# 2008 Water Column Monitoring Results

Massachusetts Water Resources Authority

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# 2008 Water Column Monitoring Results

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# 1. INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) is conducting a long-term ambient monitoring program in Massachusetts and Cape Cod Bays. The objectives of the program are to (1) verify compliance with National Pollutant Discharge Elimination System (NPDES) permit requirements; (2) evaluate whether the impact of the treated sewage effluent discharge on the environment is within the bounds projected by the EPA Supplemental Environmental Impact Statement (SEIS, EPA 1988), and (3) determine whether change within the system exceeds the Contingency Plan thresholds (MWRA 2001). A detailed description of the monitoring and its rationale is provided in the monitoring plans developed for the baseline and post-diversion periods (MWRA 1991, 1997, and 2004). The 2008 data represent the eighth full year of measurements in the bays since initiation of discharge from the bay outfall on September 6, 2000. A timeline of major upgrades to the MWRA treatment system is provided for reference in **Table 1-1**.

**Table** 1-1. Major Upgrades to the MWRA Treatment System.

| Date | Upgrade |
|---|---|
| December 1991 | Sludge discharges ended |
| January 1995 | New primary plant on-line |
| December 1995 | Disinfection facilities completed |
| August, 1997 | Secondary treatment begins to be phased in |
| July 9, 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 on-line |
| March 2001 | Upgrade to secondary treatment completed |
| October 2004 | Upgrades to secondary facilities (clarifiers, oxygen generation) |
| April 2005 | Biosolids line from Deer Island to Fore River completed and operational |

## *1.1. Outline of this report*

The purpose of this annual summary report is to present the 2008 results in Massachusetts and Cape Cod Bays in the context of (1) the seasonal patterns and the annual cycle of ecological events, (2) Contingency Plan thresholds (MWRA 2001), and (3) baseline versus post-diversion data.

Detailed results are included as appendices to this report. The appendices include copies of slides presented at MWRA's internal workshop in May 2009 by team principal investigators on the following topics:

- A: Physical Characterization (temperature, river flow, wind, waves, salinity, stratification, dissolved oxygen)
- B: Water Quality (nutrients, chlorophyll, phytoplankton, dissolved oxygen)
- C: Primary productivity (algal growth rate and related factors)
- D: Plankton (phytoplankton and zooplankton abundance)
- E: *Alexandrium* Bloom (forecasting and observations of a toxic red tide harmful algal bloom)

## *1.2. Data Sources*

The 2008 water column monitoring data have been reported in a series of survey reports and data reports.

A detailed presentation of field sampling equipment and procedures, sample handling and custody, sample processing and laboratory analysis, and instrument performance specifications and data quality objectives are discussed in the Combined Work/Quality Assurance Project Plan (CWQAPP) for Water

Quality Monitoring: 2008-2009 (Libby *et al.* 2008). For each water column survey, the survey objectives, station locations and tracklines, instrumentation and vessel information, sampling methodologies, and staffing were documented in the survey plan. Following each survey, the activities that were accomplished, details on any deviations from the methods outlined in the CWQAPP, the actual sequence of events and tracklines, the number and types of samples collected, a preliminary summary of *in situ* water quality data, >20 µm phytoplankton species abundance, whale watch information, and any deviations from the plan were summarized in the survey report. Results for 2008 water column surveys are tabulated in data reports.

## 1.3. Water Column Monitoring Program Overview

This report summarizes and evaluates water column monitoring results from the 12 water column surveys conducted in 2008 (**Table 1-2**). The surveys evaluate water quality at 7 stations in the nearfield 12 times per year, and at 27 stations in the farfield 6 times per year. The 34 stations are distributed throughout Boston Harbor, Massachusetts Bay and Cape Cod Bay (**Figure 1-1**). The nearfield is a rectangle covering an area of approximately 110 km$^2$ around the MWRA bay outfall. Station N16 is sampled twice during the combined nearfield/farfield surveys. Fifteen of the stations are sampled for phytoplankton and zooplankton. Two additional zooplankton stations (F32 and F33) in Cape Cod Bay are sampled during the February through April farfield surveys (**Figure 1-2**). We lumped the farfield stations into regional groupings for some analyses (**Figures 1-1** and **1-2**). For this report, subsets of the data have also been grouped to focus on the deep-water stations off of Cape Ann (F26 and F27 – Northern Boundary) and in Stellwagen Basin (F12, F17, F19 and F22 – see **Figure 1-1**).

The data are also grouped by season for comparisons of biological and nutrient data and also for calculation of chlorophyll, *Phaeocystis*, and *Pseudo-nitzschia* Contingency Plan thresholds. The seasons are defined as the following 4-month periods: winter/spring from January to April, summer from May to August, and fall from September to December. Comparisons of baseline and post-diversion data are made for a variety of parameters. The baseline period is defined as February 1992 to September 6, 2000 and the post-diversion is September 7, 2000 to November 2008. Spanning both periods, year 2000 data are not used for calculating annual means, but the data are typically included in plots and analyses broken out by survey and season. Specific details on how 2000 data are treated are included in the captions and text.

**Table** 1-2. Water column surveys for 2008. The nearfield day is underlined.

| Survey | Type of Survey | Survey Dates |
|---|---|---|
| WF081 | Nearfield/Farfield | February 12, 21, 22, 25 |
| WF082 | Nearfield/Farfield | March 3, 4, 6 |
| WN083 | Nearfield | March 24 |
| WF084 | Nearfield/Farfield | April 9, 10, 11 |
| WN086 | Nearfield | May 21 |
| WF087 | Nearfield/Farfield | June 9, 13, 16 |
| WN089 | Nearfield | July 22 |
| WF08B | Nearfield/Farfield | August 18, 19, 20 |
| WN08C | Nearfield | September 2 |
| WN08D | Nearfield | September 30 |
| WF08E | Nearfield/Farfield | October 24, 27, 31 |
| WN08F | Nearfield | November 21 |

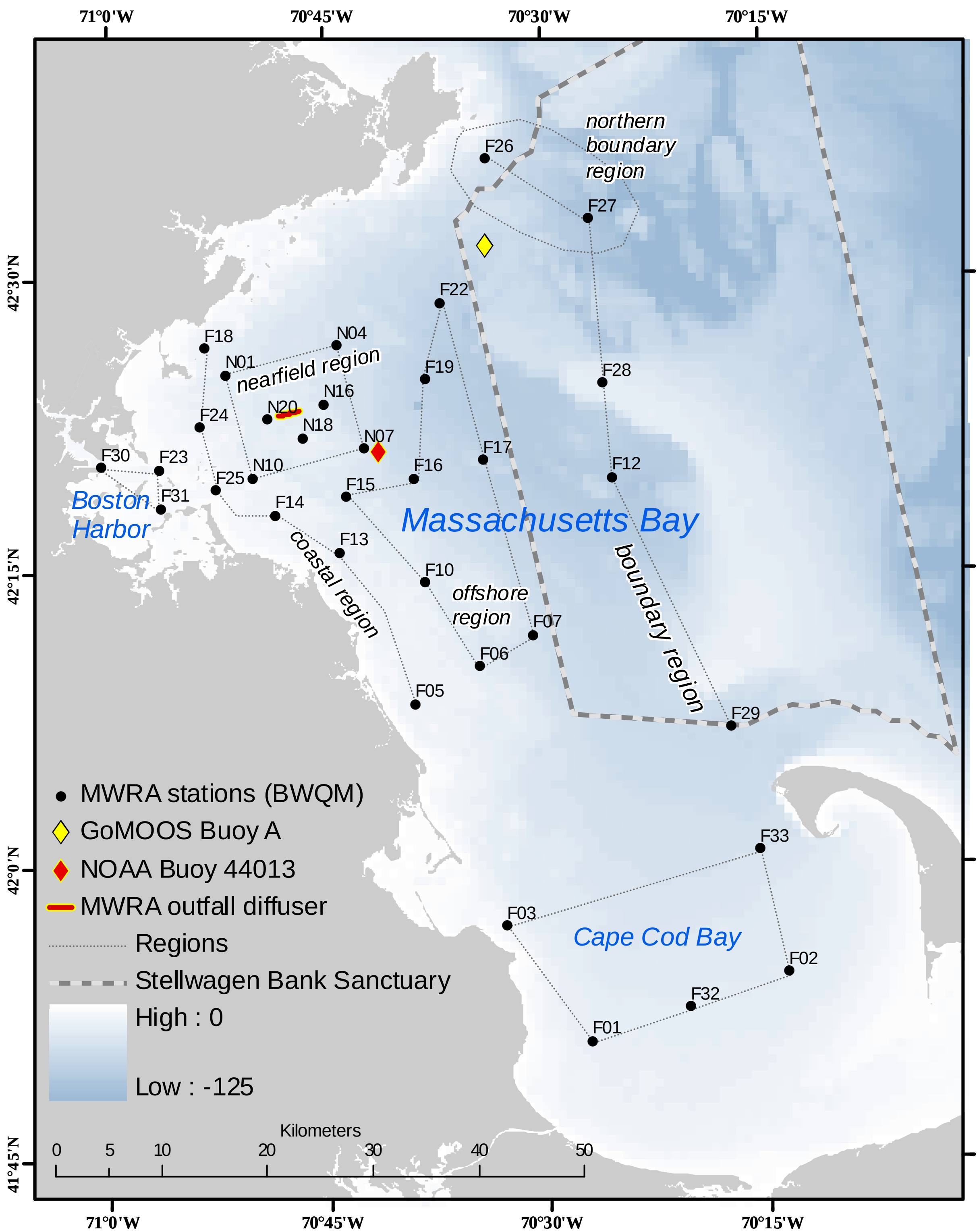


**Figure** 1-1. MWRA stations and their regional groupings. Also shown are the MWRA outfall and instrumented buoys operated by GoMOOS and NOAA's NDBC.

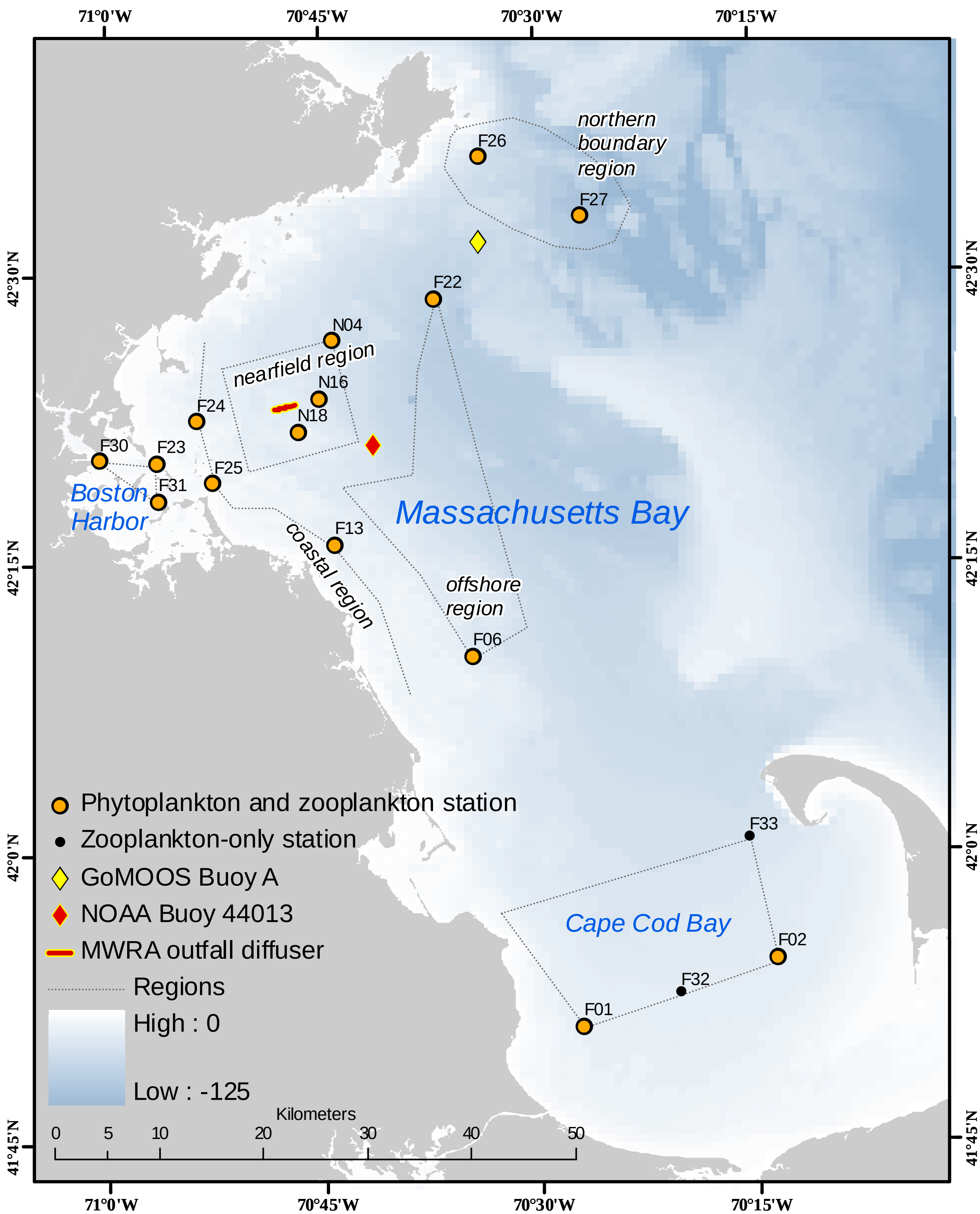


**Figure** 1-2. MWRA plankton stations (regional groupings shown for reference).

# 2. MONITORING RESULTS

Over the course of the HOM program, a general seasonal sequence of water quality events has emerged from the data collected in Massachusetts and Cape Cod Bays. The general annual pattern is evident even though the timing and year-to-year manifestations of these events are variable. A winter/spring phytoplankton bloom occurs as light becomes more available and temperatures increase; nutrients are readily available. In recent years, the winter/spring diatom bloom has been followed by a bloom of *Phaeocystis pouchetii* in April. Then late in the spring, the water column transitions from well-mixed to stratified conditions. This cuts off the nutrient supply to surface waters and terminates the spring bloom. The summer is generally a period of strong stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community. In the fall, as temperatures cool, stratification weakens and nutrients are again supplied to surface waters. This transition often contributes to the development of a fall phytoplankton bloom. Dissolved oxygen concentrations are lowest in the bottom waters prior to this fall overturn of the water column – usually in October. By late fall or early winter, the water column becomes well mixed and resets to winter conditions, when nutrients are available but waters are too dark and cold to support rapid phytoplankton growth. This sequence is evident every year. The major features in 2008 and differences from previous years are discussed below.

## *2.1. 2008 Results*

Overall, the physical, water quality, and biological conditions in 2008 were about average for the monitoring period (1992-2008) and followed typical seasonal patterns. Mean annual and mean seasonal values of many variables for 2008 were close to the average over all years: winds, temperature, stratification, nutrients, phytoplankton biomass, and dissolved oxygen levels. A notable difference in 2008 was the high freshwater input due to abundant rain through much of the year, resulting in lower than average salinities (**Appendix A**). As usual, nutrient concentrations were at a maximum in February, remained high until the March/April *Phaeocystis* bloom, were low in the summer, and then increased in the fall (**Figure 2-1**). Phytoplankton biomass patterns were driven by a major regional *Phaeocystis* bloom in April, as well as nearshore diatom blooms in winter/spring (Cape Cod Bay), summer (harbor, coastal, and nearfield), and late fall (nearfield). Chlorophyll and particulate organic carbon (POC) concentrations peaked in most areas during the April *Phaeocystis* bloom. The plankton communities were comprised of the typical assortment of species. A bloom of the red tide dinoflagellate *Alexandrium fundyense* occurred, which resulted in a Contingency Plan caution threshold exceedance. A chronological synopsis of the 2008 results is provided below and additional details are presented in Appendices A-E.

In early February nutrient concentrations were elevated relative to previous years for nitrate ($NO_3$), silicate ($SiO_4$), and phosphate ($PO_4$) (**Figure 2-1** and **Appendix B, slides 24-25**). This was likely due to the lack of a winter/early spring phytoplankton bloom in the bay. Another factor contributing to elevated nutrient concentrations was likely due to high precipitation and river flows in early 2008 (**Figure 2-2**). Merrimack River flow reached a maximum for the January-March period for 2008 compared to the other monitoring years. The wet conditions were the only notable feature for physical forcing variables in 2008.

A minor diatom bloom was evident in Cape Cod Bay in February (**Figure 2-3**) and decreases in $SiO_4$ suggest a diatom bloom occurred between the February and April surveys in coastal and Boston Harbor waters (**Figure 2-1**). In contrast, chlorophyll concentrations and diatom abundance were very low in nearfield, offshore and boundary areas in February and March and $SiO_4$ concentrations remained elevated (suggesting a diatom bloom event had not occurred in these areas; **Figures 2-1**, **2-3**, and **2-4**).

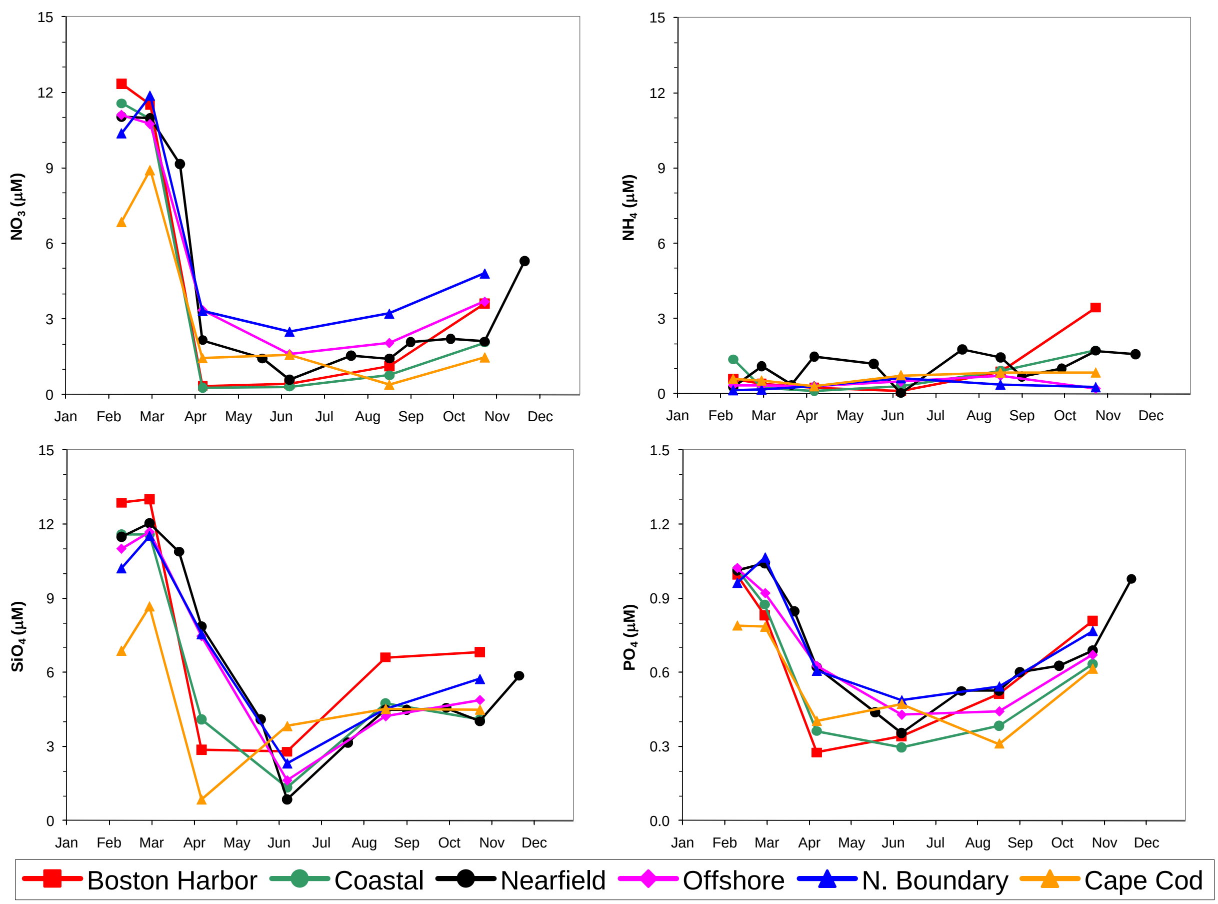


**Figure** 2-1. Time-series of survey mean nutrient concentrations in Massachusetts and Cape Cod Bays. Mean concentrations over depths and stations within each region in 2008.

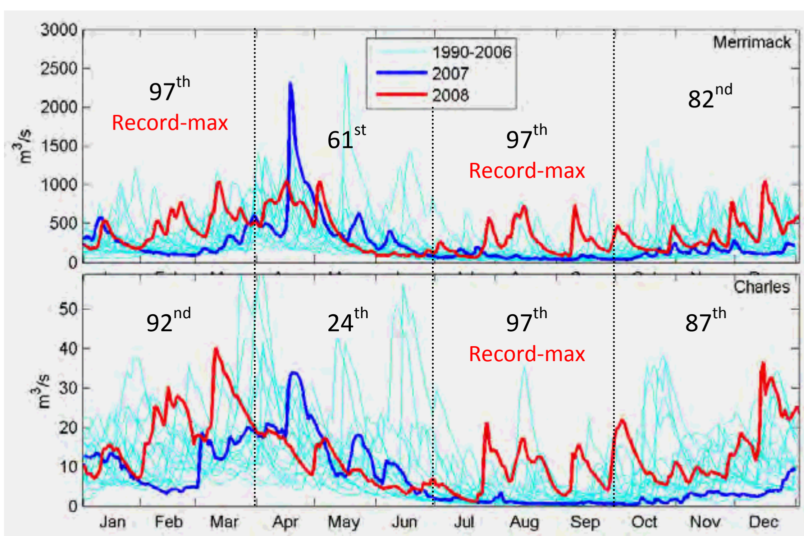


**Figure** 2-2. Comparison of the 2008 discharge of the Charles and Merrimack Rivers (solid red curve) with the observations from the previous year (solid blue curve) and 1990-2006 (light blue lines). Percentile of flow in 2008 relative to other years is presented for each river/season. Note record maxima for the 1990-2008 monitoring period.

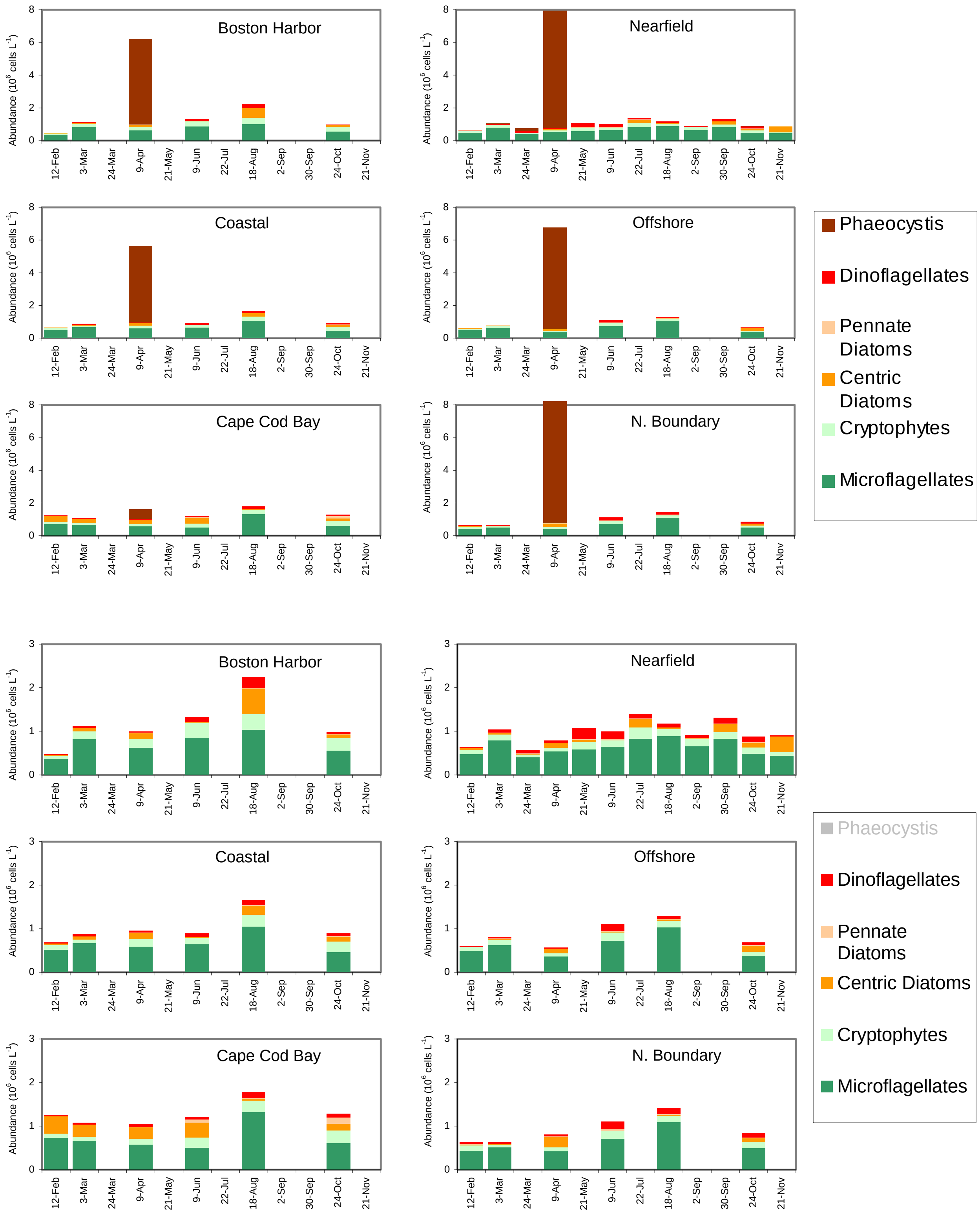


**Figure** 2-3. Phytoplankton abundance by major taxonomic group in all six areas for 2008. The lower set of graphs omits *Phaeocystis* to allow the other taxonomic groups to be seen.

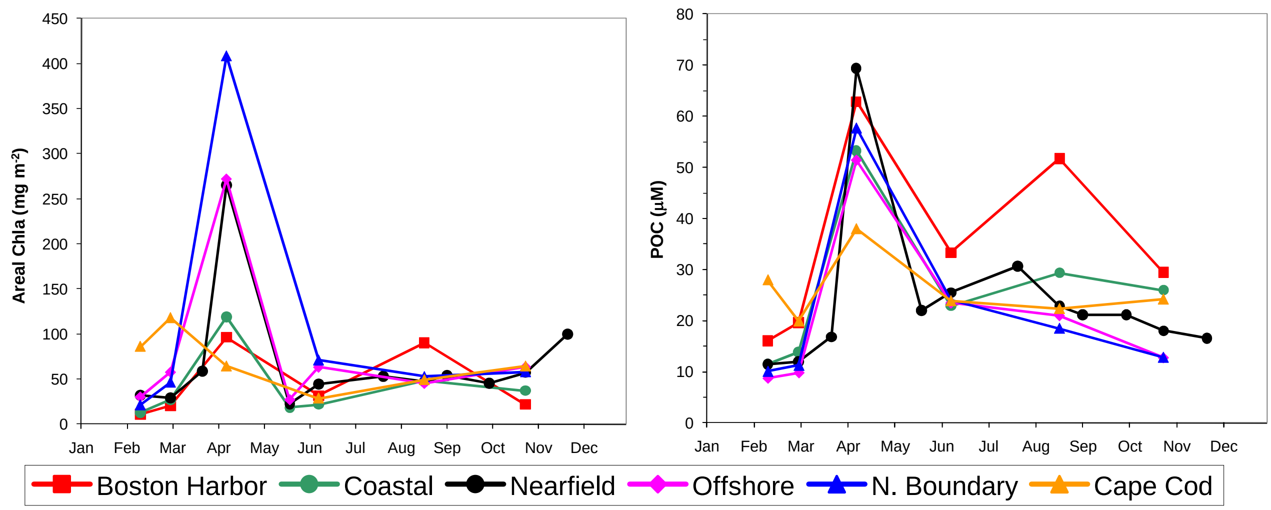


**Figure** 2-4. Time-series of survey mean areal chlorophyll (mg $m^{-2}$) and POC (μM) in Massachusetts and Cape Cod Bays. Mean concentrations over all stations and all depths for POC within each region in 2008 (chlorophyll is already depth-integrated and expressed as chl per unit area).

In April, a *Phaeocystis* bloom was noted throughout the bays (**Figure 2-5**). MODIS imagery suggests the bloom started in the western Gulf of Maine waters north of the bays and was entrained or eventually developed within the bays as has been seen during previous years (**Appendix B slide 21**). In April, high abundances (5-10 million cells $L^{-1}$) were observed in the harbor, nearfield, and to the northeast (stations F22, F26, and F27). A maximum abundance of 14 million cells $L^{-1}$ was observed in the mid-depth sample at station N16. Nitrate concentrations decreased sharply from February to April across the bay coincident with the bloom and annual peak concentrations of chlorophyll and POC (**Figures 2-1** and **2-4**). Although there was a small seasonal peak in primary productivity in April, production rates did not reach annual maxima as observed in biomass (as measured by abundance or concentration; **Figure 2-6** ). In fact, spring bloom productivity peaks in 2008 were the lowest observed during the monitoring period except for 1998 – “the year without a bloom” (**Appendix C**).

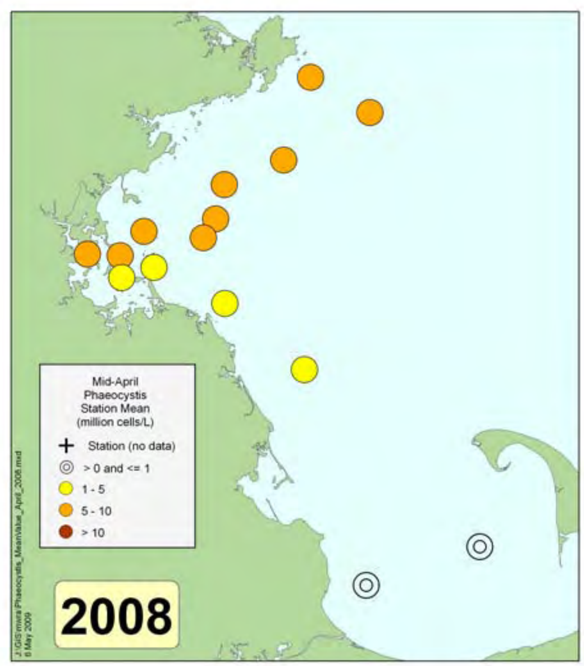


**Figure** 2-5. April 2008 mean *Phaeocystis* abundance (million cells $L^{-1}$).

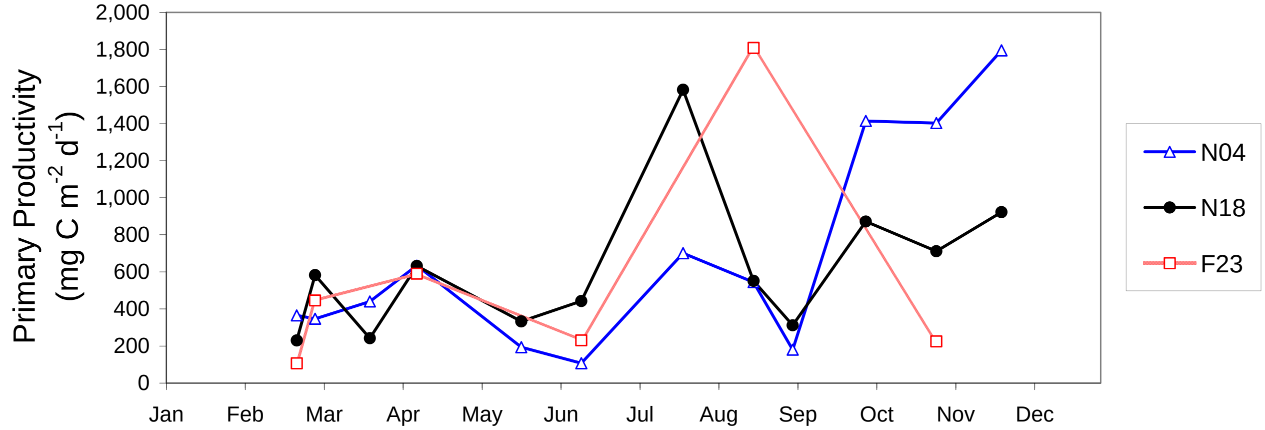


**Figure** 2-6. Potential areal productivity (mg C $m^{-2}$ $d^{-1}$) in 2008 at stations F23, N18, and N04.

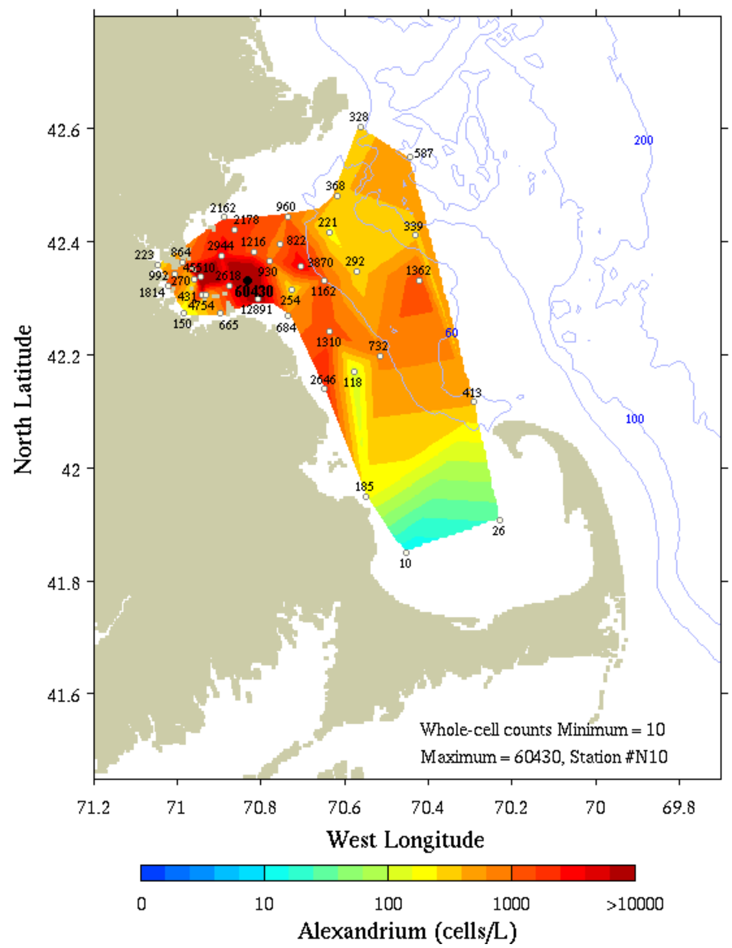


**Figure** 2-7. *Alexandrium fundyense* cell concentrations in Massachusetts Bay and Boston Harbor, June 2008.

By May, *Phaeocystis* was no longer present in the nearfield. But a bloom of the toxic dinoflagellates species *Alexandrium fundyense* was occurring in the Gulf of Maine in May 2008, as in 2005, 2006, and 2007. As with the previous blooms in 2005 and 2006, an early May northeasterly storm likely transported *Alexandrium* cells from the offshore Gulf of Maine bloom into the bay (**Appendix A slide 12** and **Appendix E**). The bloom began in a typical fashion, with measurable but low cell counts and PSP toxicity observed in April and early May along the western Maine coast. On May 6, high PSP was reported at Star Island, NH, and thereafter, the toxicity spread into northern Massachusetts and Massachusetts Bay, eventually reaching the Cape Cod Canal. *Alexandrium* abundances increased over the course of May and peaked[1] at over 60,000 cells $L^{-1}$ in the nearfield (station N10) on June 13th (**Figure 2-7**). However, by June 24th, *Alexandrium* counts in the nearfield had decreased to ≤10 cells $L^{-1}$ and the bloom was over. The initial storm in early May likely entrained the cells into the bay. However, meteorological conditions for the rest of May and June were dominated by S and

[1] *Alexandrium* is normally a very minor component of the phytoplankton community, but this unusually high abundance of 60,000 cells $L^{-1}$ would be manifest as about 0.9 μg chlorophyll $L^{-1}$.

SW winds with limited NE winds and the bloom was not consistently pushed into Cape Cod Bay, nor did it reach the high cell abundance or toxicity seen there during the 2005 bloom. High counts of *Alexandrium* were found in Boston Harbor in 2008, in contrast to 2005 when the harbor was unaffected. Additional details on the 2008 *Alexandrium* bloom are presented in Section 2.2 and **Appendix E**.

Summer and fall conditions were typical. Stratification (**Figure 2-8**) was well established partly due to large freshwater inputs that led to decreased surface water salinity (**Figure 2-9**). Surface nutrients were depleted and bottom DO concentrations declined at a normal rate. Minor summer diatom blooms were observed in the nearfield in July and at Boston Harbor and coastal stations in August (**Figure 2-3**). These blooms coincided with annual peak productivity levels at stations N18 and F23 (**Figure 2-6**). There may have been an upwelling event prior to the July nearfield survey (see **Appendix A**) that could have supported the observed elevated productivity. There were coincident peaks in chlorophyll and POC associated with these summer diatom blooms, but they were relatively low in comparison to the peak levels measured in April (except in Boston Harbor where POC levels in August were comparable to those in April; **Figure 2-4**).

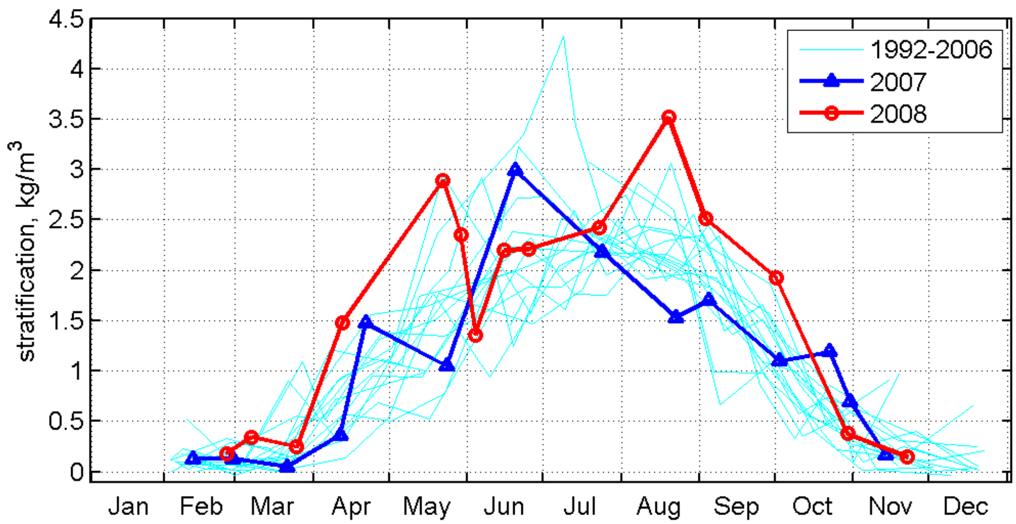


**Figure** 2-8. Stratification near the outfall site (nearfield stations N16, N18 and N20) for 2008 (red line) compared to 2007 (dark blue line) and the previous 15 years of observations (1992-2006; light blue).

A fall diatom bloom was observed (**Figure 2-3**) in the nearfield during the three surveys conducted from late September to late November with productivity levels peaking in November at station N04 (**Figure 2-6**). Biomass (abundance and concentrations) did not exhibit a similarly high peak by comparison. Overall, fall diatom abundances and resulting chlorophyll and particulate organic carbon (POC) concentrations were relatively low in comparison to previous summer and fall blooms.

Annual DO minima were quite high across all areas with all survey mean bottom water DO concentrations >7.5 mg $L^{-1}$ (**Figure 2-10**). These relatively high minima were observed in August for Cape Cod Bay, Boston Harbor, and coastal areas, in late September in the nearfield, and in October at the offshore and northern boundary stations. The nearfield annual minimum was 7.7 mg $L^{-1}$, which is the second highest minimum that has been observed (1993 being the highest, at 7.8 mg $L^{-1}$). Regression analysis predicted that the low salinity water would contribute to anomalously high dissolved oxygen, but the temperature effect would cause a negative anomaly. Thus the model prediction was for near-average near-bottom DO. The observed values (average Sept-Nov) were slightly higher than predicted by the model (see **Appendix A**

**slide 21**). Strong mixing in October returned the water column to winter, well-mixed conditions and resulted in increased nutrient and DO levels in the nearfield in November.

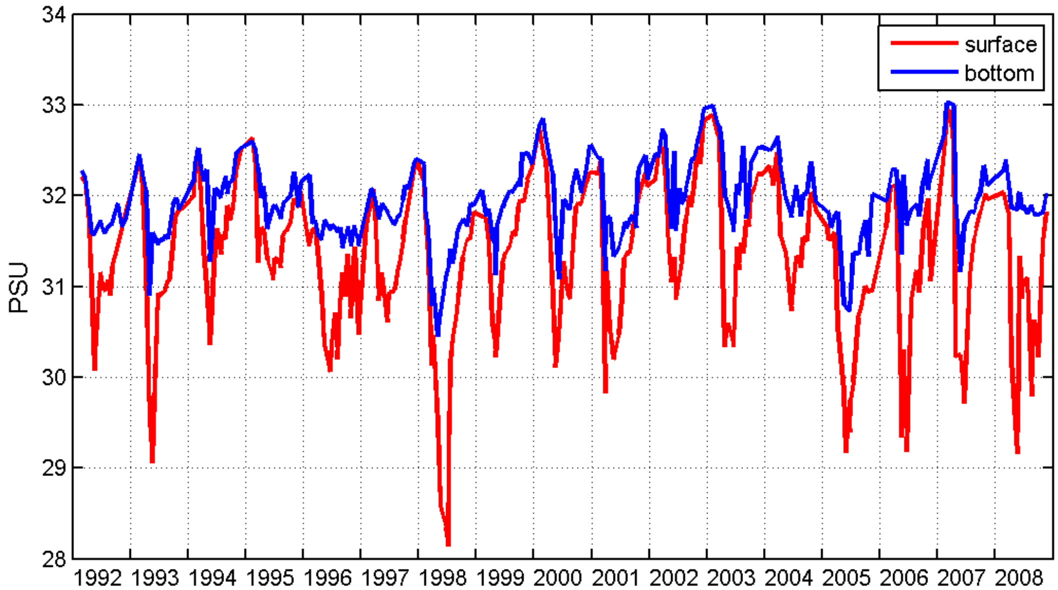


**Figure** 2-9. Surface and bottom water salinity near the outfall site (nearfield stations N16, N18 and N20) for 1992-2008.

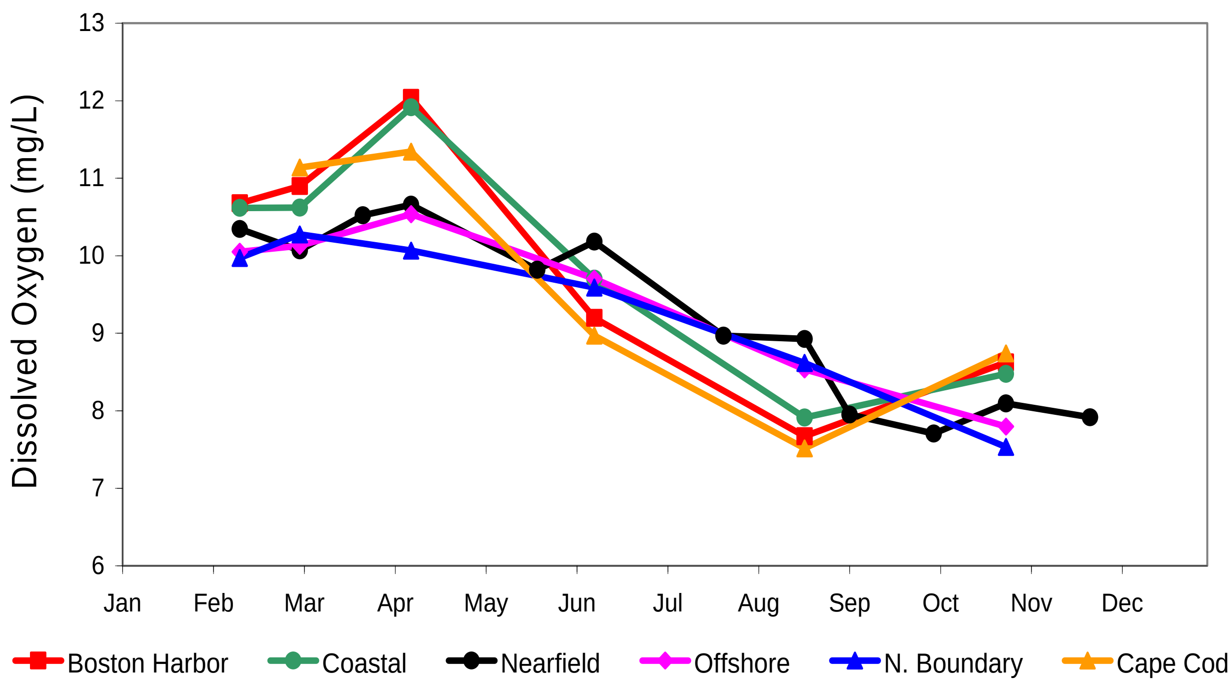


**Figure** 2-10. Time-series of average bottom dissolved oxygen concentration in Massachusetts and Cape Cod Bays in 2008. Average represents the bottom values from all stations in each region.

Total zooplankton abundance in 2008 followed a normal seasonal cycle with low abundance during the colder months, peaking in summer, and declining again in the fall. Mean abundances were <100,000 animals $m^{-3}$, and similar to years after the high abundance peaks in 1999 and 2000. Zooplankton community composition was similar to most previous years. Abundance was dominated by copepods (copepodites and adults; **Figure 2-11**), most of which were *Oithona similis*, with secondary contributions by *Pseudocalanus* spp., followed by copepod nauplii, and non-copepods. Barnacle nauplii were somewhat abundant in February and March in most locations. The appendicularian *Oikopleura dioica* was relatively abundant in the nearfield in May, and the marine cladoceran *Evadne nordmanni* was relatively abundant in most locations in June-August. Meroplankters such as bivalve and gastropod veligers made minor contributions to abundance in Boston Harbor and Cape Cod Bay in the summer and fall.

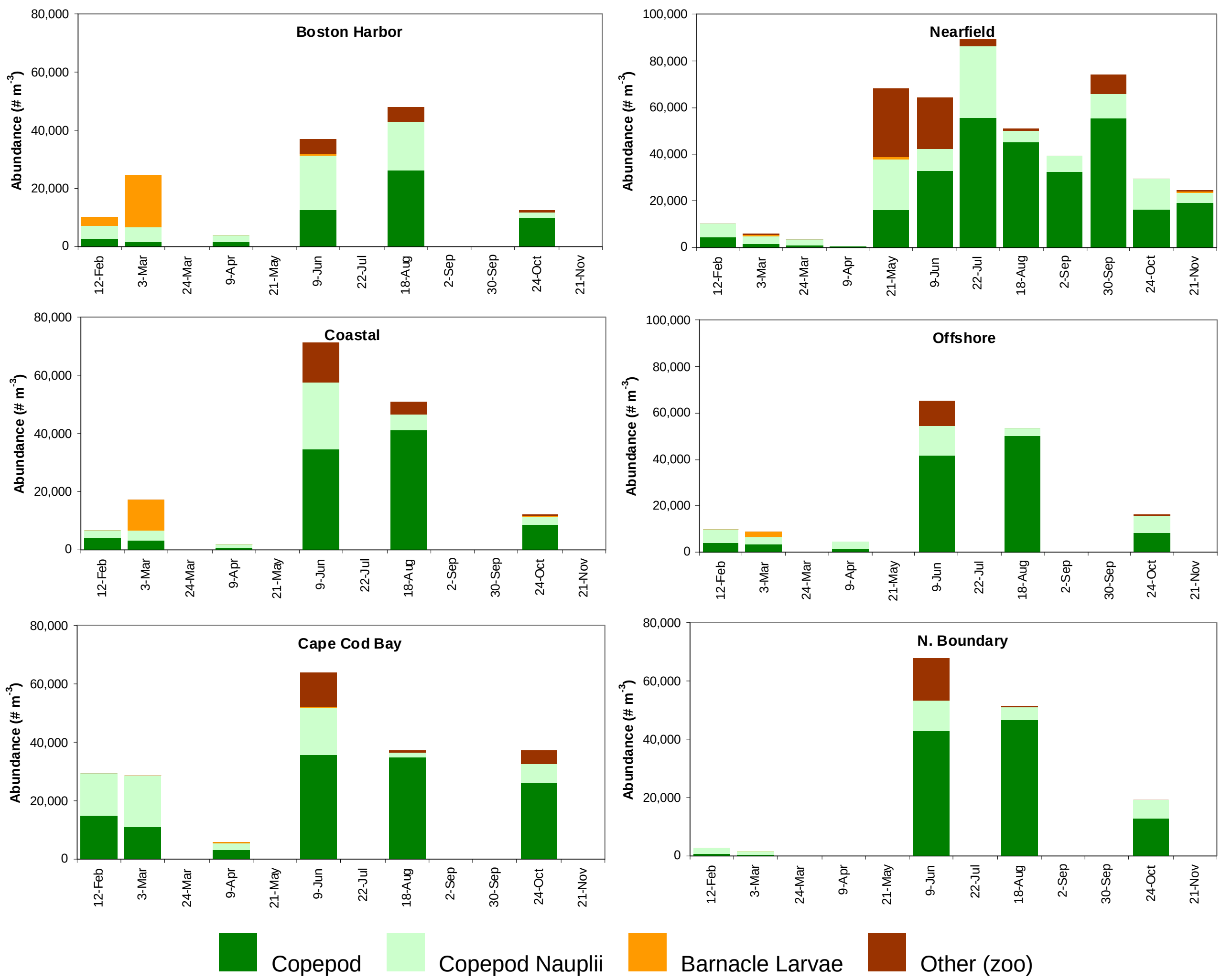


**Figure** 2-11. Zooplankton abundance by major taxonomic group in all six areas for 2008.

## 2.2. Contingency Plan Thresholds for 2008

Contingency Plan Threshold water quality parameters include DO concentrations and percent saturation in bottom waters of the nearfield and Stellwagen Basin, rate of decline of DO from June to October in the nearfield, annual and seasonal chlorophyll levels in the nearfield, seasonal means of the nuisance algae *Phaeocystis pouchetii* and *Pseudo-nitzschia pungens* in the nearfield, and individual sample counts of *Alexandrium fundyense* in the nearfield (**Table 2-1**). The DO values compared against thresholds are calculated based on the mean of bottom water values for surveys conducted from June to October. The seasonal rate of nearfield bottom water DO decline is calculated from June to October. The chlorophyll values are calculated as survey means of areal chlorophyll (mg $m^{-2}$) and then averaged over seasonal and annual time periods. The *Phaeocystis* and *Pseudo-nitzschia* seasonal values are calculated as the mean of the nearfield station means (each station is sampled at surface and mid-depth). The *Pseudo-nitzschia* "*pungens*" threshold designation can include both non-toxic *P. pungens* as well as the identical-appearing (at least with light microscopy) domoic-acid-producing species *P. multiseries* and since resolving the species identifications of these two species requires scanning electron microscopy or molecular probes, all P. *pungens* and *Pseudo-nitzschia* unidentified beyond species were included in the threshold. For *A. fundyense*, each individual sample value is compared against the threshold of 100 cells $L^{-1}$.

**Table** 2-1. Contingency plan threshold values for water column monitoring in 2008. Exceedance shaded blue.

| Parameter | Time Period | Caution Level | Warning Level | Baseline/ Background | 2008 |
|---|---|---|---|---|---|
| Bottom Water DO concentration (mg $L^{-1}$) | Survey Mean in June-October | <6.5 (unless background lower) | <6.0 (unless background lower) | Nearfield: 5.75<br>SW Basin: 6.2 | Nearfield: 7.71<br>SW Basin: 7.06 |
| Bottom Water DO %saturation | Survey Mean in June-October | <80% (unless background lower) | <75% (unless background lower) | Nearfield: 64.3%<br>SW Basin: 66.3% | Nearfield: 85.7%<br>SW Basin: 74.8% |
| Bottom Water DO Rate of Decline (Nearfield, mg $L^{-1}$ $d^{-1}$) | Seasonal June-October | 0.037 | 0.049 | 0.024 | 0.017 |
| Chlorophyll (mean, mg $m^{-2}$) | Annual | 118 | 158 | 79 | 67 |
| | Winter/spring | 238 | -- | 62 | 96 |
| | Summer | 93 | -- | 51 | 42 |
| | Autumn | 212 | -- | 97 | 64 |
| *Phaeocystis pouchetii* (mean, cells $L^{-1}$) | Winter/spring | 2,020,000 | -- | 468,000 | 1,980,000 |
| | Summer | 357 | -- | 72 | Absent |
| | Autumn | 2,540 | -- | 317 | Absent |
| *Pseudo-nitzschia pungens* (mean, cells $L^{-1}$) | Winter/spring | 21,000 | -- | 6,200 | Absent |
| | Summer | 43,100 | -- | 14,600 | 540 |
| | Autumn | 24,700 | -- | 9,940 | 171 |
| *Alexandrium fundyense* (cells $L^{-1}$) | Any nearfield sample | 100 | -- | Baseline Max 163 | 60,430 |

DO concentrations in 2008 followed trends that have been observed consistently since 1992. Bottom water DO levels are at a maximum in the winter, decrease over the course of the summer during seasonal stratification, and reach annual minimum levels just prior to stratification breaking down in the fall – usually October. Since the bay outfall came on line, there has been no change in the DO cycle in the nearfield and Stellwagen Basin (**Figure 2-12**). There is no consistent difference between the baseline and post-diversion survey means and the only difference of note in 2008 were the slightly higher and more variable DO levels in the summer and fall in the nearfield. Bottom water DO levels in the bays are primarily driven by regional physical oceanographic processes and have been unaffected by the diversion to the bay outfall (Geyer *et al.* 2002, Libby *et al.* 2009).

There were no exceedances of nearfield chlorophyll thresholds in 2008. The seasonal and annual nearfield mean areal chlorophyll levels for 2008 were all relatively low and well below threshold values (**Table** 2-1). Even with a large April *Phaeocystis* bloom, the winter/spring mean value was <100 mg m$^{-2}$, the lowest winter/spring mean areal chlorophyll level since 2001. The summer, fall, and annual 2008 nearfield areal chlorophyll means were also quite low and lower than the baseline and post-diversion means (**Figure 2-13**).

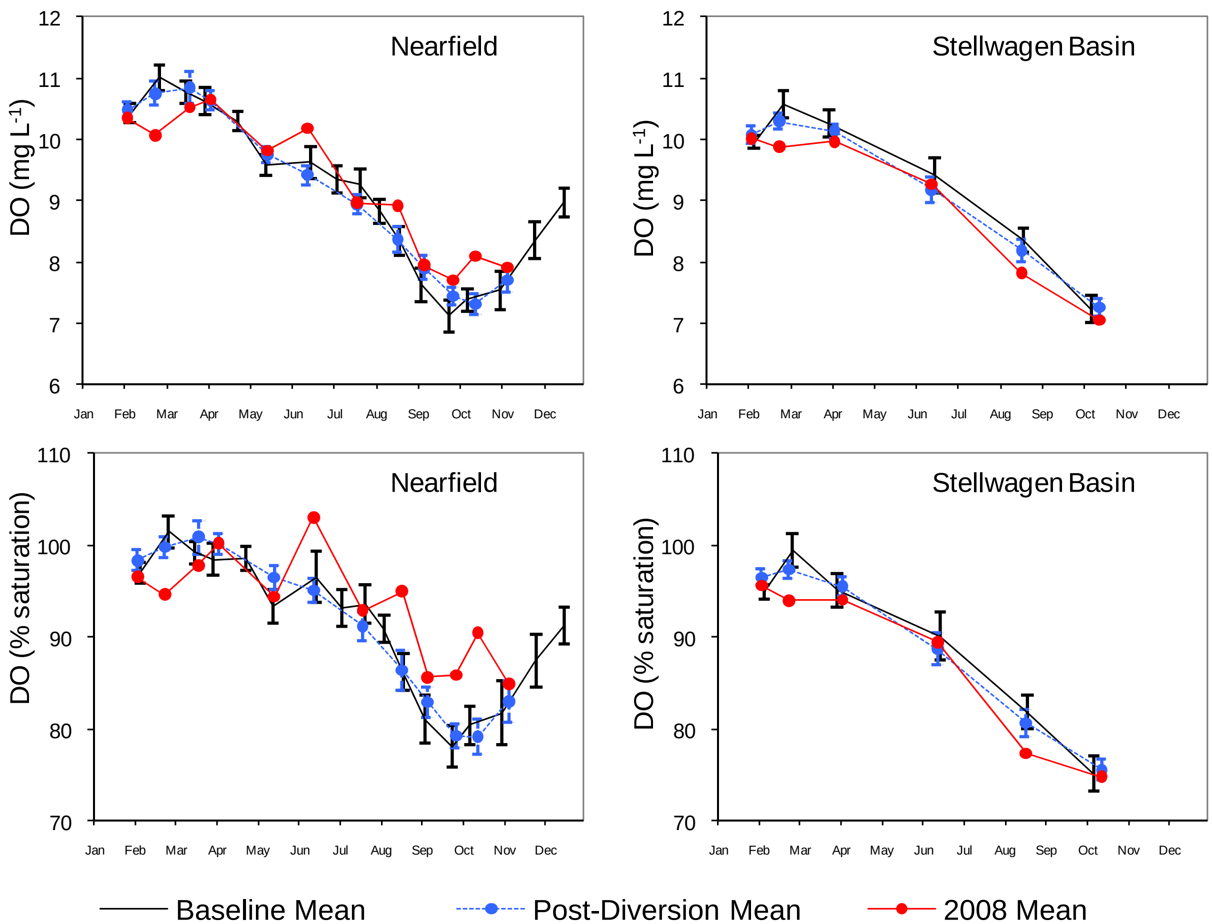


**Figure** 2-12. Time-series of the period mean of survey mean bottom water DO concentration (top) and percent saturation (bottom) in the nearfield (left) and Stellwagen Basin (right) during baseline (black), post-diversion (blue), and 2008 (red). Data for Stellwagen Basin collected from stations F12, F17, F19, and F22. Error bars represent ± SE.

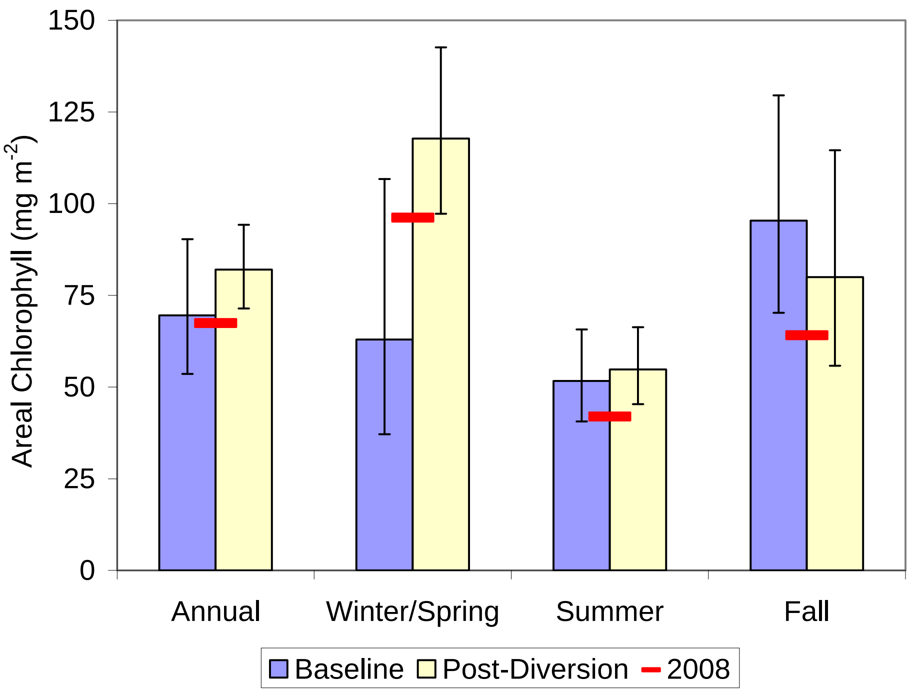


**Figure** 2-13. Comparison of baseline and post-diversion seasonal and annual mean areal chlorophyll (mg $m^{-2}$) in the nearfield. Error bars represent ± SE.

All three of the harmful or nuisance phytoplankton included in the Contingency Plan thresholds (*Pseudo-nitzschia* spp., *Alexandrium fundyense* and *Phaeocystis pouchetii*) were observed in 2008. *Alexandrium* abundance exceeded the caution level. *Alexandrium* abundances in the nearfield were comparable to the levels reached in 2005 and 2006, with a maximum count of 60,430 cells $L^{-1}$ (**Figure 2-14**). MWRA sampled for *Alexandrium* in Massachusetts Bay on seven surveys from April to June, and in Boston Harbor in early June. WHOI conducted six surveys from April to July. WHOI combined its and MWRA's survey results and made them available online[2]. Contour plots of *Alexandrium* abundance are provided in **Appendix E**. The shellfish closures for 2008 were nearly as extensive as those in 2005 (**Appendix E**). As in 2005, there is no evidence that the discharge aggravated the 2008 red tide. A review of the 2005 red tide is in Anderson *et al*. 2007.

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[2] http://science.whoi.edu/users/olga/alex_surveys_2008/WHOI_Alexandrium_Surveys_2008.html

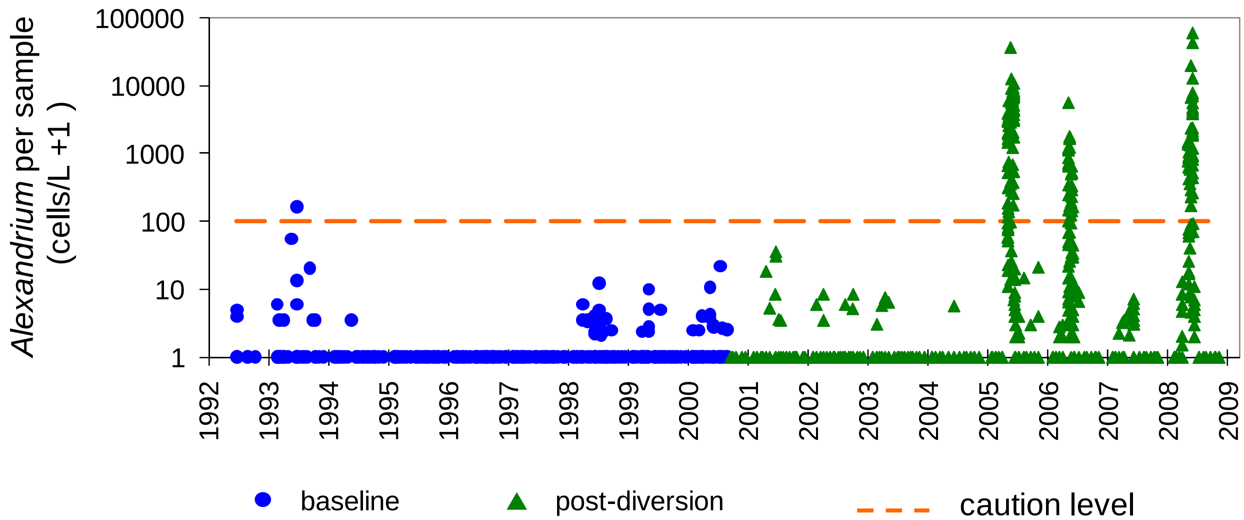


**Figure** 2-14. Nearfield *Alexandrium* abundance for individual samples (cells $L^{-1}$; note log axis). Contingency Plan threshold value shown as dotted line.

Survey mean *Phaeocystis* abundance in the nearfield in April 2008 was 1,980,000 cells $L^{-1}$, slightly lower than the threshold. It was the ninth year in a row that a bloom has been observed and was comparable in magnitude to the large blooms in 2000, 2004, and 2007 (**Figure 2-15**). The 2008 *Phaeocystis* bloom was observed in all regions of the bays, consistent with past observations (Libby *et al.* 2009), and lasted about 30 days from late March to mid April, and ending before the May survey. *Phaeocystis* blooms of up to 100 days duration were observed in 2003 and 2005. The occurrence, magnitude, and duration of these blooms have been the focus of previous reports (Libby *et al.* 2006, 2007 and 2009).

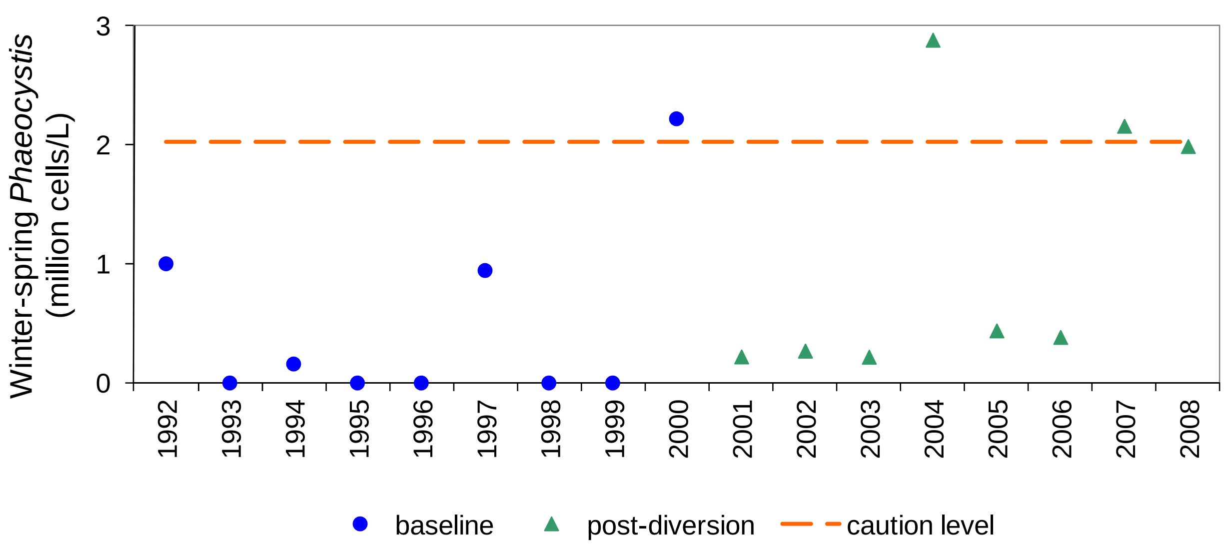


**Figure** 2-15. Winter/spring seasonal mean nearfield *Phaeocystis* abundance (cells $L^{-1}$) for 1992 to 2008. Contingency Plan threshold value shown as dotted line.

*Pseudo-nitzschia* were observed at low levels of up to ~500 cells $L^{-1}$ during the summer in the nearfield. These levels are far below those recorded in previous years and are also far below both the Contingency Plan threshold and a level that would cause amnesic shellfish poisoning.

## *2.3. Interannual Comparisons*

### 2.3.1. Nutrients and Biomass

After the 2000 diversion, the most obvious water quality difference was in $NH_4$. There was an 80% decrease in Boston Harbor, a decrease at coastal stations, and a 1 µM increase in the nearfield annual average (**Figure 2-16**). These changes are quite clear and consistent with model predictions (Libby *et al.* 2009, Signell *et al.* 1996). Ammonium concentrations above background that are associated with the effluent plume (greater than about 1uM in winter and 2uM in summer) are generally confined to an area within 10-20 km of the outfall.

Since 2003 there has been an overall decrease of about 1 µM in annual mean $NH_4$ concentrations across the bay including the nearfield and offshore waters along the northern boundary of the bay; levels in those regions are comparable to those observed in the 1990's. Those regional changes are not plausibly related to the outfall.

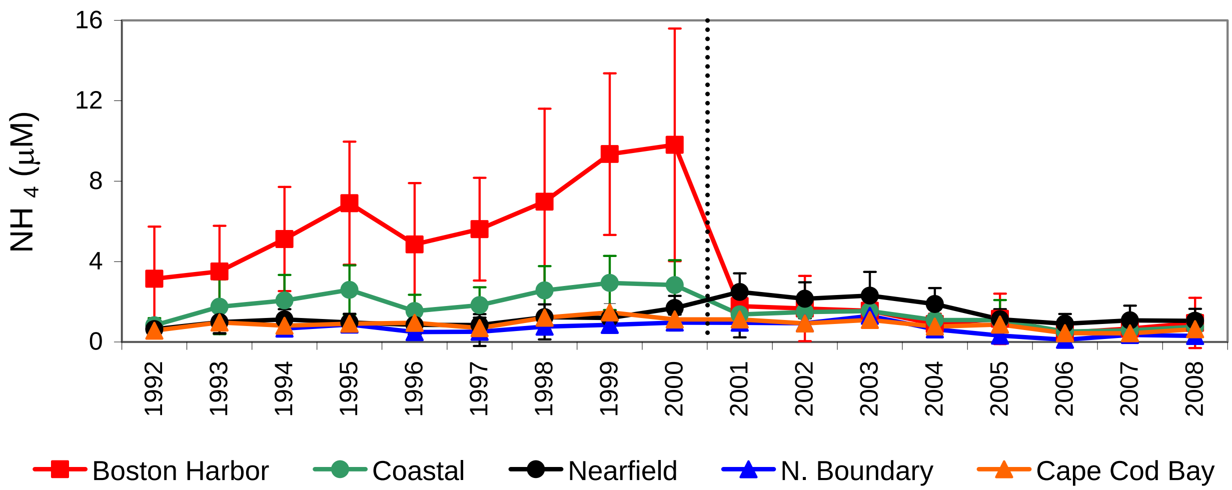


**Figure** 2-16. Time-series of annual mean $NH_4$ concentrations (µM) by area. Data collected from all depths and all stations sampled in each area. Error bars represent ±1 standard deviation.

In Boston Harbor, the dramatic decrease in $NH_4$ after 2000 is associated with other changes including significant decreases in other nutrients, chlorophyll, and POC, and an increase in bottom water dissolved oxygen (Taylor 2006). In the nearfield, regression analyses (Libby *et al.* 2009) showed the moderate increase in $NH_4$ concentrations was most apparent in summer and that there was a coincident increase in POC concentrations in the nearfield in the summer. There has also been a trend of higher winter/spring chlorophyll in most of Massachusetts Bay, including the nearfield (**Figure 2-13**), but this appears to be related to regional processes governing the consistent annual blooms of *Phaeocystis* in March-April since 2000.

"Before-After, Control-Impact" (BACI) statistical analyses put the changes in POC and $NH_4$ in context. BACI analysis found that only $NH_4$ concentrations changed between the impact (inner nearfield) and control (outer nearfield, Massachusetts Bay offshore, and Cape Cod Bay) areas (Libby *et al.* 2009). $NH_4$ was higher in the inner nearfield ($p<0.01$), but there were no changes in chlorophyll or POC in this "impact" area compared to "control" regions of the bays that are 5 to >50 km distant, supporting the understanding that observed changes in phytoplankton biomass are associated with regional processes.

Results of BACI analyses including the 2008 data are presented in **Appendix B**. Previous BACI analyses had been run on groups of stations. Here, the analyses were run on individual station data. Station N18 nearest the outfall was designated as the "impacted" site and a range of controls were compared for the harbor (F23), northeast (N04 and F22), and both 15 km (F13) and 30 km (F06) to the south. The results were similar to our previous BACI analyses (Libby *et al.* 2009). The only differences noted in the baseline vs. post-diversion comparison for each station were for $NH_4$. There were increases in $NH_4$ at station N18 (all seasons) and decreases at stations F23 (all seasons), N04 (winter/spring) and F13 (winter/spring). The BACI comparisons between station N18 and the other stations showed increases in $NH_4$ for 80% of the station and season comparisons. None of the other BACI results showed any changes between stations for $NO_3$, $SiO_4$, POC, or areal fluorescence ($p>0.05$).

Thus, as predicted, there has been an increase in $NH_4$ in the nearfield relative to the baseline and also relative to the regional background concentrations. Statistical analyses indicate that even though there are apparent trends of increasing chlorophyll and POC in the bays during the winter/spring, these changes are not related to the outfall, but are rather baywide trends associated with processes governing the greater western Gulf of Maine (i.e. consistent annual occurrence of the *Phaeocystis* blooms).

#### 2.3.2. Productivity

Productivity (a measure of phytoplankton growth rates) at station F23 was higher than the other stations in 1995-1997, as expected from nutrient loading to the harbor (**Figure** 2-17). After 1997 annual mean productivity at the 3 monitoring stations is remarkably synchronized over time, and 2008 continued that pattern. The dip in 1998 is real and thought to reflect environmental conditions (Keller *et al.* 2001).

In Boston Harbor, there has been a decrease in annual productivity since diversion ($p<0.05$), but no change in the nearfield. However, the pre- vs. post-diversion productivity comparisons are influenced by a trend of lower annual productivity that has been observed 2003 to 2008. A comparison of 1995-2002 vs. 2003-2007 annual productivity indicated that there has been a decrease ($p<0.05$) at all three stations in recent years (Libby *et al*. 2009).

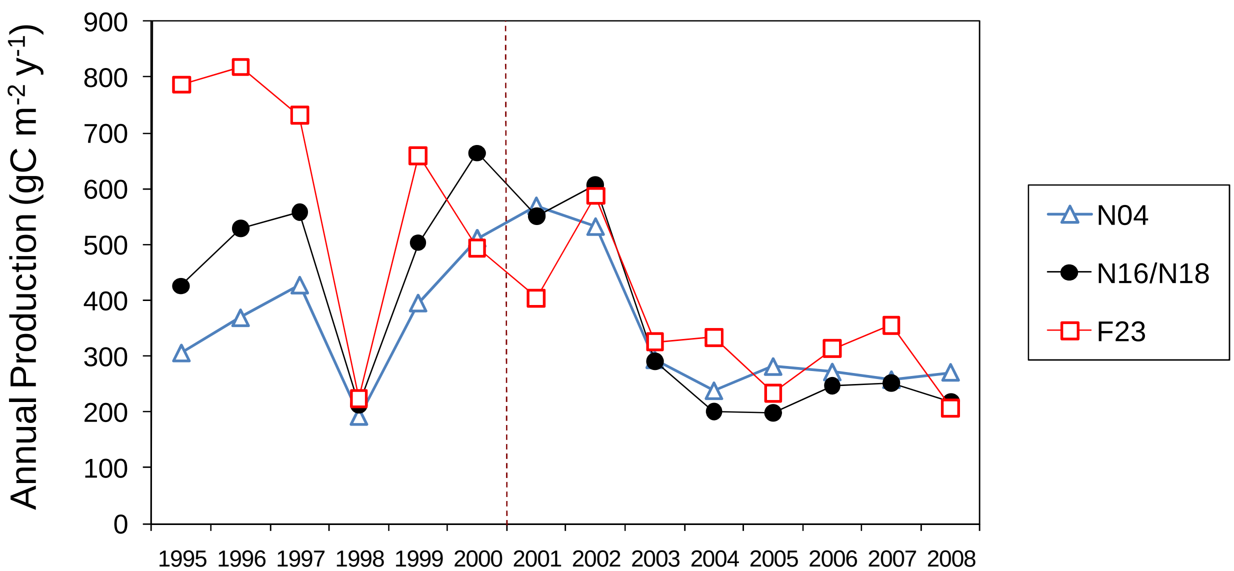

**Figure** 2-17. Potential annual production (g C $m^{-2}$ $y^{-1}$) for stations F23, N16/N18, and N04.

One factor contributing to lower areal productivity in 2003-2008 appears to be reduced wind intensity. At all three stations, primary production was positively correlated with average summer wind speed and with average summer wind gusts with r2 values of 0.5 or greater (**Appendix C**). A time series of average summer wind speed and summer wind gusts indicated that 2008 was one of the calmest since 1995. The only two years with lower values were 1998 and 2003. The mean summer wind speed and the summer average wind gusts were lower in the period 2003 to 2008 compared to the period 1995 to 2002 (**Figure 2-18**). Thus the decrease in productivity in 1998 and since 2003 at the nearfield stations and at least partly at the harbor station can be correlated with reduced wind intensities during these years. We hypothesize that enhanced stratification due to lighter winds prevented the mixing of subsurface nutrients to fuel primary production during the summer season.

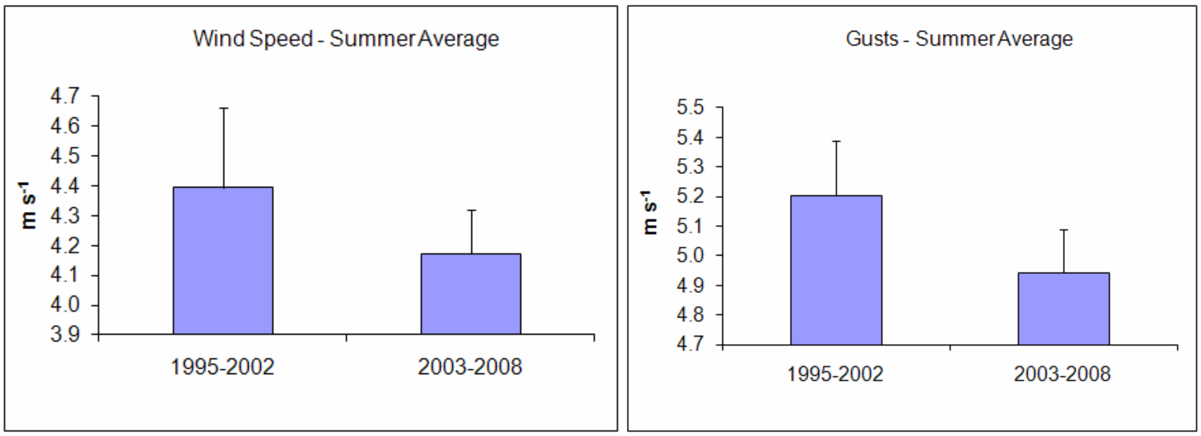


**Figure** 2-18. Summer (July-September) average wind speed and average wind gusts (m $s^{-1}$) at NOAA NDBC station 44013 for 1995-2002 and 2003-208. The error bars represent +1 standard deviation.

### 2.3.3. Plankton

**Table 2-2** shows the change in abundance of phytoplankton groups as a ratio (Mann-Whitney 2-sample test comparing regional post-diversion /pre-diversion ratio of median abundance). For example, microflagellates increased 73% in Boston Harbor. Conclusions from the table are:

- Total phytoplankton counts increased in two regions (nearfield and boundary).
- Microflagellates increased ~40% in all regions. (This is due to an apparent methodological underestimation of microflagellates during 1992-1994.)
- Dinoflagellates decreased at the nearfield and offshore.
- *Phaeocystis* increased 2-4-fold in the boundary, coastal, nearfield and offshore regions.
- Diatoms decreased to 30% to 60% of baseline levels in all regions except the boundary region.

We regressed annual mean abundance versus year (1992-2008) for each of the regions and phytoplankton groups, and then applied a comparison-of-slopes technique to identify long-term linear trends in abundance. Annual abundance levels were chosen for this linear model fitting as the annually aggregated data were normally distributed and free of temporal autocorrelation (unlike the raw data)

**Table** 2-2. Summary of Mann-Whitney 2-sample tests comparing regional median levels of phytoplankton groups during 1992-2000 vs. 2001-2008. Values indicate ratio of median values [(2001-2008) / (1992-2000)]; statistically significant ($p < 0.05$) differences in pink (increase) or blue (decline).

| Species/Group | Boston Harbor | Coastal | Nearfield | Offshore | Boundary | Cape Cod Bay |
|---|---|---|---|---|---|---|
| Total Phytoplankton | -- | -- | 1.16 | -- | 1.55 | -- |
| Microflagellates | 1.73 | 1.42 | 1.45 | 1.31 | 1.45 | 1.41 |
| Dinoflagellates | -- | -- | 0.45 | 0.34 | -- | -- |
| *Phaeocystis* | -- | 2.48 | 1.64 | 2.42 | 4.68 | -- |
| Diatoms | 0.46 | 0.44 | 0.57 | 0.28 | -- | 0.44 |

**Table 2-3** shows that total phytoplankton in the boundary region increased linearly by 104,000 cells $L^{-1}$ $yr^{-1}$, much of that due to the increase there in *Phaeocystis* (85,000 cells $L^{-1}$ $yr^{-1}$). *Phaeocystis* also increased in the offshore area. Diatoms decreased at a rate of -39,400 cells $L^{-1}$ $yr^{-1}$ in all regions except the boundary region. (The -39,400 numbers are repeated in the table because the statistical technique concluded that slopes did not differ between those regions, so it returned the region-average.) The widespread occurrence of the diatom decline suggests a region-wide driver of this phenomenon, though interestingly not at the boundary.

**Table** 2-3. Summary of significant linear trends in mean annual abundance of phytoplankton groups. Values represent mean rate of change in units of cells $L^{-1}$ $year^{-1}$. Pink indicates positive slope (=increase); blue indicates negative slope (= decrease).

| Species/Group | Boston Harbor | Coastal | Nearfield | Offshore | Boundary | Cape Cod Bay |
|---|---|---|---|---|---|---|
| Total Phytoplankton | -- | -- | -- | -- | +104,000 | -- |
| Microflagellates | -- | -- | +23,000 | -- | -- | -- |
| Dinoflagellates | -- | -- | -- | -- | -- | -300 |
| *Phaeocystis* | -- | -- | -- | +85,000 | +85,000 | -- |
| Diatoms | -39,400 | -39,400 | -39,400 | -39,400 | -- | -39,400 |

In summary, there have been apparent shifts within the phytoplankton community assemblage that are associated with long-term, regional trends. It appears that diatoms and dinoflagellates have generally declined while microflagellates and *Phaeocystis pouchetii* have increased. There is no plausible outfall-related link or causality associated with these shifts as they occur over large spatial scales; such broad patterns appear to be related to regional ecosystem dynamics in the Gulf of Maine.

The abundance and structure patterns of the zooplankton community in Massachusetts and Cape Cod Bays are generally similar from year to year. The zooplankton community assemblage in the bays is dominated throughout the year by copepod nauplii, *Oithona similis*, and *Pseudocalanus* spp. Subdominant are other copepods such as *Calanus finmarchicus*, *Paracalanus parvus*, *Centropages typicus* and *C. hamatus*. There are sporadic pulses of various meroplankters such as bivalve and gastropod veligers, barnacle nauplii, and polychaete larvae (Libby *et al.* 2007). Zooplankton abundance from 1992-2008 gave seasonal patterns of abundance that generally followed temperature, with low levels in winter, rising through spring to maximum summer levels, declining in the fall (**Figure 2-19**). The most apparent change has been the lower overall abundance of zooplankton since 2001. A time series analysis (following methods of Broekhuizen and McKenzie 1995) was applied to the nearfield zooplankton dataset to examine this apparent decline (Libby *et al.* 2009). The analysis determined that there had been a substantial long-term decline in the nearfield means for the abundance of total zooplankton from 2001-2006 and it was due to a long-term decline in total copepods. Total copepod abundance rebounded somewhat in 2007 and 2008.

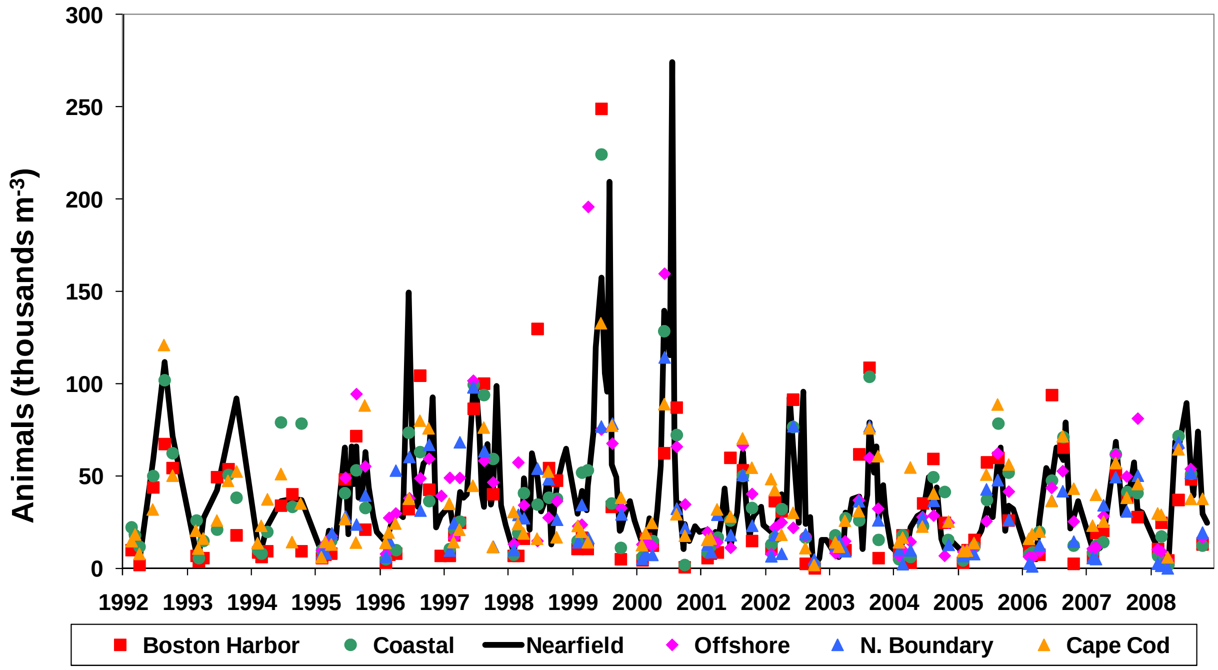


**Figure** 2-19. Time series of total zooplankton abundance by area (1992- 2008).

The long-term trend analyses indicate that zooplankton abundance in the nearfield was in decline from 2000 through 2006 before increasing again in 2007 and 2008. An examination of the baseline vs. post-diversion total zooplankton abundance in each of the areas shows that there is an apparent decrease in all of Massachusetts Bay including Boston Harbor (**Figure 2-20**). Total zooplankton in the four Massachusetts Bay areas were close to baseline mean levels from June to October 2008, but were quite low during the winter/spring. In Boston Harbor, total zooplankton has been slightly lower since outfall diversion and unlike the other areas was even lower in 2008. Interestingly, total zooplankton abundance in Cape Cod Bay is comparable over both periods (**Figure 2-20**). It is unclear why total zooplankton and copepod abundances were lower in 2001-2006 compared to baseline. The timing of this decline coincides with the diversion of the outfall, but there are no plausible cause and effect relationships between the outfall diversion and apparent region-wide decline. Several possibilities for such declines have emerged from recent studies in the Gulf of Maine and shelf waters of the western North Atlantic which hypothesize that the changes may relate to large-scale climatic phenomena such as freshening of the Northwest Atlantic due to Arctic melting (Greene and Pershing 2007).

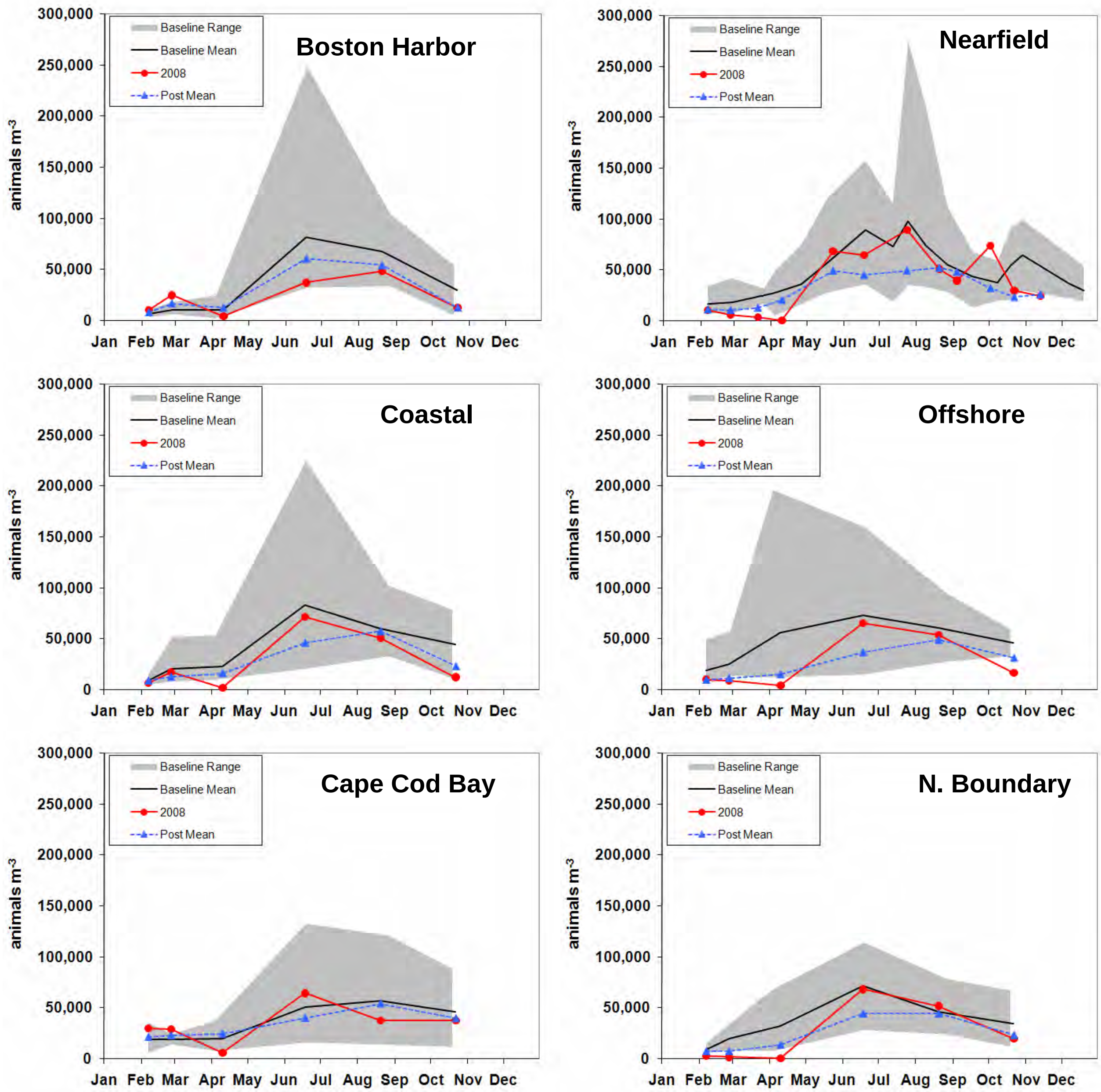


**Figure** 2-20. Survey mean total zooplankton in the six areas in 2008 (red line) compared to the baseline and post-diversion means.

Mean (black line) and range (shaded area) of baseline survey means.
Mean (blue dashed line and triangles) of post-diversion survey means.
Data collected from all stations sampled in each area.

# 3. SUMMARY

There are clear changes in the nutrient regimes following diversion – $NH_4$ has dramatically decreased in Boston Harbor (by ~80%) and nearby coastal waters while increasing less in the nearfield (the changes are consistent with model predictions made during the planning process). The elevated levels of $NH_4$ in the plume are generally confined to an area within 10-20 km of the outfall. The higher nearfield $NH_4$ concentrations, however, have not translated directly into changes in biomass, whether measured as chlorophyll, POC, or phytoplankton abundance although there has been an increase in winter/spring biomass in the nearfield and most of Massachusetts Bay due to larger scale regional trends in phytoplankton bloom dynamics.

In Boston Harbor, there have been significant decreases in seasonal chlorophyll and POC commensurate with the decreases in dissolved inorganic nutrients (Taylor 2006). The harbor has also exhibited patterns in these parameters (and productivity) that are comparable to those observed in the nearfield and other temperate coastal waters (Libby *et al.* 2009). The spatial pattern of summer decreases in chlorophyll and POC in Boston Harbor and nearby coastal waters along the South Shore is as predicted based on the removal of the source of the surface water nutrients that presumably supported the high biomass during the baseline (Signell *et al.* 1996).

The BACI statistical analyses based on stations and groups of stations indicates that the only differences ($P<0.05$) between baseline and post-diversion were for $NH_4$ concentrations, which were higher at station N18 and the inner nearfield compared to control stations or groups of stations in the outer nearfield, MB offshore, and Cape Cod Bay during all three seasons. This indicates that even though there has been an increase in $NH_4$ at these stations close to the bay outfall, there have not been any changes in chlorophyll or POC in this "impacted" area compared to "control" stations or regions of the bays that are 5 to >50 km distant. There certainly have been changes in these parameters post-diversion, but they have changed in both "impact" and "control" areas and thus appear to be associated with regional processes.

Post-diversion production data indicate there has been a decrease in Boston Harbor while there have been no significant changes in nearfield production since September 2000. Reduced productivity at the harbor mouth is correlated with reduced nutrients due to outfall relocation. However, the trends observed in productivity for the pre- versus post-diversion comparisons appear to be confounded by regional processes. The annual productivity data suggest that there has been a decrease in production since 2003 and an evaluation confirms that decreases in nearfield production have occurred from 1995-2002 versus 2003-2007 for annual, as well as fall time periods (Libby *et al.* 2009). This drop in annual nearfield productivity correlates with decreases in summer winds (average and gusts) and the associated degree of stratification. This suggests that the observed decreases in annual productivity at the harbor and nearfield stations in recent years are, at least in part, a result of decreased wind speed and increased stratification and the associated effective decrease in nutrient and light availability.

Analyses of long-term phytoplankton trends indicate that there have been shifts within the phytoplankton community assemblage since diversion to the bay outfall. Diatoms and dinoflagellates have generally declined, while microflagellates and *Phaeocystis* have had relative increases. There is no outfall-related link or causality associated with these shifts as many of the changes are occurring over larger spatial scales and, as with the changes in *Phaeocystis* (regional blooms), appear to be related broader regional ecosystem dynamics in the Gulf of Maine. Another recent change has gained more publicity as the major red tides of 2005, 2006, and 2008 have impacted local shellfishing economies. *Alexandrium* abundance had been low (0-100 cells $l^{-1}$) from 1992-2004 and now has reached bloom levels of >1,000 to 60,000 cells $L^{-1}$ and led to widespread toxicity closures in the bay three out of the last four years. Again there are no indications of a regional outfall effect on the A. *fundyense* blooms, but local effect has not been ruled out. However, a modeling analysis estimated that if an outfall effect had occurred, it would have been minor (Anderson *et al*. 2007). As observed with annual *Phaeocystis* blooms since 2000, *Alexandrium* blooms may become regular, annual events in the western Gulf of Maine and lead to frequent toxicity events in Massachusetts Bay.

Lastly, there was a general decline in total zooplankton (mainly copepods) in the nearfield and other Massachusetts Bay areas from 2001 to 2006 before increasing again in 2007-2008. The timing of this decline coincides with the diversion of the outfall, but there are no plausible linkages between the diversion and apparent baywide decline. Statistical analyses confirm these patterns, but do not provide an indication as to why they occurred. It may be that the post-diversion decreases in total zooplankton and copepod abundance are simply driven by a few anomalously high values such as those in 1999 and 2000 that are skewing the prediversion means upward or they could be due to a variety of biological (changes in grazing pressure top-down or bottom-up) or regional physical processes (i.e. different water masses, NAO or freshening of the Northwest Atlantic due to Arctic melting, etc.). Zooplankton abundance in Boston Harbor has also seen a slight decline post-diversion, but unlike the offshore waters the harbor continued to have lower abundances in 2007-2008. In Cape Cod Bay, total zooplankton and copepod abundances have remained unchanged between baseline and post-diversion periods.

As predicted, there has been an increase in $NH_4$ (about one micro molar) in the nearfield relative to the baseline and also relative to the regional background concentrations. The nitrogen levels in Massachusetts Bay (including the nearfield) vary considerably over space and time and are governed by regional factors. These factors include different loadings to the system, changes in seasonal biological patterns or circulation shifts related to larger scale processes. In summary, only subtle changes in water quality can be attributed to the outfall; the minor increase in $NH_4$ near the outfall is subjectively outweighed by the more apparent improvements in the harbor so that the net effect of relocating the outfall has been beneficial.

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# A. Physical Characterization

Massachusetts Bay physics, 2008.
Rocky Geyer, Woods Hole Oceanographic Institution

## A.1. Overview

The most notable characteristic of the physical regime in 2008 was high freshwater input through much of the year, resulting in lower than average salinities. There was a minor nor'easter in May, which may have transported *Alexandrium* and other organisms from the Western Maine Coastal Current into the bays. The wind regime was typical (both with respect to strength and upwelling-tendency). Dissolved oxygen stayed above 7.6 mg/l, which is high compared to most years of the monitoring program.

## A.2. Forcing variables

*Air temperature* was in the normal range (**slide 3)**. The only significant anomaly was a warm January.

*River flow* was the only stand-out for 2008. The Merrimack had the wettest conditions observed for the monitoring program for the Jan-Mar period and July-Sept (**slide 4**). The Charles also had a record-maximum for the July-Sept period. Interestingly, this high discharge was not associated with big events, but rather more frequent, moderate events than normal. Considering the long term trends (**slide 6**), the region seems to be getting wetter, but there is a lot of interannual variability.

*Winds* were normal in 2008, in the sense that the upwelling index (**slide 7**) was in the middle of the long-term seasonal pattern. On a month-to-month basis, July had stronger than average upwelling, and August had weaker than average.

*Waves* were also in the normal range, and there were no stand-out wave events (**slide 8**). The biggest waves of the year were 5.5 m, compared to the maximum observed in the last decade reaching 8.5 m.

## A.3. Water properties

*Surface water temperature* was warmer than normal in June and August (**slide 11**), due most likely to strong surface heating and relatively weak upwelling. Bottom temperature was relatively low in May and fairly high in Sept-Oct. Looking at the influence of individual wind events (**slide 12-14**); there is one distinctive cooling event in June and one distinctive upwelling event in July.

*Salinity* was generally lower than average (**slide 16**), consistent with the large freshwater inflow. Interestingly it was higher than average in May-June, probably because the spring "freshet" from the Charles was lower than average.

*Stratification* was higher than average (**slide 18**) — in fact it reached its second highest value over the monitoring period due to the large freshwater inputs.

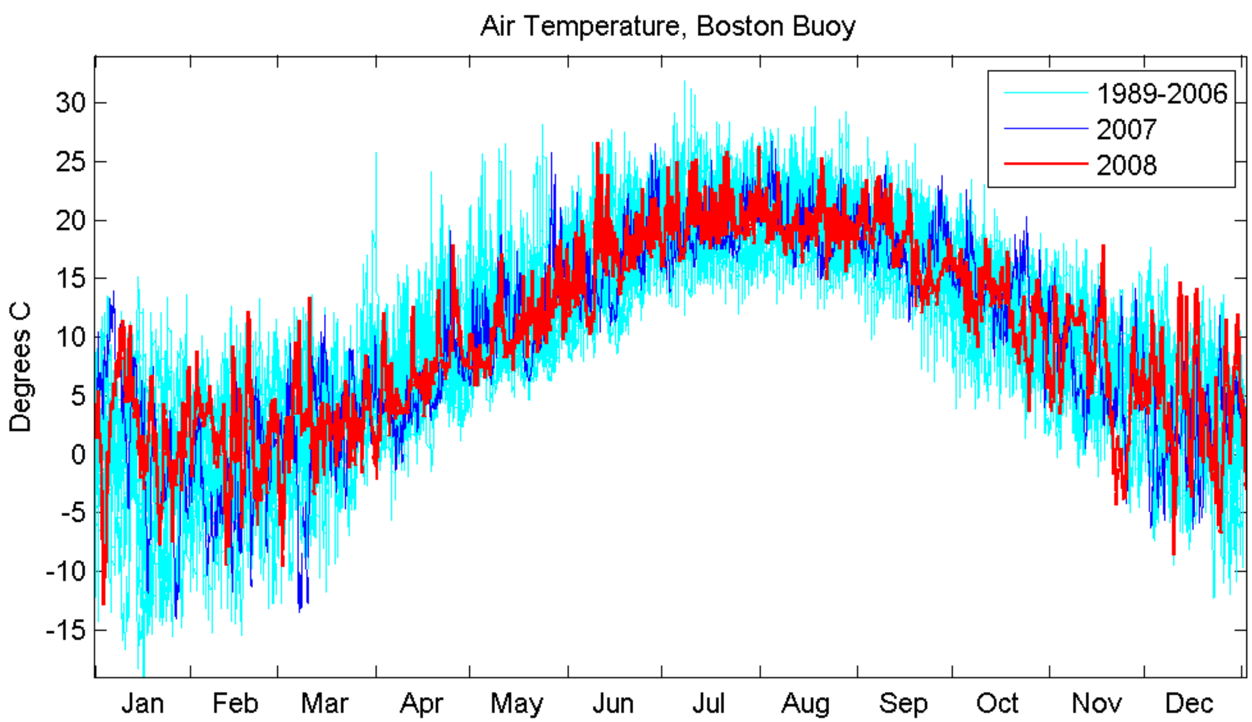
*Dissolved oxygen* showed a normal seasonal progression. The minimum dissolved oxygen in the bottom waters near the outfall site was 7.6 mg/l, which is the second highest minimum (1993 being the highest, at 7.8 mg/l) (**slide 19**). The dissolved oxygen regression analysis indicated that the low salinity water should contribute to anomalously high dissolved oxygen. The observed values (average Sept-Nov) were slightly higher than predicted by the model.

# Massachusetts Bay Physics 2008

Rocky Geyer

Woods Hole Oceanographic Institution

# forcing conditions



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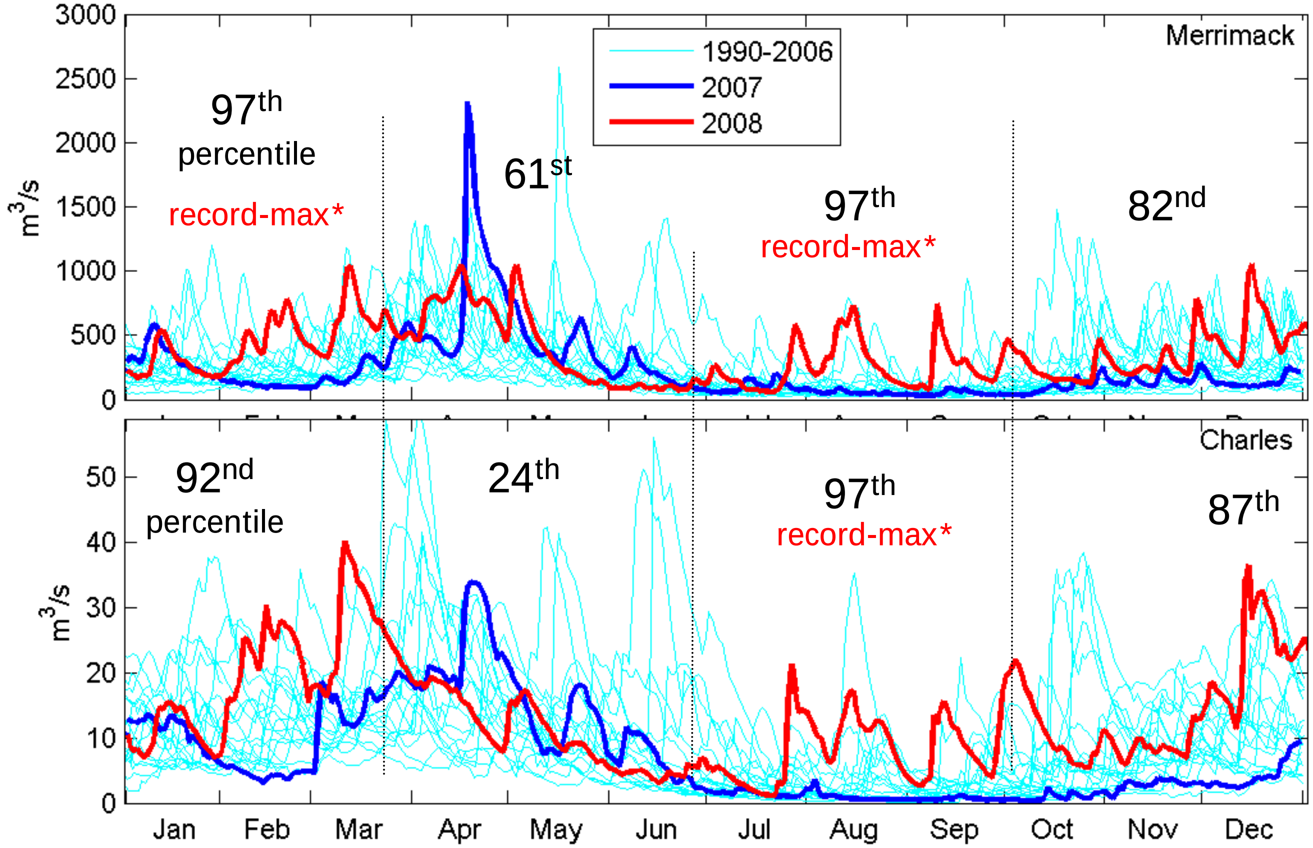
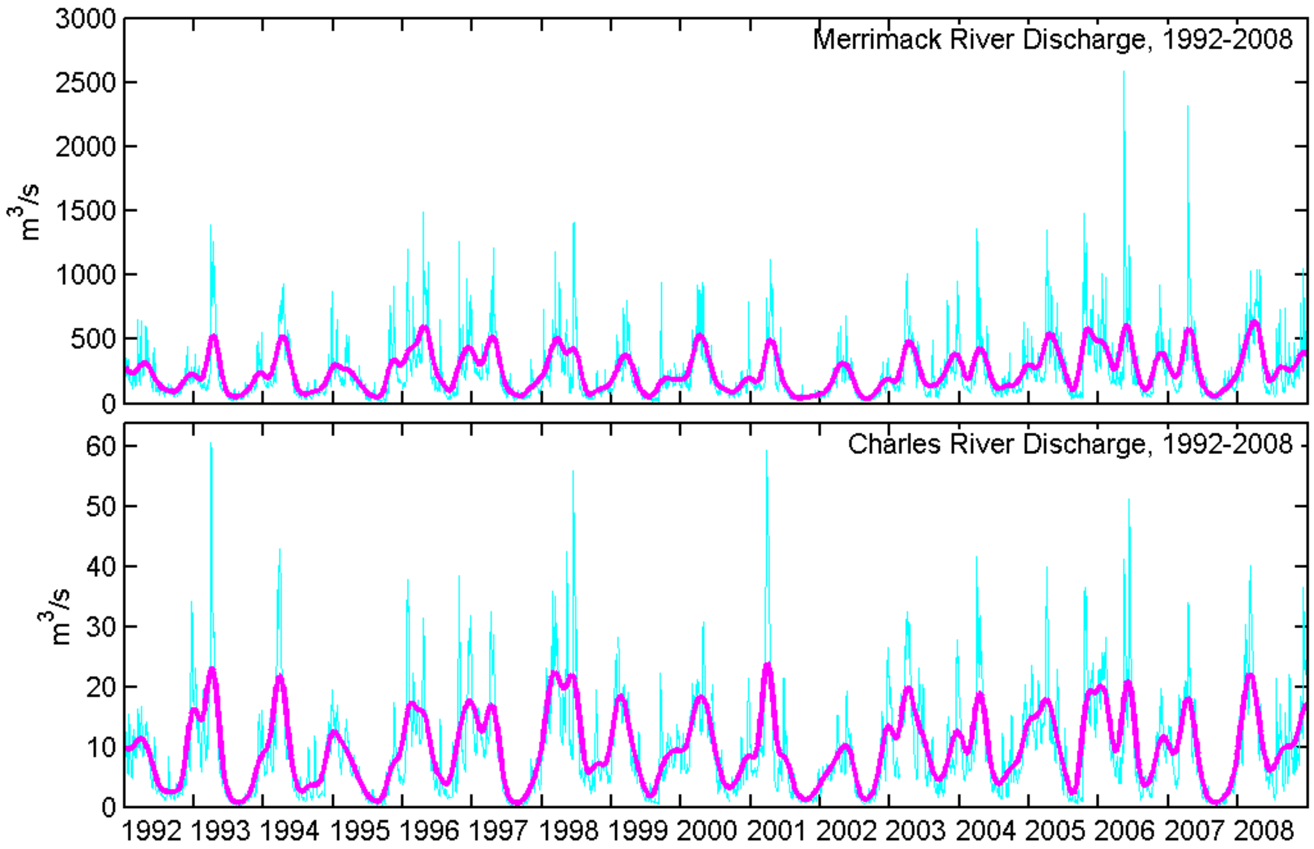
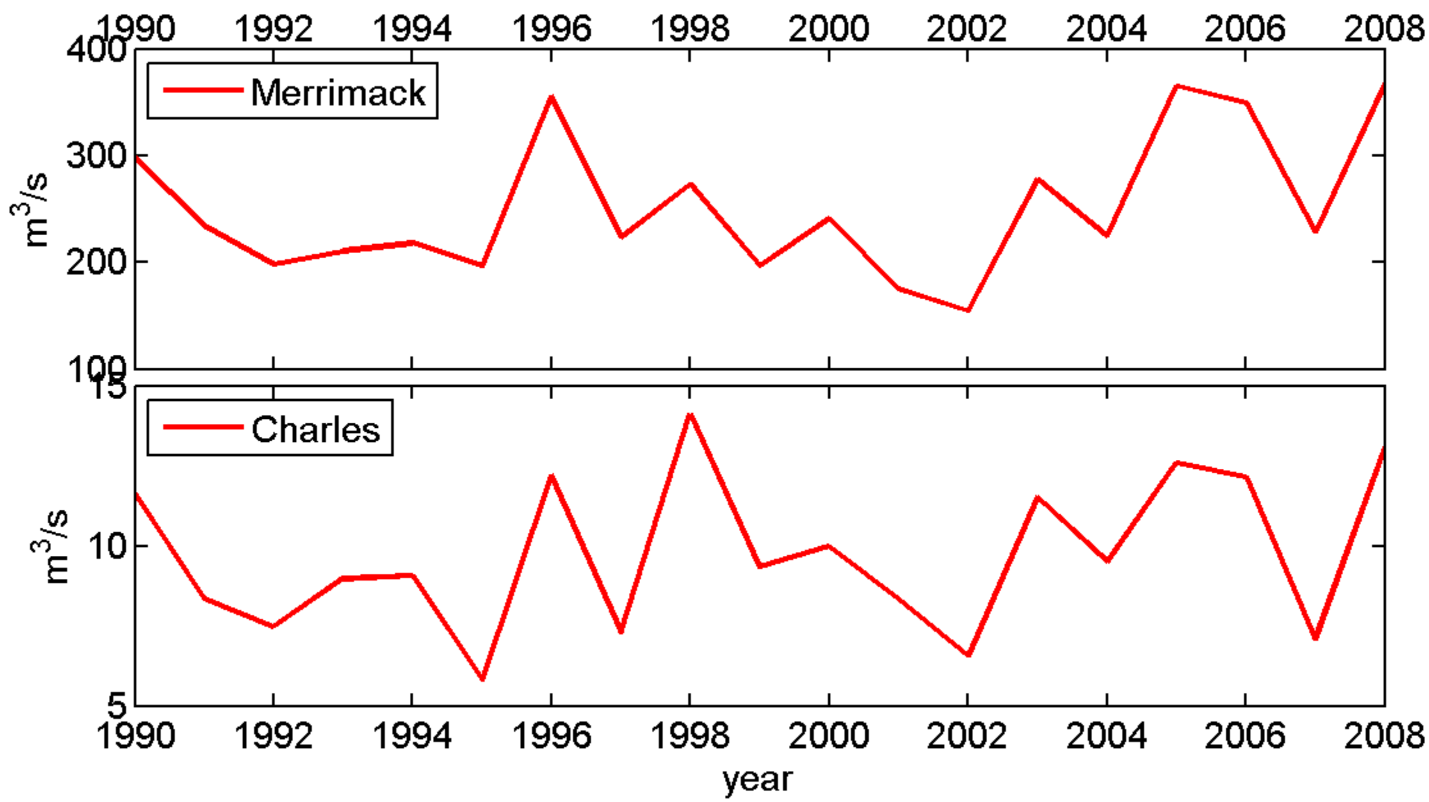
## River Flow




* from 1992 to 2008

# River Discharge





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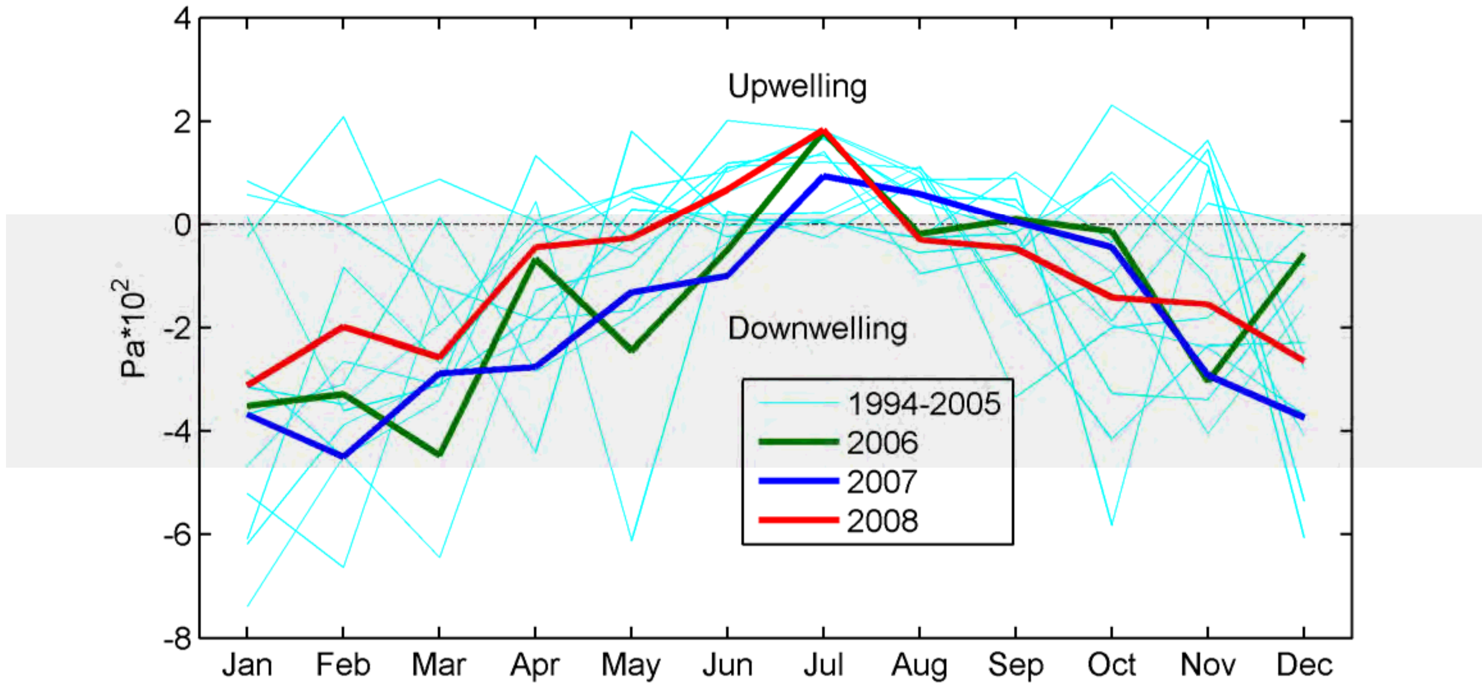
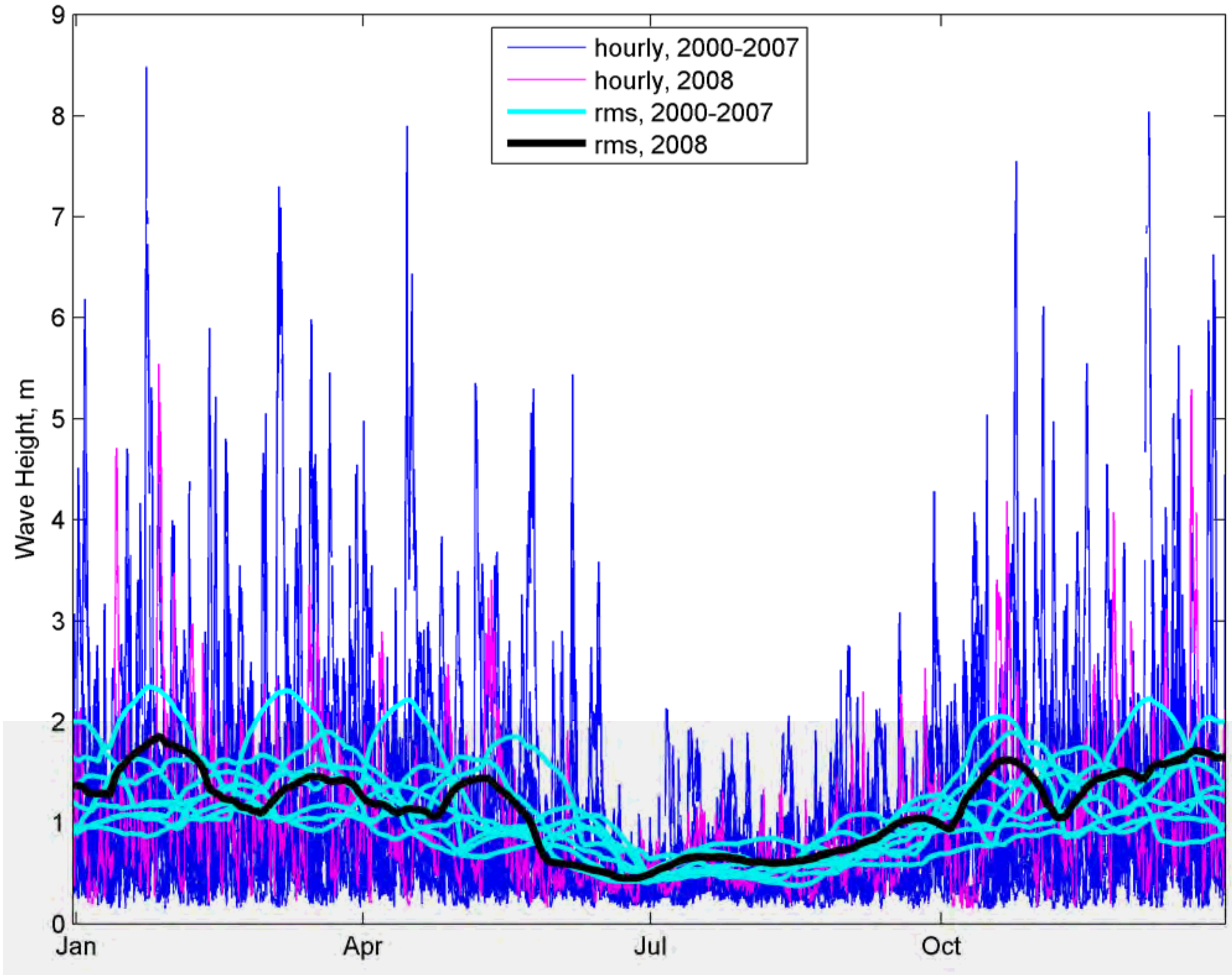
**Upwelling Index**



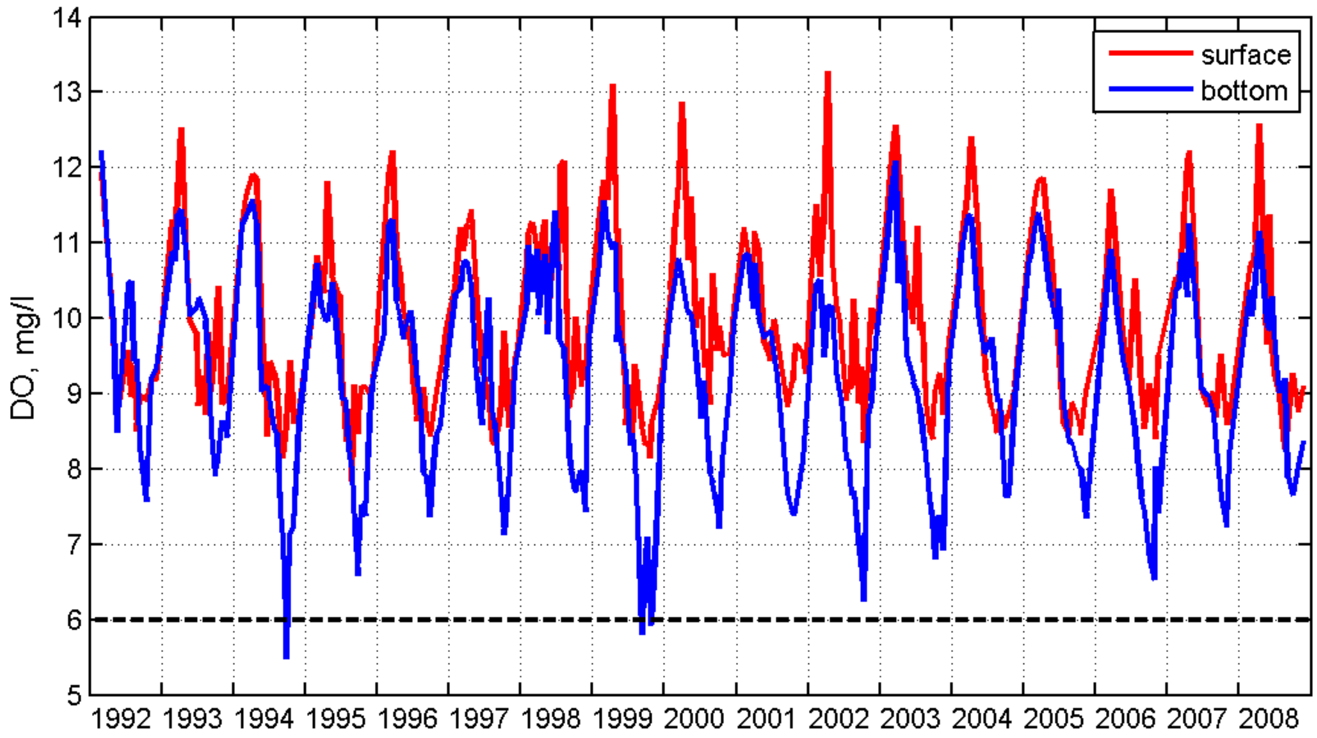
# Wave Height



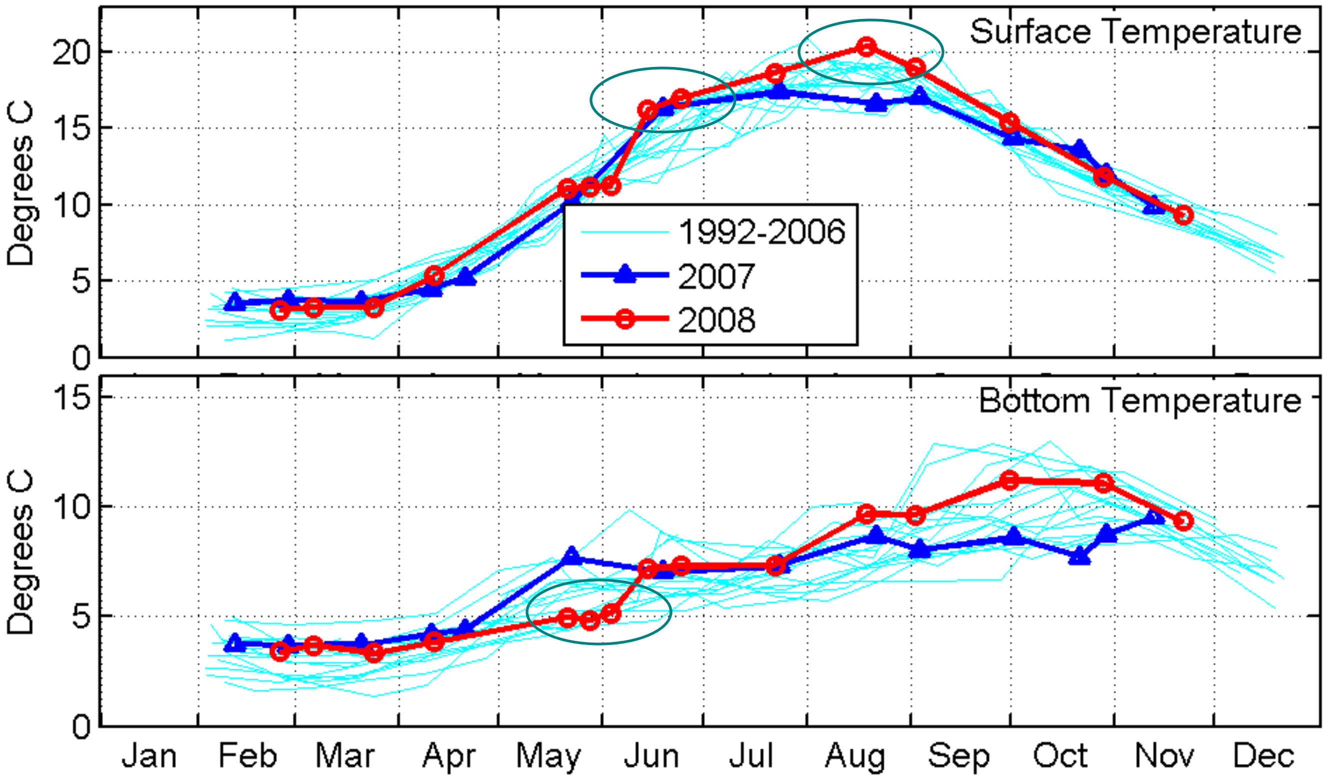
hourly, 2000-2007
hourly, 2008
rms, 2000-2007
rms, 2008
Wave Height, m
0
1
2
3
4
5
6
7
8
9
Jan
Apr
Jul
Oct

# water properties

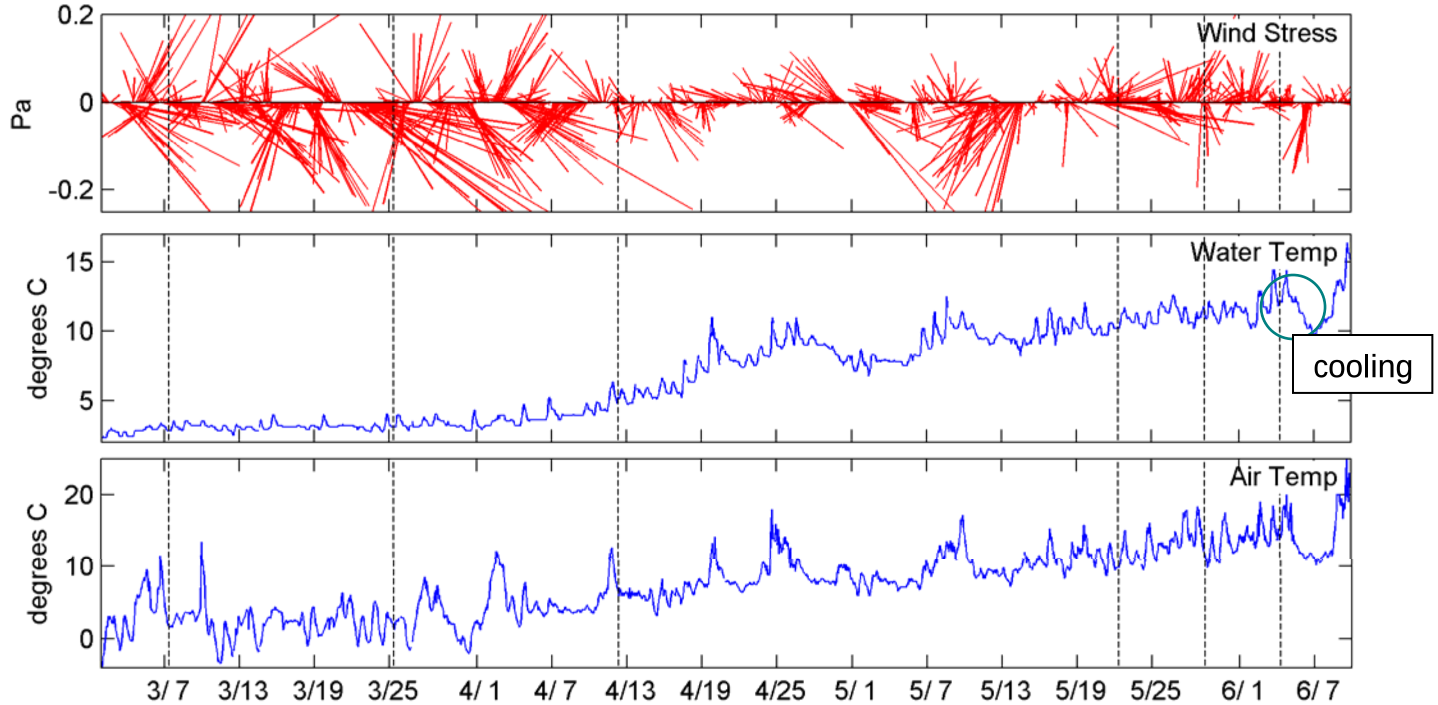
# water temperature



# water temperature

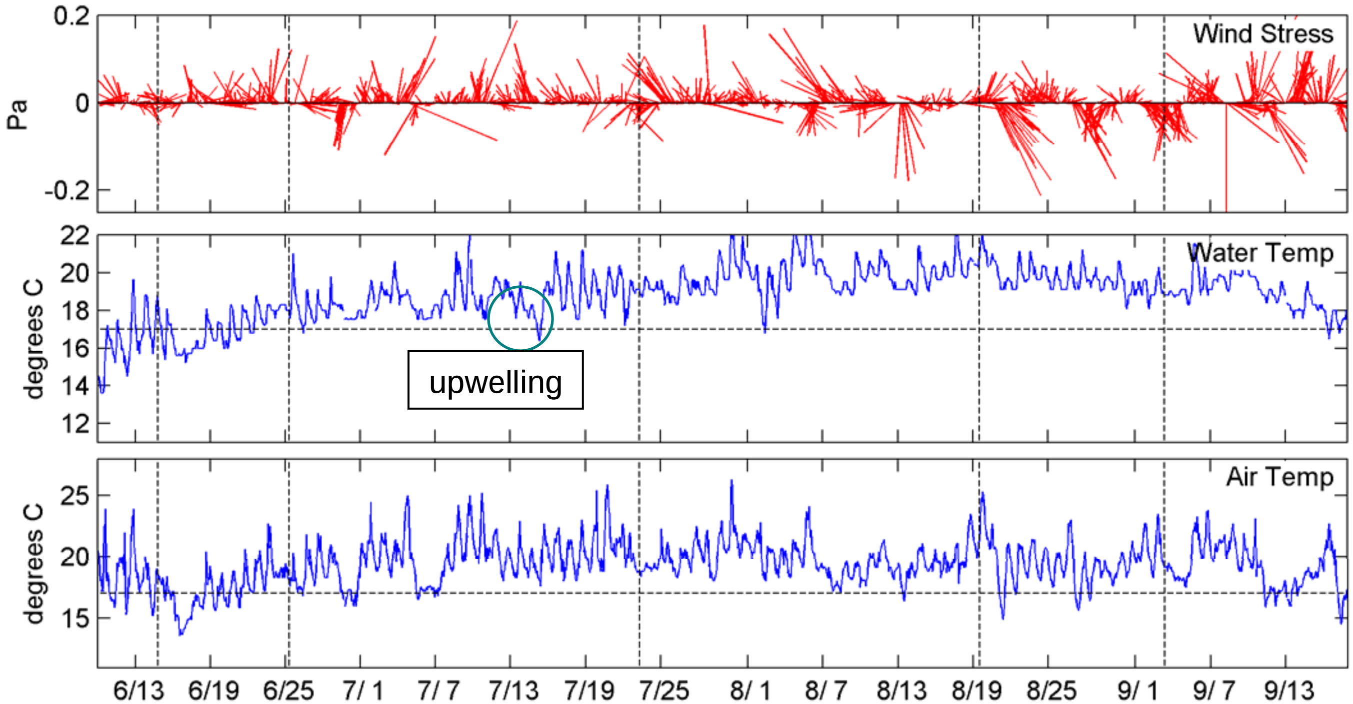


# spring winds and water temperature

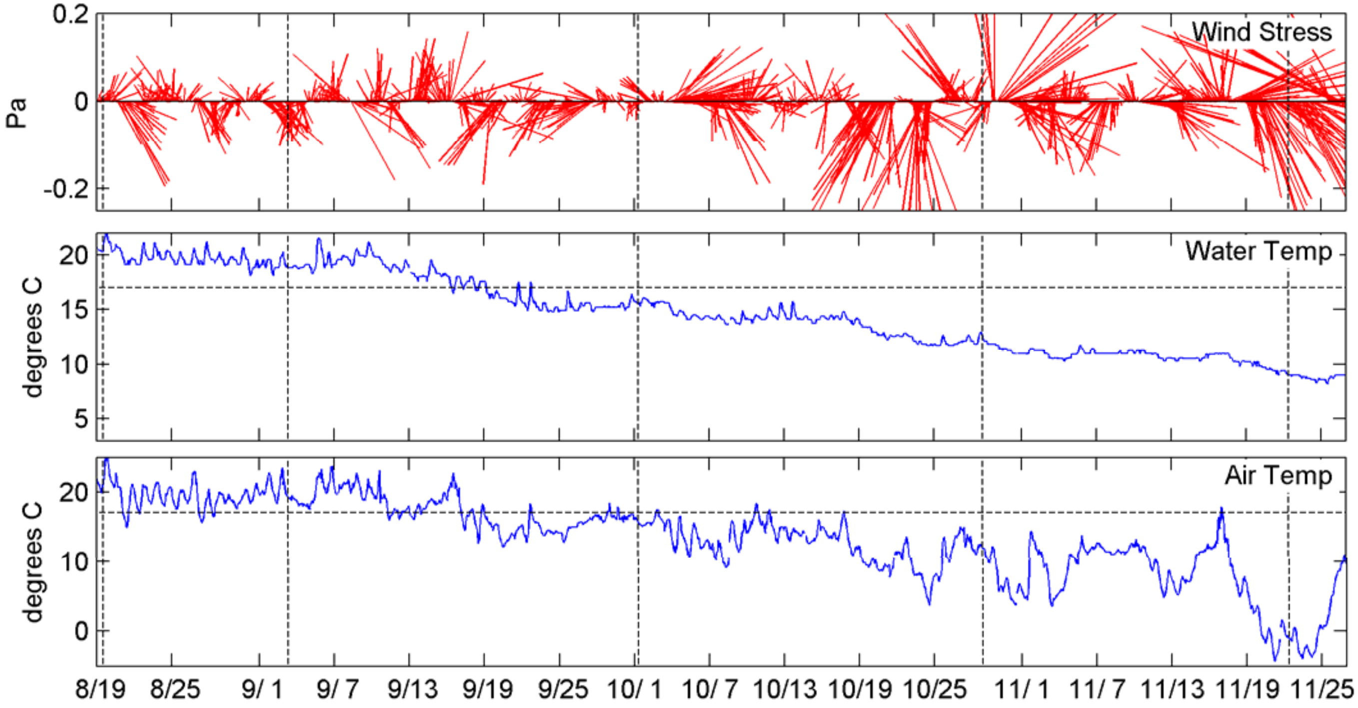



note not so many nor’easters

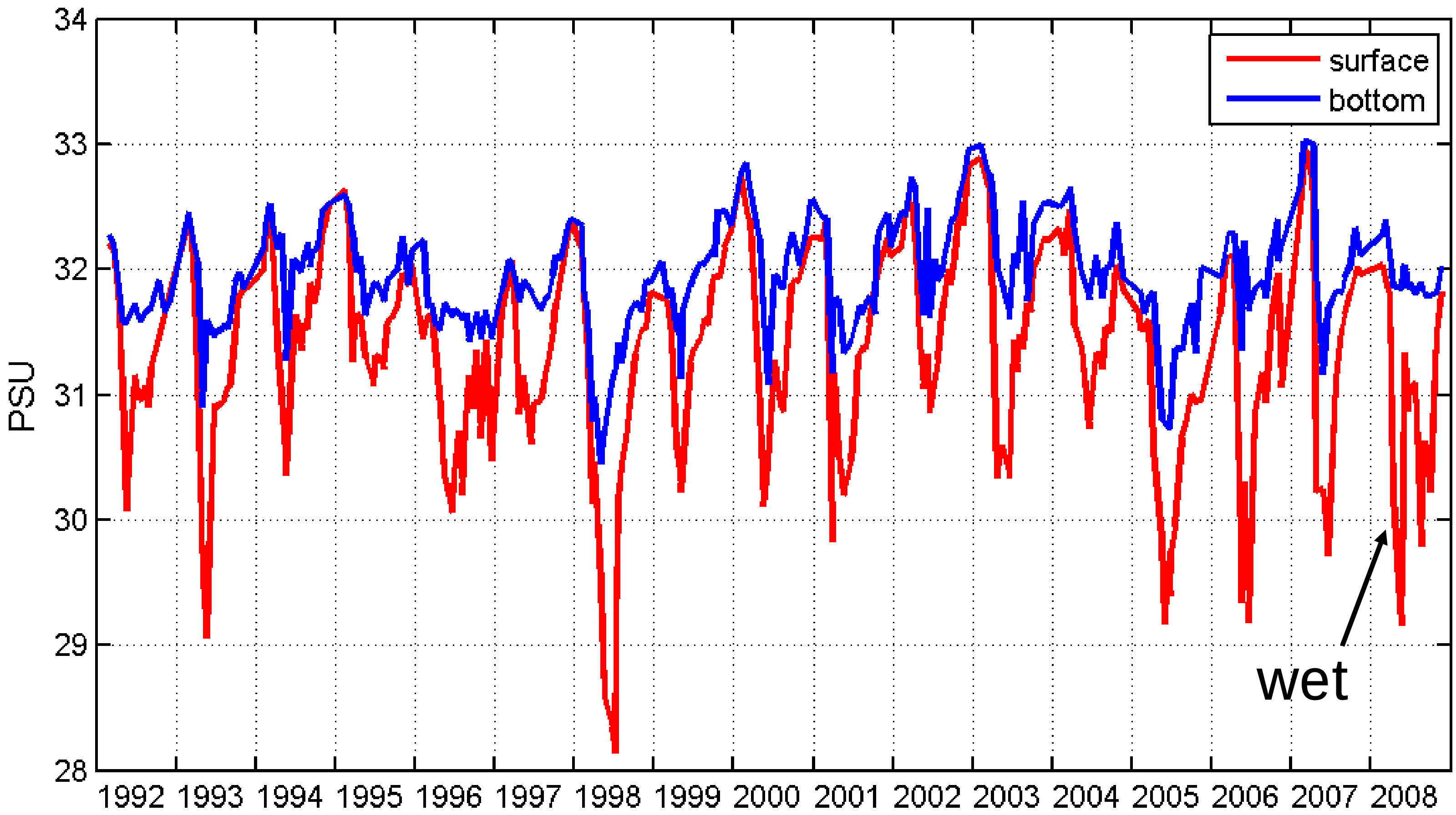
# summer winds and water temperature



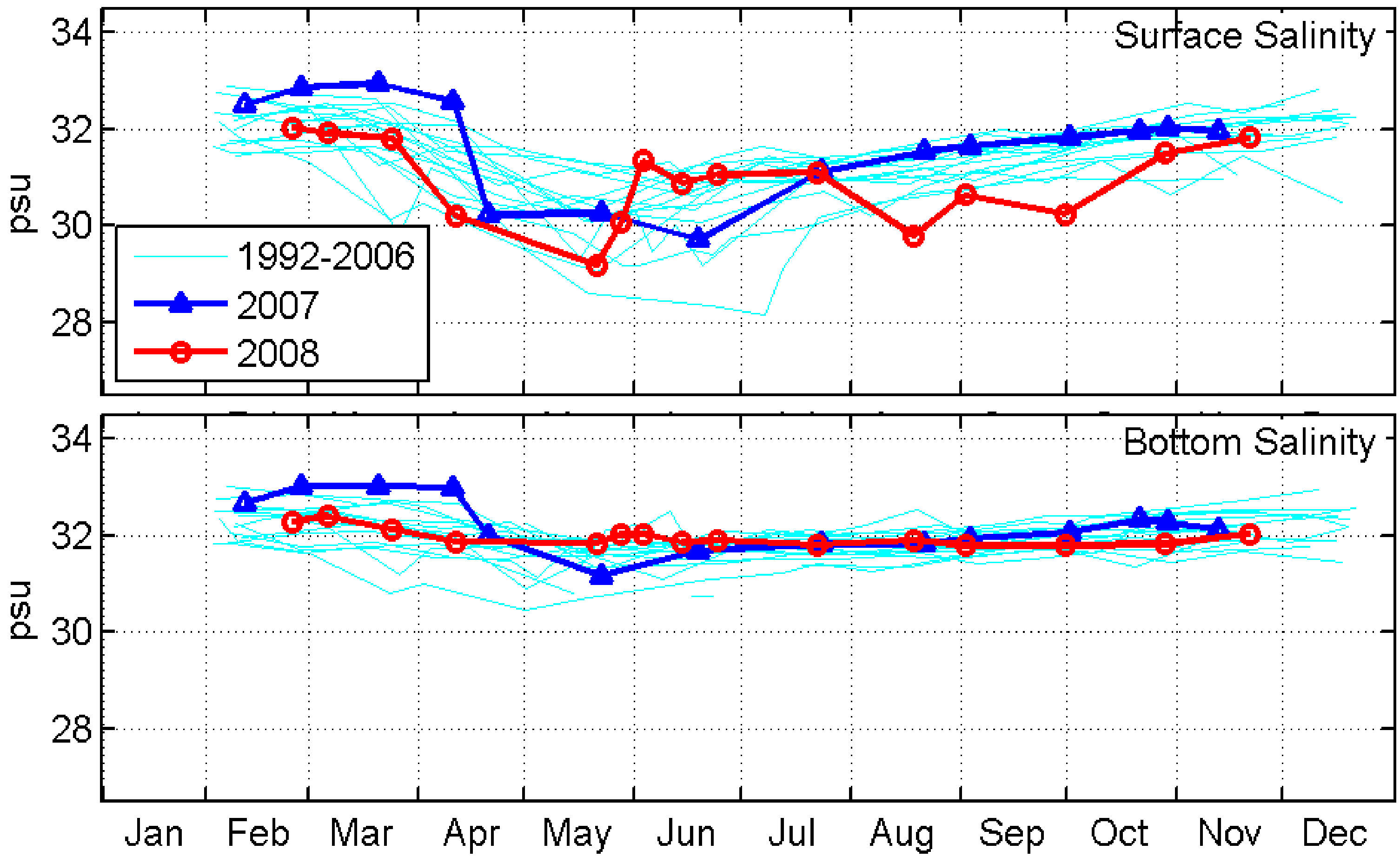
# fall winds and water temperature



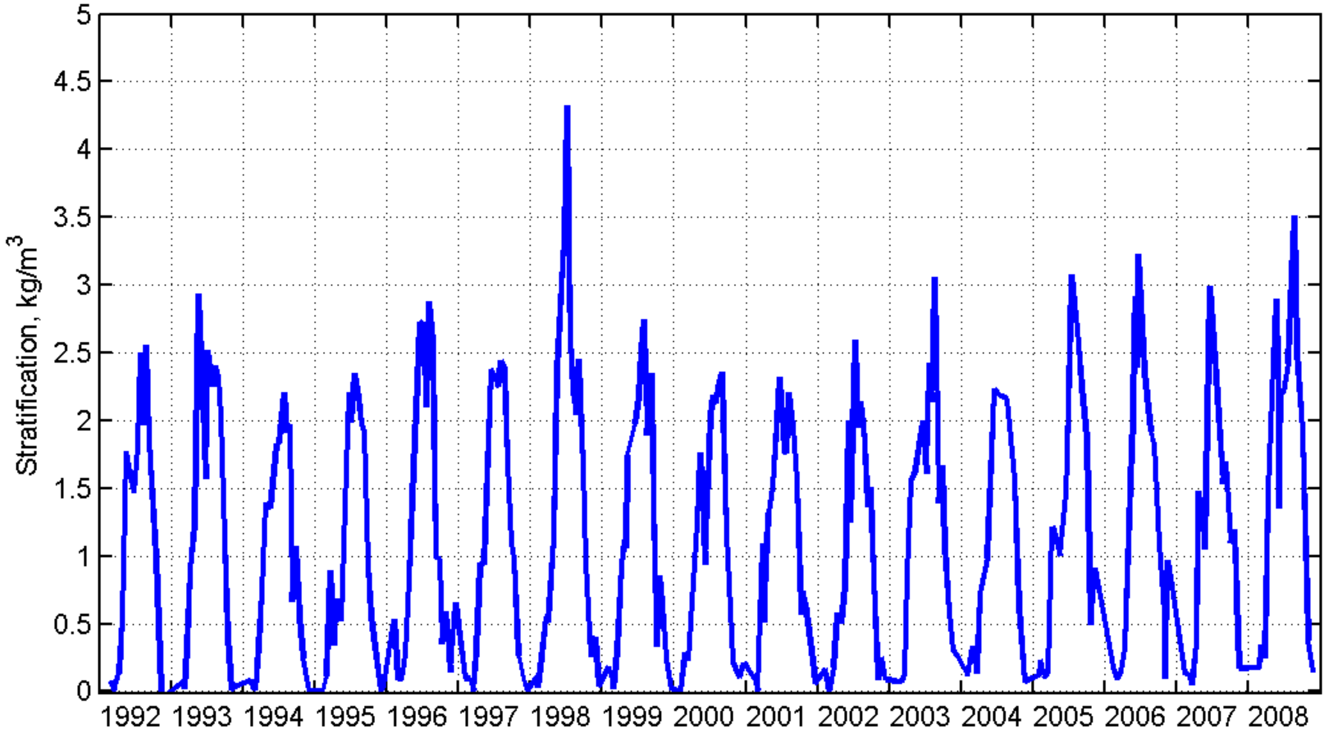
# salinity


34
33
32
31
30
29
28
PSU
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008
surface
bottom
wet

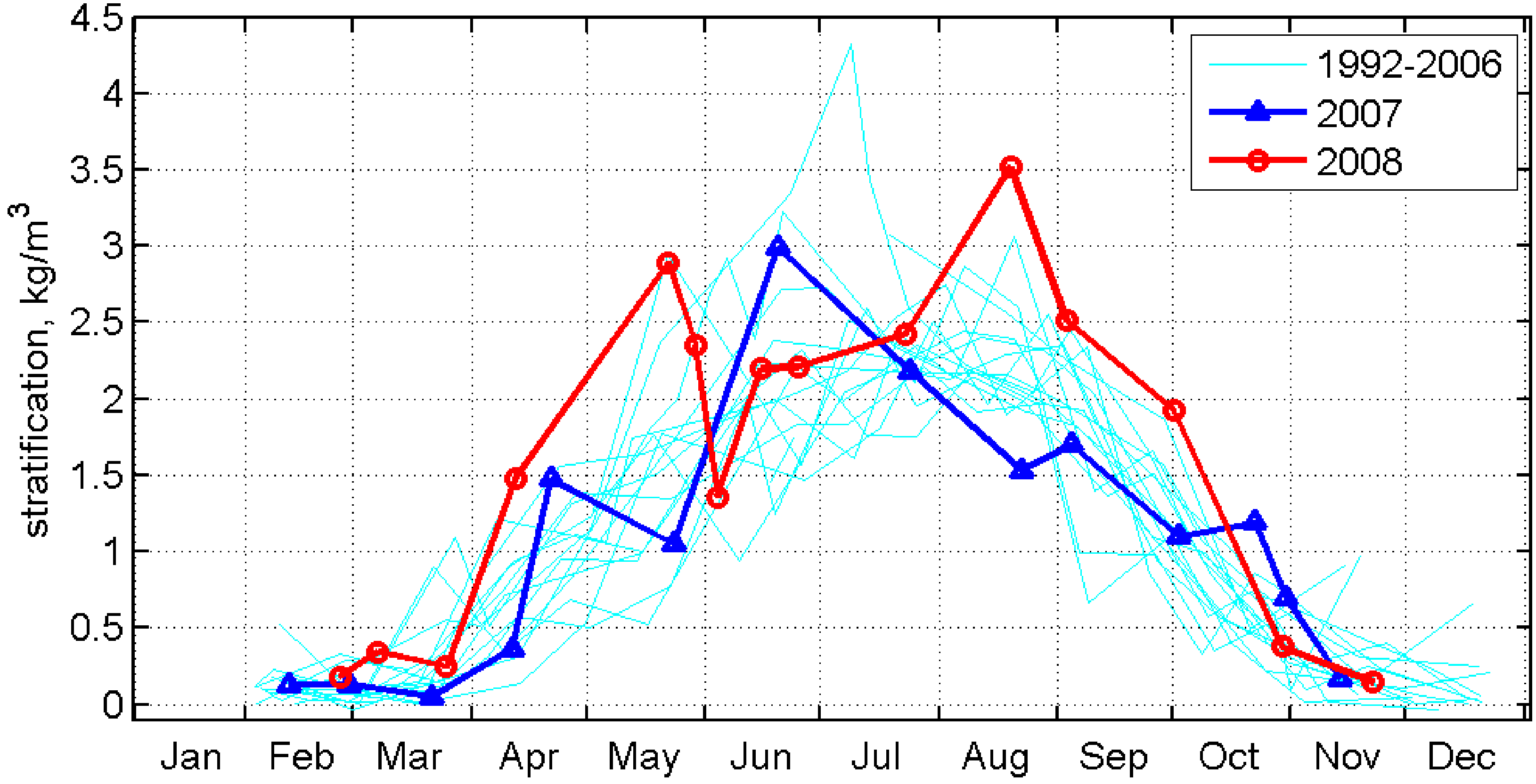
# salinity


Surface Salinity
Bottom Salinity
psu
34
32
30
28
1992-2006
2007
2008
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

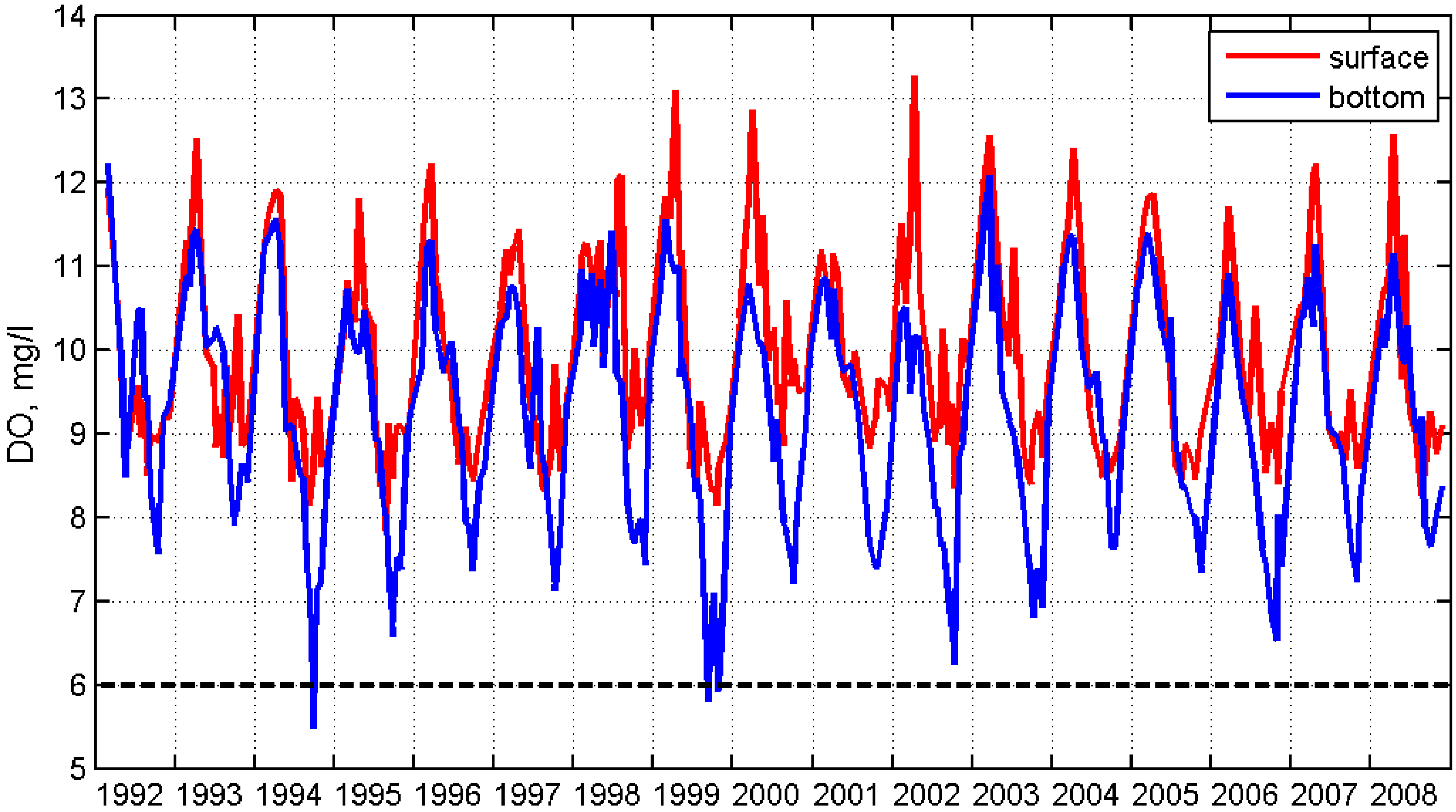
# stratification



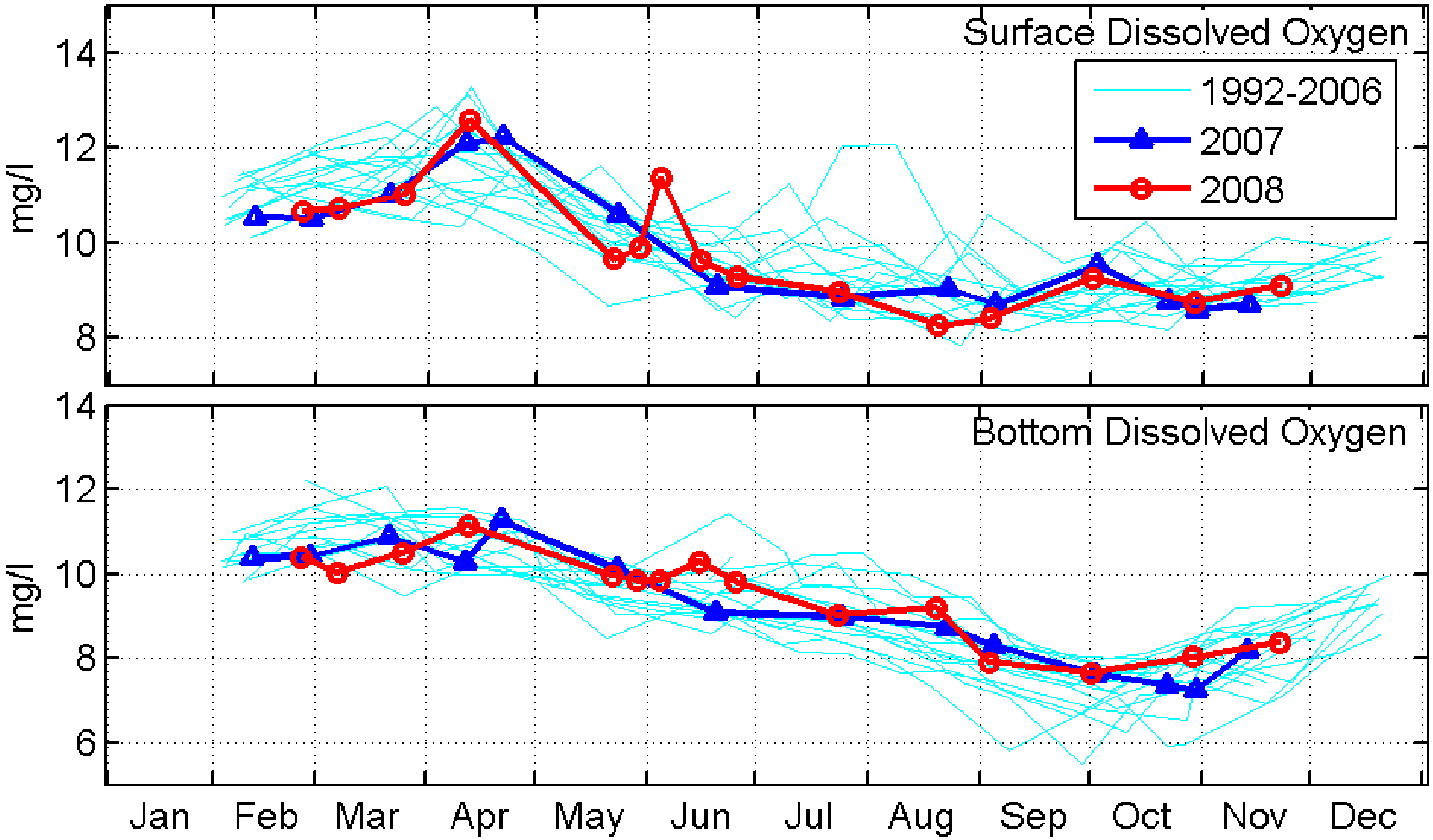
# stratification



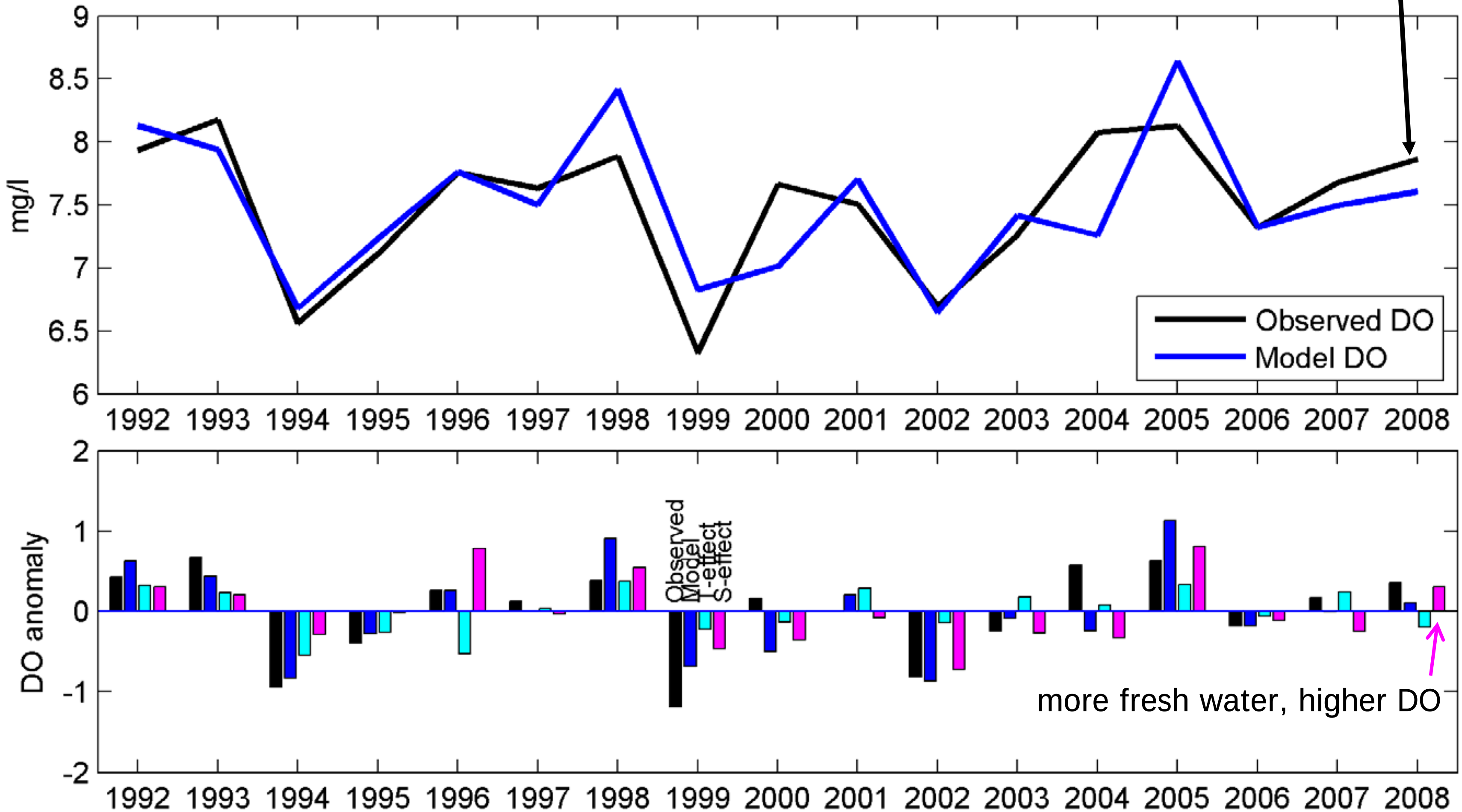
# dissolved oxygen



# dissolved oxygen



Above-average near-bottom DO observed for 2008



# summary

- generally wet year, lower salinities than average.
- No major spring-time nor'easters
- The minimum dissolved oxygen was relatively high (due in part to high freshwater inflow– lots of flushing)

# B. Water Quality

Water quality and program overview, 2008.
Scott Libby, Battelle

Over the course of the HOM program, a general sequence of water quality events has emerged from the data collected in Massachusetts and Cape Cod Bays. The trends are evident even though the timing and year-to-year manifestations of these events are variable. Typically, a winter/spring phytoplankton bloom occurs as light becomes more available, temperatures increase, and nutrients are readily available. In recent years, the winter/spring diatom bloom has been typically followed by a bloom of *Phaeocystis pouchetii* in April. Late in the spring, the water column transitions from well-mixed to stratified conditions. This cuts off the nutrient supply to surface waters and terminates the spring bloom. The summer is generally a period of strong stratification, depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community. In the fall, as temperatures cool, stratification deteriorates and nutrients are again supplied to surface waters. This transition often contributes to the development of a fall phytoplankton bloom. Dissolved oxygen concentrations are lowest in the bottom waters prior to the fall overturn of the water column – usually in October. By late fall or early winter, the water column becomes well mixed and resets to winter conditions. This sequence is evident every year. The major features and differences from the baseline in 2008 are discussed below.

## B.1. Chronological pattern

In early February nutrient concentrations were elevated relative to previous years for nitrate ($NO_3$), silicate ($SiO_4$), and phosphate ($PO_4$) (**slides 7-8**). This was likely due to the lack of a winter/early spring phytoplankton bloom in the bay. Also precipitation and river flows in early 2008 were quite high and may have contributed to elevated nutrient concentrations in nearshore areas. A minor diatom bloom was evident in Cape Cod Bay in February and decreases in nutrients (primarily $SiO_4$) suggest a diatom bloom occurred between the February and April surveys in coastal and Boston Harbor waters. In contrast, chlorophyll concentrations and diatom abundance were very low in nearfield (**slide 10**), offshore and boundary areas in February and March and $SiO_4$ concentrations remained elevated (suggesting we did not miss a diatom bloom event in these waters). The high abundance of "other" phytoplankton in April in **slides 10-11** is due to a *Phaeocystis* bloom throughout the bays (**slide 20**). MODIS imagery (**slide 22**) suggests the bloom started in the western Gulf of Maine waters north of the bays and was entrained or eventually developed within the bays as has been seen during previous years. In April, the highest abundances (>10 million cells/L) were observed in the nearfield (maximum 14 million cells/L mid-depth at station N16) and to the northeast (stations F22, F26, and F27). Nitrate concentrations decreased sharply from February to April across the bay coincident with the bloom and peak concentrations of chlorophyll and POC (**slides 7** and **10**).

By May, *Phaeocystis* was no longer present in the nearfield. As in 2005 – 2007, a bloom of the toxic dinoflagellates species *Alexandrium fundyense* was occurring in the Gulf of Maine in May 2008. As in 2005 and 2006, an early May northeasterly storm brought the bloom into the bay. *Alexandrium* abundances increased over the course of May and peaked at over 60,000 cells/L in the nearfield (station N10) on June 13 (**slide 18**). However, by June 24, *Alexandrium* counts in the nearfield had decreased to ≤10 cells/L and the bloom was over. Although the initial storm in early May likely entrained the cells into the bay, meteorological conditions were such that for the rest of May and June (S and SW winds predominant, limited NE winds) the bloom was not driven into Cape Cod Bay to achieve the levels of the 2005 bloom. In contrast, these winds may have been a factor in transporting the bloom into Boston Harbor where it had not occurred during the 2005 event.

Late summer and fall conditions were generally typical. Physical factors dominated the water column with well-established stratification partly due to high precipitation levels and river runoff the led to decreased salinity. Surface nutrients were depleted, and bottom DO concentrations steadily declined (**slide 12**). A summer diatom bloom was observed at Boston Harbor and coastal stations, and to a lesser degree in the nearfield, where there was also an increase in diatoms in November (**slide 10**). Diatom abundances and resulting chlorophyll and particulate organic carbon (POC) concentrations were relatively low in comparison to previous summer and fall blooms. The winter/spring blooms (diatoms in CCB and *Phaeocystis* everywhere else) dominated the phytoplankton and biomass trends in 2008.

The only threshold exceedance in 2008 was for *Alexandrium*, which reached abundances of well over the 100 cell/L threshold (**slides 16-17**). *Phaeocystis* abundance in the nearfield in April 2008 reached a survey mean of 1,980,000 cells/L, which is only slightly lower than the threshold – it was the ninth year in a row that a bloom has been observed and was comparable in magnitude to the large blooms in 2000, 2004, and 2007 (**slide 19**). Seasonal and annual chlorophyll levels were well below thresholds and bottom water DO levels were high in both the nearfield and Stellwagen Basin in fall 2008 (**slides 13-15**).

In comparison to baseline conditions, the changes in the nutrient regimes are quite clear and consistent with model predictions. Ammonium ($NH_4$) has dramatically decreased in Boston Harbor (>80%) and nearby coastal waters while initially increasing to a lesser degree (~1 µM) in the nearfield (**slide 26**). Since 2003 there has been an overall decrease in annual mean $NH_4$ concentrations across the bay including the nearfield. Current annual mean levels in the bay are comparable to those in the 1990's.

In Boston Harbor, the dramatic decrease in $NH_4$ has been concurrent with significant decreases in other nutrients, chlorophyll, and POC, and an increase in bottom water dissolved oxygen (Taylor 2006). In the nearfield, regression analysis showed the moderate increase in $NH_4$ concentrations was most apparent in summer and also POC increased in the nearfield in the summer (Libby *et al*. 2009). There has also been a trend of higher winter/spring chlorophyll in most of Massachusetts Bay, including the nearfield, but this appears to be related to regional processes governing the consistent annual blooms of *Phaeocystis* in March-April since 2000 (**slides 27-30**).

## B.2. Statistical tests

"Before-After, Control-Impact" (BACI) statistical analyses put the changes in POC and $NH_4$ in context (**slides 31-39**). BACI analysis found that only $NH_4$ concentrations changed between the impact (inner nearfield) and control (outer nearfield, Massachusetts Bay offshore, and Cape Cod Bay) areas (Libby *et al*. 2009). $NH_4$ was higher in the inner nearfield. The analyses did not find statistically significant changes in chlorophyll or POC in this "impact" area compared to "control" regions of the bays that are 5 to >50 km distant, supporting the understanding that observed changes in phytoplankton biomass are associated with regional processes.

The BACI analyses were rerun including the 2008 data for a set of stations rather than groups of stations (**slide 31**). The stations selected for the analysis are a subset of those proposed by MWRA for AMP revision. Station N18 nearest the outfall was designated as the "impacted" site and a range of controls were compared for the harbor (F23), northeast (N04 and F22), and both 15 km (F13) and 30 km (F06) to the south. The results were essentially the same. The only significant differences noted in the baseline vs. post-diversion comparison for each station were for $NH_4$ (**Table 1**). There were significant increases in $NH_4$ at station N18 (all seasons) and decreases at stations F23 (all seasons), N04 (winter/spring) and F13 (winter/spring). The BACI comparisons between station N18 and the other stations yielded significant increases in $NH_4$ for nearly all of the station and season comparisons (**Tables 2** and **3**). None of the other BACI results showed any significant changes between stations for $NO_3$, $SiO_4$, POC, or areal fluorescence.

As predicted, there has been an increase in $NH_4$ in the nearfield relative to the baseline and also relative to the regional background concentrations. The signature levels of $NH_4$ in the effluent plume are generally confined to an area within 10-20 km of the outfall. Statistical analyses indicate that even though there are apparent trends of increasing chlorophyll and POC in the bays during the winter/spring that these changes are not related to the outfall, but are rather baywide trends associated with processes governing the greater western Gulf of Maine (i.e. consistent annual occurrence of the *Phaeocystis* blooms.

**Table 1**: Estimated baseline average and post-diversion average and result of testing whether the averages are significantly different by species, station and season.

| Species | Station | Season | Baseline | Post-Diversion | P-value |
|---|---|---|---|---|---|
| Areal Fluor | N18 | Fall | 95.9801 | 75.2386 | 0.479 |
| | | Summer | 38.8266 | 46.4438 | 0.579 |
| | | Winter-spring | 51.0389 | 85.2052 | 0.167 |
| | N04 | Fall | 99.4423 | 84.2654 | 0.625 |
| | | Summer | 47.4479 | 55.3899 | 0.479 |
| | | Winter-spring | 64.6969 | 136.38 | 0.073 |
| | F23 | Fall | 30.8966 | 49.2058 | 0.479 |
| | | Summer | 93.2656 | 74.4175 | 0.267 |
| | | Winter-spring | 36.7508 | 71.2745 | 0.256 |
| | F13 | Fall | 85.8183 | 41.9981 | 0.392 |
| | | Summer | 51.9341 | 38.8279 | 0.479 |
| | | Winter-spring | 29.4862 | 66.5019 | 0.059 |
| | F06 | Fall | 119.69 | 50.65 | 0.167 |
| | | Summer | 55.7632 | 45.2588 | 0.479 |
| | | Winter-spring | 37.0965 | 89.6005 | 0.062 |
| | F22 | Fall | 133.06 | 48.7691 | 0.479 |
| | | Summer | 63.1501 | 57.0029 | 0.712 |
| | | Winter-spring | 84.0536 | 179.26 | 0.063 |
| NH4 | N18 | Fall | 0.6956 | 1.5549 | 0.016* |
| | | Summer | 0.6463 | 2.1385 | <.001* |
| | | Winter-spring | 0.9035 | 2.4442 | <.001* |
| | N04 | Fall | 0.4179 | 0.5335 | 0.479 |
| | | Summer | 0.9389 | 0.9081 | 0.904 |
| | | Winter-spring | 0.9327 | 0.5902 | 0.005* |
| | F23 | Fall | 9.0329 | 1.9931 | <.001* |
| | | Summer | 3.5895 | 0.8111 | 0.001* |
| | | Winter-spring | 5.7222 | 0.5531 | <.001* |
| | F13 | Fall | 0.6821 | 0.6507 | 0.925 |
| | | Summer | 0.8644 | 1.0262 | 0.59 |
| | | Winter-spring | 1.7725 | 0.8792 | 0.020* |
| | F06 | Fall | 0.4375 | 0.4748 | 0.857 |
| | | Summer | 0.6955 | 0.9589 | 0.403 |
| | | Winter-spring | 0.8847 | 0.5752 | 0.064 |
| | F22 | Fall | 0.3146 | 0.2 | 0.479 |
| | | Summer | 0.8366 | 0.8702 | 0.904 |
| | | Winter-spring | 0.8203 | 0.408 | 0.059 |
| NO3 | N18 | Fall | 1.7854 | 2.8291 | 0.225 |
| | | Summer | 0.8201 | 1.1104 | 0.617 |
| | | Winter-spring | 4.0077 | 5.7084 | 0.225 |
| | N04 | Fall | 3.4996 | 4.7263 | 0.225 |
| | | Summer | 1.9642 | 1.931 | 0.906 |
| | | Winter-spring | 4.7406 | 6.5078 | 0.225 |
| | F23 | Fall | 4.8233 | 4.3018 | 0.785 |
| | | Summer | 1.3633 | 0.823 | 0.386 |
| | | Winter-spring | 6.2636 | 5.5265 | 0.629 |

| Species | Station | Season | Baseline | Post-Diversion | P-value |
|---|---|---|---|---|---|
| | F13 | Fall | 2.2263 | 2.9658 | 0.629 |
| | | Summer | 1.06 | 1.7355 | 0.274 |
| | | Winter-spring | 5.5955 | 5.718 | 0.906 |
| | F06 | Fall | 1.5422 | 2.5842 | 0.617 |
| | | Summer | 1.2925 | 1.5284 | 0.785 |
| | | Winter-spring | 4.9502 | 5.9206 | 0.607 |
| | F22 | Fall | 5.2028 | 5.6632 | 0.778 |
| | | Summer | 3.3498 | 3.6425 | 0.785 |
| | | Winter-spring | 5.8779 | 7.5495 | 0.254 |
| POC | N18 | Fall | 28.2897 | 24.7376 | 0.629 |
| | | Summer | 21.5274 | 26.5548 | 0.225 |
| | | Winter-spring | 19.9012 | 25.0546 | 0.567 |
| | N04 | Fall | 23.4943 | 21.4346 | 0.778 |
| | | Summer | 17.9281 | 19.8512 | 0.617 |
| | | Winter-spring | 16.6726 | 20.2363 | 0.617 |
| | F23 | Fall | 25.2767 | 24.3659 | 0.906 |
| | | Summer | 36.9941 | 39.2743 | 0.785 |
| | | Winter-spring | 34.099 | 32.1054 | 0.854 |
| | F13 | Fall | 23.6574 | 21.1995 | 0.785 |
| | | Summer | 23.579 | 22.6978 | 0.854 |
| | | Winter-spring | 19.6864 | 22.6758 | 0.629 |
| | F06 | Fall | 23.7295 | 20.1107 | 0.629 |
| | | Summer | 20.3671 | 20.8548 | 0.906 |
| | | Winter-spring | 16.3421 | 20.6196 | 0.617 |
| | F22 | Fall | 16.7104 | 14.9851 | 0.818 |
| | | Summer | 14.411 | 19.9219 | 0.57 |
| | | Winter-spring | 15.4643 | 17.508 | 0.629 |
| SIO4 | N18 | Fall | 3.8998 | 4.345 | 0.617 |
| | | Summer | 3.4387 | 3.3869 | 0.907 |
| | | Winter-spring | 5.5286 | 6.4995 | 0.617 |
| | N04 | Fall | 5.1617 | 5.4876 | 0.655 |
| | | Summer | 4.2535 | 3.5951 | 0.225 |
| | | Winter-spring | 6.4009 | 6.9648 | 0.685 |
| | F23 | Fall | 7.4997 | 5.9973 | 0.629 |
| | | Summer | 4.6872 | 4.1689 | 0.818 |
| | | Winter-spring | 8.4413 | 7.193 | 0.629 |
| | F13 | Fall | 4.9402 | 5.0312 | 0.919 |
| | | Summer | 3.9619 | 4.1923 | 0.818 |
| | | Winter-spring | 6.5629 | 5.9675 | 0.785 |
| | F06 | Fall | 4.0702 | 4.3009 | 0.906 |
| | | Summer | 3.6127 | 3.5477 | 0.906 |
| | | Winter-spring | 6.2192 | 5.7921 | 0.818 |
| | F22 | Fall | 6.6763 | 6.3472 | 0.785 |
| | | Summer | 4.7353 | 4.3606 | 0.629 |
| | | Winter-spring | 7.4832 | 8.2534 | 0.629 |

* indicates that the baseline average is significantly different from the post-diversion average.

**Table 2**: Estimated ratio between N18 and five stations and result of testing whether difference between pre-diversion and post-diversion is significant by species, station and season.

| Species | Station | Season | Baseline Ratio | Post-Diversion Ratio | P-value |
|---|---|---|---|---|---|
| Areal Fluor | N18 vs. N04 | Fall | 0.9652 | 0.8929 | 0.8595 |
| | | Summer | 0.8183 | 0.8385 | 0.9336 |
| | | Winter-spring | 0.7889 | 0.6248 | 0.6252 |
| | N18 vs. F23 | Fall | 3.1065 | 1.5291 | 0.3354 |
| | | Summer | 0.4163 | 0.6241 | 0.2784 |
| | | Winter-spring | 1.3888 | 1.1955 | 0.8088 |
| | N18 vs. F13 | Fall | 1.1184 | 1.7915 | 0.5534 |
| | | Summer | 0.7476 | 1.1961 | 0.3354 |
| | | Winter-spring | 1.7309 | 1.2812 | 0.5534 |
| | N18 vs. F06 | Fall | 0.8019 | 1.4855 | 0.3354 |
| | | Summer | 0.6963 | 1.0262 | 0.3354 |
| | | Winter-spring | 1.3758 | 0.9509 | 0.5238 |
| | N18 vs. F22 | Fall | 0.7213 | 1.5428 | 0.5534 |
| | | Summer | 0.6148 | 0.8148 | 0.5238 |
| | | Winter-spring | 0.6072 | 0.4753 | 0.6145 |
| NH4 | N18 vs. N04 | Fall | 1.6647 | 2.9147 | 0.2104 |
| | | Summer | 0.6884 | 2.3548 | 0.0003* |
| | | Winter-spring | 0.9687 | 4.1416 | <.0001* |
| | N18 vs. F23 | Fall | 0.07701 | 0.7801 | <.0001* |
| | | Summer | 0.1801 | 2.6365 | <.0001* |
| | | Winter-spring | 0.1579 | 4.4193 | <.0001* |
| | N18 vs. F13 | Fall | 1.0198 | 2.3894 | 0.2365 |
| | | Summer | 0.7477 | 2.0839 | 0.0072* |
| | | Winter-spring | 0.5097 | 2.78 | <.0001* |
| | N18 vs. F06 | Fall | 1.5901 | 3.2751 | 0.1246 |
| | | Summer | 0.9293 | 2.2302 | 0.0281* |
| | | Winter-spring | 1.0212 | 4.2494 | <.0001* |
| | N18 vs. F22 | Fall | 2.2113 | 7.7763 | 0.0318* |
| | | Summer | 0.7725 | 2.4574 | 0.003* |
| | | Winter-spring | 1.1015 | 5.9912 | <.0001* |

* indicates that the baseline ratio is significantly different from the post-diversion ratio.

**Table 3**: Estimated difference between N18 and five stations and result of testing whether the difference between pre-diversion and post-diversion is significant by species, station, and season.

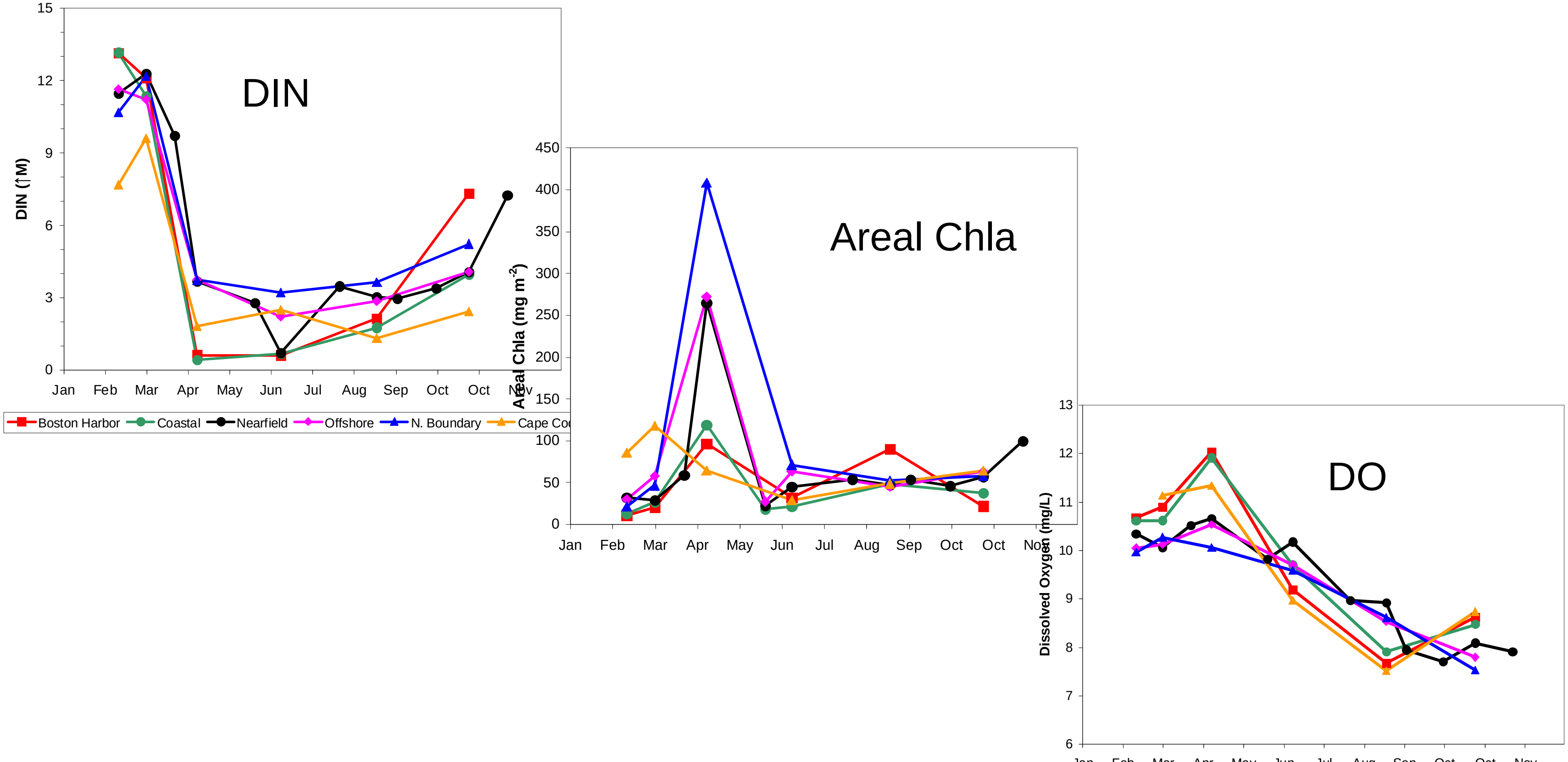
| Species | Station | Season | Baseline | Post- | P-value |
|---|---|---|---|---|---|
| NO3 | N18 vs. N04 | Fall | -1.7142 | -1.8972 | 0.9984 |
| | | Summer | -1.1441 | -0.8205 | 0.8244 |
| | | Winter-spring | -0.7328 | -0.7994 | 0.9984 |
| | N18 vs. F23 | Fall | -3.038 | -1.4727 | 0.7272 |
| | | Summer | -0.5432 | 0.2874 | 0.3489 |
| | | Winter-spring | -2.2559 | 0.182 | 0.3489 |
| | N18 vs. F13 | Fall | -0.4409 | -0.1367 | 0.9984 |
| | | Summer | -0.2399 | -0.625 | 0.828 |
| | | Winter-spring | -1.5878 | -0.00954 | 0.7272 |
| | N18 vs. F06 | Fall | 0.2432 | 0.2449 | 0.9984 |
| | | Summer | -0.4724 | -0.4179 | 0.9984 |
| | | Winter-spring | -0.9425 | -0.2122 | 0.9772 |
| | N18 vs. F22 | Fall | -3.4174 | -2.8341 | 0.9984 |
| | | Summer | -2.5297 | -2.5321 | 0.9984 |
| | | Winter-spring | -1.8702 | -1.8411 | 0.9984 |
| POC | N18 vs. N04 | Fall | 4.7954 | 3.303 | 0.9984 |
| | | Summer | 3.5993 | 6.7036 | 0.816 |
| | | Winter-spring | 3.2286 | 4.8183 | 0.9984 |
| | N18 vs. F23 | Fall | 3.013 | 0.3716 | 0.9984 |
| | | Summer | -15.4667 | -12.7194 | 0.9984 |
| | | Winter-spring | -14.1977 | -7.0508 | 0.816 |
| | N18 vs. F13 | Fall | 4.6323 | 3.538 | 0.9984 |
| | | Summer | -2.0516 | 3.857 | 0.7272 |
| | | Winter-spring | 0.2148 | 2.3788 | 0.9984 |
| | N18 vs. F06 | Fall | 4.5602 | 4.6269 | 0.9984 |
| | | Summer | 1.1603 | 5.7 | 0.816 |
| | | Winter-spring | 3.5591 | 4.435 | 0.9984 |
| | N18 vs. F22 | Fall | 11.5793 | 9.7524 | 0.9984 |
| | | Summer | 7.1163 | 6.6329 | 0.9984 |
| | | Winter-spring | 4.4369 | 7.5466 | 0.9772 |
| SIO4 | N18 vs. N04 | Fall | -1.2619 | -1.1426 | 0.9984 |
| | | Summer | -0.8149 | -0.2082 | 0.816 |
| | | Winter-spring | -0.8723 | -0.4654 | 0.9984 |
| | N18 vs. F23 | Fall | -3.5999 | -1.6522 | 0.816 |
| | | Summer | -1.2485 | -0.782 | 0.9984 |
| | | Winter-spring | -2.9127 | -0.6935 | 0.7312 |
| | N18 vs. F13 | Fall | -1.0404 | -0.6862 | 0.9984 |
| | | Summer | -0.5232 | -0.8053 | 0.9984 |
| | | Winter-spring | -1.0343 | 0.532 | 0.816 |
| | N18 vs. F06 | Fall | -0.1705 | 0.04413 | 0.9984 |
| | | Summer | -0.174 | -0.1608 | 0.9984 |
| | | Winter-spring | -0.6906 | 0.7074 | 0.816 |
| | N18 vs. F22 | Fall | -2.7765 | -2.0022 | 0.816 |
| | | Summer | -1.2966 | -0.9737 | 0.9984 |
| | | Winter-spring | -1.9546 | -1.7539 | 0.9984 |

# 2008 Water Column Overview

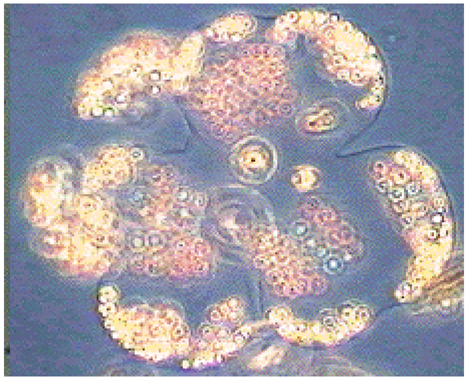
Scott Libby

# Presentation Overview

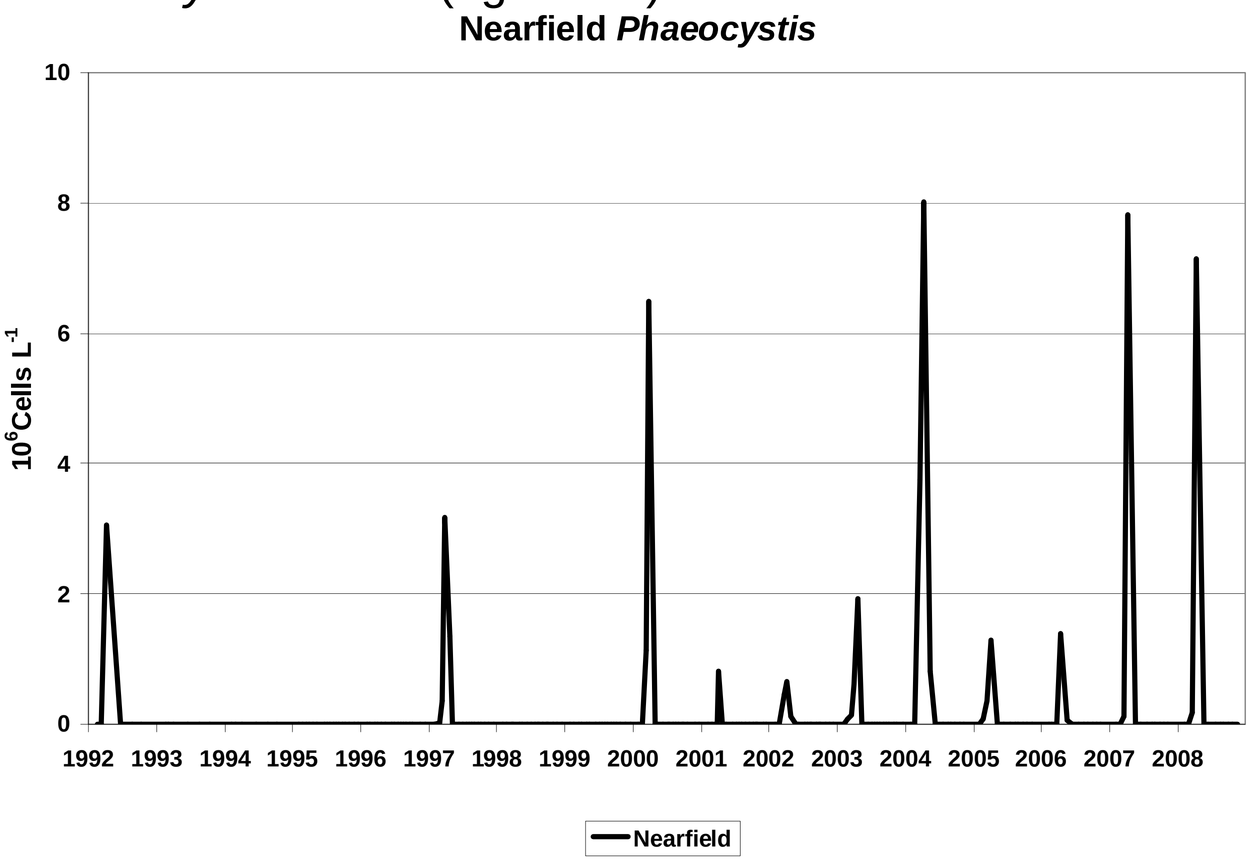
- 2008 nutrient, chlorophyll, and DO results
  - “Typical” trends generally observed in these parameters



# Presentation Overview

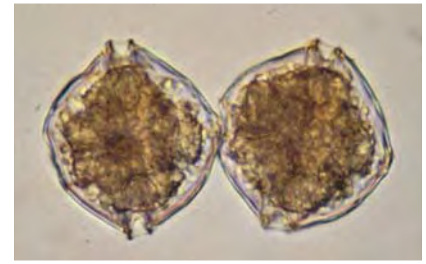


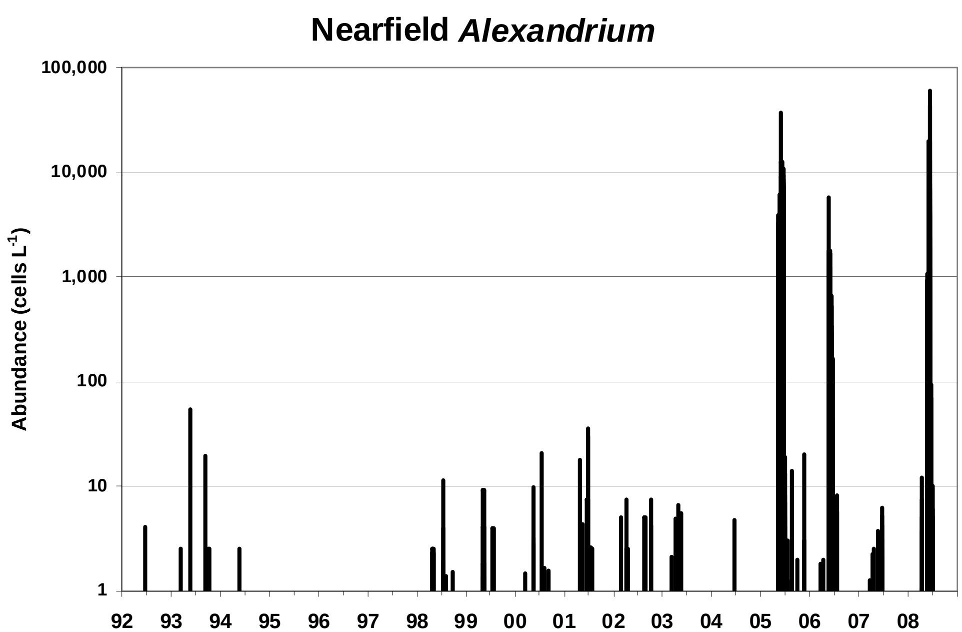
- 2008 nutrient, chlorophyll, and DO results
  - “Typical” trends generally observed in these parameters
  - Major events in 2008
    - *Phaeocystis* bloom (again…..)

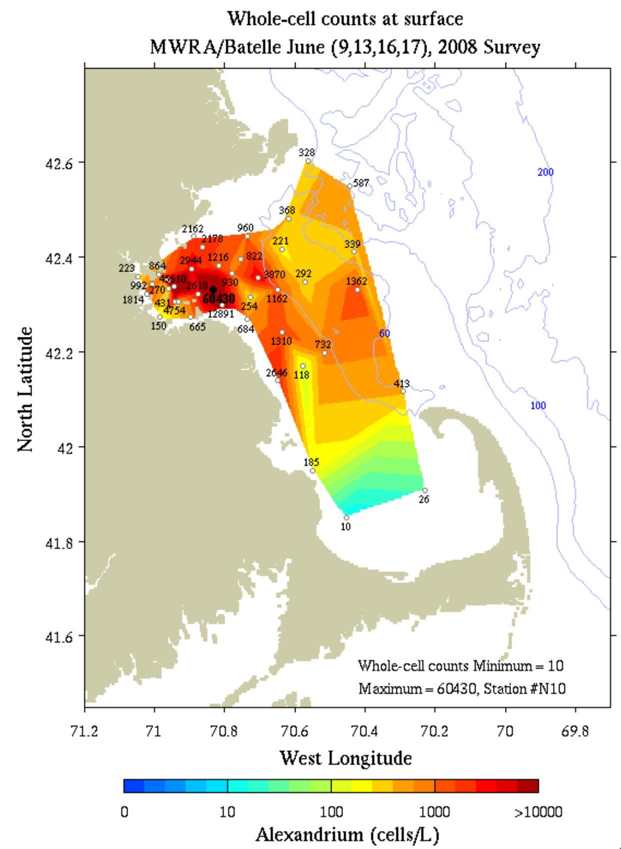


# Presentation Overview

- 2008 nutrient, chlorophyll, and DO results
  - "Typical" trends generally observed in these parameters
  - Major events in 2008
    - *Phaeocystis* bloom (again…..)
    - *Alexandrium* bloom





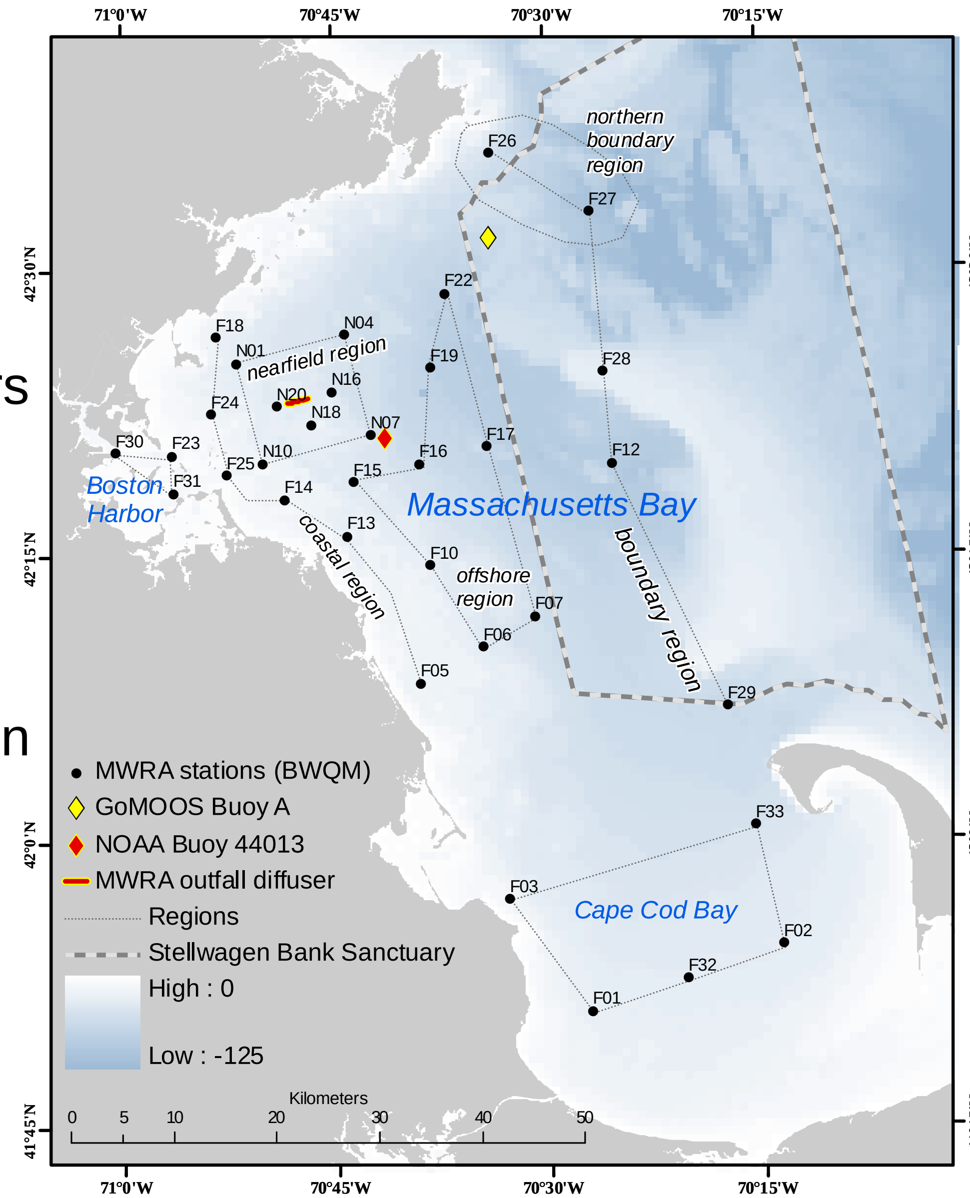
# Presentation Overview

- 2008 nutrient, chlorophyll, and DO results
  - "Typical" trends generally observed in these parameters
  - Major events in 2008
    - *Phaeocystis* bloom (again…..)
    - *Alexandrium* bloom

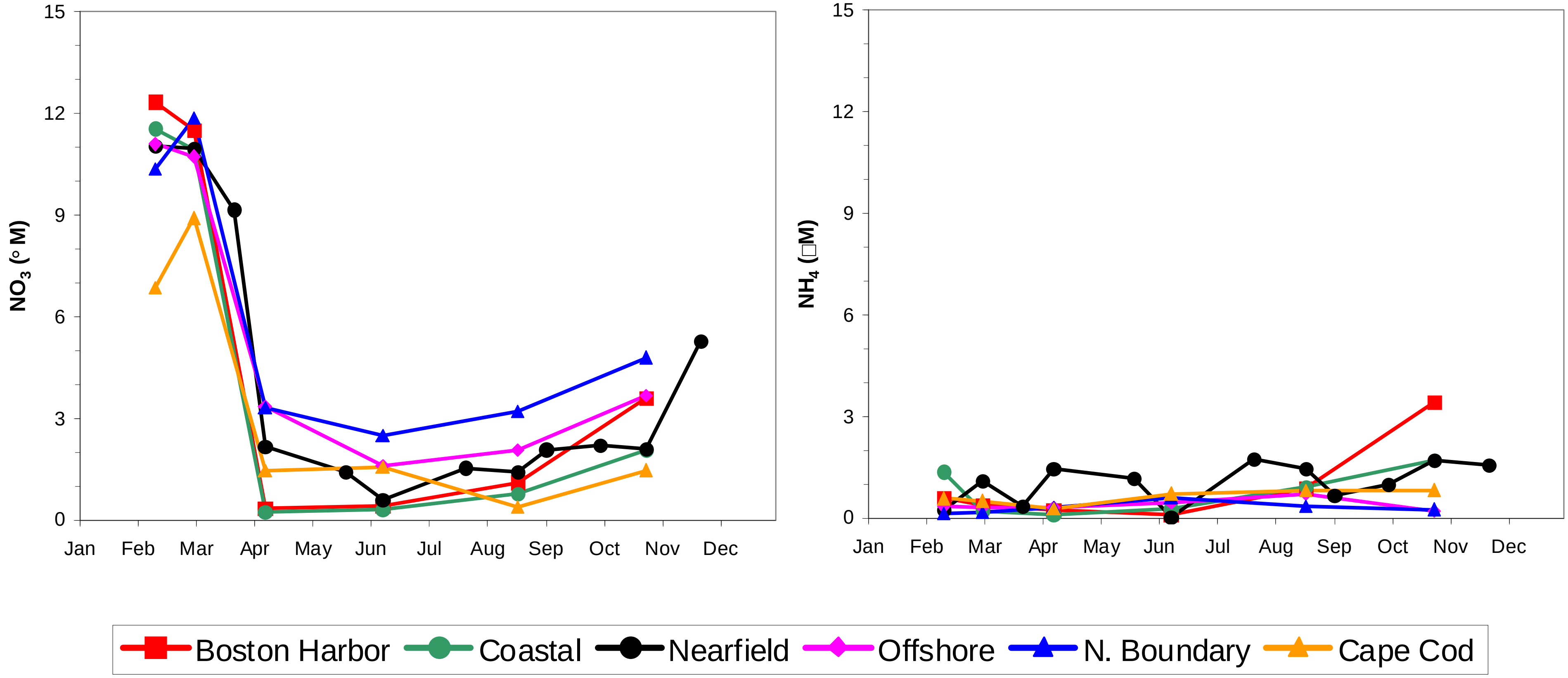
- Compare post transfer years and baseline
  - Have nutrients changed near the outfall or in the farfield? **Yes**
  - Has phytoplankton biomass changed? **Yes, but regionally**
  - Has dissolved oxygen changed? **No**

# 2008 WQ Monitoring Program

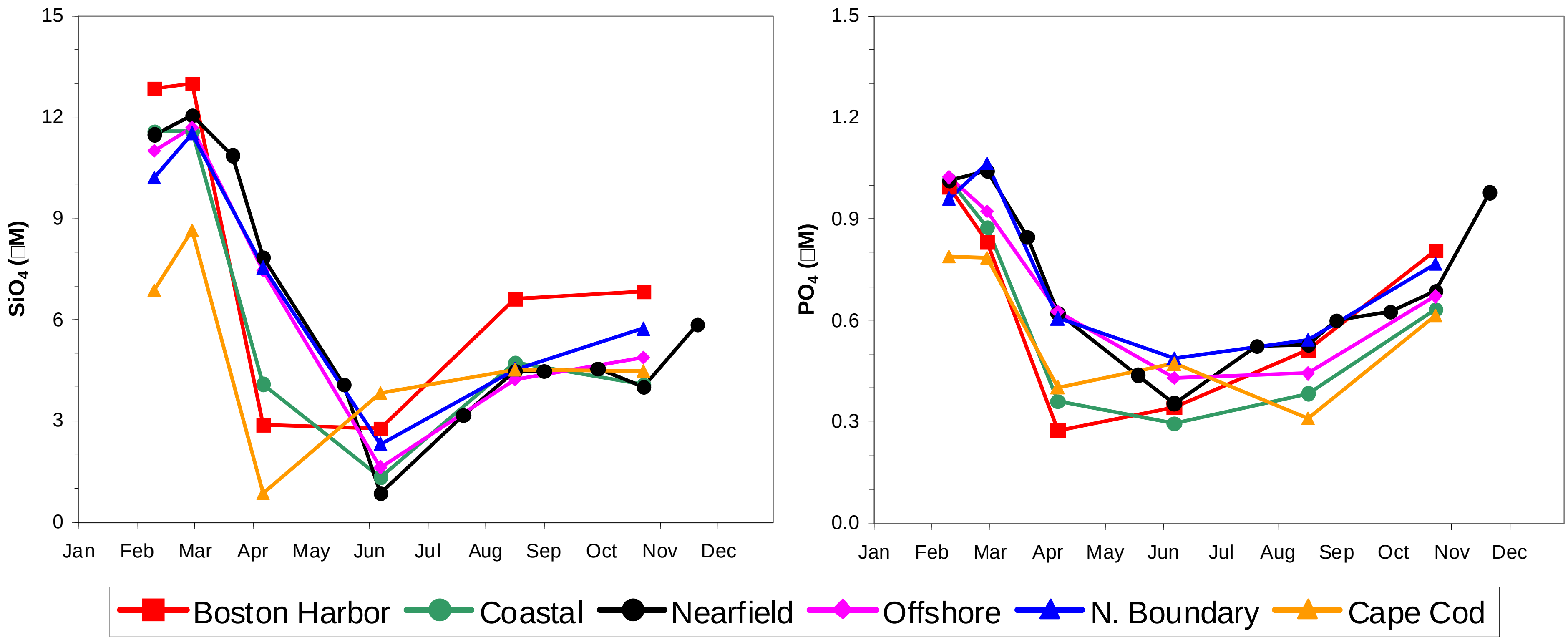
- **12 Nearfield surveys/year**
- **6 Farfield surveys/year**
- **Suite of oceanographic parameters measured –**
  - *In situ* hydrographic parameters
  - Nutrients
  - Dissolved Oxygen
  - Biomass
  - Primary Production
  - Phytoplankton and Zooplankton Community Structure
- **Additional data from –**
  - Other components of the MWRA HOM program
  - GoMOOS & NOAA buoys
  - WHOI Surveys



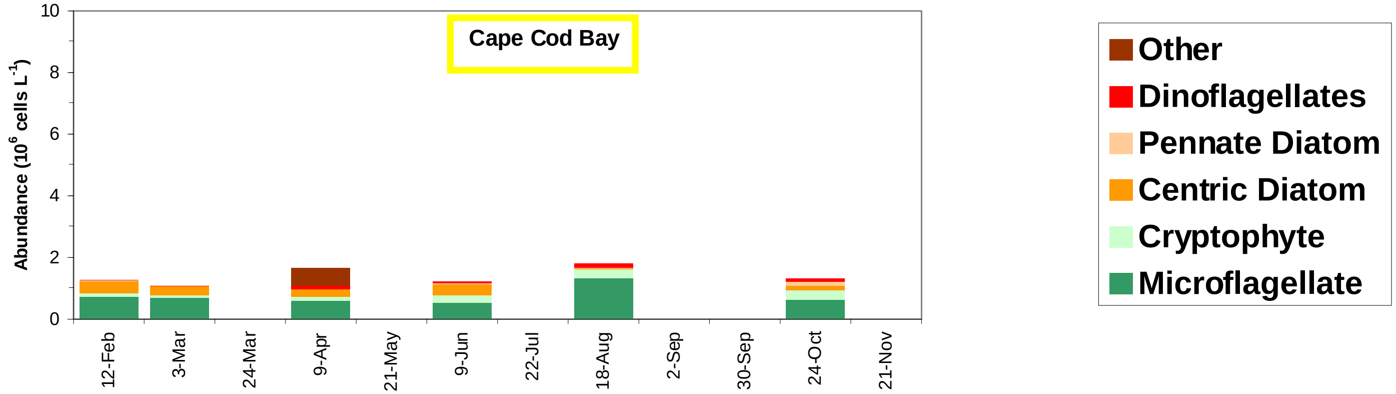
# 2008 Nutrients – $NO_3$ & $NH_4$

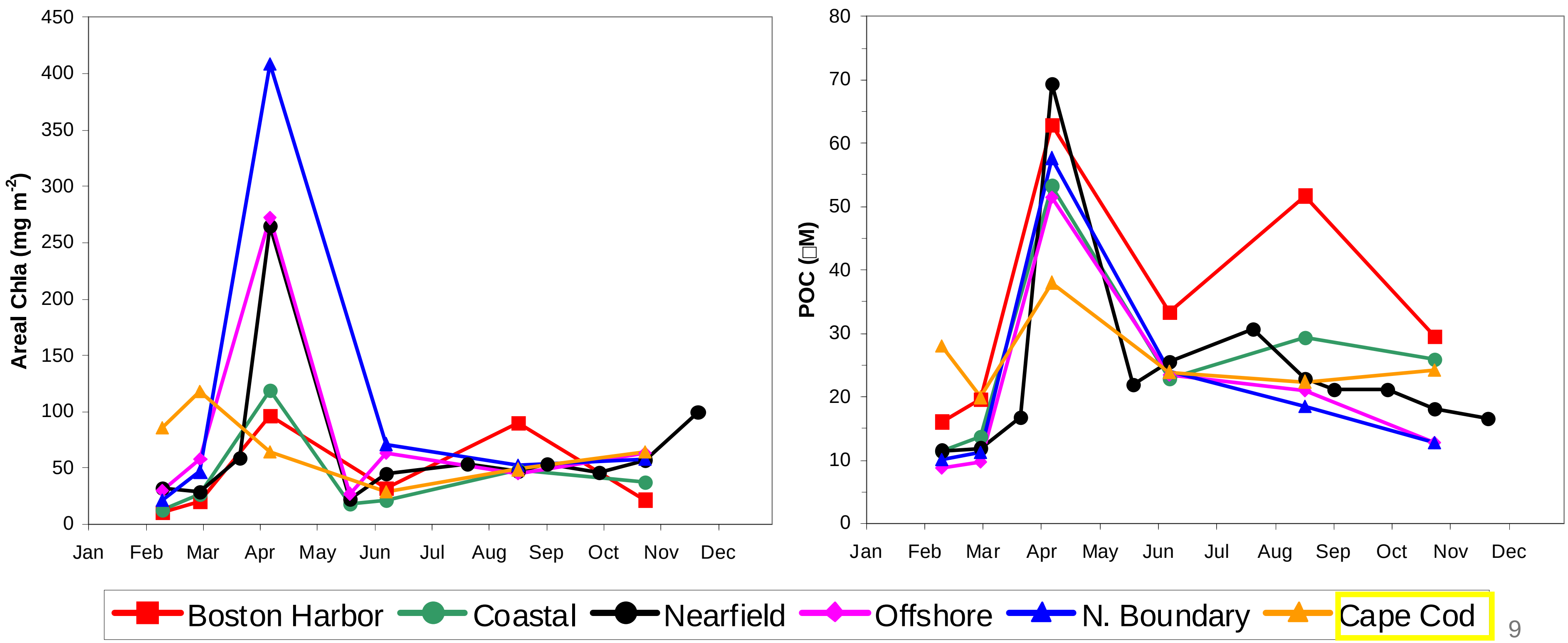


# 2008 Nutrients – $SiO_4$ & $PO_4$

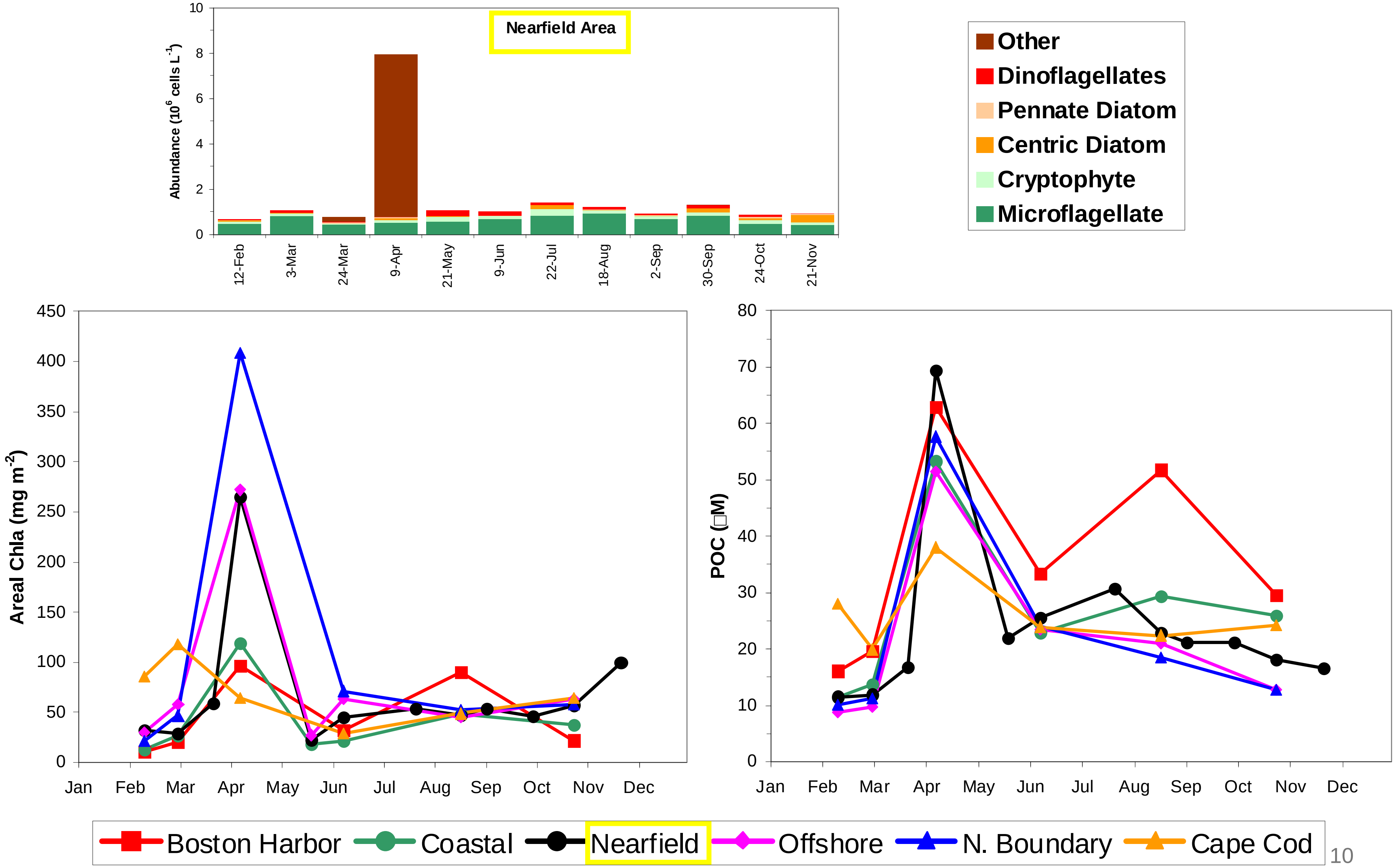


# 2008 Areal Chlorophyll & POC

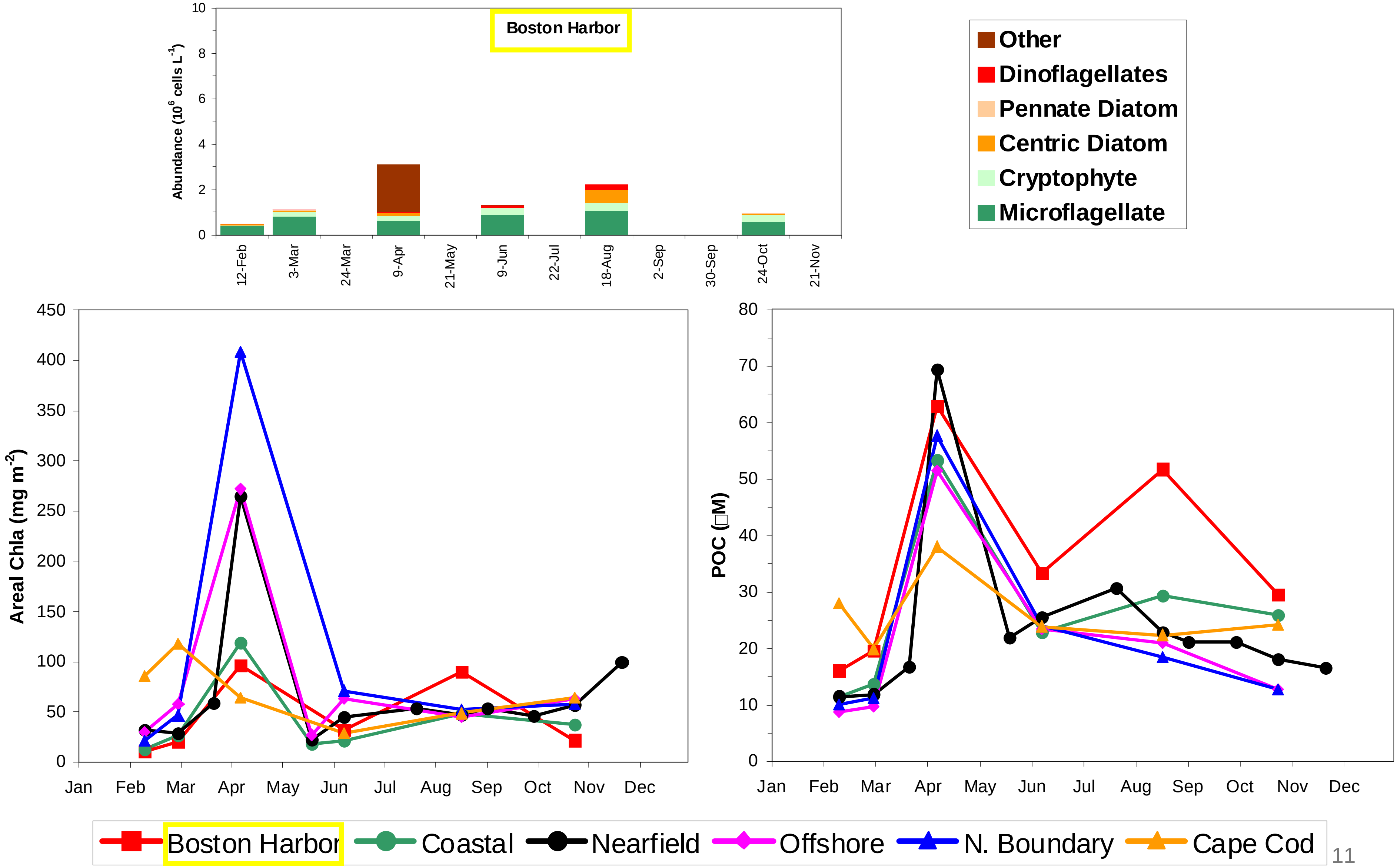


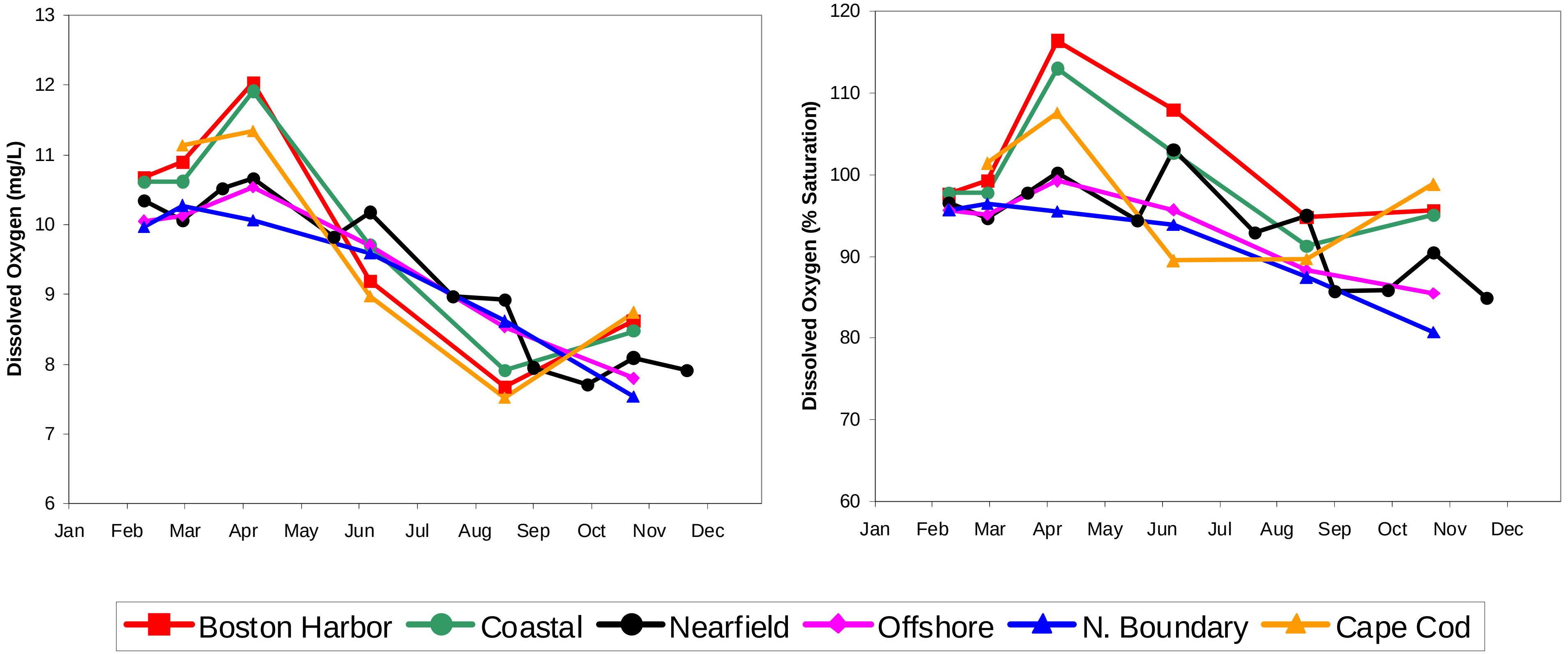
# 2008 Areal Chlorophyll & POC



# 2008 Areal Chlorophyll & POC



# 2008 – Bottom Water DO

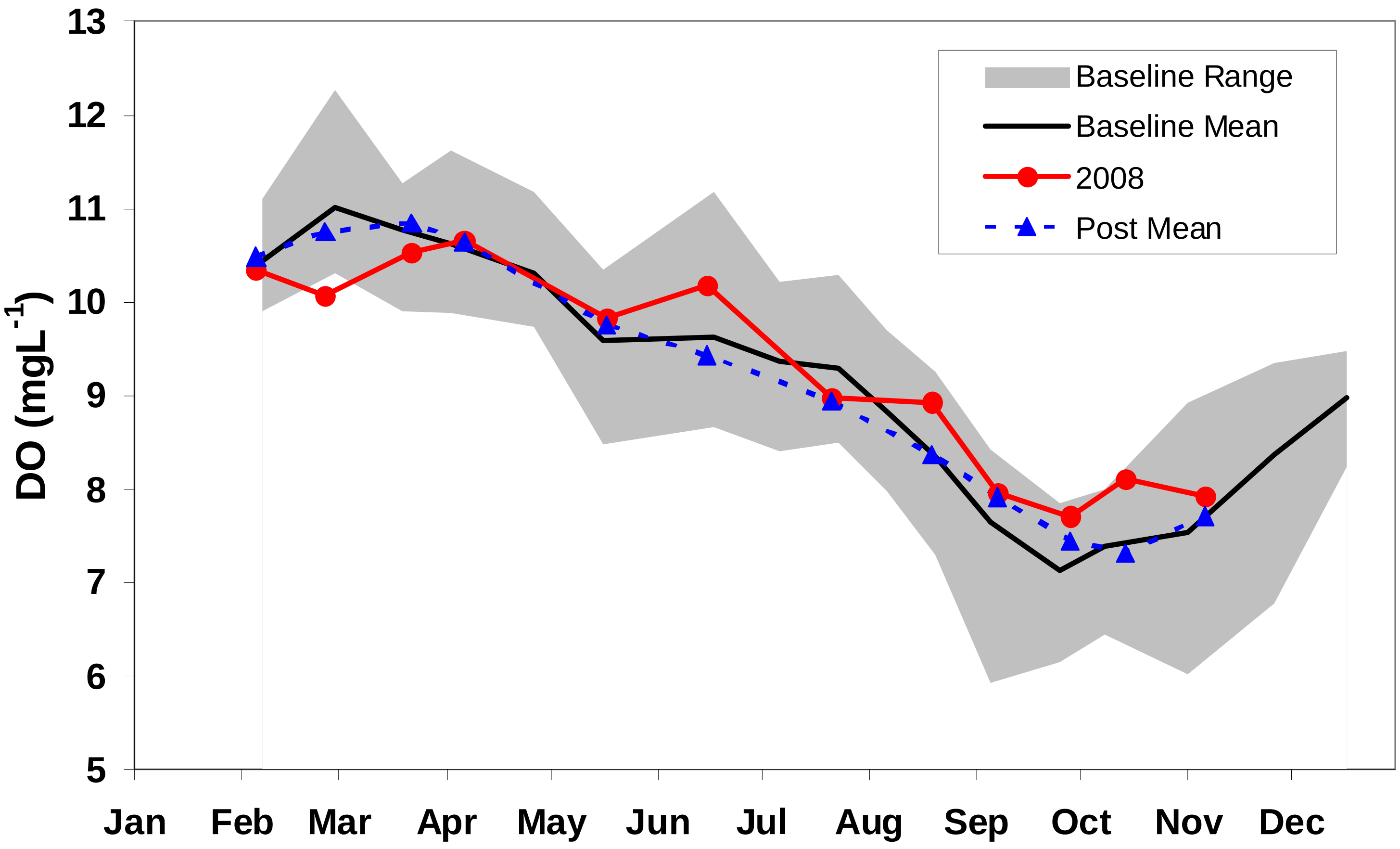


# Threshold Values for DO and Chlorophyll

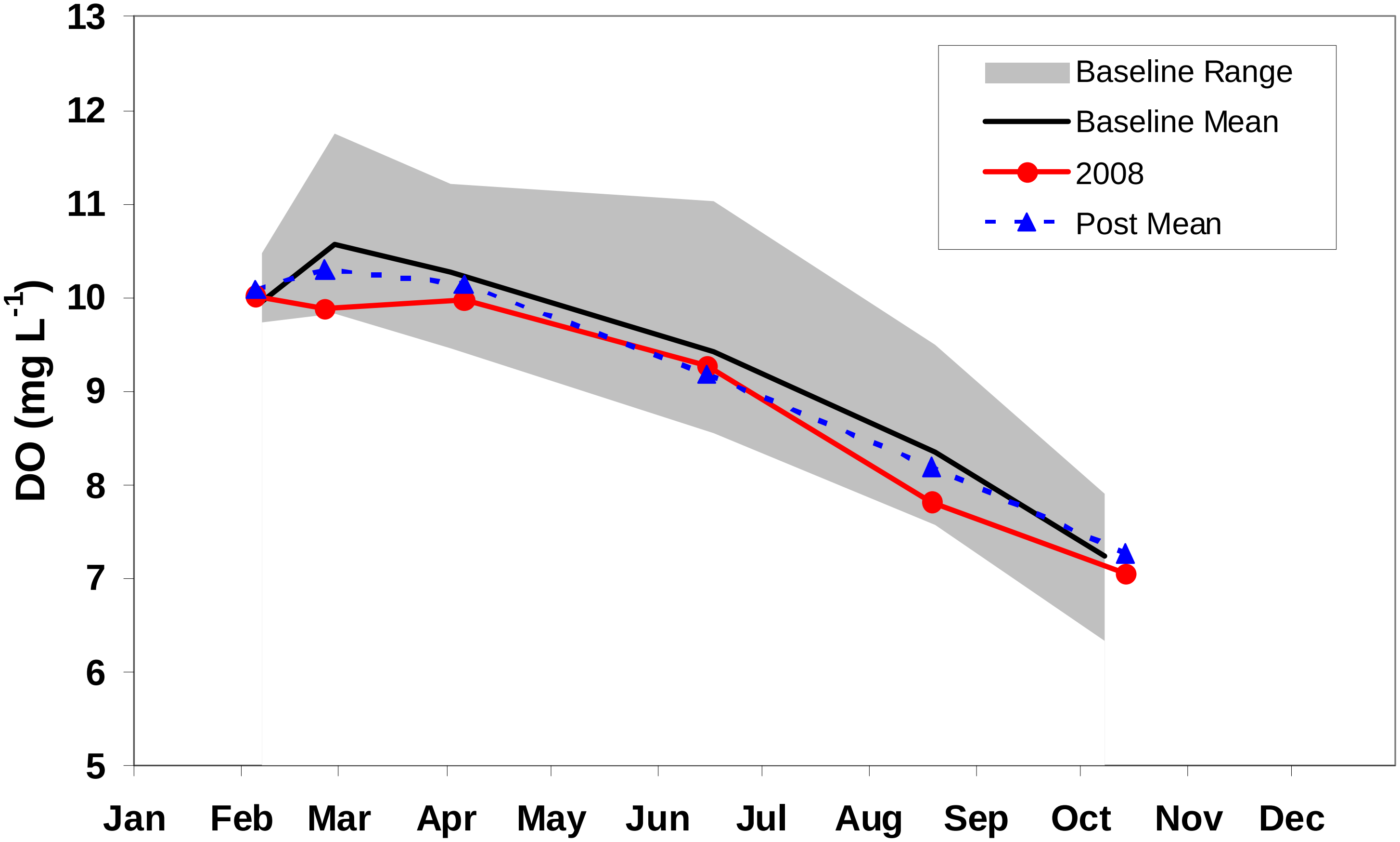
| Parameter | Time Period | Caution Level | Warning Level | Background | 2008 |
|---|---|---|---|---|---|
| Bottom Water DO concentration | Survey Mean in June-October | < 6.5 mg/l (unless background lower) | < 6.0 mg/l (unless background lower) | Nearfield 5.75 mg/l<br>Stellwagen 6.2 mg/l | 7.71 mg/l<br>7.06 mg/l |
| Bottom Water DO %saturation | Survey Mean in June-October | < 80% (unless background lower) | < 75% (unless background lower) | Nearfield - 64.3%<br>Stellwagen - 66.3% | 85.7%<br>74.8% |
| Bottom Water DO depletion rate | June to October | 0.037 | 0.049 | | 0.017 |
| Chlorophyll | Annual | 118 mg/m$^2$ | 158 mg/m$^2$ | -- | 67 mg/m$^2$ |
| | Winter/spring | 238 mg/m$^2$ | -- | -- | 96 mg/m$^2$ |
| | Summer | 93 mg/m$^2$ | -- | -- | 42 mg/m$^2$ |
| | Autumn | 212 mg/m$^2$ | -- | -- | 64 mg/m$^2$ |

**No exceedances for DO or Chlorophyll in 2008**

# Baseline vs. Post-discharge – Bottom DO Nearfield



# Baseline vs. Post-discharge – Bottom DO Stellwagen Basin

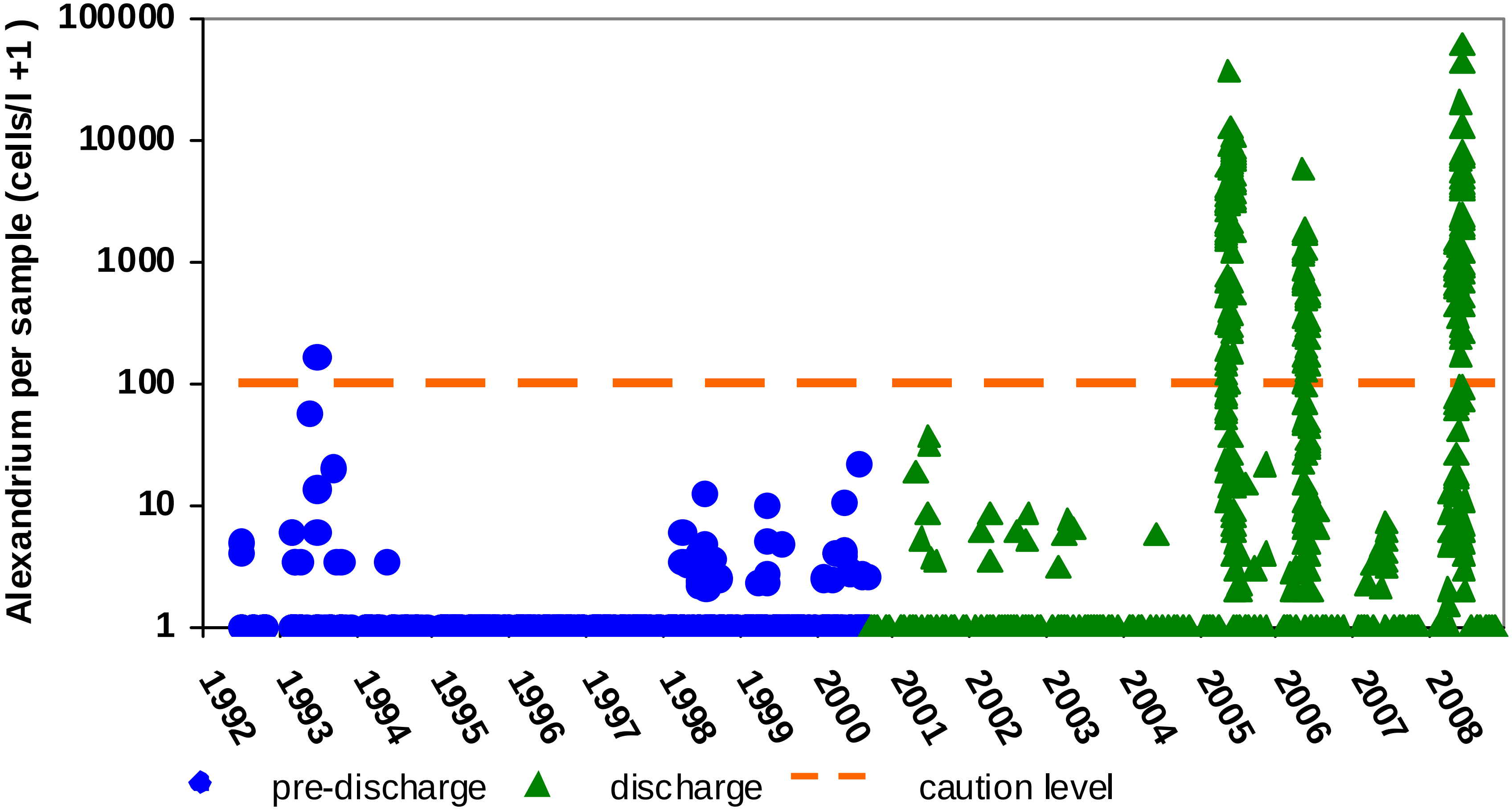


# Threshold Values for Nuisance Species

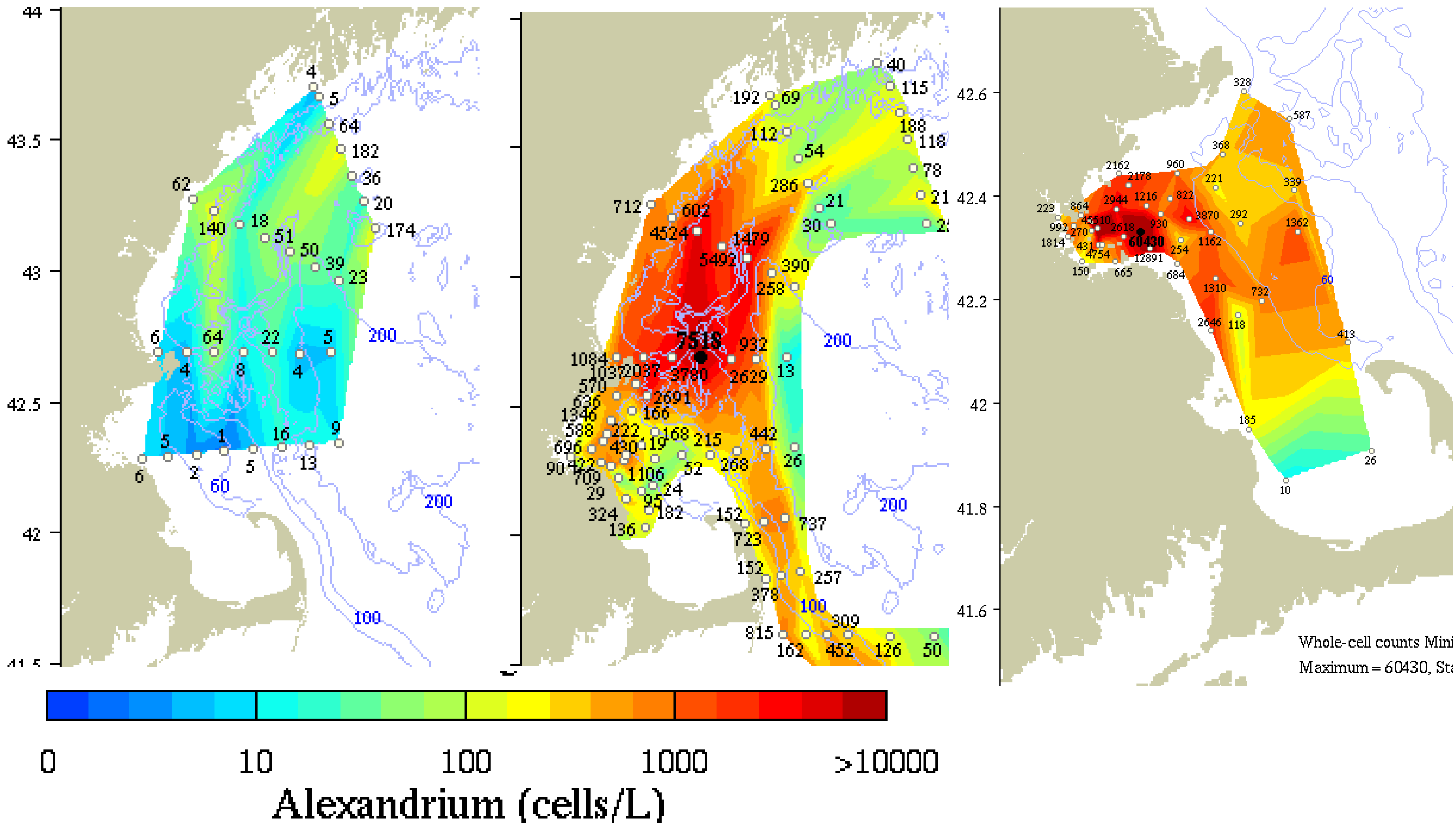
| Parameter | Time Period | Caution Level | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Phaeocystis pouchetii*** **(cells L$^{-1}$)** | **Winter/ spring** | 2,020,000 | 186,400 | 269,000 | 482,000 | **2,870,000** | 438,500 | 383,000 | **2,150,000** | 1,980,000 |
| | **Summer** | 357 | absent | **14,900** | **1,700** | **164,400** | **517** | **18,000** | absent | absent |
| | **Autumn** | 2,540 | absent | absent | absent | absent | absent | absent | absent | absent |
| ***Pseudo-nitzschia*** **(cells L$^{-1}$)** | **Winter/ spring** | 21,000 | 6,620 | 896 | 275 | 11.3 | 147 | absent | 77.5 | absent |
| | **Summer** | 43,100 | 163 | 234 | 83.5 | 380 | 3,320 | absent | absent | 540 |
| | **Autumn** | 24,700 | 6,030 | 3,210 | 12,100 | 660 | 44.7 | 222 | absent | 171 |
| ***Alexandrium*** | **Any nearfield sample** | 100 | 35 | 8 | 7 | 5 | **36,831** | **5,668** | 7.2 | **60,430** |

- **Exceedance of *Alexandrium* threshold in May 2008**
- **No *Phaeocystis* exceedance, but a large bloom in 2008**

# Nearfield Alexandrium Abundance

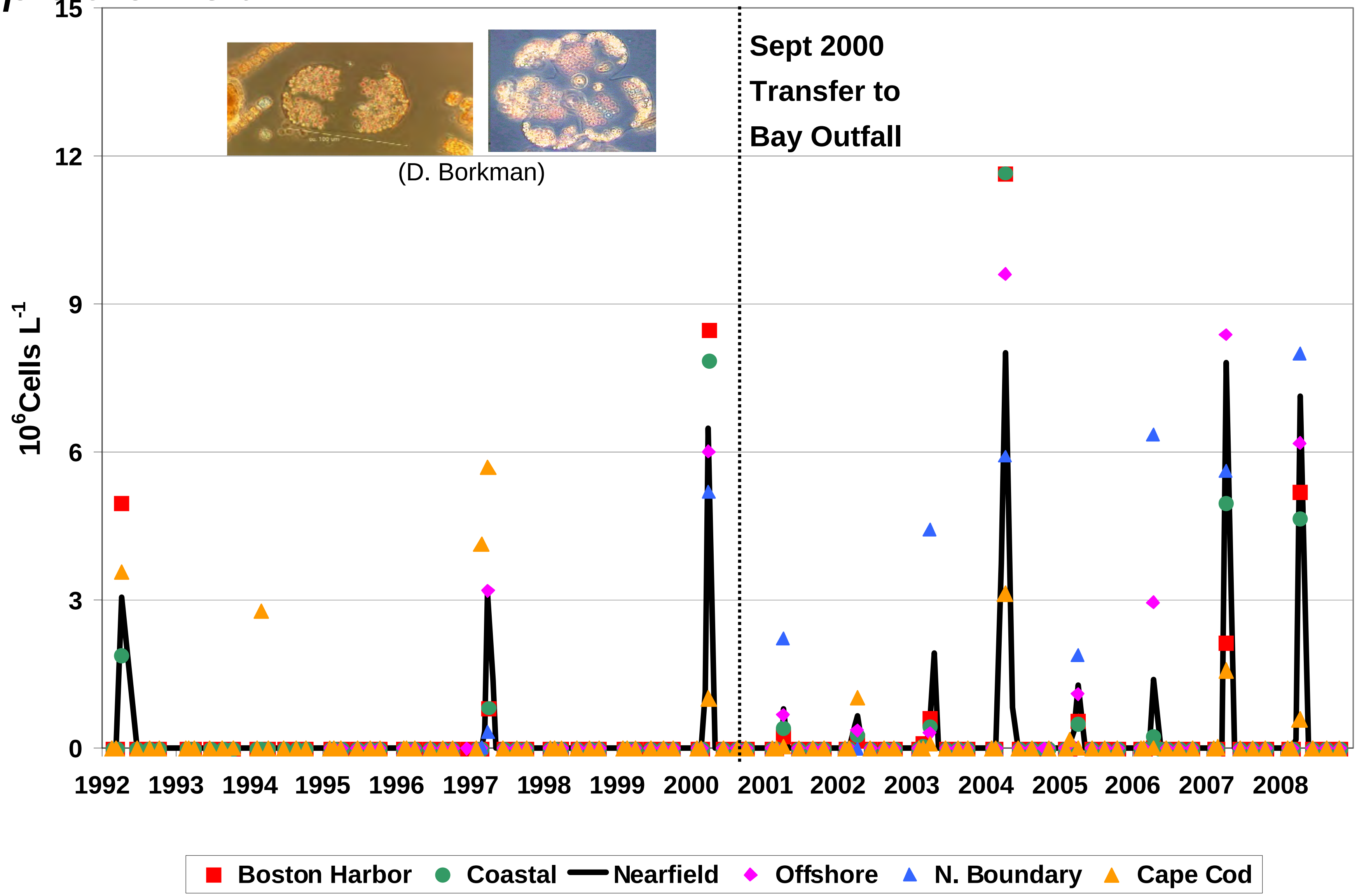


May 4-5 | May 27-29 | June 9-17

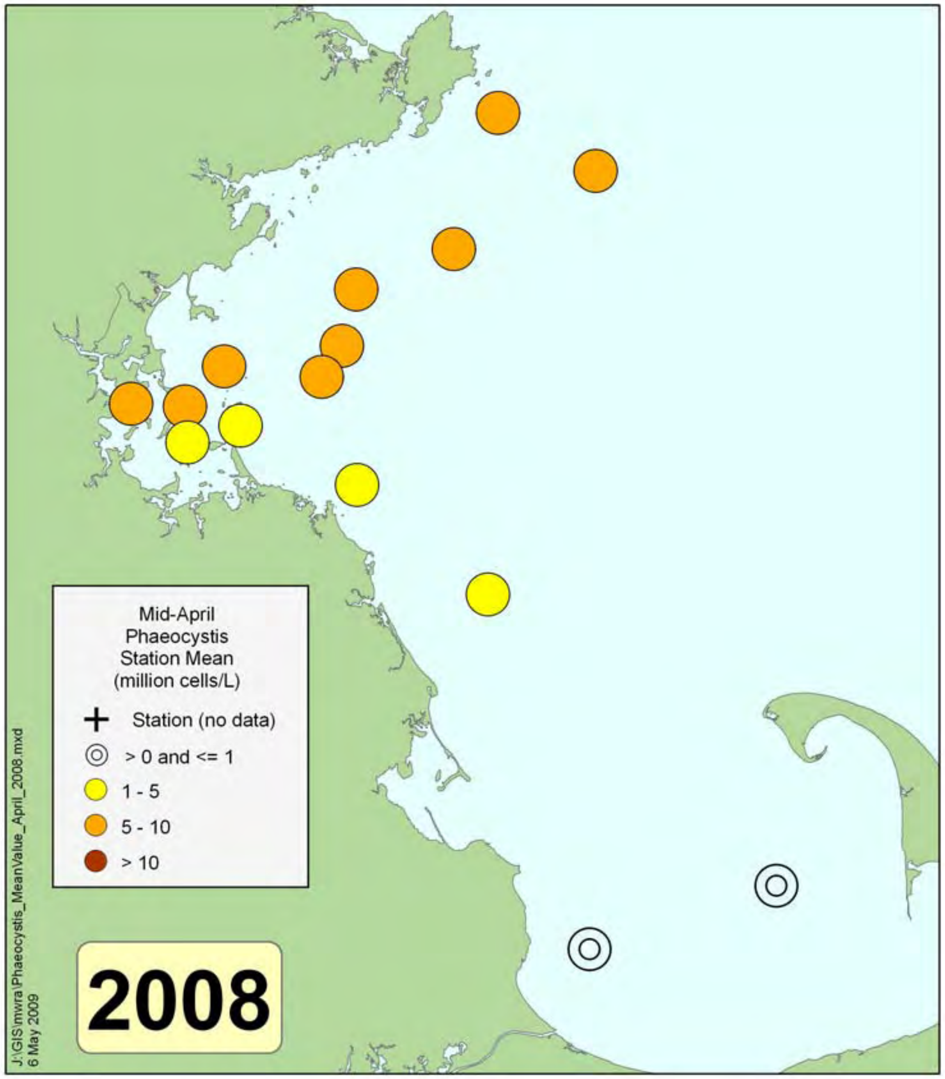



June 24 – end of bloom

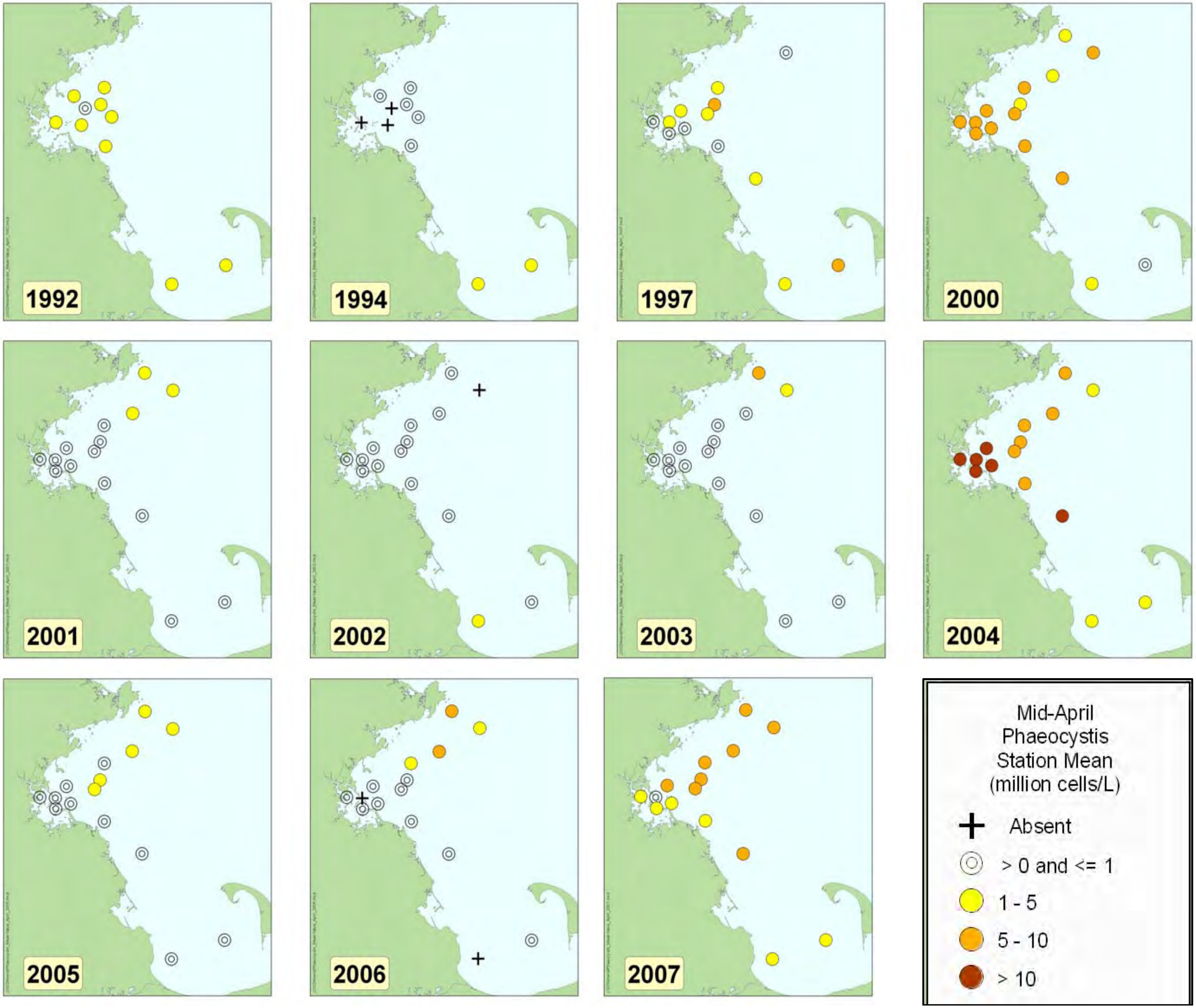
# Nuisance Species – *Phaeocystis pouchetii*

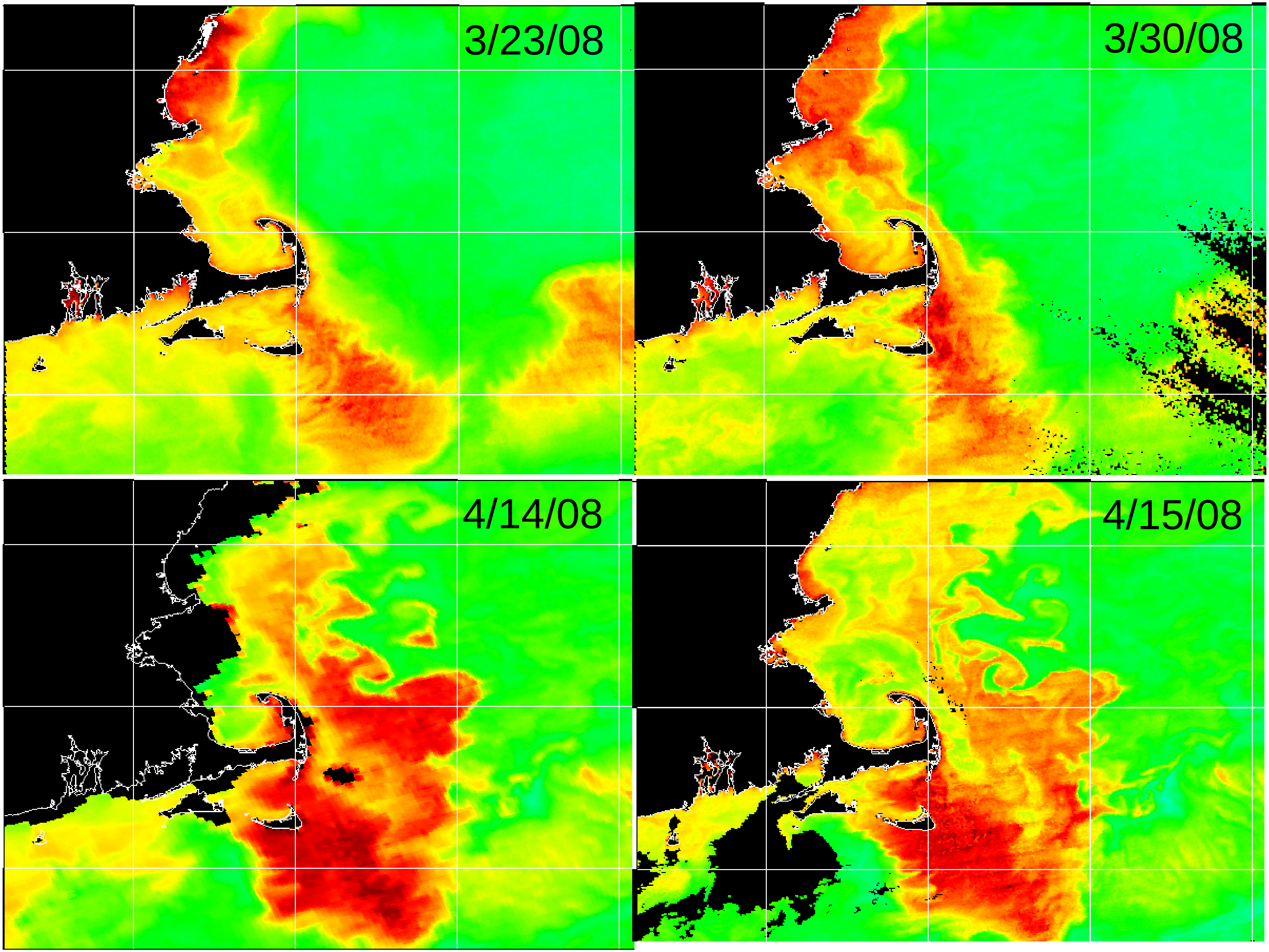


# April 2008 Phaeocystis Distribution




- Observed throughout the bays (all 15 stations)
- Highest levels (>10 million cells/L) observed to the northeast at mid-depth (F22, F26, and F27)
- With a maxima of 14 million cells/L at N16 at mid-depth
- Similar to many of the past Phaeocystis blooms – tend to be regional (bays and western Gulf of Maine)

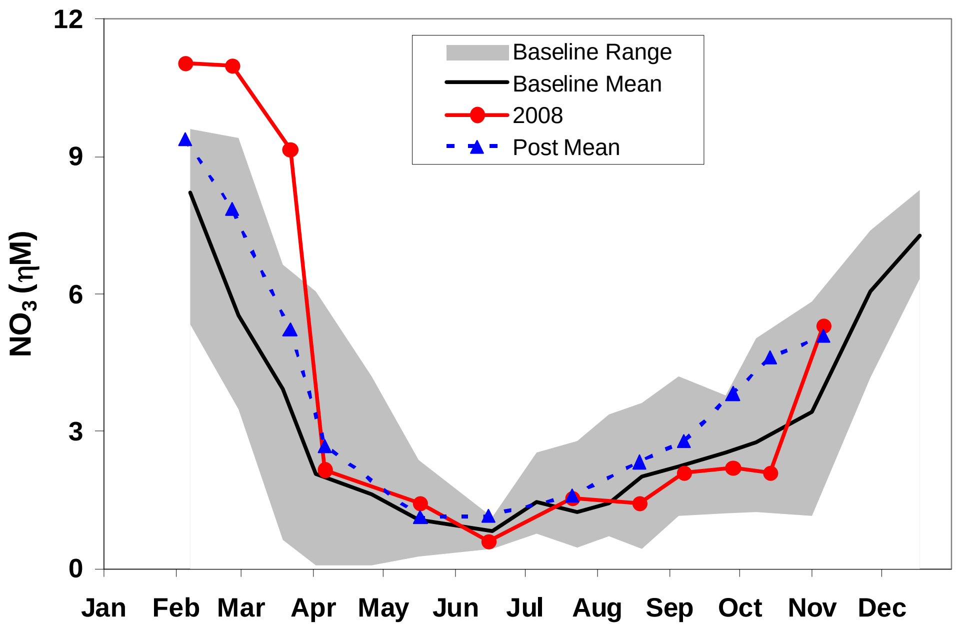

1992
1994
1997
2000
2001
2002
2003
2004
2005
2006
2007
Mid-April Phaeocystis Station Mean (million cells/L)
Absent
> 0 and <= 1
1 - 5
5 - 10
> 10

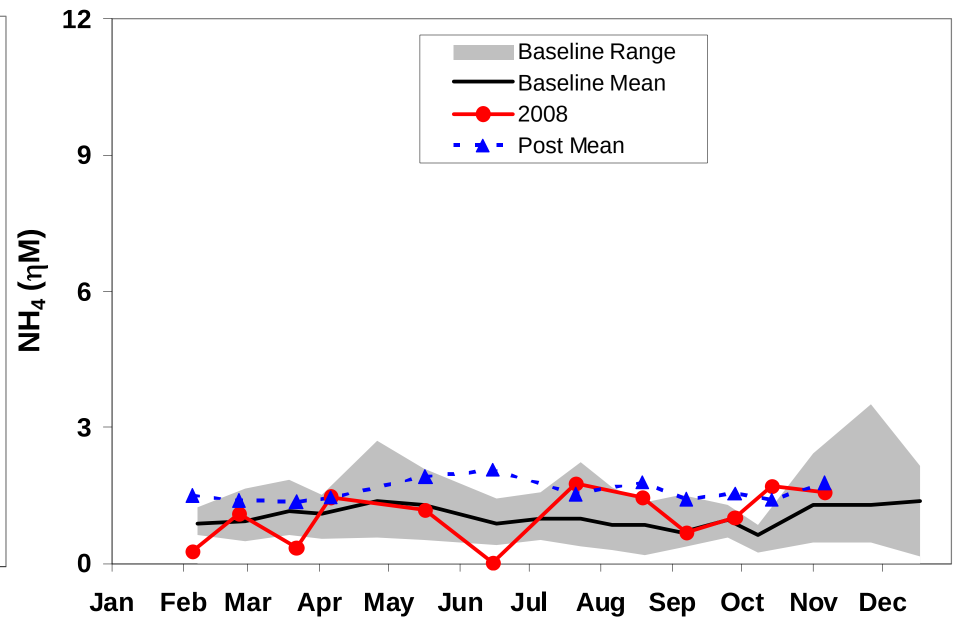

3/23/08
3/30/08
4/14/08
4/15/08

# 2008 Summary

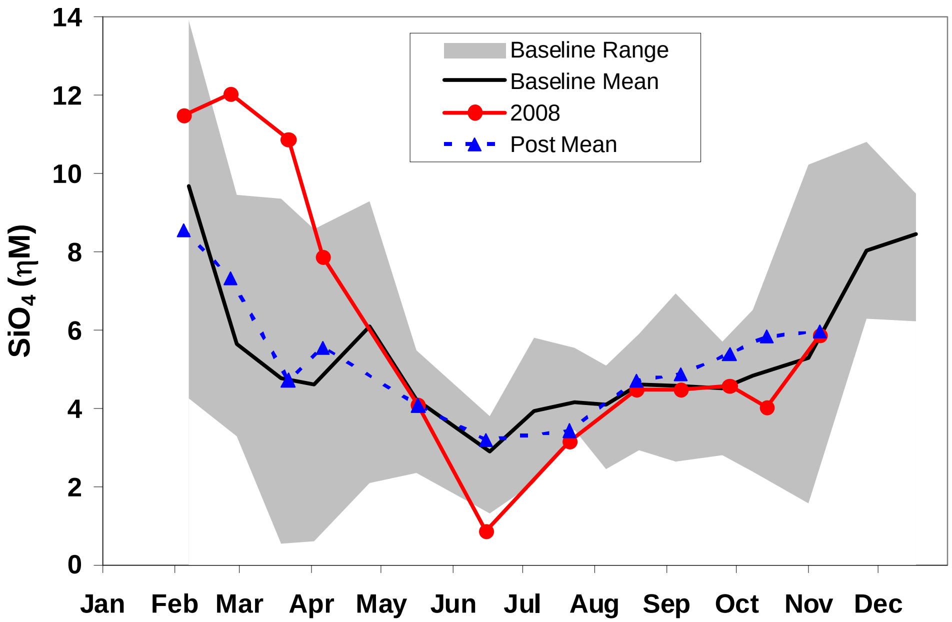
- Nutrients
  - High concentrations in February and March with sharp decline (except for $SiO_4$) coincident with the *Phaeocystis* bloom across most of MA bay
  - Slightly lower $NO_3$ and $SiO_4$ in CCB in February and a sharp decrease in $SiO_4$ from February to April in CCB, Boston Harbor and coastal areas (minor diatom bloom)
- Chlorophyll
  - Slightly elevated in CBB in February associated with minor diatom bloom
  - Annual peak survey means for chlorophyll and POC in MA Bay due to baywide *Phaeocystis* bloom in April
  - Highest concentrations associated with peak abundance in boundary, offshore, and nearfield areas
  - Increase in concentrations during summer diatom bloom observed in coastal and harbor areas
  - Late fall increase in chlorophyll, POC, and diatoms in the nearfield
- Dissolved Oxygen
  - Relatively high bottom water DO in 2008 with fall minima of >7 mg/L

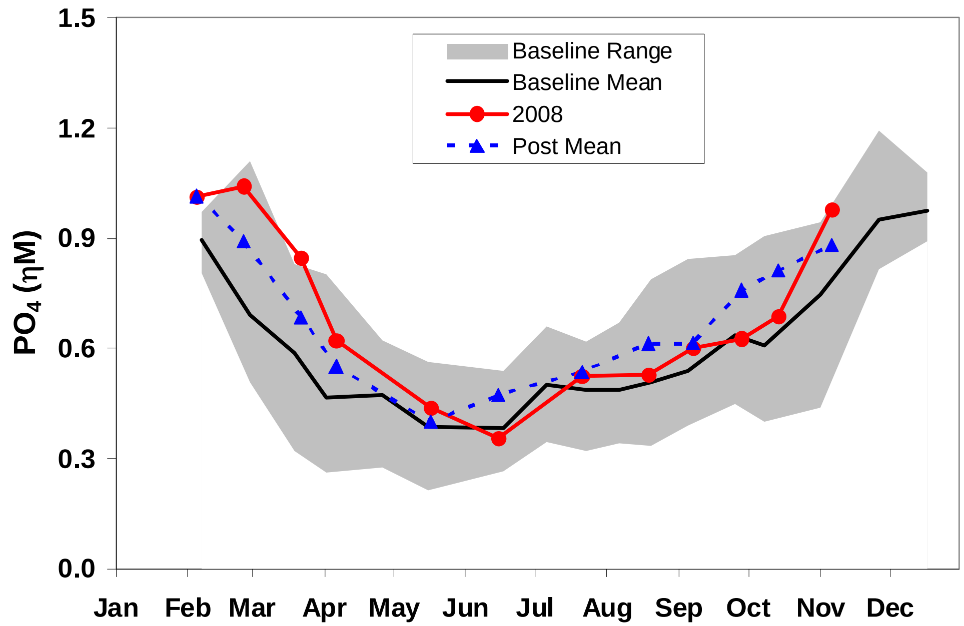
# Nearfield – $NO_3$ & $NH_4$



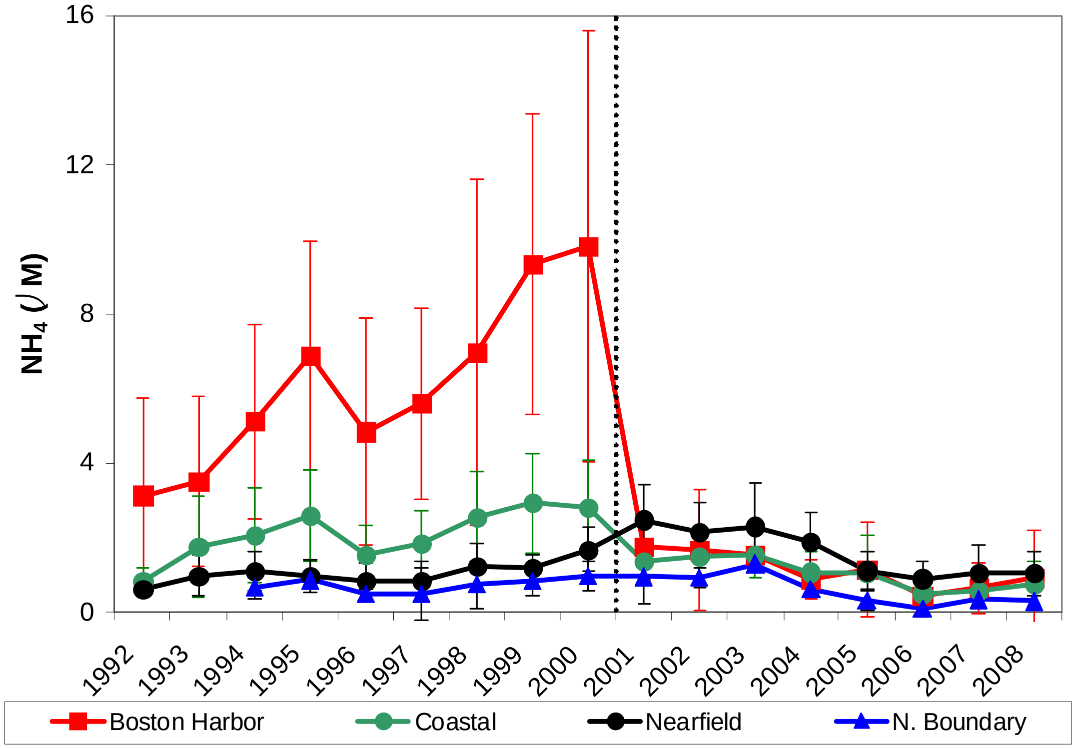
# Nearfield – $SiO_4$ & $PO_4$



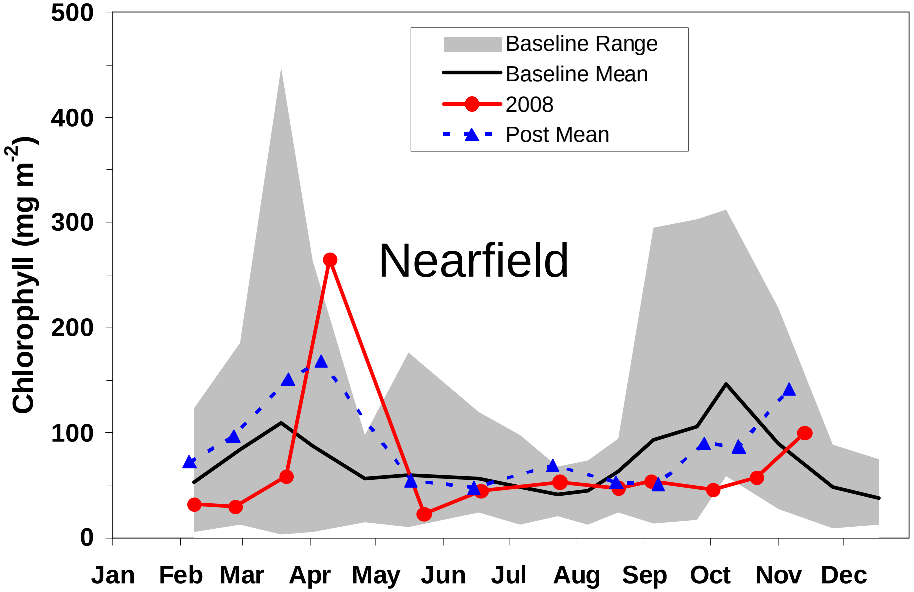



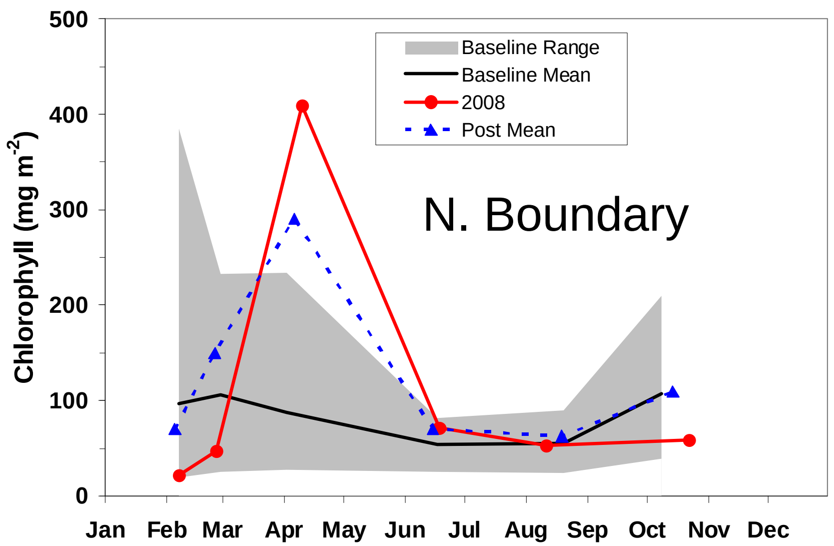
# Annual Mean Nutrients – $NH_4$

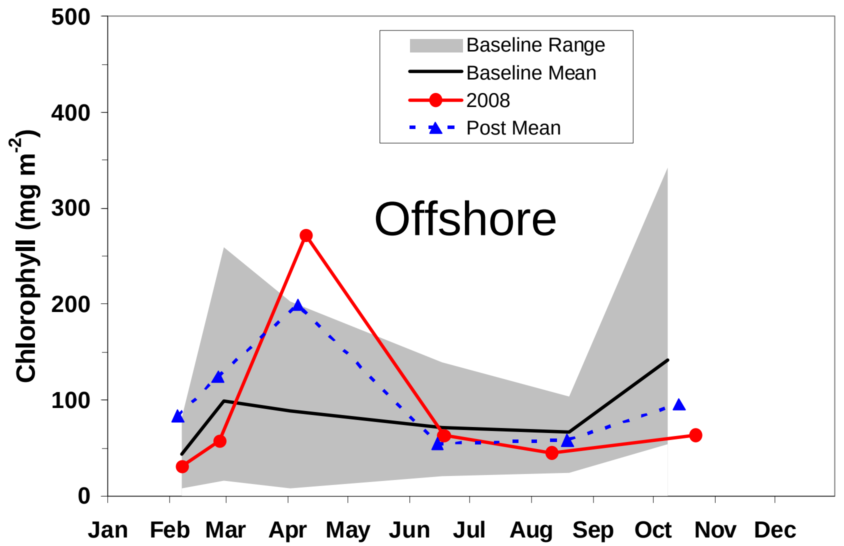
- Large Decrease in $NH_4$ in Boston Harbor
- Decrease in Coastal area
- Initial doubling of $NH_4$ in nearfield
- Decrease in $NH_4$ since 2003 across all areas
- Current nearfield levels comparable to 90's



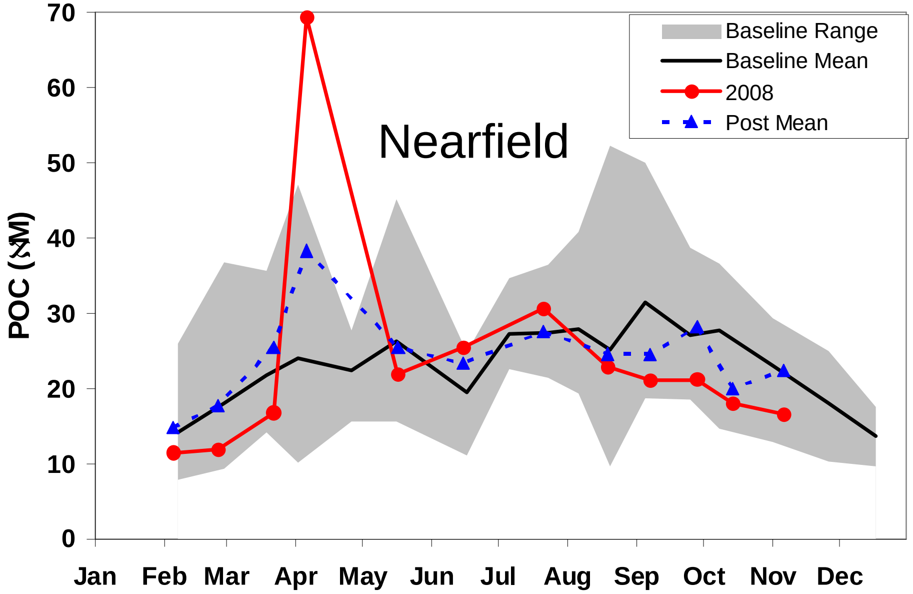
# 2008 Areal Chlorophyll vs. Baseline

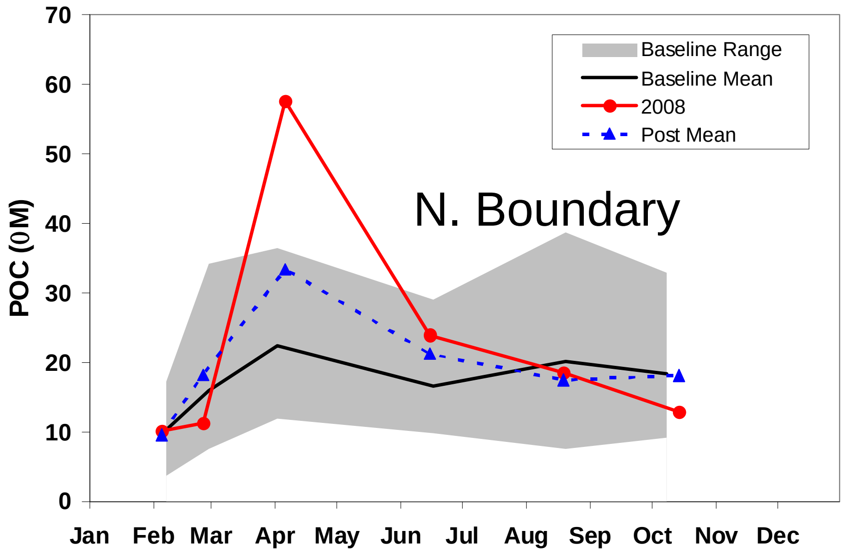


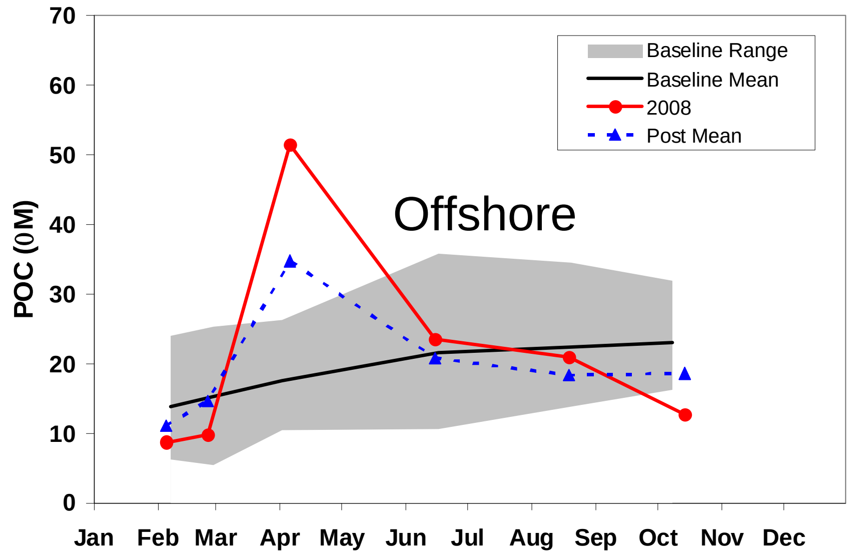



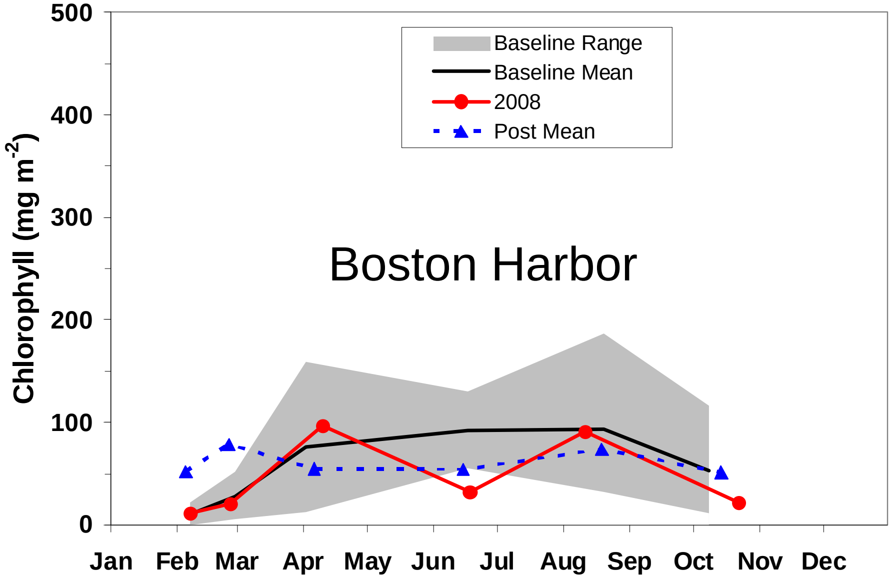
# 2008 POC vs. Baseline

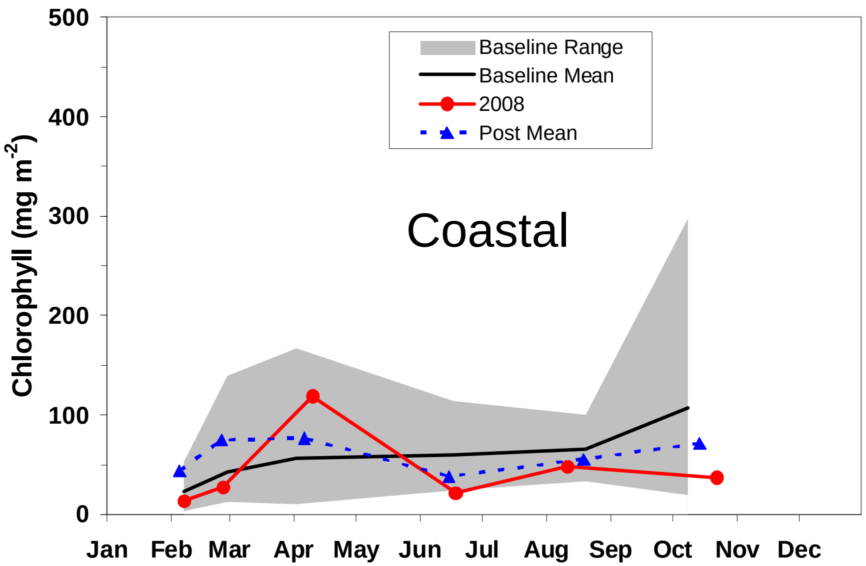


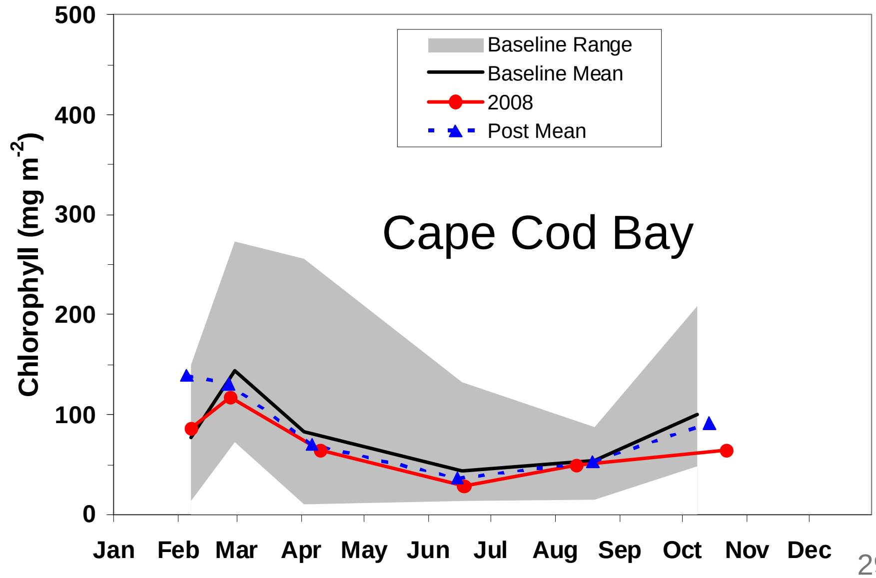



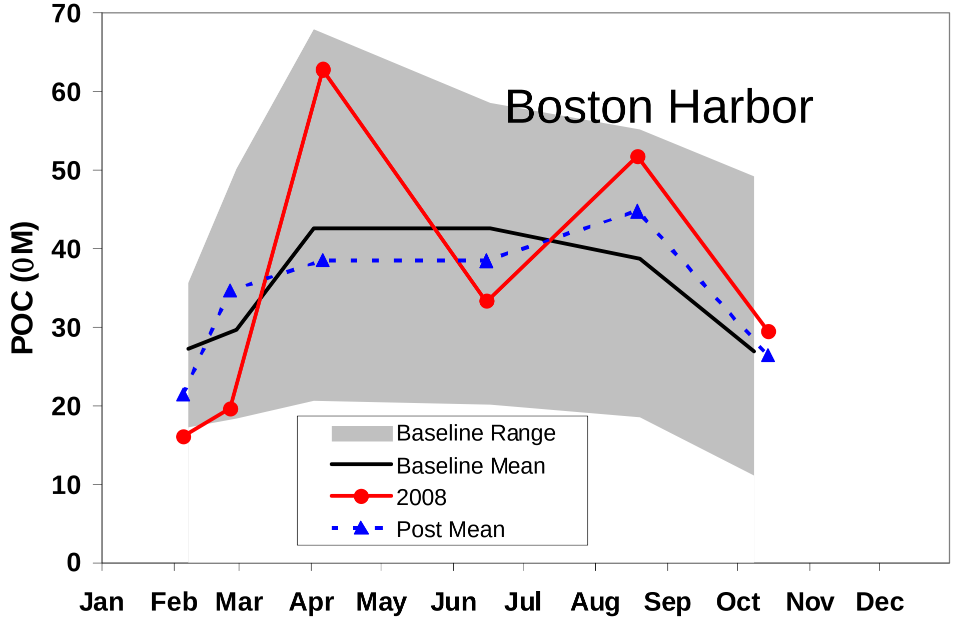
# 2008 Areal Chlorophyll vs. Baseline

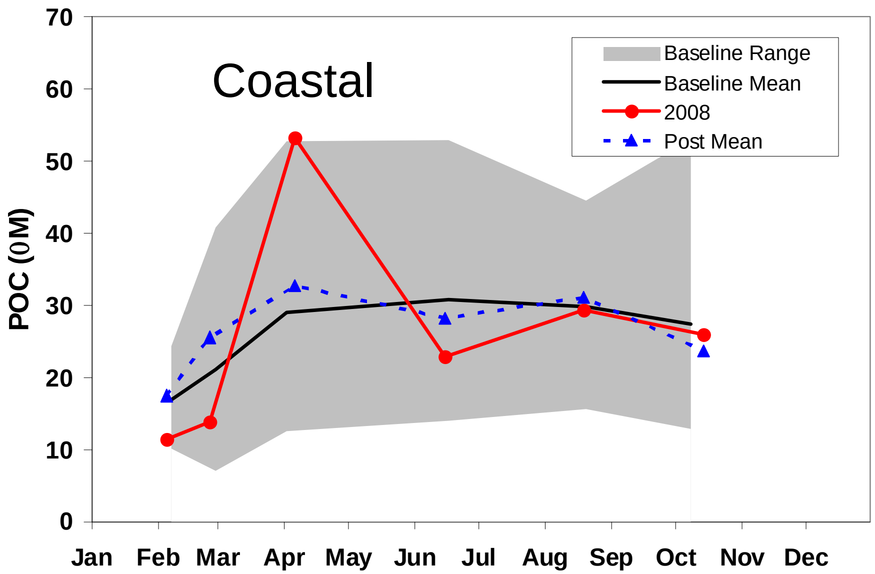


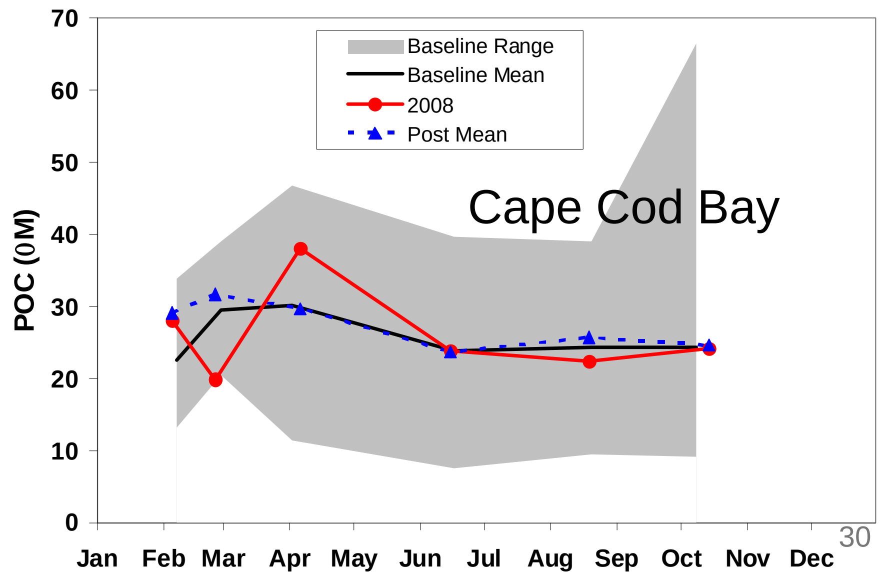



# 2008 POC vs. Baseline

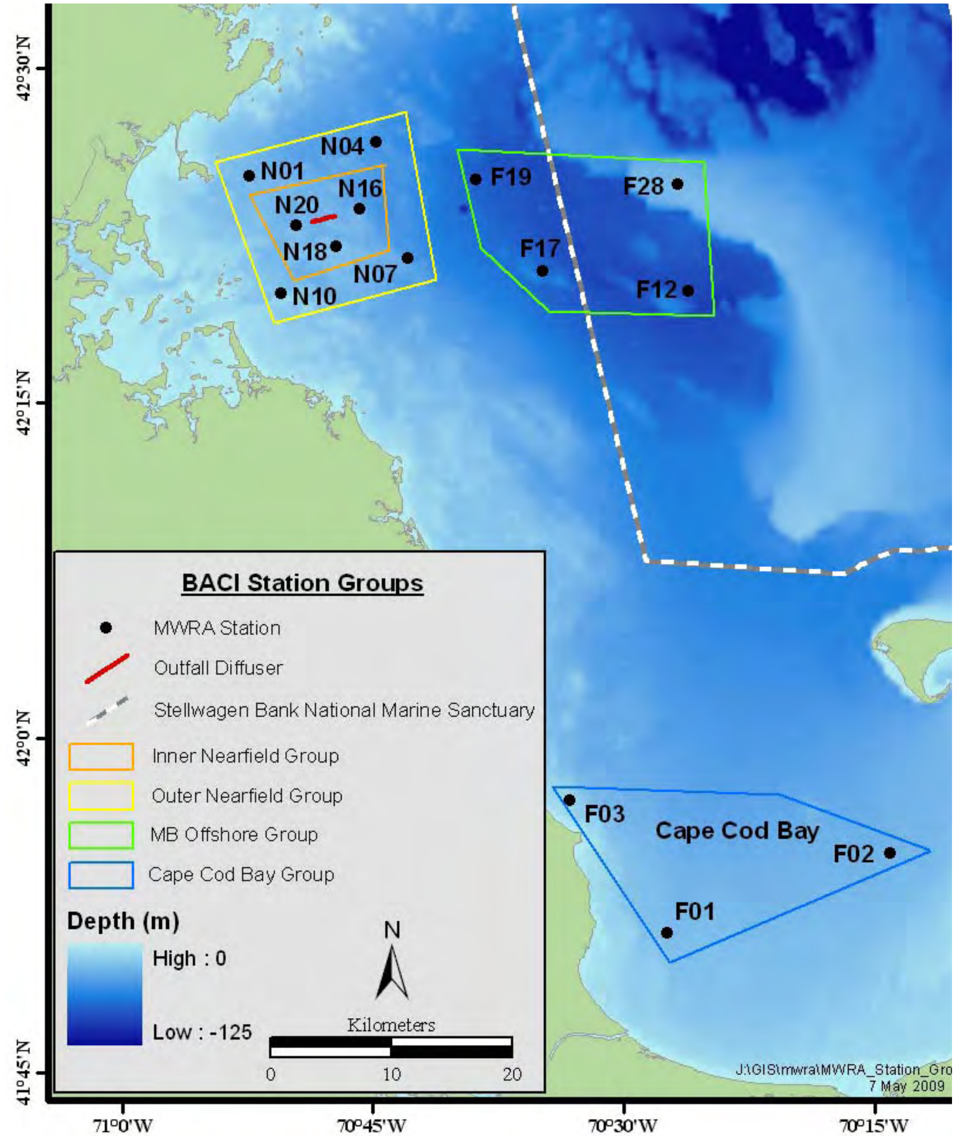


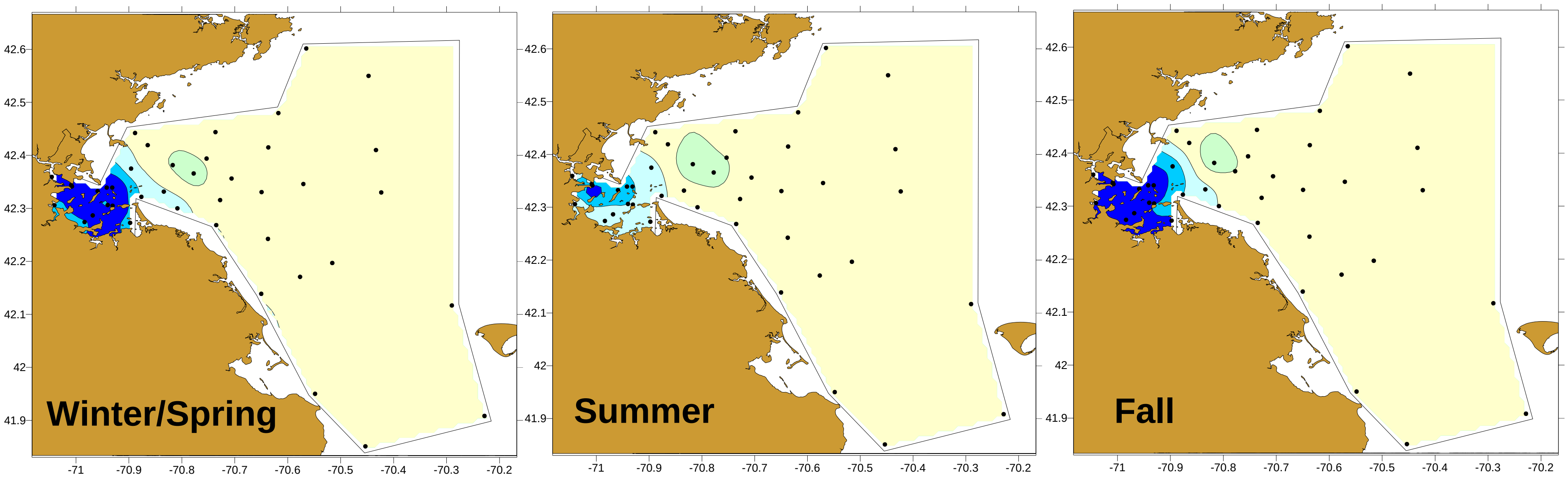
# BACI Statistical Analysis (92-07)

- Grouped stations
  - "Impacted" area
    - Inner nearfield: N16, N18 & N20
  - Control areas
    - Outer nearfield: N01, N04, N07 & N10
    - MB Offshore: F12, F17, F19 & F28
    - CCB: F01, F02 & F03
- Pre vs. Post comparisons
- Comparisons of differences between impacted and control areas pre vs. post



# Nutrient Distribution – Pre-Post changes

## Ammonium – Baseline vs. 2001-2008

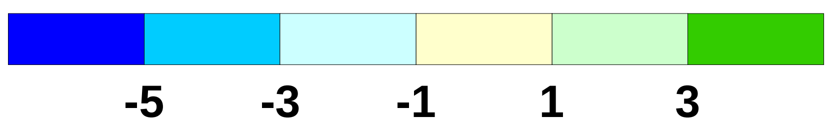



↑ Inner Nearfield

↓ Outer Nearfield

CCB & MB Off

↑ Inner Nearfield



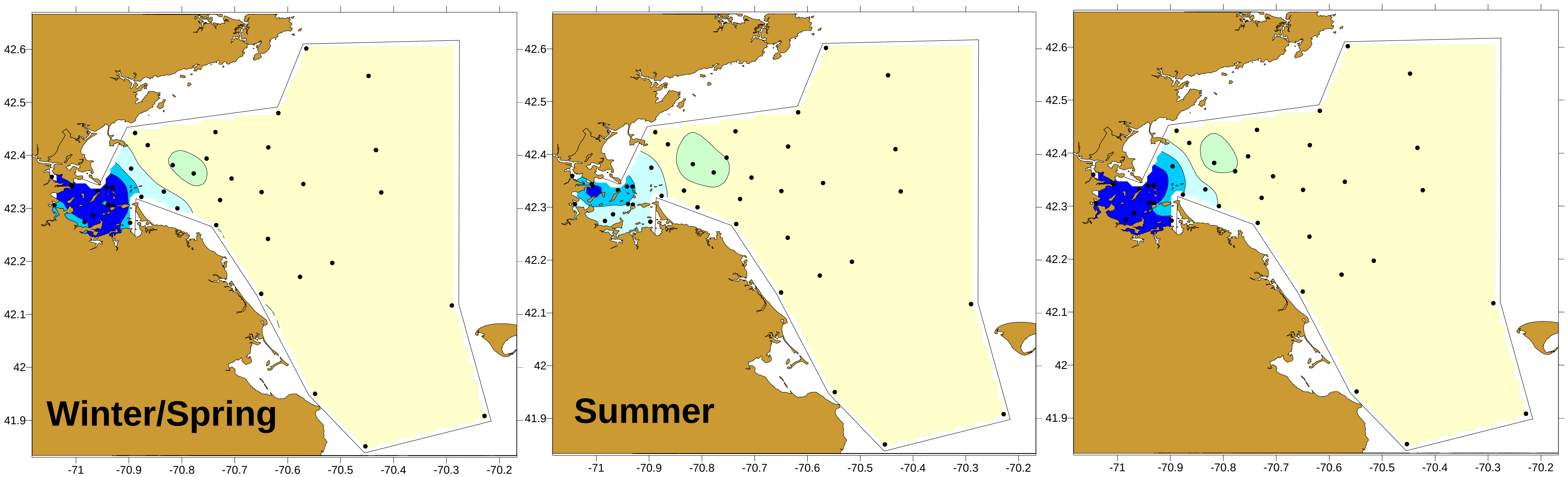

$\Delta$ µM $NH_4$

↑ Inner Nearfield

↓ MB Off

# Nutrient Distribution – Pre-Post changes

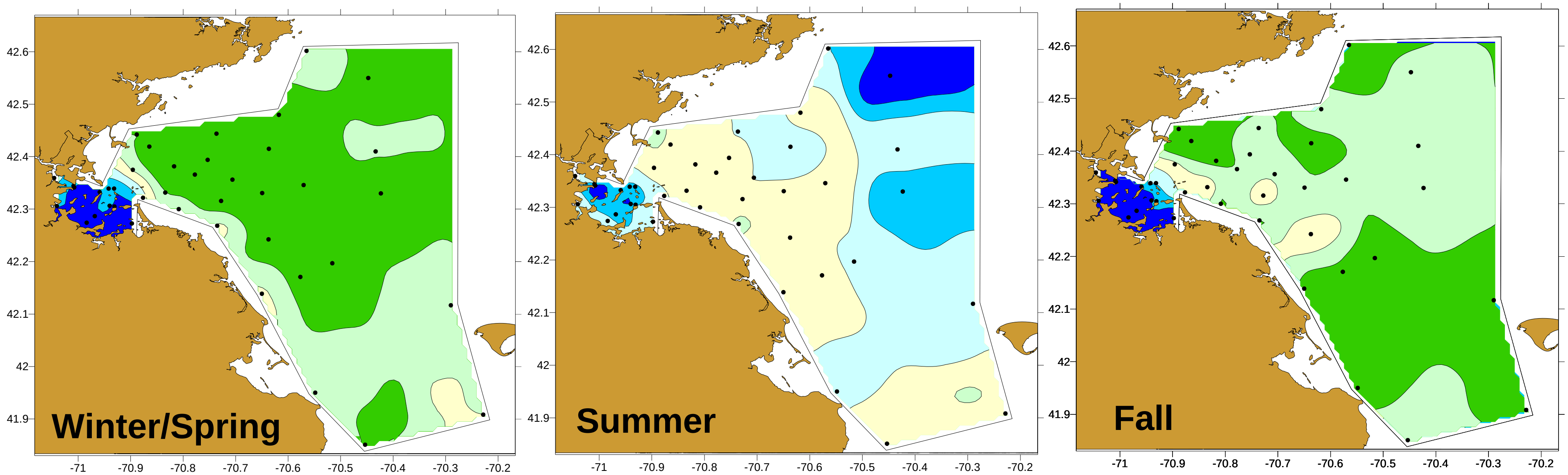
## Ammonium – Baseline vs. 2001-2008




BACI analysis indicated significant increases in NH4 above baseline levels in the Inner Nearfield compared to all three control areas for each season

# Nutrient Distribution – Pre-Post changes

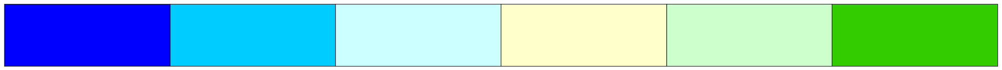
## Nitrate – Baseline vs. 2001-2008




**↑** Inner Nearfield
Outer Nearfield
& MB Off

**↑** Inner Nearfield

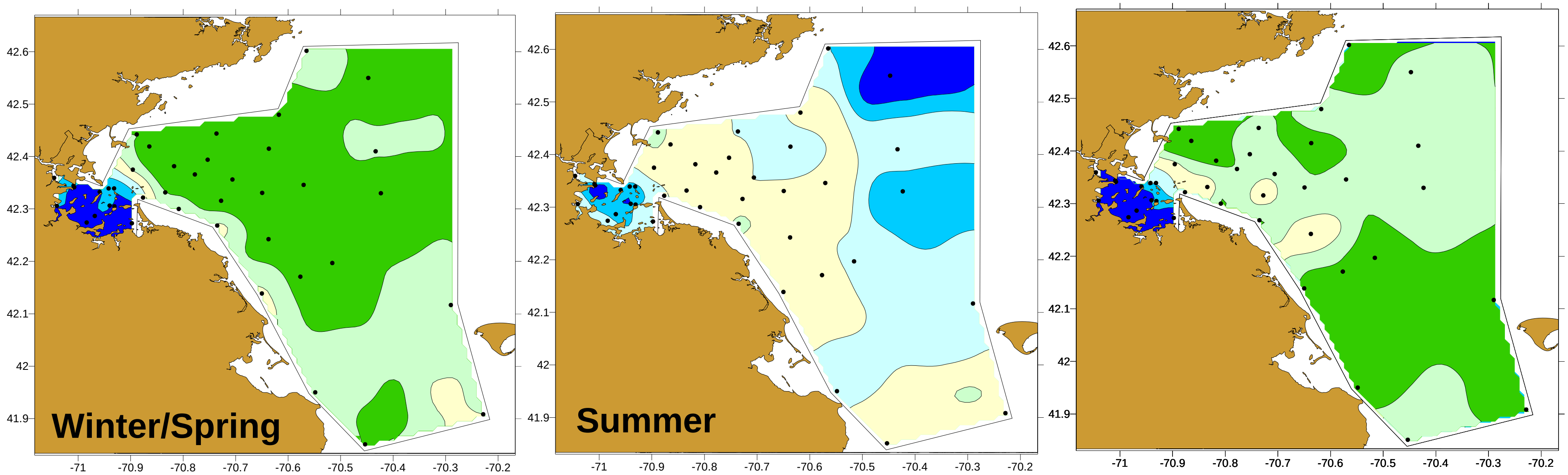
**↑** Inner Nearfield
Outer Nearfield
& CCB




$\Delta$ µM $NO_3$

# Nutrient Distribution – Pre-Post changes

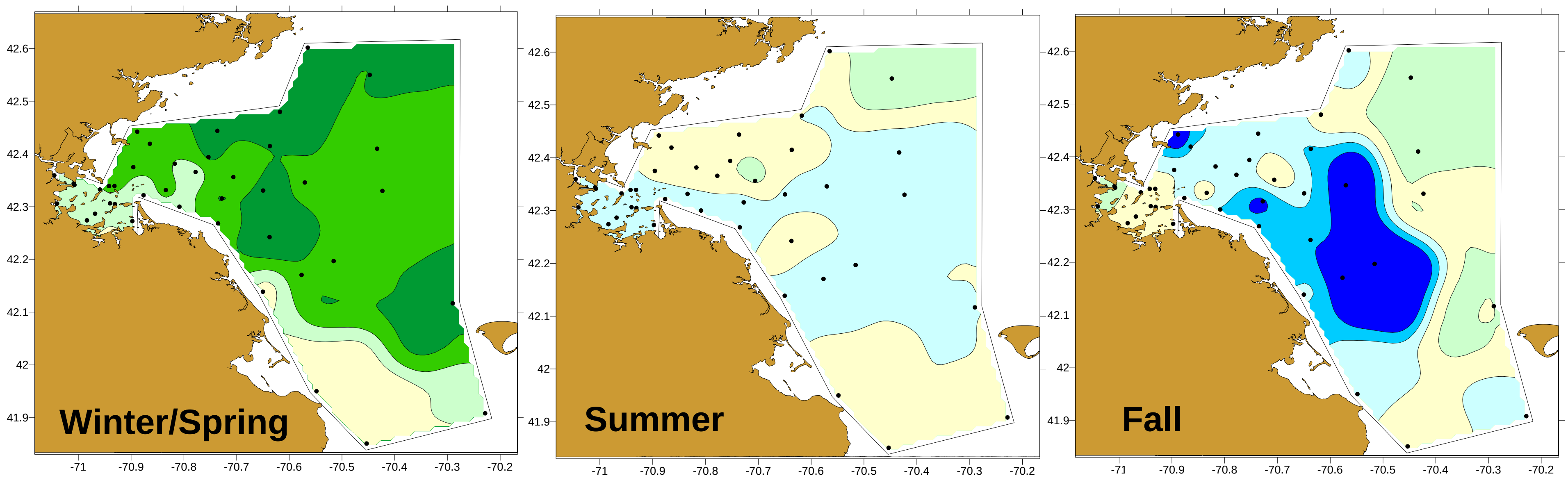
## Nitrate – Baseline vs. 2001-2008




All groups trending in the same direction – no significant change for Inner Nearfield compared to the three control areas for any season

# Chl*a* Distribution – Pre-Post changes

## **Areal Chl*a* – Baseline vs. 2001-2008**




↑ Inner Nearfield

Outer Nearfield

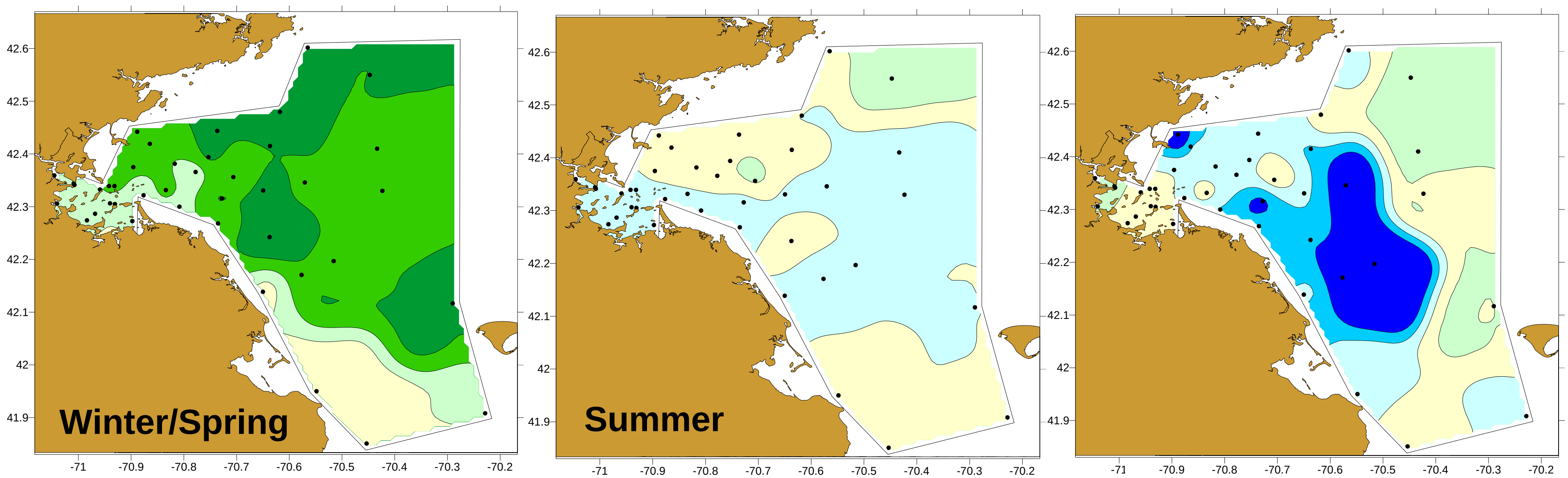
& MB Off

**-50 -30 -10 10 30 50**

Δ mg $m^{-2}$ Chl*a*

# Chl*a* Distribution – Pre-Post changes

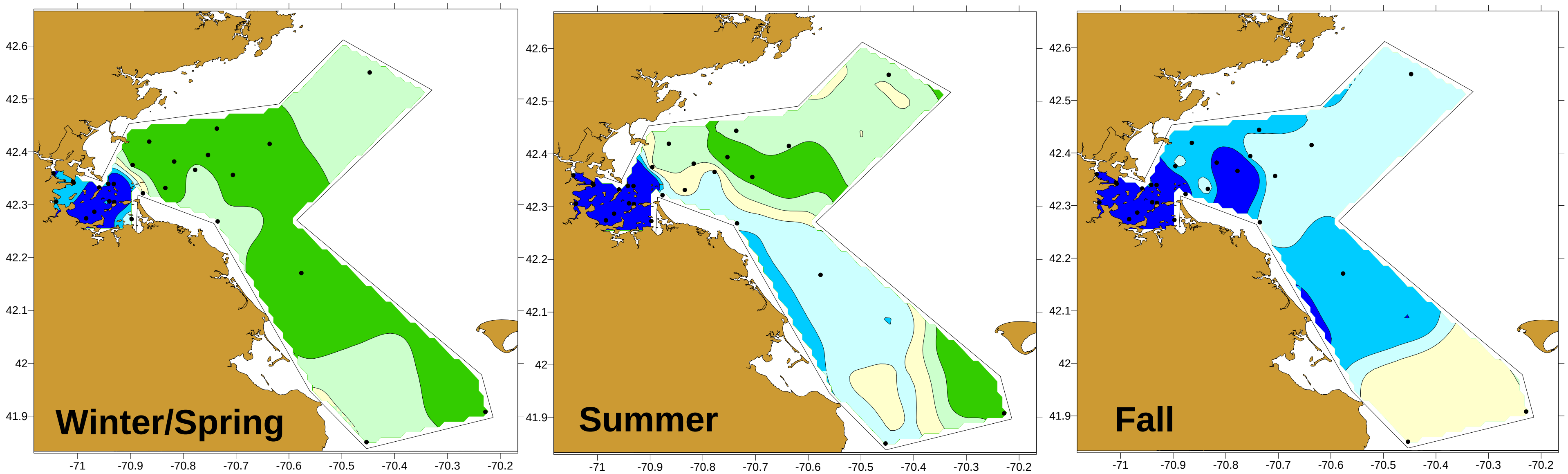
## Areal Chl*a* – Baseline vs. 2001-2008




All groups trending in the same direction – no significant change for Inner Nearfield compared to the three control areas for any season

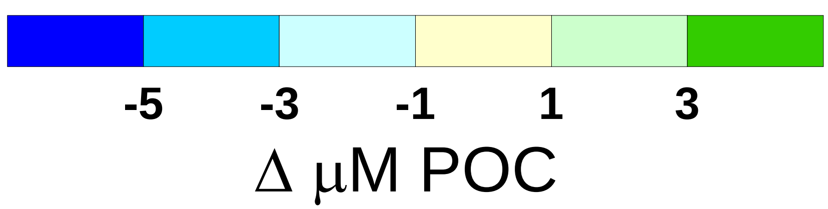
# POC Distribution – Pre-Post changes

## POC – Baseline vs. 2001-2008



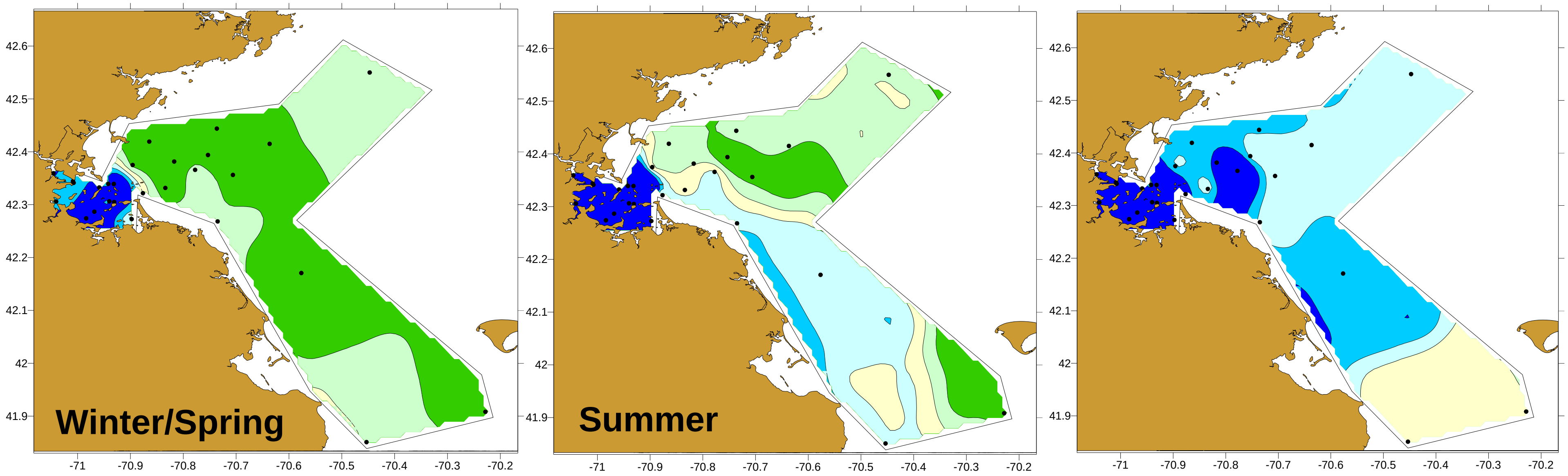

↑ Inner Nearfield
Outer Nearfield

↑ Inner Nearfield



# POC Distribution – Pre-Post changes

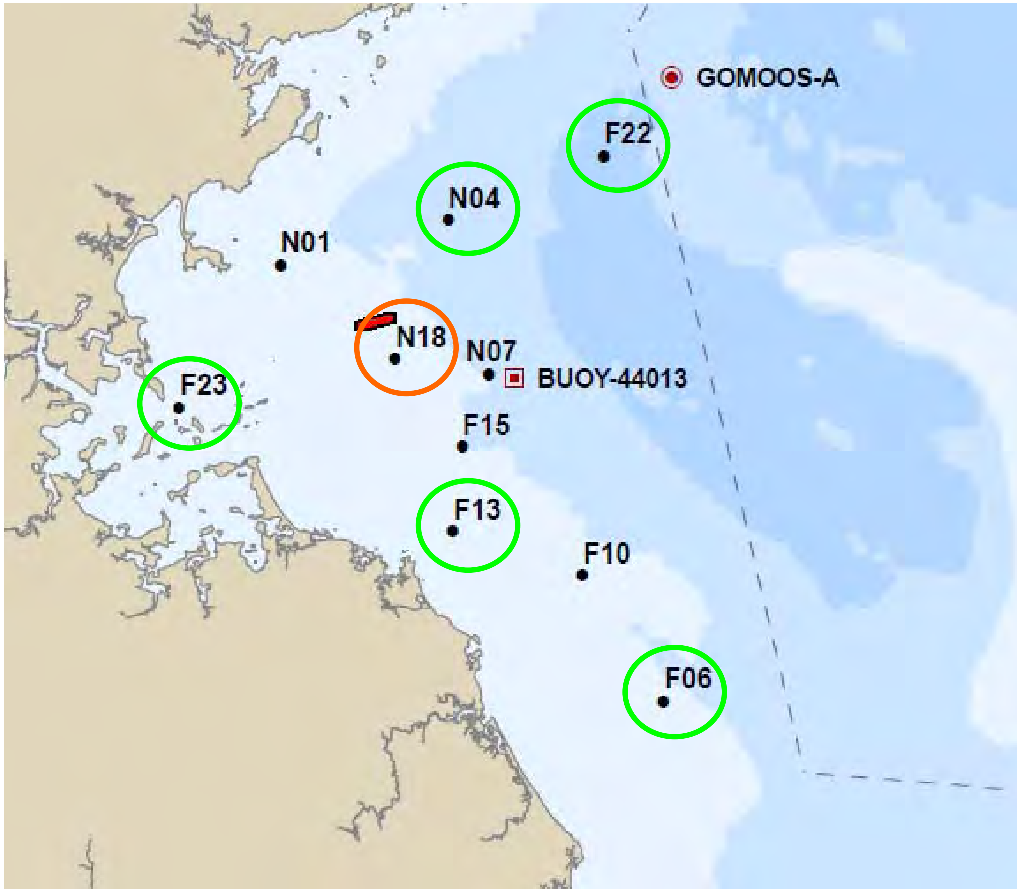
**POC – Baseline vs. 2001-2008**




All groups trending in the same direction – no significant change for Inner Nearfield compared to the three control areas for any season

# Updated BACI by stations (92-08)

- Reran analysis based on proposed AMP revision
- Pre. vs. post station differences were similar to past results
  - Significant changes for NH4 only
    - Increase at N18 all seasons
    - Decrease at F23 all seasons & W/S at F13 & N04
- Impact vs. Control sites
  - Again only significant changes were for NH4
    - Significant NH4 increase at N18 relative to nearly all other stations/season groups
    - Not significant in fall vs. F06, F13, and N04



# Baseline Comparison Summary

- "Typical" trends generally observed in comparison to baseline
- Nutrients
  - Increase in DIN in nearfield - primarily $NH_4$ but also $NO_3$
  - Overall there has been decrease in $NH_4$, $NO_3$, $SiO_4$, and $PO_4$ in Boston Harbor and adjacent coastal waters and a slight increase in $NO_3$ offshore
- Chlorophyll
  - Trends in Nearfield compared to baseline
    - Higher in winter/spring with March/April (*Phaeocystis*)
    - Summer levels comparable
    - Overall, fall levels have decreased compared to baseline
  - Spring *Phaeocystis* blooms continue to be annual, regional events (2000-2008)
    - Have changed April biomass levels in N. Boundary, Offshore and nearfield areas
- Dissolved Oxygen
  - 2008 levels comparable to baseline in the nearfield and Stellwagen Basin
  - No change in DO (interannual variability driven by regional processes)

# Conclusions

- Changes in the nutrient regimes following diversion are unambiguous.
  - Ammonium has dramatically decreased in Boston Harbor (80%) and nearby coastal waters while increasing to a lesser degree in the nearfield - consistent with predictions.
  - The signature levels of $NH_4$ in the plume are generally confined to an area within 10-20 km of the outfall.
- In Boston Harbor, there have been concurrent, significant decreases in other nutrients, chlorophyll, and POC.
- In the nearfield, there have been concurrent changes in chlorophyll, POC, and phytoplankton, but….
  - BACI analysis found that the only significant change between impact and control stations was for $NH_4$ concentrations
  - The analyses did not find statistically significant changes in chlorophyll
  - Primarily because the changes have been regional in nature – occurring throughout Massachusetts Bay and further offshore in the western Gulf of Maine

# Acknowledgements

**The data presented are the result of the efforts from many HOM6 team members including:**

- **Battelle Field and Logistics Operations Group**
- **Battelle, subcontractor, and MWRA labs**
- **Matt Fitzpatrick for helping with data analysis & graphics**
- **MWRA Database folks – especially Wendy and Jianjun for pulling the data together for us –Thanks!**


# C. Primary productivity

Primary Productivity in Massachusetts Bay, 2008

Candace Oviatt, University of Rhode Island

Since 2003 relatively low primary productivity has been measured compared to earlier monitoring years and 2008 was consistent with this pattern (**slide 2**). The pattern of lower productivity in recent years was not apparently linked to outfall relocation in fall 2000 as the two years prior and since the move had high and not significantly different levels of potential primary production at all three stations. Since 2003, there has been a trend of reduced productivity at the Harbor station, likely associated with reduced nutrients since outfall relocation. This year unlike most previous years, the Harbor station was not the station with the highest values and had values slightly lower than the nearfield stations. Annual potential value for the Harbor station was 207 g C $m^{-2}$ $y^{-1}$ and for the two nearfield stations the values were 271 and 219 g C $m^{-2}$ $y^{-1}$ for N04 and N18, respectively (**slide 3**).

The seasonal patterns indicated a diminished winter spring bloom at all stations and a dominance of summer and fall blooms in 2008 (**slide 3**). The spring blooms at all stations remained at less than about 0.6 g C $m^{-2}$ $d^{-1}$. The peak values for the year were about 1.7 g C $m^{-2}$ $d^{-1}$ at the Harbor station during summer, 1.8 g C $m^{-2}$ $d^{-1}$ at N04 during fall and 1.6 g C $m^{-2}$ $d^{-1}$ during summer at N18. At the Harbor station, areal rates were low except for the August measurement and generally beneath the baseline mean and twice beneath the baseline range (**slide 4**). At the nearfield station N04, generally low rates occurred prior to the fall bloom which dominated the yearly production rates with rates equal to the baseline average in October and exceeding the baseline range in November (**slide 5**). The natural logarithm of the areal production at N04 diminishes the apparent height of this fall bloom compared to the baseline mean (**slide 6**). By contrast, the nearfield station N18 had low rates throughout the year except for the August measurement which was close to the baseline mean (**slide 7**). The pattern of alternating fall/summer blooms at the nearfield stations suggests events which reduce the stratification at one nearfield station but not the other station.

Early in the time series spring or fall blooms dominated the annual patterns of productivity. Since 2003 this dominance has decreased. The spring bloom at the nearfield stations in 2008 was the lowest of all years except 1998 and about a factor of three lower than spring blooms during low bloom years since 2003 (**slide 8**). The fall bloom intensity at the nearfield stations was similar to other low bloom years since 2003 (**slide 9**).

While the outfall relocation has reduced the nutrient load to the Harbor station, the trend of reduced productivity at this station and the nearfield stations suggests nutrient loadings from the outfall prior/post relocation are not the only factor.

At the Harbor station average areal production post outfall relocation remained low through the warm months compared to pre outfall location whereas the values during colder months remain low and overlapping pre/post outfall relocation (**slide 10**). The error bars on the means are standard errors. Chlorophyll specific production at the Harbor station in 2008 was at the lower edge of the baseline range throughout the year (**slide 11**). Chlorophyll specific production at the nearfield stations followed a similar pattern suggesting generally low nutrient conditions throughout the area (**slides 12** and **13**). Spring areal production at both the Harbor station and the nearfield stations was lower in the post outfall location compared to the pre outfall location period (**slide 14**). The bars on the means indicate standard errors. This pattern of lower areal productivity post outfall also occurred during the summer and fall at all stations (**slides 15** and **16**). The lower low values at the Harbor station compared to the nearfield are consistent with reduced nutrient loading at this station post outfall relocation. The lower values in all seasons at the nearfield do not appear to be related to outfall relocation. Thus, annual productivities at the Harbor and nearfield stations were similar and lower than the period prior to outfall relocation (**slide 17**).

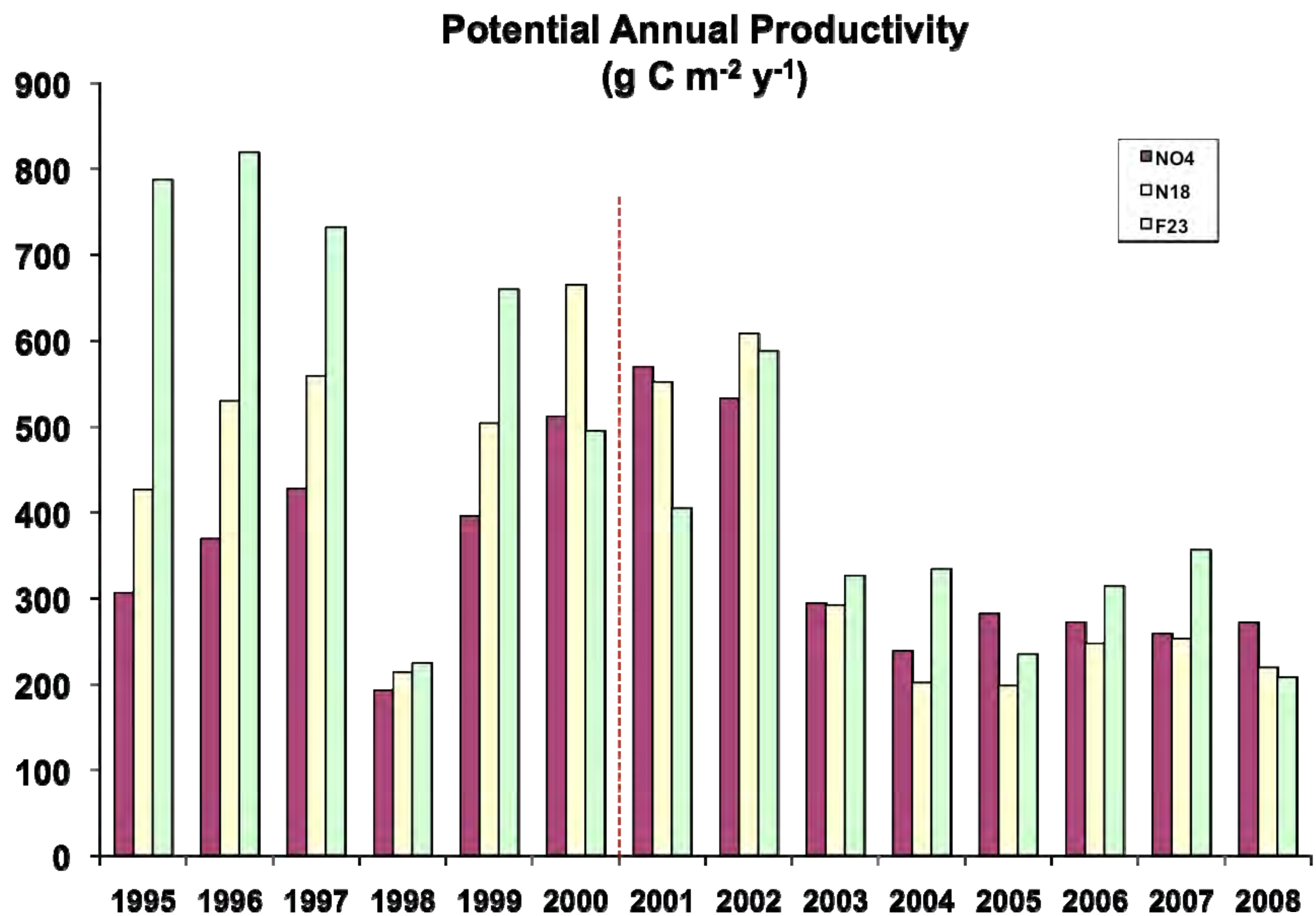
By all measures, the lower productivities since 2003 were consistent and striking. A factor contributing to lower areal productivity since 2003 and including 2008 appears to be reduced wind intensity (**slide 18**). At all three stations primary production was positively correlated with average summer wind speed and with average summer wind gusts with $r^2$ values of 0.5 or greater. The wind data were from the NOAA buoy station 44013 in Massachusetts Bay. Over an average summer wind range of about 4.0 to 4.5 m $s^{-1}$ annual production values increase from 200 to 500 g C $m^{-2}$ $y^{-1}$ at nearfield stations and to higher values at the Harbor station (**slide 18**). Over an average summer wind gust range of 4.5 to 5.5 m $s^{-1}$ a similar increase in production occurred (**slide 18**). The inverse was also true and consistent with the recent trend of reduced wind (**slide 19**). Thus, low winds were correlated with low productivity. A time series of average summer wind speed and summer wind gusts indicated that 2008 had one of the lowest values of the years since the time series began in 1994. The only two years with lower values were 1998 and 2003 (**slide 19**). The mean summer wind speed and the summer average wind gusts were lower in the period 2003 to 2008 compared to the period 1995 to 2002 (**slide 20**). The bars on the means indicate standard deviations. Since 2003 wind intensity has been lower than in prior years and this pattern was correlated with the low primary production occurring at all stations since 2003 (**slide 2**).

In summary since outfall relocation the Harbor station has shown a dramatic decrease in productivity consistent with reduced sewage effluent nutrient loading to this station (**slide 2**). By contrast, the nearfield area of the new sewage outfall in Massachusetts Bay showed no increase or decrease in primary productivity associated with outfall relocation. Years prior to and after relocation had similar productivities. A decrease in productivity in 1998 and since 2003 at the nearfield stations and to some extent the Harbor station can be correlated with climate related reduced wind intensities during these years. The enhanced stratification due to lighter winds has prevented the mixing of sub surface nutrients to fuel primary production during summer at particularly, the nearfield stations.

# Primary Productivity 2008

Candace Oviatt
Aimee Keller
Matt Schult

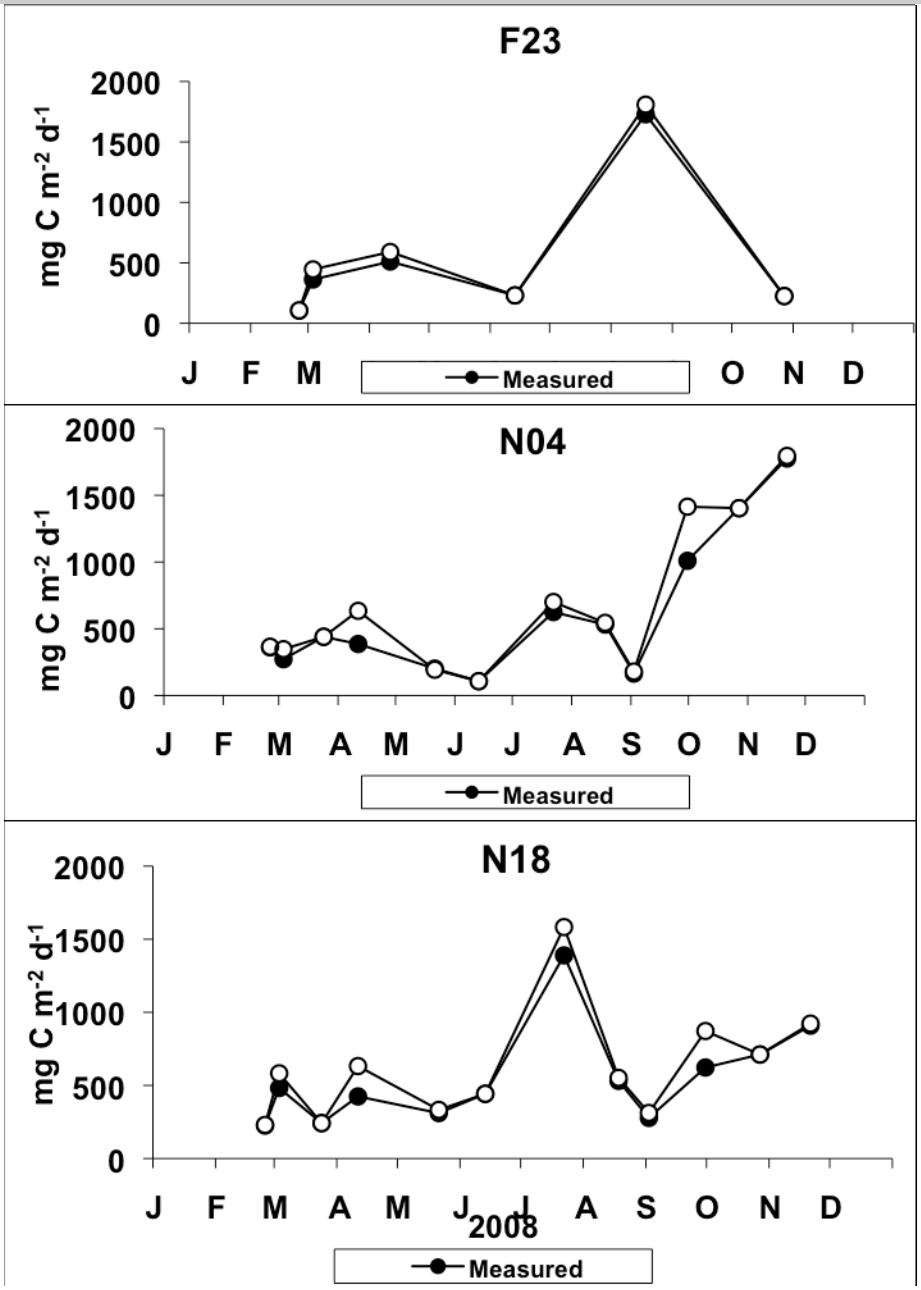
May 2009

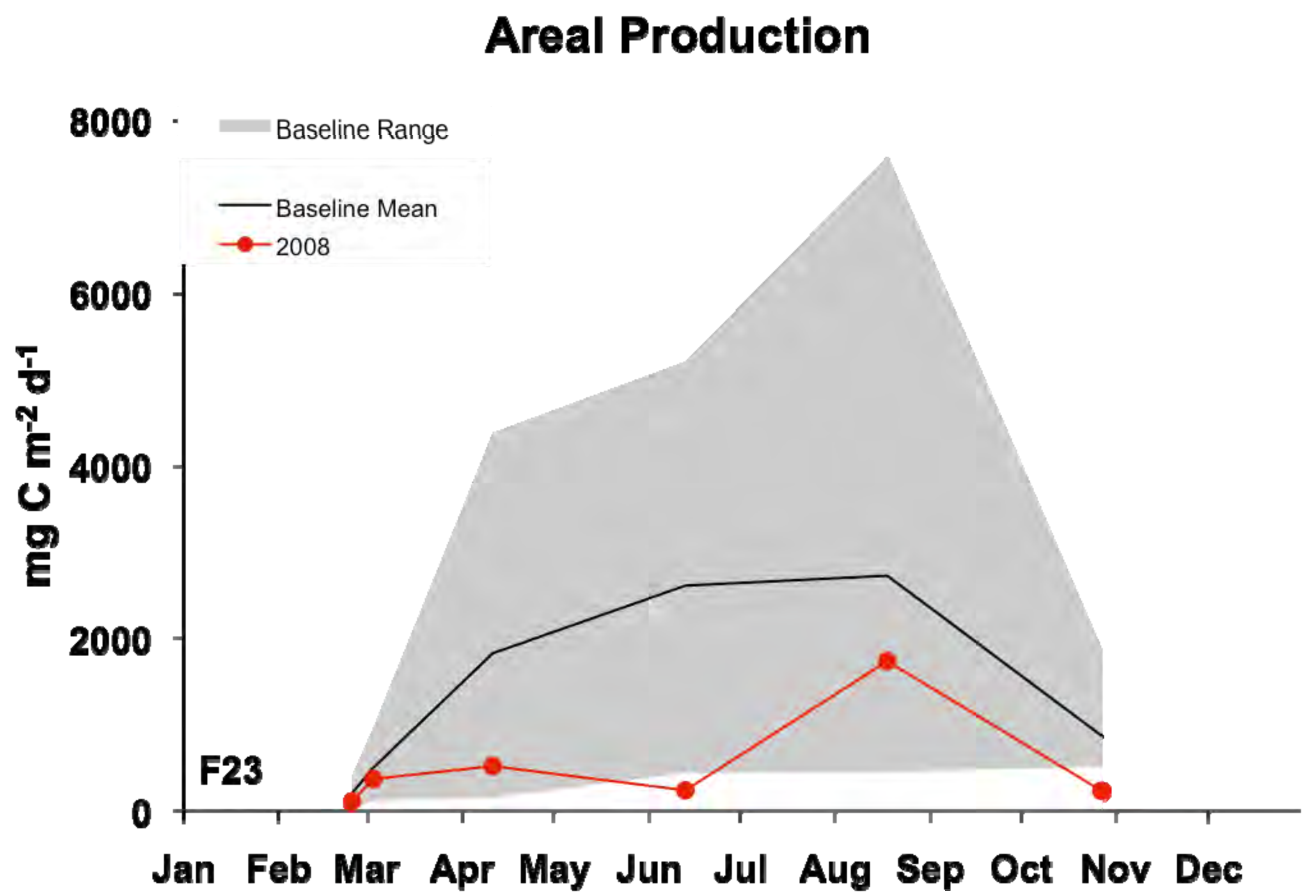


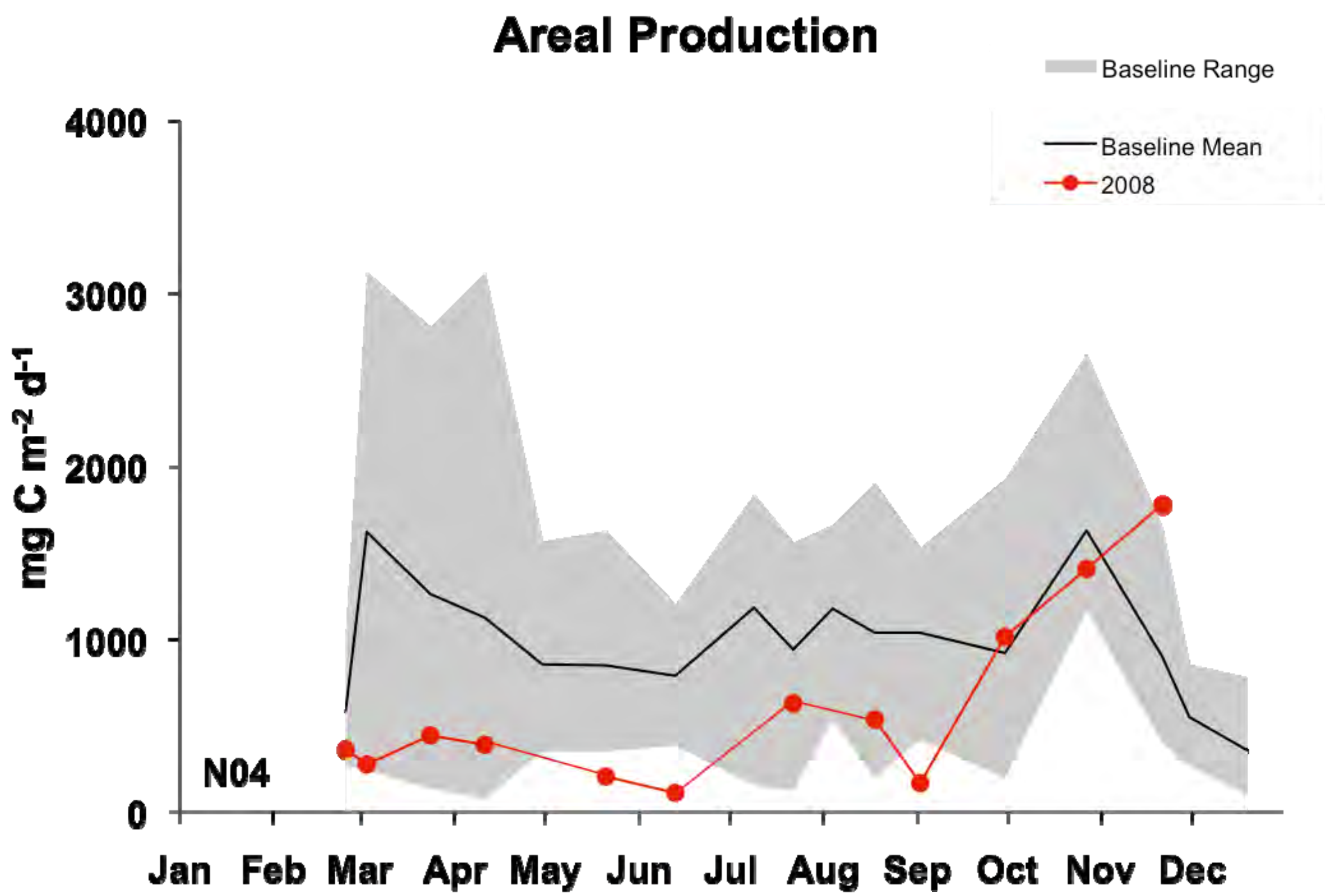
Potential Annual Productivity
(g C m-2 y-1)
NO4
N18
F23
900
800
700
600
500
400
300
200
100
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008

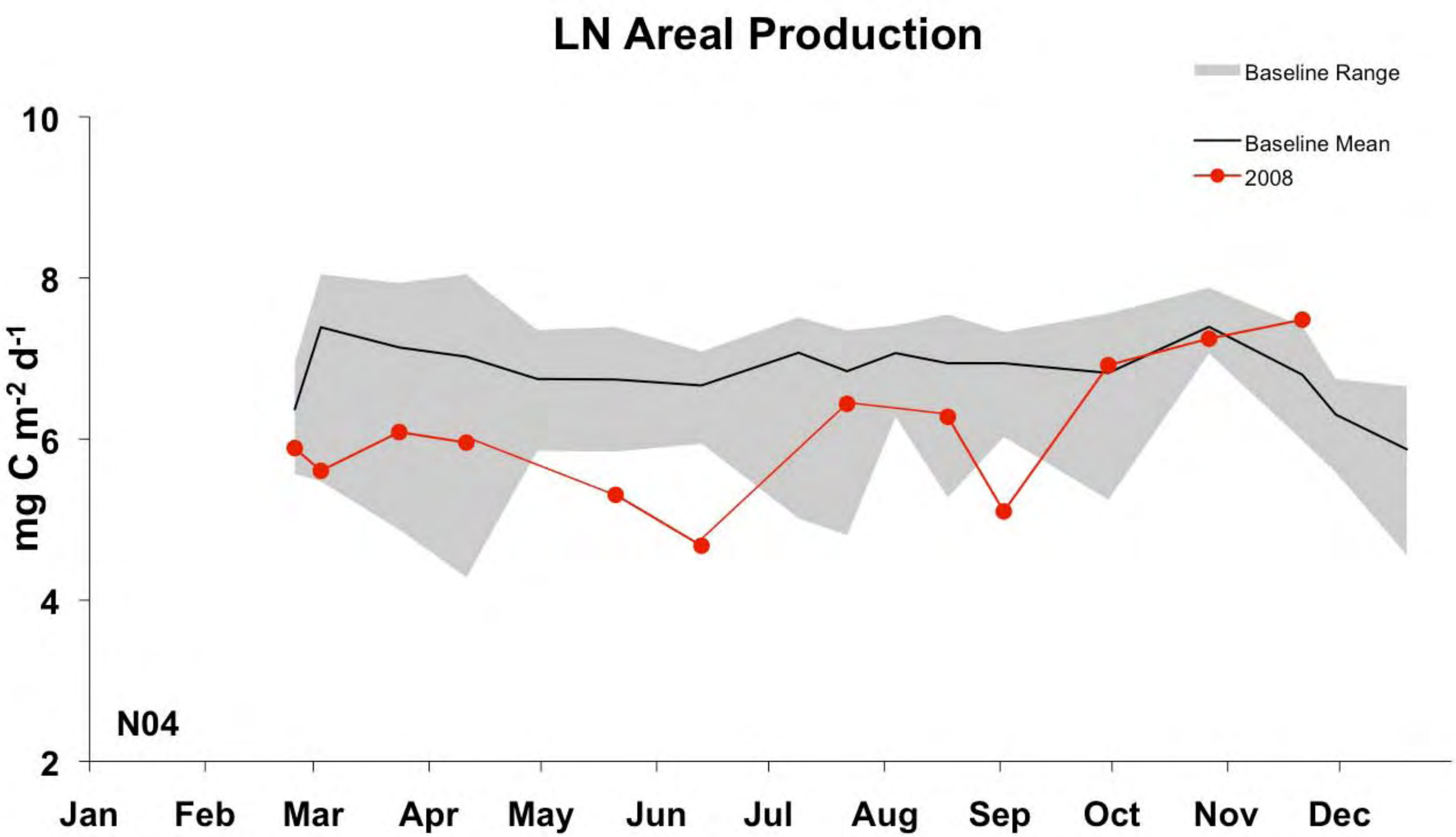
| year | N04 | N16-18 | F23 |
|---|---|---|---|
| 2008 | 271 | 219 | 207 |

gC m$^{-2}$y$^{-1}$

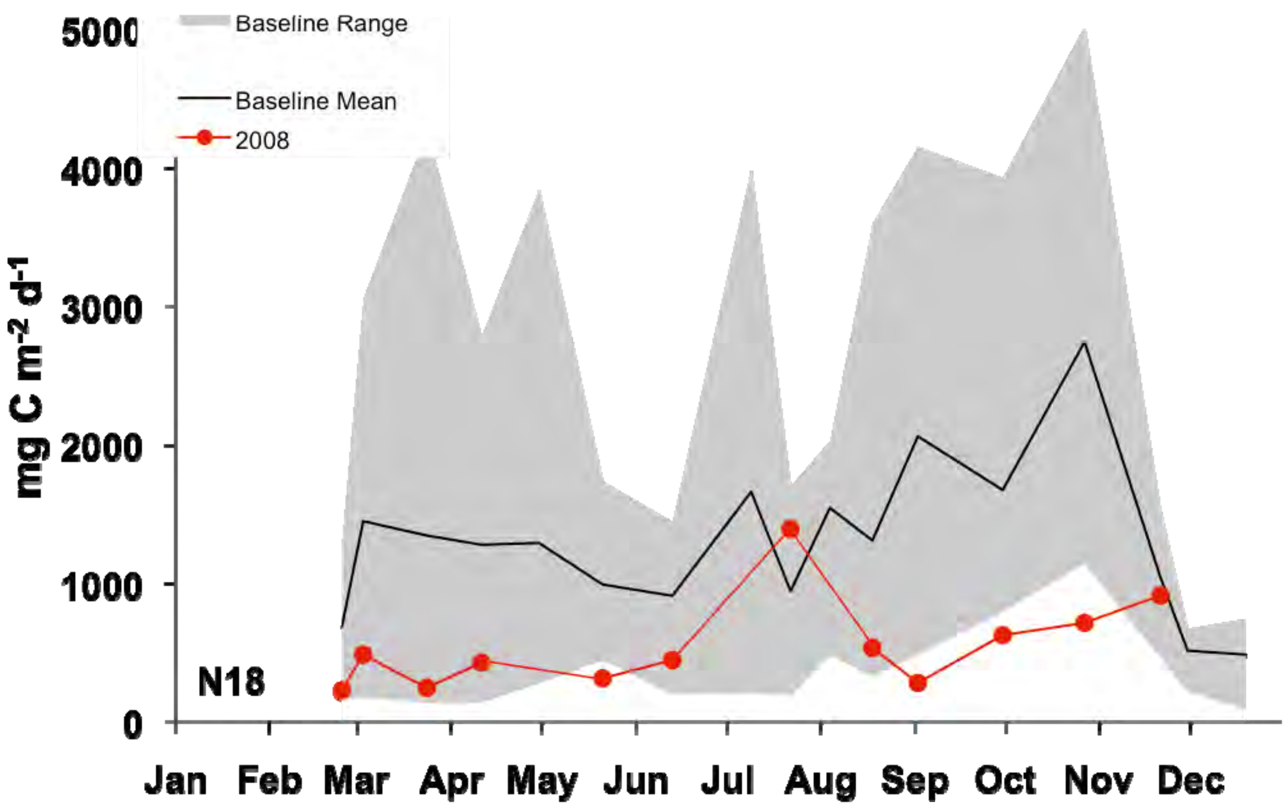


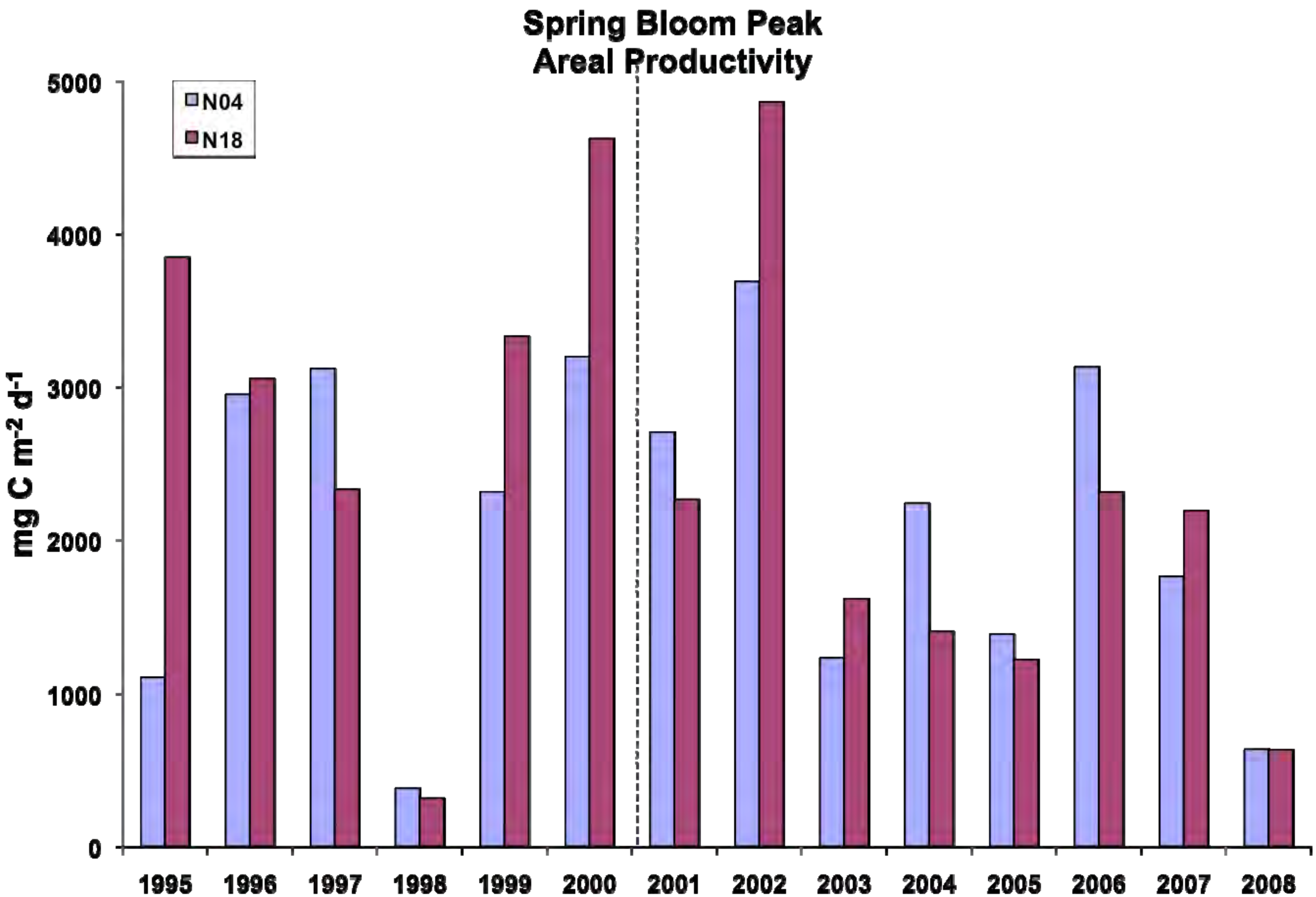

Areal Production
Baseline Range
Baseline Mean
2008
mg C m-2 d-1
8000
6000
4000
2000
0
F23
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

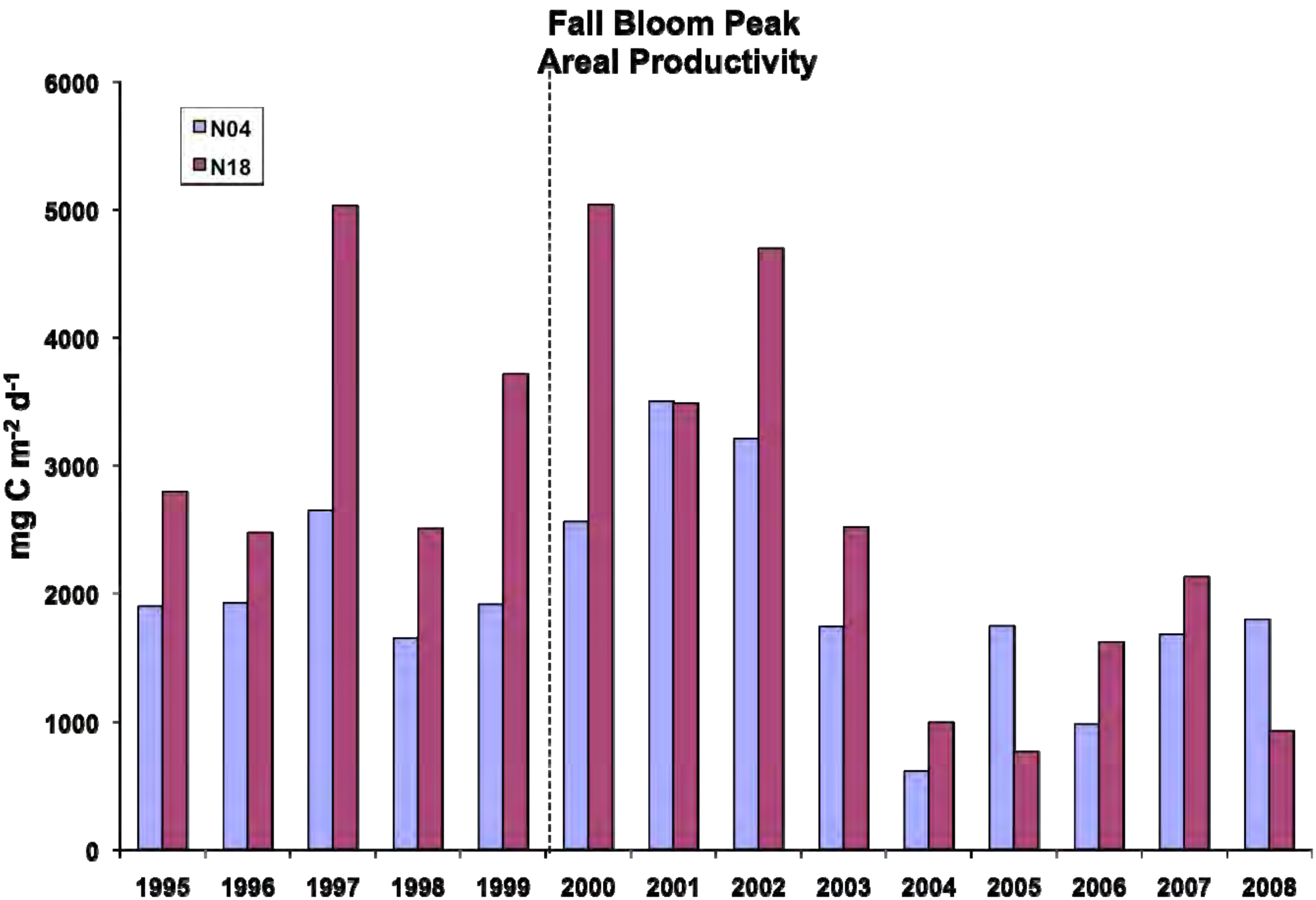

Areal Production
Baseline Range
Baseline Mean
2008
4000
3000
2000
1000
0
mg C m-2 d-1
N04
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

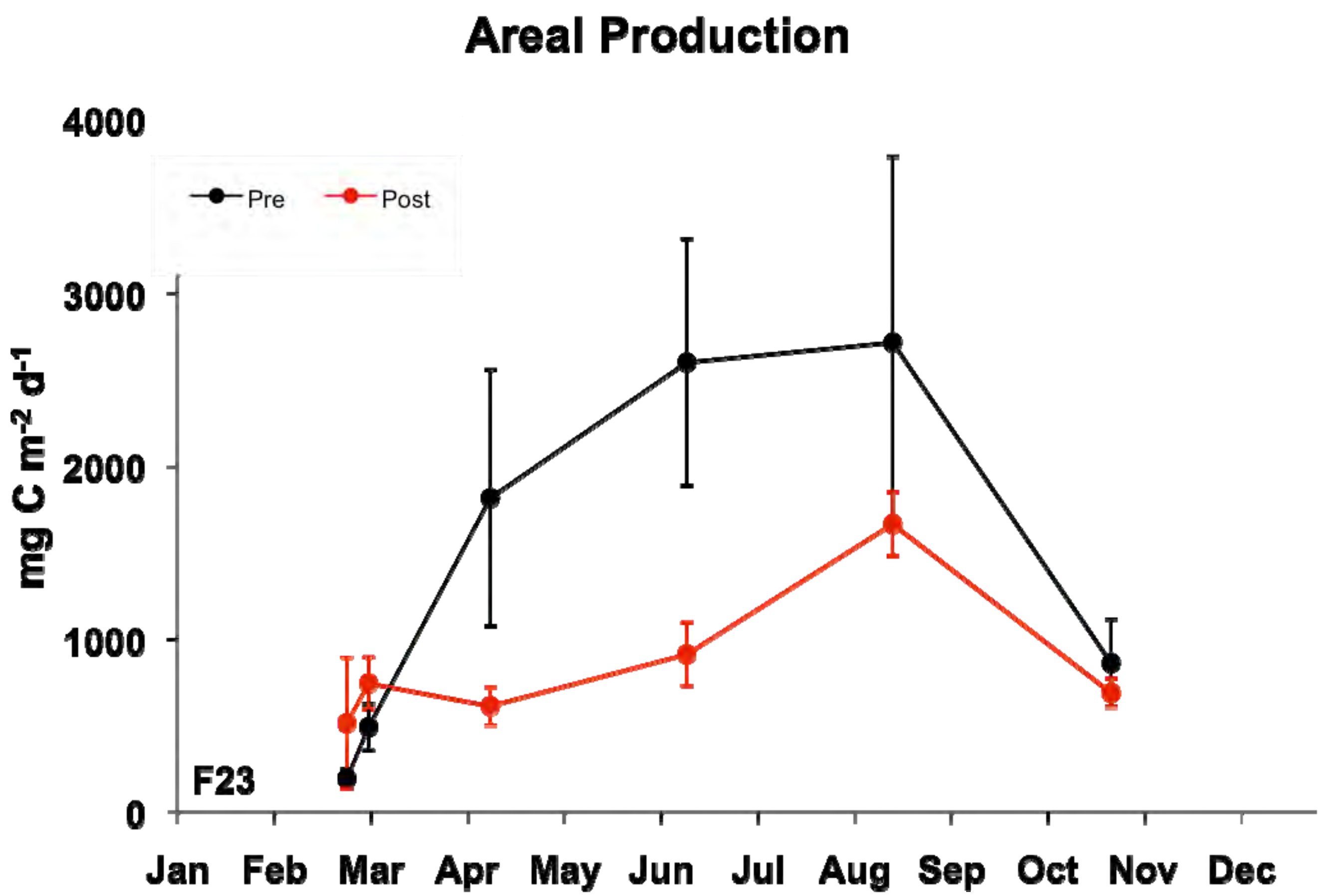

LN Areal Production
Baseline Range
Baseline Mean
2008
10
8
6
4
2
mg C m-2 d-1
N04
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

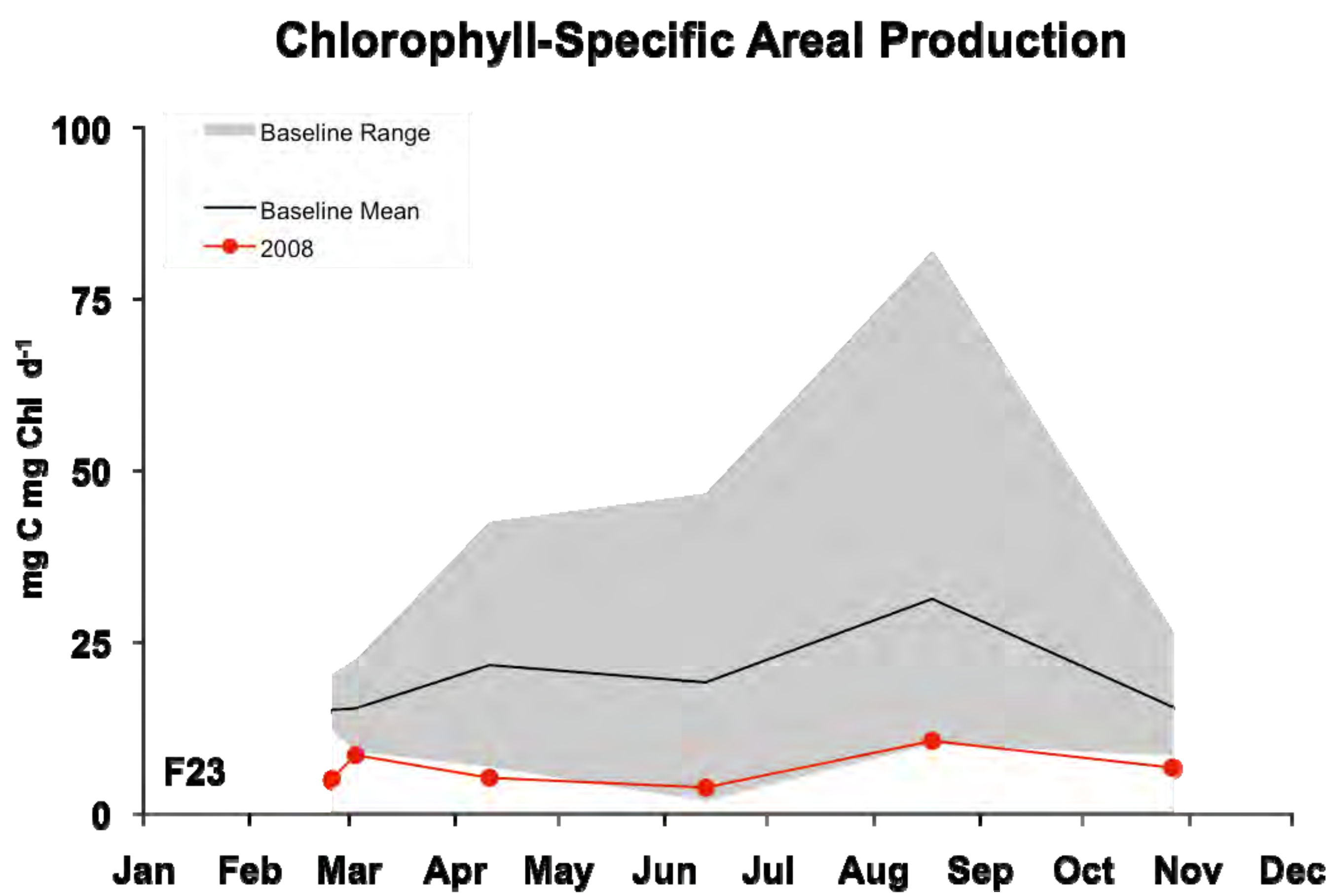
## Areal Production




Spring Bloom Peak
Areal Productivity
N04
N18
mg C m-2 d-1
5000
4000
3000
2000
1000
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008

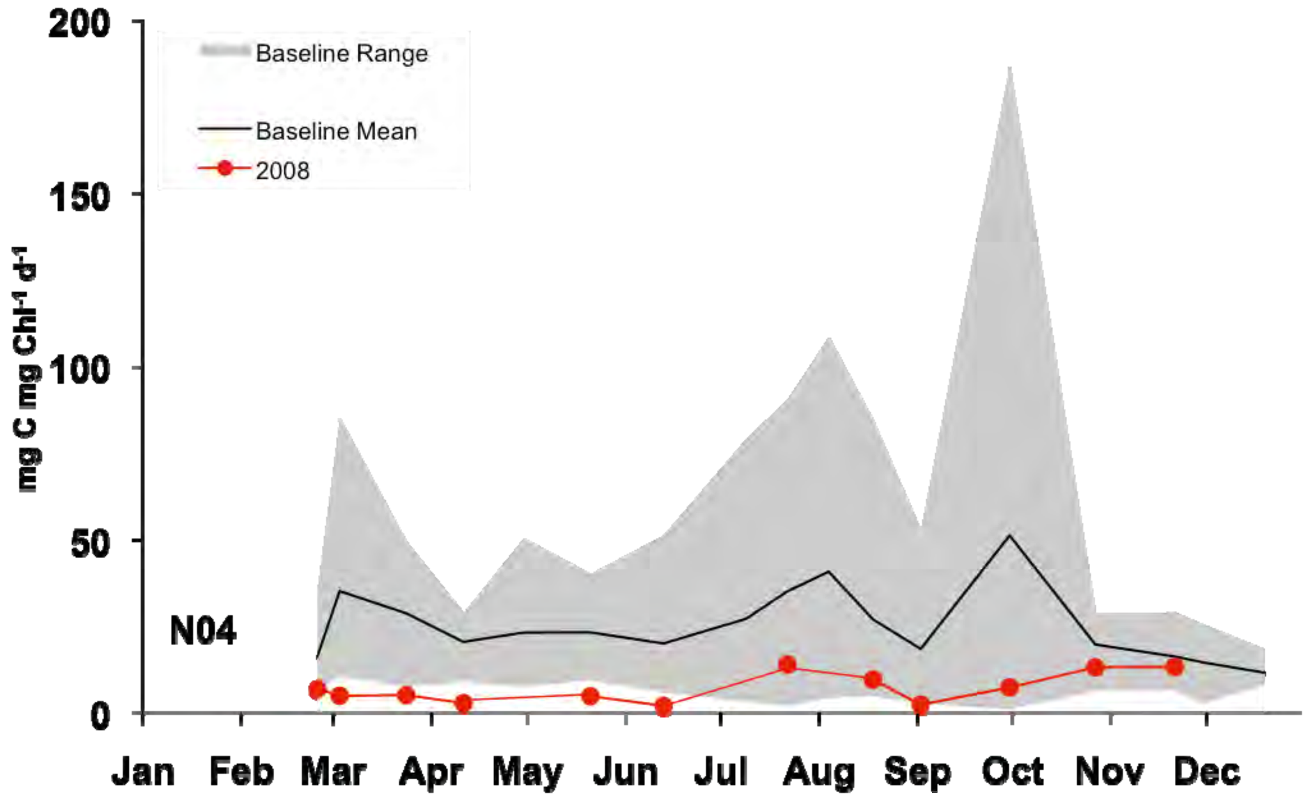

Fall Bloom Peak
Areal Productivity
N04
N18
mg C m-2 d-1
6000
5000
4000
3000
2000
1000
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008


Areal Production
4000
3000
2000
1000
0
mg C m-2 d-1
Pre
Post
F23
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

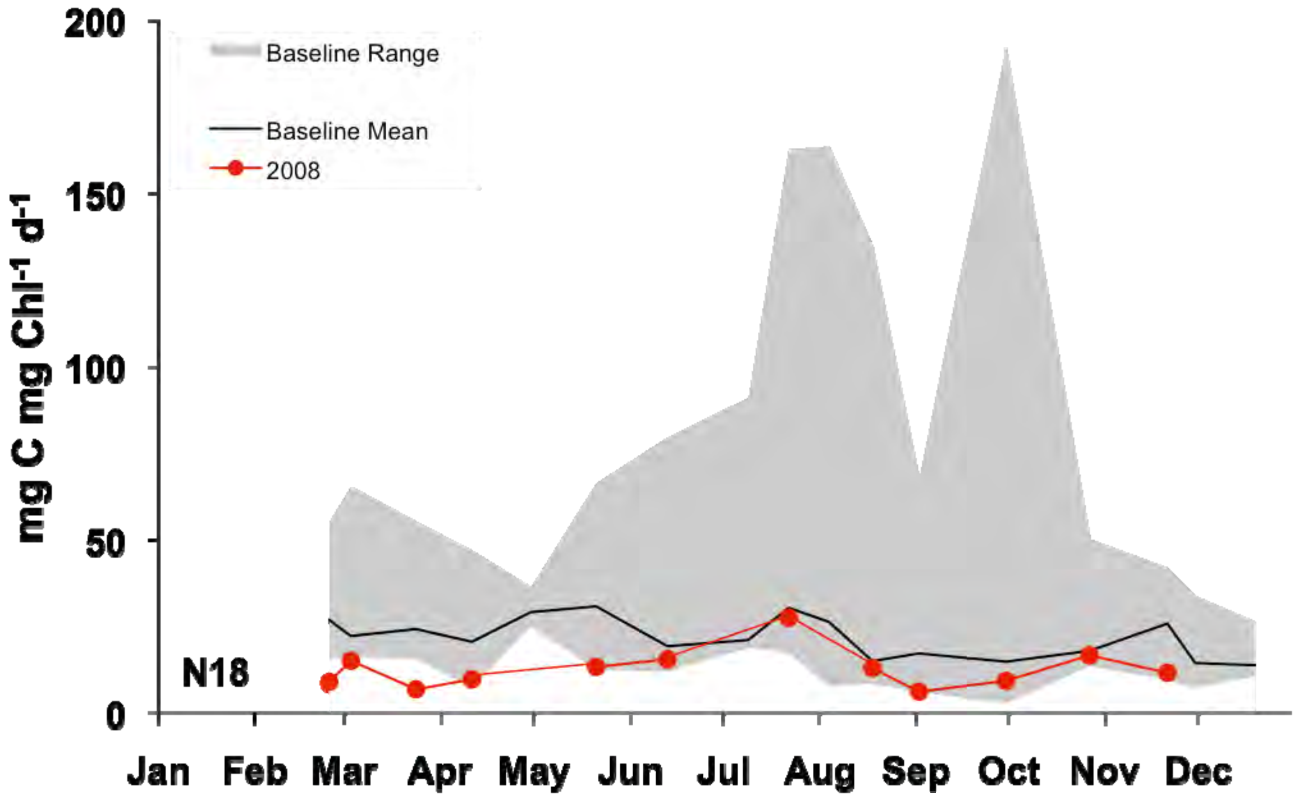


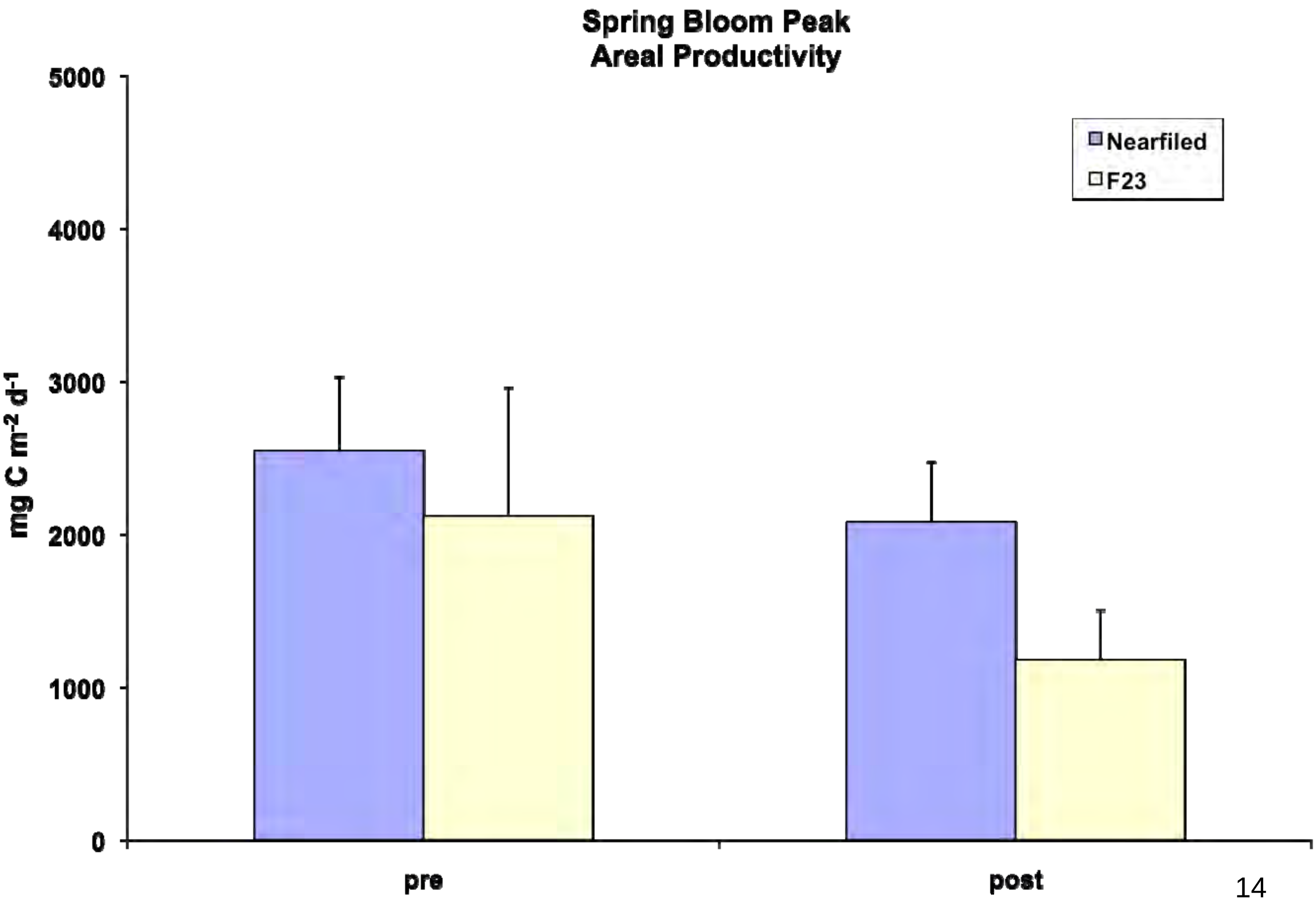
Chlorophyll-Specific Areal Production
Baseline Range
Baseline Mean
2008
100
75
50
25
0
mg C mg Chl d-1
F23
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

# Chlorophyll-Specific Areal Production

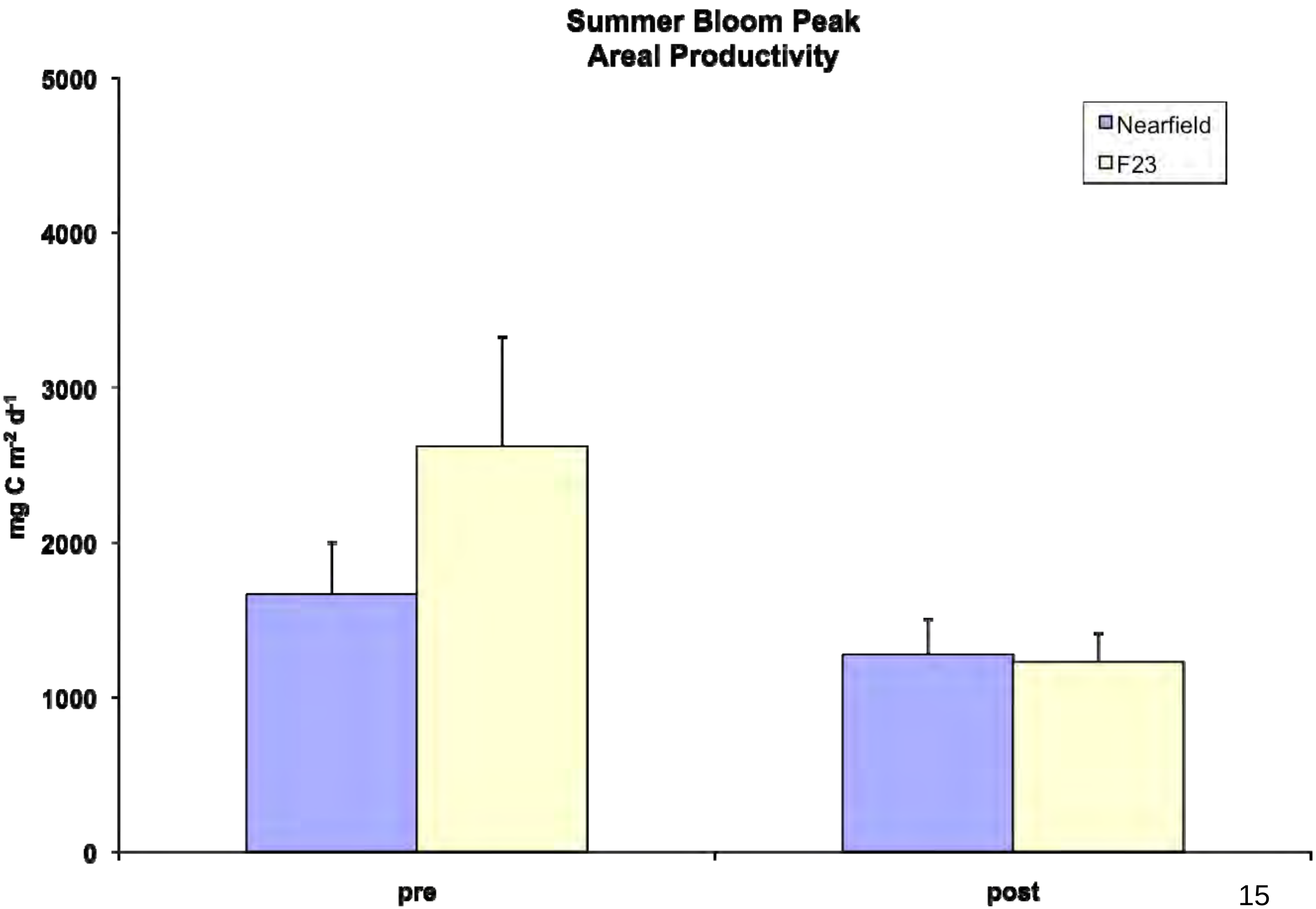


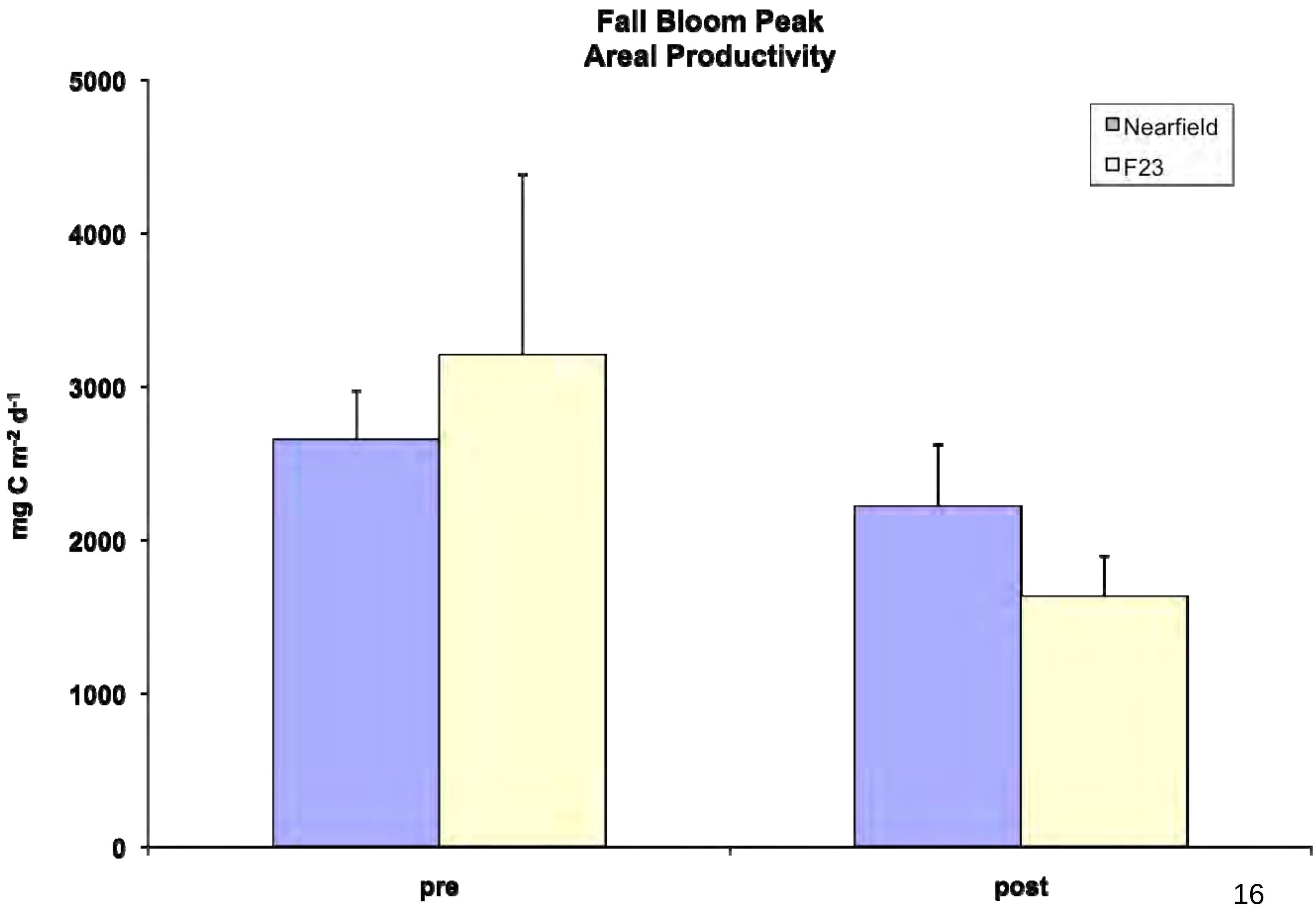
## Chlorophyll-Specific Areal Production

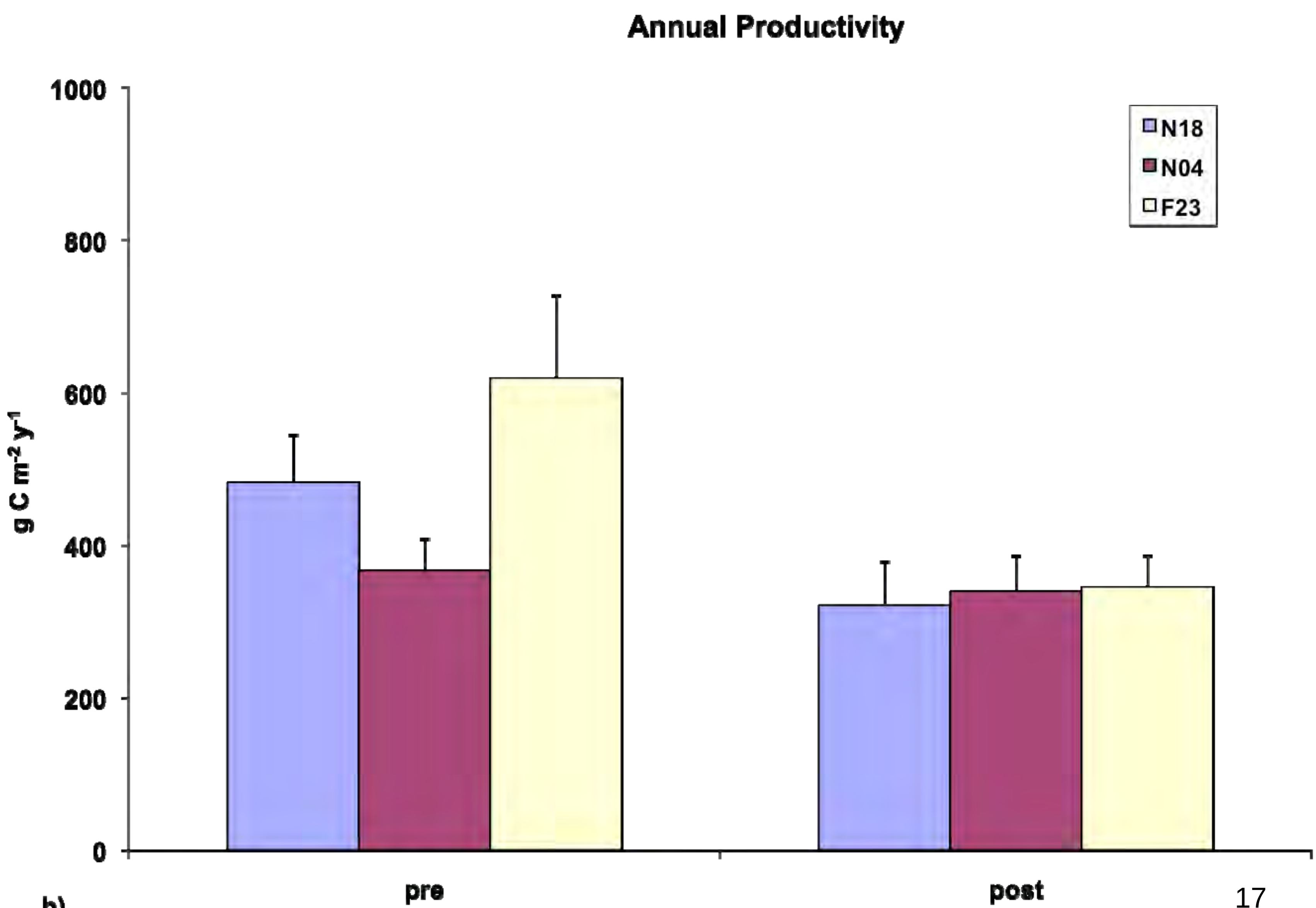




Spring Bloom Peak
Areal Productivity
5000
4000
3000
2000
1000
0
mg C $m^{-2}$ $d^{-1}$
Nearfiled
F23
pre
post

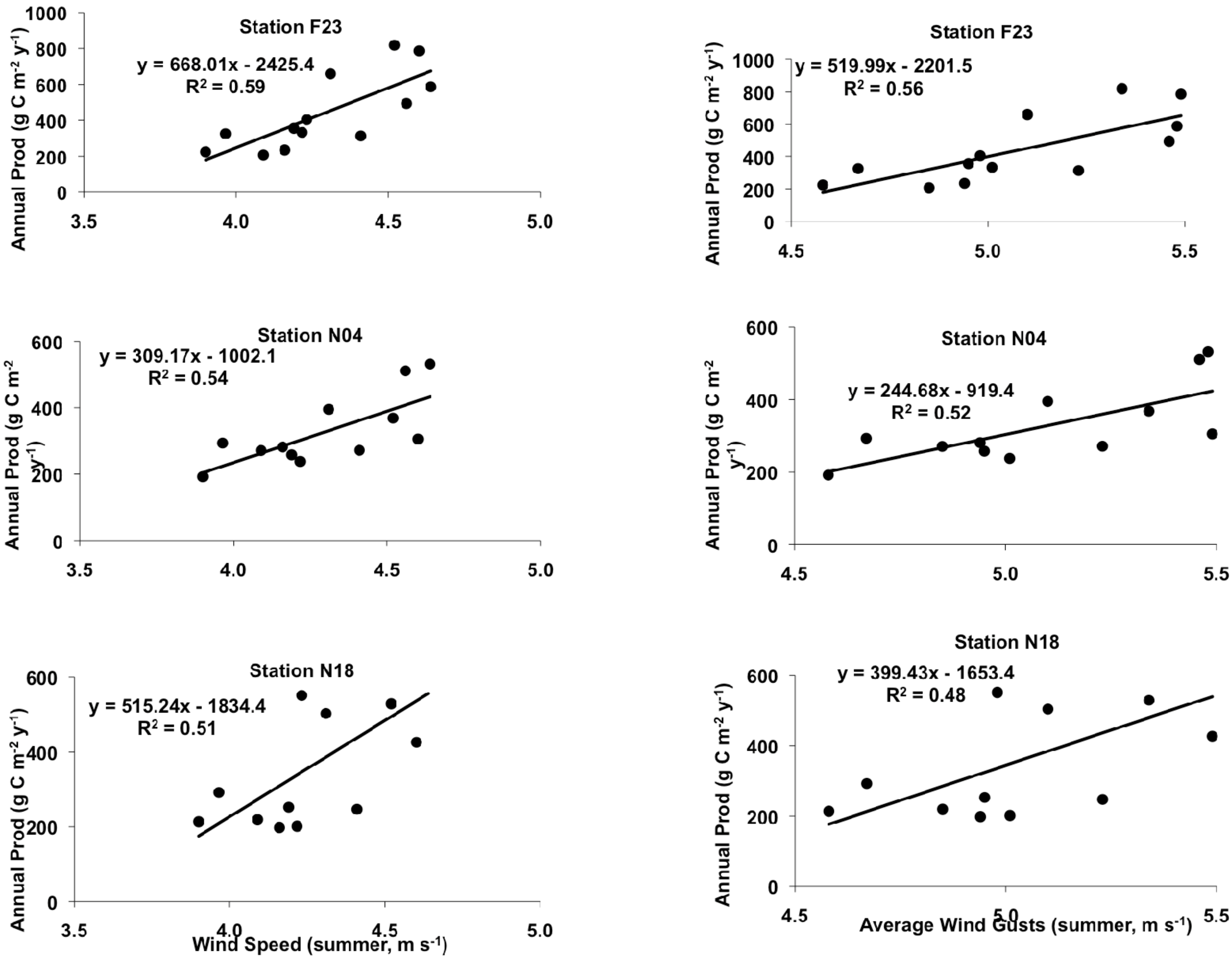

Summer Bloom Peak
Areal Productivity
5000
4000
3000
2000
1000
0
mg C m-2 d-1
Nearfield
F23
pre
post

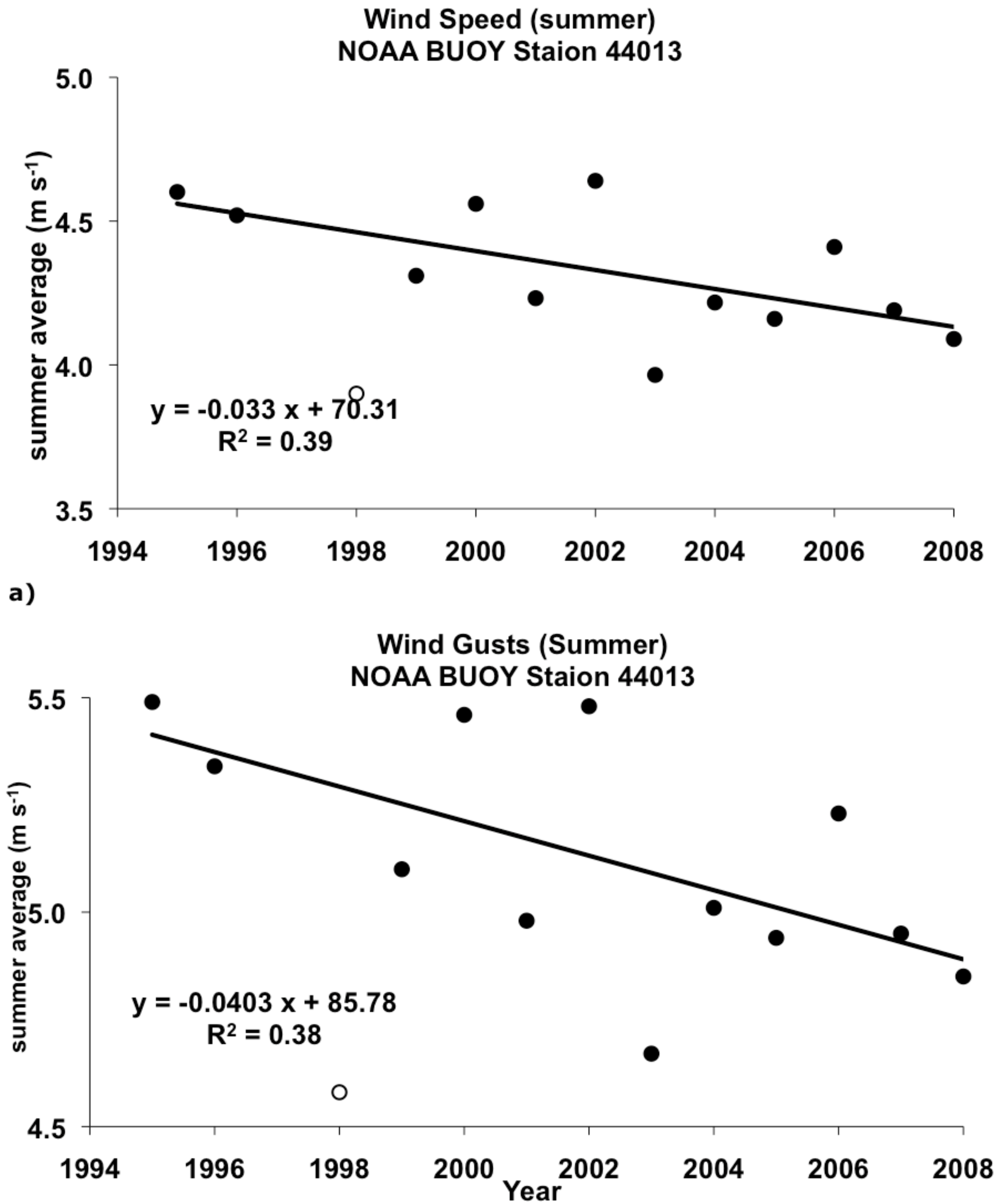

Fall Bloom Peak
Areal Productivity
5000
4000
3000
2000
1000
0
mg C m-2 d-1
Nearfield
F23
pre
post

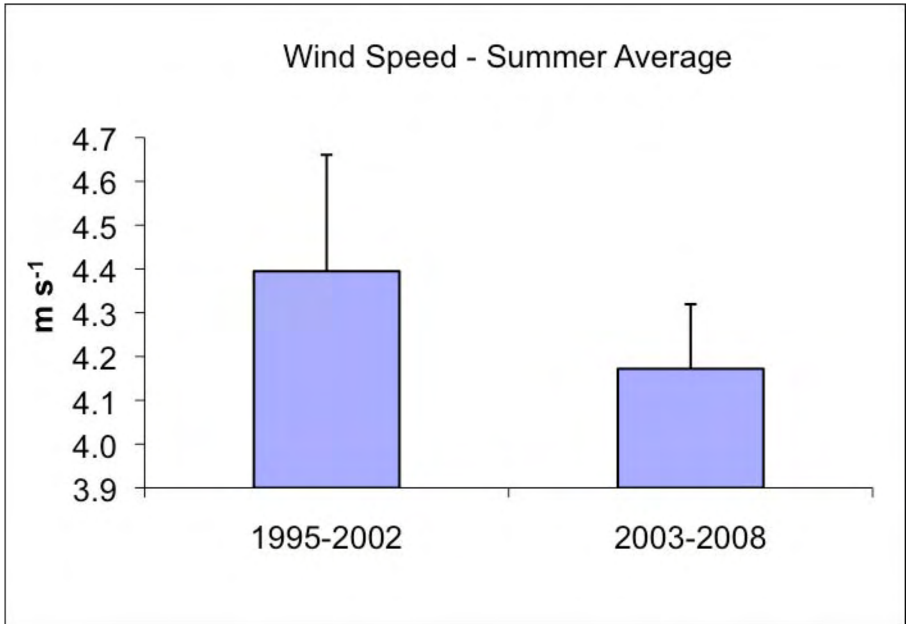


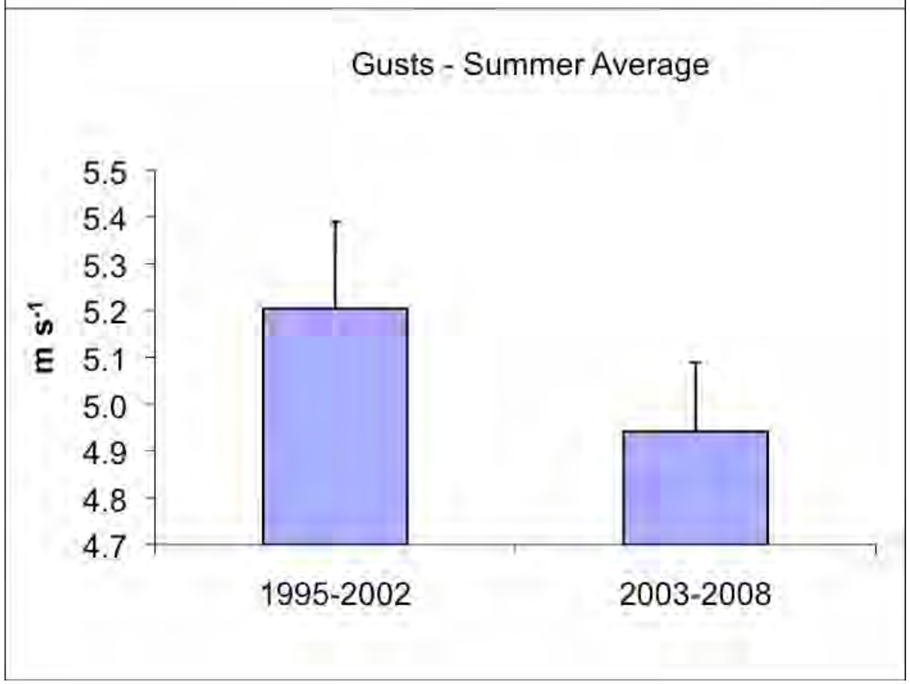
Annual Productivity
1000
800
600
400
200
0
g C m-2 y-1
N18
N04
F23
pre
post

b)


Station F23
y = 668.01x - 2425.4
R² = 0.59
Annual Prod (g C m⁻² y⁻¹)
1000
800
600
400
200
0
3.5
4.0
4.5
5.0
Station F23
y = 519.99x - 2201.5
R² = 0.56
Annual Prod (g C m⁻² y⁻¹)
1000
800
600
400
200
0
4.5
5.0
5.5
Station N04
y = 309.17x - 1002.1
R² = 0.54
Annual Prod (g C m⁻² y⁻¹)
600
400
200
0
3.5
4.0
4.5
5.0
Station N04
y = 244.68x - 919.4
R² = 0.52
Annual Prod (g C m⁻² y⁻¹)
600
400
200
0
4.5
5.0
5.5
Station N18
y = 515.24x - 1834.4
R² = 0.51
Annual Prod (g C m⁻² y⁻¹)
600
400
200
0
3.5
4.0
4.5
5.0
Wind Speed (summer, m s⁻¹)
Station N18
y = 399.43x - 1653.4
R² = 0.48
Annual Prod (g C m⁻² y⁻¹)
600
400
200
0
4.5
5.0
5.5
Average Wind Gusts (summer, m s⁻¹)


Wind Speed (summer)
NOAA BUOY Staion 44013
summer average (m s-1)
5.0
4.5
4.0
3.5
y = -0.033 x + 70.31
R2 = 0.39
1994
1996
1998
2000
2002
2004
2006
2008
a)
Wind Gusts (Summer)
NOAA BUOY Staion 44013
summer average (m s-1)
5.5
5.0
4.5
y = -0.0403 x + 85.78
R2 = 0.38
1994
1996
1998
2000
2002
2004
2006
2008
Year


Wind Speed - Summer Average
m s-1
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
1995-2002
2003-2008


Gusts - Summer Average
m s-1
5.5
5.4
5.3
5.2
5.1
5.0
4.9
4.8
4.7
1995-2002
2003-2008

# D. Plankton

## D.1. Phytoplankton

Dave Borkman, University of Rhode Island

Phytoplankton abundance and species composition were assessed *via* quantitative phytoplankton counts using phase contrast light microscopy (250X and 500X) of whole-water (Lugol's preserved) and >20 µm size-fractionated (formalin preserved) phytoplankton samples. 204 whole-water and 204 >20 µm screened water phytoplankton samples collected during 12 cruises between February and November 2008 were analyzed as part of the comprehensive MWRA outfall monitoring program. Two nearfield stations (N04 and N18) were sampled 12 times during 2008 and an additional 13 stations in Massachusetts Bay and Cape Cod Bay were sampled 6 times (February, March, April, June, August, and October) during 2008. Near-surface and chlorophyll maximum (or mid-depth) samples were analyzed from each of the phytoplankton stations. 2008 was the 17$^{th}$ consecutive year of monitoring (1992-2008).

The 2008 phytoplankton annual cycle was dominated by a bloom (peaking at ca. 14 x $10^6$ cells $L^{-1}$ in the nearfield) of the colonial prymnesiophyte *Phaeocystis pouchetii* during April 2008 (**slides 4-6**). The 2008 *Phaeocystis* bloom marked the ninth consecutive year (every year since 2000) that winter-spring *Phaeocystis* blooms of >$10^6$ cells $L^{-1}$ were detected (**slide 12**). The 2008 *Phaeocystis* bloom was detected in all regions (Boundary, Cape Cod Bay, Coastal, Harbor, Nearfield, and Offshore). Phytoplankton species composition patterns during 2008 were generally regionally coherent, with some noted exceptions (**slides 5-6**). 2008 *Phaeocystis* concentrations appeared to be reduced in the Harbor and Cape Cod Bay relative to the other regions. Other features of the 2008 phytoplankton annual cycle included reduced total phytoplankton abundance relative to baseline means for most of the year (excluding during April) in all regions (**slide 8** – nearfield). Diatom abundance was below baseline levels during 2008 in all regions. For example, median diatom abundance in the nearfield during 2008 of 52,160 cells $L^{-1}$ was significantly different from the baseline median diatom abundance of 175,000 cells $L^{-1}$ (Mann-Whitney test, p= 0.0408; **slide 9**). The 2008 diatom annual cycle also appeared to have regionally variable bloom timing, with a winter-spring (April) diatom peak occurring in the Boundary region; summer diatom peaks observed in Cape Cod Bay (June) and the Coastal (August) and Harbor (August) regions; and an autumn diatom annual peak observed in the Nearfield (November) and Offshore (October) regions.

In contrast to diatoms, the 2008 dinoflagellate annual cycle featured abundance levels that were above the baseline mean levels during May, June and July of 2008 (**slide 10**). Median dinoflagellate abundance (6,256 cells $L^{-1}$) in the nearfield during May-July 2008 was ca. 3-fold the baseline median May-July dinoflagellate abundance of 2,324 cells $L^{-1}$ (Mann-Whitney test, p = 0.0386). A large portion of this late-spring to early summer dinoflagellate increase was due to the 2008 bloom of *Alexandrium fundyense* which reached a peak of ca. 4,000 cells $L^{-1}$ (screened water count) at station N18 during June 2008. Note that in addition to the >20um screened samples discussed here, *Alexandrium* abundance levels of >$10^4$ cells $L^{-1}$ were detected during June 2008 utilizing *Alexandrium*-specific probes (**slide 13**).

Building on previous years' observations, several previously-noted long-term patterns in phytoplankton abundance continued during 2008 (**slide 16**). Comparison to baseline (1992-2000) levels showed that 2001-2008 levels of microflagellates increased ca. 40% in all regions (**Table 1**). This is likely related to a methodological underestimation of microflagellates during 1992-1995. A regionally variable post-2000 increase of two- to four-fold in *Phaeocystis* abundance was detected in the Boundary, Coastal, Nearfield and Offshore regions. Post-2000 diatom abundance was significantly reduced to levels of ca. 30% to 60% of pre-2000 levels in all regions except the Boundary region (**Table 1**). Changes in post-2000 total phytoplankton were only detected in two regions (Boundary and Nearfield), perhaps partially due to the increasing microflagellate abundance pattern being compensated for by the declining diatom pattern in most regions.

A comparison of slopes technique was applied to regionally averaged mean annual abundance levels of various phytoplankton groups for the detection of long-term linear trends in abundance. Annual abundance levels were chosen for this linear model fitting as the annually aggregated data were normally distributed (raw data deviated significantly from a normal distribution) and annual averaged data did not have the temporal (seasonal) autocorrelation present in the raw observations. A significant linear increase of *ca*. 100,000 cells $L^{-1}$ $yr^{-1}$ during 1992-2008 was detected in mean annual total phytoplankton in the Boundary region (**Table 2**). Much of this may be explained by the linear increase of 85,000 cells $L^{-1}$ $yr^{-1}$ in mean annual *Phaeocystis* abundance that was detected in the Boundary and Offshore regions. A significant linear decrease in mean annual diatom abundance at a rate of *ca*. -39,000 cells $L^{-1}$ $yr^{-1}$ was detected in all regions except the Boundary region (**Table 2**). The widespread occurrence of the diatom decline suggests a region-wide driver of this phenomenon.

**Table 1**: Summary of Mann-Whitney 2-sample tests comparing regional median levels of phytoplankton groups during 1992-2000 vs. 2001-2008. Values indicate percent change in median value [(2001-2008) / (1992-2000)]; statistically significant ($p < 0.05$) differences in red (increase) or blue (decline).

| | *BNDRY* | *CCBAY* | *CSTL* | *HBR* | *NFLD* | *OFFSHR* |
|---|---|---|---|---|---|---|
| Total PPL | 1.55 | --- | --- | --- | 1.16 | --- |
| UFLAGS | 1.45 | 1.41 | 1.42 | 1.73 | 1.45 | 1.31 |
| Dinoflags | --- | --- | --- | --- | 0.45 | 0.34 |
| Phaeocystis | 4.68 | --- | 2.48 | --- | 1.64 | 2.42 |
| Diatoms | --- | 0.44 | 0.44 | 0.46 | 0.57 | 0.28 |

**Table 2**: Summary of significant linear trends in mean annual abundance of phytoplankton groups. Values represent mean rate of change in units of cells L-1 year-1. Red indicates positive slope (=increase); blue indicates negative slope (= decrease).

| | BNDRY | CCBAY | CSTL | HBR | NFLD | OFFSHR |
|---|---|---|---|---|---|---|
| Total PPL | + 104,000 | --- | --- | --- | --- | --- |
| UFLAGS | --- | --- | --- | --- | + 23,000 | --- |
| Dinoflags | --- | - 300 | --- | --- | --- | --- |
| Phaeocystis | + 85,000 | --- | --- | --- | --- | + 85,000 |
| Diatoms | --- | - 39,400 | - 39,400 | - 39,400 | - 39,400 | - 39,400 |

## D.2. 2008 Zooplankton Summary

Jeff Turner, University of Massachusetts Dartmouth

Zooplankton abundance in 2008 was similar to most previous years. Mean abundances for most regions were < 100,000 animals $m^{-3}$ (**slides 23-26**) and similar to most previous years since the abundance spikes in 1999 and 2000 (**slide 31**). The nearfield mean for total zooplankton was generally similar to the baseline and post-outfall means, and within the baseline range except for being slightly below the baseline range in March and April, and slightly above the baseline range in September (**slide 27**). These departures for total zooplankton abundance were driven by the data for total copepod adults and copepodites, and those data were driven mainly by values for *Oithona similis* (**slides 28-30**) Long-term trend analyses for nearfield abundance of total zooplankton, total copepods (copepodites and adults), copepod nauplii, and *Oithona similis* (copepodites and adults), were all similar in that they fluctuated about the mean, all showing increases since the most-recent low in 2005 (**slides 32-33**). Patterns for copepodites and adults of *Pseudocalanus* spp. and *Calanus finmarchicus* were different (**slide 33**).

Zooplankton community composition was similar to most previous years. Abundance was dominated by copepods (copepodites and adults), most of which were of *Oithona similis*, with secondary contributions by *Pseudocalanus* spp., followed by copepod nauplii, and non-copepods (**slides 24-26**). Barnacle nauplii were somewhat abundant in February and March in most locations. The appendicularian *Oikopleura dioica* was relatively abundant in the nearfield in May, and the marine cladoceran *Evadne nordmani* was relatively abundant in most locations in June-August. Meroplankters such as bivalve and gastropod veligers made minor contributions to abundance in Boston Harbor and Cape Cod Bay in the summer and fall.

Abundance and composition of zooplankton in Boston Harbor was similar to patterns seen in most previous years (**slides 37-39**). Copepods of the genus *Acartia* (*A. hudsonica* and *A. tonsa*) were a noticeable component of the copepod abundance at the three harbor stations (F23 (**slide 40**), F30, F31), whereas they were rarely recorded for other locations outside the harbor. The expansion of *Acartia* abundance from the harbor to the nearfield, possibly due to lowered salinity from the outfall, that was predicted during HOM 2, has not materialized. Also, the relatively large baseline range for total zooplankton abundance in the harbor appears mainly due to abundance spikes of various meroplankters such as barnacle nauplii in winter, and bivalve and gastropod veligers during the warmer months, and polychaete larvae at various times of the year. These spikes are likely driven by temperature or food criteria that prompt reproductive events by the benthic parents of such larvae.

In conclusion, 2008 was a typical year for the zooplankton throughout the MWRA sampling area.

# 2008 Plankton Overview

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*2009 Technical Workshop*
*8 May 2009*

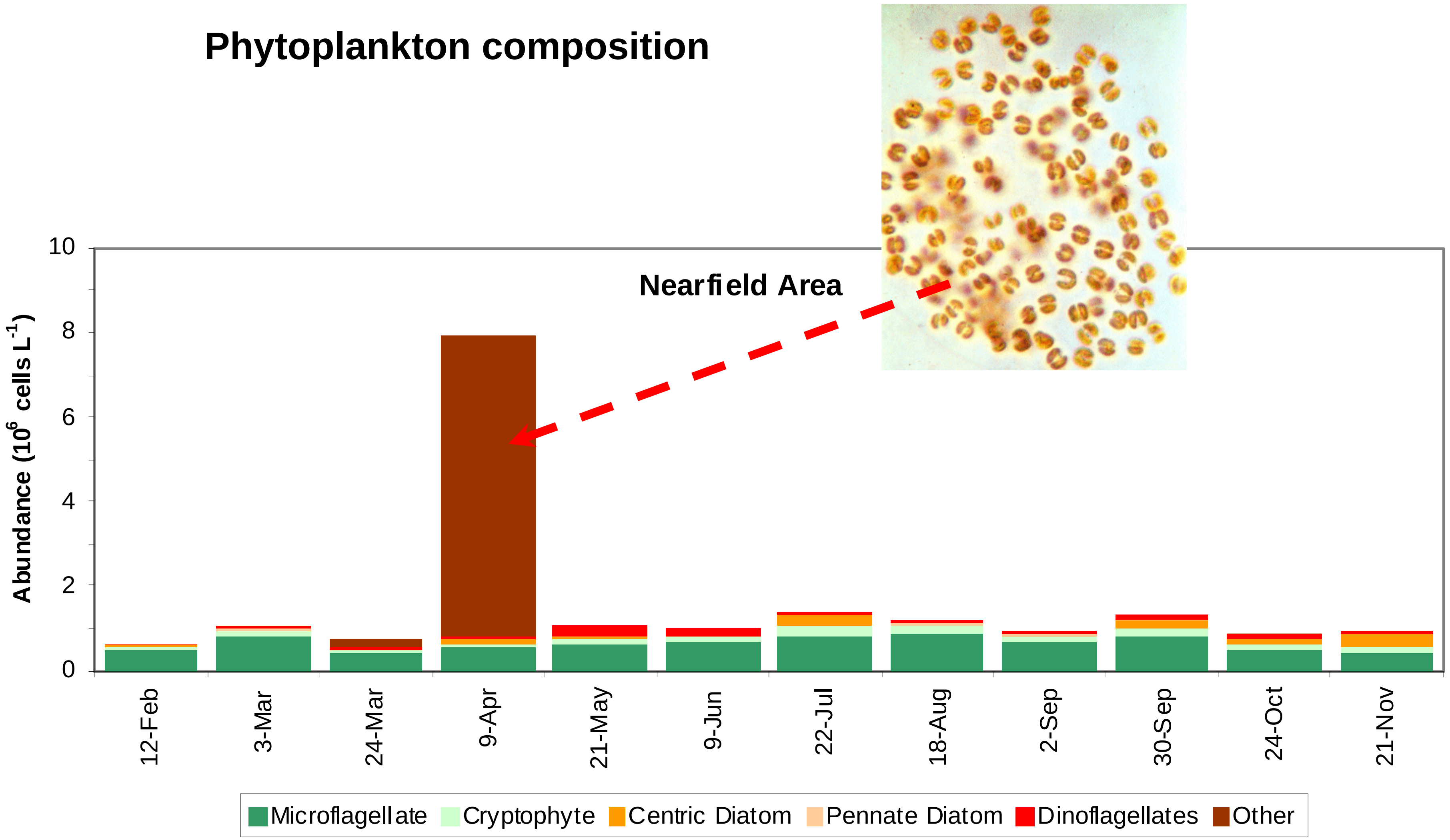
# 2008 Plankton Overview

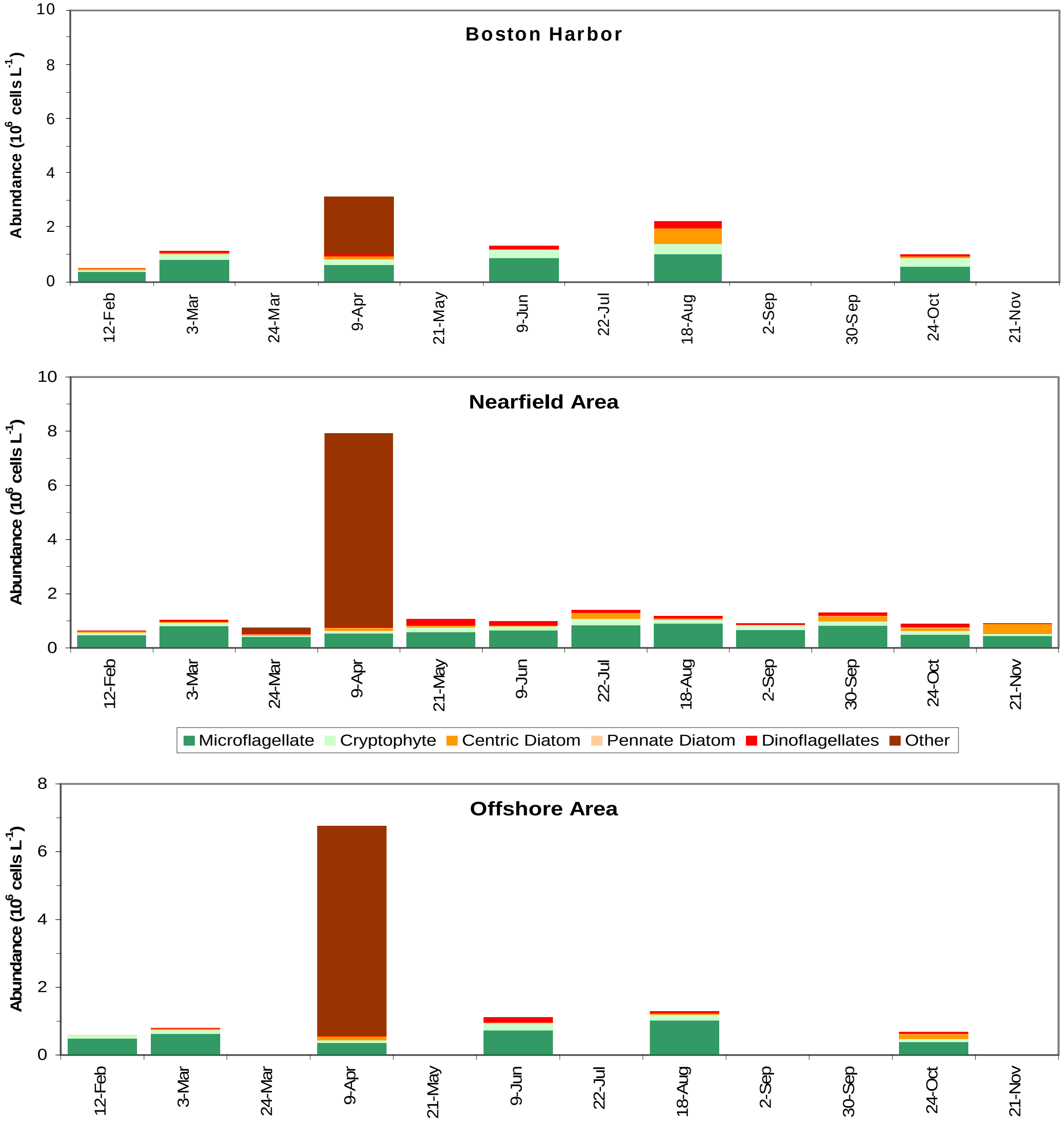
- Phytoplankton and Zooplankton Monitoring
  - Species and abundance
  - 2 stations (NFLD), 12 times annually
  - 13 stations (FFLD), 6 times annually
  - Surface and mid-depth (or CHL max) samples (phytoplankton)
  - Vertical oblique net hauls, 102 μm mesh net (zooplankton)
- 2008 annual pattern
  - Species composition
  - Abundance levels
  - Nuisance phytoplankton species
- Long-term patterns & trends
  - How to quantify?
  - Regional differences?

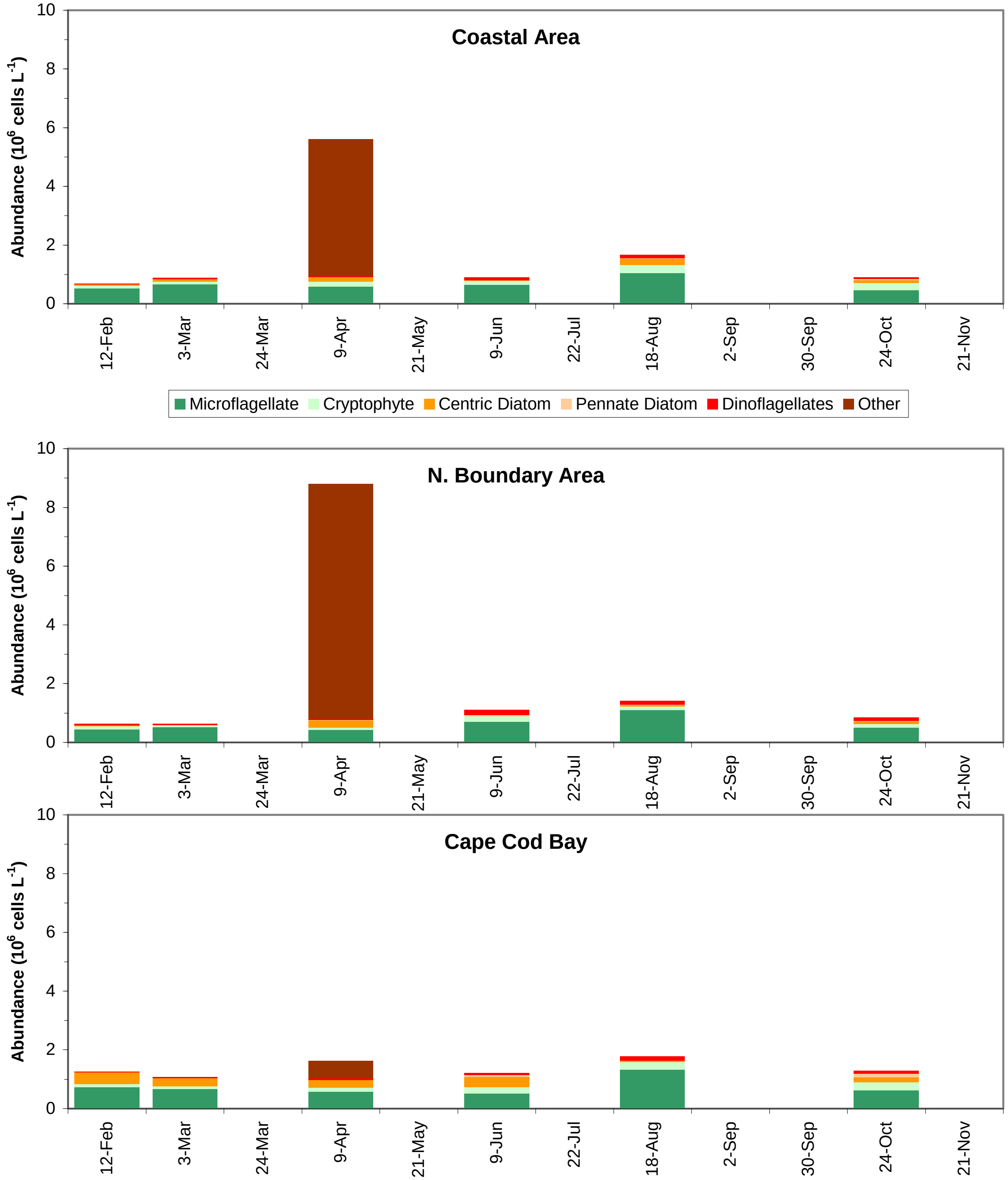
# 2008
# Phytoplankton

**2008:**
**Another "*Phaeocystis* year"**
**12 of 17 years with *Phaeocystis* detected**
***Phaeocystis* blooms (>$10^6$ $L^{-1}$) in past 9 years**

# Phytoplankton composition




Boston Harbor
Nearfield Area
Offshore Area
Abundance (10^6 cells L^-1)
0
2
4
6
8
10
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Microflagellate
Cryptophyte
Centric Diatom
Pennate Diatom
Dinoflagellates
Other

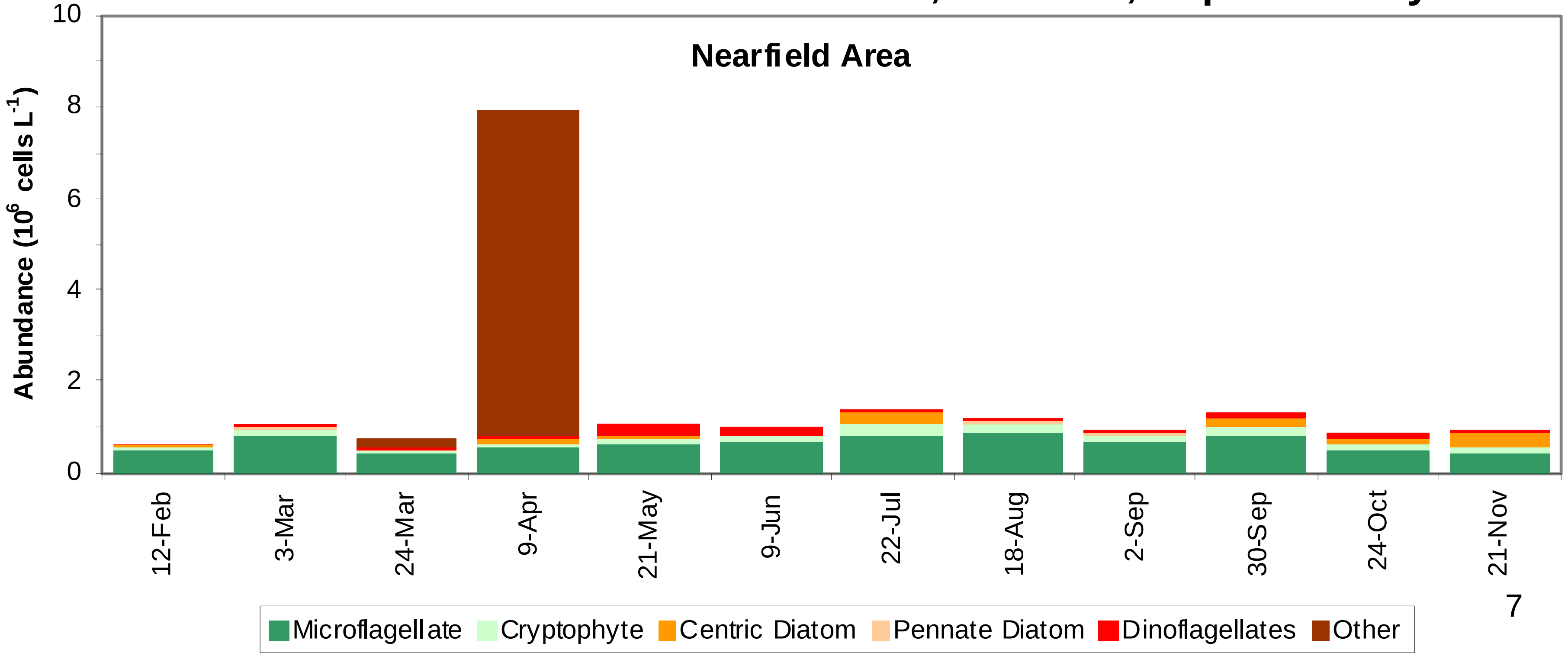

Coastal Area
N. Boundary Area
Cape Cod Bay
Abundance (10^6 cells L^-1)
0
2
4
6
8
10
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Microflagellate
Cryptophyte
Centric Diatom
Pennate Diatom
Dinoflagellates
Other

**Regionally coherent phytoplankton composition pattern (mostly….)**

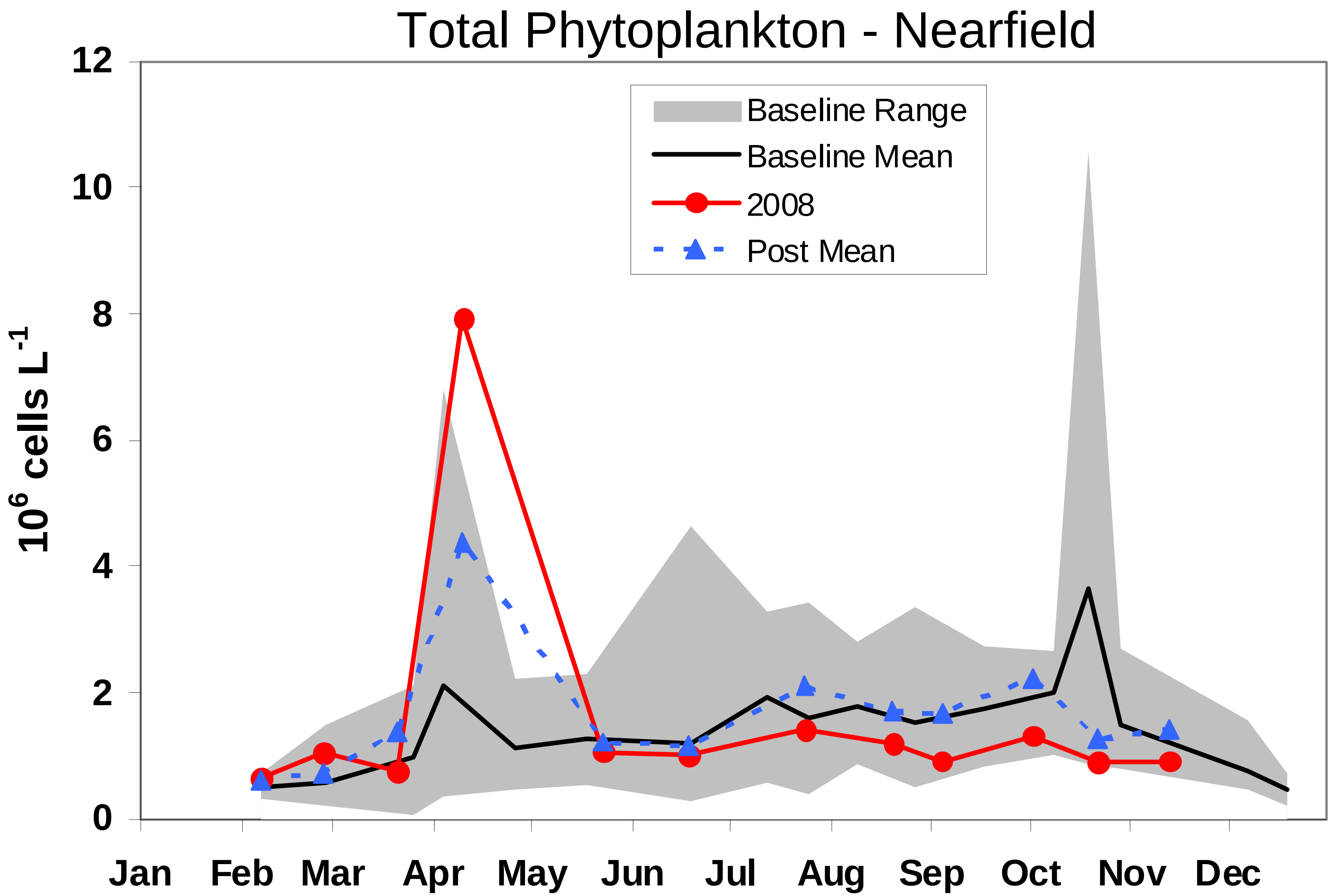
**Microflagellate 'baseline' varies seasonally with T**

***Phaeocystis*, all regions in April**

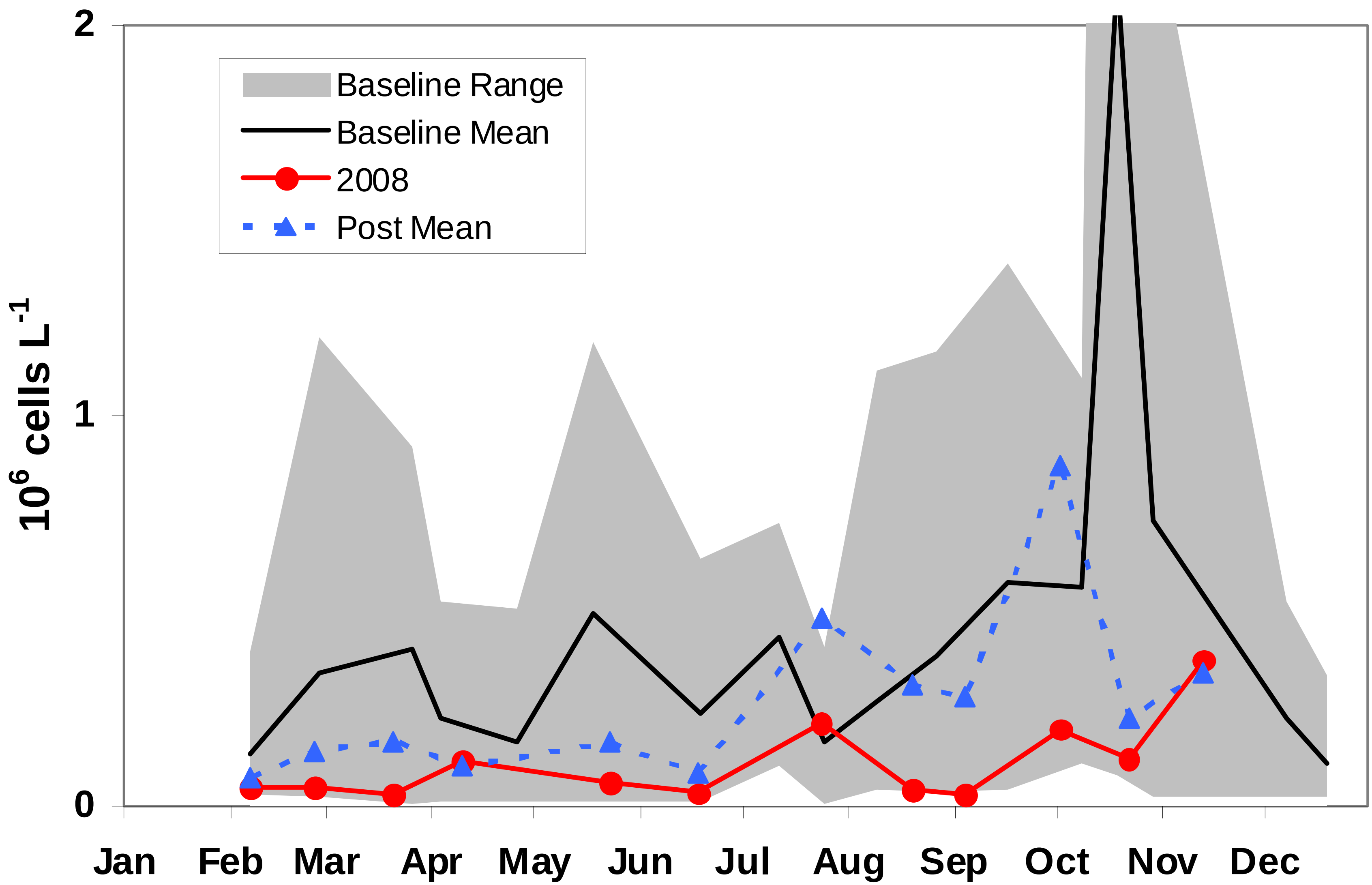
**Diatoms**
**Summer: more abundant in Harbor, Coastal, Cape Cod Bay**
**Winter-Spring:  relative increase in Cape Cod Bay**
**Autumn: more abundant in Nearfield, Offshore, Cape Cod Bay**



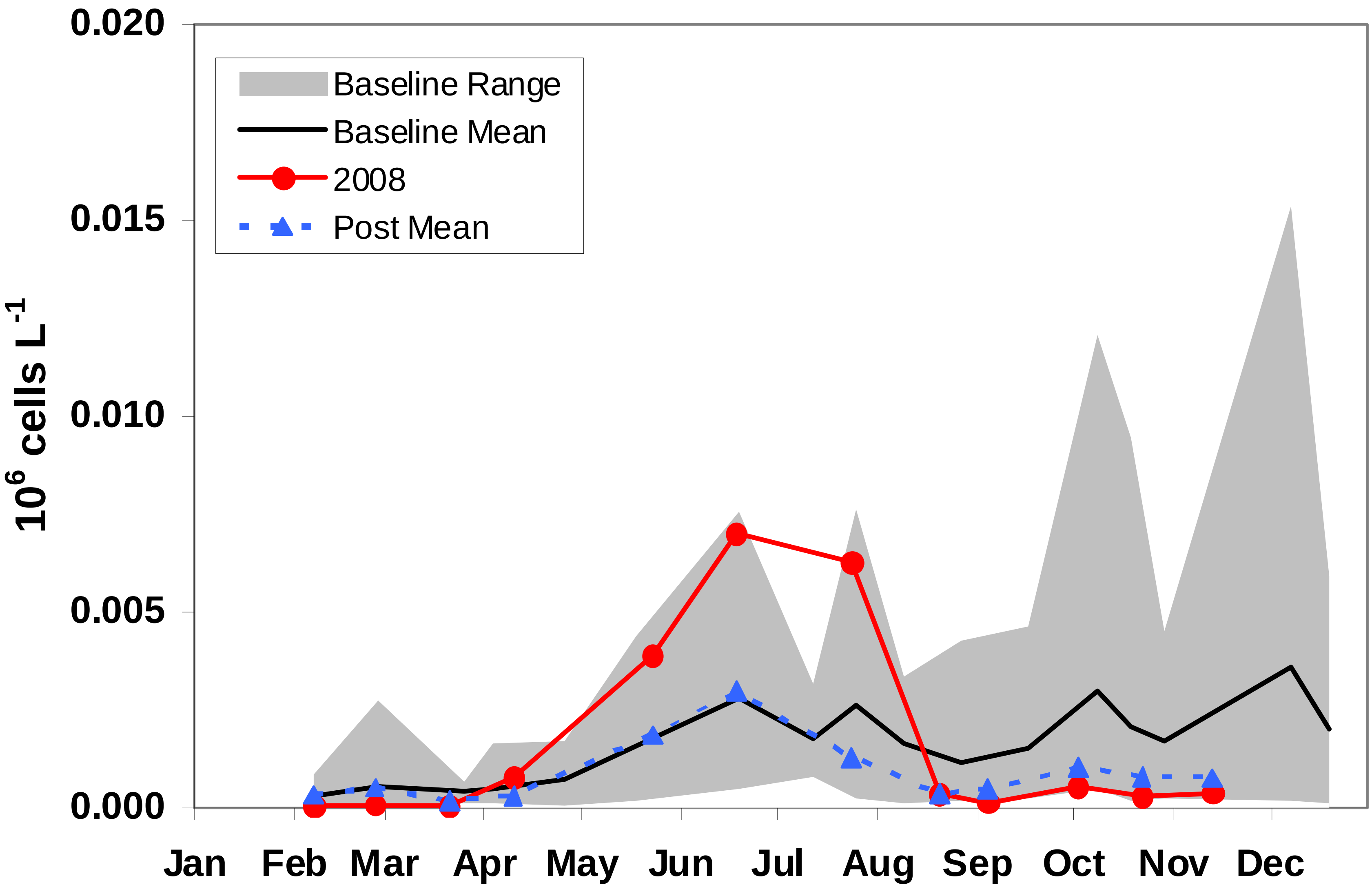
## Annual nearfield patterns of dominant phytoplankton groups
## 2008 versus pre- and post-diversion levels



# Diatoms - Nearfield



# Dinoflagellates (SW) - Nearfield

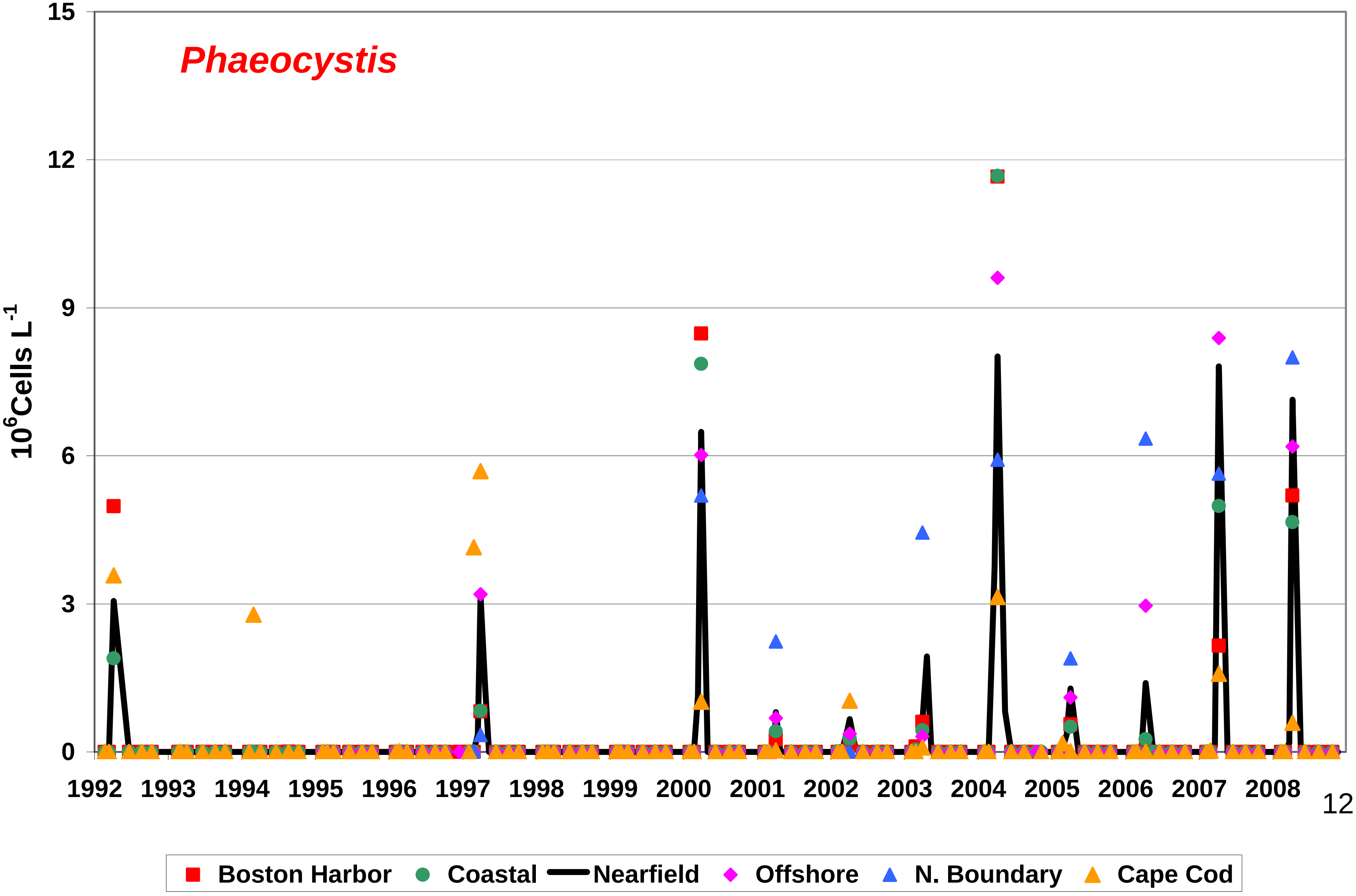


# 2008 Nearfield Phytoplankton Annual cycle:

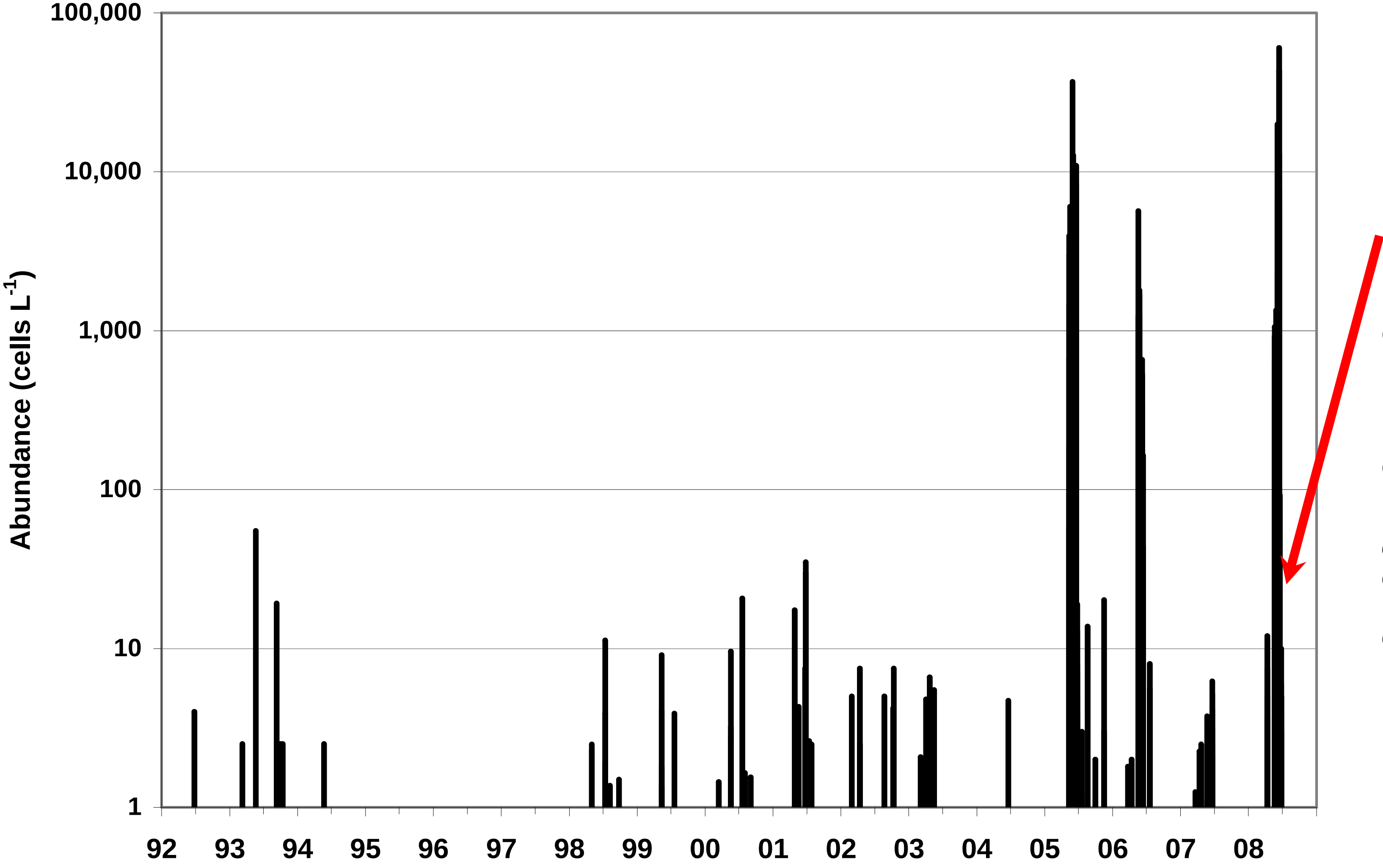
## Relative to baseline ranges:

- **Total phytoplankton**
  - **elevated April (*Phaeocystis*)**
  - **reduced  in October**
- **Microflagellates**
  - **elevated in late February**
  - **reduced in October**
- **Diatoms**
  - **generally reduced except July and November**
- **Cryptophytes**
  - **elevated during February**
  - **reduced during November**
- **Dinoflagellates**
  - **near high end of baseline range during June – July**
  - **reduced during September - November**

# Harmful and Nuisance Phytoplankton



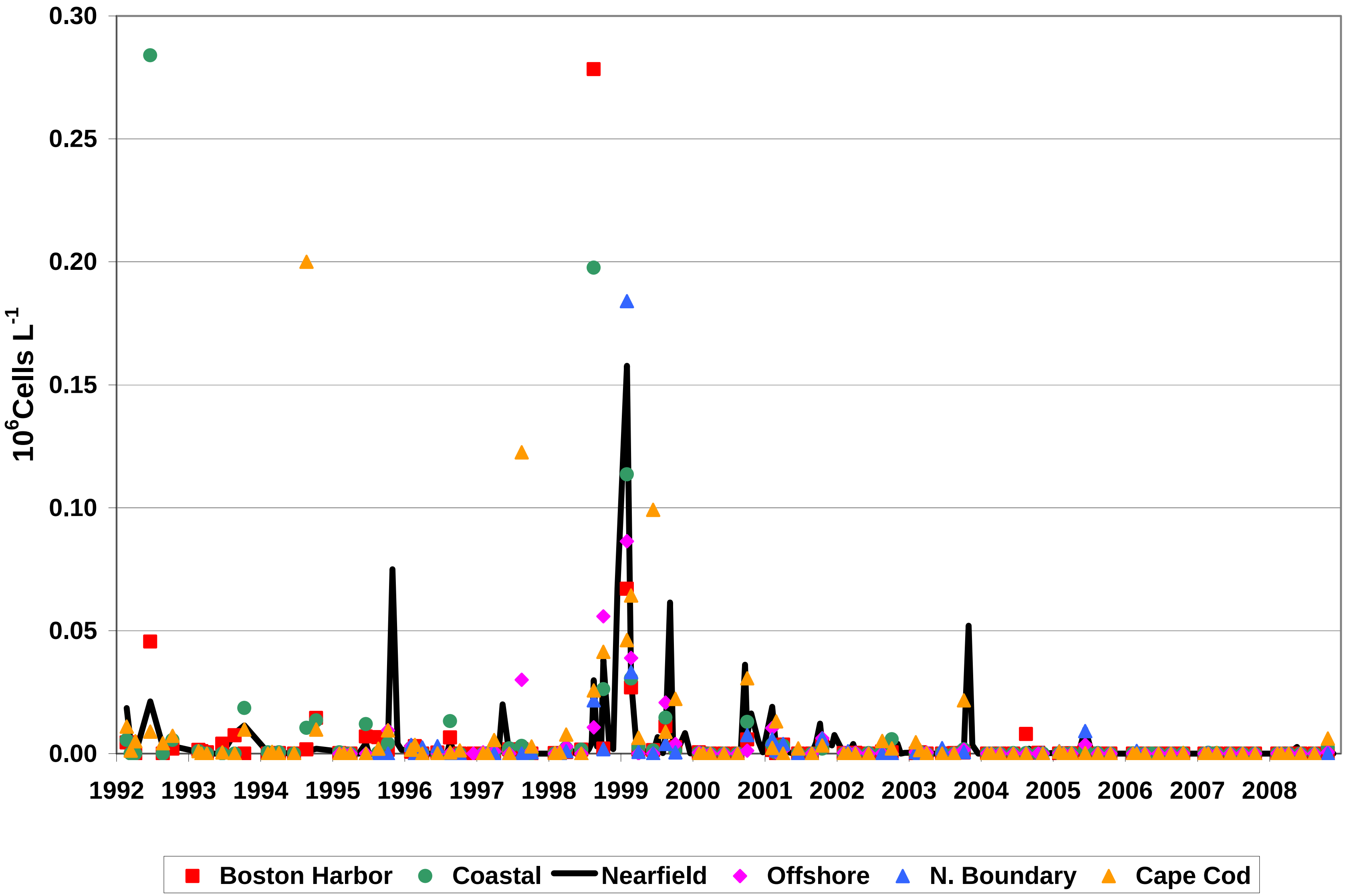
# *Alexandrium* – Nearfield (1992-2008)




**OCT 2008**

**10 - 100 cells L$^{-1}$**

Offshore
Coastal
Harbor
Cape Cod Bay




**Consistently reduced *Pseudo-nitzschia* spp. abundance since 1998-1999**

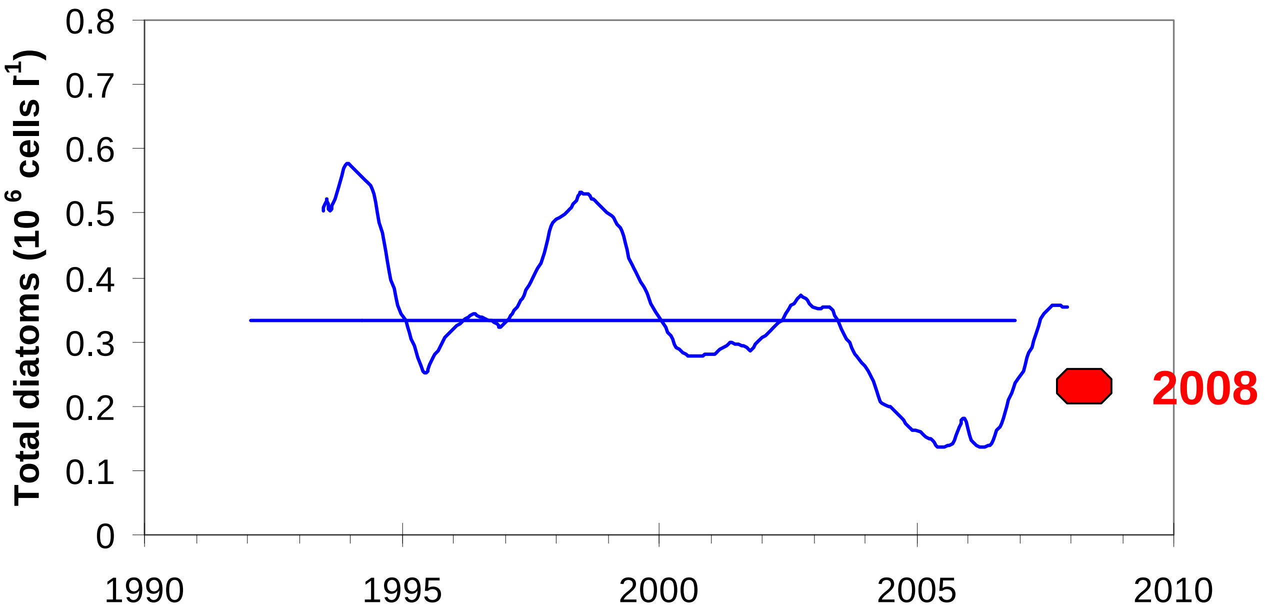
**2008 Nuisance and Harmful Species Summary:**

**Another *Phaeocystis* bloom year ($10^6$ cells $L^{-1}$)**
**(March and April)**

**2008 *Alexandrium* bloom ($10^3$ - $10^4$ cells $L^{-1}$)**
**(April - June bloom; present in October)**

**Reduced *Pseudo-nitzschia* ($10^3$ cells $L^{-1}$)**
**(2008 peak = 6000 cells $L^{-1}$, CC Bay in October)**

# Trends, changes, regional differences in phytoplankton functional groups????




**Two different approaches:**

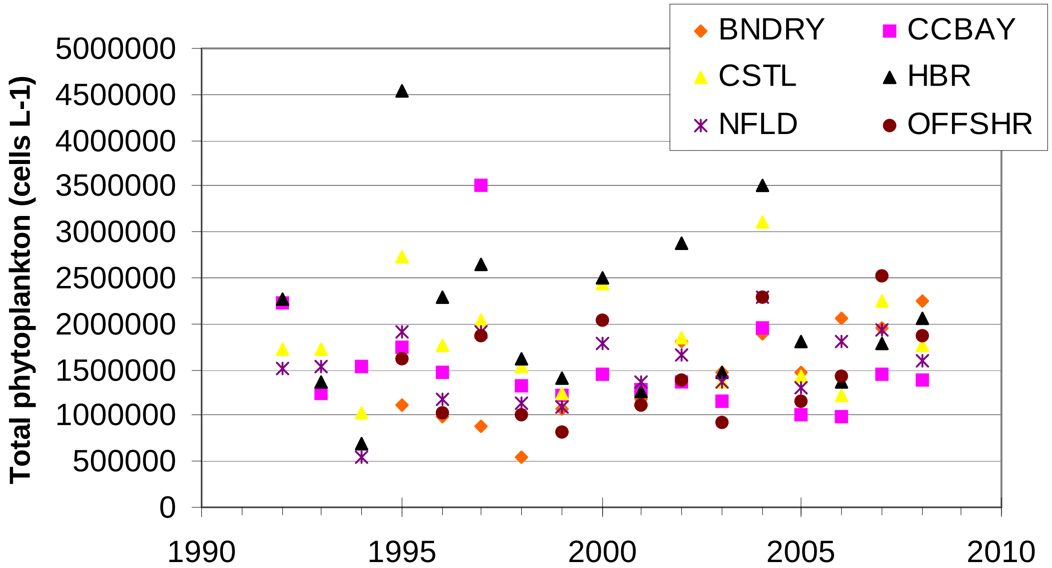
**2 sample tests (1992-2000 *vs.* 2001-2008 median levels)**
**comparison of slopes (= linear trends)**

**Table _ : Summary of Mann-Whitney 2-sample tests comparing median levels of phytoplankton groups during 1992-2000 vs. 2001-2008. Values indicate change in median value [(2001-2008) / (1992-2000)]; statistically significant differences in red (increase) or blue (decline).**

| | *BNDRY* | *CCBAY* | *CSTL* | *HBR* | *NFLD* | *OFFSHR* |
|---|---|---|---|---|---|---|
| Total PPL | 1.55 | --- | --- | --- | 1.16 | --- |
| UFLAGS | 1.45 | 1.41 | 1.42 | 1.73 | 1.45 | 1.31 |
| Dinoflags | --- | --- | --- | --- | 0.45 | 0.34 |
| Phaeocystis | 4.68 | --- | 2.48 | --- | 1.64 | 2.42 |
| Diatoms | --- | 0.44 | 0.44 | 0.46 | 0.57 | 0.28 |

**Increases**
**Microflagellates (=methodological)**
***Phaeocystis* doubling+++**

**Decreases**
**Dinoflagellates (-40% nfld +offshr)**
**Diatoms – 30 to 60 % most regions**

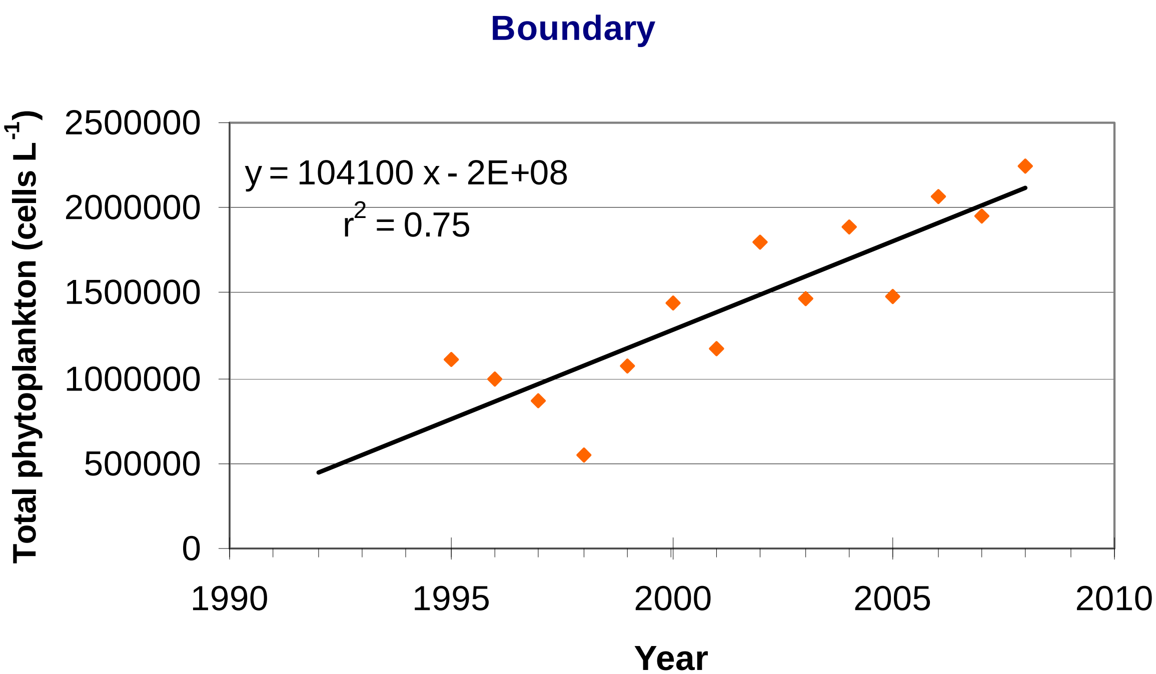


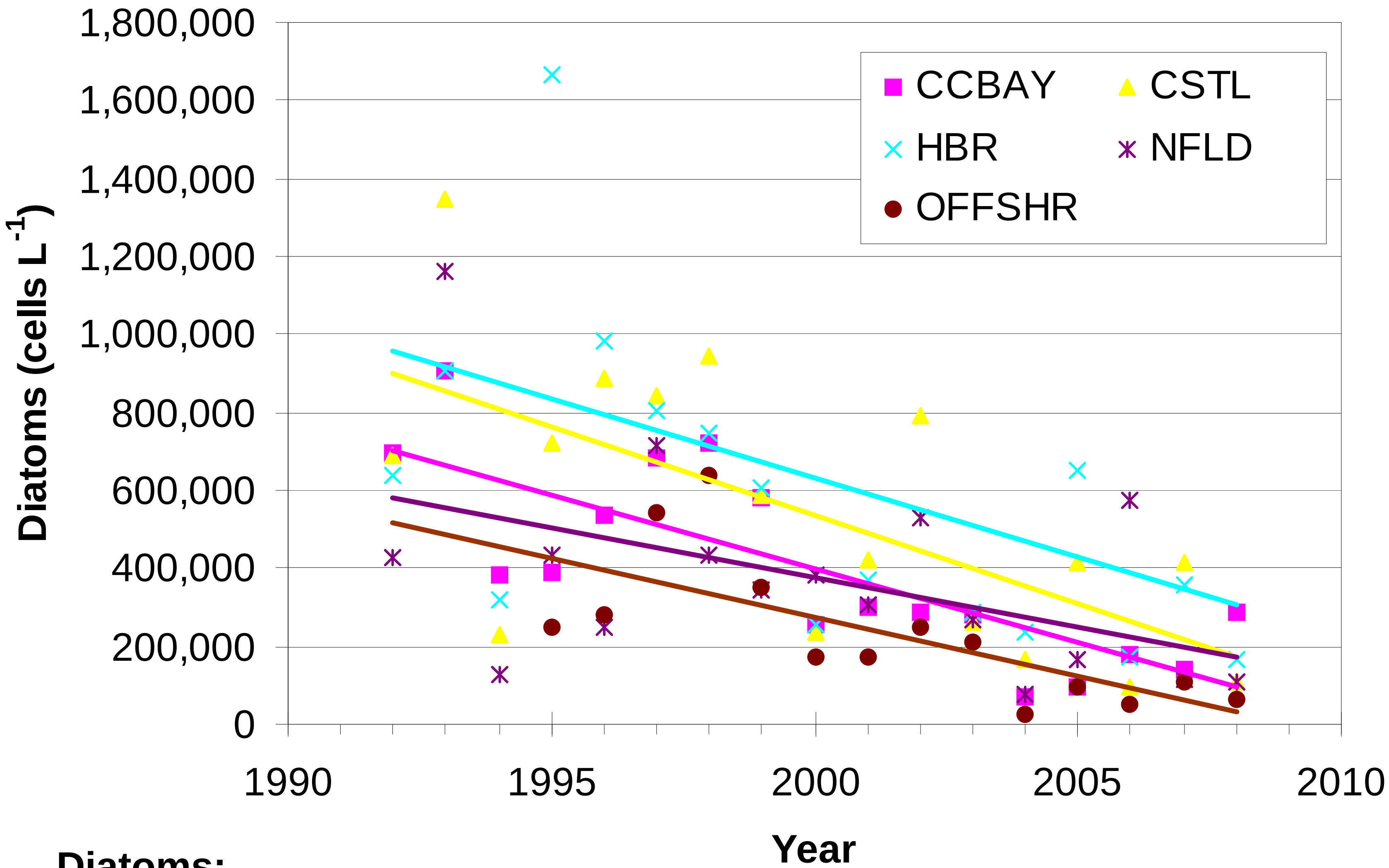

**Nature of changes?**
**- rates of change?**
**- linear, steps, cyclical?**

**Comparison of slopes applied to annual mean values**

**Total Phytoplankton:**

**Significant linear increase (ca. 100,000 cells $L^{-1}$ $y^{-1}$) in Boundary region**






**Diatoms:**

**Significant linear decreases in all regions except Boundary.**
**Mean rate of decrease = 39,400 cells $L^{-1}$ $yr^{-1}$**

**Table _: Summary of significant linear trends in mean annual abundance of phytoplankton groups. Values represent mean rate of change in units of cells $L^{-1}$ $year^{-1}$. Red indicates positive slope (=increase); blue indicates negative slope (= decrease).**

| | BNDRY | CCBAY | CSTL | HBR | NFLD | OFFSHR |
|---|---|---|---|---|---|---|
| Total PPL | + 104,000 | --- | --- | --- | --- | --- |
| UFLAGS | --- | --- | --- | --- | + 23,000 | --- |
| Dinoflags | --- | - 300 | --- | --- | --- | --- |
| Phaeocystis | + 85,000 | --- | --- | --- | --- | + 85,000 |
| Diatoms | --- | - 39,400 | - 39,400 | - 39,400 | - 39,400 | - 39,400 |

## *2008 Phytoplankton Summary*

**2008 was a *Phaeocystis* bloom year**

**Phytoplankton community composition regionally coherent**

- **Diatoms elevated in Cape Cod Bay (all seasons) and coastal and harbor (summer)**
- **Reduced *Phaeocystis* in harbor and Cape Cod Bay**

**2008 Phytoplankton abundance remained at low end of baseline range**

- ***Phaeocystis* (elevated in April)**
- **Dinoflagellates (elevated June & July)**

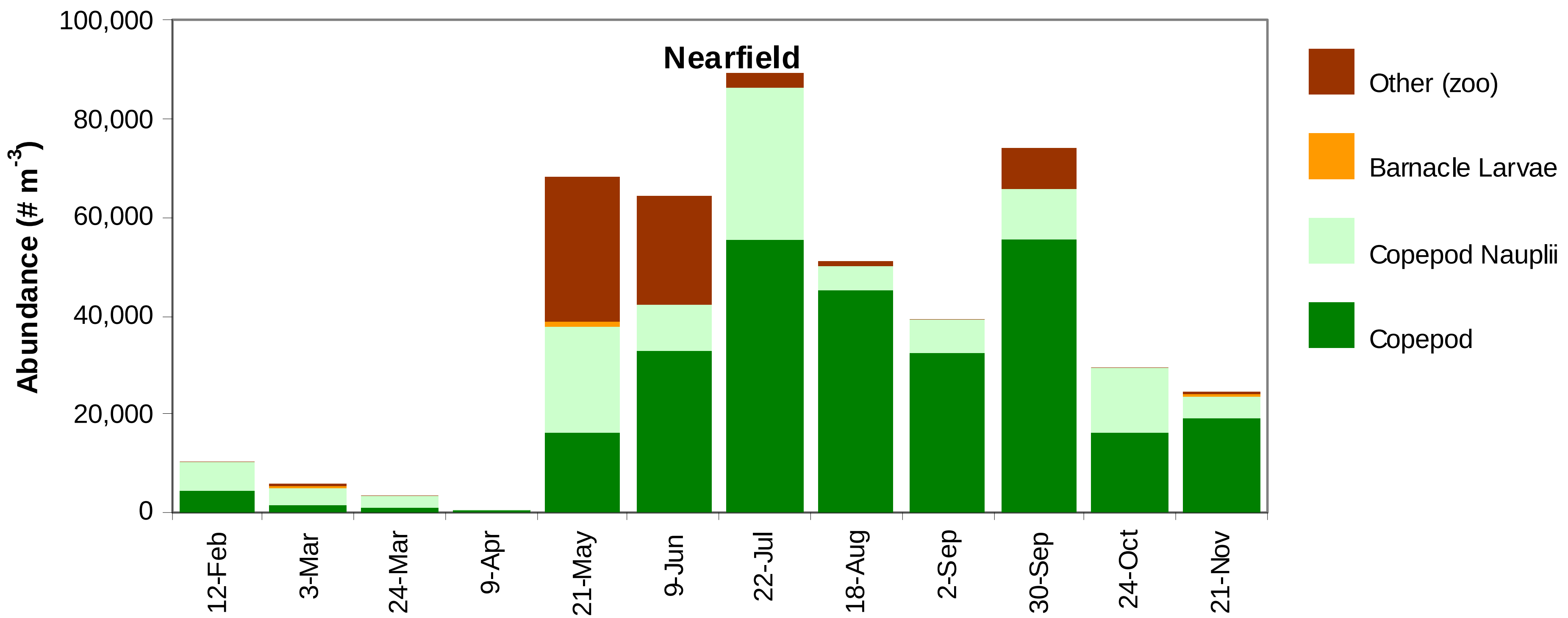
**Long-term changes**

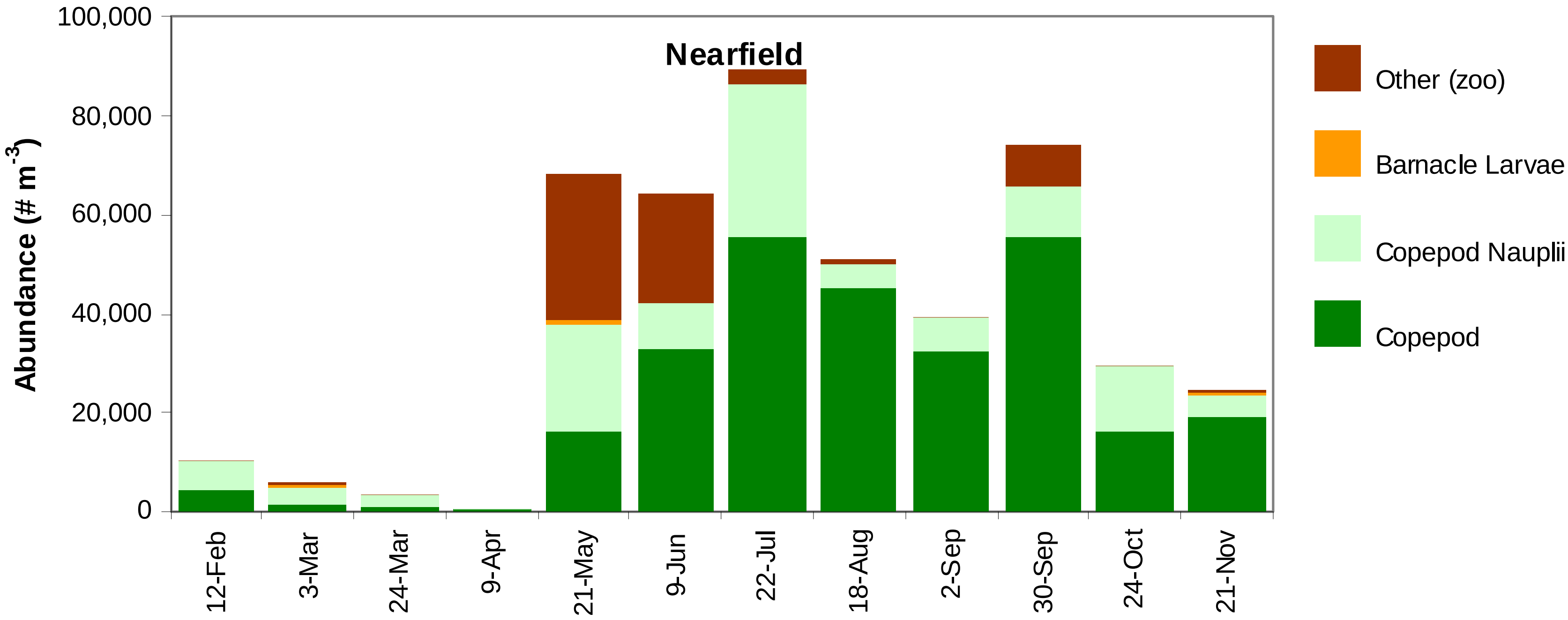
- **Increasing *Phaeocystis*, esp. boundary and offshore regions**
- **ca. 30% - 40% decline in diatom abundance post-2000 in all regions except the boundary region**

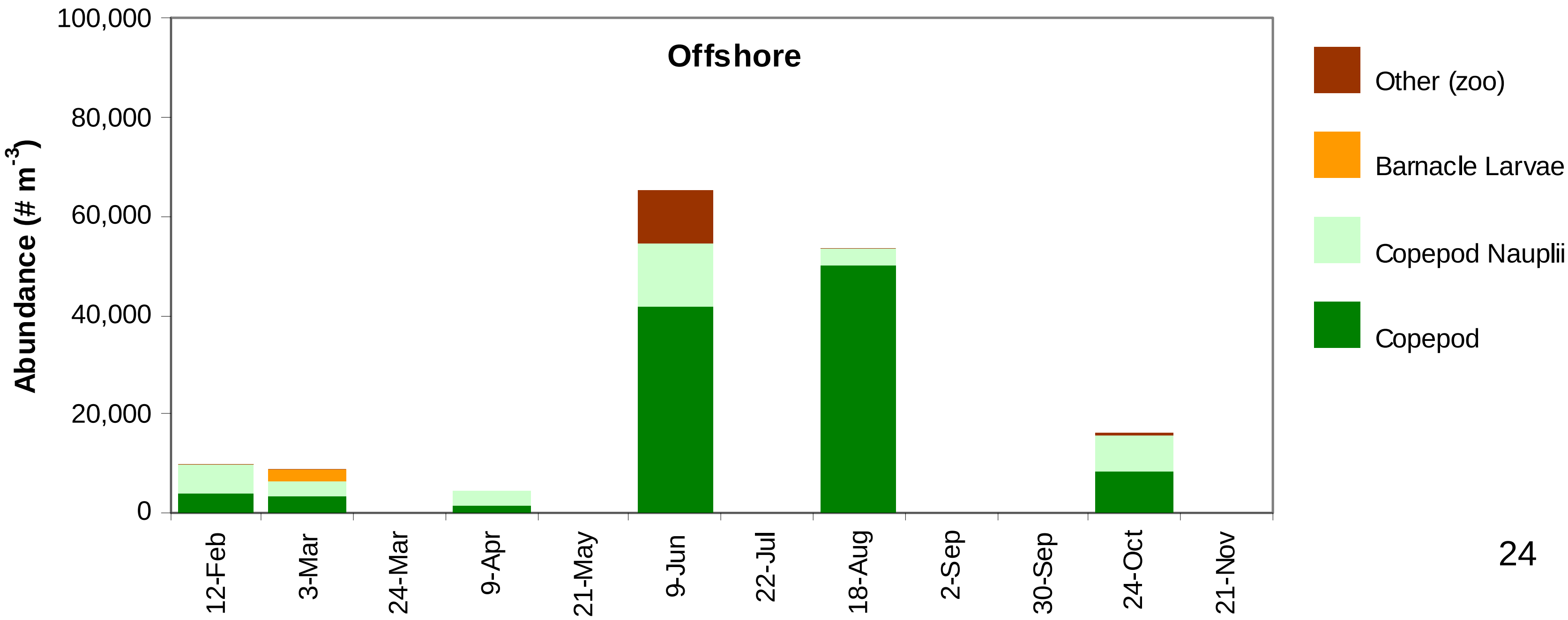
# 2008 Zooplankton

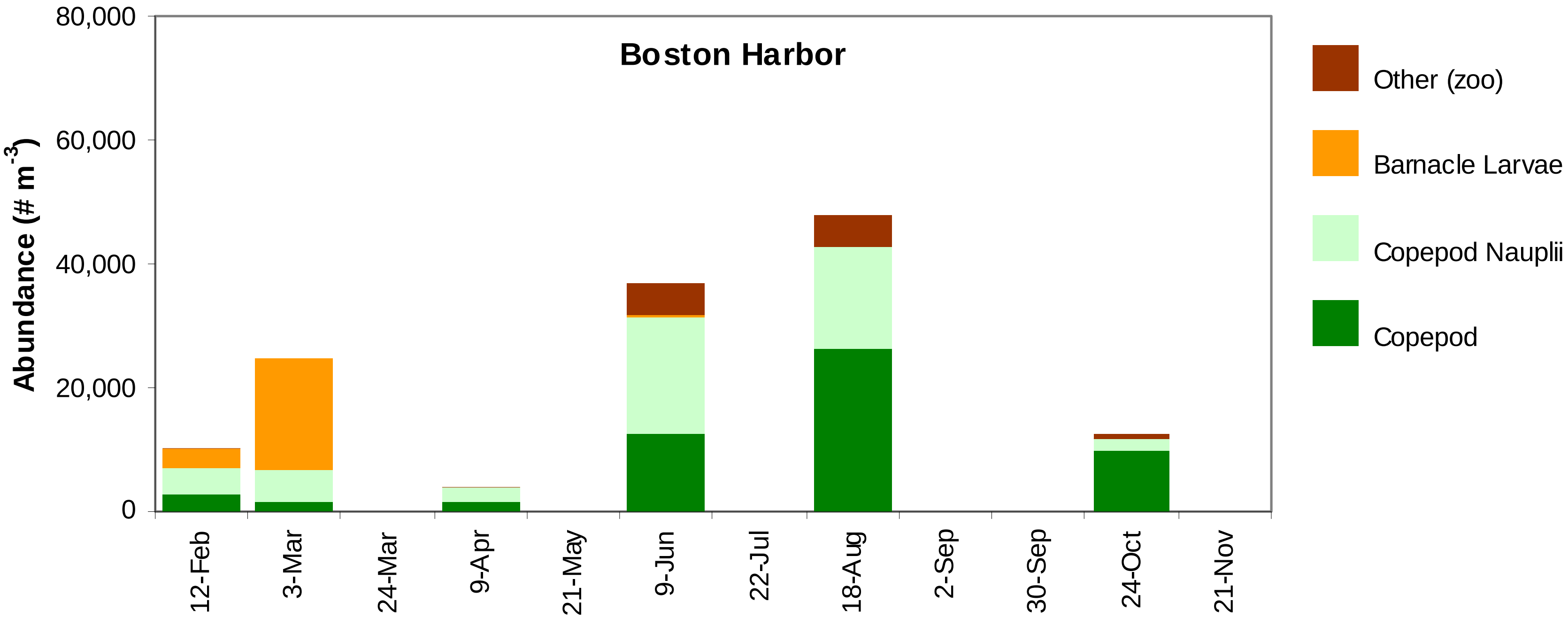
- **2008 annual pattern**
  - **Species composition of the zooplankton was similar to previous years**
  - **Abundance levels of the zooplankton were similar to previous years**
  - **Abundances of copepods, driven primarily by *Oithona similis* continue to increase from 2005 lows.**

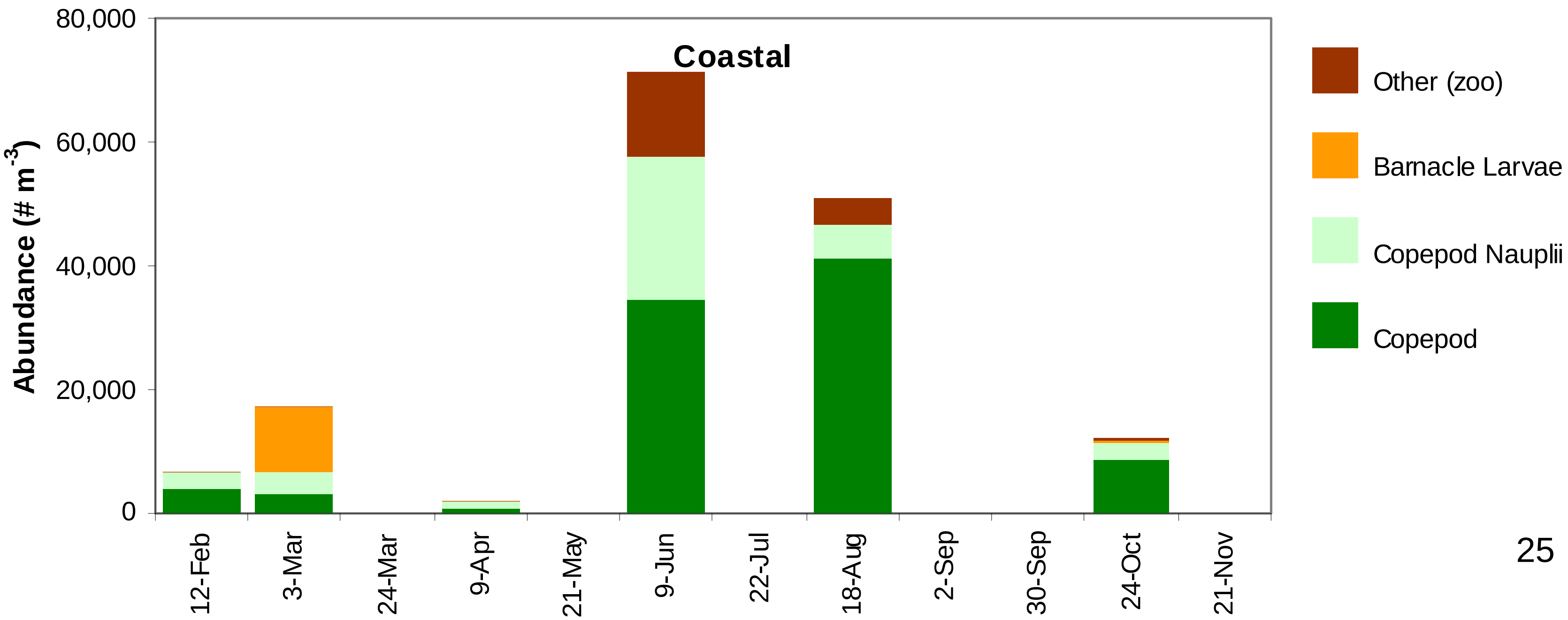
# 2008 Zooplankton

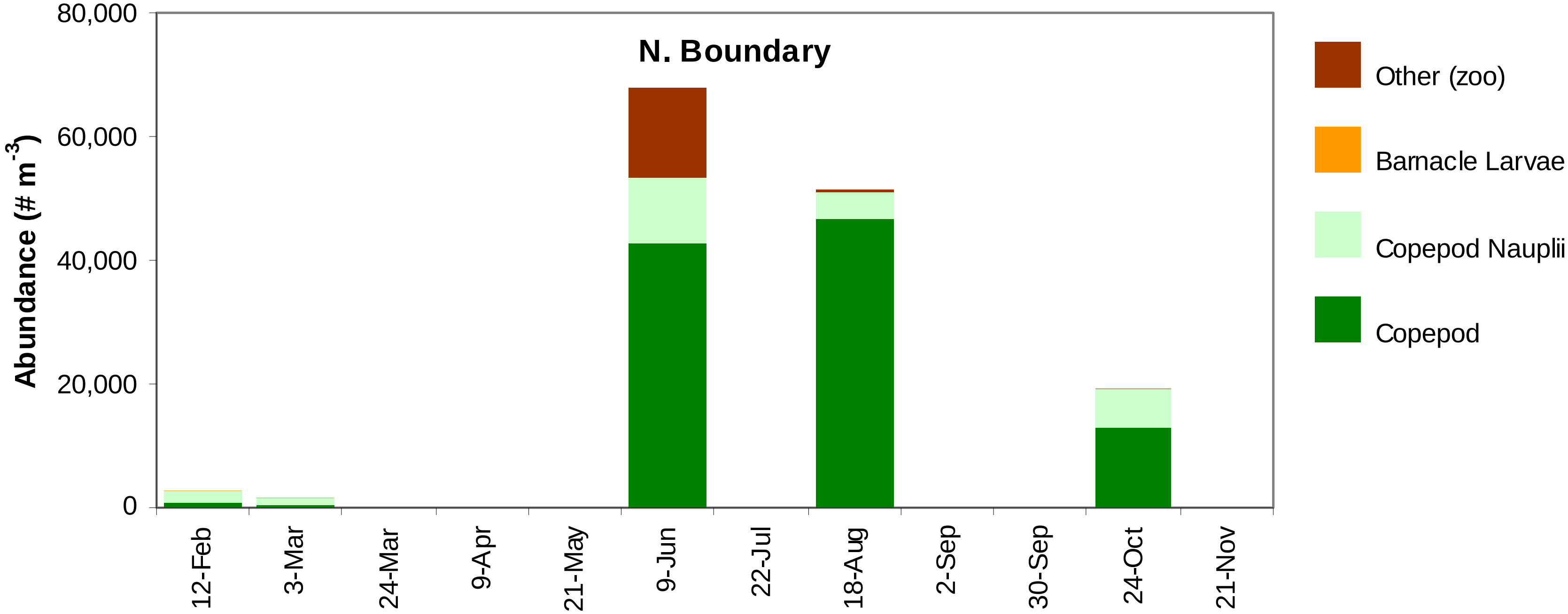


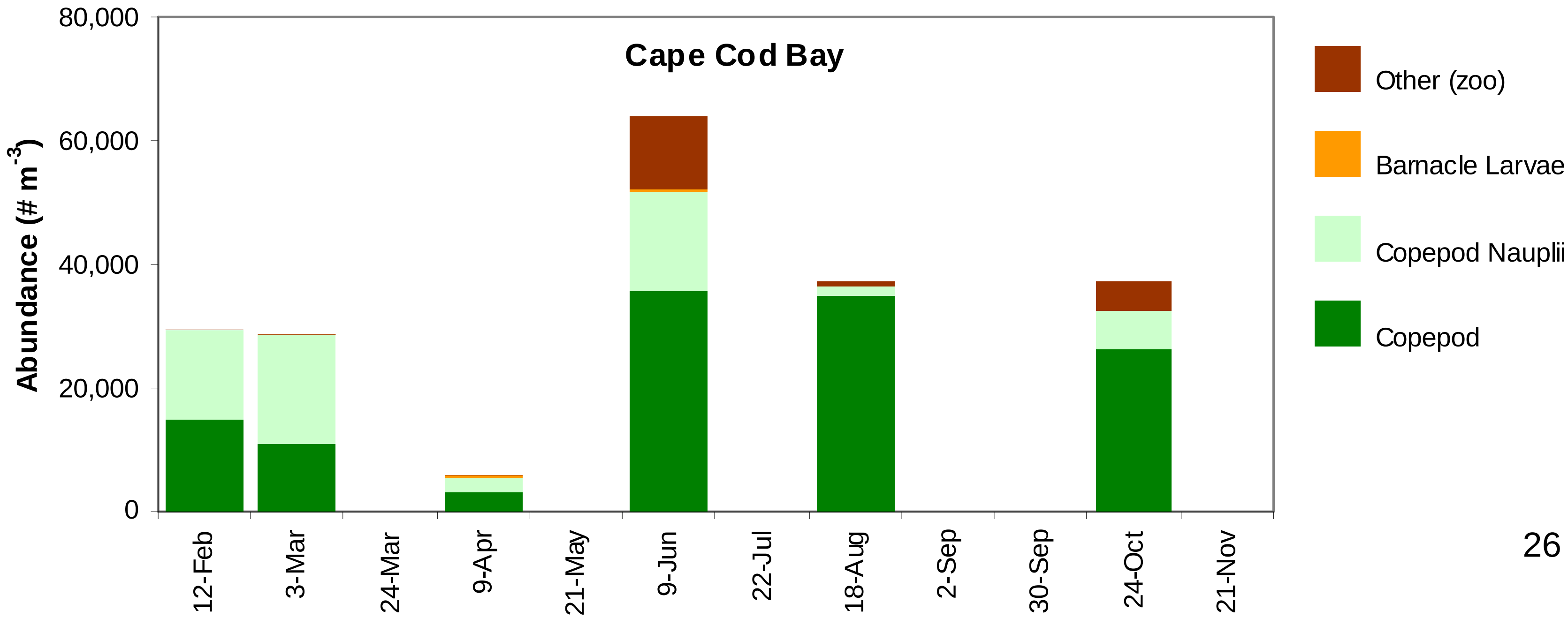

Nearfield
Abundance (# m$^{-3}$)
100,000
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod

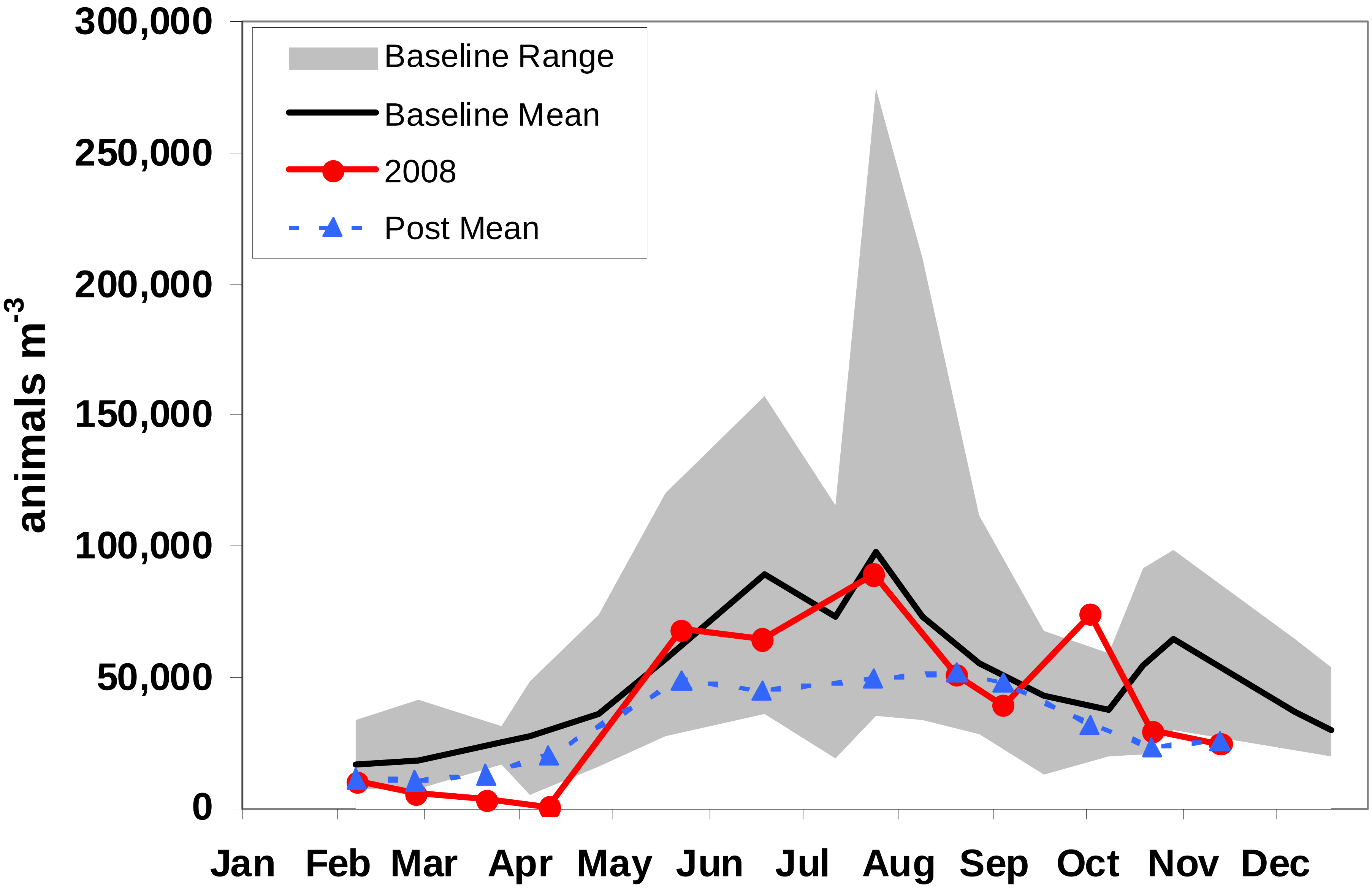

Offshore
Abundance (# m$^{-3}$)
100,000
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod


Boston Harbor
Abundance (# m$^{-3}$)
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod


Coastal
Abundance (# m$^{-3}$)
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod

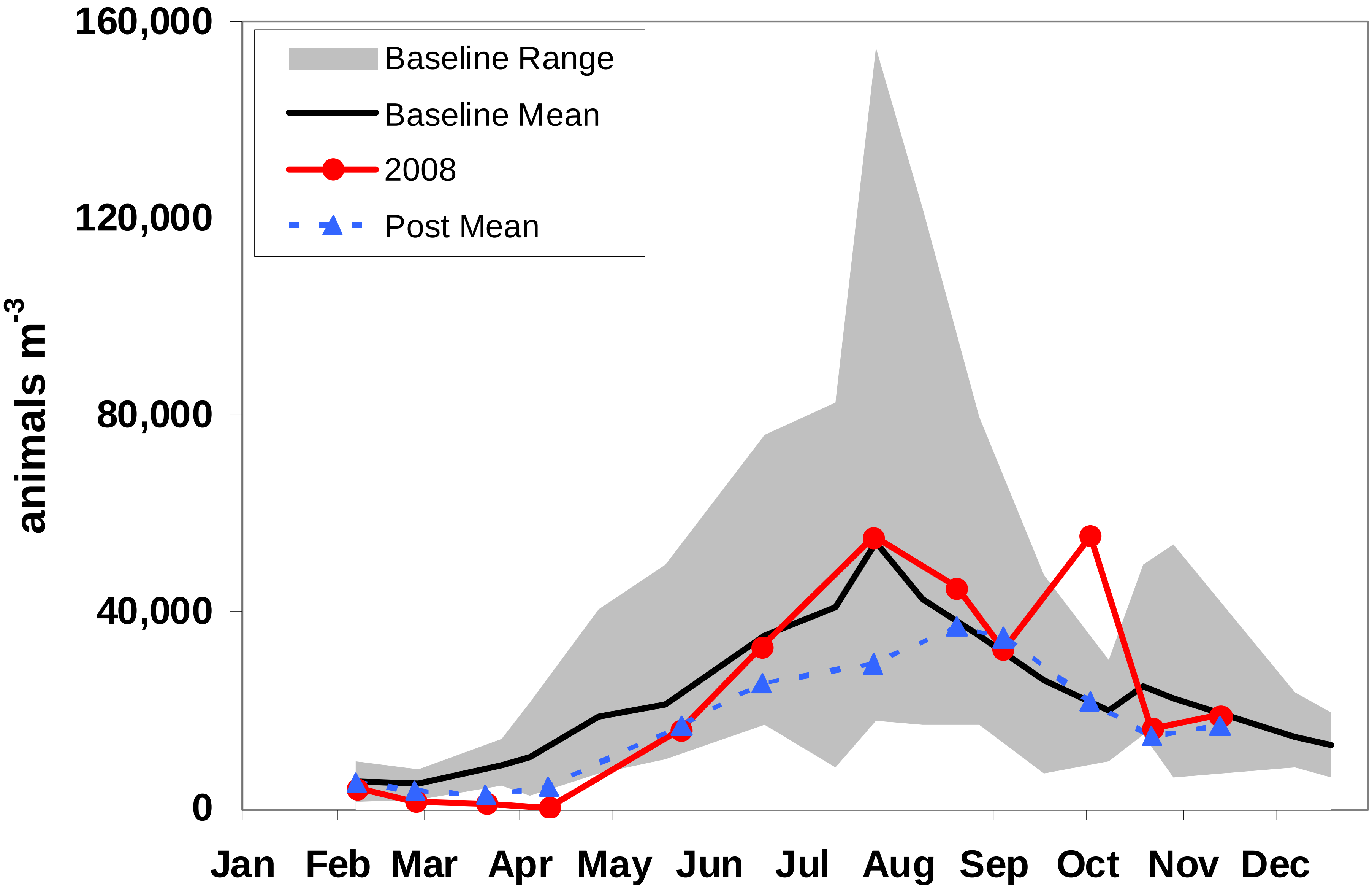

N. Boundary
Abundance (# m-3)
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod


Cape Cod Bay
Abundance (# m-3)
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod



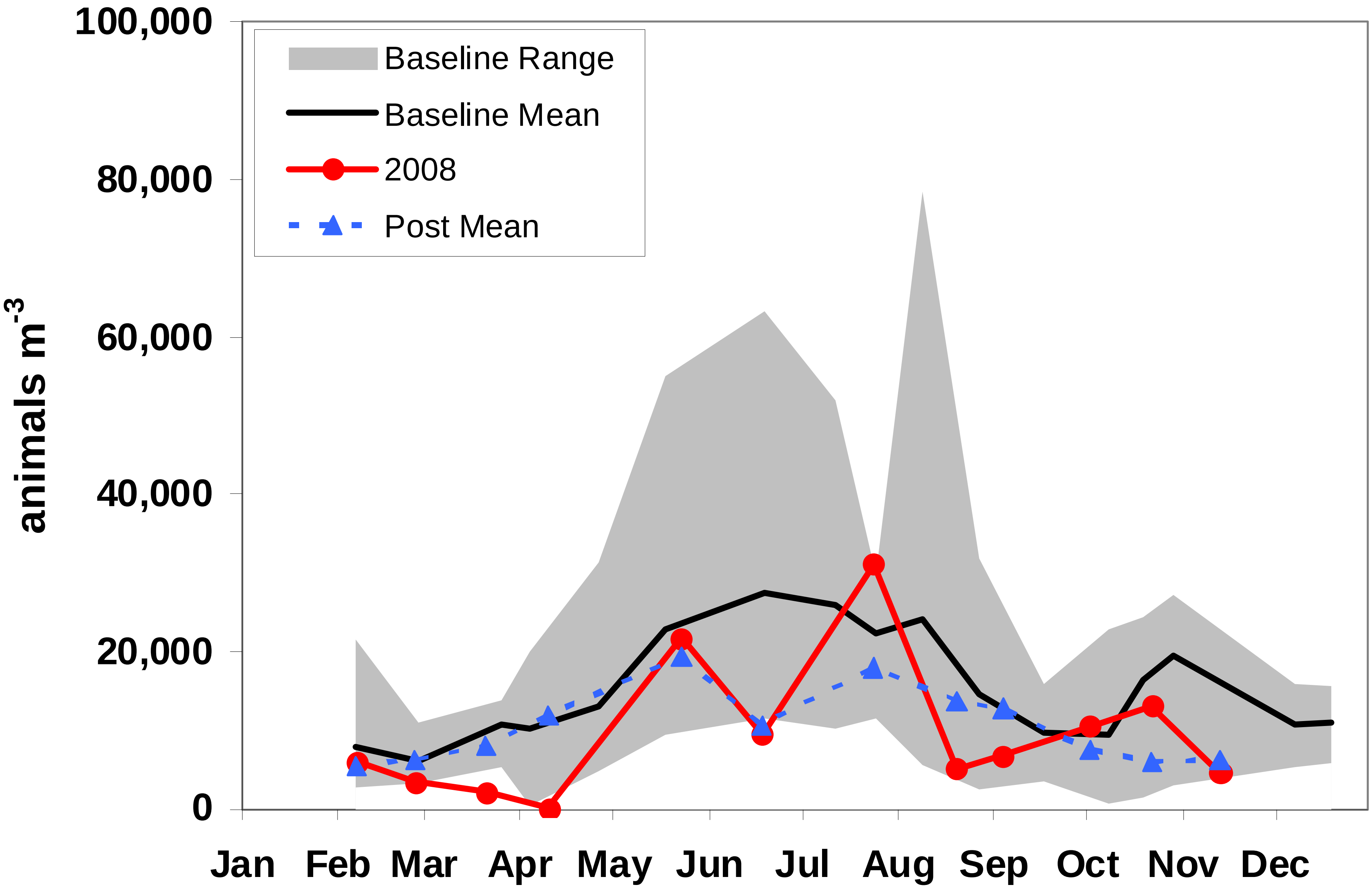



# Nearfield total zooplankton



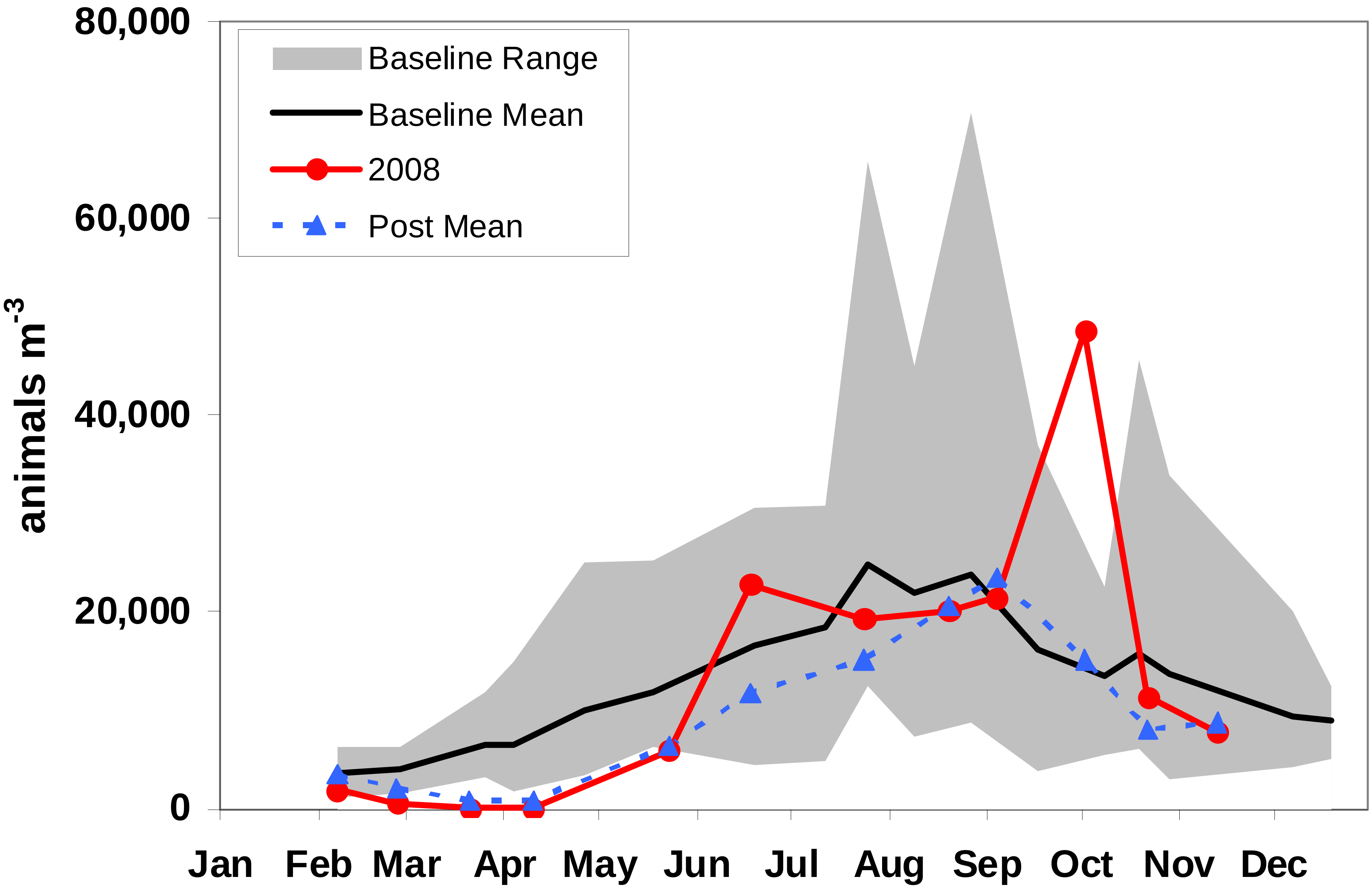



## Nearfield adult and copepodite copepods



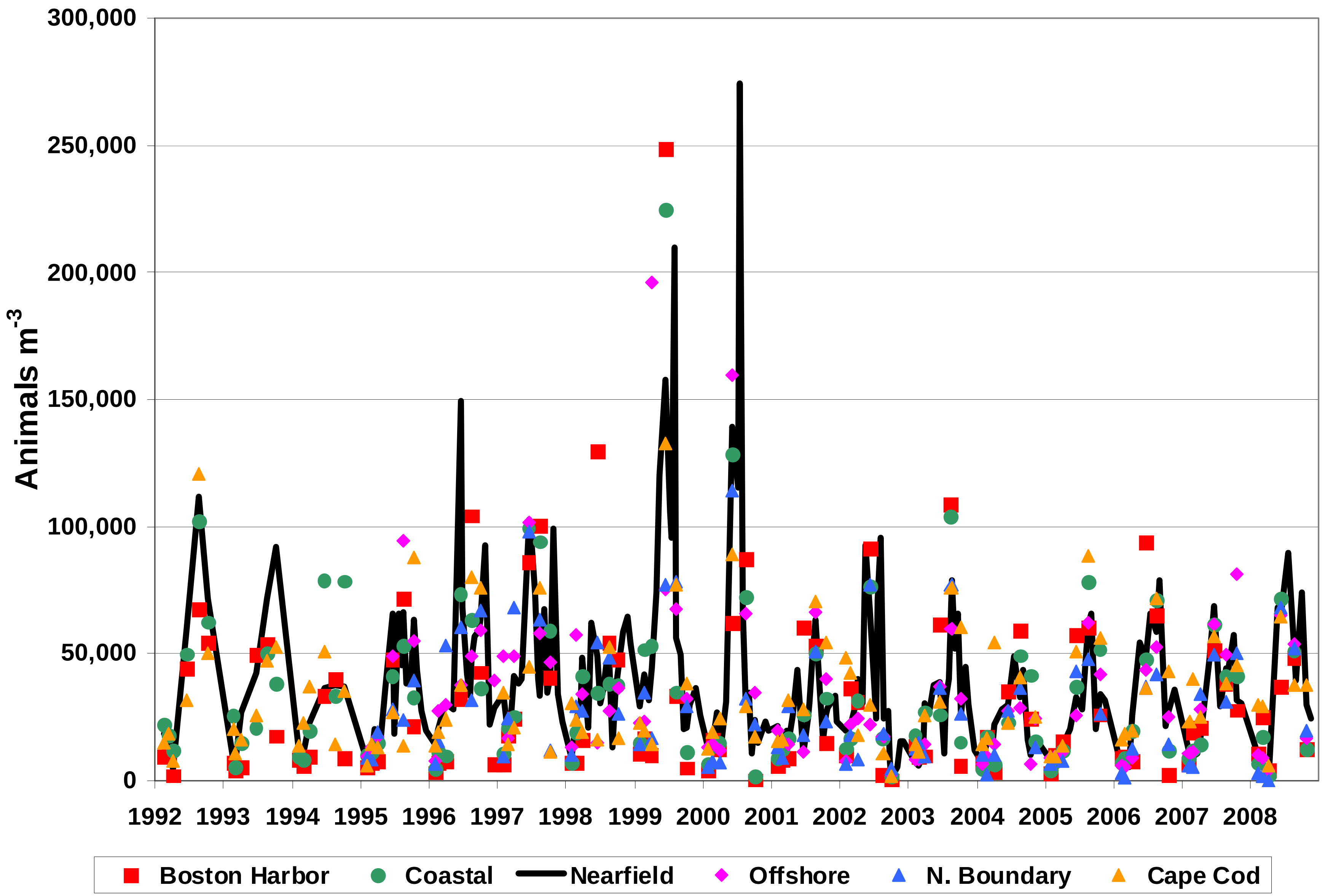



# Nearfield copepod nauplii



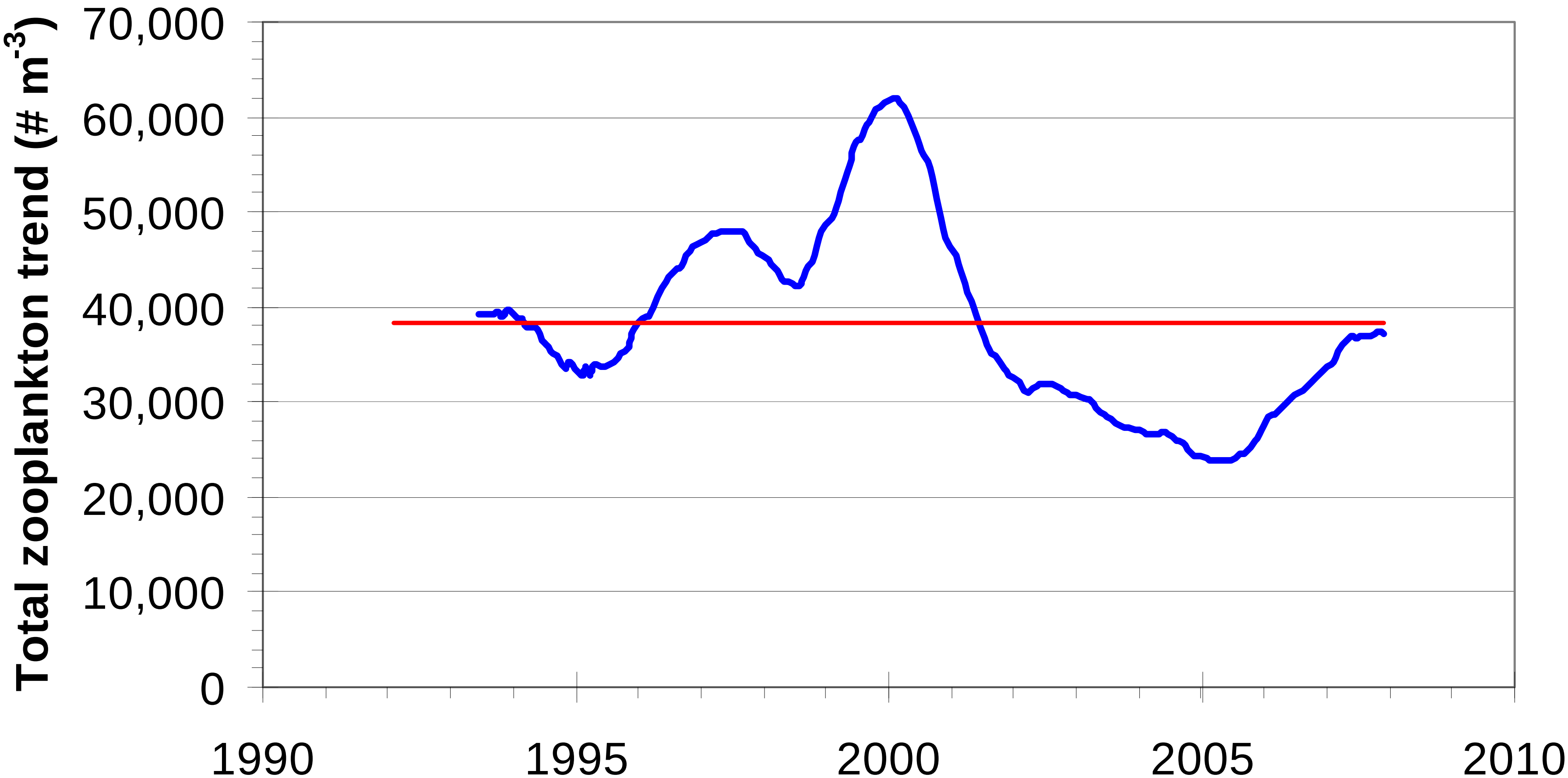



**Nearfield *Oithona spp.* total**



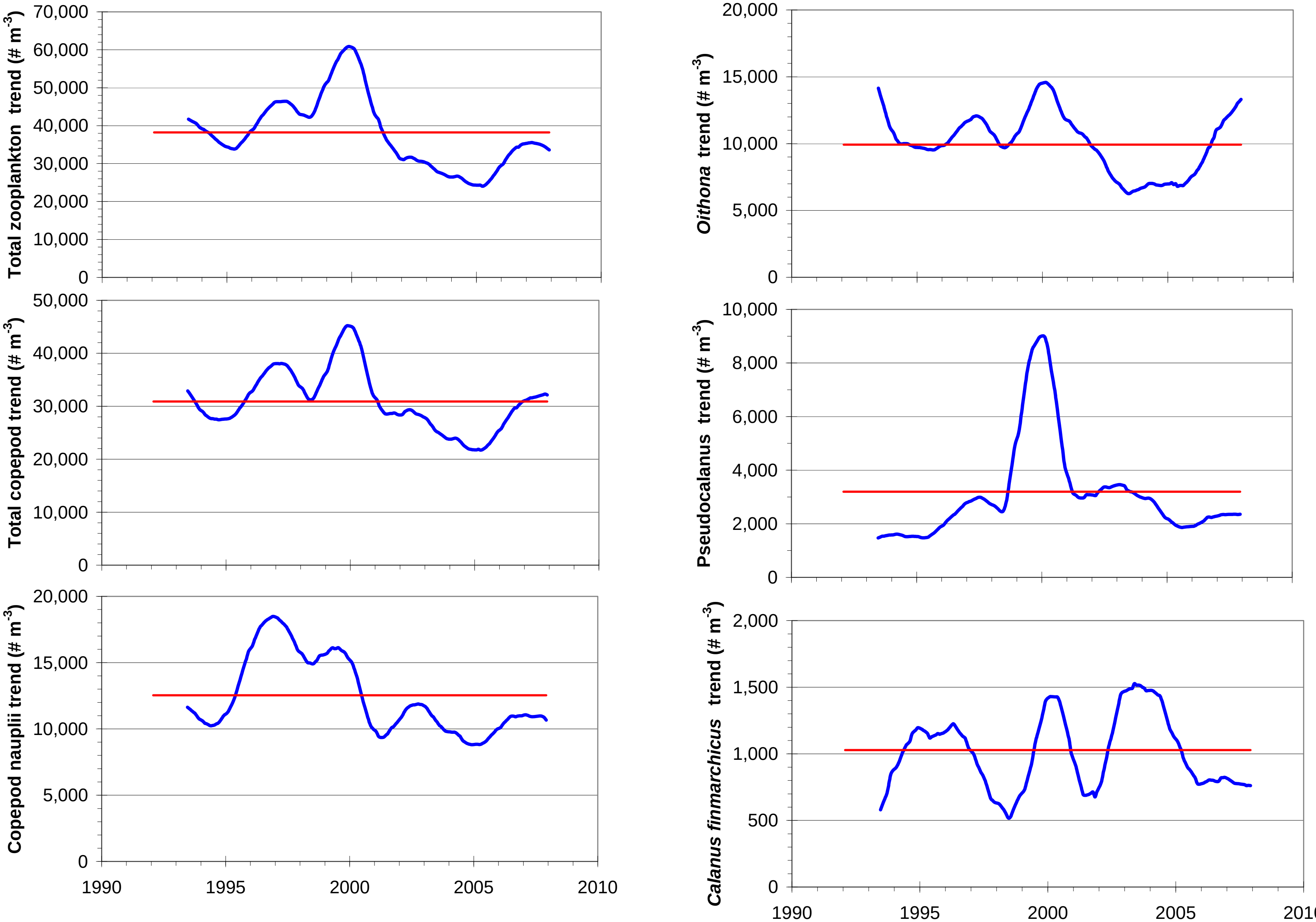



**Total zooplankton, 1992-2008**

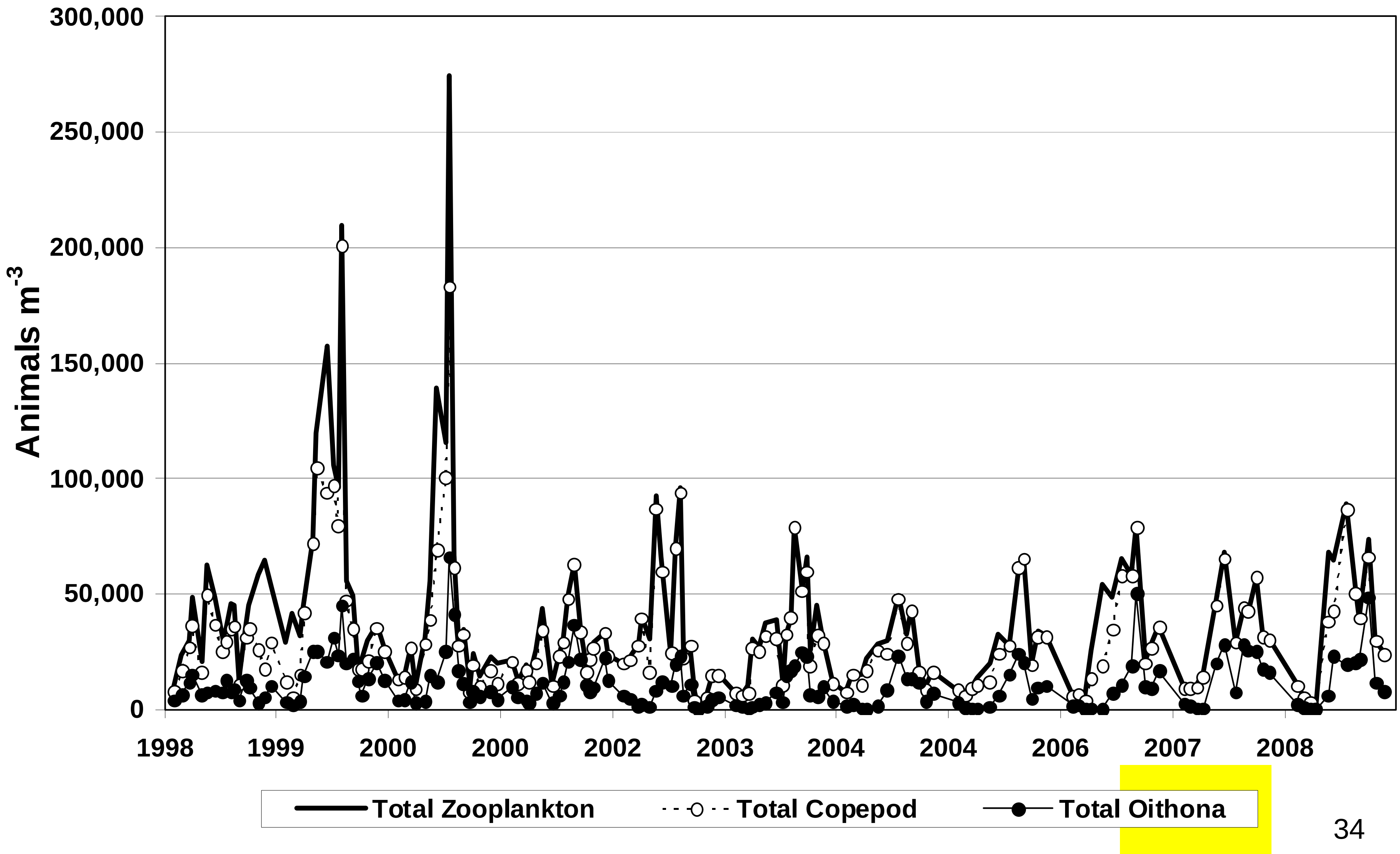


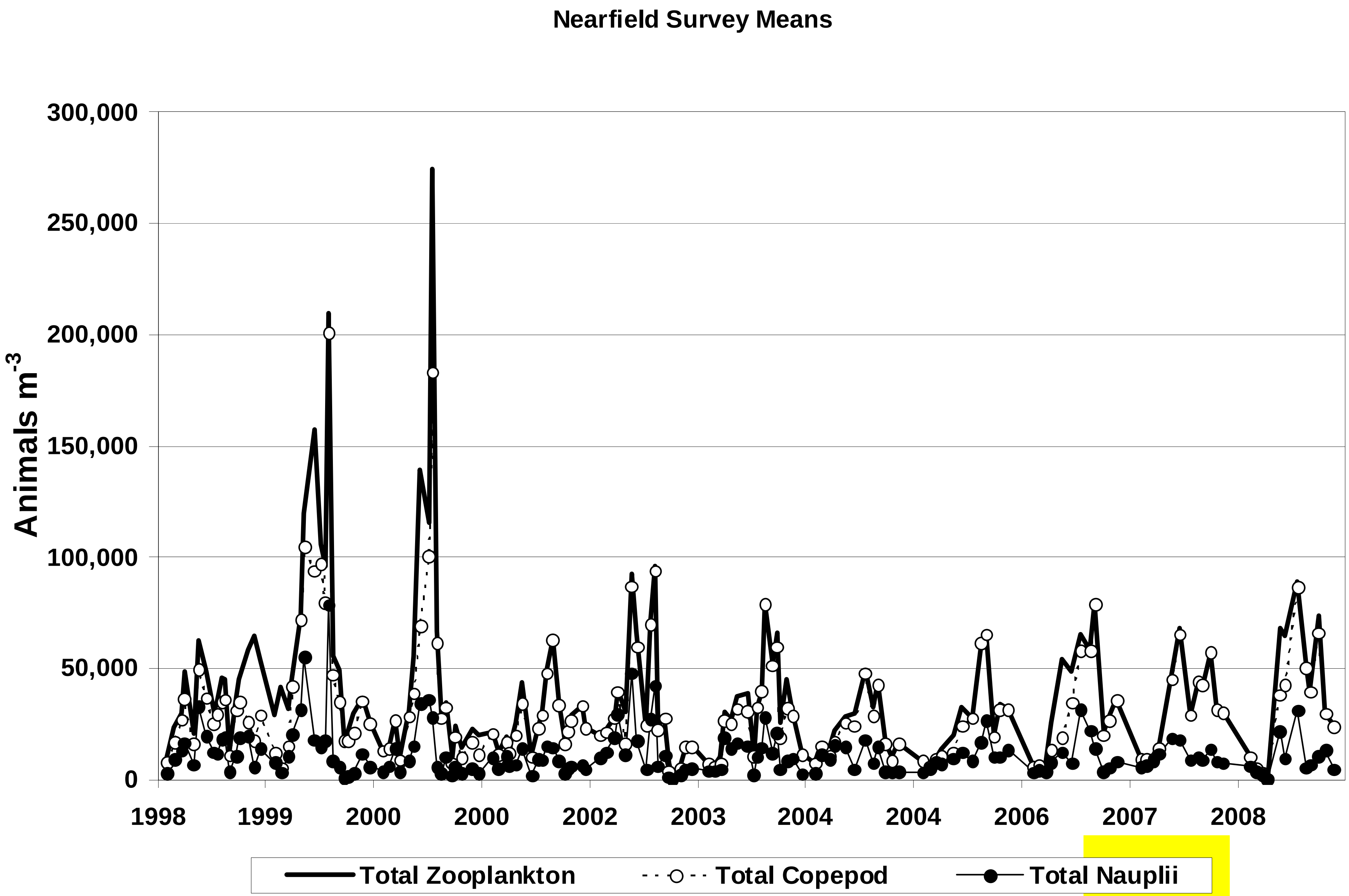

**Nearfield mean trend for total zooplankton abundance**

# Zoo time series from 2007 annual



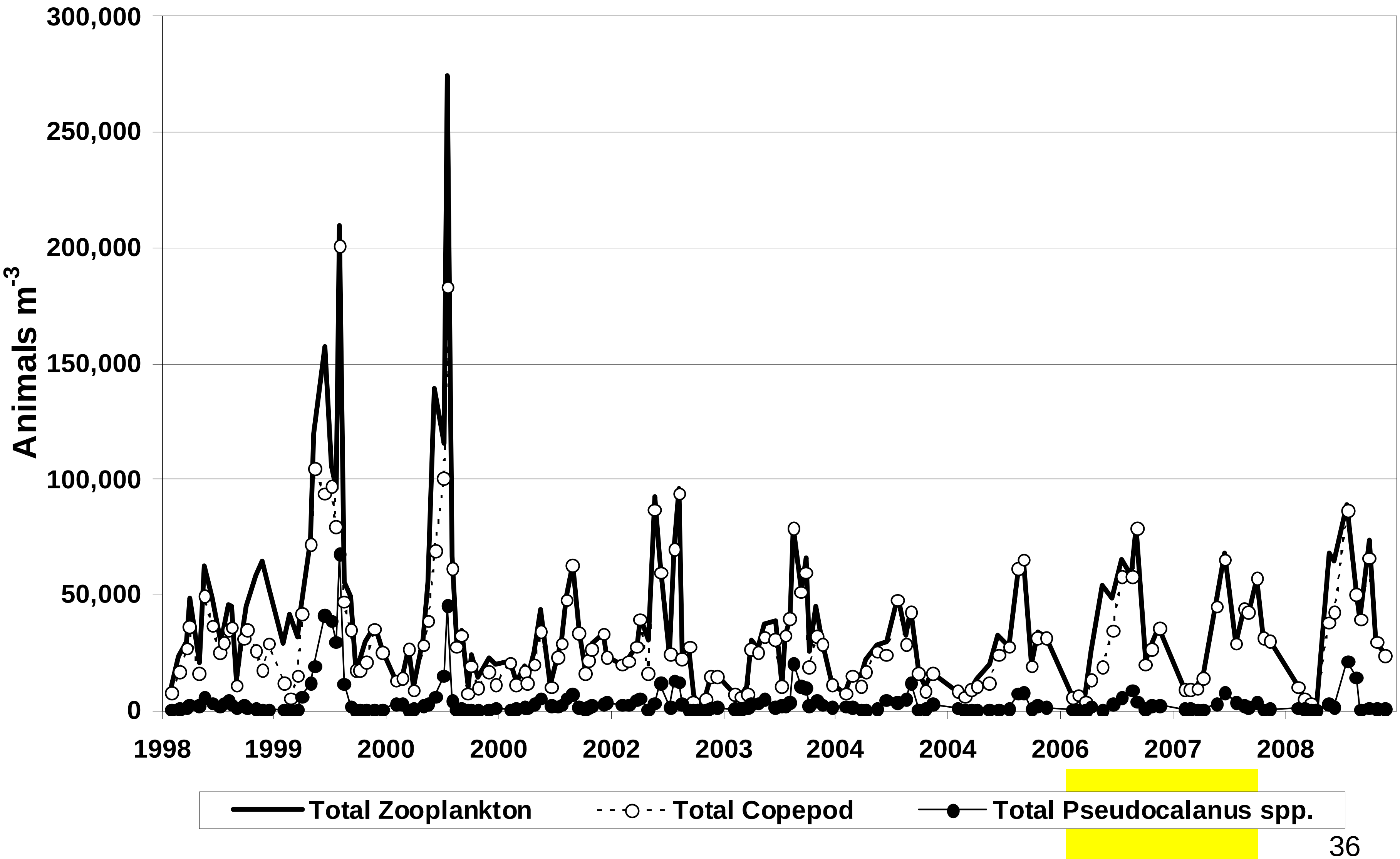
Nearfield Survey Means

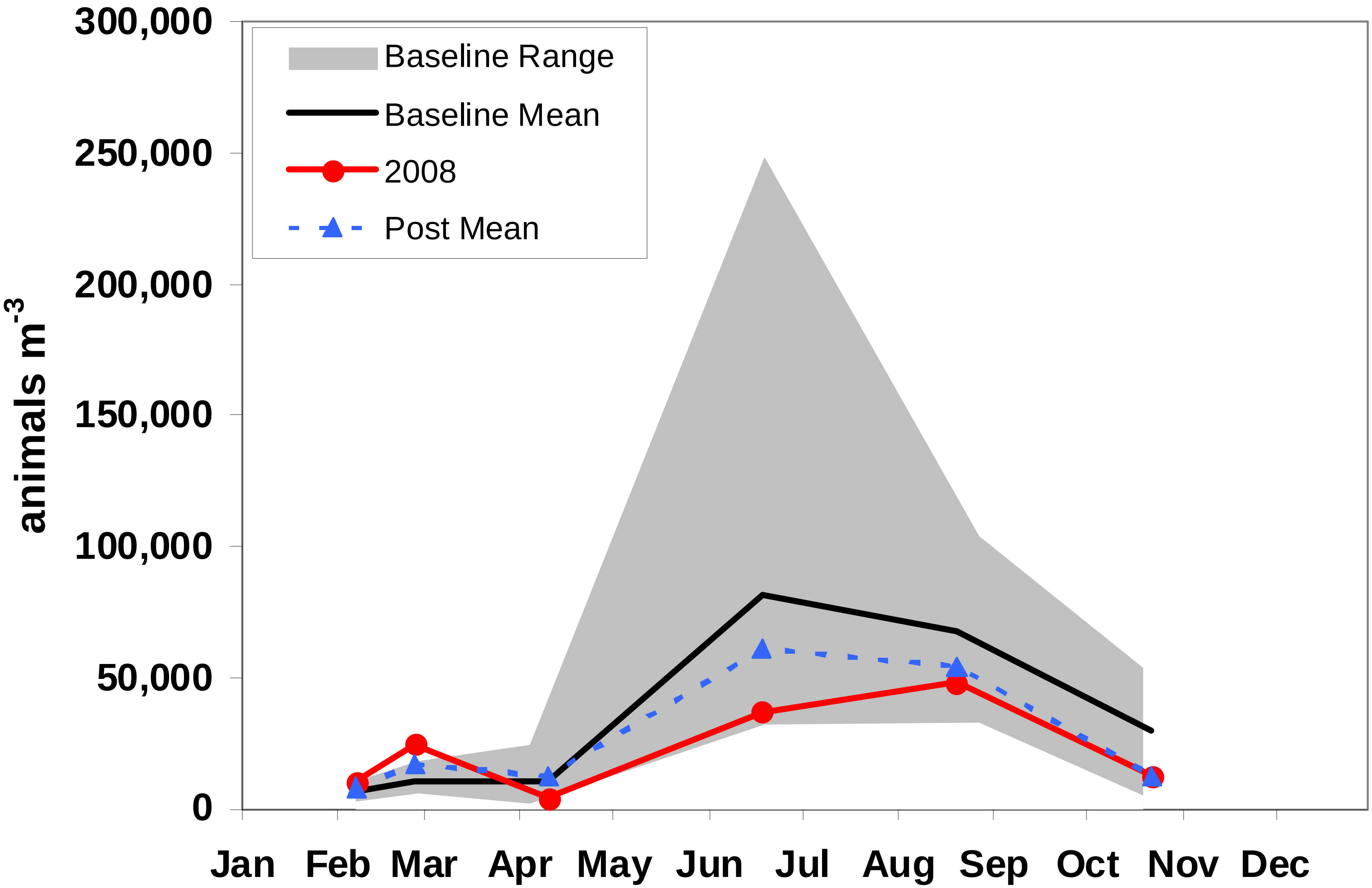




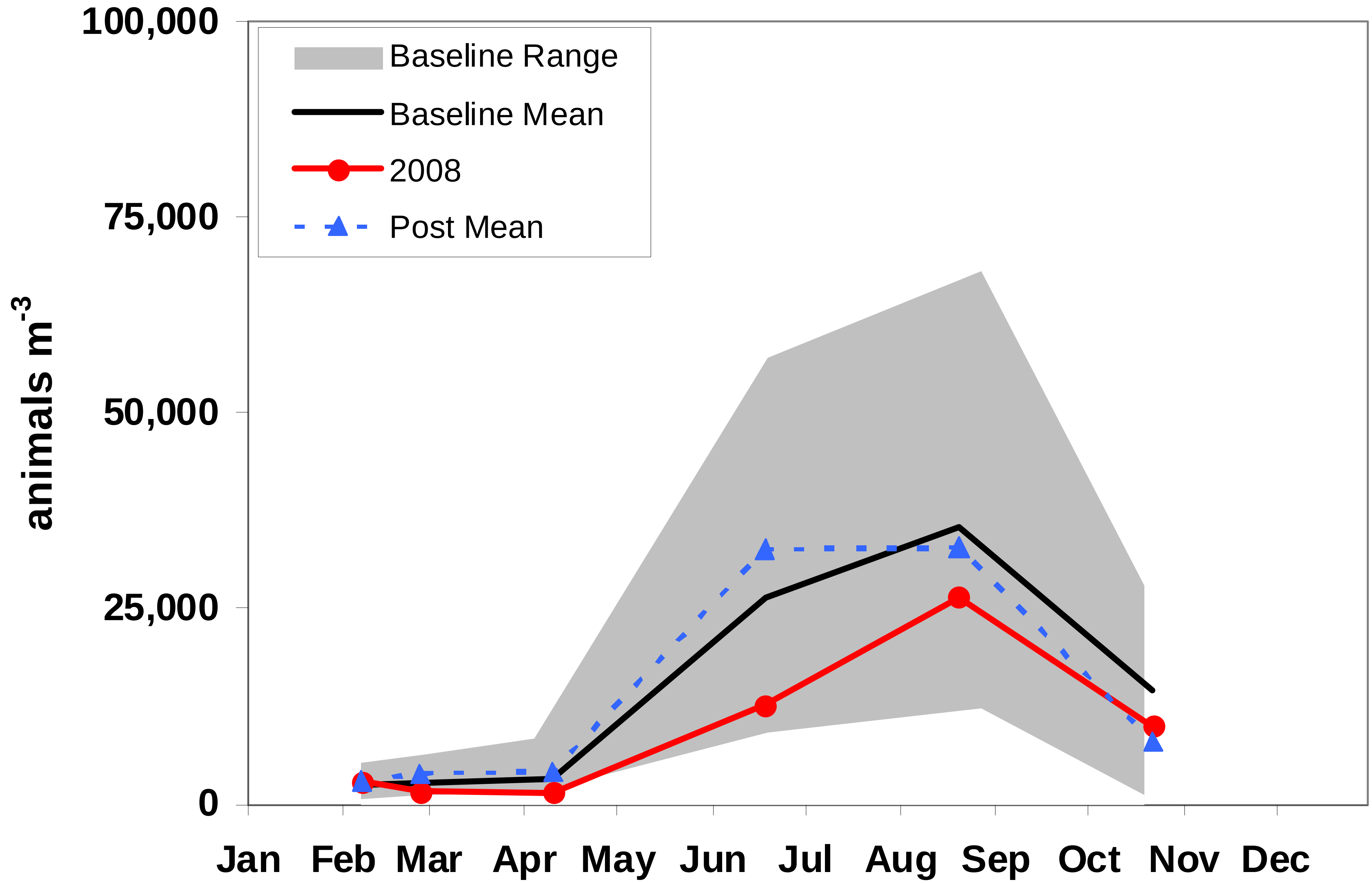
Nearfield Survey Means
300,000
250,000
200,000
150,000
100,000
50,000
0
Animals m-3
1998
1999
2000
2000
2002
2003
2004
2004
2006
2007
2008
Total Zooplankton
Total Copepod
Total Nauplii

## Nearfield Survey Means

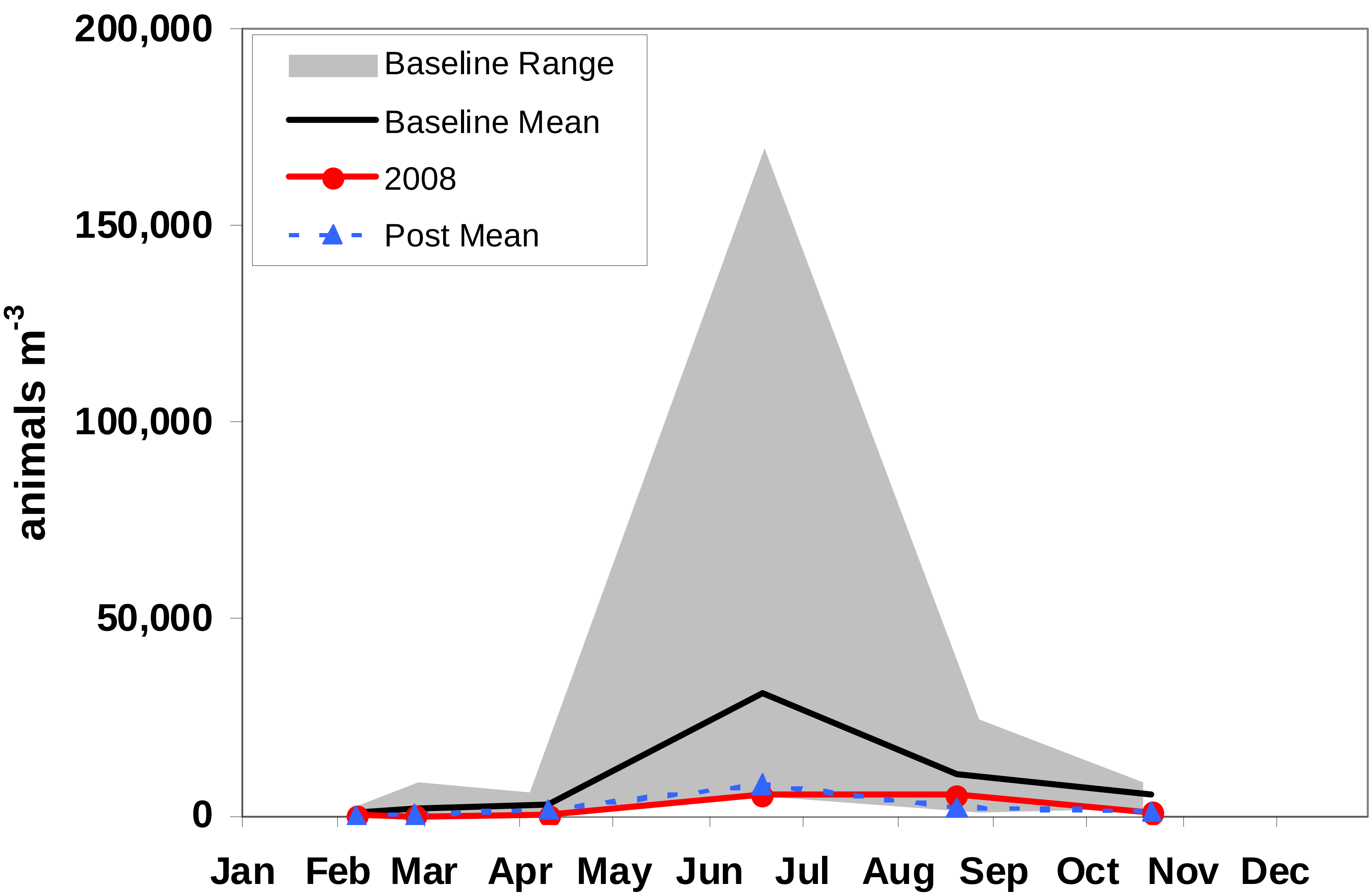




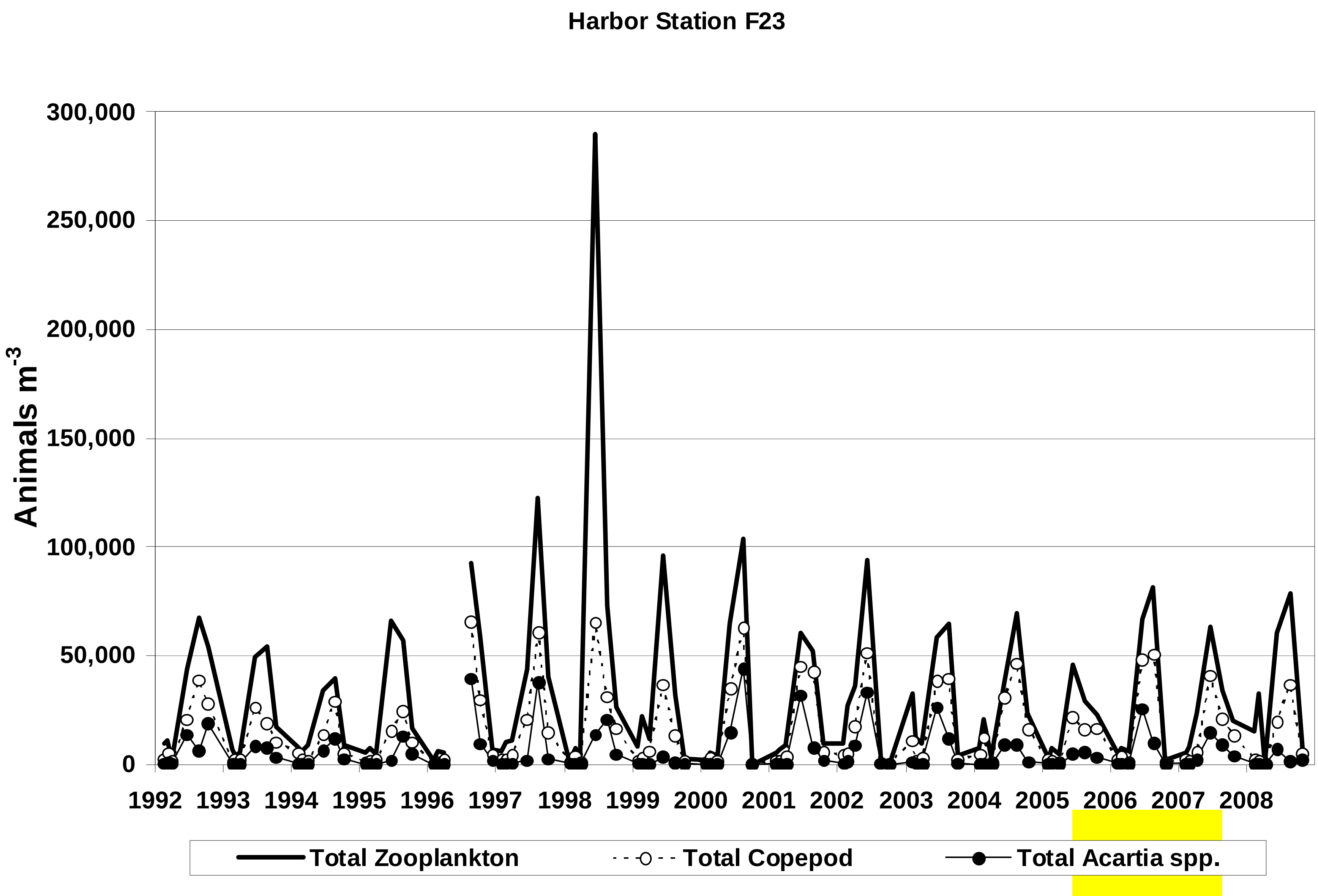

# Total Zooplankton - Harbor




Copepods A&C - Harbor




# Other zoo (Meroplankton) - Harbor


Harbor Station F23
Animals m-3
300,000
250,000
200,000
150,000
100,000
50,000
0
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Total Zooplankton
Total Copepod
Total Acartia spp.

# 2008 Zooplankton Summary

- Zooplankton abundance and species composition were generally similar to most previous years.
- Nearfield mean abundance was within the baseline range, except for being slightly below it in March and April, and slightly above it in September. These departures were driven by *Oithona similis* values.
- Dominant taxa were copepod nauplii and copepodites, primarily those of *Oithona similis*.
- Non-copepods exhibiting sporadic abundance included *Evadne nordmani, Oikopleura dioic*a, and meroplankters such as barnacle nauplii, bivalve and gastropod veligers and polychaete larvae.
- Trends for copepods, primarily driven by *Oithona similis abundance* showed fluctuations around the mean, with continued increases from low values in 2005.

# E. *Alexandrium* Bloom

The 2008 and 2009 *Alexandrium* blooms
Don Anderson, Woods Hole Oceanographic Institution

## E.1. Background

As directed by the Ambient Monitoring Plan and Contingency Plan, the MWRA prepared an *Alexandrium* Rapid Response Plan to evaluate the potential impact of the MWRA outfall on *Alexandrium* blooms within Massachusetts Bay. The *Alexandrium* rapid response is triggered when cell counts within the bay exceed 100 cells per liter, or when shellfish toxicity is measured at sites within the state that suggests that a bloom within the bay is likely.

Following more than a decade in which *Alexandrium* abundance and shellfish toxicity were very low within the bay, major blooms were observed in 2005 and 2006, and again in 2008, all with cell concentrations well above the Contingency Plan Threshold Exceedance level. The bloom of 2008 was significant in several respects. First, very high cell concentrations were observed in Boston Harbor. Second, the scale of the bloom was predicted several months in advance on the basis of resting cyst abundance estimates and numerical model simulations. The following discussion addresses the observations within the bay and adjacent waters, as well as the prediction of that outbreak. The bloom outlook for 2009 is also presented.

## E.2. The 2008 forecast.

The *Alexandrium fundyense* population dynamics model (McGillicuddy *et al*. 2005) is initiated from maps of cyst abundance in the prior year. Comparisons between field observations and model runs indicate that cyst abundance in the mid-coast Maine seedbed is a first-order predictor of regional bloom magnitude, and therefore that observations in the winter of one year can be used to estimate the size of the bloom that might occur in the subsequent year. Note that this does not mean that the cyst abundance correlates with levels or extent of paralytic shellfish poisoning (PSP) toxicity (though that is sometimes the case), as it is possible to have a high abundance of cells in offshore waters that are not delivered to shore (and the toxin monitoring stations) by ocean currents (influenced by wind and other factors).

**Figure 1** shows a map of the *A. fundyense* cysts that were in surface sediments of the Gulf of Maine in late 2007. Also shown are maps for 1997, 2004, 2005, 2006, and 2008. Considerable interannual variability in cyst abundance is evident. Note several features of the cyst data. First, cyst abundance in surface sediments actually decreased by about 50% after the massive 2005 bloom (Anderson *et al*. 2005), suggesting that cyst germination exceeded the input of new cysts from that bloom. This led to a 2006 bloom that was quite large, but not as extensive as the one in 2005. Cyst abundance fell again in 2006, but increased thereafter to historic levels in 2007. Based on the extremely high cyst abundance observed in the fall of 2008, and an ensemble of model runs using the 2007 cyst map with a range of meteorological conditions, an advisory was issued in April 2008 saying that a major regional *Alexandrium* bloom was likely in 2008

## E.3. Field observations.

This forecast was borne out in every way. The bloom began in a typical fashion, with low cell counts and PSP toxicity observed in April and early May along the western Maine coast. On May 6, high PSP was reported at Star Island, NH, and thereafter, the toxicity spread into northern MA and Mass Bay, eventually reaching the Cape Cod Canal. Toxicity was also reported in Pleasant Bay on the outer Cape, and along Monomoy Island, though much of the outer Cape remained toxin free. These shellfish closure data are presented in **Figure 2**, along with similar data for the years 2005 - 2007. MWRA sampled for *Alexandrium* on seven surveys from April to June, and WHOI conducted six surveys from April to July. MWRA conducted a detailed survey in Boston Harbor when toxicity was detected in early June. WHOI combined these survey results into a single dataset, available at
http://science.whoi.edu/users/olga/alex_surveys_2008/WHOI_Alexandrium_Surveys_2008.html

One unique aspect of the 2008 bloom was the high concentration of *Alexandrium* cells observed in Boston Harbor in mid June (**Figure 3**). Concentrations as high as 45-60,000 cells/L were detected, levels that were higher than those observed during the 2005 outbreak. It is unclear why this difference occurred, though comparison of wind patterns between the two years suggests that in 2008 there were more winds out of the South/Southwest in late May and early June. This may have caused surface waters to move out of the bay, being replaced by deeper waters containing high abundance of *Alexandrium* cells. In 2005, the winds were more from the Northeast. In this regard, Boston Harbor may respond differently to winds then the other portions of the Massachusetts coast, where north easterly winds are associated with high levels of toxicity. This hypothesis deserves further scrutiny in the coming years.

## E.4. 2009 Bloom Advisory.

What can we say in advance about the 2009 bloom season? Given the working hypothesis that the size of the mid-Maine cyst population is a predictor of regional bloom magnitude, the cyst abundance shown in **Figure 1** would suggest that 2009 could be a moderate year for toxicity. To be more quantitative, the *Alexandrium* population dynamics model was run using the 2008 cyst map as input, forced by the weather and oceanographic conditions of 2004 to 2008. In all cases, the simulations suggest a moderate year of toxicity – similar perhaps to 2006, when much of the Maine, New Hampshire, and Massachusetts coasts were closed to harvesting of shellfish (**Figure 2**). We are not able to predict short-term weather patterns (such as the frequency and strength of northeast storms that cause downwelling and shoreward transport of water and cells), so we are not willing to issue a firm forecast. Instead we have issued an advisory to the management community and other scientists that there is a significant possibility of a large regional bloom in 2009 (See press release at
<http://www.whoi.edu/page.do?pid=7545&tid=282&cid=56847&ct=162>http://www.whoi.edu/page.do?pid=7545&tid=282&cid=56847&ct=162). This forecast is also consistent with an apparent upward trend in overall PSP toxicity in the western Gulf of Maine region that began in late 2003 and 2004, following a decade or more of low toxicity years (unpublished data).

In summary, modeling efforts and our conceptual understanding of *A. fundyense* dynamics in the Gulf of Maine have progressed to the point where we can issue both long- and short-term advisories of bloom magnitude. It is also possible to provide near real-time maps of potential cell distributions along the coast, working from an annual cyst map from the preceding fall.

Through data assimilation techniques, these latter forecasts could be made even more accurate once remote, automated cell detection of *A. fundyense* becomes a reality (Scholin *et al.* 2009).

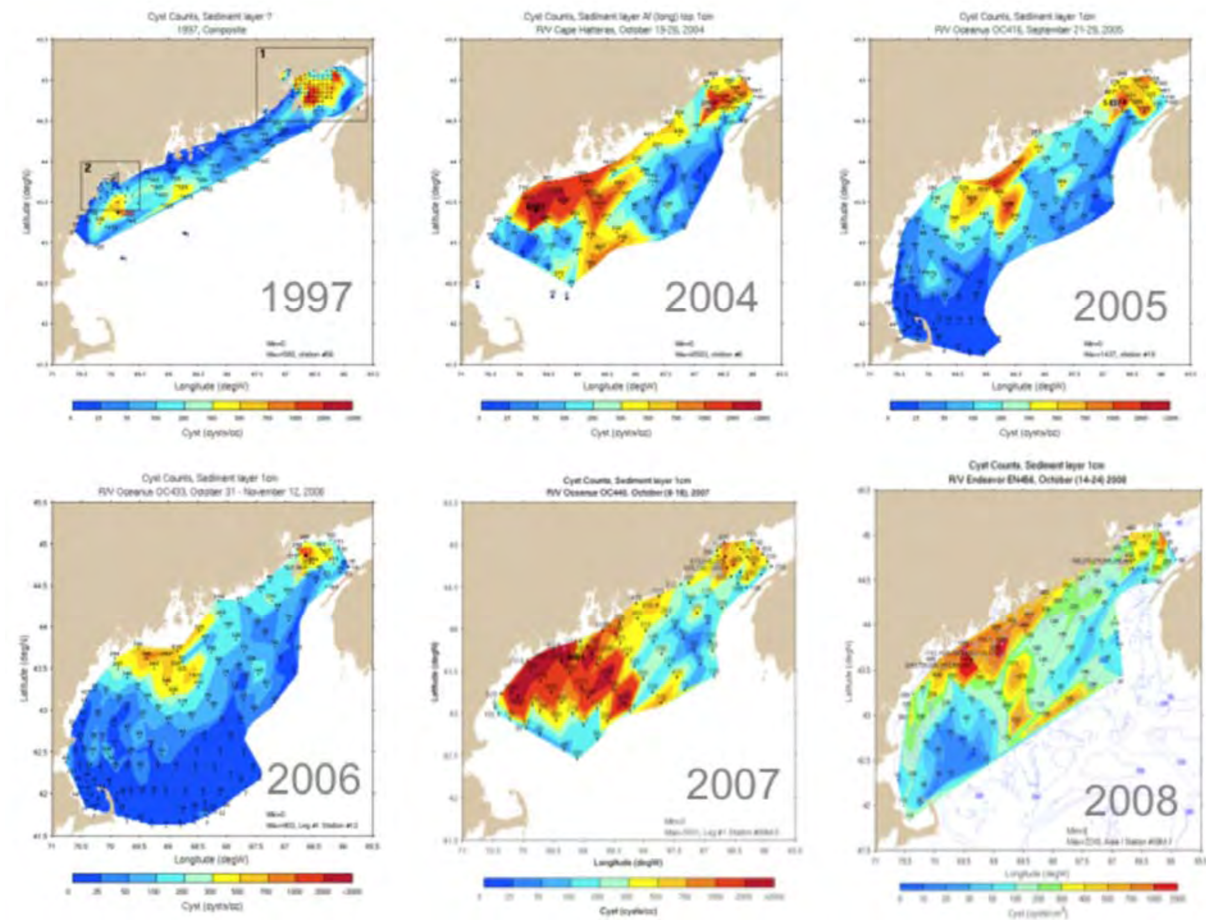



**Figure 1**. Maps of *Alexandrium fundyense* cyst abundance (cysts $cm^{-2}$) in surface sediments of the Gulf of Maine for 1997, 2004, 2005, 2006, 2007, and 2008. (D.M. Anderson, unpub. data).


**Figure 2**. Harvesting closures (red lines and red and blue boxed area) resulting from the blooms of *Alexandrium fundyense* in the Gulf of Maine, 2005 - 2008. In every respect, the 2008 outbreak was a large regional bloom, consistent with the prediction or forecast described in the text.

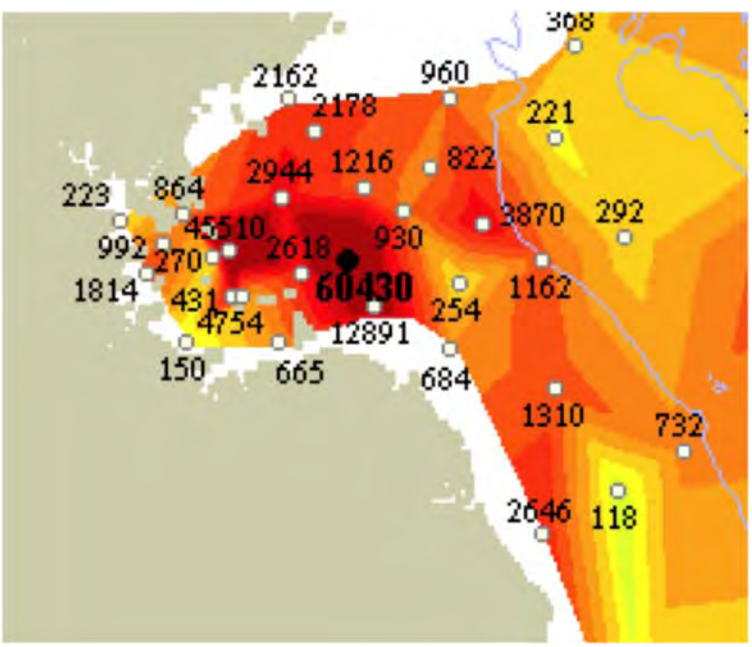
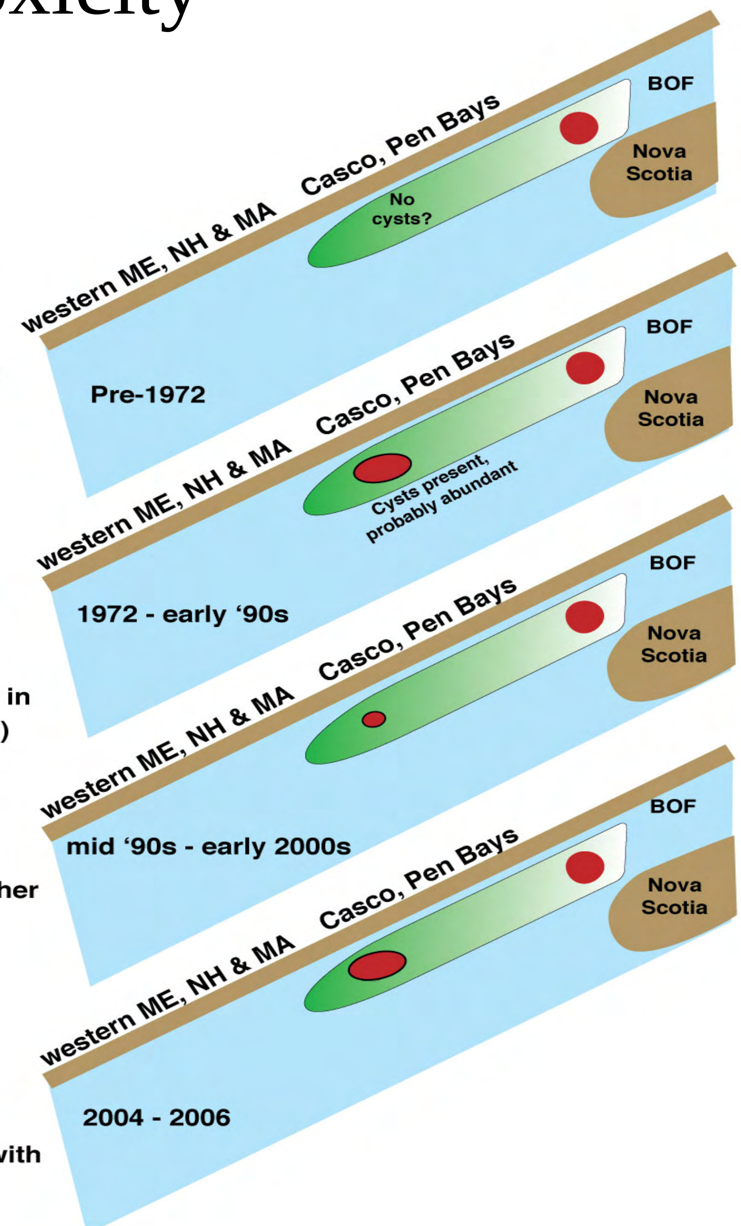



**Figure 3**. *Alexandrium* fundyense cell concentrations observed in Boston Harbor, June 2008.

# Intrannual variability in cyst abundance and PSP toxicity



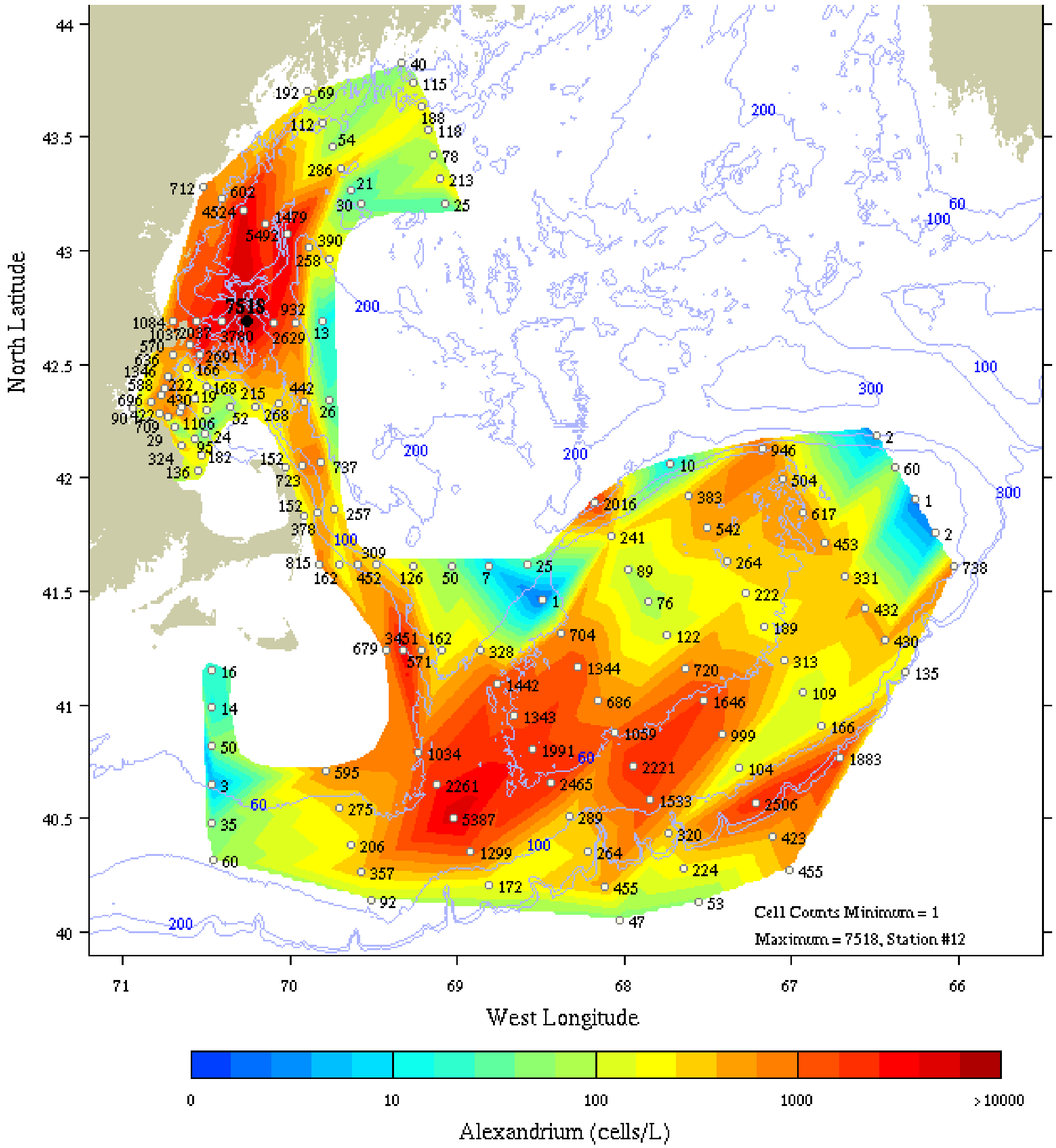

**Pre 1972**: Cysts present in BOF, but not abundant in western GOM

**1972 - early '90s**: Cysts accumulate in WGOM due to 1972 bloom and subsequent blooms; start of 70's, 80's "regime" of frequent and high toxicity in western GOM. Gradual (or precipitous) decline in cyst abundance.

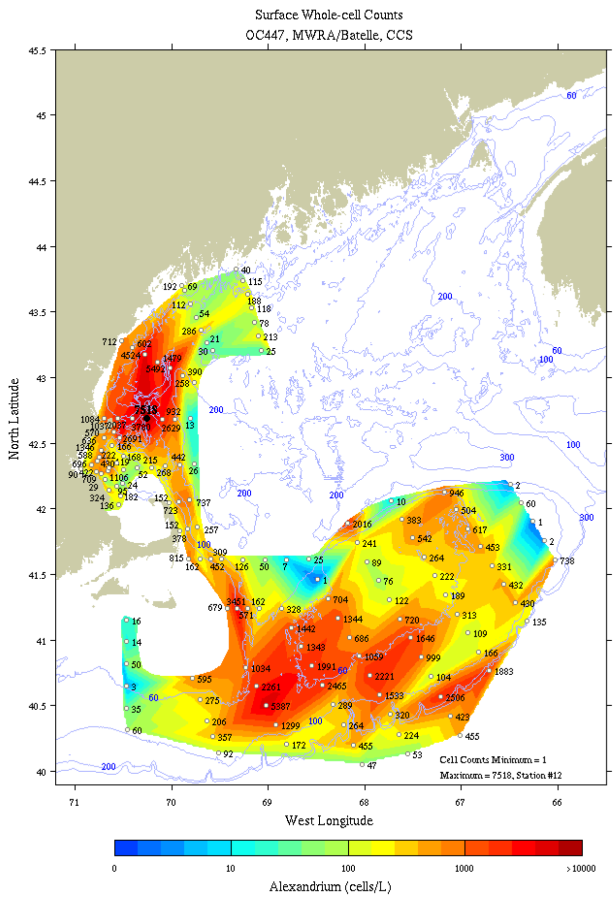
**mid '90s - early 2000s**: Low abundance of WGOM cysts in 1997 and maybe other years; low toxicity in WGOM

**2004 - 2006**: Cysts abundant in WGOM once again; start of 2000's "regime" with high toxicity in the WGOM.

# May 27-29


North Latitude
44
43.5
43
42.5
42
41.5
41
40.5
40
West Longitude
71
70
69
68
67
66
Cell Counts Minimum = 1
Maximum = 7518, Station #12
0
10
100
1000
> 10000
Alexandrium (cells/L)

# The 2008 (and 2009) *Alexandrium* bloom




**Donald M. Anderson- Woods Hole Oceanographic Institution**

**Scott Libby - Battelle, Brunswick, ME**

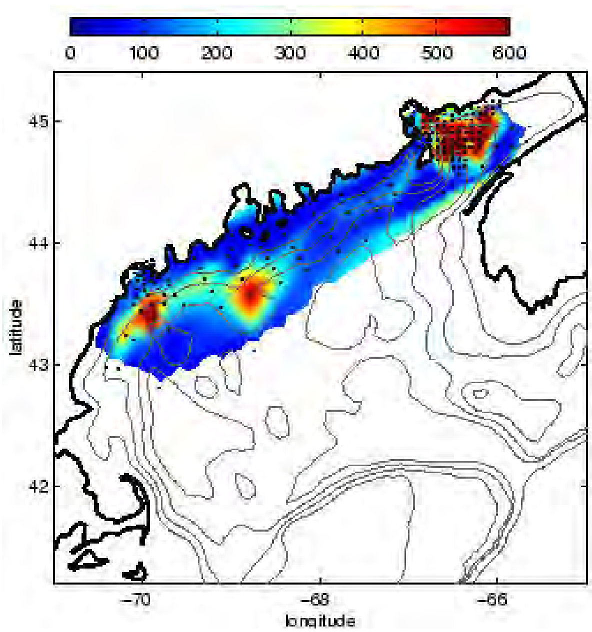
# Overview of MWRA's Involvement

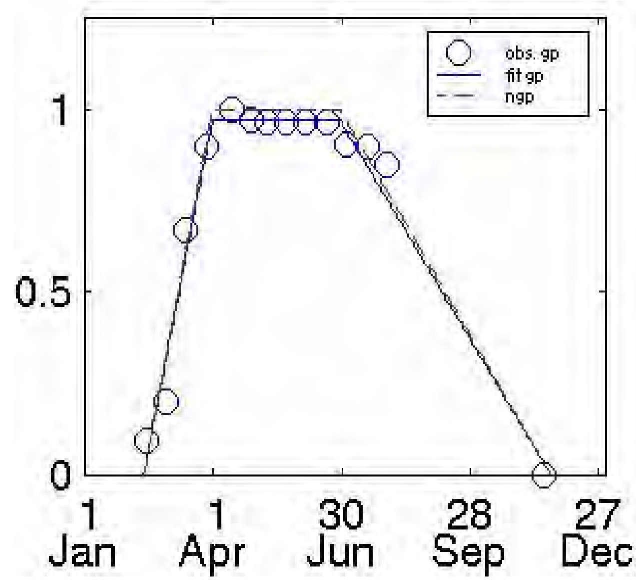
- **Ambient Monitoring Plan and Contingency Plan call on MWRA to support targeted *Alexandrium* monitoring**
  - **Development of the *Alexandrium* Rapid Response Plan**
    - **Gain a better understanding of bloom dynamics and**
    - **Evaluate the potential impact of MWRA outfall**

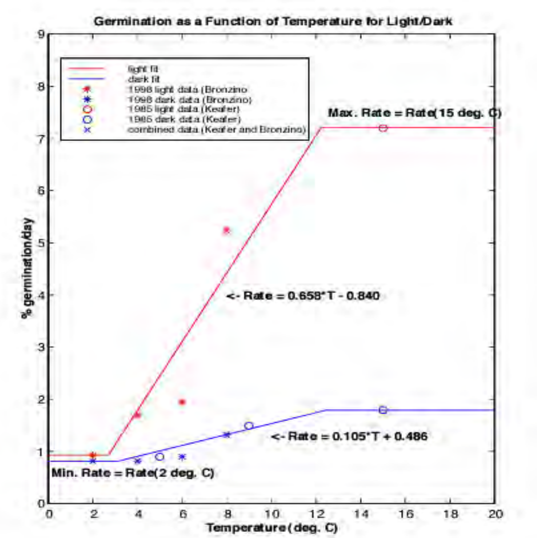
**So what happened in 2008?**
**– A major regional red tide, with high toxicity in Mass Bay and Boston Harbor**

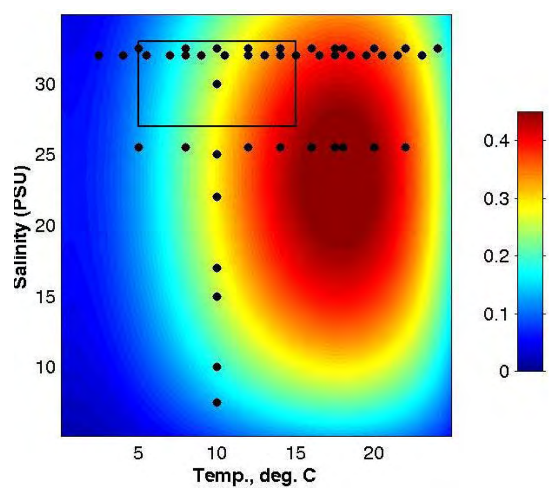
# But first – the 2008 forecast/advisory

# *Alexandrium* Population Dynamics Model



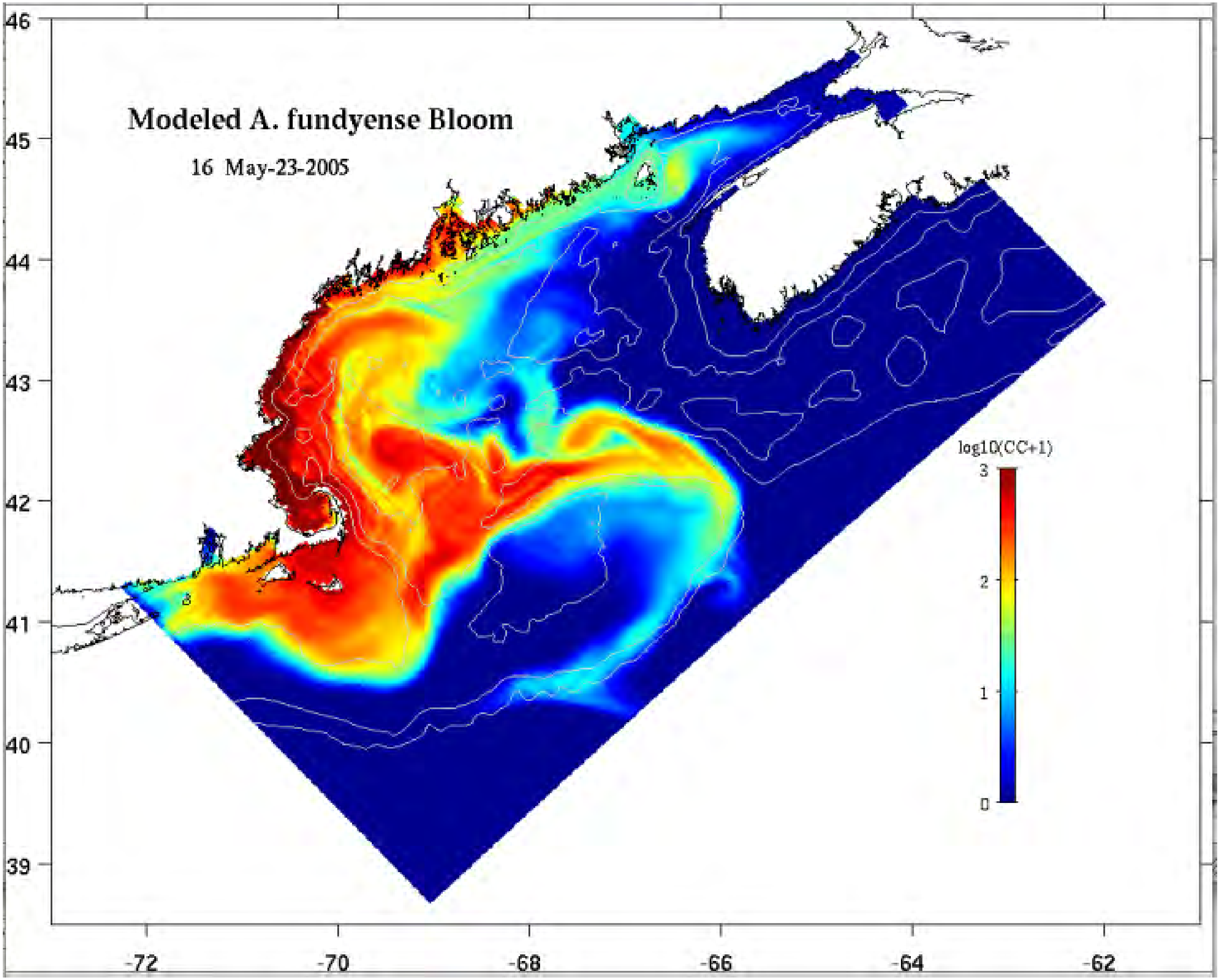



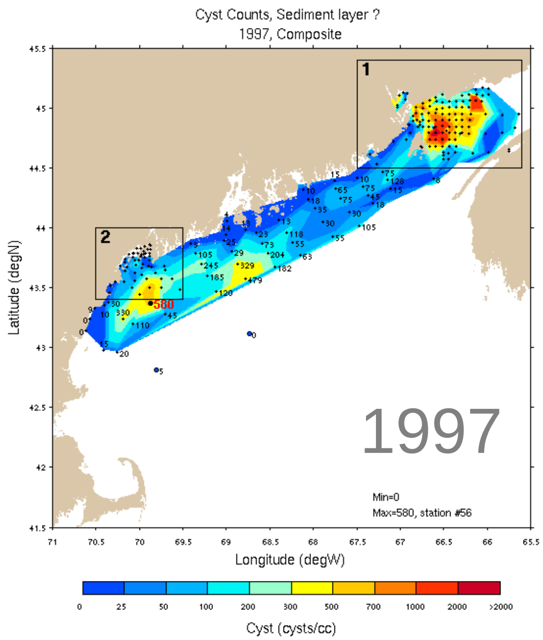

Growth = min ( f(PAR) , g(T,S) )

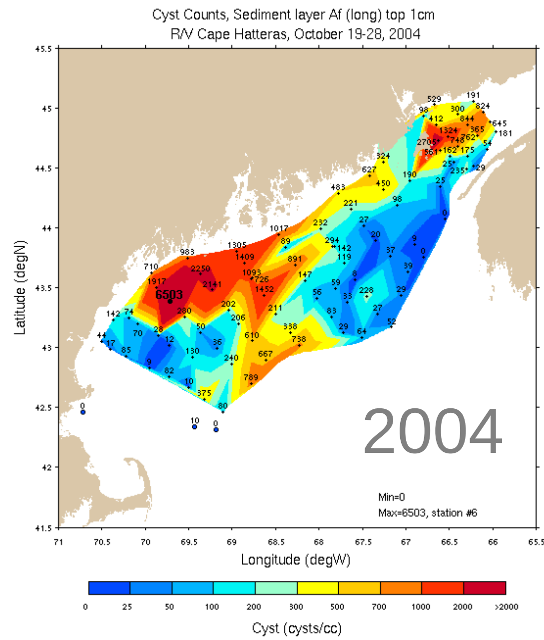
Upward swimming 10 m/day

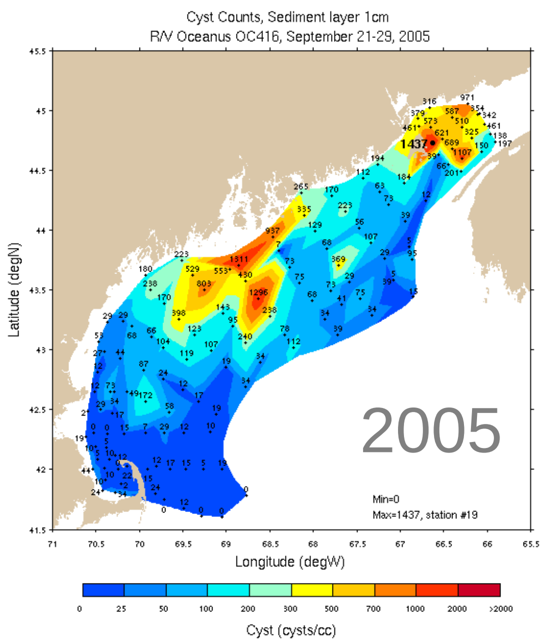
“Mortality” = 0.1 per day, with a temperature dependence

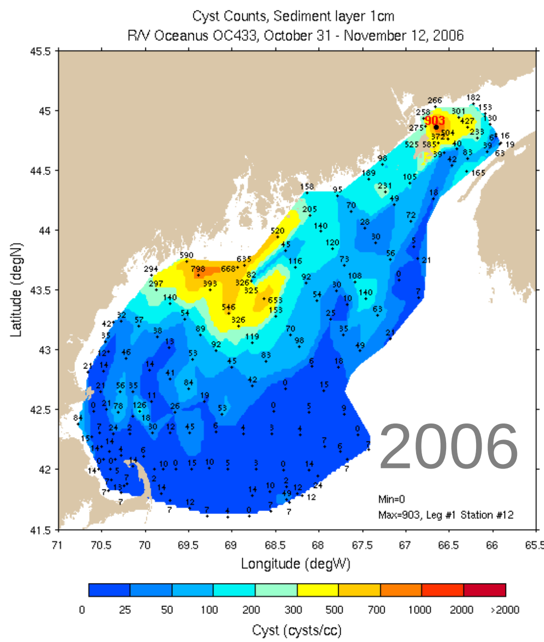

Modeled A. fundyense Bloom
16 May-23-2005
log10(CC+1)
3
2
1
0
46
45
44
43
42
41
40
39
-72
-70
-68
-66
-64
-62

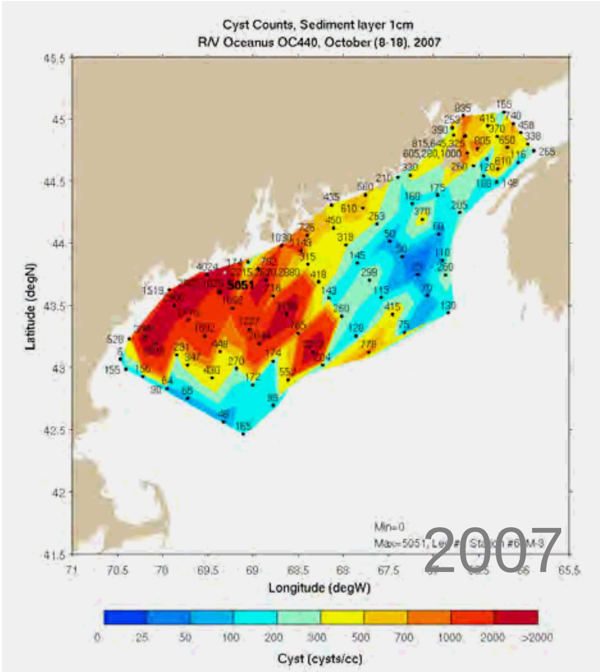
# Interannual variations in cyst abundance



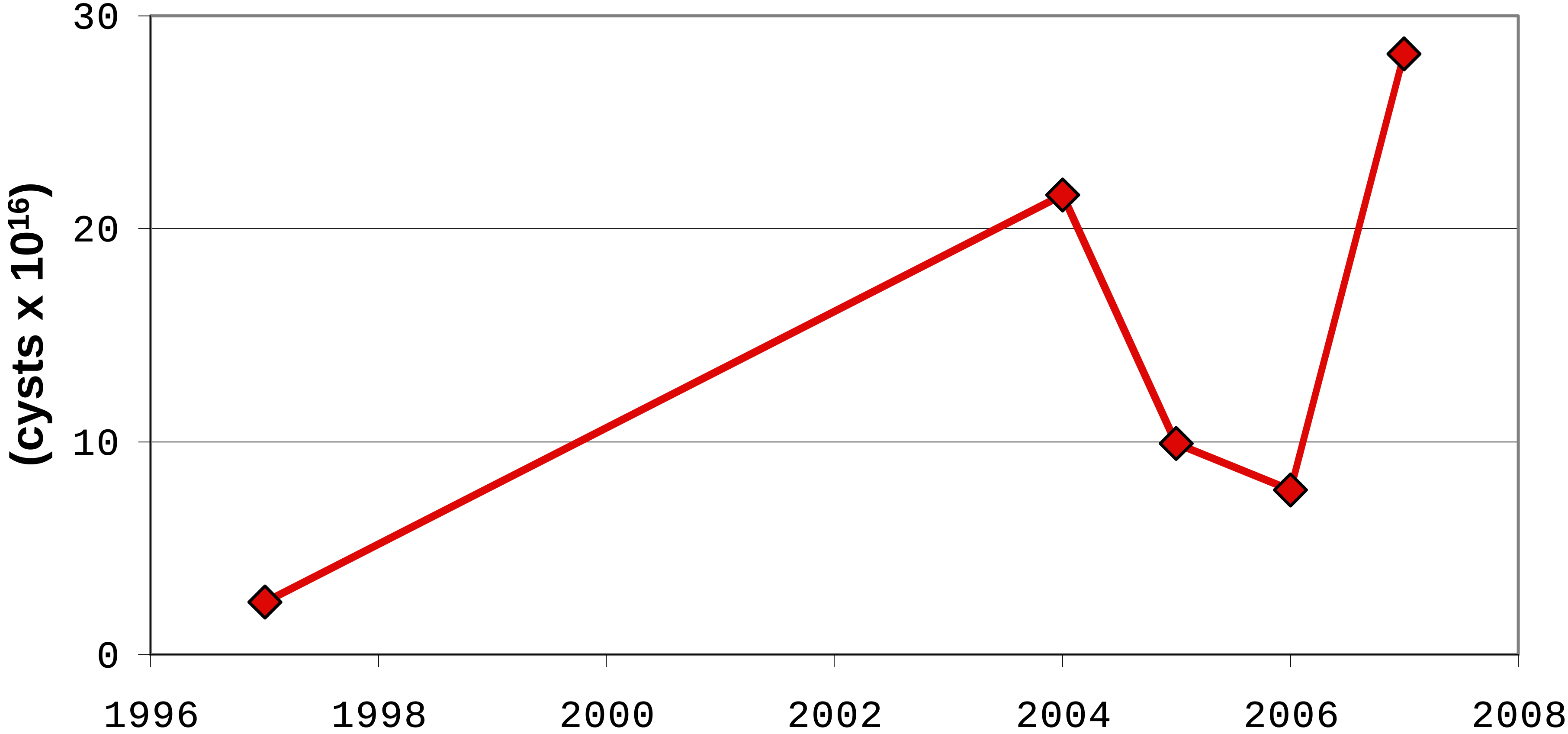



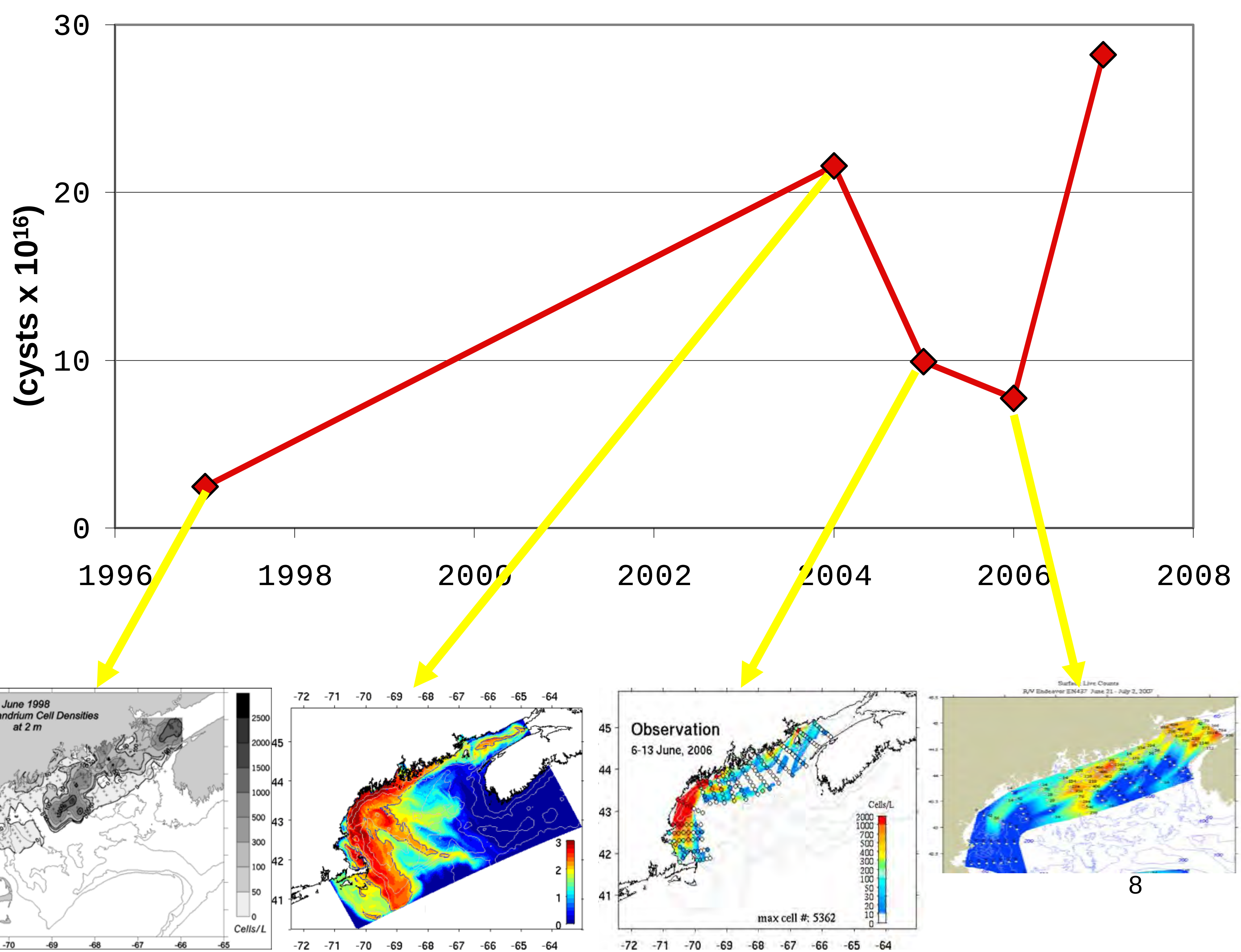



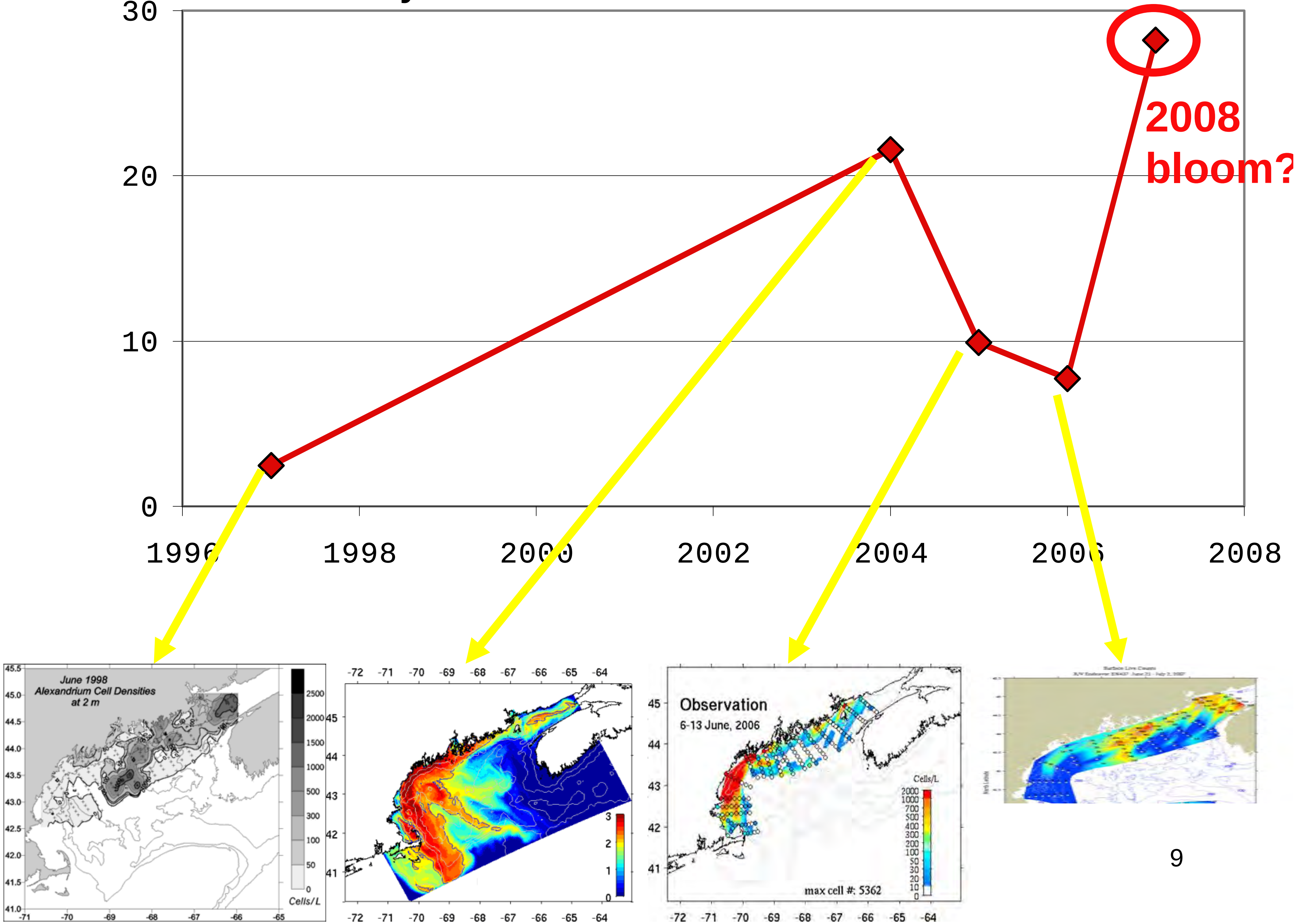



# Cyst abundance in Gulf of  Maine sediments (top cm)

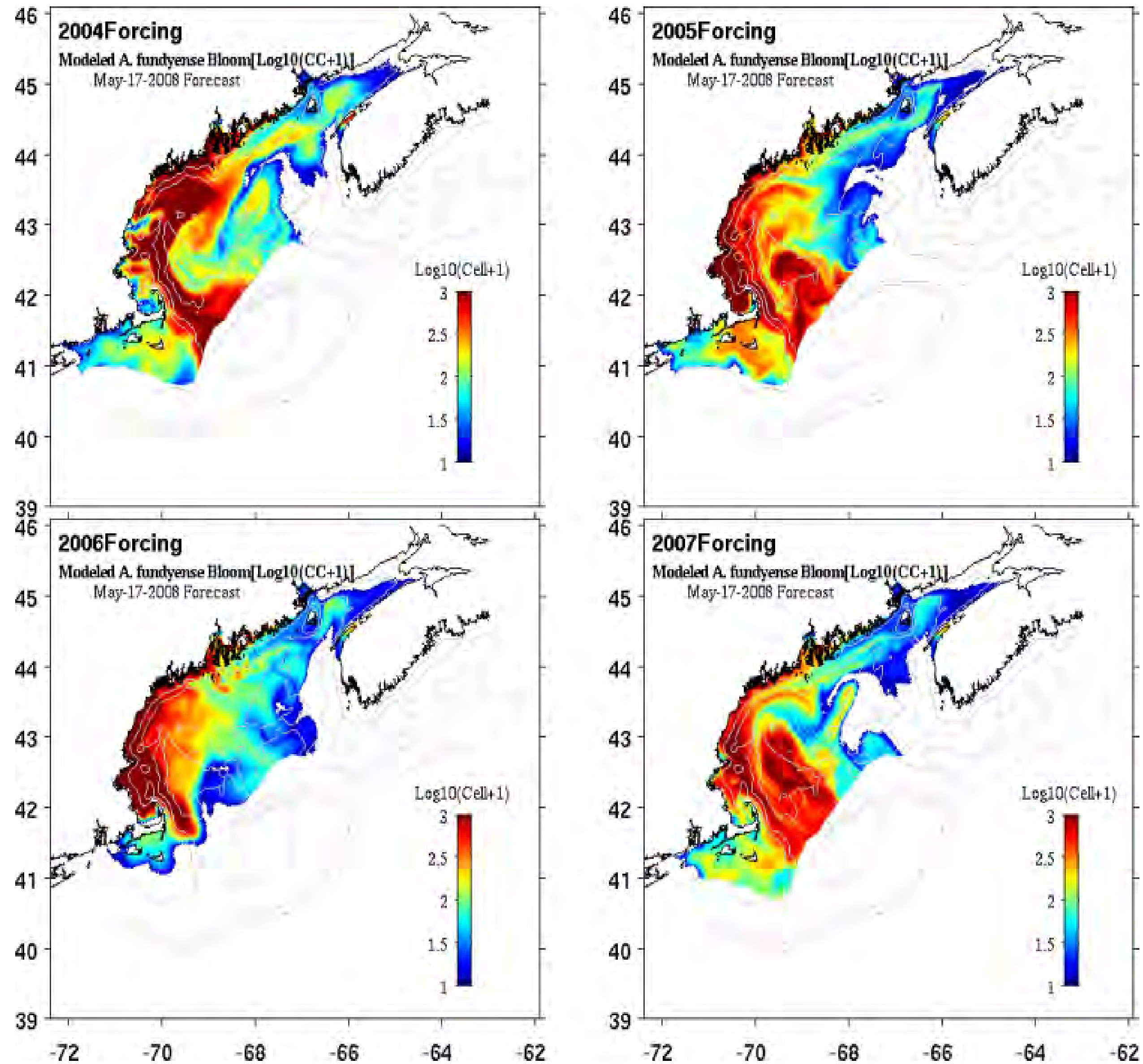



(cysts x 10^16)
30
20
10
0
1996
1998
2000
2002
2004
2006
2008
June 1998
Alexandrium Cell Densities
at 2 m
Cells/L
Observation
6-13 June, 2006
Cells/L
max cell #: 5362

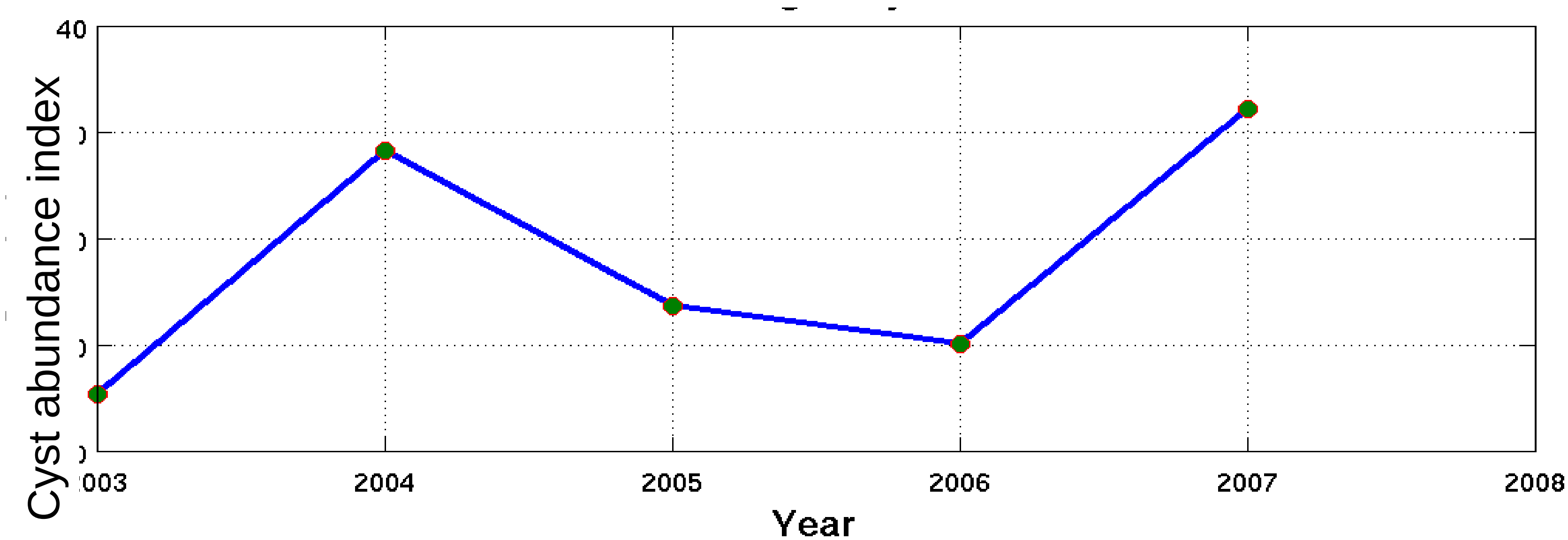
# Cysts in surface cm of GOM sediments

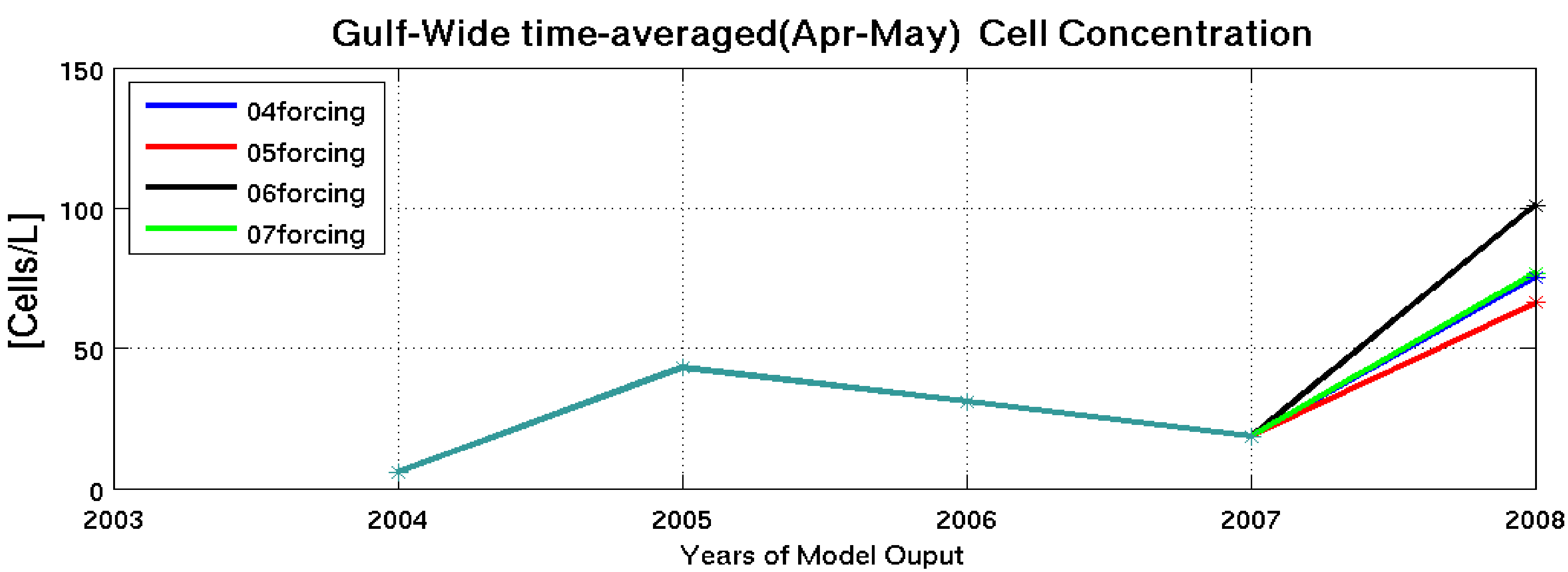


# Model runs – 2004 – 2007 weather, tides, etc., but all using the 2007 *Alexandrium* cyst map



# Impact of cyst abundance on the next year's bloom



# WOODS HOLE OCEANOGRAPHIC INSTITUTION



## News Release : In Computer Models and Seafloor Observations, Researchers See Potential for Significant 2008 "Red Tide" Season

***Conditions are ripe for another large bloom in New England waters; weather and ocean conditions will determine outcome***

Printer-friendly | E-mail to a friend
font size: T T T

FOR IMMEDIATE RELEASE
(508) 289-3340
media@whoi.edu

April 24, 2008
Media Relations Office
Bell House MS #54
Woods Hole Oceanographic Institution

Source: Media Relations

The end of April usually brings the first signs of harmful algae in New England waters, and this year, a research team led by the Woods Hole Oceanographic Institution (WHOI) is preparing for a potentially big bloom.

A combination of abundant beds of algal seeds and excess winter precipitation have set the stage for a harmful algal bloom similar to the historic "red tide" of 2005, according to WHOI biologist Don Anderson, principal investigator of the Gulf of Maine Toxicity (GOMTOX) study. The 2005 bloom shut down shellfish beds from the Bay of Fundy to Martha's Vineyard for several months and caused an estimated $50 million in losses to the Massachusetts shellfish industry alone.

Weather patterns and ocean conditions over the next few months will determine whether this year's algal growth approaches the troubles of 2005.

Oceanographers Dennis McGillicuddy (WHOI) and Ruoying He (North Carolina State University) are several years along in the development of a computer model to predict the intensity and location of blooms of the toxic algae *Alexandrium fundyense* in the Gulf of Maine.

Scientists are reluctant to make a "forecast" of precisely where and when the bloom will make landfall because bloom transport depends on weather events that cannot be predicted months in advance. However, colleagues in coastal management and fisheries believe that the regional-scale, seasonal forecast that McGillicuddy and colleagues produce can be useful in preparing for contingencies.

"With advance warning of a potentially troublesome year for algae, shellfish farmers and fishermen might shift the timing of their harvest or postpone plans for expansion of aquaculture beds," said Anderson, a WHOI senior scientist in the Biology Department and director of the Coastal Ocean Institute.

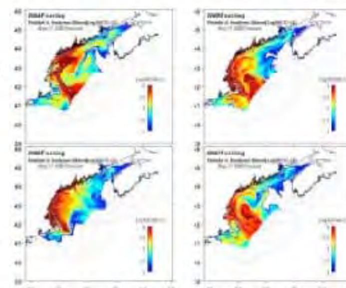
"Restaurants might make contingency plans for supplies of seafood during the summer," Anderson added, "and state agencies can ensure they have adequate staff for the significant monitoring efforts that might be required to protect public health and the shellfish industry."

Seeds or "cysts" of *A. fundyense* naturally germinate and turn into cells that swim up from the seafloor around April 1 of each year. By the end of April, cells usually begin to appear in large numbers in the waters off coastal Maine.

The algae are notorious for producing a toxin that accumulates in clams, mussels, and other shellfish and can cause paralytic shellfish poisoning (PSP) in humans who consume them.

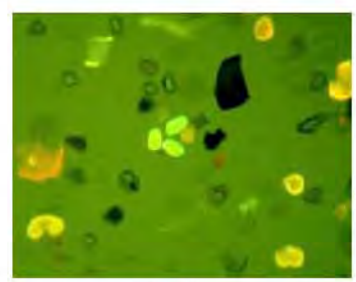
According to a seafloor survey conducted in the fall of 2007 by Anderson's team, the number of *Alexandrium* cysts—the dormant, seed-like stage of the algae's life-cycle—is more than 30 percent higher than what was observed in the sediments prior to the historic bloom of 2005.

The seed beds were especially rich in mid-coast Maine, origin of many of the cells that affect western Maine, New Hampshire, and Massachusetts.



Enlarge Image

Maps show the results of four different runs of a computer simulation of the cell concentrations of *Alexandrium fundyense* under four different weather scenarios. (Graphic by Dennis McGillicuddy, Woods Hole Oceanographic Institution, and Ruoying He, North Carolina State University)

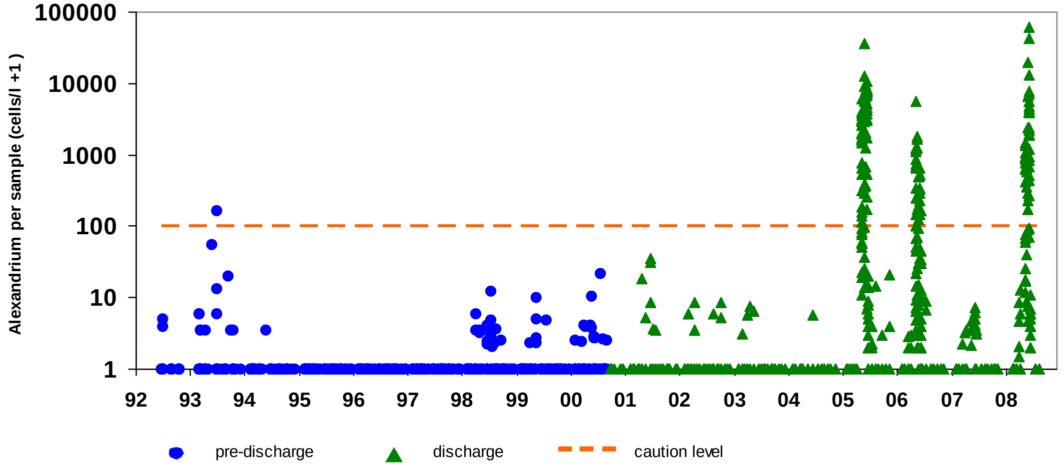


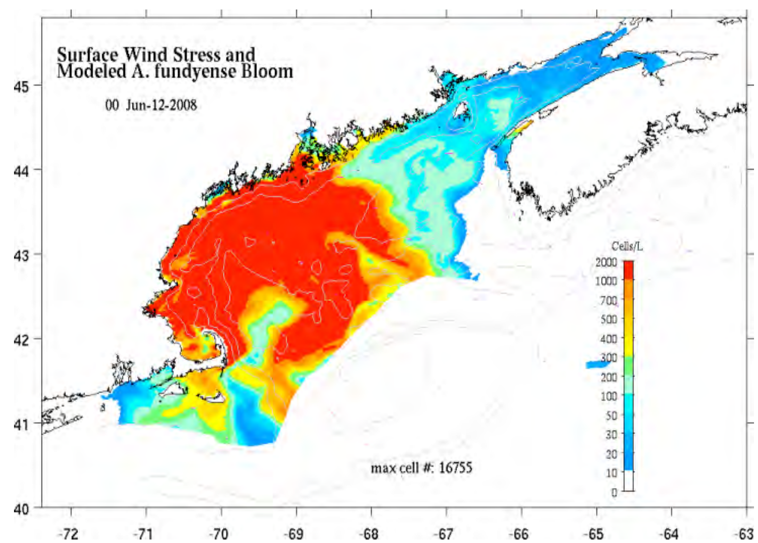
Enlarge Image

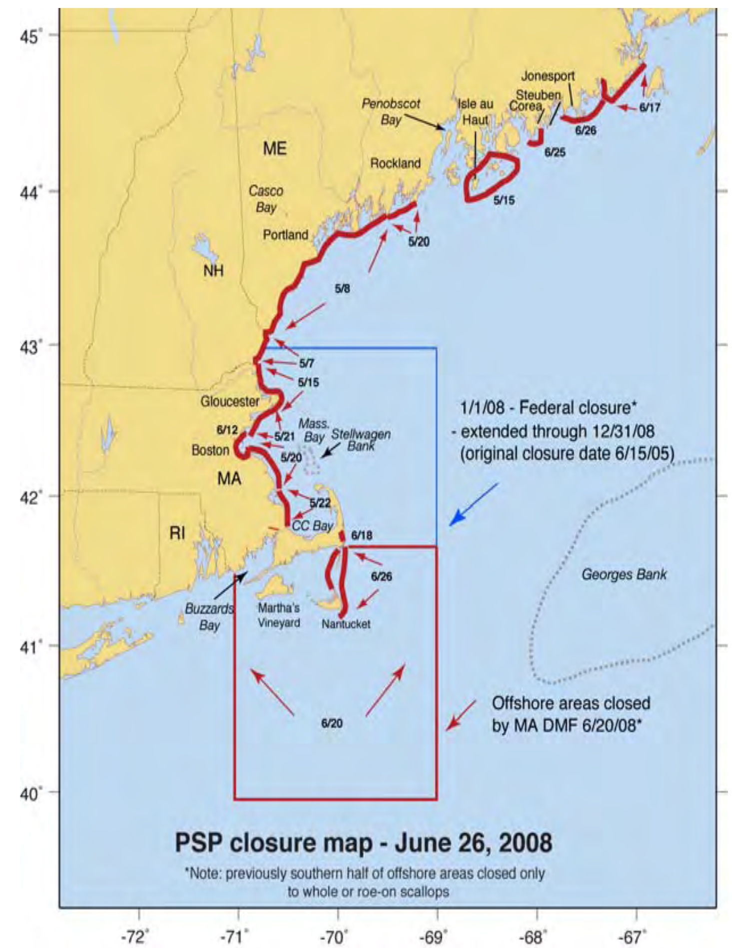
Stained with primulin dye and viewed under a microscope, cysts of *Alexandrium fundyense* and

Done

# The 2008 *Alexandrium fundyense* bloom

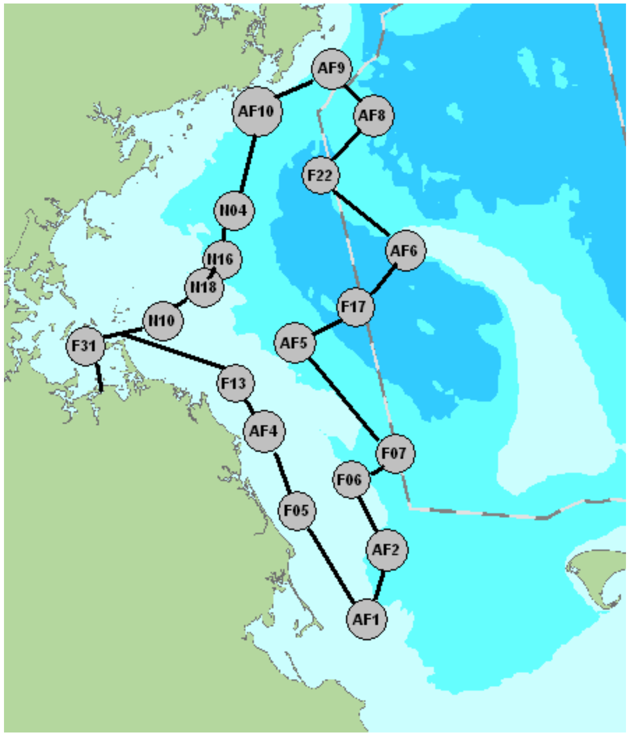


# 2008 *Alexandrium* chronology

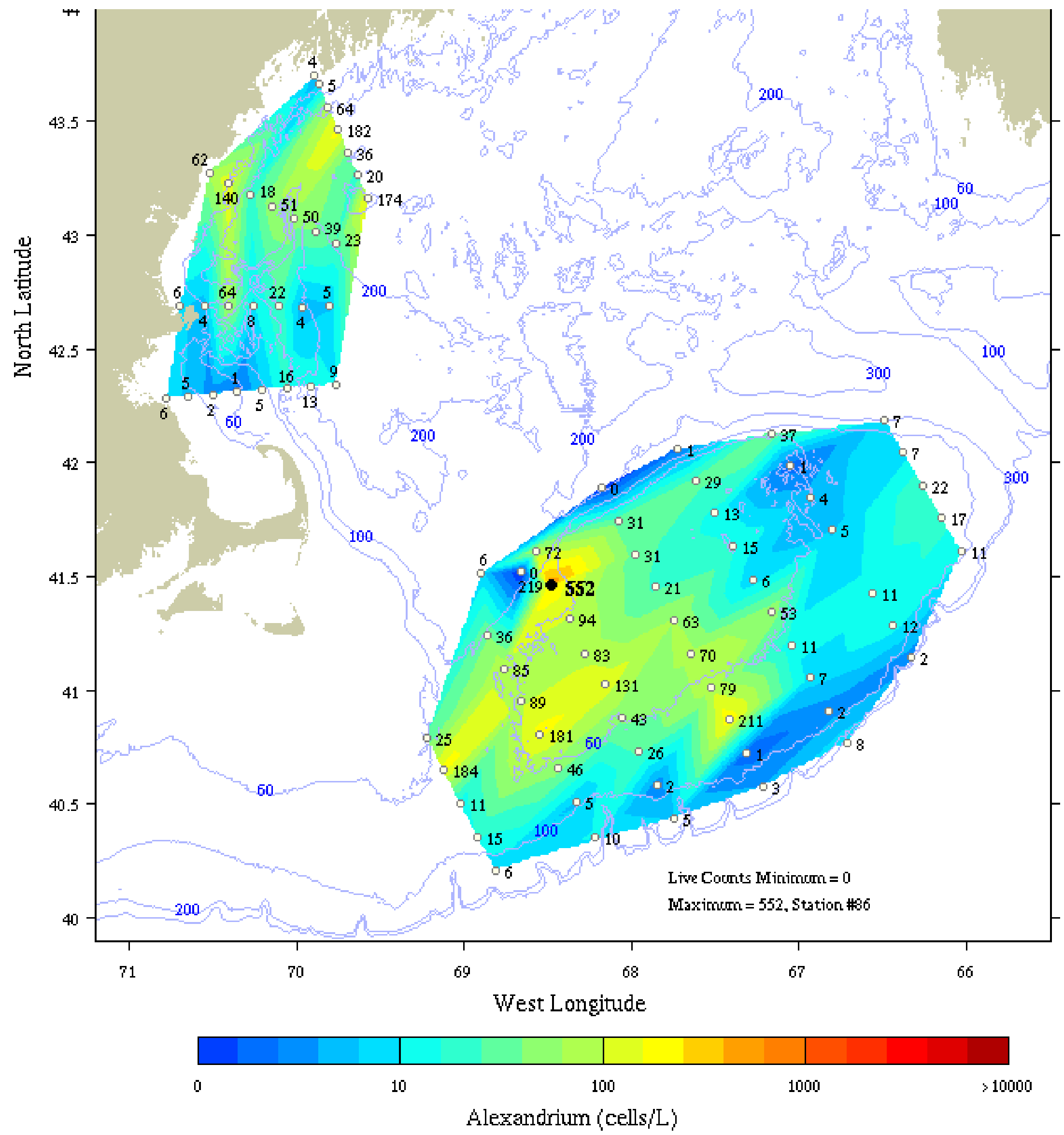
- **March 7 – WHOI releases 2007 cyst data and predicts large red tide event for 2008**
- **Low cell counts and PSP toxicity observed April through early May**
- **May 6 – High PSP reported at Star Island, NH**
- **MWRA sampled for *Alexandrium* on seven surveys from April to June**
- **WHOI conducted six surveys from April to July**
- **MWRA conducted a detailed survey in Boston Harbor when toxicity was detected in early June**
- **WHOI has combined datasets from the separate efforts in the bays – WHOI, MWRA, and CCS**



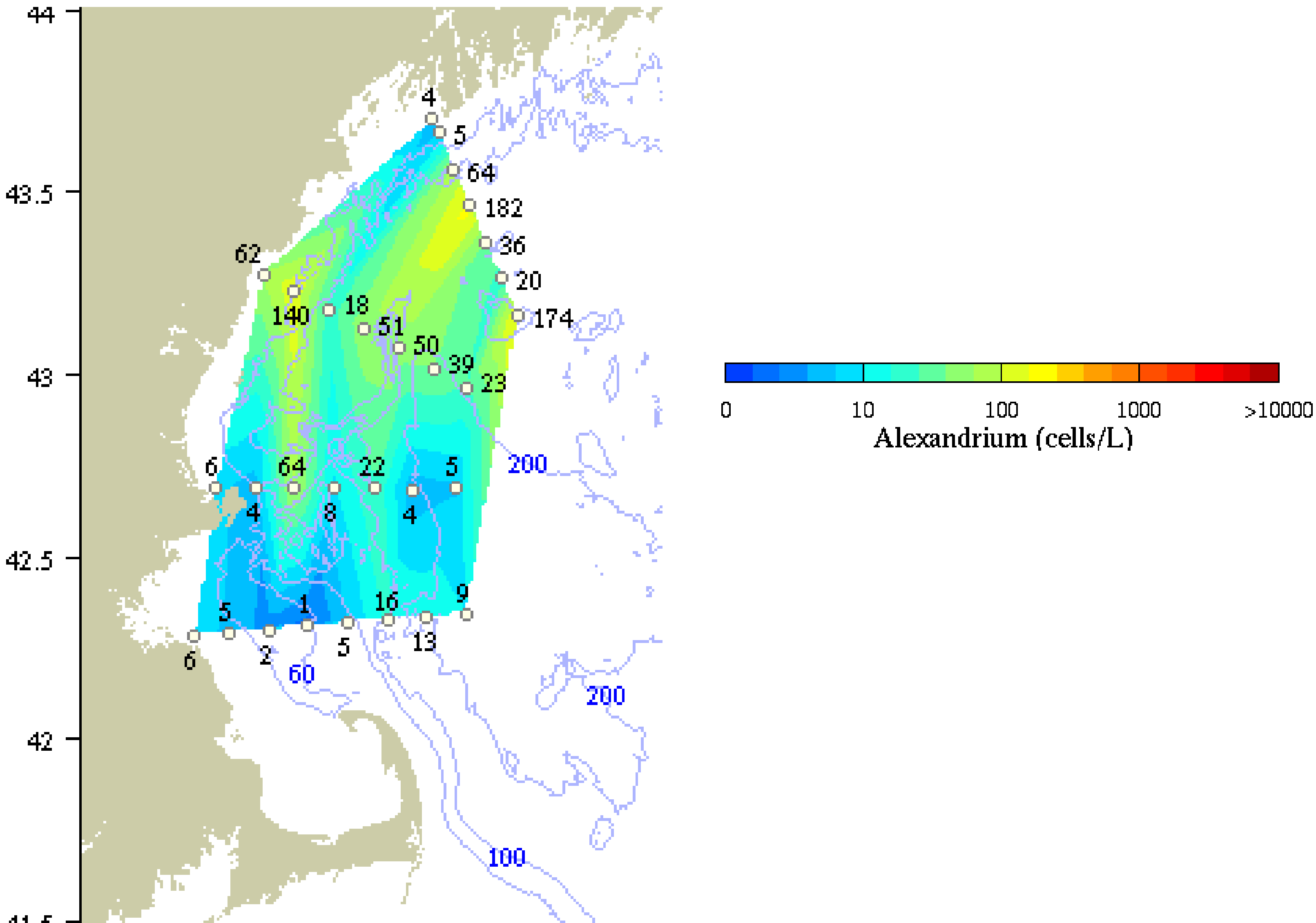



http://science.whoi.edu/users/olga/alex_surveys_2008/WHOI_Alexandrium_Surveys_2008.html

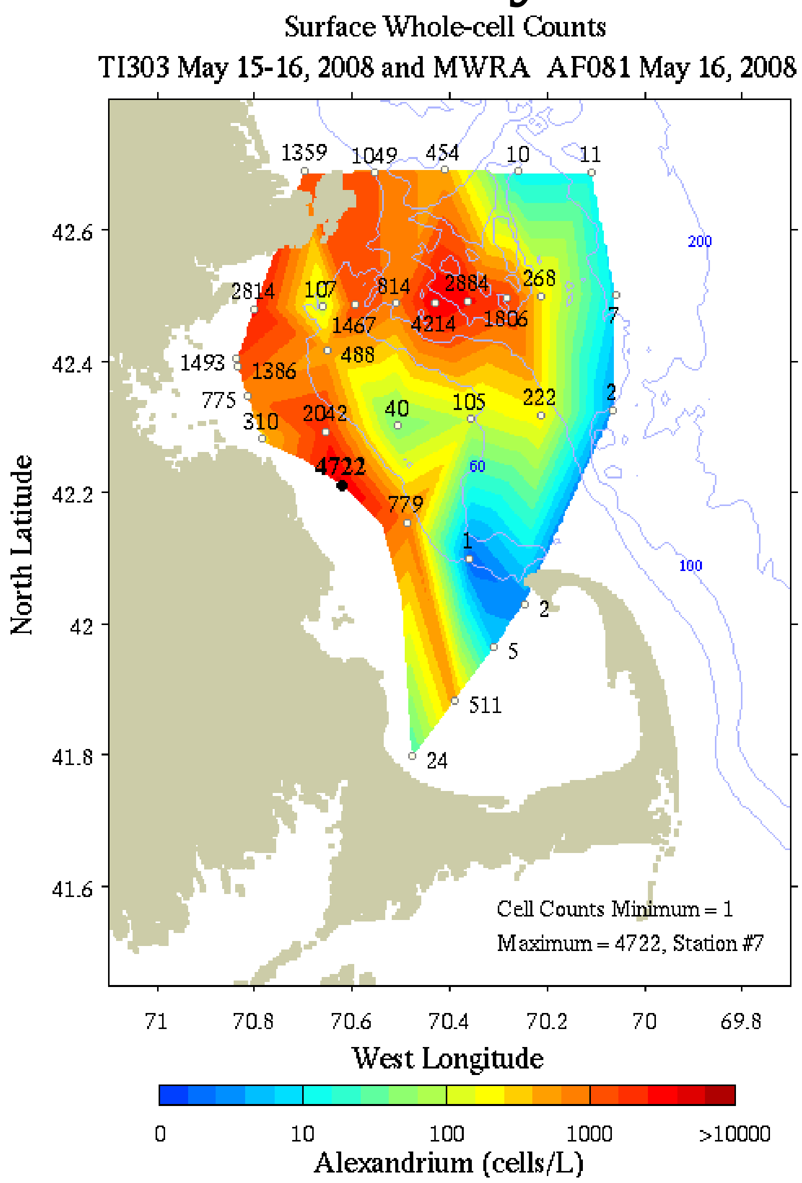
# R/V Oceanus April 28-May 5, 2008



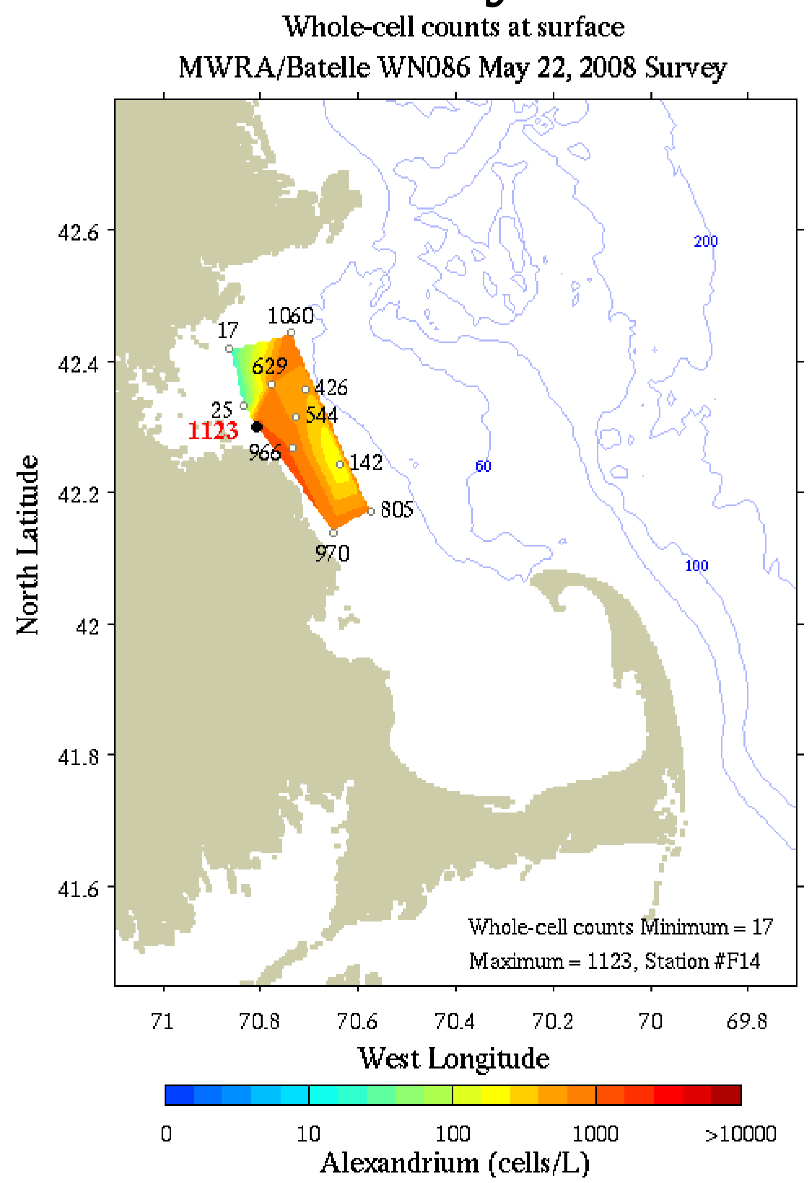
# R/V Oceanus May 4-5, 2008



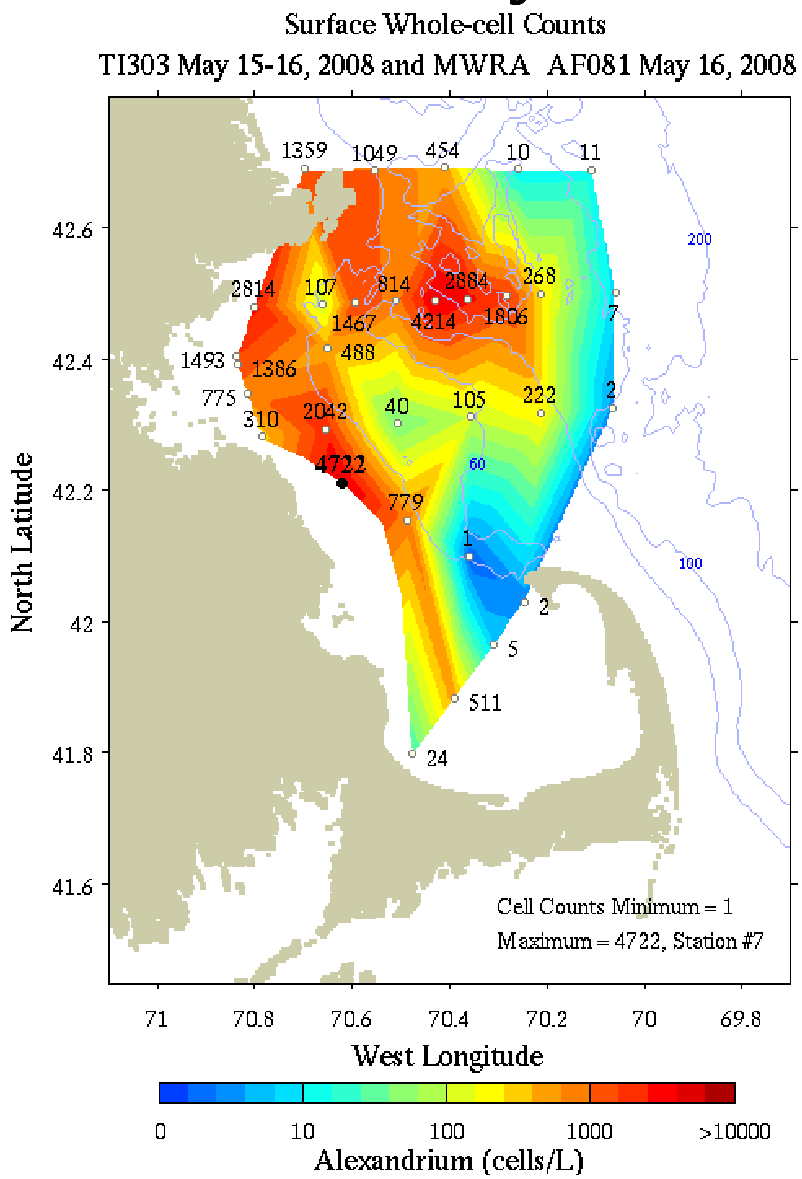
# May 15-16



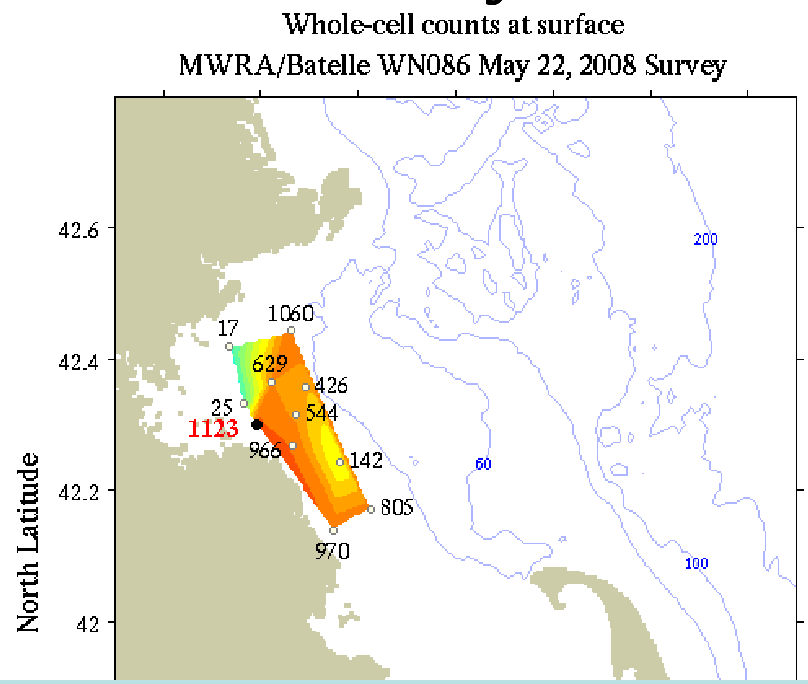

# May 22



# May 15-16



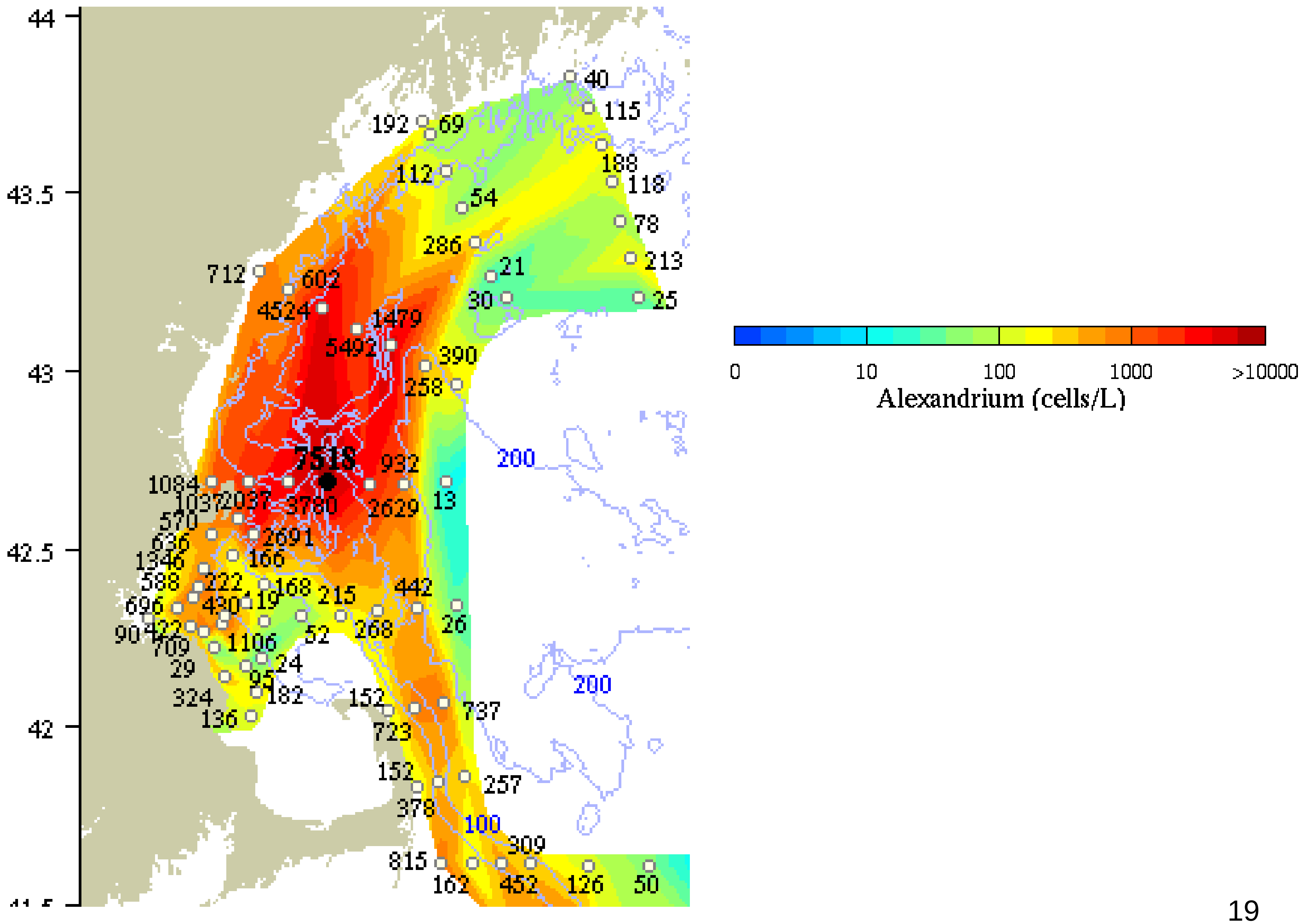

# May 22




1) A major northeaster occurred just prior to the survey on the left. In 2005 and 2006, we also had major northeasters in this same time frame.
2) 2) Note the high cell concentrations “downstream” of the outfall (but also the high concentrations upstream).

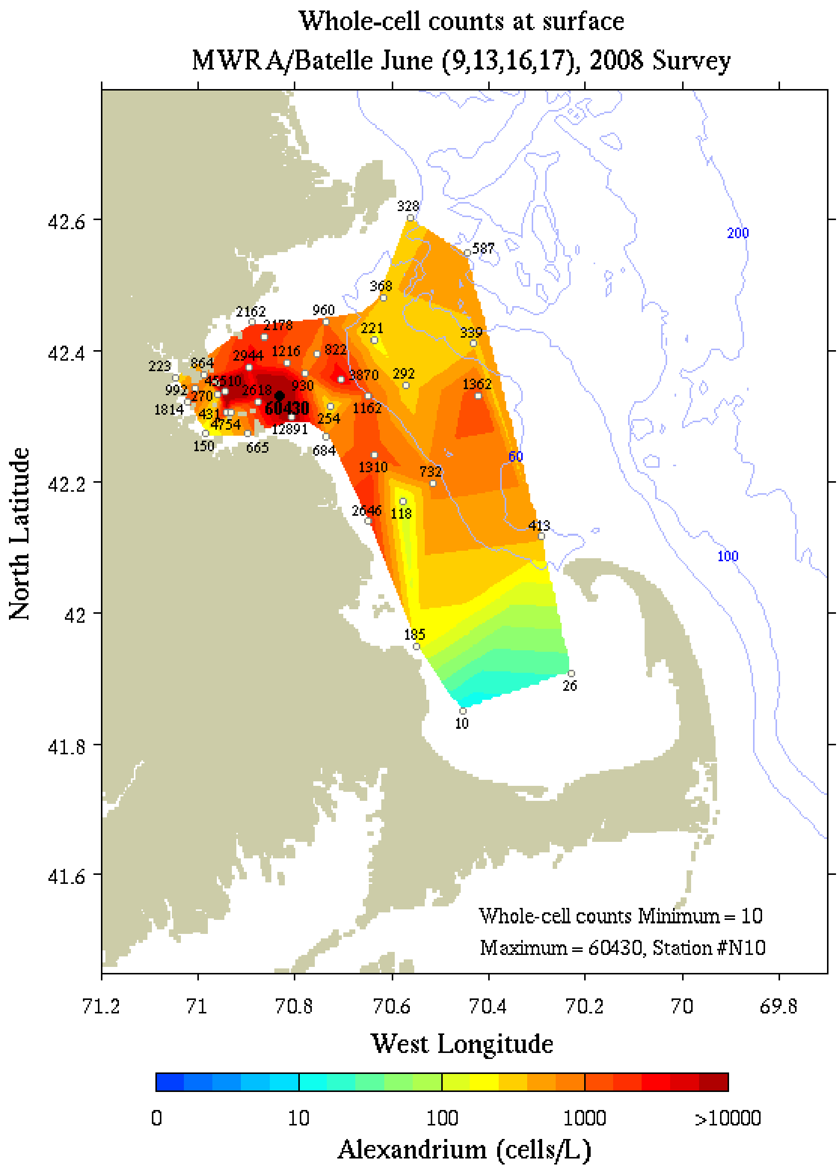
Alexandrium (cells/L)

# May 27-29

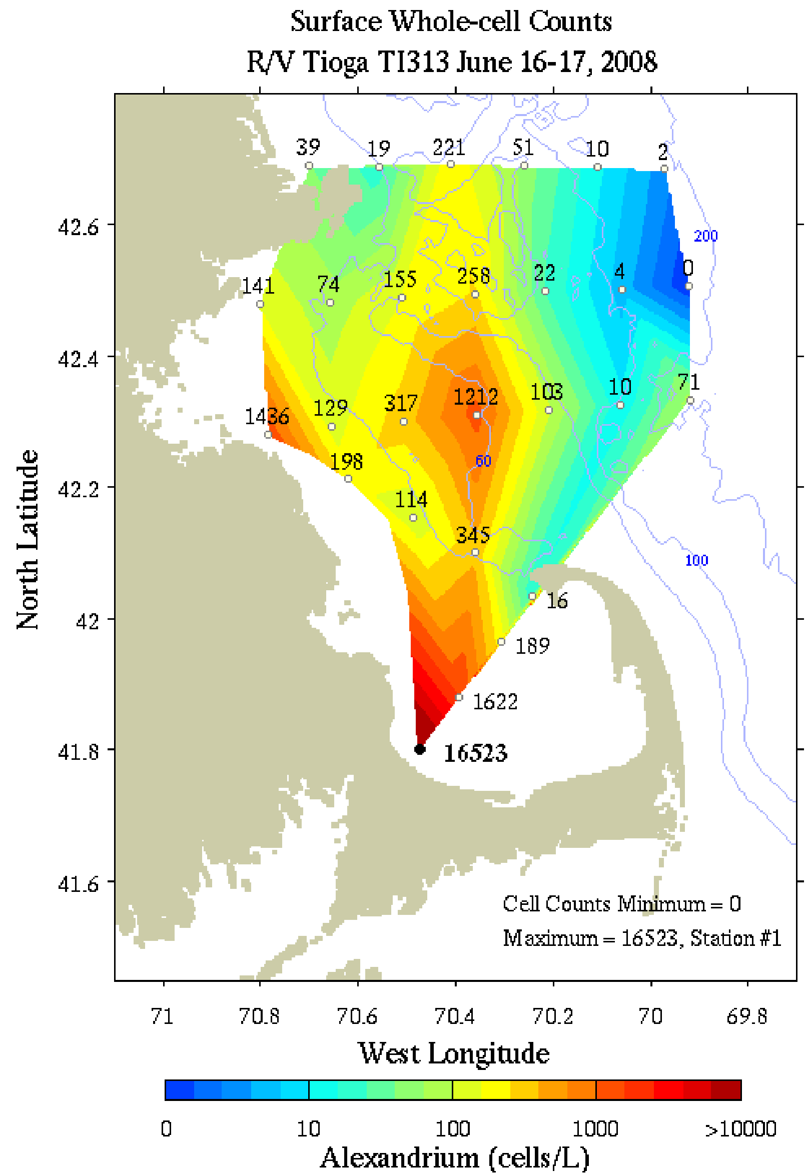


44
43.5
43
42.5
42
0
10
100
1000
>10000
Alexandrium (cells/L)
200
200
100

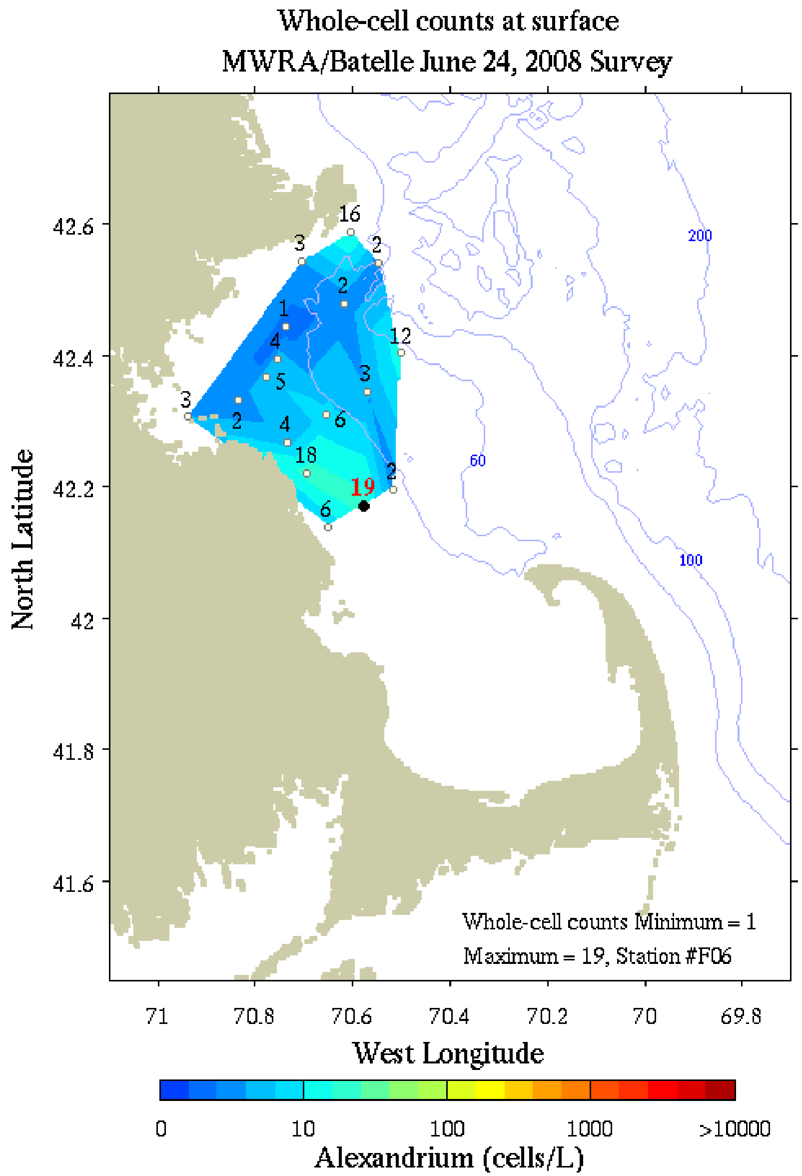
# June 9-17



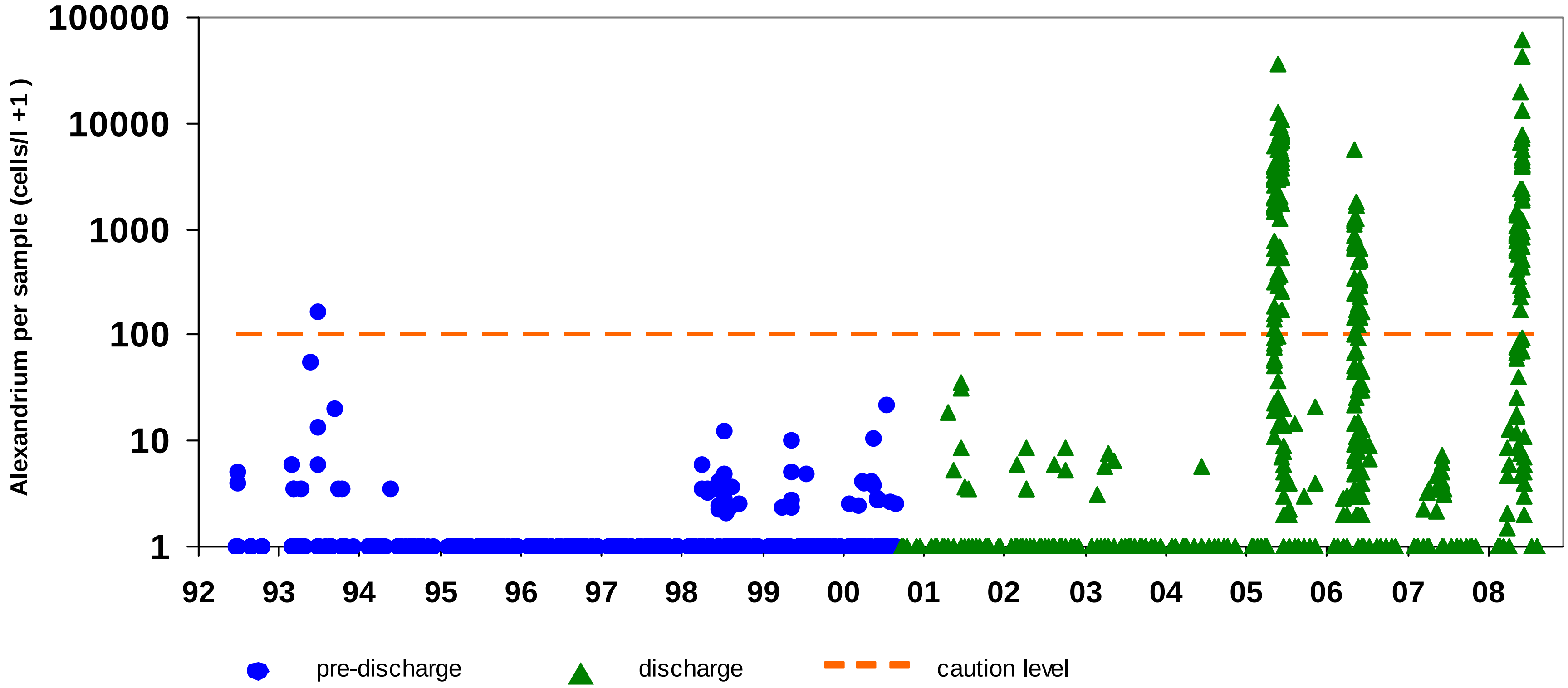

# June 16-17



# June 24 – end of bloom in the bay

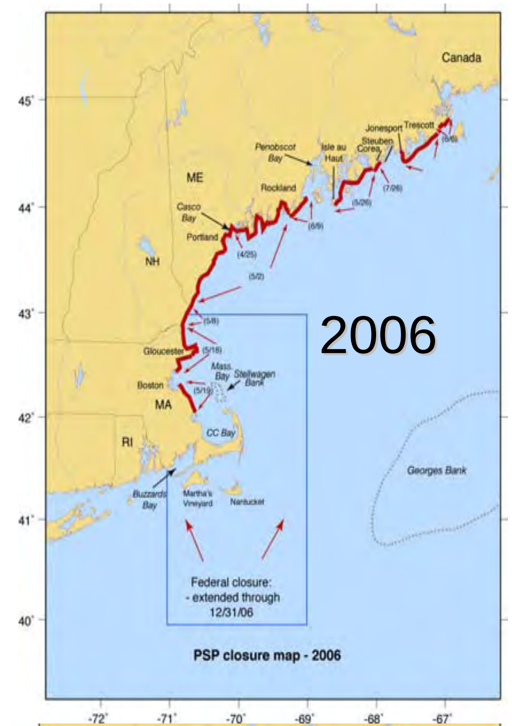


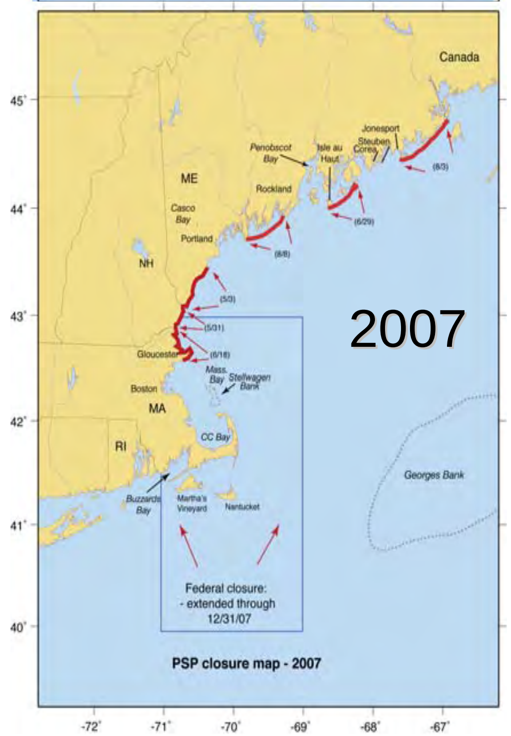
# *Alexandrium* abundance – MWRA nearfield area

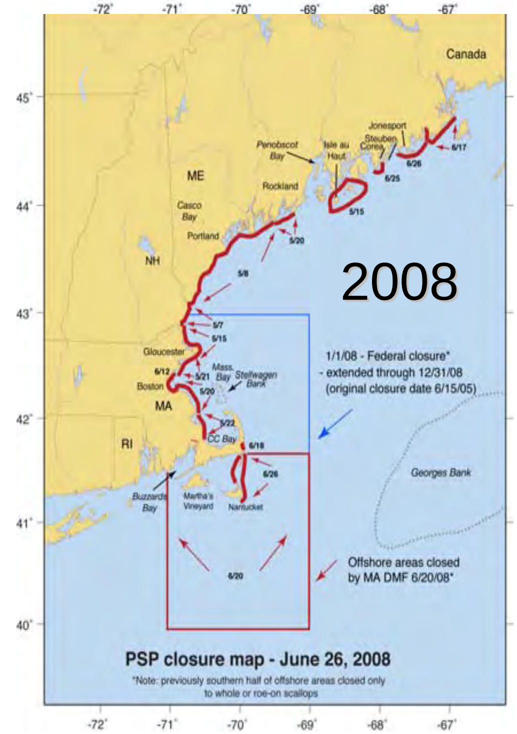



**Contingency Plan Threshold Exceedance: >100 cells/L from May 16th to June 17th**

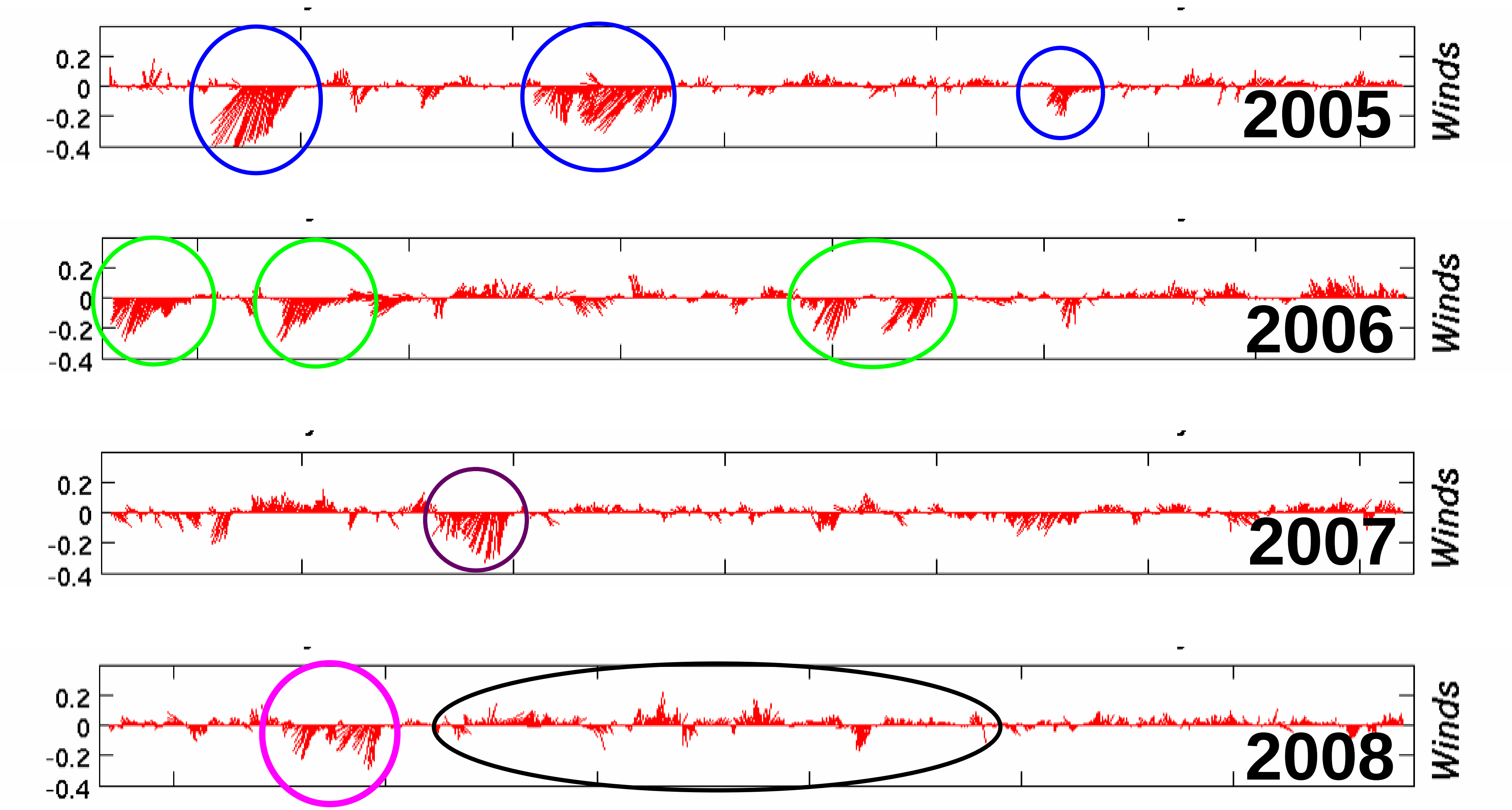
# Shellfish harvesting closures

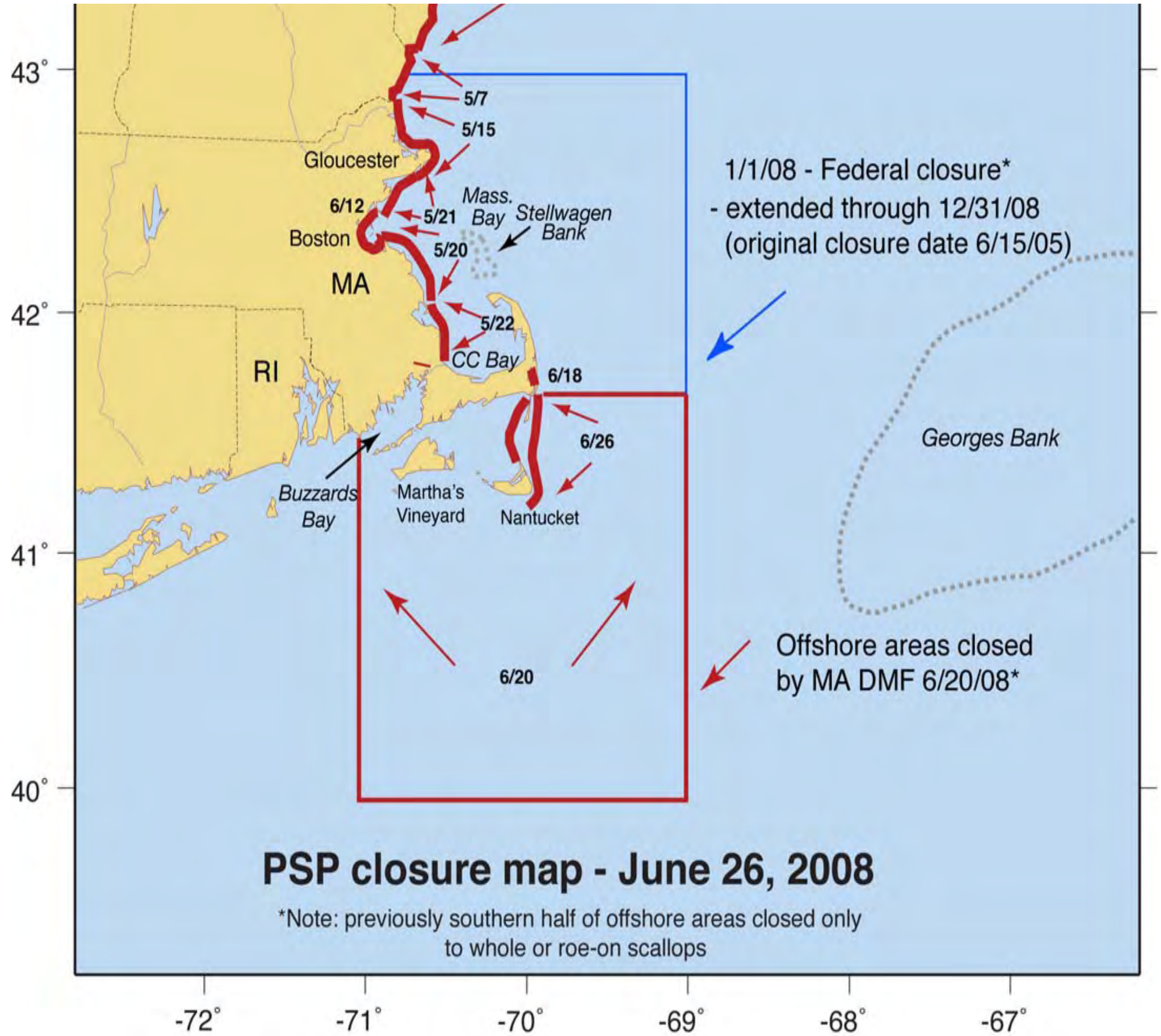



# Importance of winds for Mass Bay blooms

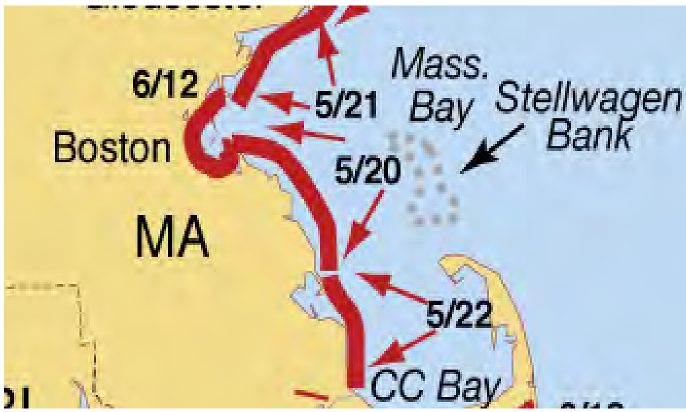




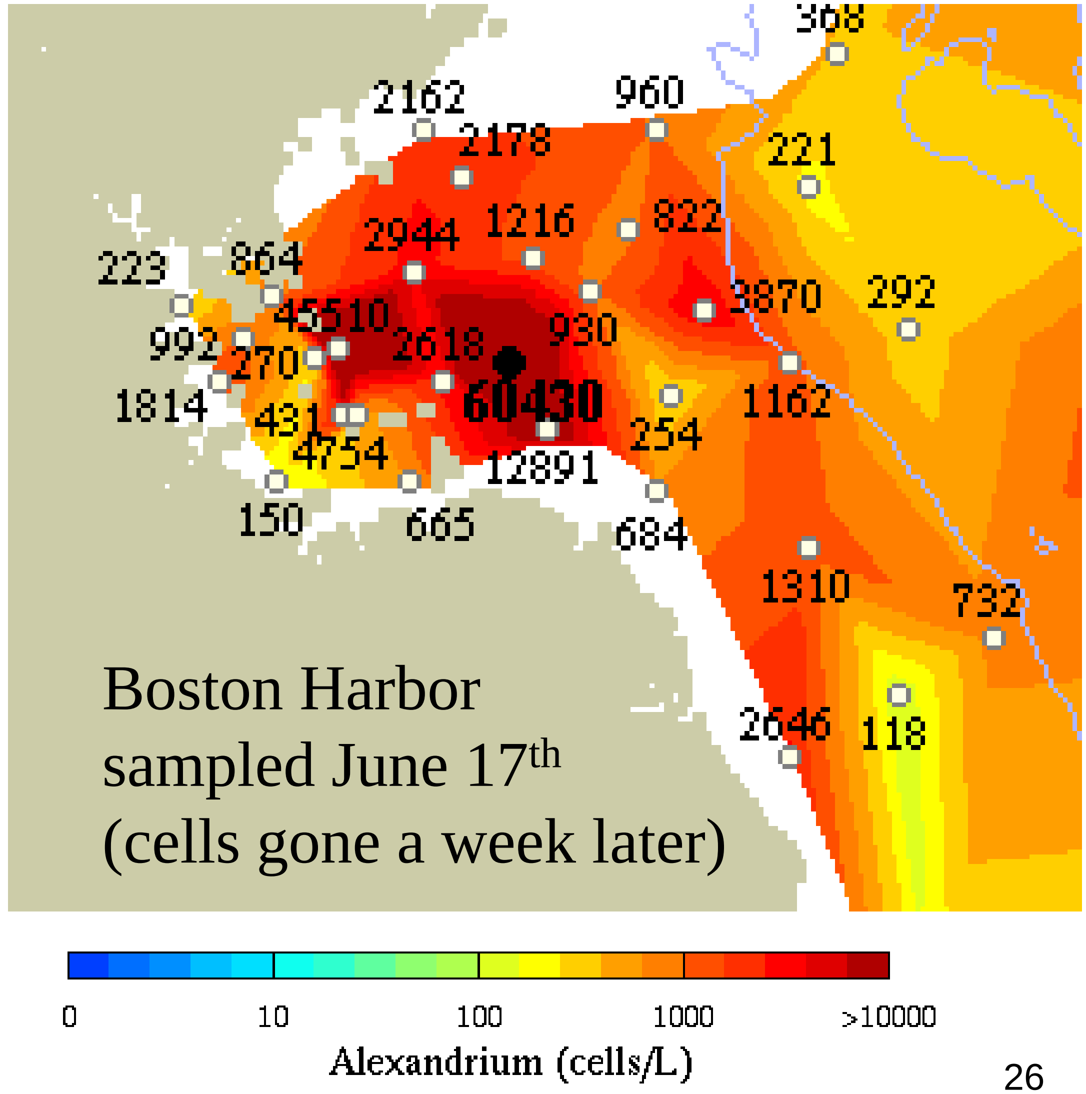

GoMOOS Buoy A data supplied by Neal Pettigrew's group at the University of Maine


43°
42°
41°
40°
-72°
-71°
-70°
-69°
-68°
-67°
5/7
5/15
Gloucester
6/12
5/21
Mass. Bay
Stellwagen Bank
Boston
5/20
MA
5/22
CC Bay
RI
6/18
6/26
Buzzards Bay
Martha's Vineyard
Nantucket
Georges Bank
6/20
1/1/08 - Federal closure*
- extended through 12/31/08
(original closure date 6/15/05)
Offshore areas closed
by MA DMF 6/20/08*
PSP closure map - June 26, 2008
*Note: previously southern half of offshore areas closed only
to whole or roe-on scallops

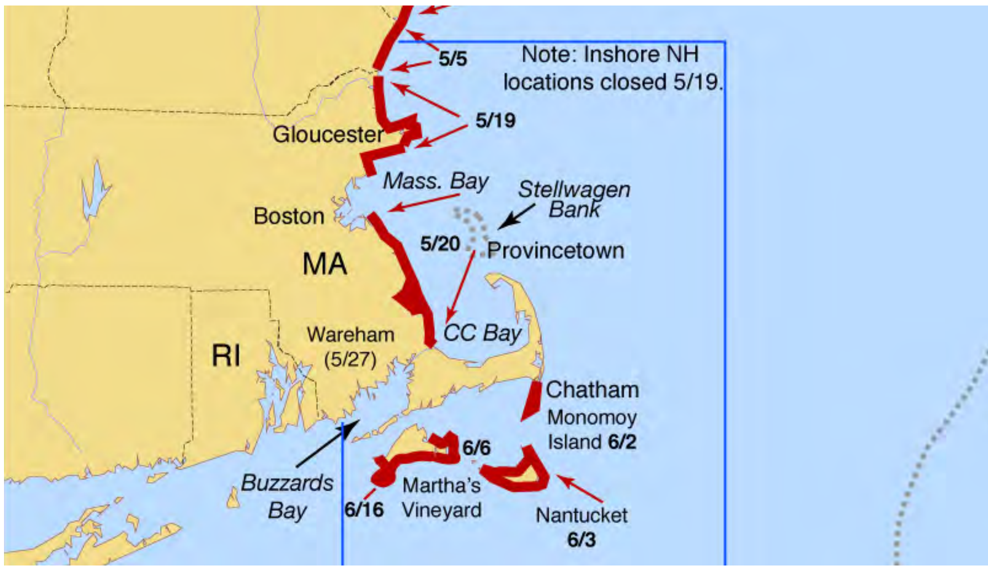
# Noteworthy feature: a major red tide bloom in Boston Harbor, with shellfish closure.




**Boston Harbor Closed June 12th**



# What happened in 2005? Were conditions that different?




No closures, but relatively high cell concentrations

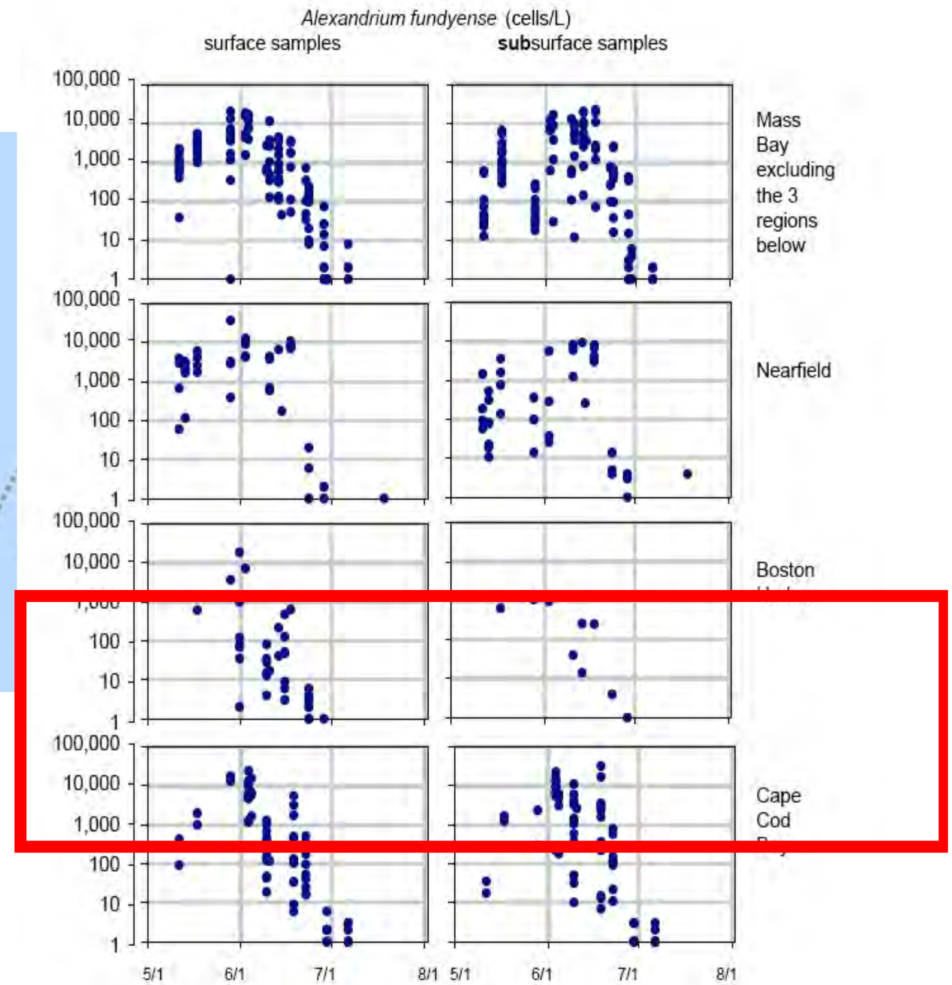
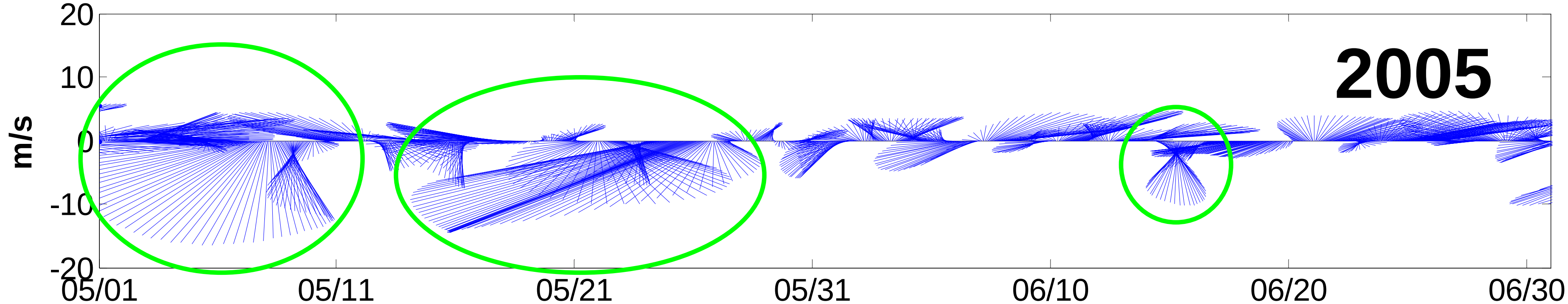
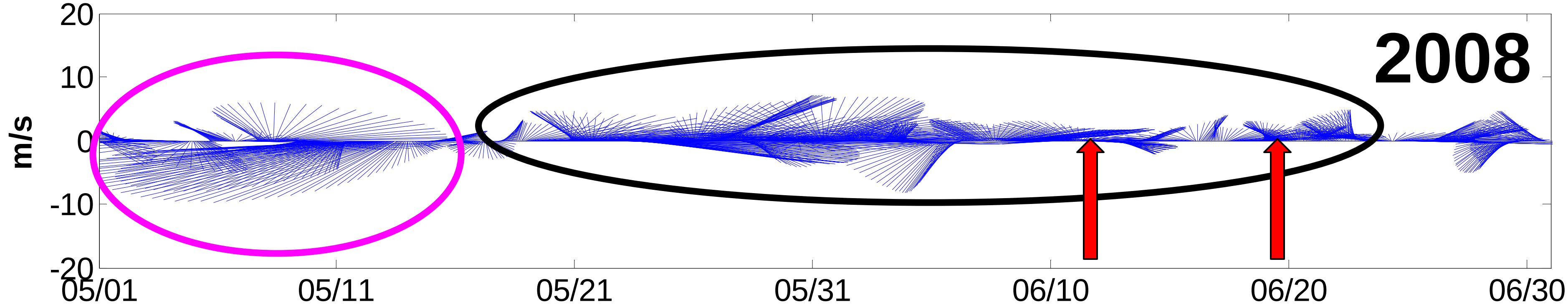


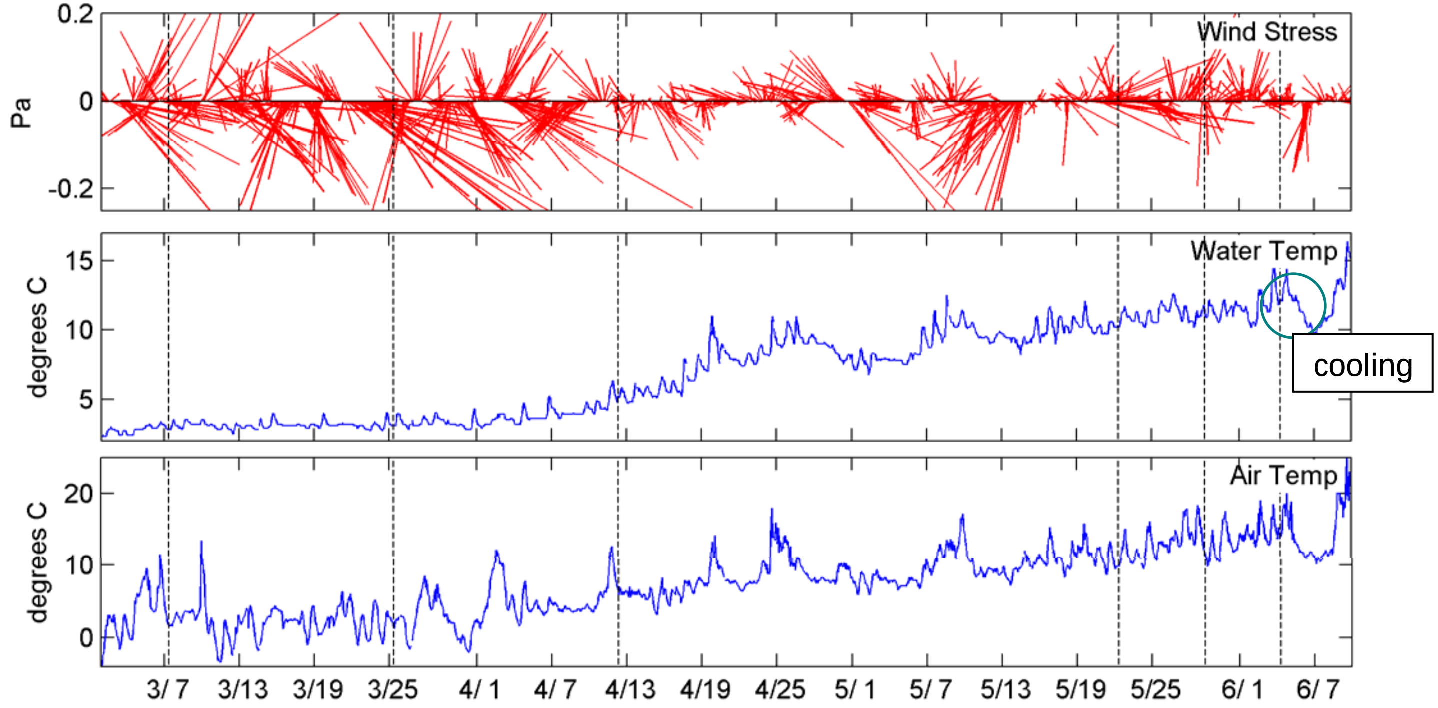

Figure 2-11. *Alexandrium* abundance+1 in surface and subsurface samples, grouped into four nonoverlapping regions ("Massachusetts Bay" here excludes the other 3 regions shown: the outfall nearfield region, Boston Harbor, and Cape Cod Bay.)

# NOAA NDBC Boston Buoy Winds



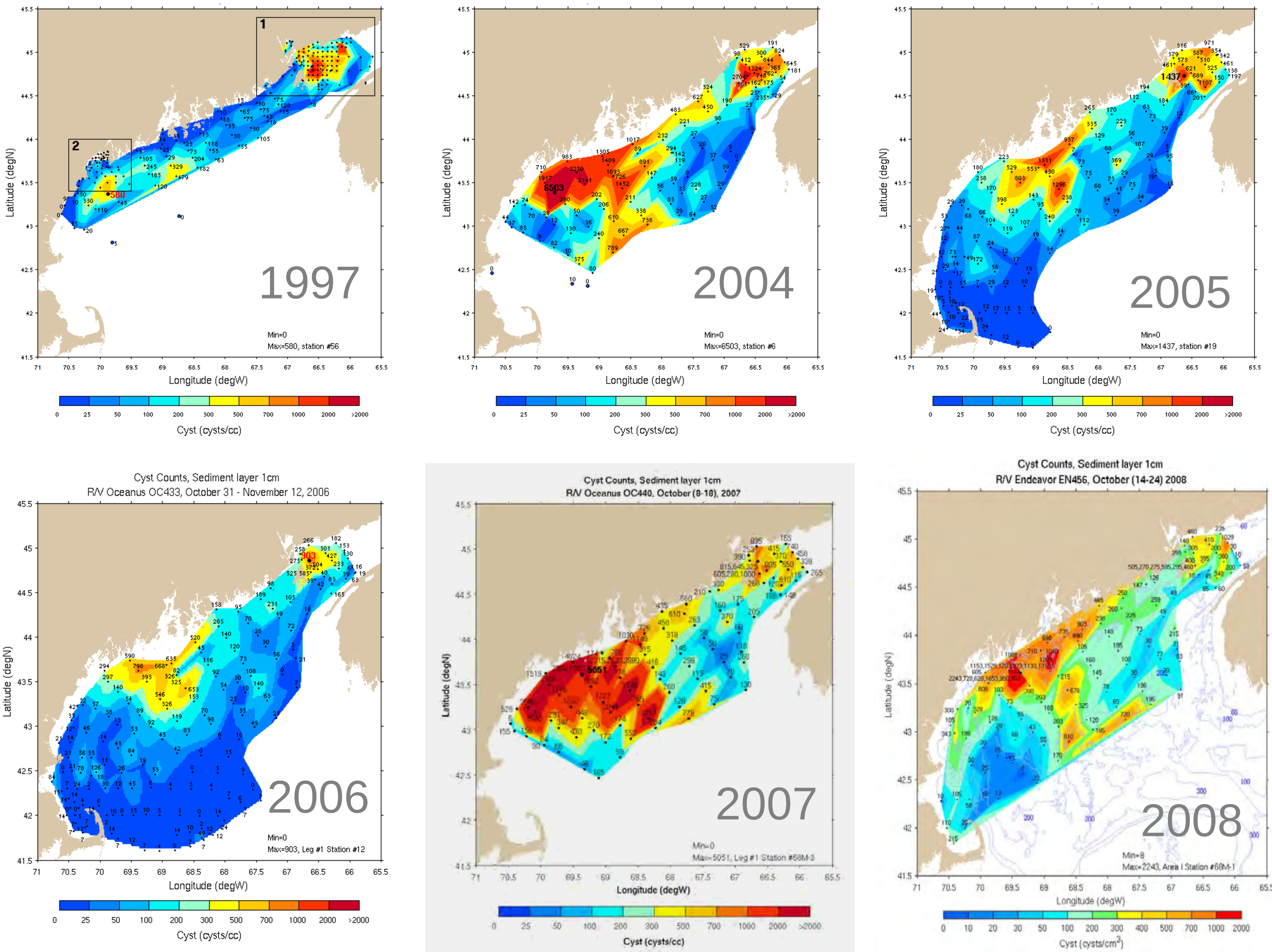



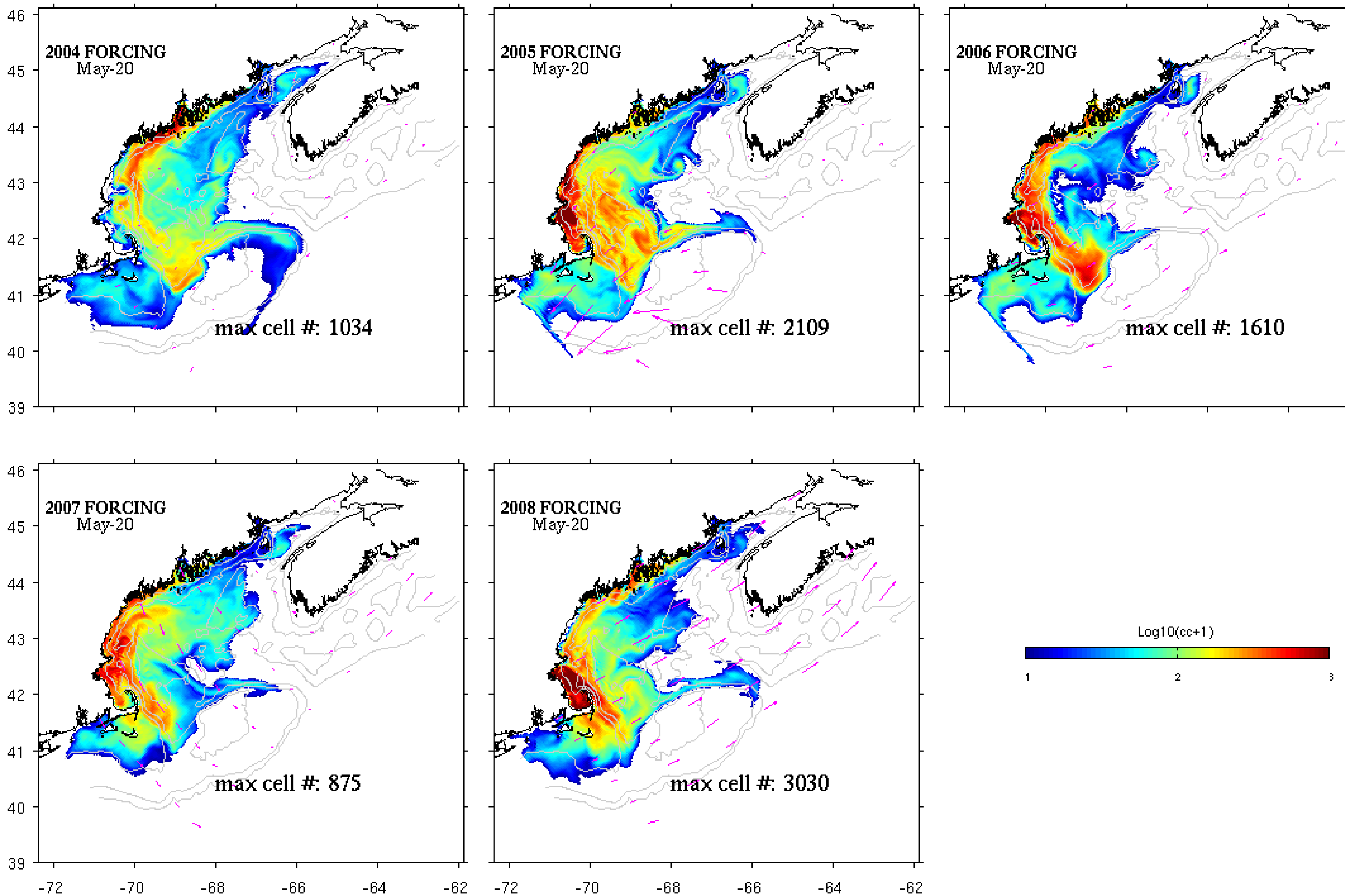
# spring winds and water temperature



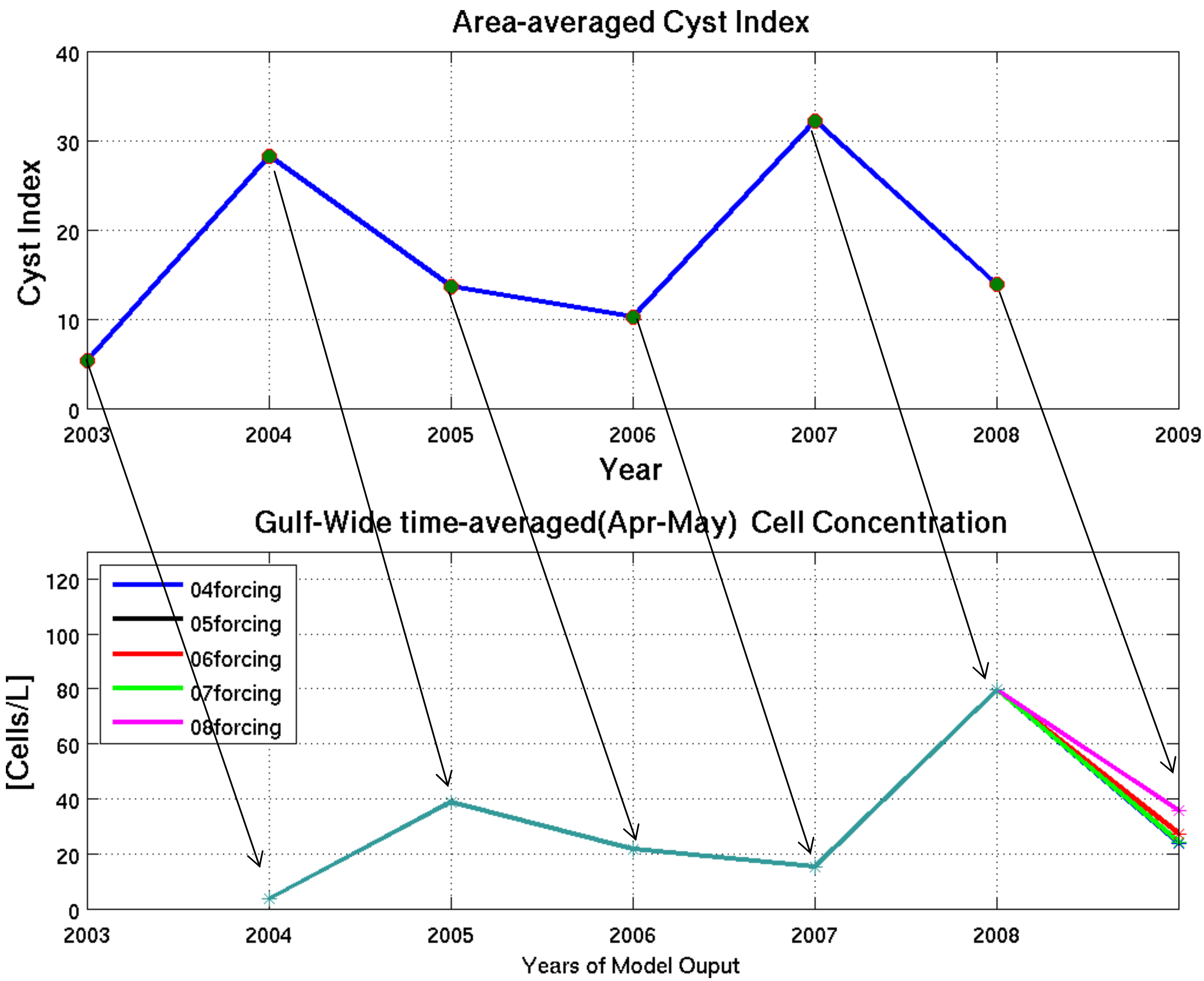

note not so many nor'easters

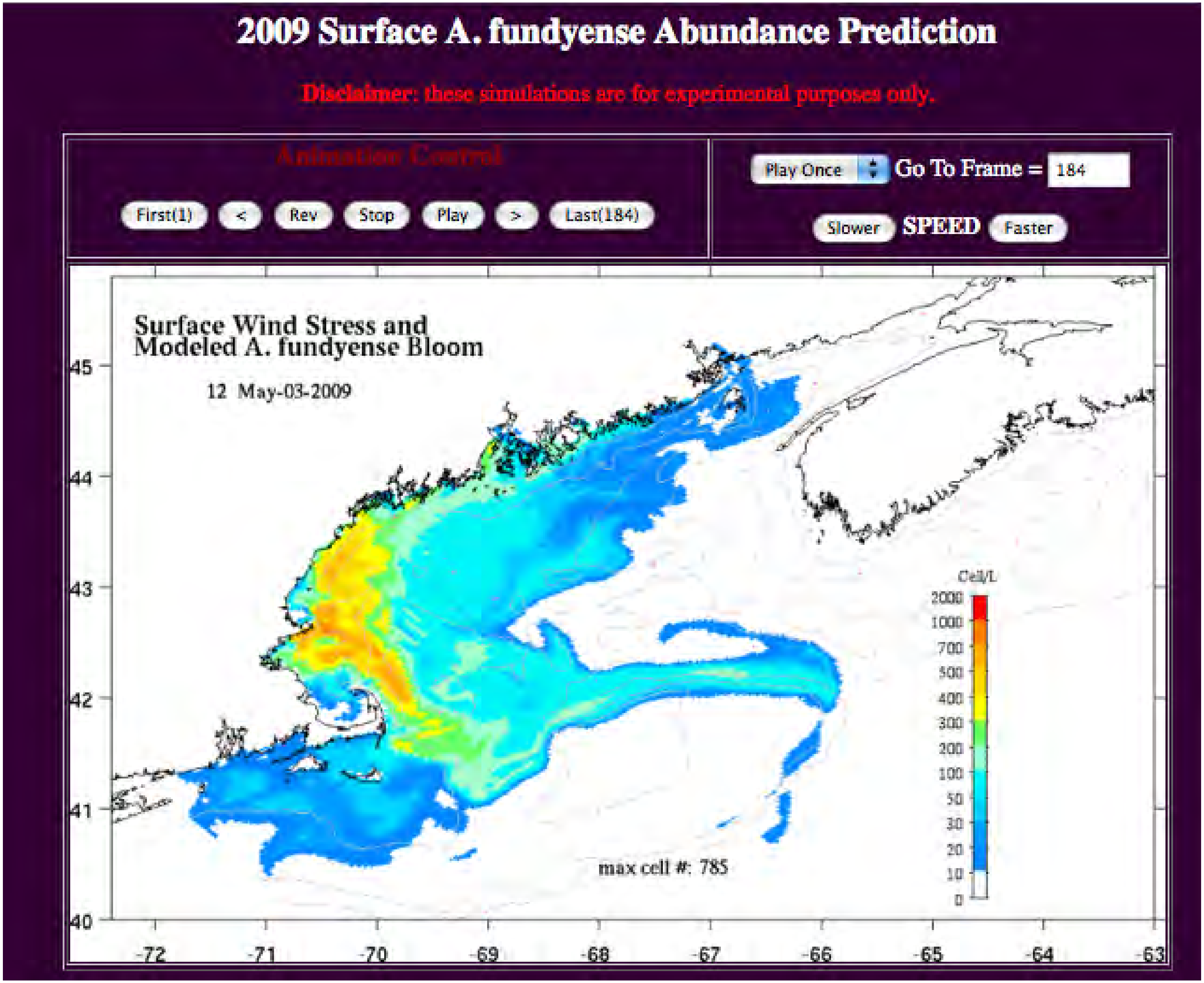
# What are we expecting for 2009?


1997
Latitude (degN)
Longitude (degW)
Min=0
Max=580, station #56
Cyst (cysts/cc)
2004
Min=0
Max=6503, station #6
Cyst (cysts/cc)
2005
Min=0
Max=1437, station #19
Cyst (cysts/cc)
Cyst Counts, Sediment layer 1cm
R/V Oceanus OC433, October 31 - November 12, 2006
2006
Min=0
Max=903, Leg #1 Station #12
Cyst (cysts/cc)
Cyst Counts, Sediment layer 1cm
R/V Oceanus OC440, October (8-18), 2007
2007
Min=0
Max=5051, Leg #1 Station #68M-3
Cyst (cysts/cc)
Cyst Counts, Sediment layer 1cm
R/V Endeavor EN456, October (14-24) 2008
2008
Min=8
Max=2243, Area I Station #68M-1
Cyst (cysts/cm³)


2004 FORCING
May-20
max cell #: 1034
2005 FORCING
May-20
max cell #: 2109
2006 FORCING
May-20
max cell #: 1610
2007 FORCING
May-20
max cell #: 875
2008 FORCING
May-20
max cell #: 3030
Log10(cc+1)
1
2
3
46
45
44
43
42
41
40
39
-72
-70
-68
-66
-64
-62

# Impact of cyst abundance on the next year's bloom





2009 Surface A. fundyense Abundance Prediction
Disclaimer: these simulations are for experimental purposes only.
Animation Control
First(1)
<
Rev
Stop
Play
>
Last(184)
Play Once
Go To Frame = 184
Slower
SPEED
Faster
Surface Wind Stress and
Modeled A. fundyense Bloom
12 May-03-2009
max cell #: 785
Cell/L
2000
1000
700
500
400
300
200
100
50
30
20
10
0
45
44
43
42
41
40
-72
-71
-70
-69
-68
-67
-66
-65
-64
-63

# Summary

- **_Alexandrium_ population dynamics model & cyst abundance were good predictors of the magnitude of the 2008 bloom**
  - **2008 bloom prediction was the first prediction of a major regional red tide**
- **May/June 2008 bloom cell abundance and PSP toxicity comparable to 2005 bloom in Massachusetts Bay**
- **Early May winds transported the bloom into Massachusetts Bay, but unlike 2005, there were not subsequent storms to push it into Cape Cod Bay or south of Cape Cod**
- **Major _Alexandrium_ bloom in Boston Harbor, including shellfish closure**
  - **Probably reflects NE winds**
  - **Short lived – SW winds**
  - **2005 situation was similar, but not as severe**
- **We still believe we have entered a "new era" of frequent and high levels of PSP toxicity in the western Gulf of Maine.**

# Acknowledgements

**The data presented are the result of the efforts from a variety of intuitions and programs including:**

- **MWRA/Battelle HOM6 team**
- **WHOI scientists and GOMTOX Program (funded via NOAA/ Center for Sponsored Coastal Ocean Research/Coastal Ocean Program Grant #NA06NOS4780245) and the Woods Hole Center for Oceans and Human Health**
- **MA DMF PSP data**
- **GoMOOS & Pettigrew's group at University of Maine**

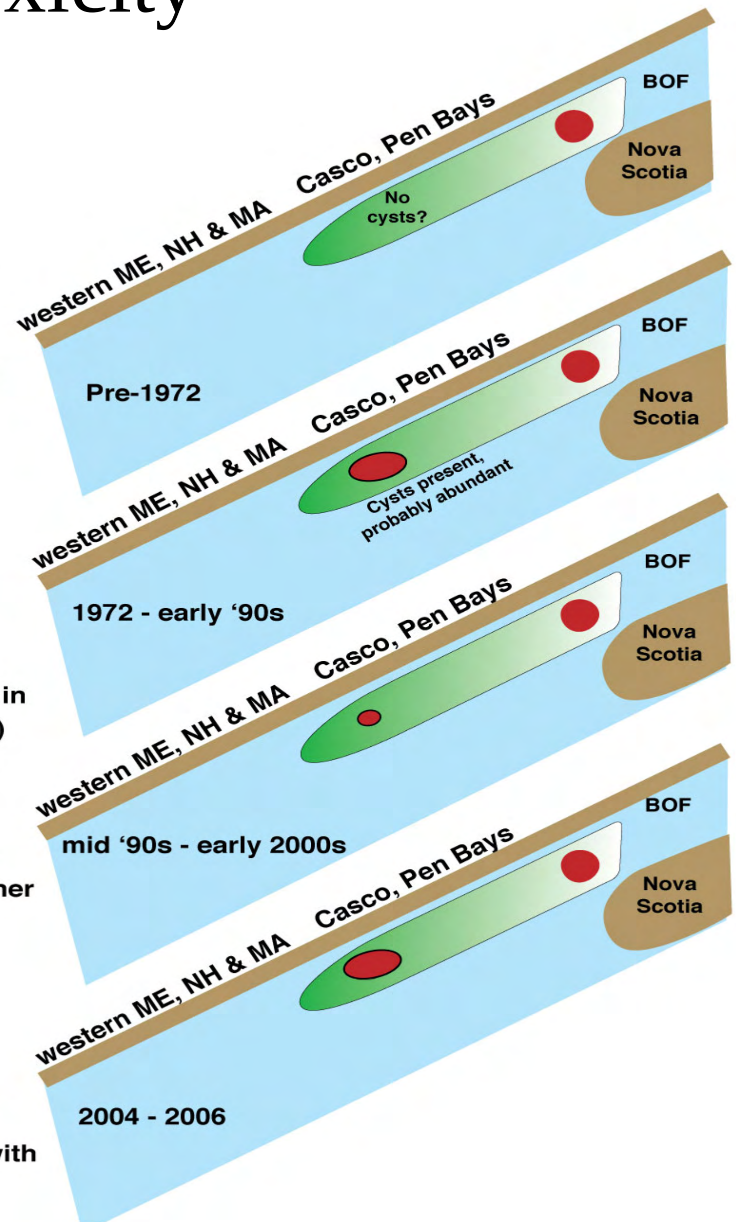
# Intrannual variability in cyst abundance and PSP toxicity

<u>Pre 1972</u>: Cysts present in BOF, but not abundant in western GOM

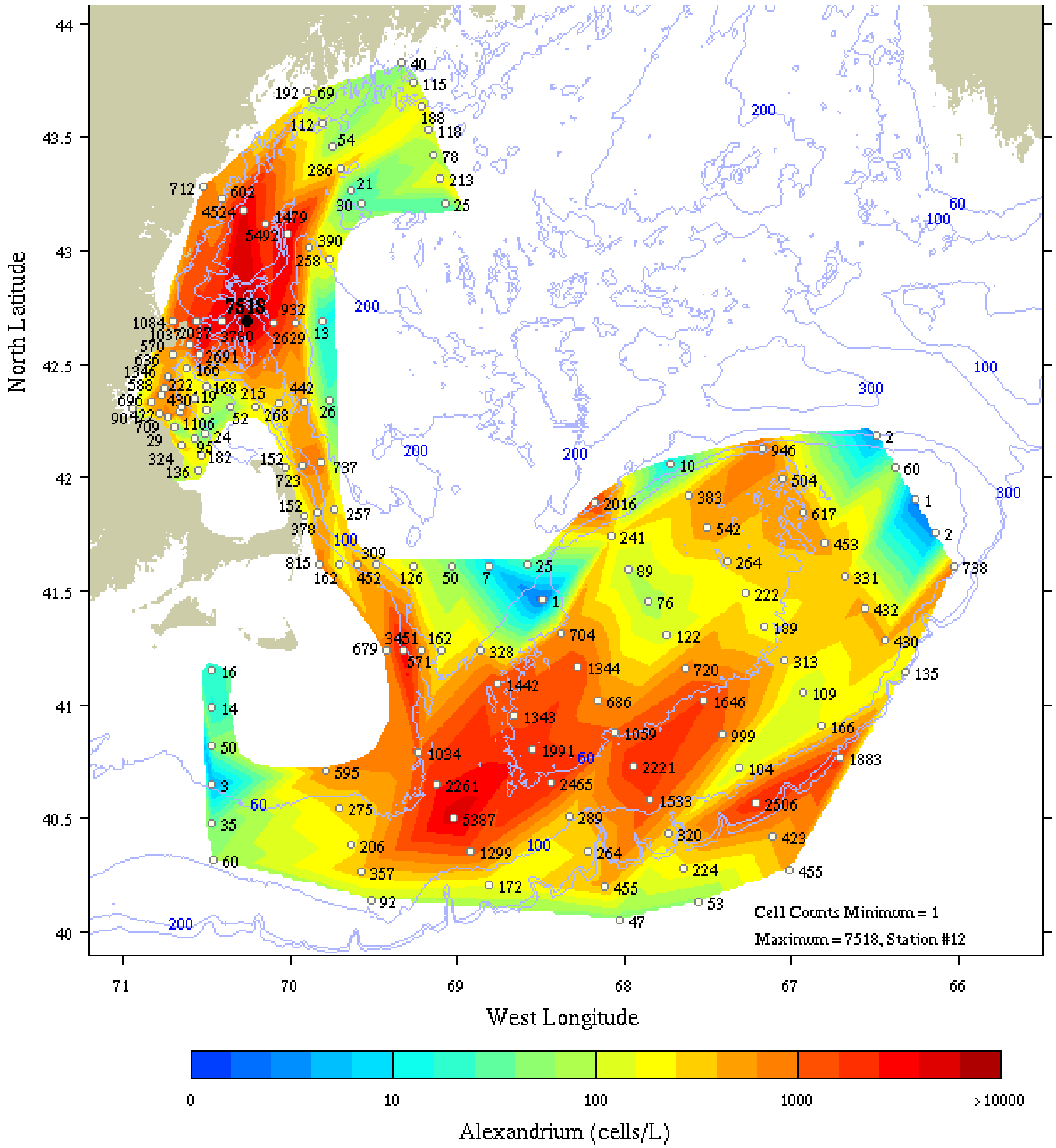
<u>1972 - early '90s</u>: Cysts accumulate in WGOM due to 1972 bloom and sub-sequent blooms; start of 70's, 80's "regime" of frequent and high toxicity in western GOM. Gradual (or precipitous) decline in cyst abundance.

<u>mid '90s - early 2000s</u>: Low abundance of WGOM cysts in 1997 and maybe other years; low toxicity in WGOM

<u>2004 - 2006</u>: Cysts abundant in WGOM once again; start of 2000's "regime" with high toxicity in the WGOM.



# May 27-29



North Latitude
West Longitude
Alexandrium (cells/L)
Cell Counts Minimum = 1
Maximum = 7518, Station #12

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**Charlestown Navy Yard**
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**Boston, MA 02129**
**(617) 242-6000**
**http://www.mwra.state.ma.us**