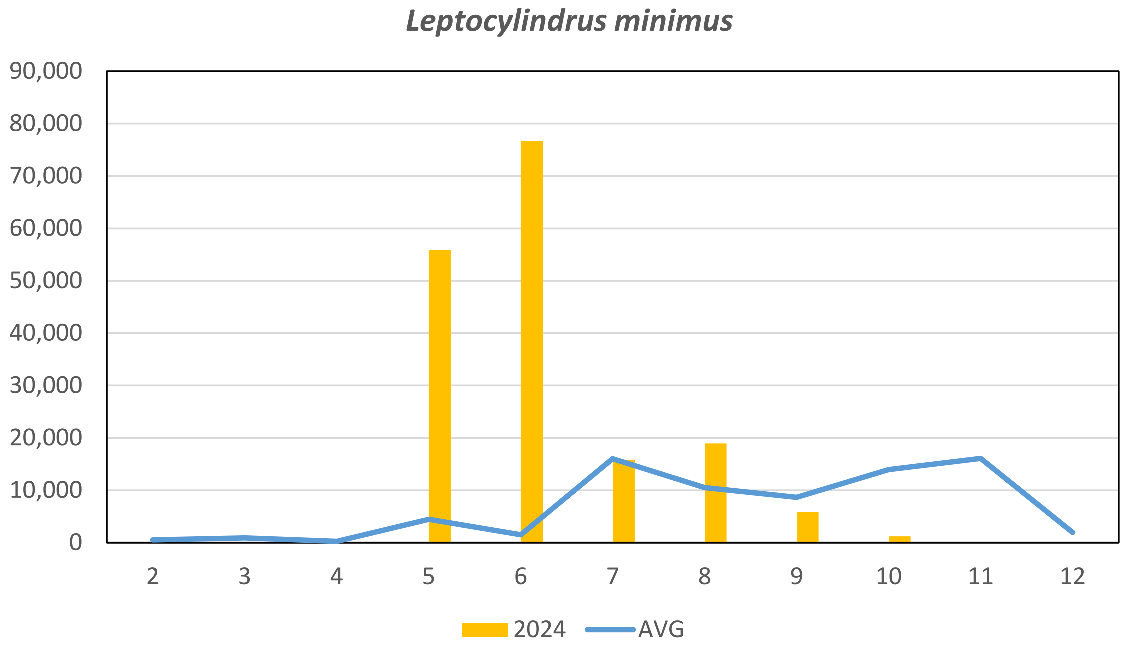


Figure 2-20. Monthly nearfield *Leptocylindrus danicus* and *Leptocylindrus minimus* abundances in 2024 compared to long-term median (1992-2023).

Following the pattern observed in recent years, 2024 was not a *'Phaeocystis* year*'* in Massachusetts Bay. *Phaeocystis pouchetii* was not observed in any nearfield samples collected during 2024, nor were they observed in 2023. Note that maximum *Phaeocystis* abundances of tens of millions of cells L^{-1} have been recorded in Massachusetts Bay during major bloom years (2000, 2004, 2007, and 2008). Historically, *Phaeocystis* is one of the dominant phytoplankton taxa in the Bay. The low to moderate abundances and more recent absence of *Phaeocystis* during the last decades has contributed to the long-term decline in total phytoplankton abundance relative to the levels observed during the early 2000s (**Figure 2-21**).

Microflagellates (spherical cells less than 10 µm diameter) are the most numerically abundant phytoplankton group in the Massachusetts Bay monitoring area, comprising ~69% of phytoplankton cells in 2024; a decrease compared to ~79% in 2023. Microflagellate abundance was slightly above long-term median levels for most of 2024, with levels in the upper quartile of historical levels in May, June, and July 2024 (data not shown). Elevated summer abundances in 2024 led to a nearfield microflagellate concentration of 756,943 cells L^{-1}, which was approximately 1.4-fold higher than the concentration observed from 2019 to 2023 (530,880 cells L^{-1}). This represents a significant increase and ranks 2024 as the 9th highest year out of 33 in terms of microflagellate abundance (**Table 2-1**).

Mean pennate diatom abundance in the nearfield during 2024 (23,659 cells L^{-1}) was not significantly different than observed during 2019-2023 (22,642 cells L^{-1}). Pennate diatom abundance was below long-term mean levels for much of 2024, with the exception of a regional bloom of *Pseudo-nitzschia* spp. during May. In the nearfield, average *Pseudo-nitzschia* spp. abundance was 100,968 cells L^{-1} with a maximum value of 231,068 cells L^{-1} during the May 2024 bloom. The vast majority of *Pseudo-nitzschia* cells observed during the May bloom were 'narrow' cells (< 3 µm transverse axis). 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 May 2024 *Pseudo-nitzschia* bloom. The low *Pseudo-nitzschia* toxicity observed in Massachusetts Bay during 2024 appears to be part of a regional trend with low *Pseudo-nitzschia* abundance and toxicity reported by shellfish-harmful algal bloom (HAB) phytoplankton monitoring programs from Nova Scotia to Rhode Island (Northeast HAB Conference, March 2025).

Dinoflagellate abundance was relatively low in Massachusetts Bay during 2024 and ranked 27th out of 33 years (**Table 2-1**). Mean nearfield dinoflagellate abundance during 2024 (41,559 cells L^{-1}) was approximately 47% lower than that observed during 2019 to 2023 (78,269 cells L^{-1}). This change is due to the low 2024 abundance of *Tripos muelleri* in comparison to the regional bloom observed in 2023, as well as low levels of *Karenia mikimotoi.* Comparison of *Karenia mikimotoi* abundance during 2020 (maximum of 879,087 cells L^{-1} and present in 84% of samples) and 2024 (maximum abundance of 53,870 cells L^{-1}; present in 17% of samples) illustrates the change in *Karenia* abundance. Time series analysis suggests that dinoflagellate abundance in Massachusetts Bay is cyclical and 2024 is the start of a downward trend in the cycle (**Figure 2-21**).

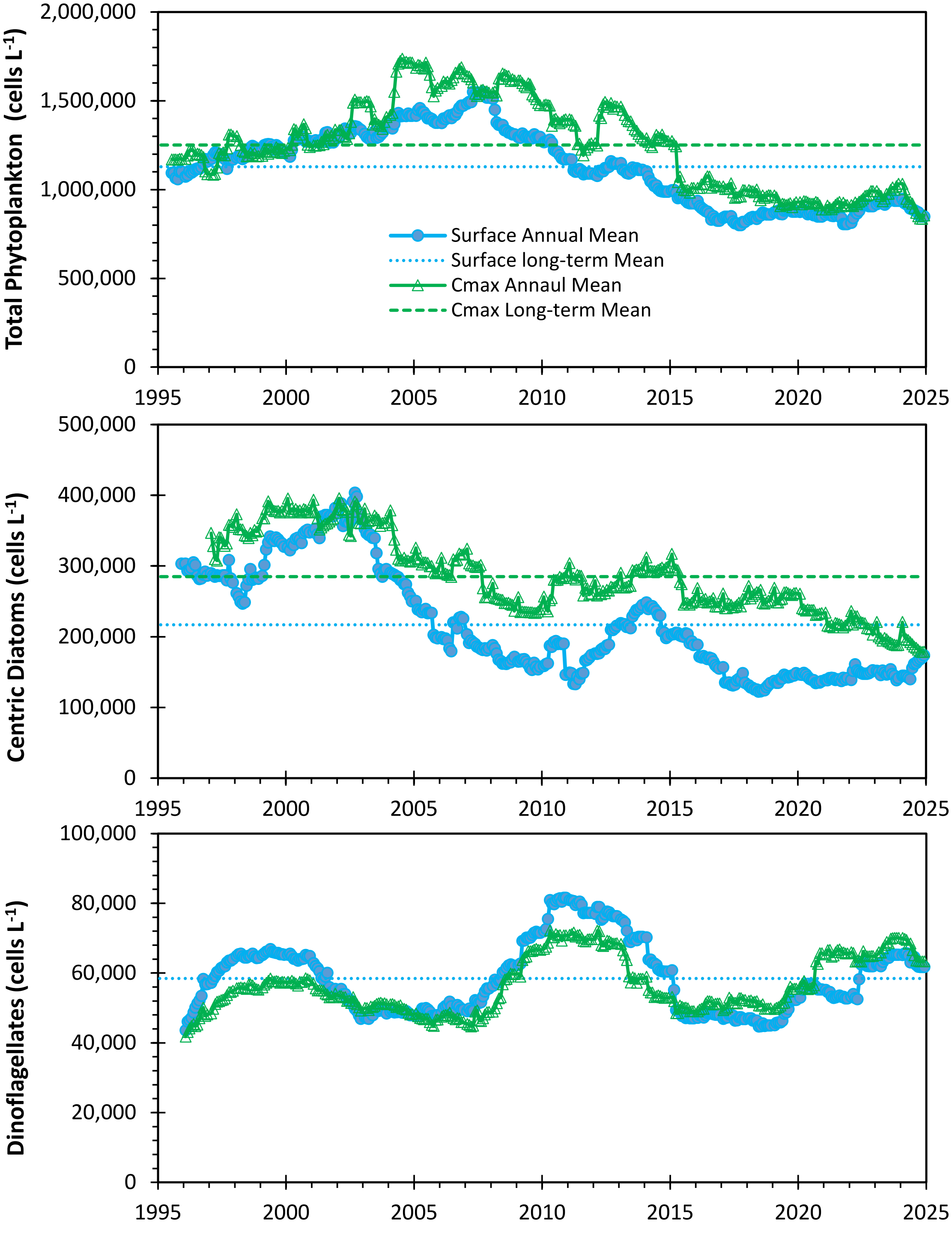


Figure 2-21. **Estimated long-term (1992-2024) abundances of phytoplankton groups in the nearfield region (stations N04 and N16/N18) derived from time series analysis.** Each panel shows the deseasonalized annual mean abundance at the surface (blue) and at the chlorophyll maximum depth (green) during 1992-2024. Horizontal dashed lines are 1992-2024 mean abundances. Panels show total phytoplankton (top panel), centric diatoms (middle panel), and dinoflagellates (bottom panel). Monthly deseasonalized abundance estimates have been smoothed with a 15% smoothing window equivalent to the ~48 months preceding the sample date (Broekhuizen and McKenzie 1995).

2.5.2 2024 Harmful Algal Bloom and Nuisance Phytoplankton

There were no threshold exceedances for nuisance species in 2024 (**see Table i**). *Pseudo-nitzschia* have not typically been an issue in Massachusetts Bay, and abundances of this potentially toxic species in 2024 were orders of magnitude lower than threshold levels in the winter and fall but were more than half the summer threshold. This was due to the regional bloom of *Pseudo-nitzschia* spp. in May 2024. Most of these cells were narrow (< 3 um wide) forms (i.e., *Pseudo-nitzschia delicatissima*) and no toxin production was detected by shellfish monitoring during this bloom. Species of *Pseudo-nitzschia* have exhibited blooms and toxicity in the Gulf of Maine recently and continue to be the focus of study in the region.

Alexandrium abundances were low in Massachusetts Bay in 2024 (**Figure 2-22**), and MA DMF did not detect any PSP toxicity in Massachusetts coastal waters from the New Hampshire border to Cape Ann and within the bay. This was also the case throughout the Gulf of Maine (eastern and western), with low *Alexandrium* abundances and no PSP toxicity except for a few embayments along the eastern side of Cape Cod. The highest *Alexandrium* abundance of 96 cells L^{-1} in 2024 was observed at station N01 in July and was just below the rapid response and Contingency Plan thresholds of 100 cells L^{-1}. Although *Alexandrium* abundances were low overall and no PSP was detected, the abundances observed in the nearfield in July and August 2024 were some of the highest levels seen in late summer during the monitoring program, which nearly triggered a rapid response survey (**Figure 2-23**).

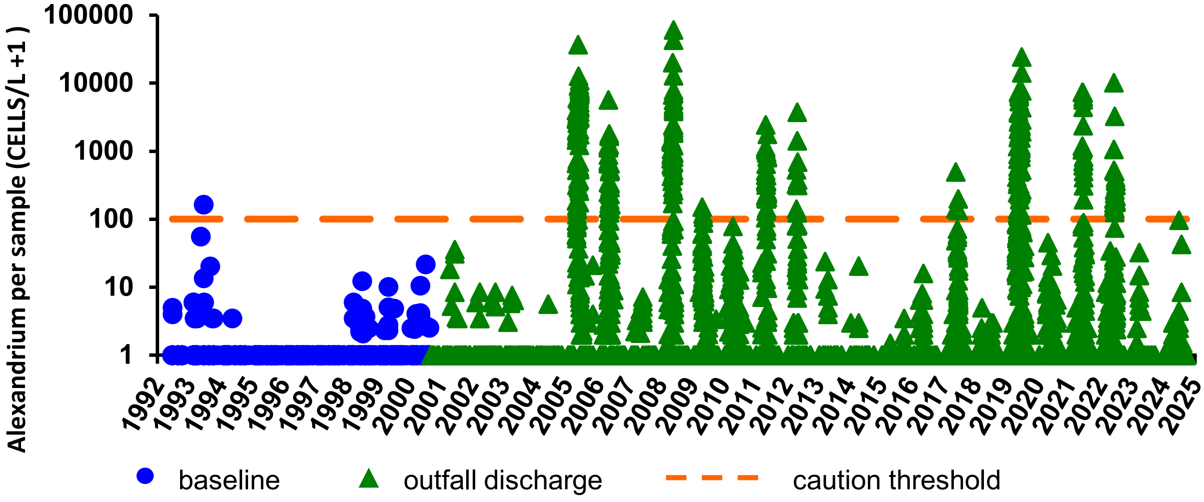


Figure 2-22. Nearfield *Alexandrium* abundance (cells L^{-1} +1) from 1992 to 2024. The dashed line represents the Contingency Plan caution threshold of 100 cells L^{-1}.

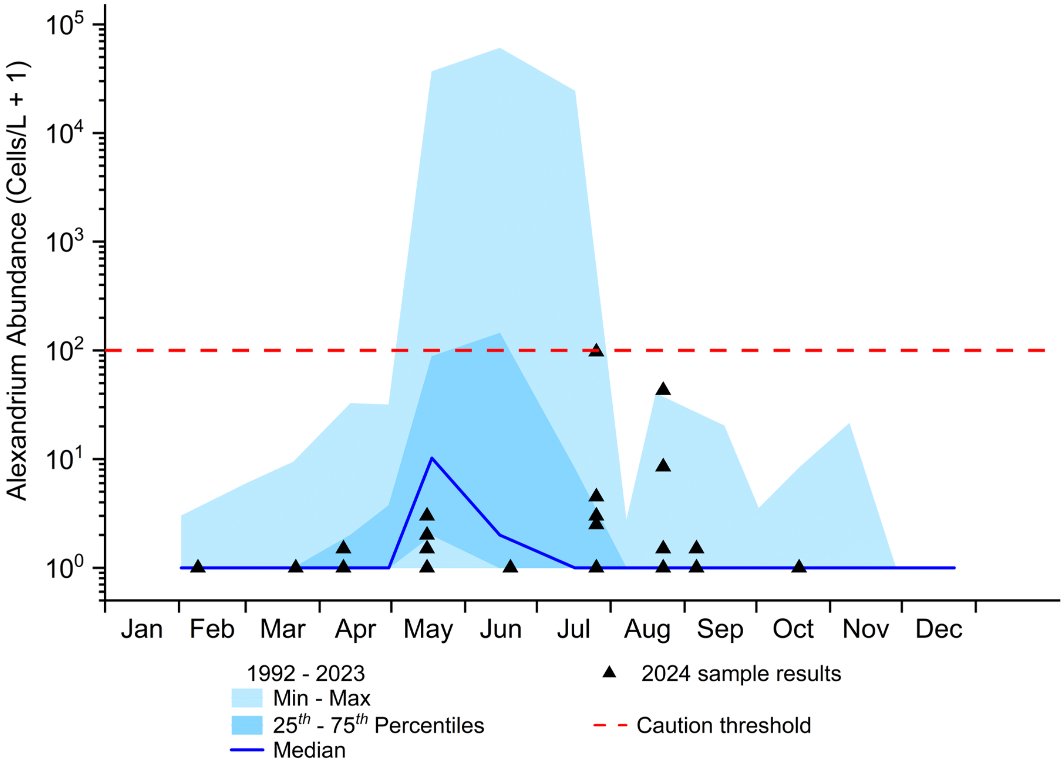


Figure 2-23. Nearfield sample abundance of *Alexandrium* in 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.6 ZOOPLANKTON ABUNDANCE

Zooplankton taxa and abundances in 2024 were generally similar to those observed during the monitoring program, with abundances for total zooplankton close to the long-term median for most of the year (**Figure 2-24**). Seasonal patterns of total zooplankton abundance were atypical, showing only small increases from winter lows to moderate peaks in spring and summer at most stations, followed by declines in fall, except at stations that exhibited substantial increases in October. The high total zooplankton abundances in October was overwhelmingly dominated by radiolarians (**Figure 2-25**).

Seasonal patterns for copepods were typical, increasing from winter lows to summer peaks in abundance, and declining in the fall (**Figure 2-26**). Abundances of copepod adults and copepodites were driven primarily by June/July peaks of copepodites of *Pseudocalanus* spp.. Overall, *Oithona similis* were low in abundance from February to August 2024 compared to historical levels. Copepodites of *Calanus finmarchicus* were present in March and April with elevated abundances of 3,000 to 10,000 individuals m^{-3} observed at most of the bay stations. As usual, estuarine copepods/copepodites of the genus *Acartia* were found almost exclusively in Boston Harbor with highest abundances in May, August, September, and October. Patterns for non-copepods were also similar to previous years. Barnacle nauplii were sporadically present in varying abundance throughout the year, with high abundance in February and March, and the planktonic tunicate *Oikopleura dioica* was abundant in May.

Radiolarians have not been recorded in the monitoring program prior to 2020 but have now appeared in summer and/or fall for five years in a row. The high abundances of radiolarians in October 2024 at stations N04 and N18 were well above those observed in 2020-2023 and were comparable to the historically high abundances of meroplankton observed during summer peaks due to bivalve veliger larvae in previous years (**Figure 2-25**).

Radiolarians are more typical of offshore, warm oceanic waters than the continental shelf waters of Massachusetts and Cape Cod Bays. They may have been transported into the study area each year in separate intrusions of warmer waters from offshore. Alternatively, it could be that the radiolarians in Massachusetts Bay were the result of an initial injection from offshore in 2020, followed by annual reappearances of cells in the water column from hatching of cysts with gametes in the sediments. A review of the limited literature on radiolarians suggests that there is no evidence of sexual reproduction in radiolarians (Anderson 1983). Thus, the radiolarians recorded for Massachusetts Bay were likely transported into the bay each year since 2020, in separate injections of warmer waters from offshore in late summer to fall. It may be that Massachusetts Bay is showing signs of warming associated with the northward extension of the Gulf Stream, which has been reported in recent years (Townsend et al 2023; Goncalves Neto et al. 2021).

Since the early 2000s, the long-term trends in total zooplankton and copepod abundance had been similar, but around 2020 these trends began to diverge (**Figure 2-27**). The divergence is partially due to the increase in radiolarians during summer and fall, which appears to be associated with warming. It is unclear what other influence the warming waters of the greater Gulf of Maine may be having on the zooplankton community or other aspects of the Massachusetts Bay system. Such changes will continue to be a focus of this long-term monitoring program.

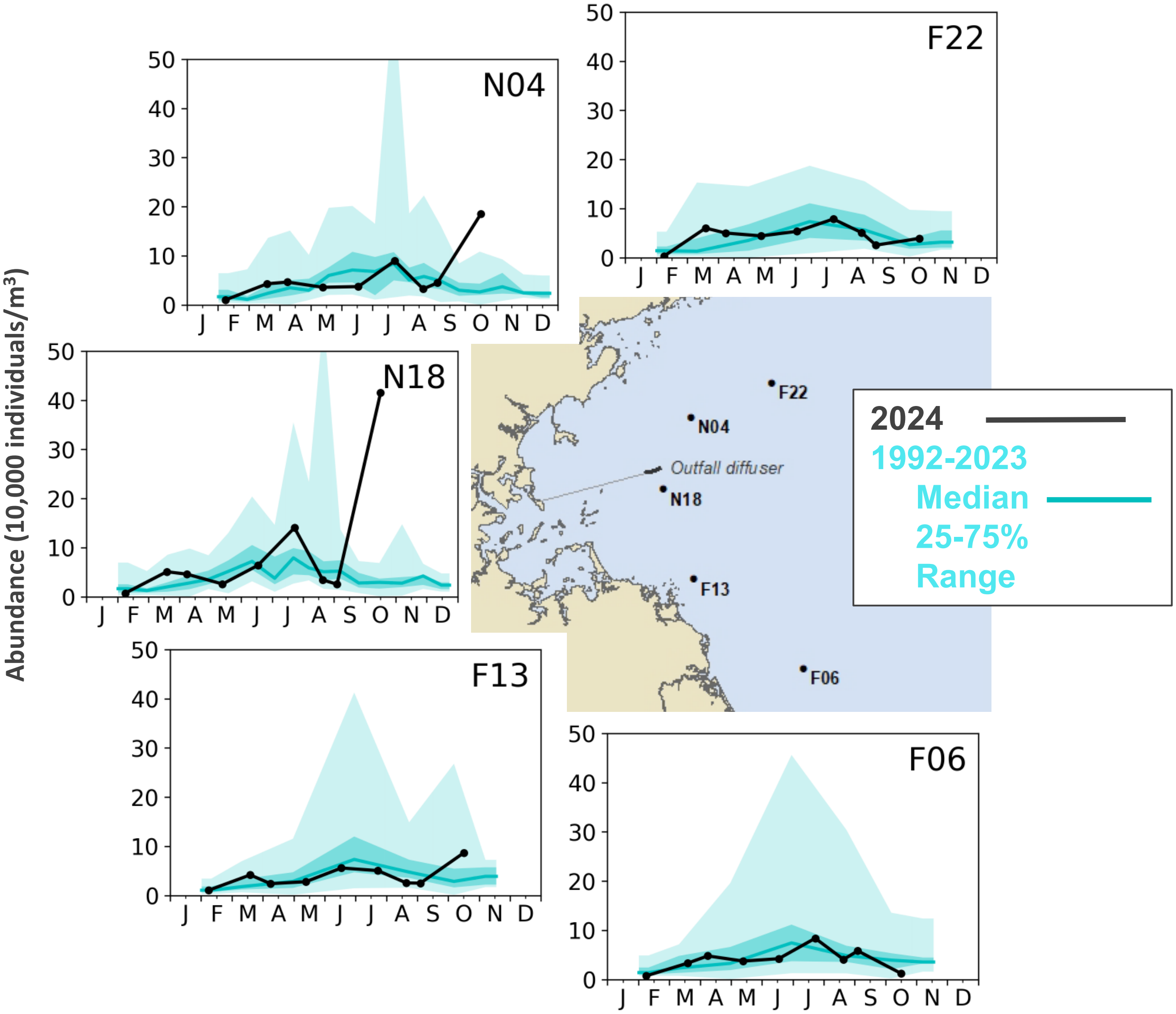


Figure 2-24. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans 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}.

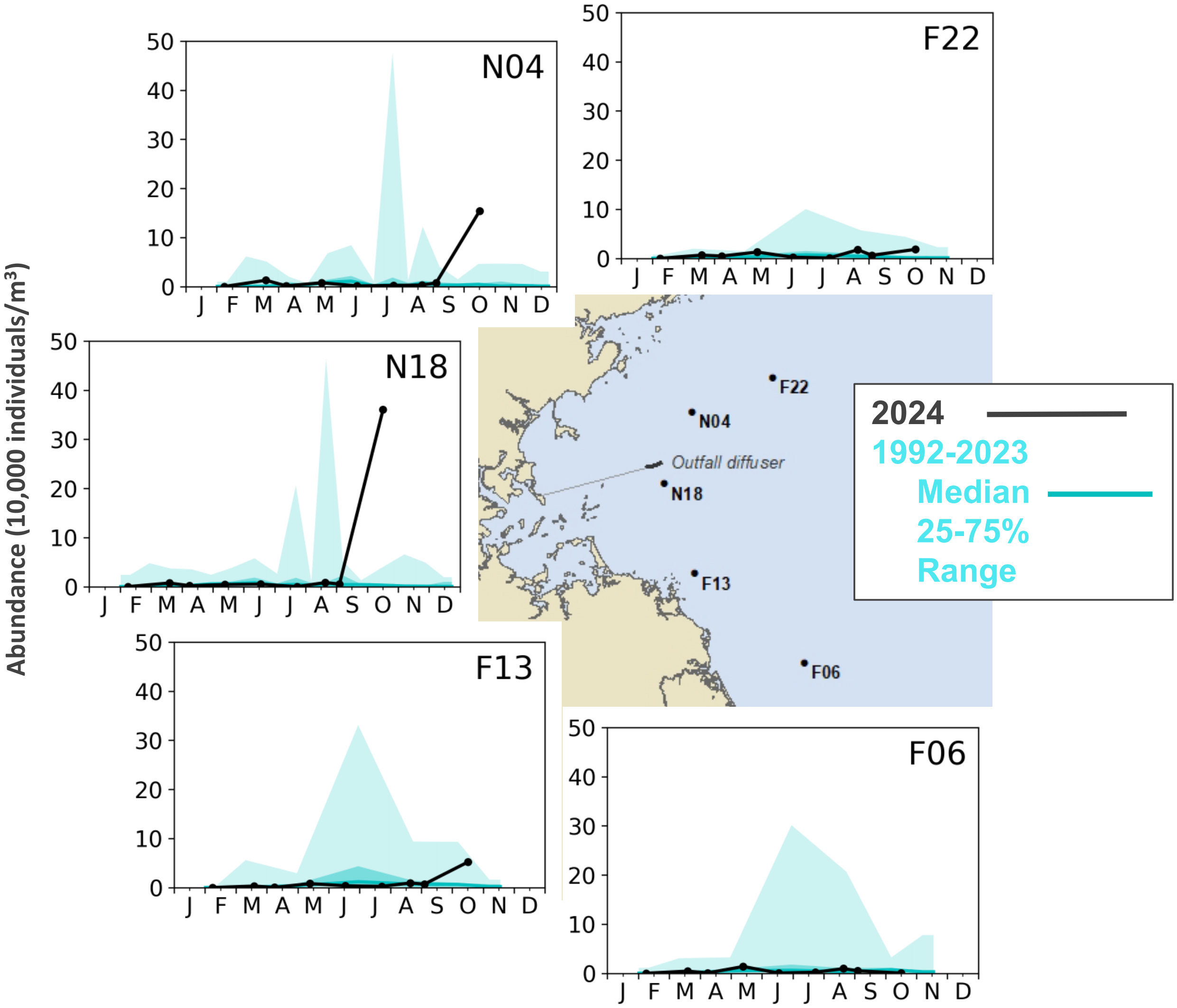


Figure 2-25. **Meroplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2024 compared to prior years.** 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. Note the October peak is dominated by Radiolaria.

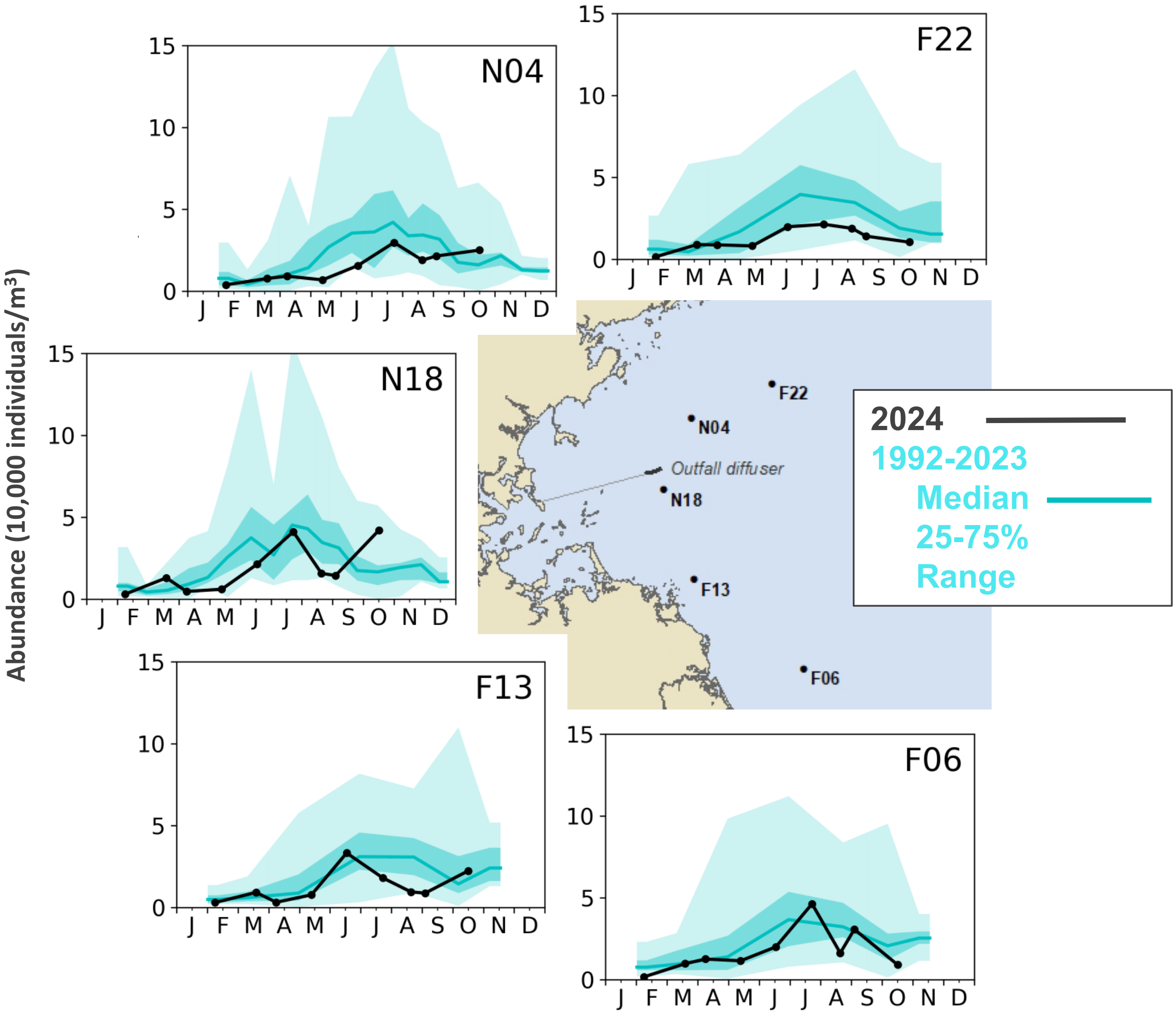


Figure 2-26. Total copepod adults and copepodites (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2024 compared to prior years. 2024 results are in black. Results from 1992–2023 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

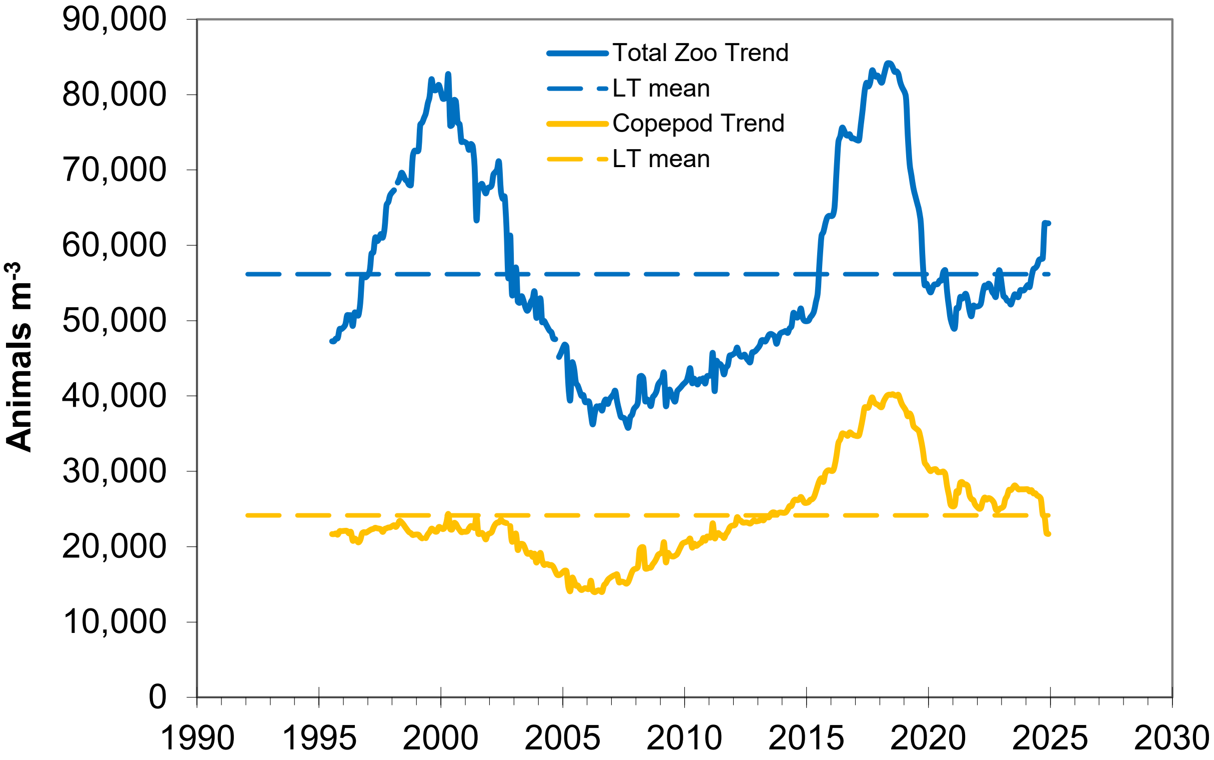


Figure 2-27. Estimated long-term (1995-2024) abundance levels of total zooplankton (blue) and total copepods (orange) in the nearfield (stations N04 and N16/N18) derived from time series analysis. Data lines based on 15% smoothing windows (~4 years).

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 2024, three humpback whales (*Megaptera novaeangliae*), one North Atlantic right whale (*Eubalaena glacialis*), two unidentified baleen whales, and six minke whales (*Balaenoptera acutorostrata*) were observed during the MWRA surveys in Massachusetts Bay (**Table 2-2** and **Figure 2-28**). Other marine mammal sightings included 14 Atlantic white-sided dolphins (*Lagenorhynchus acutus),* five common dolphins, two gray seals (*Halichoerus grypus*), eight harbor porpoises (*Phocoena phocoena*), and 22 harbor seals (*Phoca vitulina*).

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 2-2** and the 2024 results are shown geographically in **Figure 2-28**.

Table 2-2. Number of whale sightings from 1998 to 2024.

Year	Finback whale	Humpback whale	North Atlantic right whale	Fin or Sei whale	Unidentified baleen whale	Unidentified whale	Minke whale	Pilot whale	Unidentified toothed whale	Year Totals
1998		5	3		5	3	7			23
1999	27	12	2		9	5	4			59
2000	5	22			11	2	3	21		64
2001		4	11		3		4			22
2002	6	9	2		2	1	1			21
2003	1	3			4		6			14
2004	3		3			3	2			11
2005	1	5			9	1	17			33
2006	9	32	1		1	4	7			54
2007	1	7	1		1	3	4			17
2008	5	9	13	1	10		5			43
2009	1	12	1		10	4	10			38
2010	4	9	4		6		9	1	1	34
2011	1						5			6
2012		4	2			1	1			8
2013			4			1				5
2014					1		2			3
2016			2				3			5
2017		2	8		3	1	4			18
2018	1				2		4			7
2019	1	1			2		1		1	6
2020		2	1				4			7
2021	1	2	5			2	3			13
2022		1	5		1		1		1	9
2023					2		1		7	10
2024		3	1		2		6			12
Totals	**67**	**144**	**69**	**1**	**84**	**31**	**114**	**22**	**10**	**542**

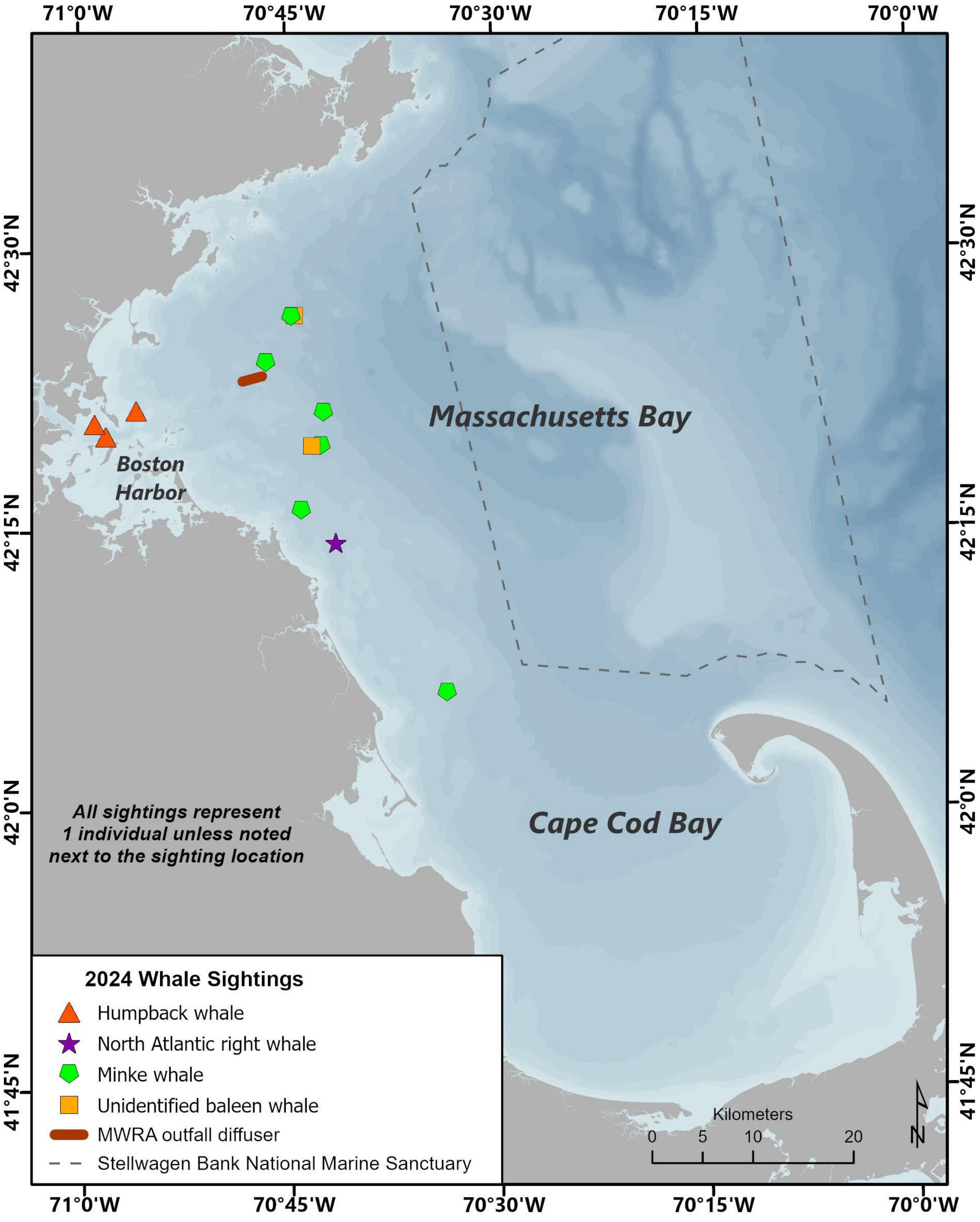


Figure 2-28. **Locations and number of whale sightings and whale species sighted during the 2024 surveys.**

3 SUMMARY

Overall, 2024 was an unremarkable year with typical seasonal patterns, water quality parameters close to long-term medians, no large phytoplankton or harmful algal blooms, and moderate bottom water DO levels. There were no exceedances of the water column thresholds for chlorophyll and bottom water DO concentrations or harmful algal bloom species *Alexandrium* and *Pseudo-nitzschia* (**Table i**).

The most notable physical oceanographic characteristics of 2024 were the unusually wet winter/spring and strong upwelling in June and July. River flows were the highest observed during the 33-year monitoring program in the winter, remaining high into April before decreasing and being relatively dry for the rest of the year (**Figure 2-1**). Surface and bottom water salinity reflected the wet winter/spring and high river flows with low values from February to May 2024. Persistent upwelling favorable winds in June and July (**Figure 2-4**) resulted in decreased surface water temperatures. Upwelling also contributed to a leveling off or increase in bottom water DO levels across most of Massachusetts and Cape Cod Bays in the summer, which helped moderate the fall DO minima in 2024 (**Figure 2-16** and **Figure 2-17**).

Nutrient concentrations in Massachusetts and Cape Cod Bays generally followed typical seasonal patterns, with naturally elevated levels of nitrate (NO_3), silicate (SiO_4) and phosphate (PO_4) during the winter and spring, followed by declines during the summer months and into the fall (**Figure 2-8**). A sharp decline in SiO_4 concentrations from February to March suggests there may have been a diatom bloom in the bay during the period between these two surveys. This observation was consistent with a slight increase in chlorophyll fluorescence observed at some stations in March (**Figure 2-13**). However, it could not be corroborated with remote sensing data as the NERACOOS Buoy A01 did not report data until late summer, and MODIS imagery showed elevated fluorescence levels throughout most of 2024. Nutrient levels continued to be variable into April and May which were likely influenced by the high level of precipitation and river flows observed during this period. Strong upwelling in June and July kept nutrient levels at or above historical long-term medians over most of the summer. By October, nutrient concentrations decreased to lower levels (**Figure 2-8** and **Figure 2-9**). This was concomitant with increases in areal chlorophyll levels across the bay and was also observed at the NERACOOS Buoy A01, which coincided with a prolonged period of high fluorescence readings in the surface water from late September until early November (**Figure 2-15**).

As typically observed, the extent of the bay outfall effluent plume was characterized by elevated NH_4 concentrations. In 2024, NH_4 concentrations were similar to levels observed after the diversion of the outfall, when compared to the baseline period before operation of the outfall. Lower concentrations of NH_4 were observed in Boston Harbor, higher in the nearfield, and generally unchanged in the rest of Massachusetts and Cape Cod Bays (**Figure 2-10**). The survey-to-survey variability in where high concentrations of NH_4 are observed at the stations nearest the outfall is due to the location of the effluent plume during sampling. Each survey is a snapshot in time, and the location of the effluent plume changes based on current direction and magnitude, as well as stratification. The spatial variability of the plume is illustrated by high NH_4 concentrations at stations 10-20 km to the south of the outfall in May and August 2024. The plume can also be transported to the north as observed in July 2024 when NH_4 concentrations were very low at station N18 and elevated at station N04 to the northeast of the outfall. These patterns as well as historical patterns are consistent with pre-diversion model simulations (Signell et al. 1996; Taylor 2016; Libby et al. 2007).

Bottom water DO levels were close to historical median levels at most stations from February to April 2024, before reaching surprisingly low concentrations in May at many stations in both Massachusetts and Cape Cod Bays. Interestingly, the annual minima at station F01 was observed in June. Fortunately, strong upwelling-favorable conditions in June and July mitigated the decreases in bottom water DO concentrations in the bays, averting seasonal decreases to lower levels in the late summer and fall. NERACOOS Buoy A01 DO data indicated that the water column started to mix to 50 meters in mid-

October after the final MWRA survey but did not fully mix until mid-November (**Figure 2-18**). The 2024 annual DO minima in Massachusetts Bay were moderate, with levels ≥6.25 mg L^{-1} observed in October (**Figure 2-16**). DO bottom water minima in Cape Cod Bay were above the long-term median from August to October 2024, remaining above 6.5 mg L^{-1} and well above the hypoxic levels observed in recent years (**Figure 2-17**). No bottom water DO thresholds were exceeded in 2024 (**Table i**).

The comparison of the decrease in DO at nearfield station N18 to the farfield station F22 and the NERACOOS Buoy A01 shows that the variations of DO are regional, rather than local at the outfall site. As noted, the fall overturn of the water column in Massachusetts Bay is strongly influenced by storm wind-mixing events (see **Figure 2-7**). Strong winds prior to the October survey lowered near-surface temperatures and caused mixing deep enough to ventilate the bottom waters at station N18 near the outfall. However, the mixing was not deep enough to significantly ventilate the waters at 50 m depth at NERACOOS Buoy A01 (**Figure 2-18**). More intense mixing occurred in late November. This pattern is typical of fall mixing in Massachusetts Bay, in which the shallow sites mix earlier than the deeper sites.

Total phytoplankton abundances measured in 2024 were near long-term mean levels with no exceptional bloom activity (**Figure 2-19**). This was partially due to low winter-spring diatom abundances, the lack of *Phaeocystis pouchetii*, and reduced dinoflagellate abundance. Conditions were different in Cape Cod Bay, which had higher phytoplankton abundances and a March-April 2024 bloom of *Guinardia delicatula* that was not observed in Massachusetts Bay. Microflagellate abundance, which is greatest during summer, was higher during 2024 compared to the previous5 years. There were summer and autumn increases in the centric diatoms *Leptocylindrus minimus*, *Leptocylindrus danicus*, *Dactyliosolen fragilissimus*, and *Skeletonema* spp., which led to a mixed assemblage bloom of centric diatoms and a 2024 average abundance in the nearfield that was 76% greater than the 2019-2023 average (**Table 2-1**).

There were no threshold exceedances for nuisance species in 2024 (**Table i**). *Alexandrium* abundances were low in 2024 (**Figure 2-22**) and MA DMF did not detect any PSP toxicity in Massachusetts Bay waters. This was also the case throughout the Gulf of Maine (eastern and western), with low *Alexandrium* abundances and no PSP toxicity except for a few embayments along the eastern side of Cape Cod. The other potentially harmful algal species targeted by the monitoring program is *Pseudo-nitzschia* which have not been previously an issue in Massachusetts Bay. Abundances of this potentially toxic species in 2024 were well below threshold levels in the winter and fall and about half the summer threshold. This was due to a regional bloom of *Pseudo-nitzschia* spp. in May 2024 that consisted primarily of narrow cell (< 3 um wide) forms (i.e., *Pseudo-nitzschia delicatissima*) and no domoic acid toxin was detected by shellfish monitoring during this bloom. Species of *Pseudo-nitzschia* have exhibited blooms and toxicity in the Gulf of Maine recently and continue to be the focus of study in the region.

Zooplankton taxa and abundances in 2024 were generally similar to those observed during the previous years of the monitoring program, with abundances for total zooplankton close to the long-term median for most of the year (**Figure 2-24**). Seasonal patterns of total zooplankton abundance were atypical with only small increases from winter lows to moderate spring and summer peaks at most stations. There were fall declines at some stations, but most stations exhibited substantial increases in zooplankton abundance in October. The high total zooplankton abundance in October was overwhelmingly dominated by radiolarians and was comparable to the historically high abundance of meroplankton observed during summer peaks due to bivalve veliger larvae in previous years (**Figure 2-25**). Radiolarians have not been recorded in the monitoring program prior to 2020 but have now appeared in summer and/or fall for five years in a row. Radiolarians are more oceanic and warmer water taxa than those typically observed in the MWRA sampling area. It may be that Massachusetts Bay is showing signs of warming associated with the northward extension of the Gulf Stream, which has been reported in recent years (Townsend et al 2023; Gonçalves Neto et al. 2021). The warming waters may be influencing changes in the species distribution and abundance in Massachusetts Bay and are important to consider when evaluating trends in many Massachusetts Bay monitoring parameters going forward.

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Massachusetts Water Resources Authority
100 First Avenue • Boston, MA 02129
www.mwra.com

617-242-6000