2009 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 (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 (MWRA 1991, 1997) and post-diversion periods (MWRA 2004). The 2009 data represent the ninth 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

Twelve water column monitoring surveys were conducted in 2009. The data generated during the surveys have been reported in a series of survey reports and data reports. The purpose of this annual summary report is to present the 2009 results in the context of the seasonal patterns and the annual cycle of ecological events in Massachusetts and Cape Cod Bays. The 2009 data are also compared against the Contingency Plan thresholds (MWRA 2001) and baseline and post-diversion data. Appendices A-D provide abstracts and presentations from the May 2010 Annual Technical meeting focused on physical, chemical, and biological parameters.

1.1 Data Sources

A detailed presentation of field sampling equipment and procedures, sample handling and custody, sample processing and laboratory analysis, instrument performance specifications and data quality objectives is given in the Quality Assurance Project Plan (Libby *et al.* 2009a). 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, a survey report was prepared to summarize the activities that were accomplished, details on any deviations from the methods outlined in the QAPP, the actual sequence of events and tracklines, the number and types of samples collected, a preliminary summary of *in situ* water quality data, a rapid analysis of >20 µm phytoplankton species abundance in one sample, whale watch information, and any deviations from the survey plan. Results for 2009 water column surveys are tabulated in data reports.

1.2 Water Column Monitoring Program Overview

This report summarizes and evaluates water column monitoring results from the 12 water column surveys conducted in 2009 (**Table** 1-2). The surveys collected water quality samples and observations at 7 stations in the nearfield 12 times per year, and at 27 stations in the farfield 6 times per year. Each station is sampled once per survey except station N16 which is sampled twice during the combined nearfield/farfield surveys. 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 outfall diffuser. 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 and April farfield surveys (**Figure** 1-2). The farfield stations have been organized into regional groupings for some analyses (**Figure** 1-1 and **Figure** 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 2009. Spanning both periods, year 2000 data are not used for calculating annual means, but the 2000 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 2009. The nearfield day is underlined.

Survey	Type of Survey	Survey Dates
WF091	Nearfield/Farfield	February 6, 7, 10, <u>11</u>
WF092	Nearfield/Farfield	February 25, <u>26</u>
WN093	Nearfield	March <u>18</u>
WF094	Nearfield/Farfield	April 8, <u>9</u>, 10
WN096	Nearfield	May <u>12</u>
WF097	Nearfield/Farfield	June 15, 16, <u>17</u>
WN099	Nearfield	July <u>21</u>
WF09B	Nearfield/Farfield	August 17, <u>18</u>, 19
WN09C	Nearfield	September <u>1</u>
WN09D	Nearfield	September <u>30</u>
WF09E	Nearfield/Farfield	October 20, 21, <u>22</u>
WN09F	Nearfield	November <u>10</u>

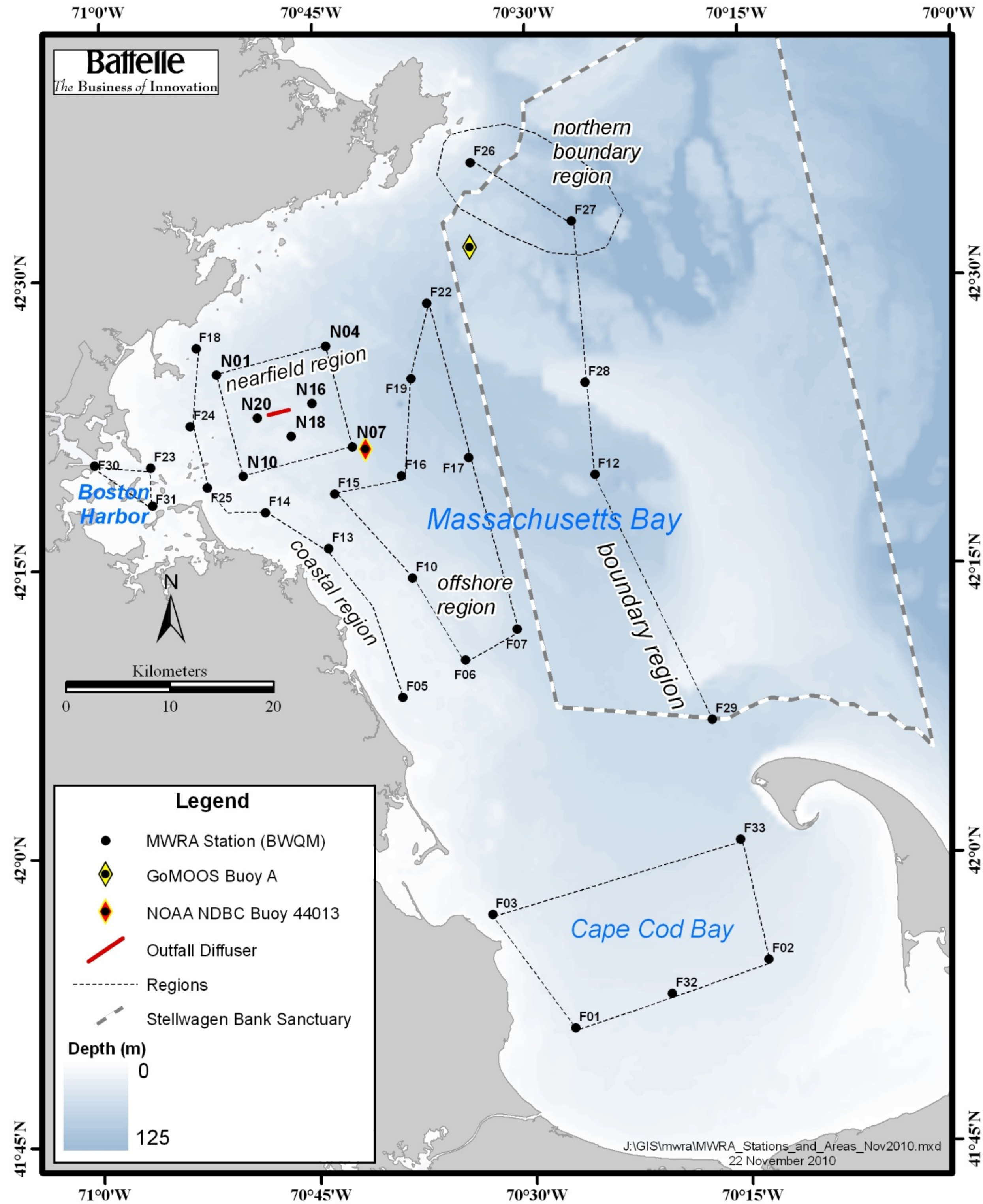


Figure 1-1. MWRA stations and their regional groupings. Also shown are the MWRA outfall and instrumented buoys operated by GoMOOS and NOAA's NDBC.

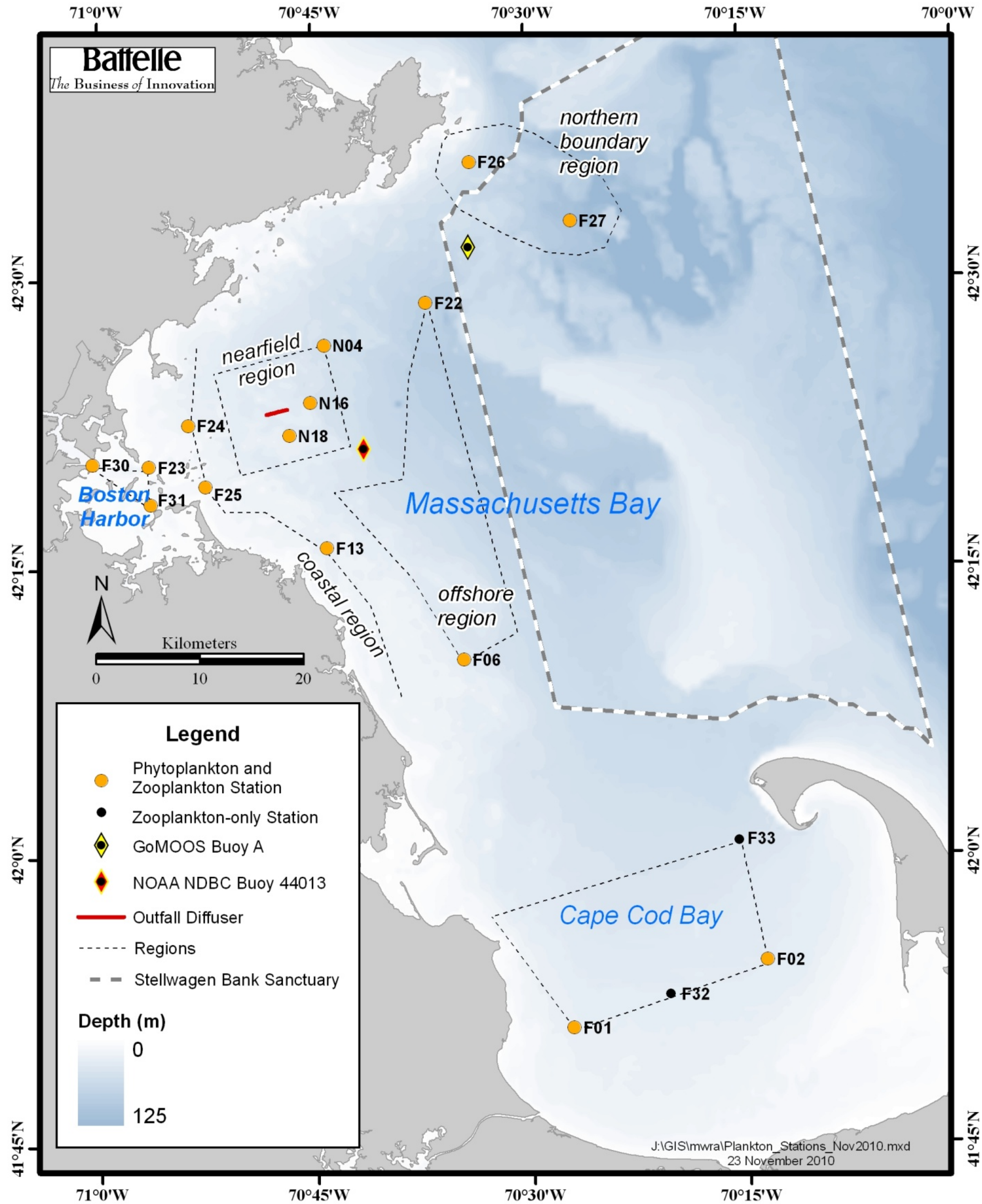


Figure 1-2. MWRA plankton stations (regional groupings shown for reference).

2 MONITORING RESULTS

Over the course of the HOM program, the expected seasonal pattern of water column events for this latitude has been observed in the data collected in Massachusetts and Cape Cod Bays. The general pattern is evident though the timing and year-to-year manifestations of the 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 2009 and differences from previous years are discussed below.

2.1 2009 Results

Overall, the physical, water quality, and biological conditions in 2009 followed typical seasonal patterns observed previously in the monitoring program (1992-2008). Mean annual and mean seasonal values of many variables for 2009 were close to the averages over all years including: winds, temperature, stratification, nutrients, phytoplankton biomass, dissolved oxygen and zooplankton abundance and community structure. The most notable characteristic of the physical environment in 2009 were the cold, stormy conditions during June and July and the associated high river flow during this summer period. These conditions resulted in less upwelling than normal, rough sea conditions with sporadic mixing, and large pulses of freshwater. It was also stormier during the late fall of 2009 contributing to the seasonal turnover of the water column.

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. Phytoplankton biomass patterns varied as a result of a major regional *Phaeocystis* bloom in April, as well as nearshore diatom blooms in summer (observed in the harbor, coastal, and Cape Cod Bay regions) and in fall throughout the bays to varying degrees. Chlorophyll and particulate organic carbon (POC) concentrations peaked in most areas during the February to April *Phaeocystis* bloom. There was an *Alexandrium fundyense* Contingency Plan caution threshold exceedance, but overall the *Alexandrium* bloom was minor and short lived. A chronological synopsis of the 2009 results is provided below and additional details are presented in Appendices A-D.

In early February nutrient concentrations were elevated across Massachusetts Bay for nitrate (NO_3), silicate (SiO_4), and phosphate (PO_4) (**Figure** 2-1). Levels in Cape Cod Bay were slightly lower than those in Massachusetts Bay, though not as low as typically observed for February in Cape Cod Bay. This may have been due to the lack of the usual winter diatom bloom in Cape Cod Bay (**Figure** 2-2). There was a slight decrease in SiO_4 concentrations in the shallow waters of Cape Cod Bay, Boston Harbor, and the coastal region that may have been related to an increase in diatoms that was not captured during the February surveys. By late February, instead of diatoms, there was a minor bloom of *Phaeocystis* in Cape Cod Bay that exhibited the maximum survey mean areal fluorescence in the bay for 2009. Riverine inputs were normal during February and much lower than observed in 2008 (**Figure** 2-3).

There was a sharp decline in NO_3 and PO_4 by April throughout the bays, while SiO_4 concentrations remained elevated with survey mean concentrations in the nearfield remaining around 9 µM into May. The decrease in NO_3 was coincident with a large *Phaeocystis* bloom observed across the bay in April (**Figure** 2-2). The bloom was strongest in the offshore and northern boundary areas of Massachusetts Bay with mean area abundances increasing from <1 million cells L^{-1} inshore to ~5 million cells L^{-1} in the offshore area and 10 million cells L^{-1} at the northern boundary area. A maximum abundance of ~15 million cells L^{-1} was observed in the mid-depth sample at station F26 along the northern boundary (Appendix B Slide 18).

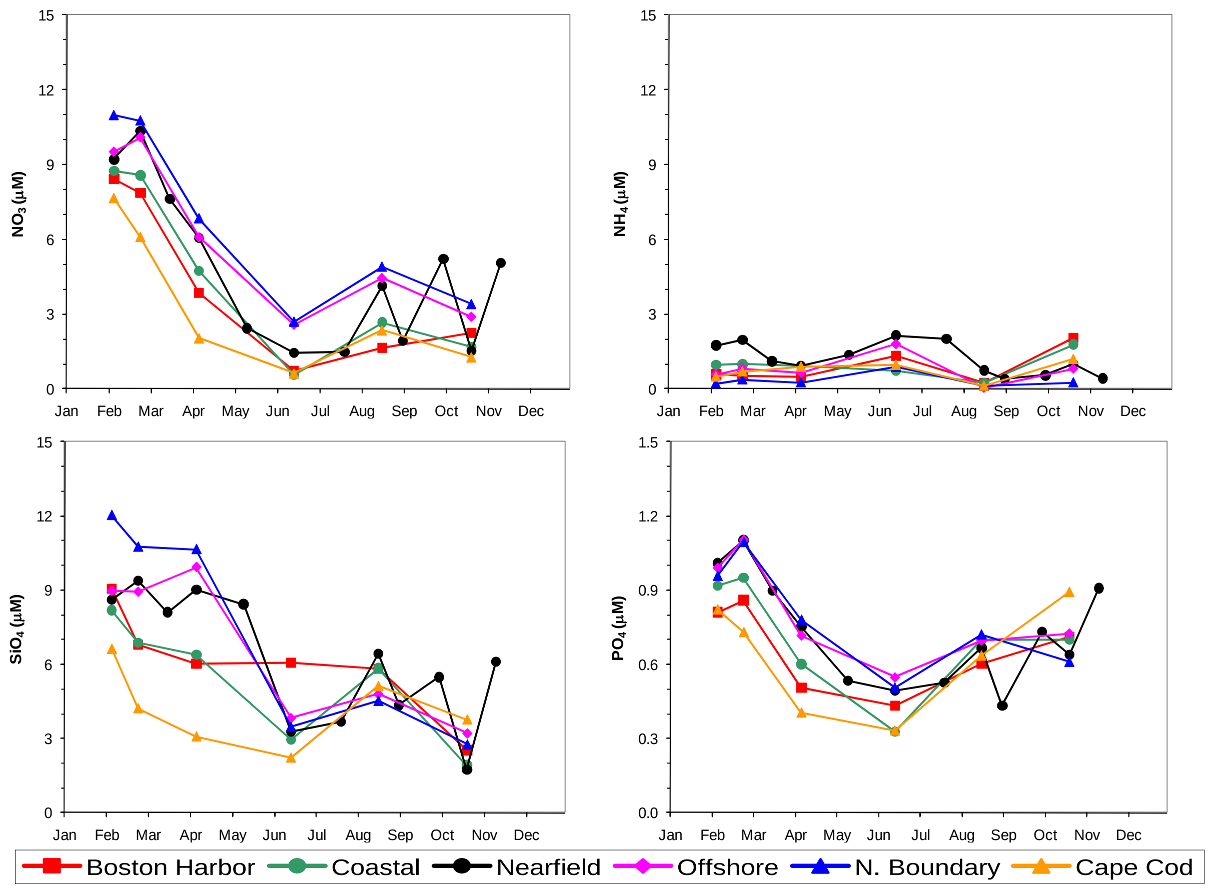


Figure 2-1. Time-series of survey mean nutrient concentrations in Massachusetts and Cape Cod Bays. Mean concentrations over depths and stations within each region in 2009.

The high April abundances of *Phaeocystis* resulted in peak survey mean concentrations of chlorophyll and POC for the year at the offshore and northern boundary stations (**Figure** 2-4). A coincident April peak in productivity was observed at station N04 while at stations F23 and N18 there was only a slight increase in productivity from low winter values (**Figure** 2-5). The peak in nearfield chlorophyll concentrations occurred in March when dinoflagellate, cryptomonads, and microflagellate abundances were relatively high during the onset of the *Phaeocystis* bloom. A similar pattern of increased microflagellate abundance was observed in the nearfield prior to the 2008 *Phaeocystis* bloom. One possible mechanism may be an increase in single celled (rather than colonial) *Phaeocystis* prior to the March or April bloom, which could have been inadvertently classified as microflagellates. The spring peak in POC concentrations in the nearfield was observed in May, which is odd considering that phytoplankton abundances were relatively low (**Figure** 2-2 and **Figure** 2-4).

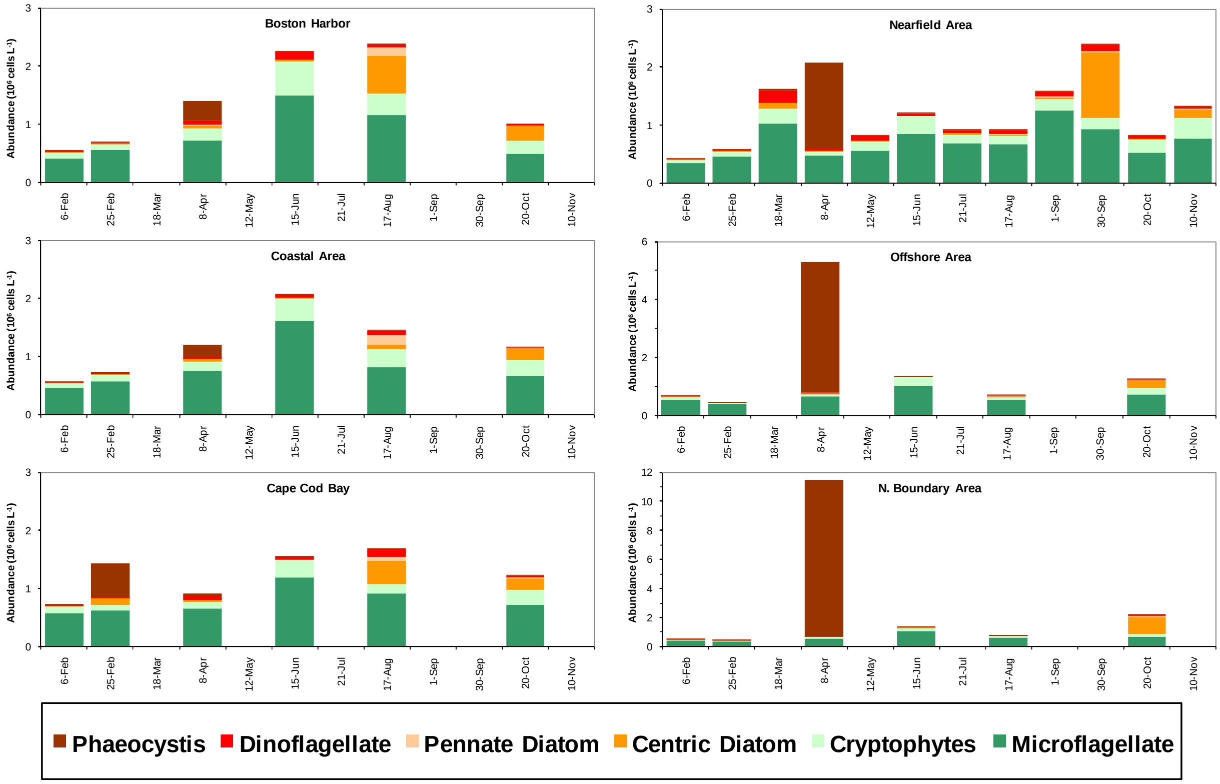


Figure 2-2. Phytoplankton abundance by major taxonomic group in all six areas for 2009. Note change in scale for Offshore and N. Boundary Areas.

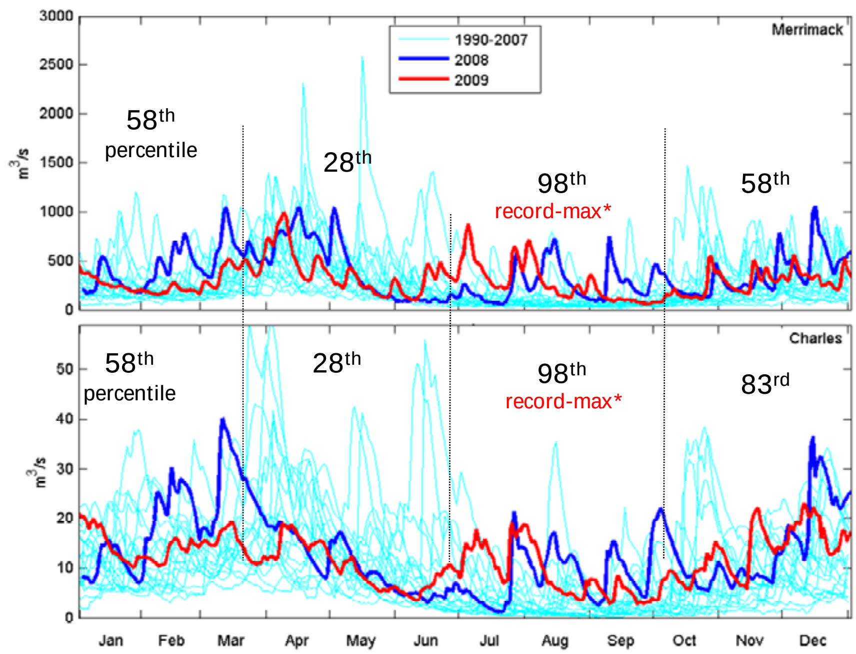


Figure 2-3. Comparison of the 2009 discharge of the Charles and Merrimack Rivers (solid red curve) with the observations from 2008 (solid blue curve) and 1990-2007 (light blue lines). Percentile of flow in 2009 relative to other years is presented for each river/season. Note record maxima for the 1990-2009 monitoring period, largely due to the rainy July.

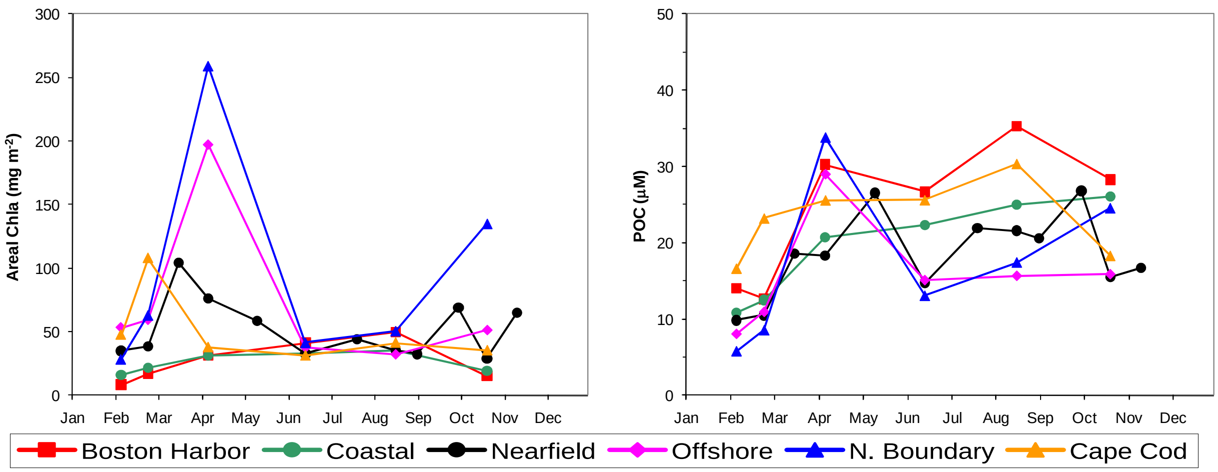


Figure 2-4. Time-series of survey mean areal chlorophyll (mg m^{-2}) and POC (µM) in Massachusetts and Cape Cod Bays. Mean concentrations over all stations and all depths for POC within each region in 2009 (chlorophyll is already depth-integrated).

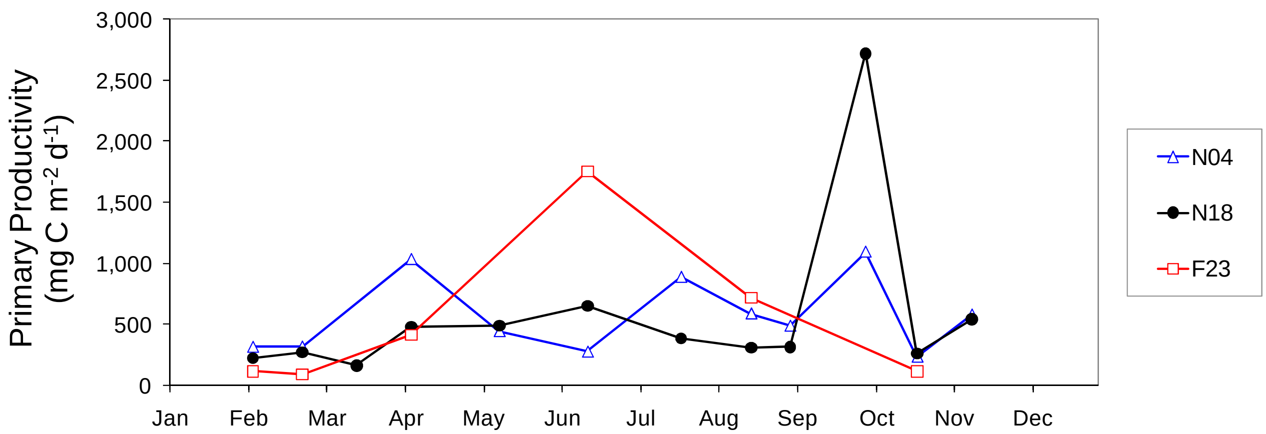


Figure 2-5. Potential areal productivity (mg C m^{-2} d^{-1}) in 2009 at stations F23, N18, and N04.

In May, *Phaeocystis* was no longer present in the nearfield. As in 2005 – 2008, a bloom of the toxic dinoflagellates species *Alexandrium fundyense* was occurring in the Gulf of Maine in May 2009. As in 2005, 2006 and 2008, an early May northeasterly storm brought the bloom into the bay, but this storm was relatively weak and unlike previous years no additional storms occurred in May 2009 (**Figure** 2-6). Model forecasts[1] and early toxicity to the north of Massachusetts Bay led MWRA to request additional sampling for *Alexandrium* during the May 12, 2009 nearfield survey. A maximum *Alexandrium* abundance of 151 cells L^{-1} was measured in the surface waters at station N18, which triggered initiation of the *Alexandrium* Rapid Response Surveys (Libby 2006). A series of three rapid response surveys were conducted on May 20, May 27, and June 8. *Alexandrium* abundances remained relatively low during these surveys and by June 8 the bloom was essentially over in the bay (Appendix B Slide 16).

[1] http://www.whoi.edu/page.do?pid=39136&tid=282&cid=56567&ct=162 for details on WHOI forecast for 2009.

The summer of 2009 was one of the wettest summers on record with major storm/rainfall events from late June into August. River flows for the July to September period were the highest observed over the course of the MWRA monitoring program (**Figure** 2-3). Coincident with these meteorological events there was an overall increase in nutrient concentrations throughout the bays from June to August (**Figure** 2-1). There was also a summer diatom bloom dominated by *Skeletonema* and comprised of other diatoms such as *Dactyliosolen fragilissimus* in Boston Harbor, coastal waters, and Cape Cod Bay (**Figure** 2-2). Harbor productivity peaked at 1,755 mg C m^{-2} d^{-1} during this summer bloom, but remained relatively low at the nearfield stations (**Figure** 2-5).

Bottom water dissolved oxygen (DO) concentrations declined over the April to August time period, though in the nearfield there was a slight increase in bottom DO levels from June to July (**Figure** 2-7). This increase may have been the result of mixing caused by the large storm event in late June (Appendix A Slide 14). Overall the relatively high riverine inputs led to lower surface salinity and stronger stratification in the nearfield from mid-June through August (**Figure** 2-8 and **Figure** 2-9). The lower salinity surface layer is even more pronounced in the high-resolution data from the NOAA NDBC Buoy 44013 located to the south east of the nearfield (**Figure** 2-8). The storm induced increase in bottom water DO levels observed in the nearfield between the June and July surveys (and presumably throughout the region since DO dynamics respond directly to regional physical forcing mechanisms) likely prevented very low annual mean bottom water DO levels from being reached in the fall (**Figure** 2-7).

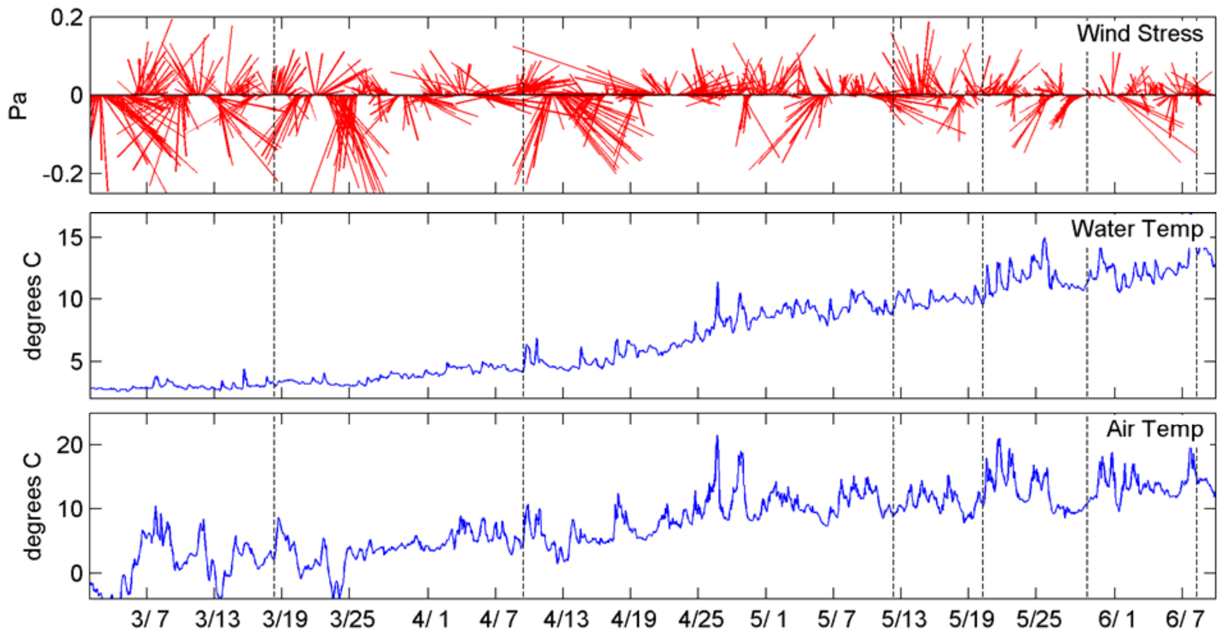


Figure 2-6. Time-series of wind stress and water and air temperature at GoMOOS Buoy A in March-June 2009. The dashed lines indicate water column surveys.

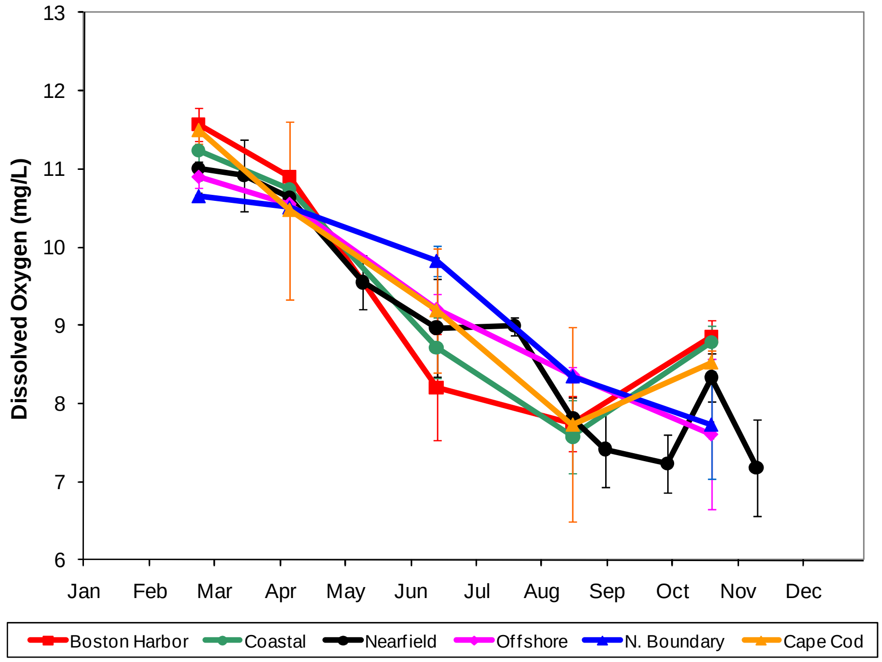


Figure 2-7. Time-series of average bottom dissolved oxygen concentration in Massachusetts and Cape Cod Bays in 2009. Average represents the bottom values from all stations in each region. Error bars represent ±1 standard deviation.

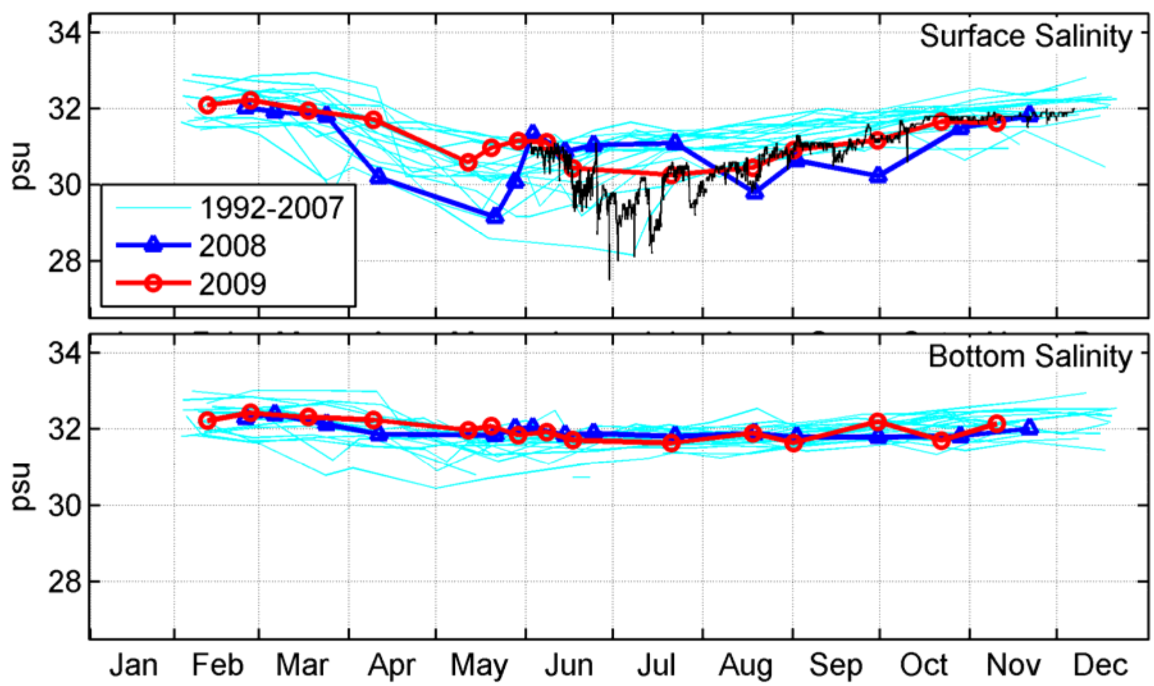


Figure 2-8. Comparison of the 2009 surface and bottom salinity near the outfall site (nearfield stations N16, N18 and N20) for 2009 (red line) compared to 2008 (dark blue line) and the previous 16 years of observations (1992-2007; light blue). The surface salinity data (June-December 2009) recorded at NOAA NDBC Buoy 44013 is in black.

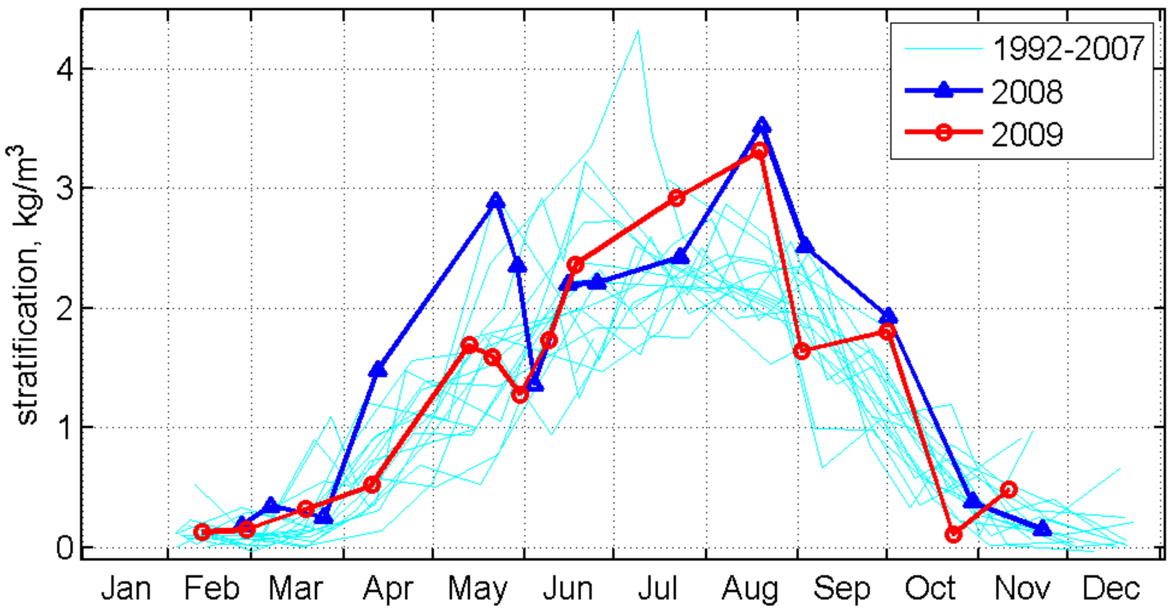


Figure 2-9. Stratification near the outfall site (nearfield stations N16, N18 and N20) for 2009 (red line) compared to 2008 (dark blue line) and the previous 16 years of observations (1992-2007; light blue).

In the fall of 2009, blooms of diatoms *Skeletonema* and *Dactyliosolen* (and others) were observed in the nearfield in late September and throughout the bays in October (**Figure** 2-2). These were the same species that dominated the August diatom bloom at the inshore harbor, coastal and Cape Cod Bay areas. The fall diatom blooms in the nearfield and northern boundary areas resulted in secondary peaks in chlorophyll and POC concentrations (**Figure** 2-4). Annual maxima in primary productivity were measured at the nearfield stations N04 and N18 (1,091 and 2,718 mg C m^{-2} d^{-1}; respectively) in late September (**Figure** 2-5). By October, productivity levels in the nearfield and Boston Harbor had decreased to <300 mg C m^{-2} d^{-1}. Nutrient concentrations were quite variable in the nearfield during the fall likely due to the frequency and magnitude of fall storms in 2009 (Appendix A slide 15). Similar variability at the farfield areas was not observed due to more limited sampling (August and October).

Bottom water DO concentrations reached a minimum in late September of 7.23 mg L^{-1} in the nearfield (**Figure** 2-7). By October, DO levels in the nearfield and other inshore areas had increased to >8 mg L^{-1}, while DO levels at the offshore and northern boundary stations remained lower. The stormy weather in the fall likely kept the DO levels well above 6 mg L^{-1}. The observed fall values (average Sept-Nov) were consistent with the regression model (Appendix A Slide 24). The model indicated that the temperature effect (due to downwelling conditions) should have resulted in lower than normal DO, but the salinity effect produced higher DO values. Note that the model does not take into account the intensity of fall storms, which is also a potentially important variable affecting the fall DO values.

Total zooplankton abundance in 2009 followed a normal seasonal cycle with low abundance during the colder months, peaking in summer, and declining again in the fall. Zooplankton patterns appeared to be regionally coherent. Mean abundances for most regions peaked at close to 80,000 animals m^{-3} with Cape Cod Bay slightly lower at 65,000 animals m^{-3} and the northern boundary area having the highest peak abundance of 115,000 animals m^{-3} (**Figure** 2-10). The peaks in total zooplankton abundance occurred in June in the inshore waters (coastal, Boston Harbor and Cape Cod Bay) and in August in the nearfield, offshore and north boundary areas. Zooplankton community composition was similar to most previous years. Abundance was dominated by copepods (copepodites and adults; most of which were *Oithona similis*, with secondary contributions by *Pseudocalanus* spp., followed by copepod nauplii, and non-copepods. Barnacle nauplii were relatively abundant in February and April in Boston Harbor and coastal areas. Other non-copepod zooplankton such as *Evadne nordmani* and *Oikopleura dioic*a, comprised >10% of total zooplankton in the nearfield during the months of May, August and September (**Figure** 2-10).

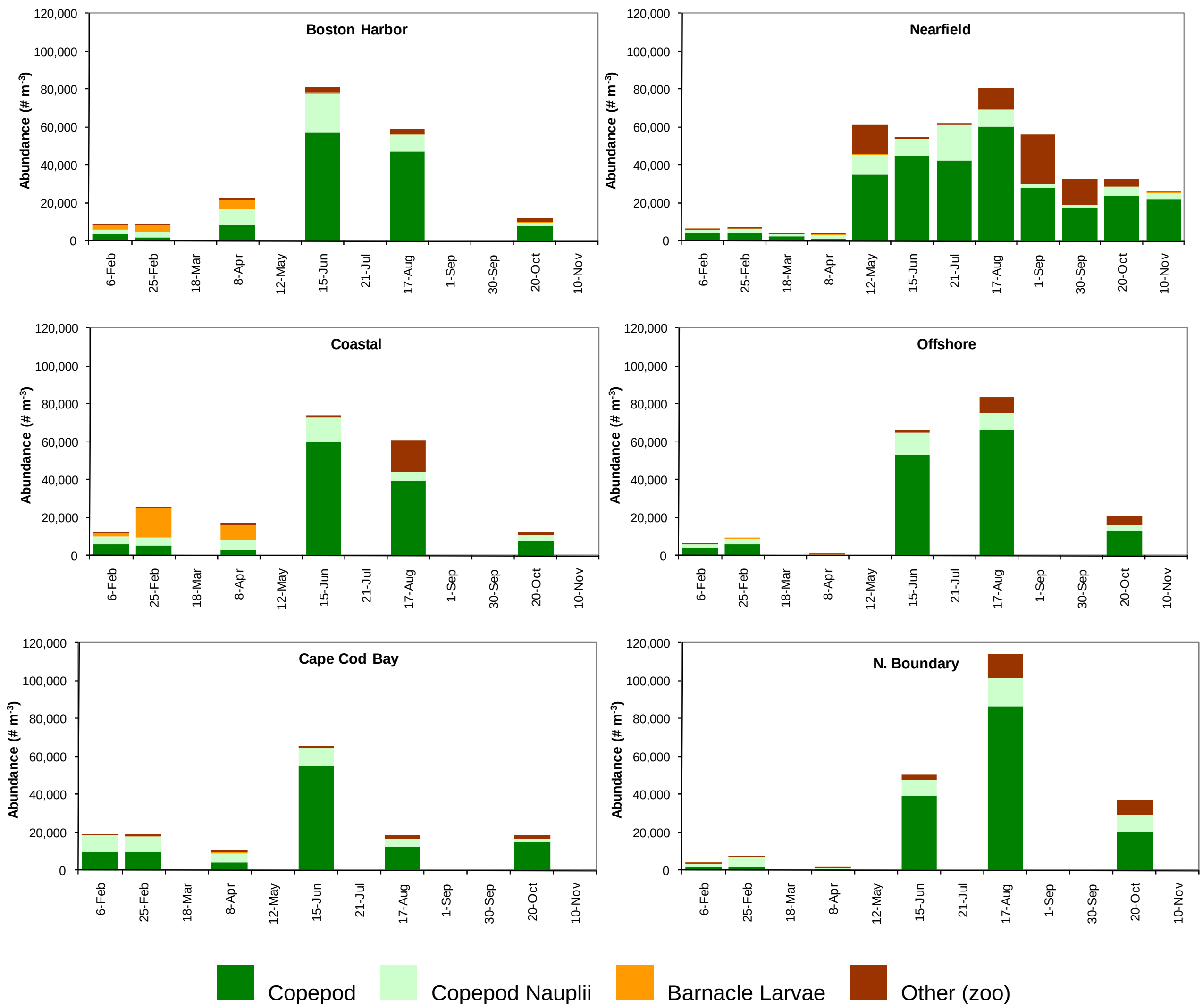


Figure 2-10. Zooplankton abundance by major taxonomic group in six areas during 2009.

2.2 Contingency Plan Thresholds for 2009

Contingency Plan Threshold water quality parameters include 1) DO concentrations and percent saturation in bottom waters of the nearfield and Stellwagen Basin, 2) rate of decline of DO from June to October in the nearfield, 3) annual and seasonal chlorophyll levels in the nearfield, 4) seasonal means of the nuisance algae *Phaeocystis pouchetii* and *Pseudo-nitzschia pungens* in the nearfield, and 5) 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 surface and mid-depth). The *Pseudo-nitzschia* "*pungens*" threshold designation can include both non-toxic *P. pungens* as well as the domoic-acid-producing species *P. multiseries*; these appear identical under a light microscope. 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 2009. Exceedance shaded blue.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2009
Bottom Water DO concentration (mg L^{-1})	Survey Mean June-October	<6.5 (unless background lower)	<6.0 (unless background lower)	Nearfield: 5.75 SW Basin: 6.2	Nearfield min: 7.23 SW Basin min: 6.79
Bottom Water DO percent saturation (%)	Survey Mean June-October	<80% (unless background lower)	<75% (unless background lower)	Nearfield: 64.3% SW Basin: 66.3%	Nearfield min: 77.5% SW Basin min: 71.8%
Bottom Water DO rate of decline (Nearfield, mg L^{-1} d^{-1})	Seasonal June-October	0.037	0.049	0.024	0.010
Chlorophyll (mean, mg m^{-2})	Annual	118	158	79	52
	Winter/spring	238	--	62	63
	Summer	93	--	51	43
	Autumn	212	--	97	49
Phaeocystis pouchetii (mean, cells L^{-1})	Winter/spring	2,020,000	--	468,000	402,000
	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	Absent
	Autumn	24,700	--	9,940	1,460
Alexandrium fundyense (cells L^{-1})	Any nearfield sample	100	--	Baseline Max 163	151

As described earlier, DO concentrations in 2009 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** 2-11). The 2009 bottom water minimum in the nearfield was comparable to the baseline and post-diversion mean minima and well above the Contingency Plan thresholds (**Table** 2-1). In Stellwagen Basin, the 2009 minimum DO concentration was slightly lower than the baseline and post-diversion means. Also note that the June nearfield bottom water DO concentration was below these previous minima while the October 2009 DO levels were well above previous levels. It is expected that these valleys (June) and peaks (October) in nearfield bottom water DO levels are related to physical forcing dynamics – wet summer and stormy fall. 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.* 2009b).

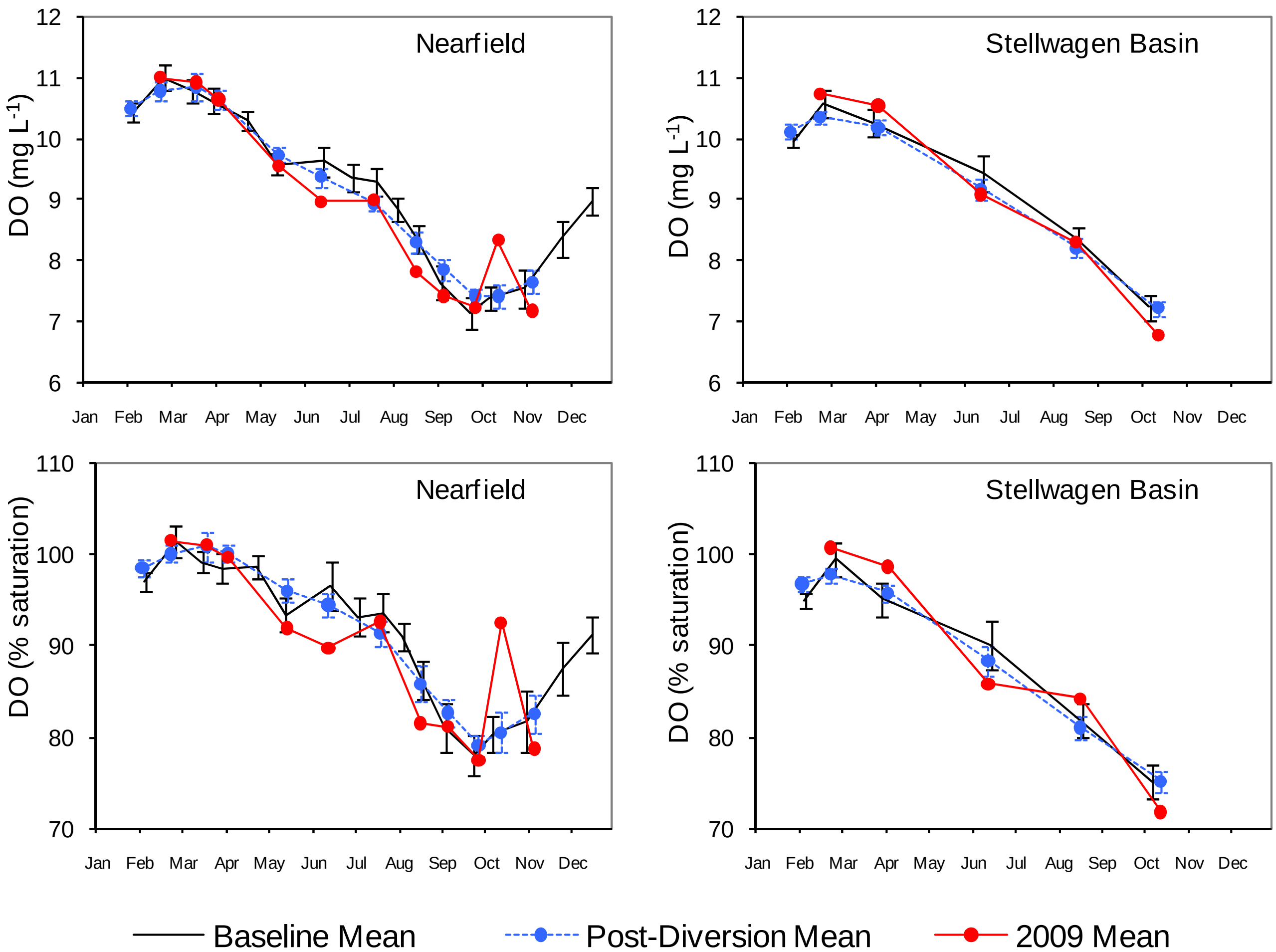


Figure 2-11. Time-series of survey mean bottom water DO concentration (top) and percent saturation (bottom) in the nearfield (left) and Stellwagen Basin (right) during baseline (black), post-diversion (blue), and 2009 (red). Data for Stellwagen Basin collected from stations F12, F17, F19, and F22. Error bars represent ± SE.

There were no exceedances of nearfield chlorophyll thresholds in 2009. The seasonal and annual nearfield mean areal chlorophyll levels for 2009 were all relatively low and well below threshold values (**Table** 2-1). Even with the April *Phaeocystis* bloom, the winter/spring mean value was only 63 mg m^{-2}, the lowest winter/spring mean areal chlorophyll level since 1998 – "the year without a bloom" (**Figure** 2-12). The summer, fall, and annual 2009 nearfield areal chlorophyll means were also quite low and lower than the baseline and post-diversion means.

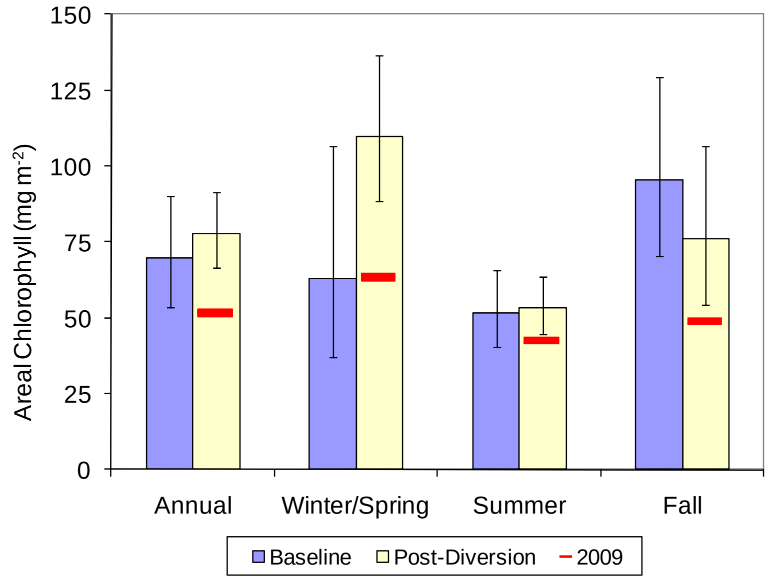


Figure 2-12. Comparison of baseline and post-diversion seasonal and annual mean areal chlorophyll (mg m^{-2}) in the nearfield. Error bars represent ± SE.

All three of the harmful or nuisance phytoplankton species included in the Contingency Plan thresholds (*Pseudo-nitzschia* spp., *Alexandrium fundyense* and *Phaeocystis pouchetii*) were observed in 2009. The only threshold exceedance in 2009 was for *Alexandrium*, which reached abundances of 151 cells L^{-1} in the nearfield, which is just over the 100 cells L^{-1} caution threshold (**Table** 2-1). The 2009 *Alexandrium* abundances were similar to the low levels seen in 2007 and much lower than observed during the *Alexandrium* blooms of 2005, 2006, and 2008 (**Figure** 2-13). Overall the 2009 *Alexandrium* bloom in Massachusetts Bay was small, of short duration, and led to limited and relatively brief shellfishing closures.

MWRA sampled for *Alexandrium* in Massachusetts Bay using the probe method on four surveys from May to June, and again during the nearfield survey in July following a report of "red water" off of Portsmouth, NH on July 10, 2009 (B. Keafer pers. comm.). Subsequent analyses by WHOI researchers of the samples collected of Portsmouth showed *Alexandrium* abundances of 25,000 to nearly 1,800,000 cells L^{-1}! WHOI conducted a rapid response survey on July 12, 2009 that showed elevated abundances off Cape Ann with levels reaching 7,200 cells L^{-1} offshore but much lower abundances in Massachusetts Bay (**Figure** 2-14). Subsequent surveys by MWRA (July 21) and WHOI (July 19-23) showed that this July bloom had ended and abundances in and to the north of Massachusetts Bay had decreased to <5 cells L^{-1}. The WHOI survey results are available online[2]. The stormy conditions, elevated runoff and downwelling favorable winds in June and July may have contributed to the conditions conducive for this July 2009 "red tide" event. Also of note is that low levels of *Alexandrium* (2.5 cells L^{-1}) were detected in October 2009. This marks the second year in a row that low levels of *Alexandrium* were detected in autumn.

[2] http://science.whoi.edu/users/olga/alex_surveys_2009/WHOI_Alexandrium_Surveys_2009.html

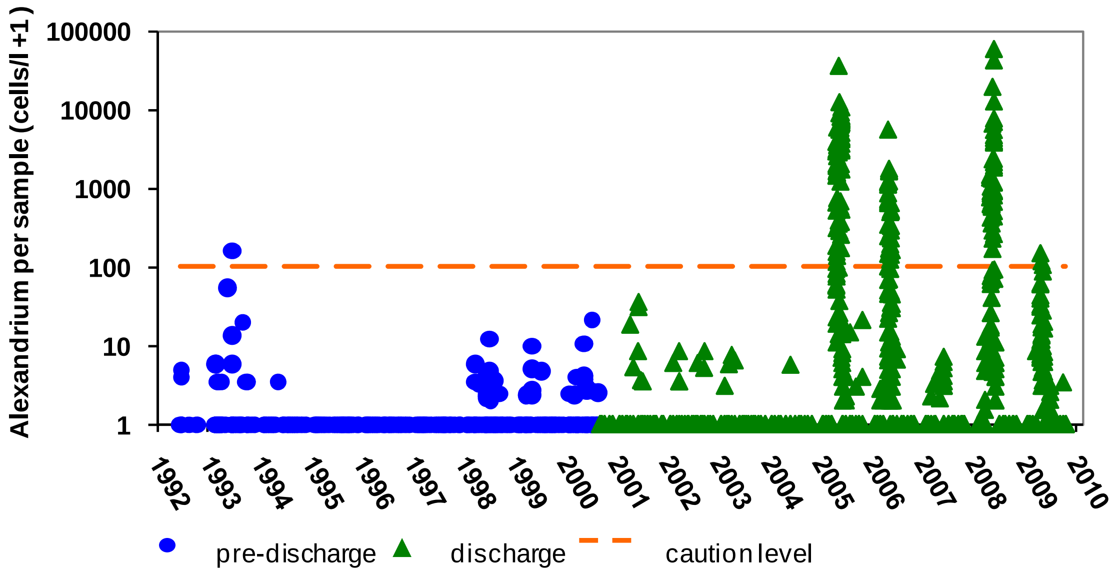


Figure 2-13. Nearfield *Alexandrium* abundance for individual samples (cells L^{-1}; note log axis). Contingency Plan threshold value shown as dashed line.

Phaeocystis abundance in the nearfield in April 2009 reached a sample maximum of 2.8 million cells L^{-1}, but the seasonal mean was only 402,000 cells L^{-1} which is well below the winter/spring threshold – it was the tenth year in a row that a bloom has been observed in the bays (**Figure** 2-15). *Phaeocystis* blooms appear to be a normal occurrence for the system.

Pseudo-nitzschia were absent in the winter/spring and summer and observed at low levels (mean 1,470 cells L^{-1}) during the fall in the nearfield. These levels continue the trend of low abundances since the peaks in 1998-1999 and are well below the fall Contingency Plan threshold and levels that would cause amnesic shellfish poisoning.

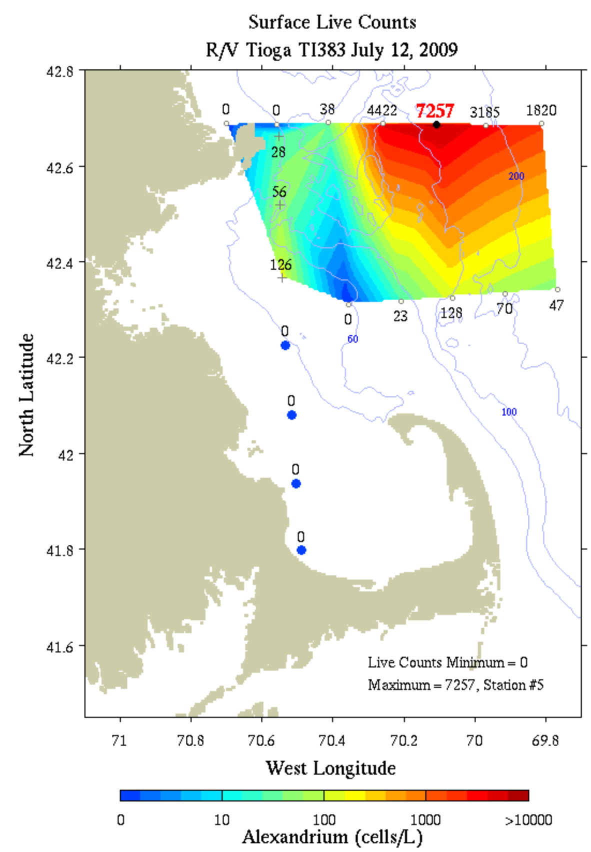


Figure 2-14. *Alexandrium fundyense* cell

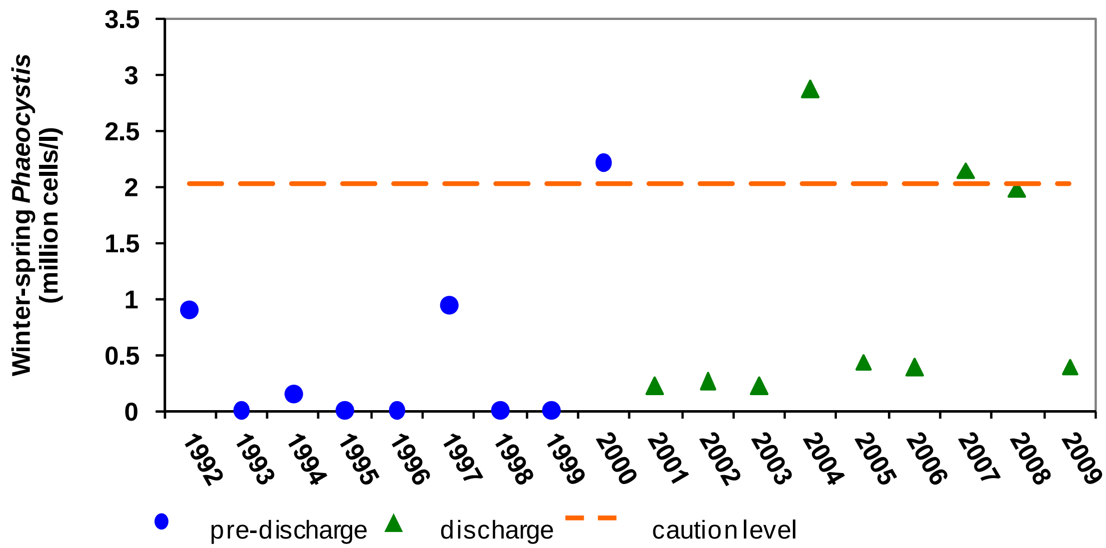


Figure 2-15. Winter/spring seasonal mean nearfield *Phaeocystis* abundance (cells L^{-1}) for 1992 to 2009. Contingency Plan threshold value shown as dashed line.

2.3 Interannual Comparisons

2.3.1 Nutrients and Biomass

In comparison to baseline conditions, the changes in the nutrient regimes are quite clear and consistent with model predictions (Libby *et al.* 2009b, Signell *et al.* 1996). 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 (**Figure** 2-16). This increase has been expressed as elevated levels of NH_4 in the effluent plume, which are generally confined to an area within 10-20 km of the outfall (**Figure** 2-17). 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 observed in the 1990's. The nearfield, since diversion, has averaged about 1 µM above background (as represented by data from the northern boundary).

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 that POC also increased in the nearfield in the summer (Libby *et al*. 2009b). There has also been a trend of higher winter/spring chlorophyll in most of Massachusetts Bay, including the nearfield area (**Figure** 2-17 and Appendix B Slides 24-27). The higher chlorophyll is largely from *Phaeocystis* blooms, which are regional and have occurred every year since 2000.

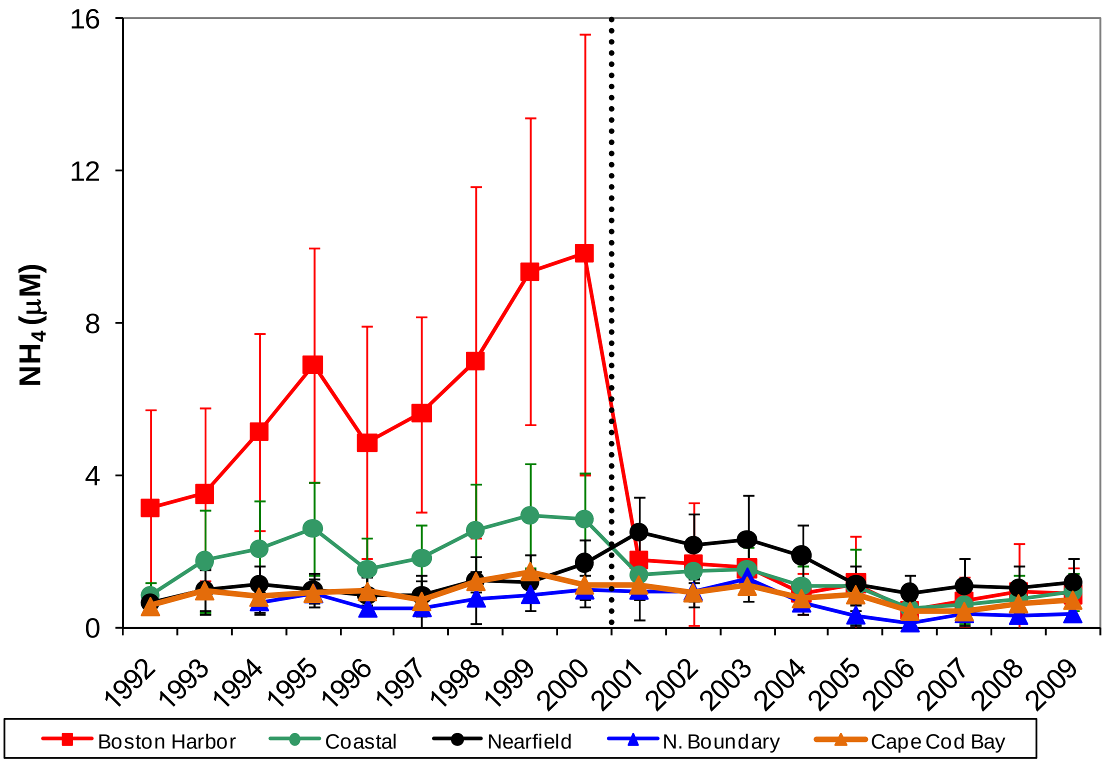


Figure 2-16. Time-series of annual mean NH_4 concentrations (µM) by area. Data collected from all depths and all stations sampled in each area. Error bars represent ±1 standard deviation.

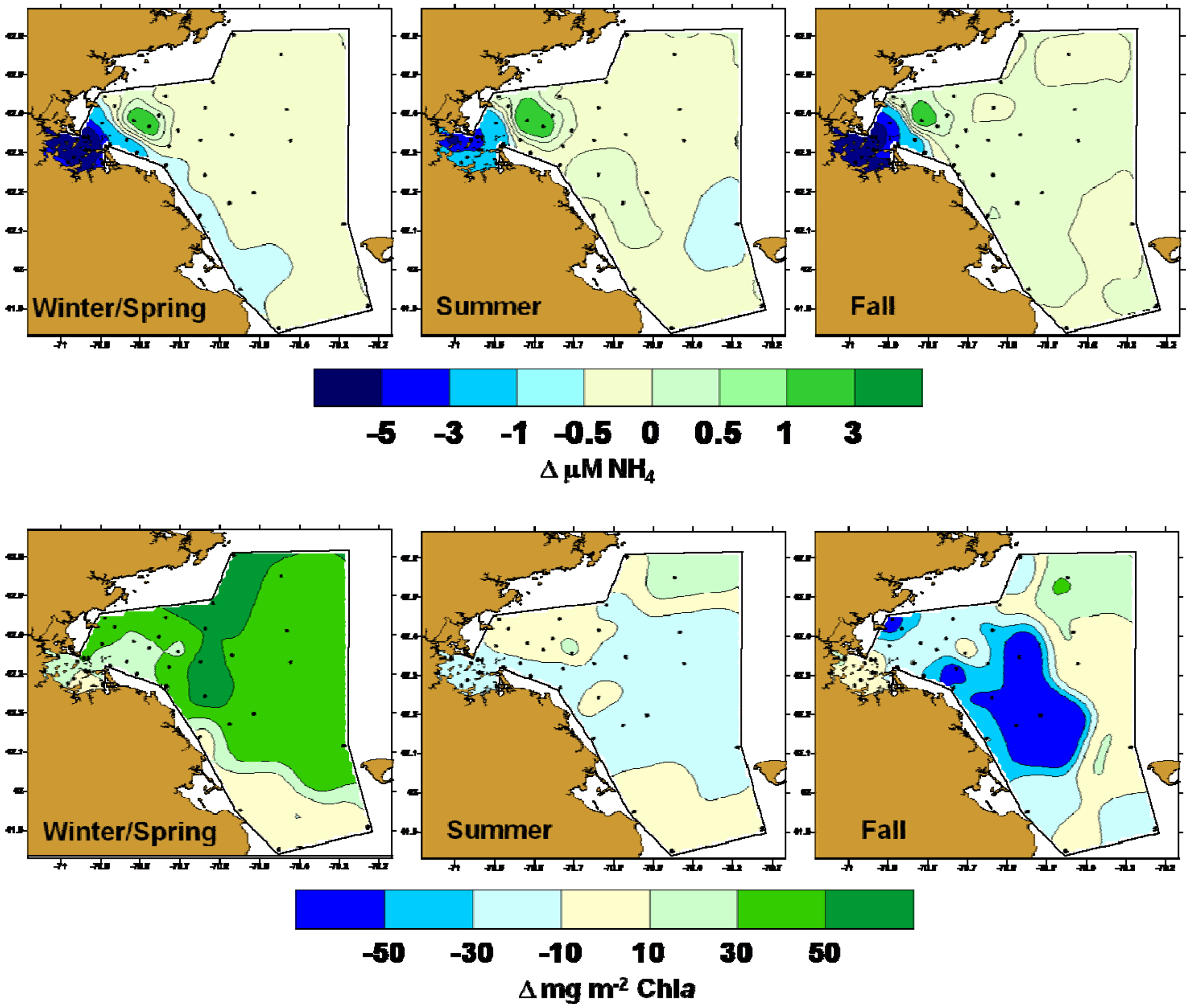


Figure 2-17. Change in seasonal NH_4 concentrations (µM; top row) and areal chlorophyll (mg m^{-2}; bottom row) from baseline to post-diversion. Change calculated as the difference in means over all depths for each season from each station.

"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*. 2009b). NH_4 was higher in the inner nearfield. The analyses did not find statistically notable 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.

BACI analyses were carried out including the 2009 data, focusing on a set of stations (**Figure** 2-18) that are a subset of those included in the proposed revised monitoring plan (MWRA 2010). Station N18 nearest the outfall was designated as the "impacted" site and compared to a range of control stations: Boston Harbor (F23), northeast of the outfall (N04 and F22), and 15 km (F13), 30 km (F06) and >50 km (F01 and F02) to the south of the outfall. The results were essentially the same as those seen previously for groups of stations (Libby *et al.* 2009b). The only statistical differences ($p \leq 0.05$) noted in the baseline vs. post-diversion comparison for each station were for NH_4, which increased at station N18 (winter/spring and summer) and decreased at station F23 (all seasons). The BACI comparisons between station N18 and the other stations yielded increases in NH_4 at station N18 for nearly all 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.

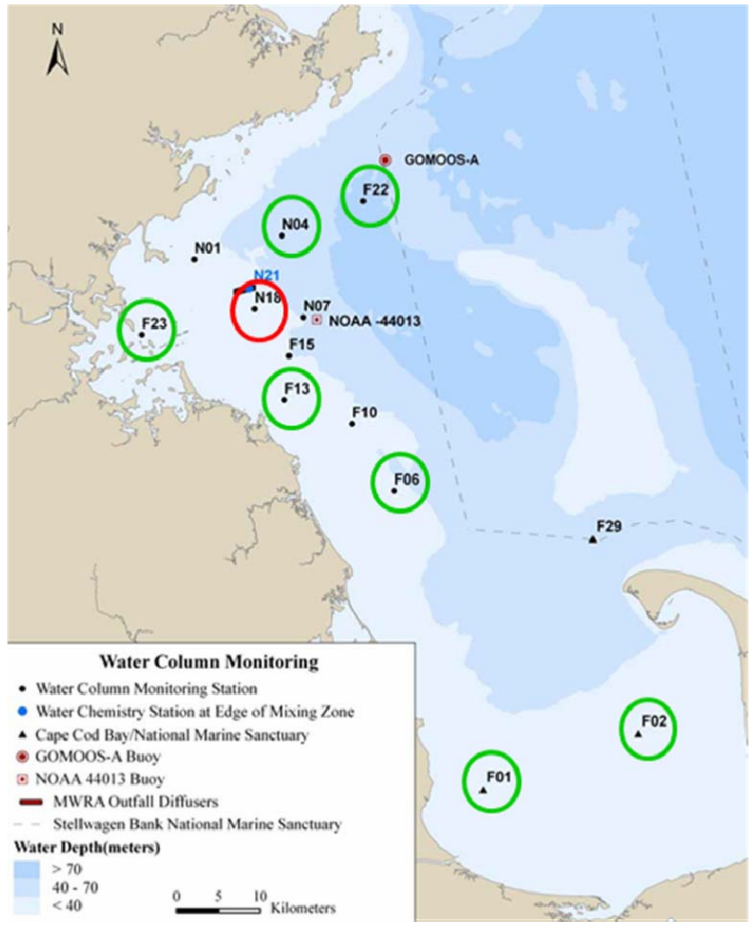


Figure 2-18. Stations included in the BACI analyses.

Red = "impacted" station,
Green = "control" stations.

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. Annual *Phaeocystis* blooms have caused elevated chlorophyll and POC in spring, but those blooms are regional and not caused by the outfall.

2.3.2 Productivity

Productivity (a measure of phytoplankton growth rates) at station F23 was higher than the other stations in 1995-1997 (**Figure** 2-19). After 1997 annual mean productivity at the 3 monitoring stations is generally comparable and remarkably synchronized over time. In 2009, annual productivity was low (~200 g C $m^{-2}d^{-1}$) and comparable across all three stations and continued the pattern of lower potential annual productivity values for all stations since 2003 (**Figure** 2-19). The 2009 annual productivity is comparable to the low values measured for 1998, which was thought to reflect environmental conditions (Keller *et al*. 2001).

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*. 2009b). The decreased began two years after outfall relocation (September 2000). Reduced nutrient loading at the Boston Harbor station has likely played a role in the decreased productivity there, but the recent decreases in productivity at the nearfield stations do not seem related to the outfall as the slight increase in NH_4 concentrations in the nearfield would be expected to lead to increases rather than decreases in productivity. Rather, as in noted for 1998, environmental conditions may be playing a role with reduced wind speeds contributing to lower productivity in both the harbor and nearfield areas.

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 0.44 or greater. The mean summer wind speed and the summer average wind gusts were lower in the period 2003 to 2009 compared to the period 1995 to 2002 (**Figure** 2-20). Thus the decrease in productivity since 2003 at the nearfield stations and 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 especially during the summer season.

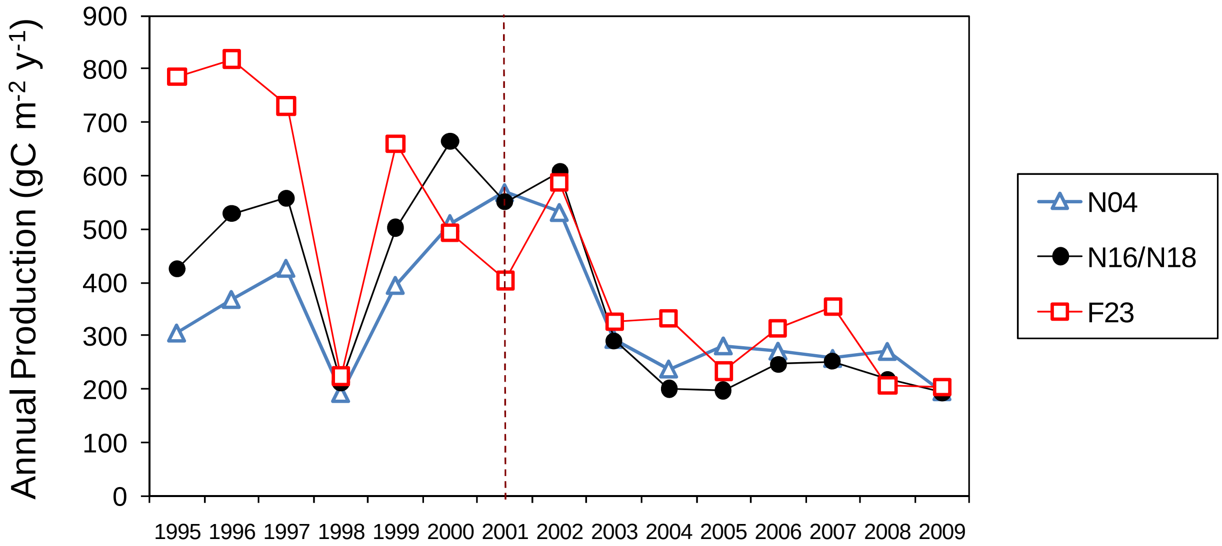


Figure 2-19. Potential annual production (g C m^{-2} y^{-1}) for stations F23, N16/N18, and N04.

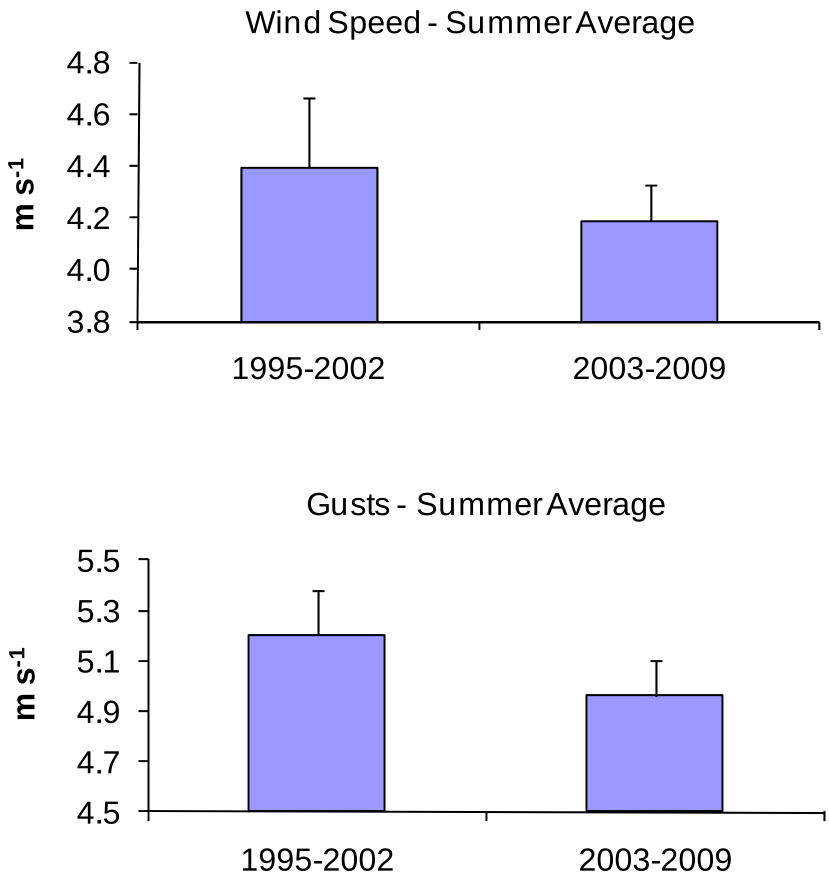


Figure 2-20. Summer (July-September) average wind speed and average wind gusts (m s^{-1}) at NOAA NDBC station 44013 for 1995-2002 and 2003-2009. The error bars represent +1 standard deviation.

2.3.3 Plankton

The 2009 phytoplankton patterns generally followed observed long-term trends, including the long-term decline in diatom abundance (**Figure** 2-21). No changes in total phytoplankton abundance were detected, but changes in phytoplankton functional groups have been occurring. For example, 2009 mean diatom abundance in the nearfield (131,400 cell L^{-1}) was one-third the 1992-2008 mean of 368,100 cells L^{-1} (Mann-Whitney U test, $p = 0.0030$). This long-term decline in diatom abundance has been ongoing since 2004, and is largely due to a reduction in winter-spring diatom bloom magnitude during the last decade of *Phaeocystis* dominance of the winter-spring bloom (Libby *et al*. 2009c). The increase in *Phaeocystis* has been especially dramatic in the coastal, nearfield, offshore, and boundary regions where there have been 2 to 4-fold increases. Another group that appears to be increasing in abundance is cryptomonads which during 2009 had a mean nearfield abundance level of 185,600 cells L^{-1} compared to a 1992-2008 long-term mean of 127,400 cells L^{-1} (Mann-Whitney U test, $p = 0.0186$).

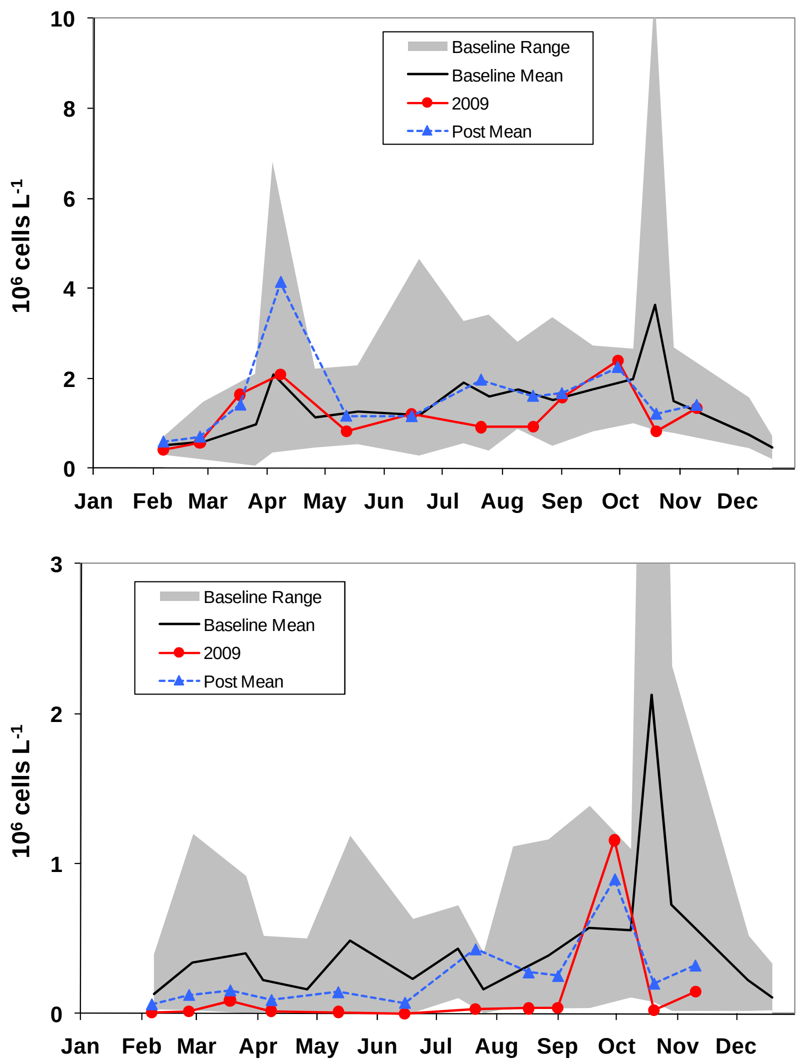


Figure 2-21. Time-series of survey mean total phytoplankton (top) and diatom (bottom) abundance (10^6 cells L^{-1}) in the nearfield in 2009 compared against the baseline range, baseline mean and post-diversion mean.

Patterns and trends assessed only by phytoplankton numerical abundance will not show changes in the relative contribution of variously sized phytoplankton groups or species to total phytoplankton biomass (expressed as µg phytoplankton carbon L^{-1}). A preliminary investigation of long-term patterns of phytoplankton biomass since 1992 is presented here (**Figure** 2-22; Appendix C Slides 20-28). For the nearfield, based on the findings that there has been a decline in diatoms since 2004 (Libby *et al.* 2009c), the abundance and biomass observed during the most recent five years (2005-2009) was compared to that observed during the first 13 years of monitoring (1992-2004). These results are summarized in **Table** 2-2.

Table 2-2. Summary of nearfield phytoplankton biomass and abundance changes in recent years (2005 – 2009) compared to 1992-2004. Comparisons made using Mann-Whitney test. Surface nearfield observations used; typically n = 182 (1992-2004) and n = 60 (2005-2009); statistically significant ($p < 0.05$) differences in red (increase) or blue (decline).

	1992 - 2004	2005 - 2009	change	P value
Biomass (µg C L^{-1})				
Total phytoplankton	95	73	- 22	0.0023
Diatoms	57	43	- 14	0.0008
Dinoflagellates	14	4	- 10	0.0040
Abundance (cells L^{-1})				
Total phytoplankton	1.384×10^6	1.334×10^6		0.6699
Diatoms	273,600	167,300	- 106,300	< 0.0001
Dinoflagellates	18,700	34,000	15,300	0.0297
Cell Carbon (pg C $cell^{-1}$)				
Total phytoplankton	67	41	- 26	<0.0001
Diatoms	268	435	167	0.0003
Dinoflagellates	1,812	570	- 1,242	<0.0001

At the community level, total phytoplankton carbon during 2005-2009 (73 g C L^{-1}) was about 75% of that observed during 1992-2004 (95 µg C L^{-1}; **Table** 2-2). The majority of this decline was due to a change in mean diatom biomass from 57 µg C L^{-1} (1992-2004) to 43 µg C L^{-1} (2005-2009). A large decline in dinoflagellate biomass also contributed to the overall decline (14 to 4 g C L^{-1}).

There was a shift toward bigger diatoms (more carbon per cell) and lighter dinoflagelates and other cells making up the total. Even though total diatom biomass has decreased over this period, diatoms appear to have increased their mean carbon per cell content. Recent summer increases in *Dactyliosolen fragilissimus* and other large diatoms (*Guinardia flaccida*, for example) appear to be driving the long-term increase in mean diatom cellular carbon. For dinoflagellates and total phytoplankton there has been a decline in carbon per cell between the two periods examined. The decline in dinoflagellate cellular carbon was driven by a decline in large dinoflagellates (*Ceratium* spp.) and a recent increase in smaller species (small *Gymnodinium* spp. and *Heterocapsa rotundatum*). The dominance of winter-spring phytoplankton by small cells (*Phaeocystis*) appears to be driving the decline in mean phytoplankton size. Other factors contributing to this decrease in total phytoplankton carbon per cell include the recent increase in microflagellate and cryptomonads abundances.

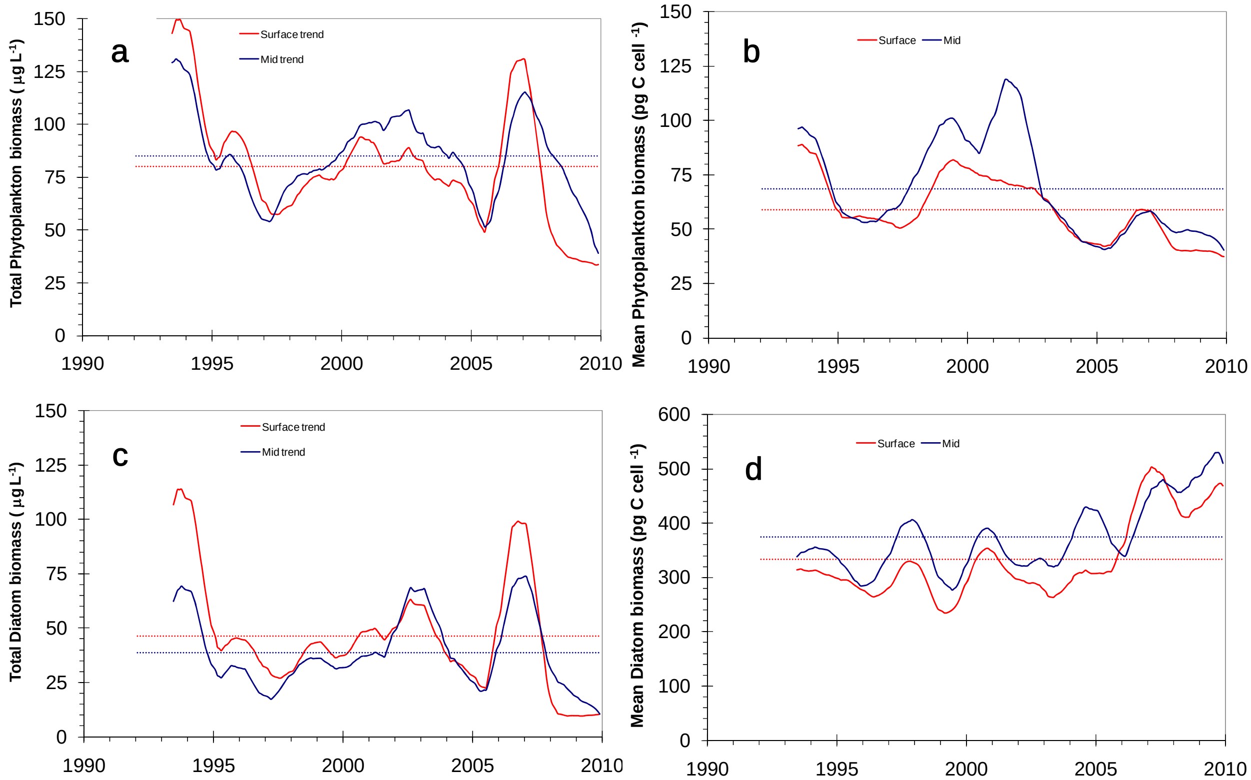


Figure 2-22. Long-term trend (1992- 2009) in (a) total phytoplankton biomass (µg L^{-1}), (b) total phytoplankton average carbon per cell (pg C $cell^{-1}$), (c) diatom biomass (µg L^{-1}), and (d) diatom average carbon per cell (pg C $cell^{-1}$) derived from time series analysis. Long-term mean levels are also shown (dotted lines). Data from stations N04, N16 and N18, only. Note difference in axes for mean biomass.

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 in abundance while microflagellates and *Phaeocystis* have increased. This change has driven the overall phytoplankton biomass (µg C L^{-1}) lower, but at the same time there have been community changes towards larger diatoms and smaller dinoflagellates. There is no plausible outfall-related link or causality associated with these shifts as they occur over large spatial scales; such broad patterns appear instead 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 1992-2009 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. The most apparent change has been the lower overall abundance of zooplankton since 2001 throughout the bays (**Figure** 2-23).

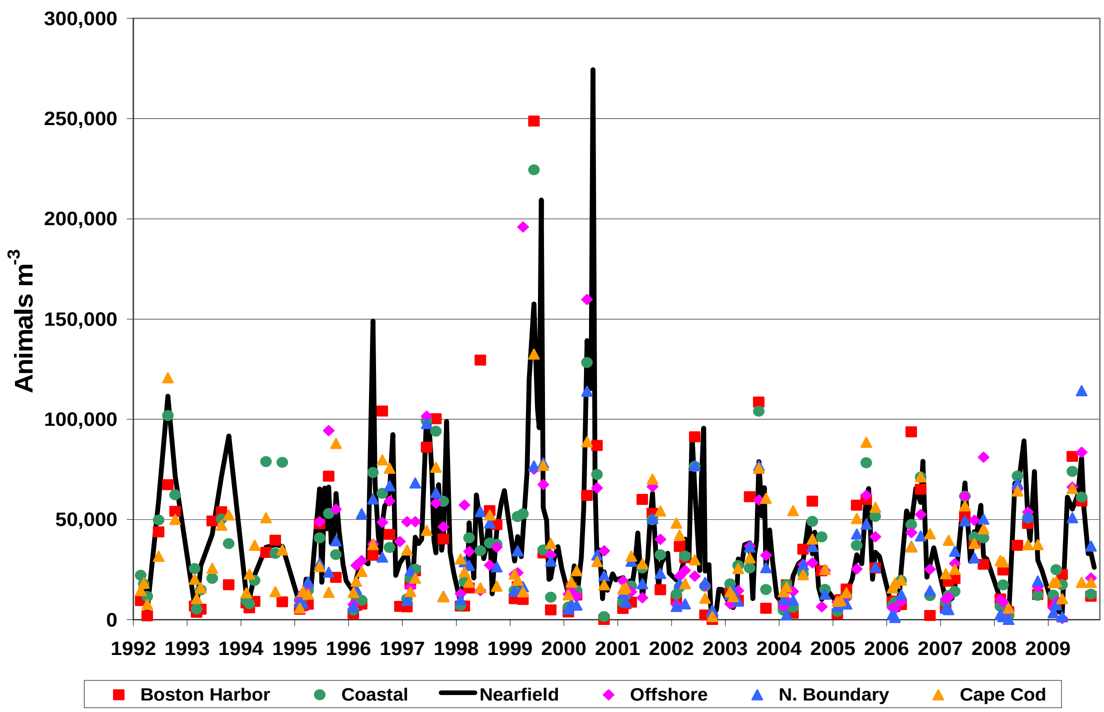


Figure 2-23. Time series of total zooplankton abundance by area (1992- 2009).

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.* 2009b). 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 due to a long-term decline in total copepods. Total copepod abundance rebounded somewhat in 2007-2009 (**Figure** 2-24). This increase in zooplankton/copepod abundance appears to have been led by a rebound in *Oithona* abundance to above the long-term mean level since 2007 (Appendix C Slide 45). Nearfield *Calanus finmarchicus* attained elevated abundance during 2009 (Appendix C Slide 46), featuring the greatest nearfield average abundance levels recorded during 18 years of monitoring. 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 (Green and Pershing 2007; Pershing *et al.* 2005).

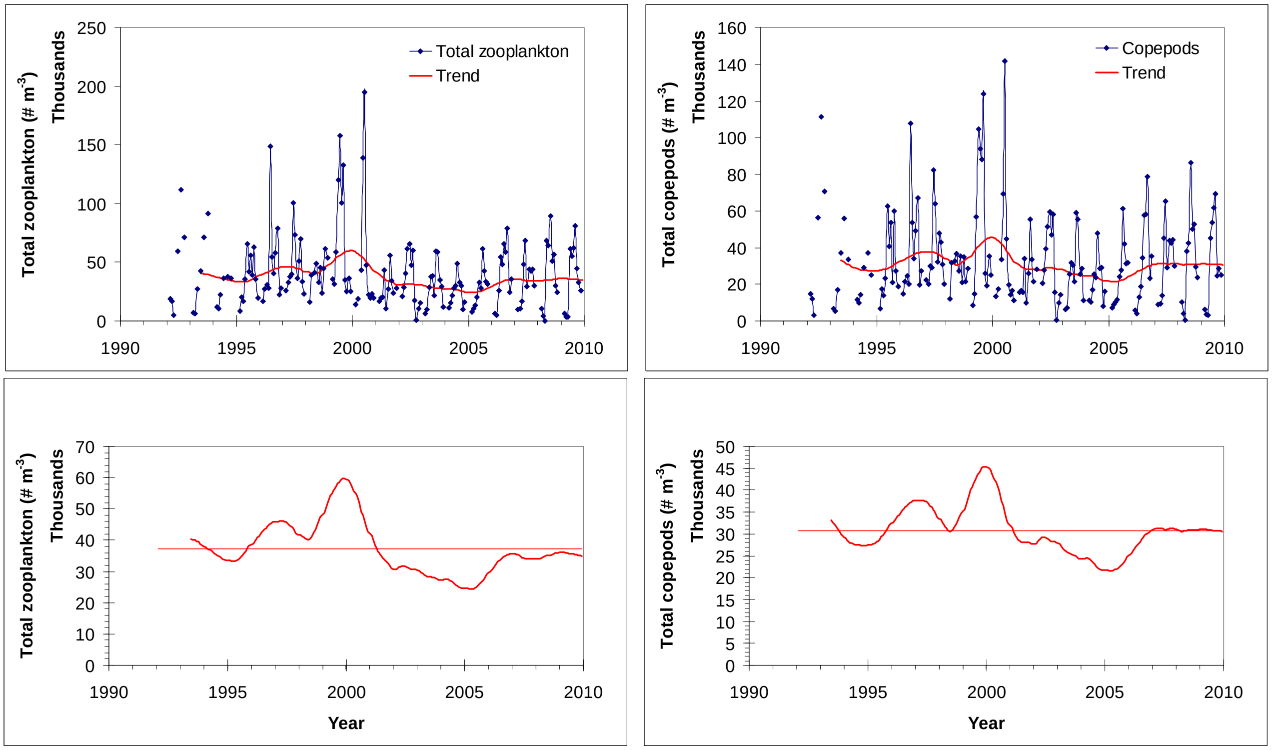


Figure 2-24. Time series of nearfield total zooplankton and total copepod abundance (thousands m^{-3}; top) and long term trends for both (bottom).

3 SUMMARY

In general, water column conditions in 2009 exhibited typical seasonal patterns observed over the course of the monitoring program (1992-2008). Mean annual and mean seasonal values of many variables for 2009 were close to the averages over all years including: winds, temperature, stratification, nutrients, phytoplankton biomass, dissolved oxygen and zooplankton abundance and community structure. The most notable differences in 2009 resulted from the cold, stormy conditions and associated high river flow during the summer. These conditions resulted in less upwelling than normal, rough sea conditions/sporadic mixing, and large pulses of freshwater. The stormier trend for 2009 was also evident in late fall during the seasonal turnover of the water column. In Massachusetts Bay, these physical conditions led to variable nutrient concentrations from survey to survey in the nearfield (late summer/fall) as well as changes in bottom water DO concentrations (increases in late June and October)that likely precluded low bottom water DO levels (<6.0 mg L^{-1}) from occurring in fall 2009. In the western Gulf of Maine (Portsmouth to Cape Ann), the stormy conditions in June and early July may have contributed to the development of the *Alexandrium* "red tide" event observed by WHOI scientists on July 10, 2009. Overall, the water column characteristics in 2009 were comparable to those observed during the baseline and post-diversion periods.

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 signature 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. There has been an increase in winter/spring biomass in the nearfield and most of Massachusetts Bay but this is 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.* 2009b). 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 supported the high biomass during the baseline (Signell *et al.* 1996). Although there appears to be a direct relationship between decreases in nutrients and biomass in Boston Harbor, for the bay the association between observed changes is not as clear.

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 (Libby *et al*. 2009b). 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.

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. Similar changes have also been observed in overall phytoplankton biomass and levels of carbon per cell. Total phytoplankton, diatom and dinoflagellate biomass (μg C L^{-1}) has decreased in recent years as has the levels of carbon per cell for dinoflagellates and total phytoplankton. The decrease in carbon per cell for dinoflagellates has been due to a decrease in large cell species such as *Ceratium* spp. and a commensurate increase in dominance of smaller cell species (small *Gymnodinium* spp. and *Heterocapsa rotundatum*). The overall decrease in phytoplankton carbon per cell can be attributed to the dominance of the winter/spring blooms by the small celled *Phaeocystis* and the recent increase in microflagellate and cryptomonads abundances. 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.

In 2009, the *Alexandrium* "bloom" was minor compared to the major red tides of 2005, 2006, and 2008; the maximum cell abundance in Massachusetts Bay only reached 150 cells L^{-1}. However, the major red tides of 2005, 2006, and 2008 garnered much publicity due to their novelty (lack of blooms in Massachusetts Bay) and impact on local shellfishing economies. During the first 13 years of the monitoring program, *Alexandrium* abundance had been low (0-100 cells l^{-1}), but in recent years it 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 five years. Again there are no indications of a regional outfall effect on the A. *fundyense* blooms. A modeling analysis estimated that if an outfall effect had occurred, it would have been minor (Anderson *et al.* 2007). *Alexandrium* blooms may become regular, annual events in the western Gulf of Maine and Massachusetts Bay.

There was a general decline in total zooplankton (mainly copepods) in the nearfield and other Massachusetts Bay areas from 2001 to 2006 followed by a rebound in 2007-2009. The timing of the decline coincides with the diversion of the outfall, but there are no plausible linkages between the diversion and apparent baywide decline, nor the subsequent increase. The values in 1999 and 2000 were anomalously high. Abundance can change in response to a variety of biological processes (changes in grazing pressure top-down or bottom-up; e.g. Frank *et al.* 2005) or regional physical processes (i.e. different water masses, NAO or freshening of the Northwest Atlantic due to Arctic melting, etc.; e.g. Turner *et al*. 2006, Jiang *et al*. 2007, and Pershing *et al.* 2005).

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. 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. This local relative increase in ammonium has not had adverse effects either near or distant from the discharge. Meanwhile, the corresponding decrease in nutrient loadings to Boston Harbor has resulted in significant improvements in water quality (Taylor 2006).

4 REFERENCES

Anderson DM, Libby PS, Mickelson MJ, Borkman DG, He R, McGillicuddy DJ. 2007. The 2005 New England red tide of *Alexandrium fundyense*: observations, causes, and potential outfall linkages. Boston: MWRA Report 2007-10. 85 p.

Broekhuizen N and McKenzie E. 1995. Patterns of abundance for Calanus and smaller copepods in the North Sea: time series decomposition of two CPR data sets. Mar. Ecol. Prog. Ser. 118:103-120.

EPA. 1988. Boston Harbor Wastewater Conveyance System. Supplemental Environmental Impact Statement (SEIS). Boston: Environmental Protection Agency Region 1.

Frank KT, Petrie B, Choi JS, Leggett WC. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308: 1621-1623.

Geyer WR, Libby PS, Giblin A. 2002. Influence of physical controls on dissolved oxygen variation at the outfall site. Boston: Massachusetts Water Resources Authority. Letter Report. 20 p.

Greene CH, Pershing AJ. 2007. Climate drives sea change. Science 315: 1084-1085.

Jiang M, Brown WM, Turner JT, Kenney RD, Mayo CA, Zhang Z, Zhou M. 2007. Springtime transport and retention of *Calanus finmarchicus* in Massachusetts and Cape Cod Bays, USA, and implications for right whale foraging. Mar. Ecol. Prog. Ser. 349:183-197.

Keller AA, Taylor C, Oviatt C, Dorrington T, Holcombe G, Reed L. 2001. Phytoplankton production patterns in Massachusetts Bay and the absence of the 1998 winter-spring bloom. Marine Biology 138:1051–1062.

Libby PS. 2006. Standing survey plan: rapid response *Alexandrium* survey. Boston: Massachusetts Water Resources Authority. Report 2006-05. 19 p.

Libby PS, Geyer WR, Keller AA, Mansfield AD, Turner JT, Anderson DM, Borkman DG, Rust S, Hyde K, Oviatt CA. 2007. Water Column Monitoring in Massachusetts Bay: 1992-2006. Boston: Massachusetts Water Resources Authority. Report 2007-11. 228 p.

Libby PS, Fitzpatrick MR, Buhl RL, Lescarbeau GR, Leo WS, Borkman DG, Turner JT, Oviatt CA. 2009a. Quality assurance plan (QAPP) for water column monitoring 2008-2009, Revision 1 Tasks 4, 5, 6, 7, 8, 11. Boston: Massachusetts Water Resources Authority. Report 2008-02. 99 p.

Libby PS, Borkman DG, Geyer WR, Keller AA, Turner JT, Mickelson MJ, Oviatt CA. 2009b. Water column monitoring in Massachusetts Bay 1992-2007: focus on 2007 results. Boston: Massachusetts Water Resources Authority. Report 2009-04. 162 p.

Libby PS, Anderson DM, Borkman DG, Geyer WR, Keller A, Oviatt CA, Turner JT. 2009c. 2008 Water column monitoring results. . Boston: Massachusetts Water Resources Authority. Report 2009-12. 31 p. plus appendices.

MWRA. 1991. Massachusetts Water Resources Authority effluent outfall monitoring plan: Phase I baseline studies. Boston: Massachusetts Water Resources Authority. Report ms-02. 95p.

MWRA. 1997. Massachusetts Water Resources Authority effluent outfall monitoring plan: Phase II post discharge monitoring. Boston: Massachusetts Water Resources Authority. Report ms-044. 61 p.

MWRA. 2001. Massachusetts Water Resources Authority Contingency Plan Revision 1. Boston: Massachusetts Water Resources Authority. Report ms-071. 47 p.

MWRA. 2004. Massachusetts Water Resources Authority Effluent Outfall Ambient Monitoring Plan Revision 1. Boston: Massachusetts Water Resources Authority. Report ms-092.

MWRA. 2010. Massachusetts Water Resources Authority effluent outfall ambient monitoring plan Revision 2. July 2010. Boston: Massachusetts Water Resources Authority. Report 2010-04. 107 p.

Pershing AJ, Greene CH, Jossi JW, O’Brien L, Brodziak JKT, Bailey BA. 2005. Interdecadal variability in the Gulf of Maine zooplankton community, with potential impacts on fish recruitment. ICES J. Mar. Sci. 62: 1511-1523.

Scholin CA, Doucette GJ, Cambella AD. 2009. Prospects for developing automated systems for *in situ* detection of harmful algae and their toxins. Monographs on oceanographic methodology. Babin, M., Roesler, C. and J. Cullen [eds.] UNESCO. In Press.

Taylor DI. 2006. 5 years after transfer of Deer Island flows offshore: an update of water-quality improvements in Boston Harbor. Boston: Massachusetts Water Resources Authority. Report 2006-16.

Turner JT, Borkman DG, Hunt, CD. 2006. Zooplankton of Massachusetts Bay, USA, 1992-2003: relationships between the copepod *Calanus finmarchicus* and the North Atlantic Oscillation. Mar. Ecol. Prog. Ser. 311:115-124.

A. Physical Characterization

Massachusetts Bay physics, 2009.
Rocky Geyer, Woods Hole Oceanographic Institution

A.1. Overview

The most notable characteristic of the physical regime in 2009 was cold, stormy conditions during June and July, resulting in less upwelling than normal, rough sea conditions, and pulses of freshwater input. The late fall was also stormier than normal. Otherwise the conditions were in the normal range.

A.2. Forcing variables

Air temperature (**slide 3**) was below normal during June and July, due to the low pressure systems that hit the system during June and July.

River flow (**slide 4**) was normal during January and February, but the spring freshet was essentially absent in 2009, so the months of March-May were dryer than normal. Two major storms during the summer, one in late June and the other in late July, caused higher than normal run-off during the summer. 2009 had the wettest summer of the monitoring program, based on the flow of the Merrimack and Charles Rivers. The fall was back to normal for the Merrimack and higher than normal for the Charles. 2009 continues the trend of wetter than normal conditions that has been continuing since 2004 (**slide 6**).

Winds showed the influence of the summertime storms, resulting in net downwelling conditions during June and weak upwelling in July (**slide 7**). The anomalous wind conditions are mainly due to two storms, one around June 23 and the other around July 24 (**slide 14**). Strong downwelling occurred during the fall due to stormier than normal conditions from late October to the end of the year **(slide 15**).

Waves were larger than normal during June and July and from October to December (**slide 8**), due to the storminess during those time periods.

A.3. Water properties

Surface water temperature did not show significant anomalies from the MWRA surveys (**slide 11**), but the continuous NOAA data (**slide 12**) showed a significant drop in late June and late July due to the passage of low pressure systems. Water temperature was warmer than normal during the fall, but otherwise normal.

Salinity was significantly lower than average during June and July (**slide 18**), due to the freshwater inflow. The lowest salinity happened between the MWRA cruises, but it was recorded by the NOAA buoy, reaching the lowest value (27.5 psu) that has been observed during the monitoring program.

Stratification was slightly higher than average during the summer due to the freshwater inflow.

Dissolved oxygen got down to near 7 mg/l during September in the nearfield bottom water (**slide 23**), but it came back up in October, due to an early storm event. The downwelling conditions during the summer resulted in lower DO conditions than normal, but the storminess of the fall kept the DO from getting close to 6 mg/l. The observed values (average Sept-Nov) were consistent with the regression model (**slide 24**), which indicated that the temperature effect (due to downwelling conditions) should have resulted in lower than normal DO, but the salinity effect produced higher DO values. Note that this model does not take into account the intensity of fall storms, which is also a potentially important variable affecting the fall DO values.

1

Massachusetts Bay Physics 2009

Rocky Geyer
Woods Hole Oceanographic Institution

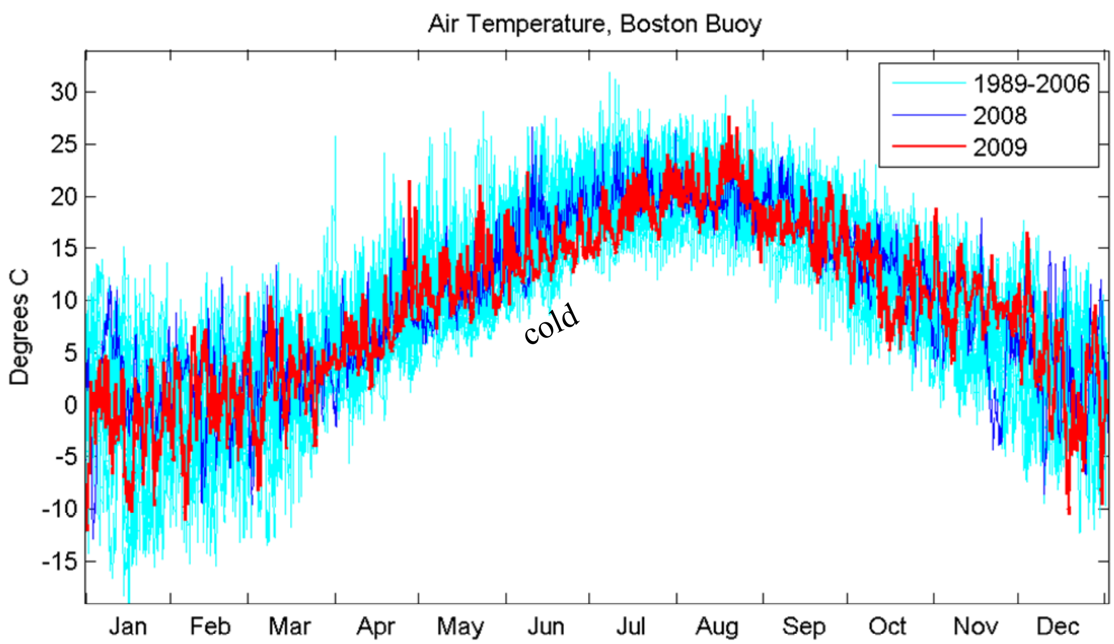
2

Forcing conditions

- Air temperature
- River flow
- Wind
- Wave height

3

Air temperature (Boston buoy)



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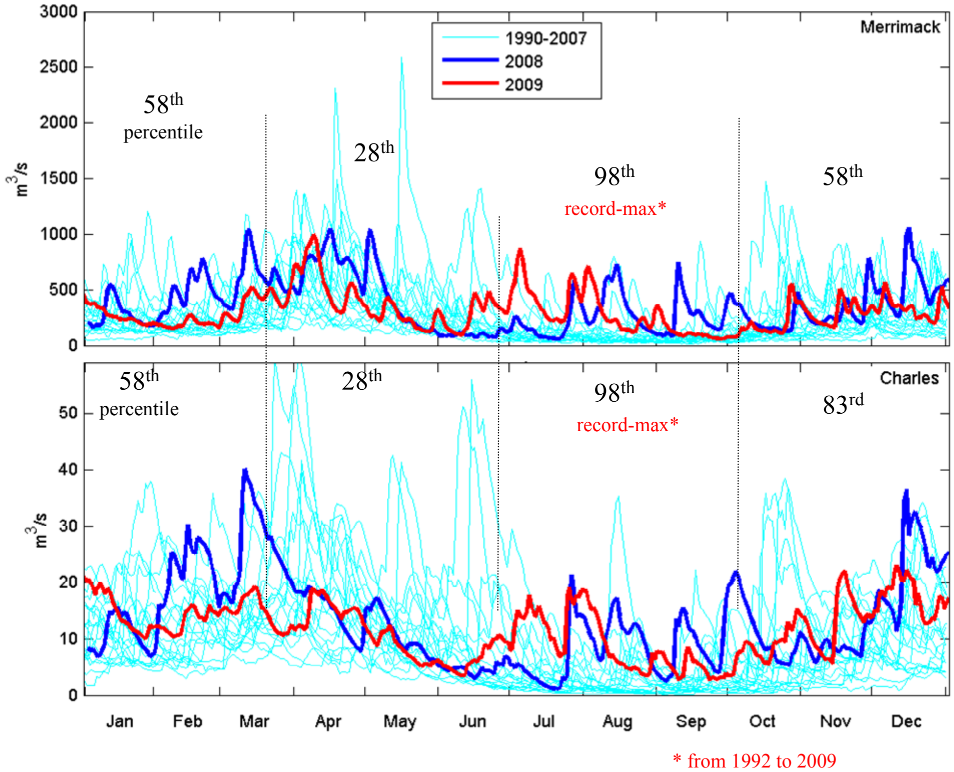
River flow: seasonal pattern



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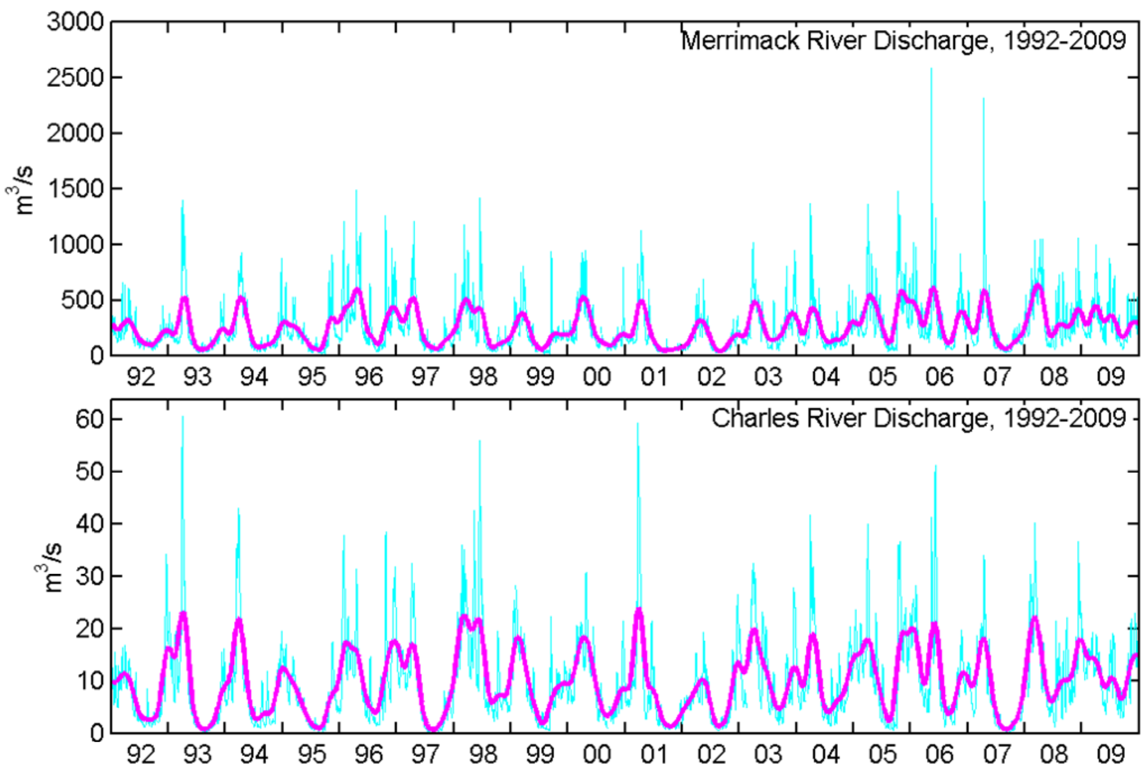
River flow: time series



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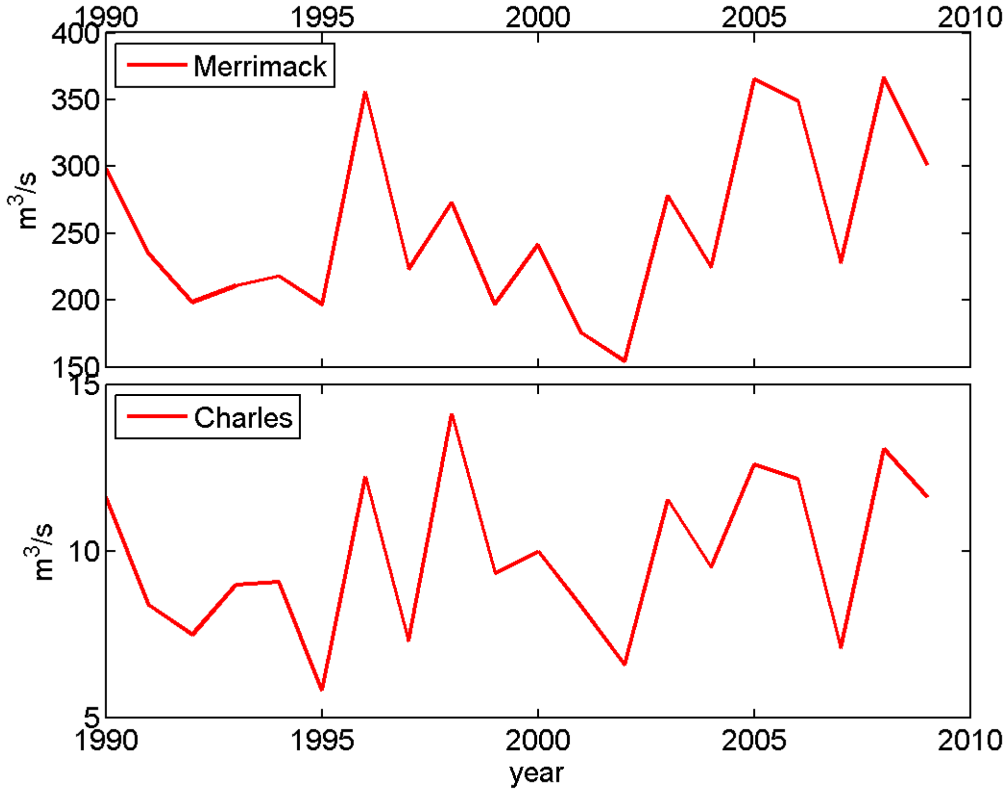
River flow: annual averages



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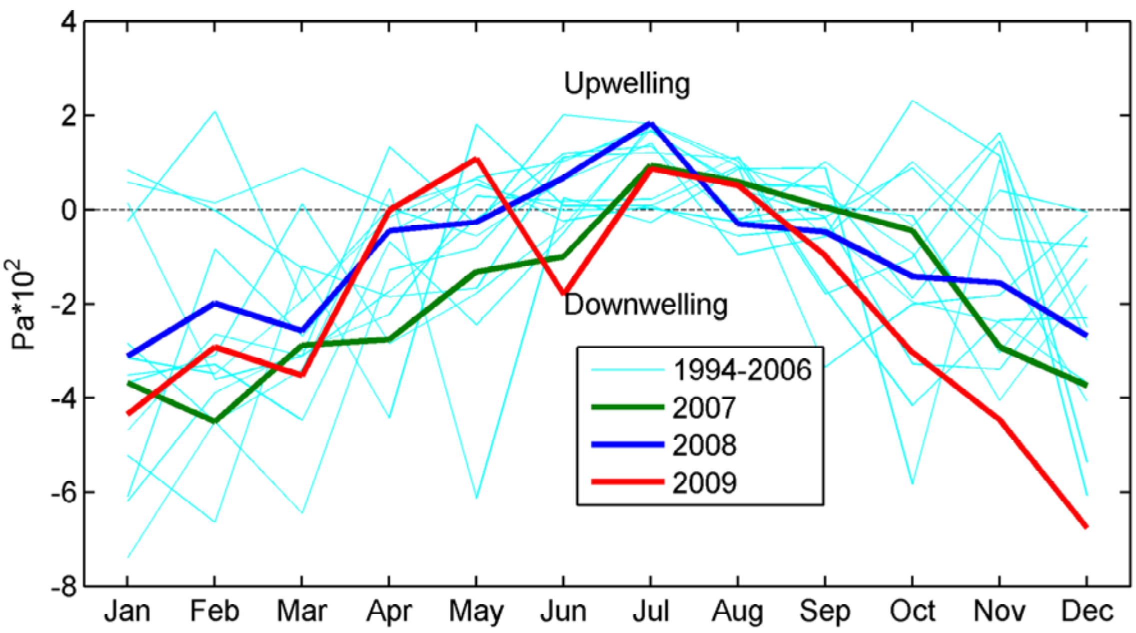
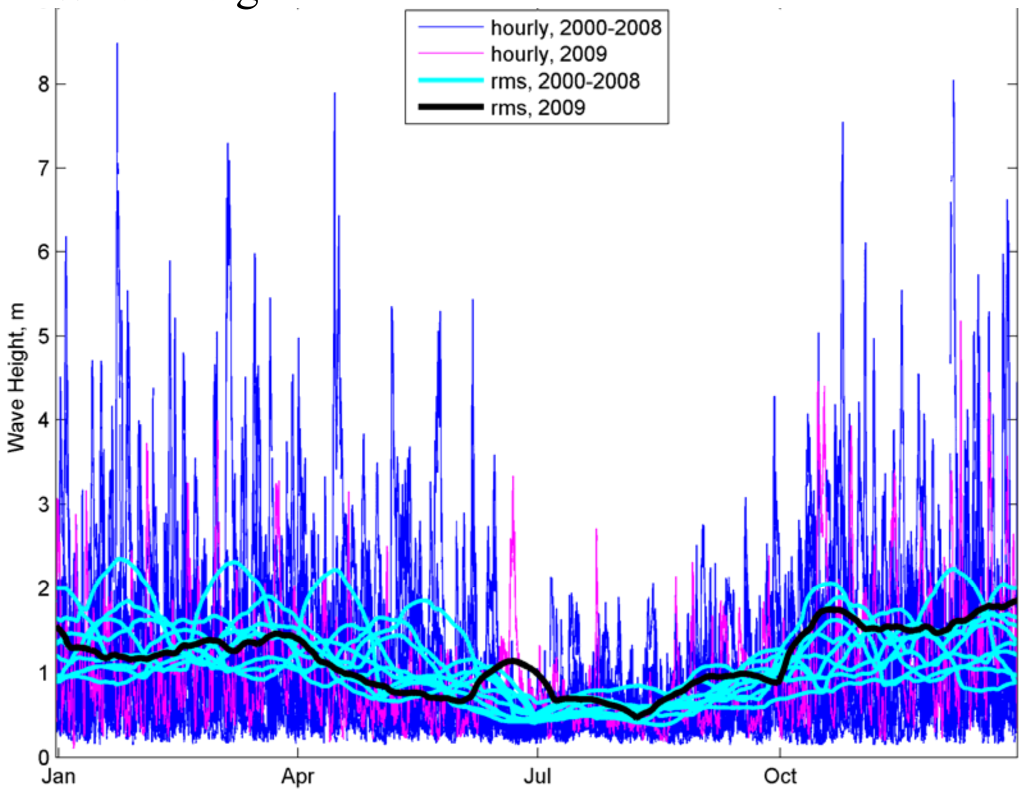
Wind effect on upwelling



Wave Height 8

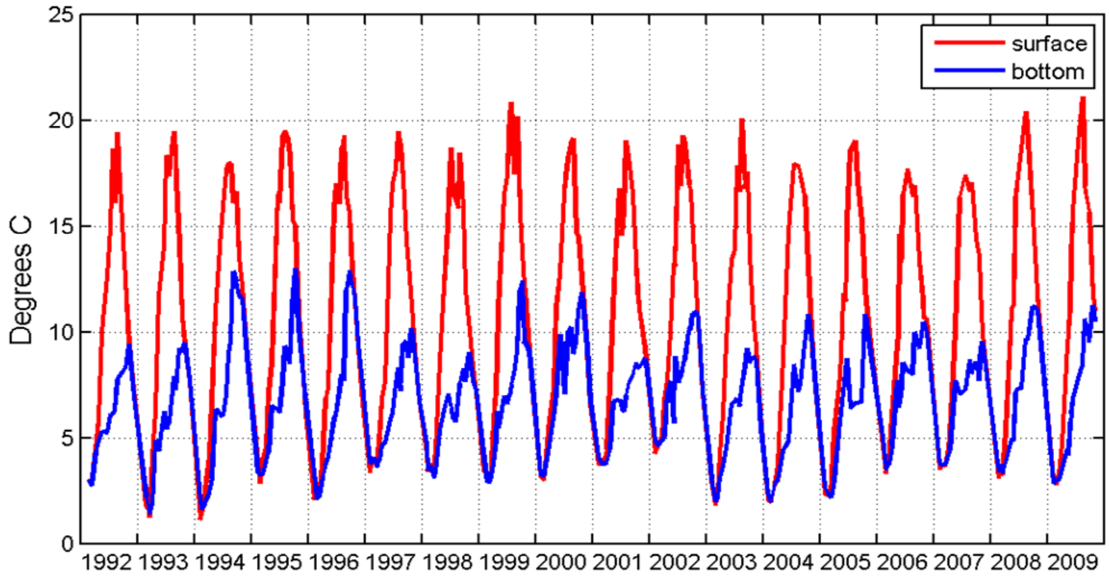


Water properties 9

- Temperature
- Salinity
- Stratification
- Dissolved oxygen

10

Water temperature: time series



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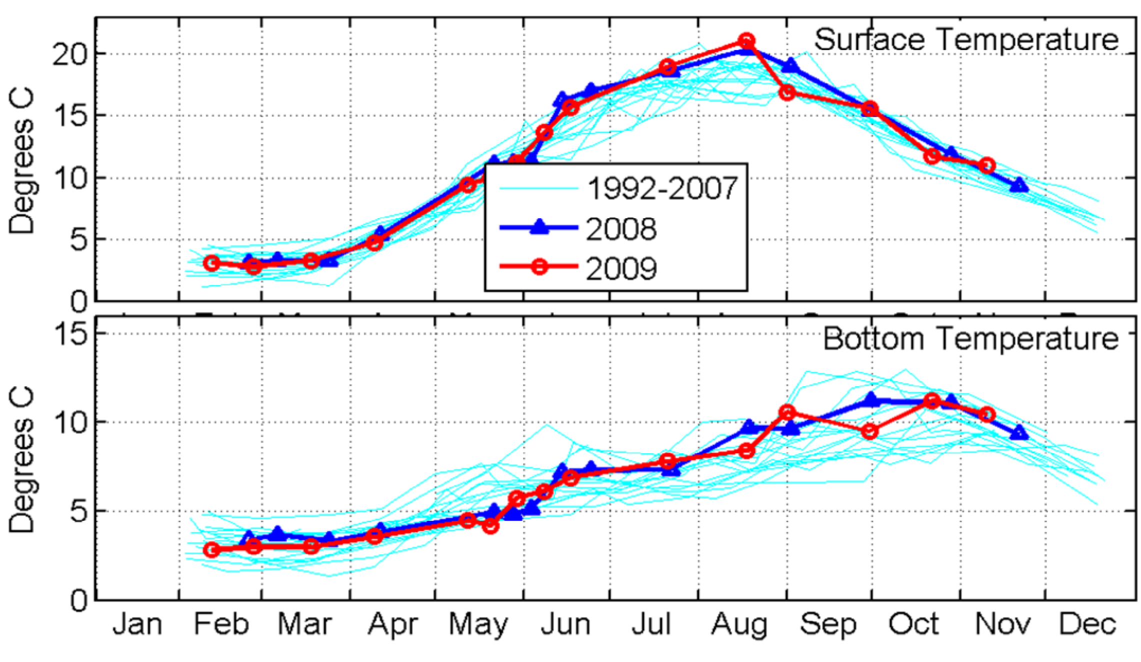
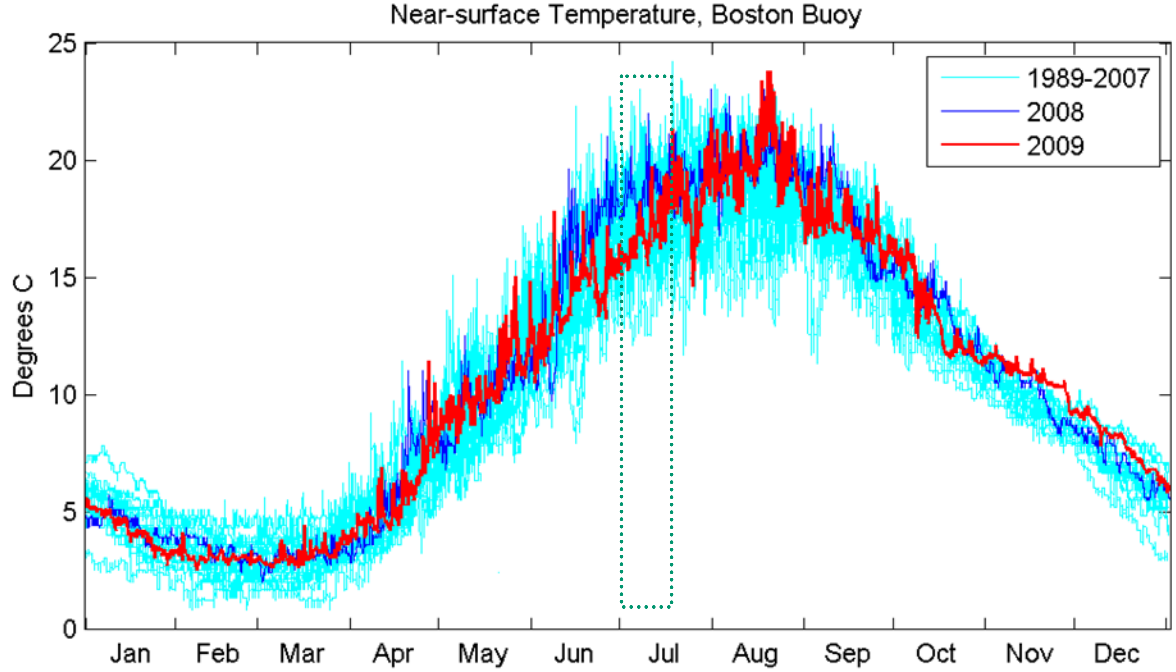
Water temperature: seasonal pattern



Water temperature: seasonal pattern from buoy data

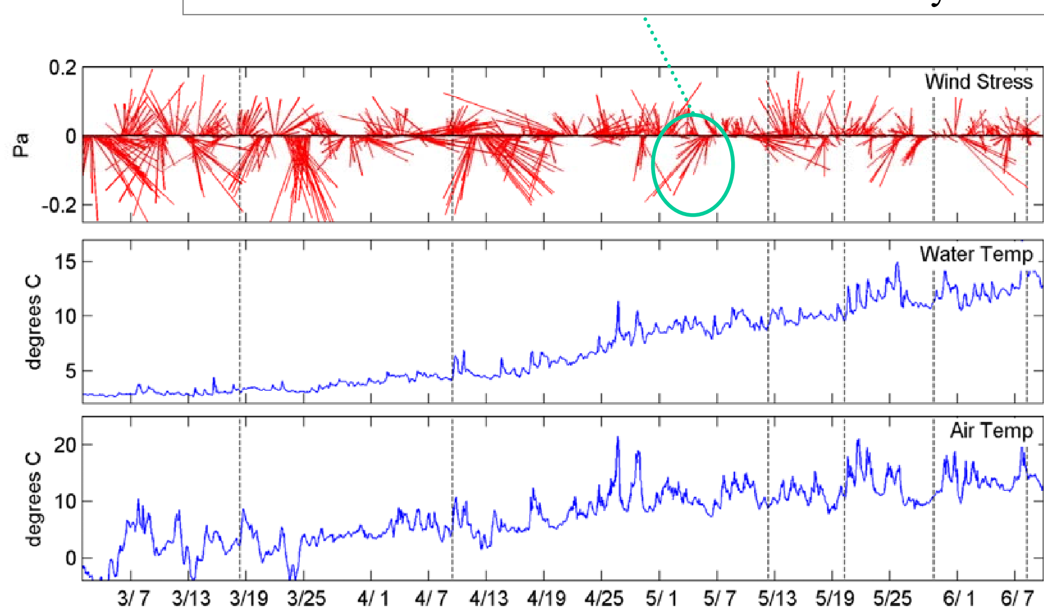
12



Spring winds and surface water temperature

13

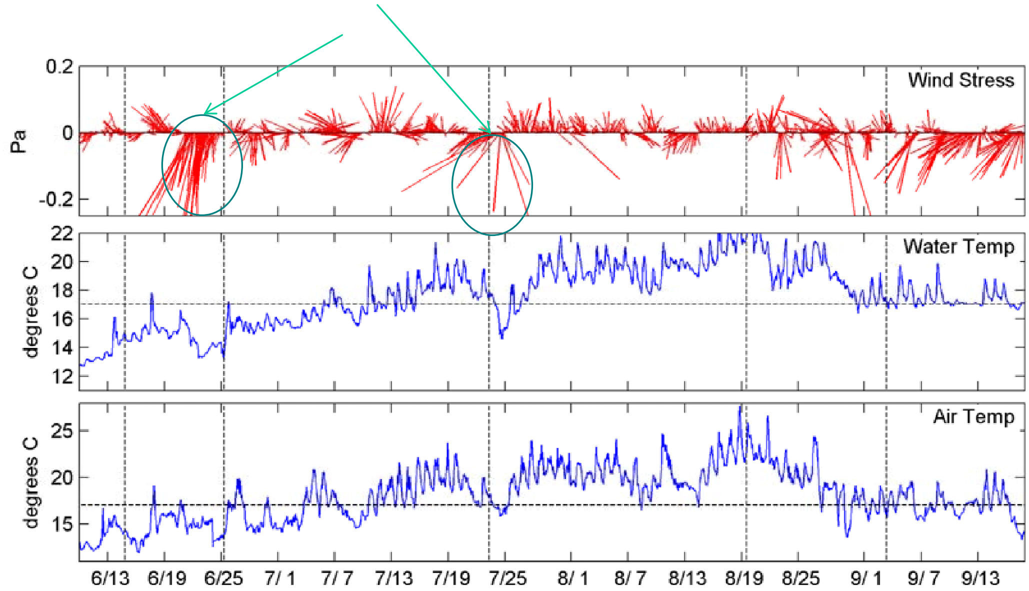
Early May Nor'easter, though not as big as in 2008. Potential to advect *Alexandrium* into Mass Bay?



14

Summer winds and surface water temperature

Summer Storms



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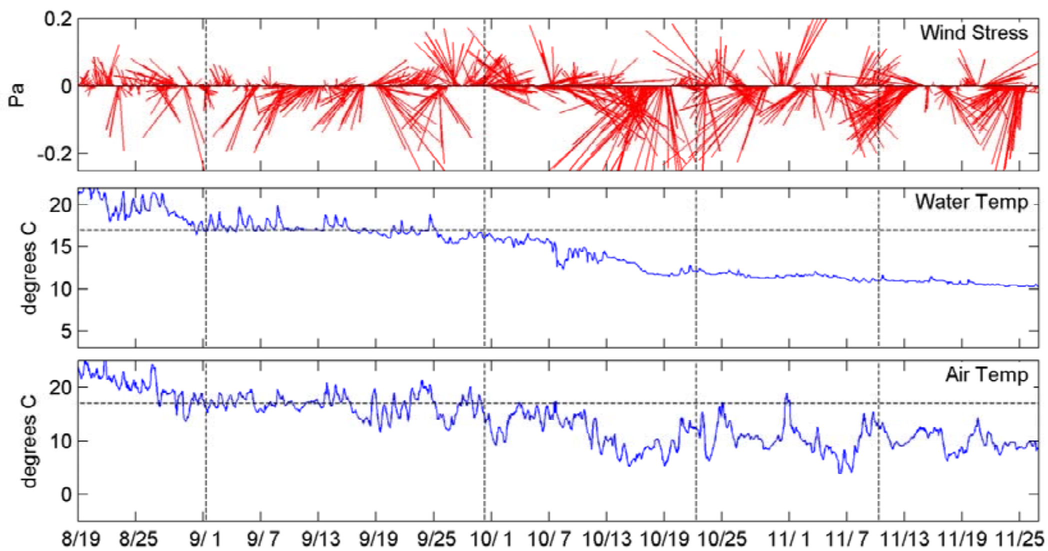
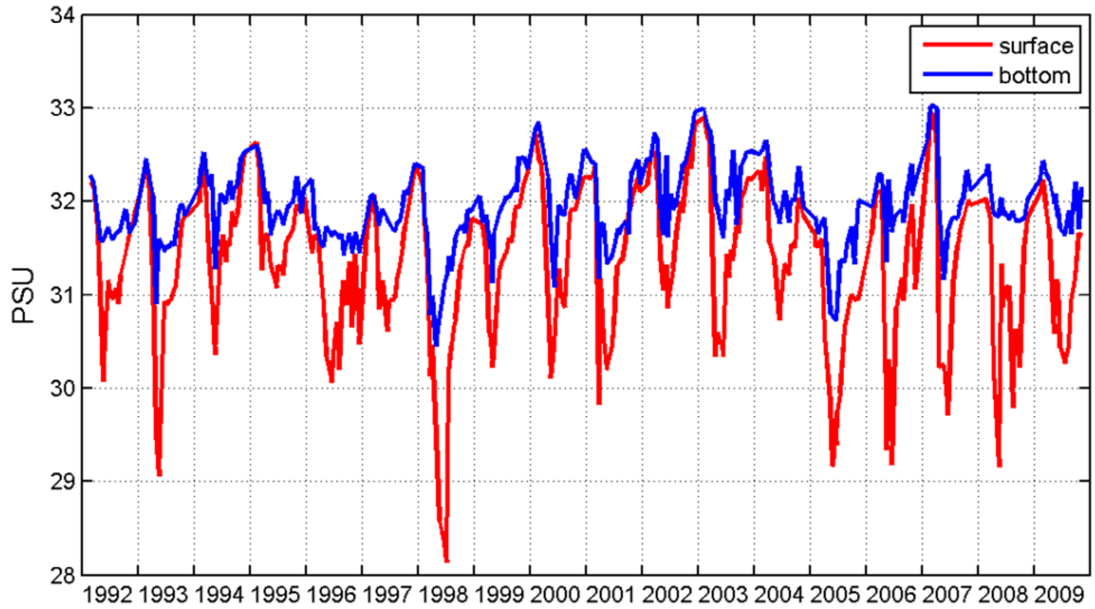
Autumn winds and surface water temperature

Rough fall



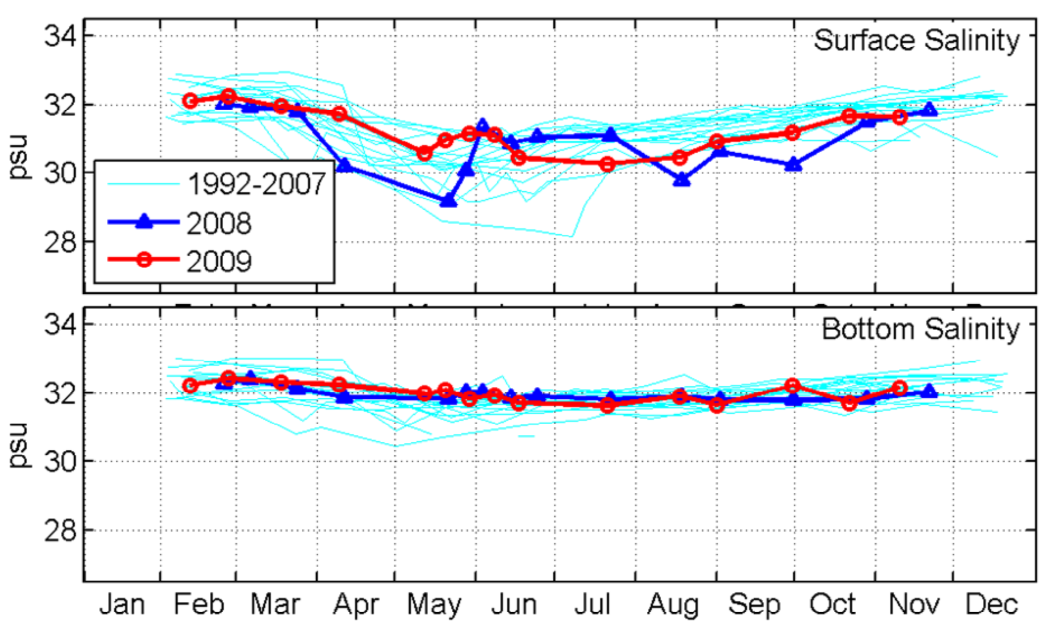
16

Water salinity: time series



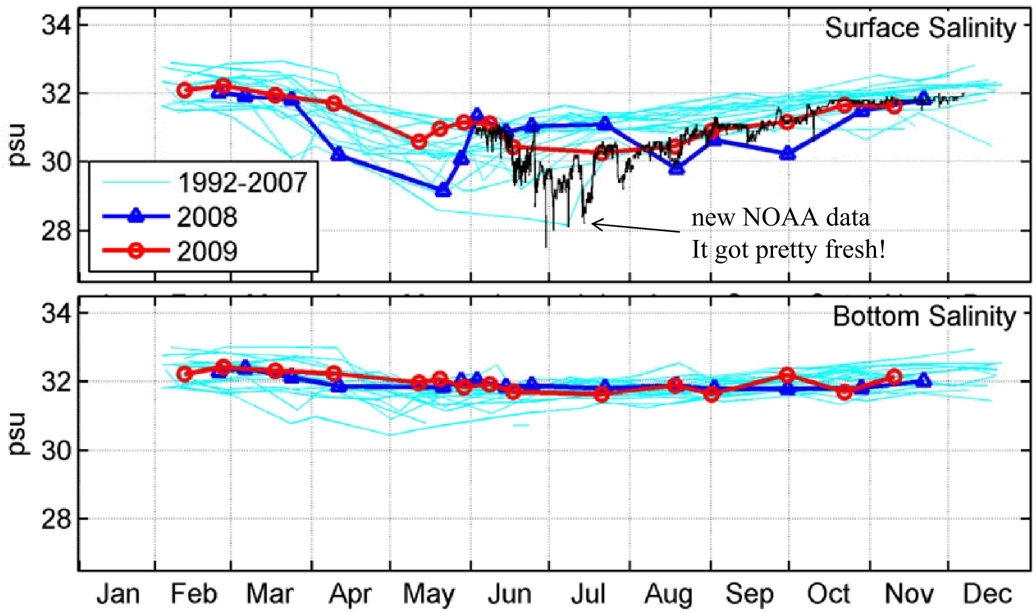
17

Water salinity: seasonal pattern



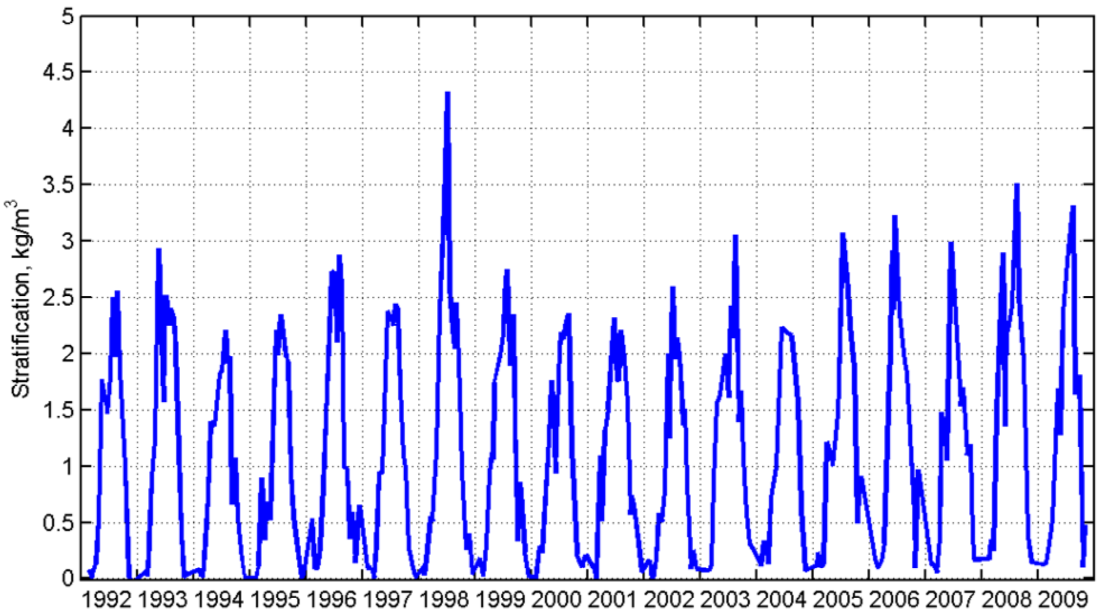
18

…ditto, overlaying buoy data



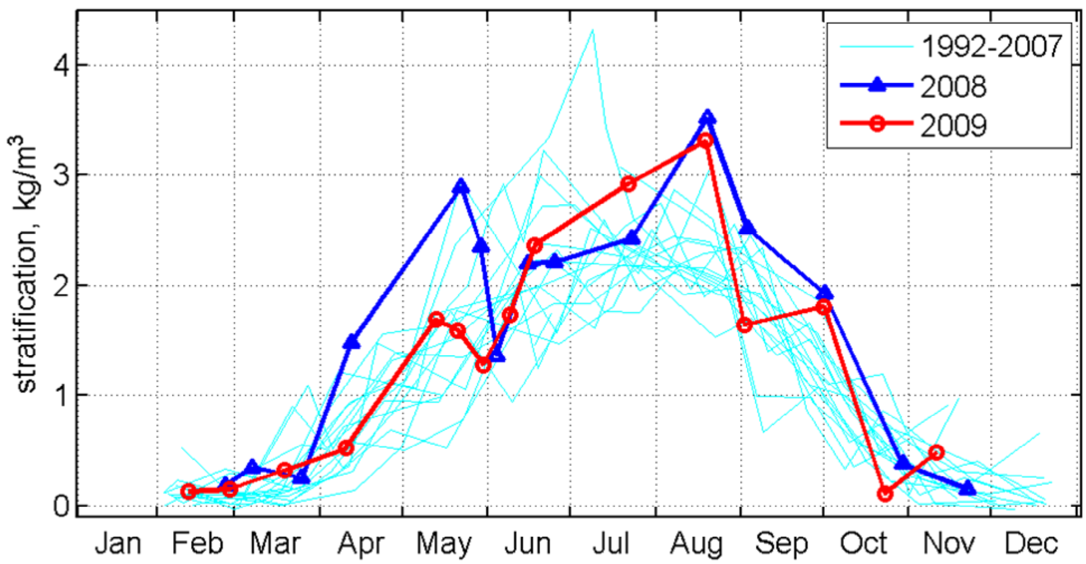
19

Water stratification: time series
(bottom minus surface density)



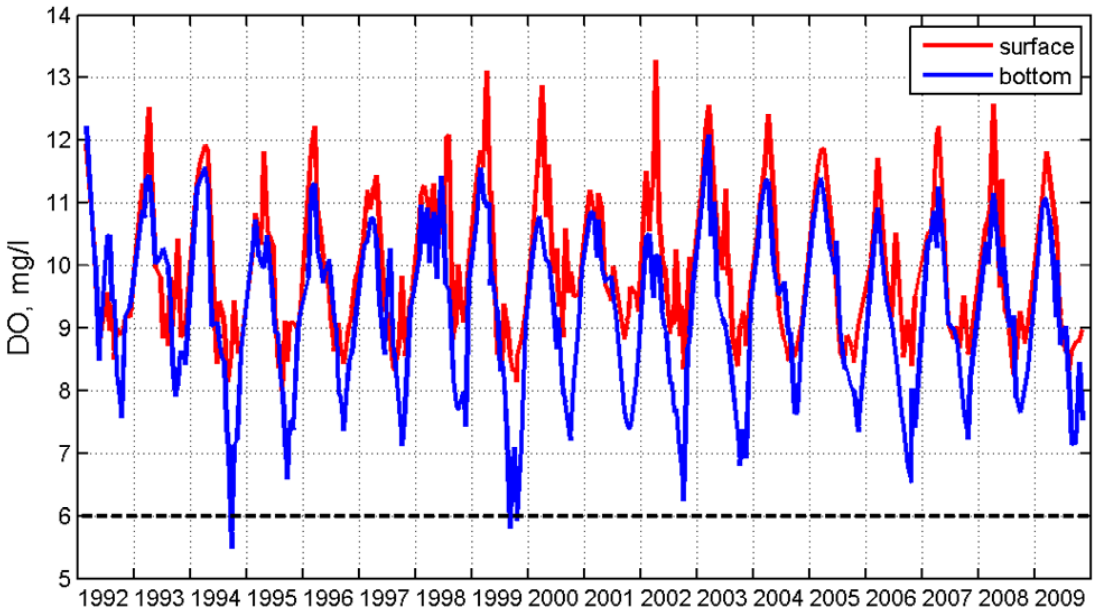
20

Water stratification: seasonal pattern



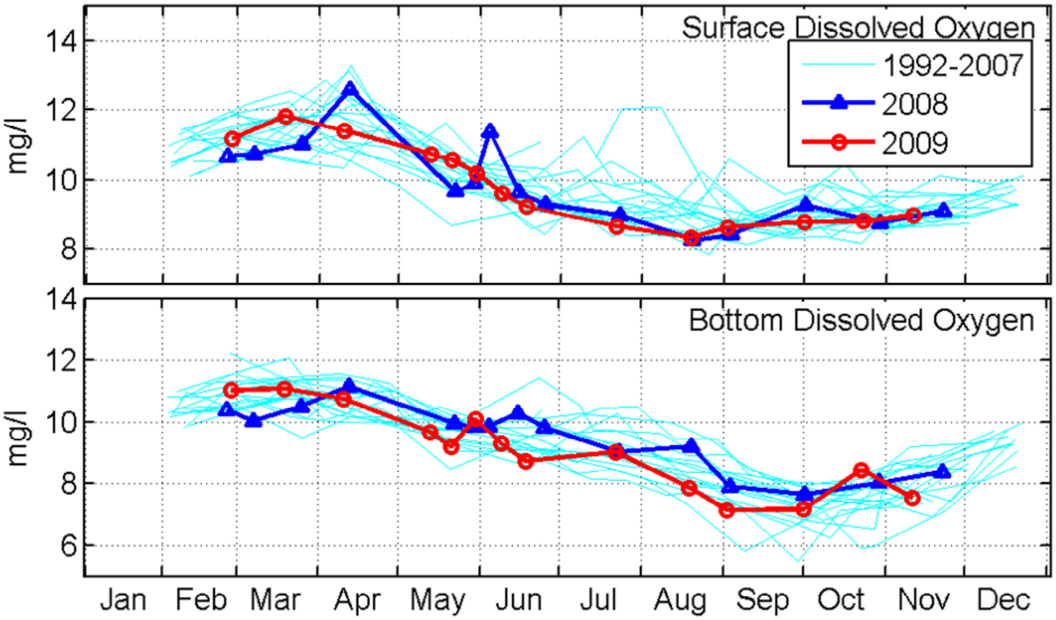
21

Dissolved Oxygen: time series



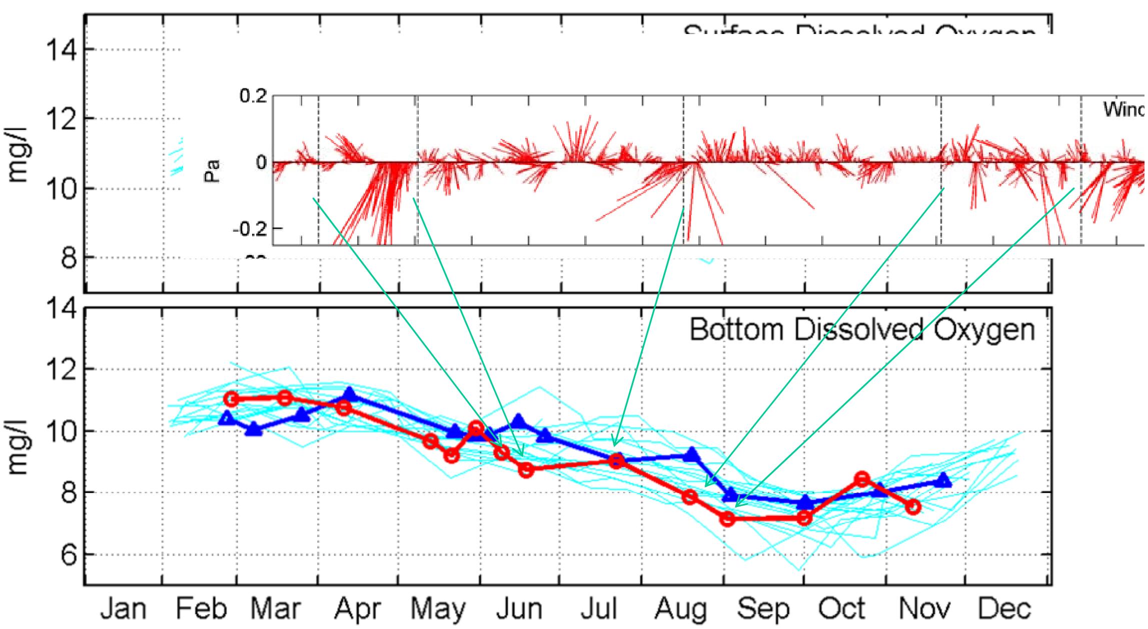
Dissolved Oxygen: seasonal pattern

22



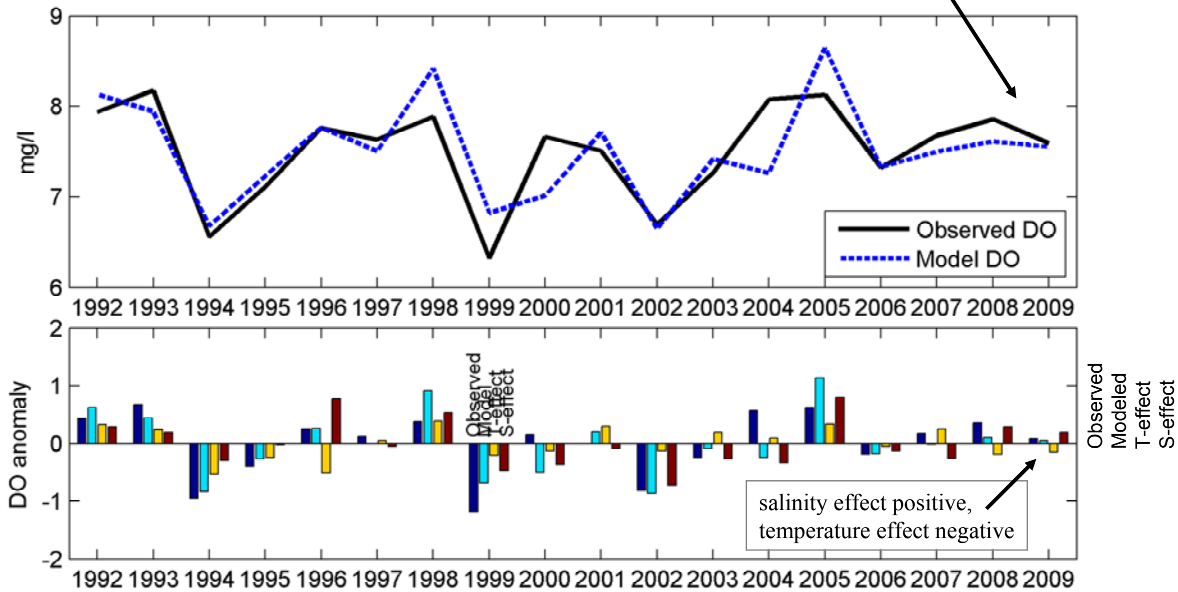
… ditto, overlaying wind stress data

23



24

DO(T,S) regression model continues to correctly predict bottom DO. Values for 2009 are about average.



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Summary

- Pretty normal year.
- Upwelling was not too strong.
- Did the early May Nor'easter advect *Alexandrium* into Mass Bay?
- Summer storms. Low surface salinity in July
- The summer was cold.
- Fall was stormier than normal.

B. Water Quality

Water quality and program overview, 2009.
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 2009 are discussed below.

B.1. Chronological pattern

In early and late February nutrient concentrations were elevated across Massachusetts Bay for nitrate (NO_3), silicate (SiO_4), and phosphate (PO_4) (**Slides 4 and 5**). Levels in Cape Cod Bay were slightly lower than those in Massachusetts Bay, but higher than typically observed for February and possibly due to the lack of a winter diatom bloom the Cape Cod Bay (**Slide 7**). Instead of diatoms, there was a minor bloom of *Phaeocystis* in Cape Cod Bay in late February that exhibited the maximum survey mean areal fluorescence in the bay for 2009. There was a sharp decline in NO_3 and PO_4 by April throughout the bays, while SiO_4 concentrations remained elevated with survey mean concentrations in the nearfield remaining around 9 μM into May. The decrease in NO_3 was coincident with a large *Phaeocystis* bloom observed across the bay in April (**Slides 7-10**). The bloom was strongest in the offshore areas of Massachusetts Bay with abundances of 5 million cells L^{-1} at stations in the nearfield and offshore areas and a maximum abundance of ~15 million cells L^{-1} at mid-depth at station F26 along the northern boundary (**Slide 18**). The high abundances of *Phaeocystis* resulted in annual peak survey mean concentrations of chlorophyll and POC at the offshore and northern boundary stations. The annual peak in nearfield chlorophyll concentrations occurred in March when dinoflagellate and microflagellate abundances were relatively high and preceded or occurred during the onset of the *Phaeocystis* bloom. The spring peak in POC concentrations in the nearfield was observed in May, which is odd in that phytoplankton abundances were relatively low.

In May, *Phaeocystis* was no longer present in the nearfield. As in 2005 – 2008, a bloom of the toxic dinoflagellates species *Alexandrium fundyense* was occurring in the Gulf of Maine in May 2009. As in 2005, 2006 and 2008, an early May northeasterly storm brought the bloom into the bay, but unlike previous years this storm was relatively weak and no subsequent storm events occurred in May 2009 (see Phys-O **slide 13**). Model forecasts and early toxicity to the north led MWRA to request additional sampling for *Alexandrium* during the May 12, 2009 nearfield survey. A maximum *Alexandrium* abundance of 150 cells L^{-1} was measured in the surface waters at station N18, which triggered initiation of the *Alexandrium* Rapid Response Surveys (Libby 2006). A series of three rapid response surveys were conducted on May 20, May 27, and June 8. *Alexandrium* abundances remained relatively low during these surveys and by June 8 the bloom was essentially over in the bay (**Slide 16**).

The summer of 2009 was one of the wettest summers on record with major storm/rainfall events from late June into August. River flows for the July to September period were the highest observed over the course of the MWRA monitoring program (see Phys-O **Slide 4**). Coincident with these meteorological events there was an overall increase in nutrient concentrations throughout the bays from June to August. There was also a summer diatom bloom dominated by *Skeletonema* and also comprised of other diatoms such as *Dactyliosolen fragilissimus* in Boston Harbor, coastal waters, and Cape Cod Bay (**Slides 7 and 10**). Additionally, bottom water dissolved oxygen (DO) concentrations declined over the April to August time period, though in the nearfield there was an increase in bottom DO levels from June to July that may have been associated with the physical dynamics of the system associated with the storms, riverine inputs, or pervasive downwelling favorable conditions. The summer increase in bottom water DO levels that was observed in the nearfield, and presumably throughout the region since DO dynamics are regional physical forcing mechanisms, likely prevented very low annual mean bottom water DO levels from being reached in the fall (**Slide 13**).

In the fall of 2009, blooms of diatoms *Skeletonema* and *Dactyliosolen* (and others) were observed in the nearfield in late September and further offshore (offshore and northern boundary areas) in October (**Slides 8-9**). These were the same species that dominated the August diatom bloom at the inshore harbor, coastal and Cape Cod Bay areas. The fall diatom blooms at these offshore areas resulted in secondary peaks in chlorophyll and POC concentrations. Nutrient concentrations were quite variable in the nearfield during the fall and likely due to the frequency of strong fall storms in 2009. We did not observe similar variability at the farfield areas due to limited sampling (August and October). Bottom water DO concentrations reached a minimum in late September of 7.23 mg L^{-1} (**Slide 11**). By October, nearfield, as well as at other inshore areas, DO levels had increased to >8 mg L^{-1} while DO levels at the offshore and northern boundary stations remained lower. The 2009 bottom water minimum in the nearfield was comparable to the baseline and post-diversion mean minima (**Slide 13**). In Stellwagen Basin, the 2009 minimum DO concentration was slightly lower than the baseline and post-diversion means. Also note that the June nearfield bottom water DO concentration was below these previous minima while the October 2009 DO levels were well above previous levels. It is expected that these valleys (June) and peaks (October) in nearfield bottom water DO levels are related to physical forcing dynamics – wet summer and stormy fall.

In 2009, seasonal and annual chlorophyll levels were well below threshold values (**Slide 12**) and although 2009 bottom water DO levels were quite low in Stellwagen Basin compared to baseline and post-diversion means, both nearfield and Stellwagen DO levels were well above the DO thresholds. The only threshold exceedance in 2009 was for *Alexandrium*, which reached abundances of 151 cells L^{-1} in the nearfield, which is just over the 100 cells L^{-1} threshold (**Slide 14**). Overall the 2009 *Alexandrium* bloom in Massachusetts Bay was small, short duration, and led to limited shellfishing closures (both spatially and also of short duration). *Phaeocystis* abundance in the nearfield in April 2009 reached a sample maximum of 2.8 million cells L^{-1}, but the seasonal mean was only 402,000 cells L^{-1} which is well below the winter/spring threshold – it was the tenth year in a row that a bloom has been observed in the bays (**Slide 17**). *Phaeocystis* blooms appear to be more of a normal occurrence for the system than was thought following the baseline monitoring period.

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 21**). 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 observed 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*. 2008). There has also been a trend of higher winter/spring chlorophyll in most of Massachusetts Bay, including the nearfield (**Slides 24-27** and **31-32**), but this appears to be related to regional processes governing the consistent annual blooms of *Phaeocystis* in March-April since 2000.

B.2. Statistical tests

"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*. 2008). NH_4 was higher in the inner nearfield. The analyses did not find statistically notable 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 2009 data for a set of stations rather than groups of stations (**Slide 33**). 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 15 km (F13), 30 km (F06) and >50 km (F01 and F02) to the south. The results were essentially the same. The only statistical differences ($p \leq 0.05$) noted in the baseline vs. post-diversion comparison for each station were for NH_4, which increased at station N18 (winter/spring and summer) and decreased at stations F23 (all seasons). The BACI comparisons between station N18 and the other stations yielded increases in NH_4 for nearly all 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.

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).

B.3. REFERENCES

Libby PS. 2006. Standing survey plan: rapid response *Alexandrium* survey. Boston: Massachusetts Water Resources Authority. Report 2006-05. 19 p.

Libby PS, Borkman D, Geyer WR, Keller AA, Turner JT, Mickelson MJ, Oviatt CA. 2008. Water column monitoring in Massachusetts Bay 1992-2007: focus on 2007 results. Boston: Massachusetts Water Resources Authority. Report 2008-16. 170 p.

Taylor DI. 2006. 5 years after transfer of Deer Island flows offshore: an update of water-quality improvements in Boston Harbor. Boston: Massachusetts Water Resources Authority. Report 2006-16.

1

2009 Water Column Overview

MWRA Annual Technical Meeting
April 29, 2010

Scott Libby

2

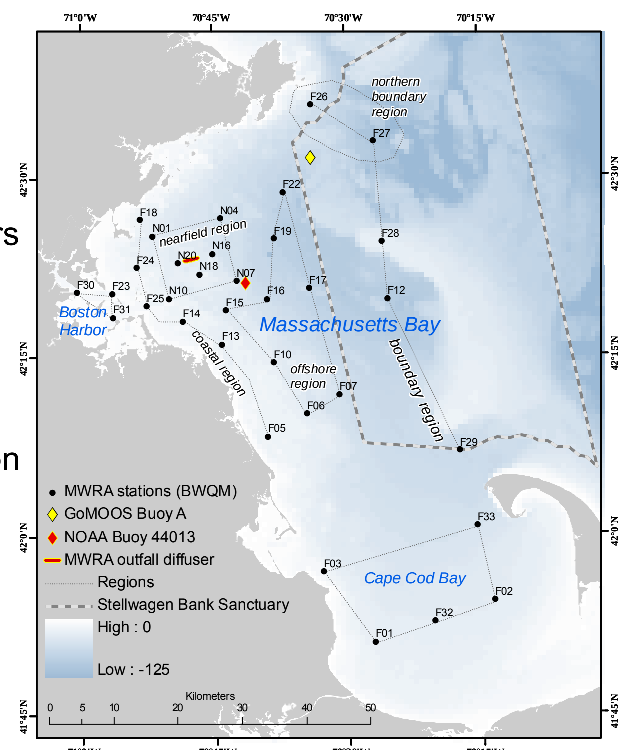
Presentation Overview

- 2009 nutrient, chlorophyll, and DO results
  - "Typical" trends generally observed in these parameters
  - Major events in 2009
    - *Phaeocystis* bloom (again…..)
    - *Alexandrium* bloom (again…..)
- 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.

3

2009 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



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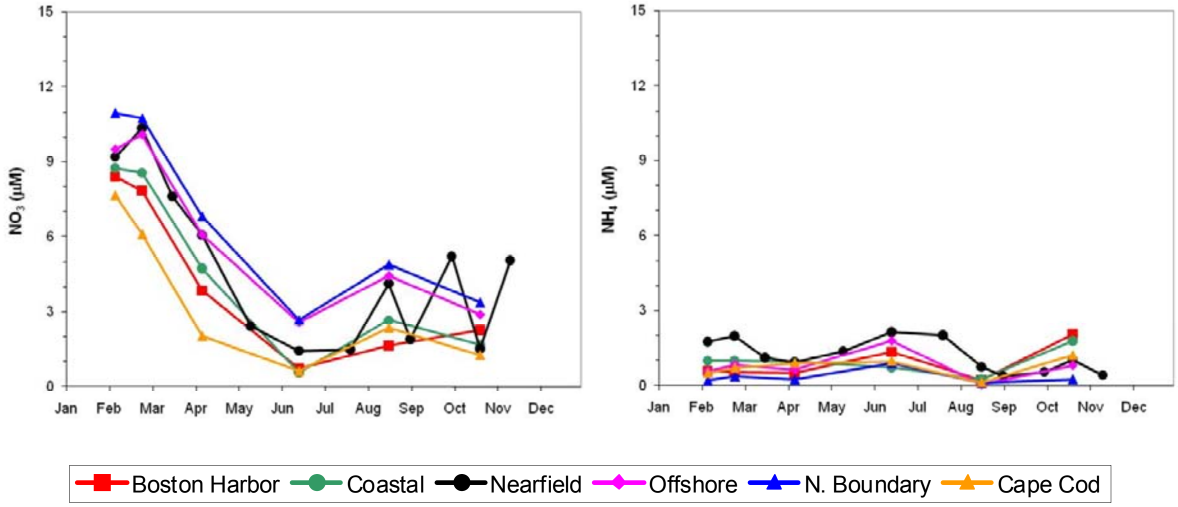
2009 Nutrients across regions

NO_3 nitrate

NH_4 ammonium



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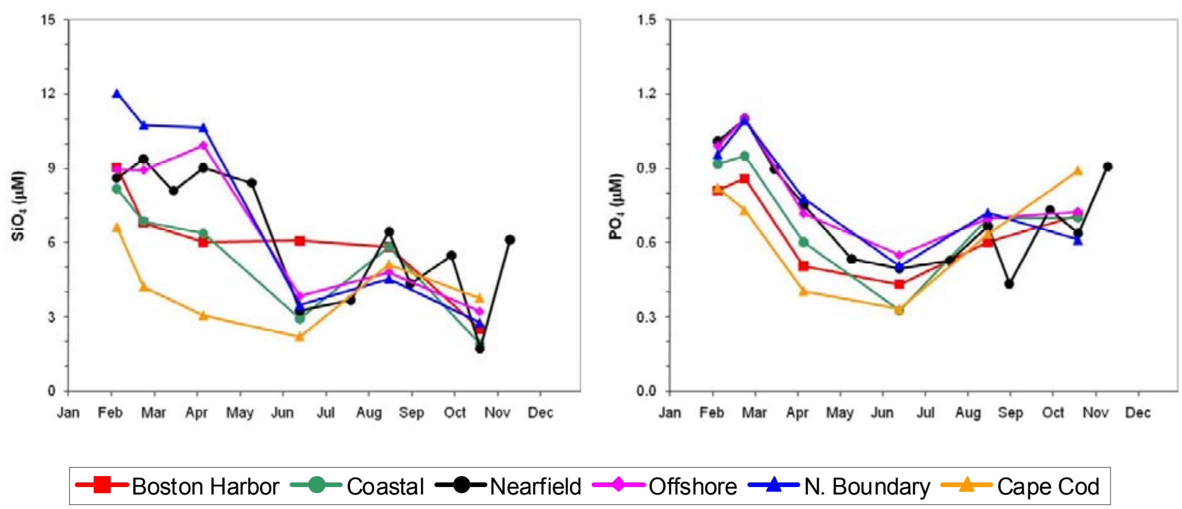
2009 Nutrients across regions

SiO_4 silicate

PO_4 phosphate

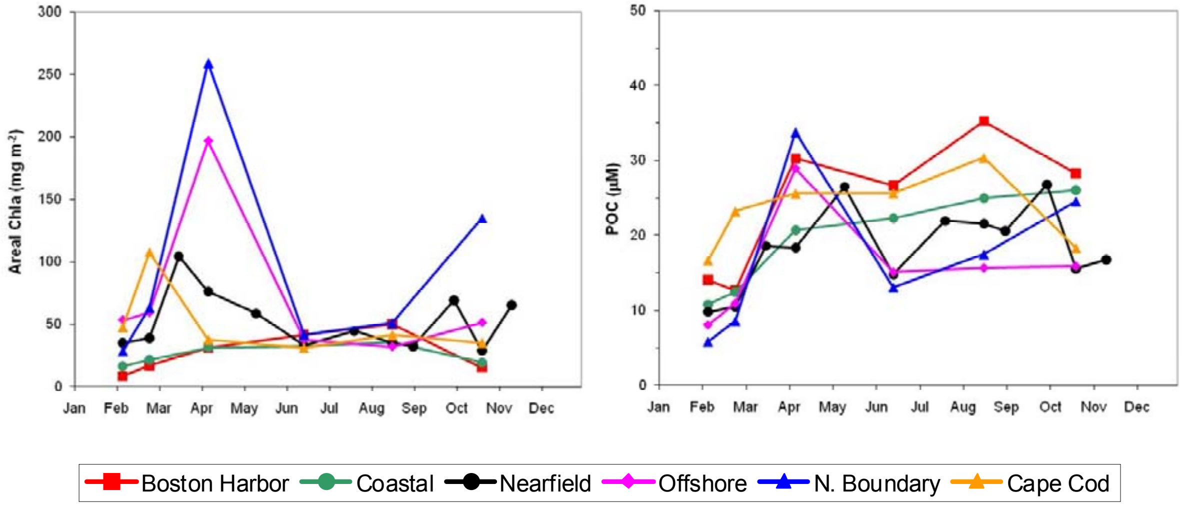


2009 Biomass across regions

6

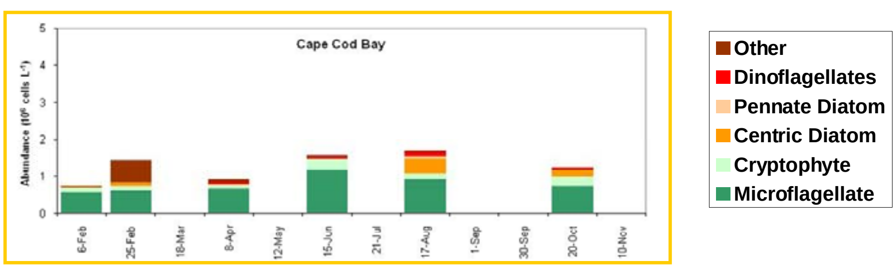
Areal Chlorophyll

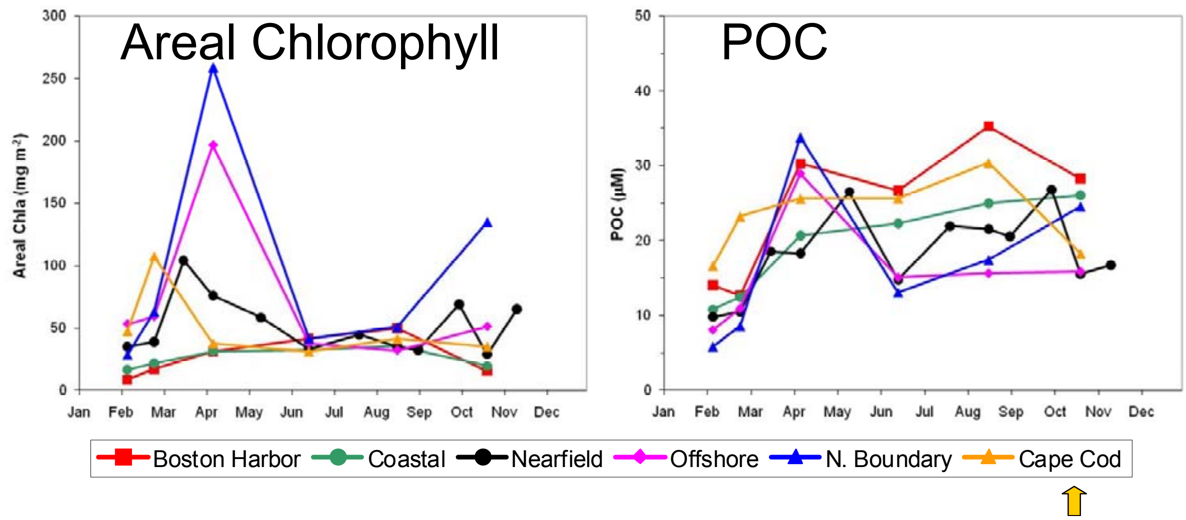
POC particulate organic carbon



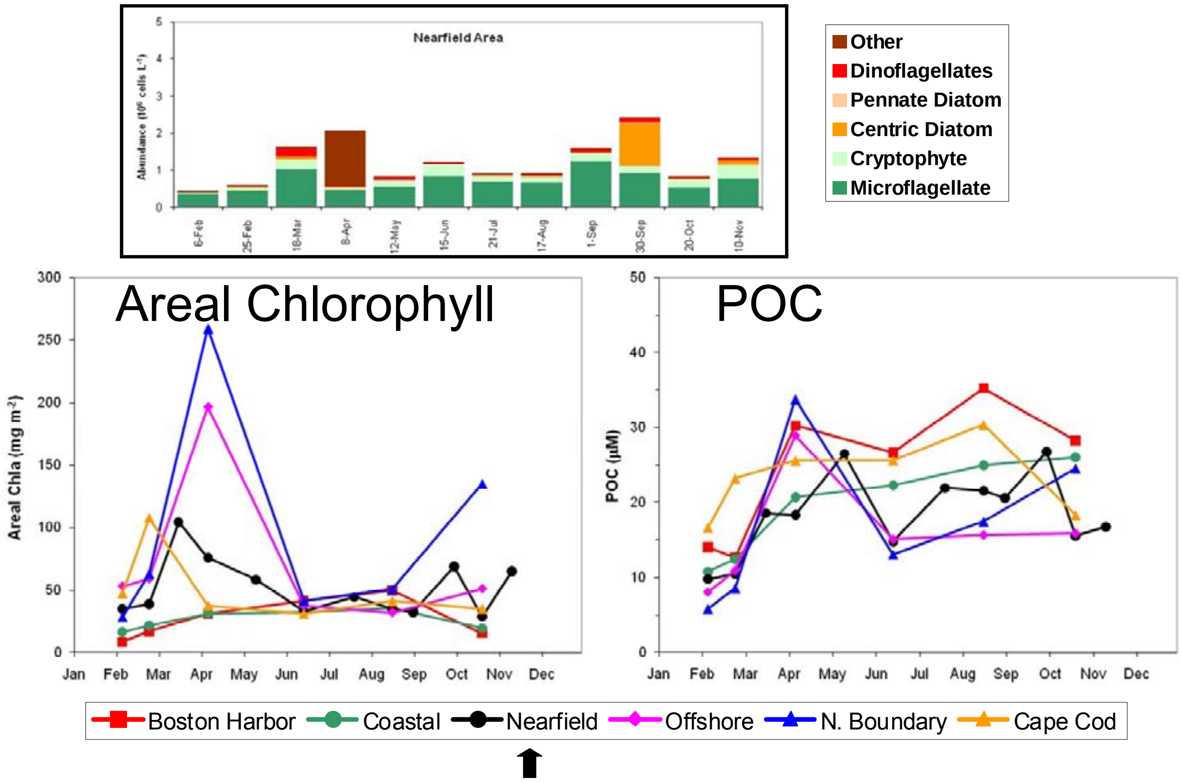
2009 Phytoplankton in Cape Cod Bay

7

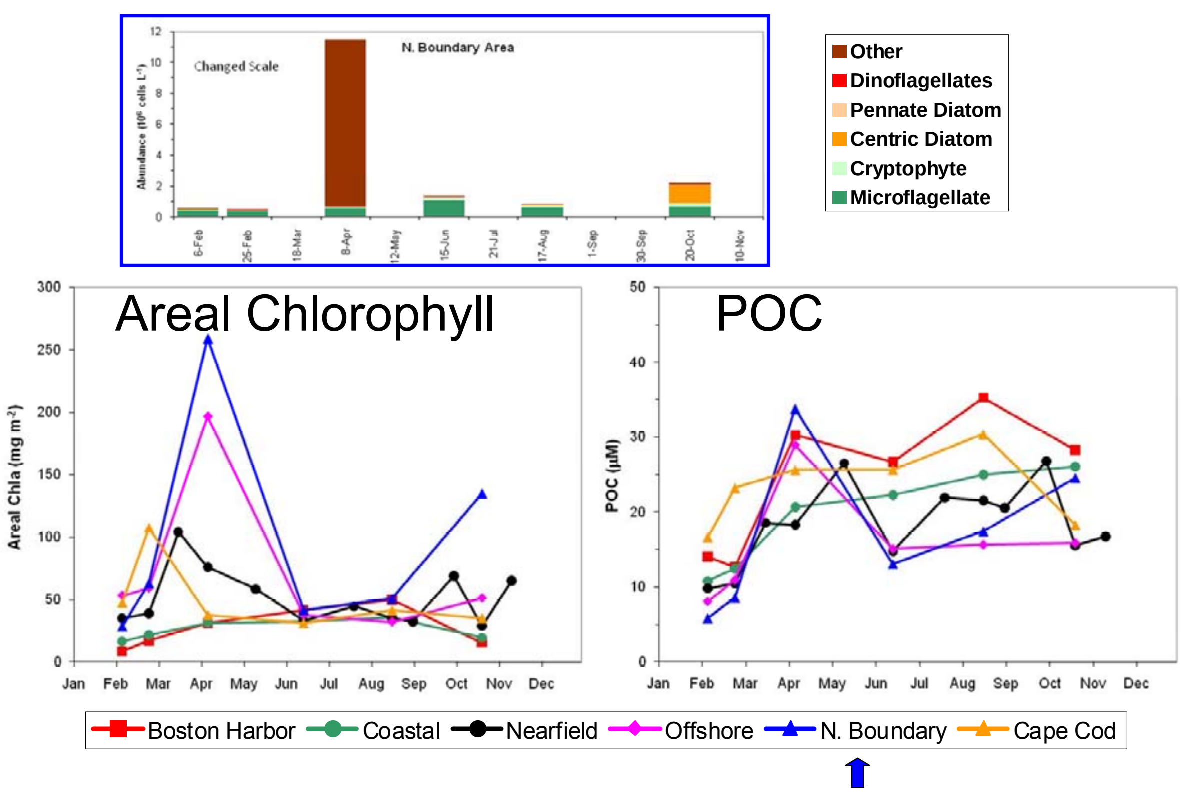




2009 Phytoplankton in the Nearfield 8

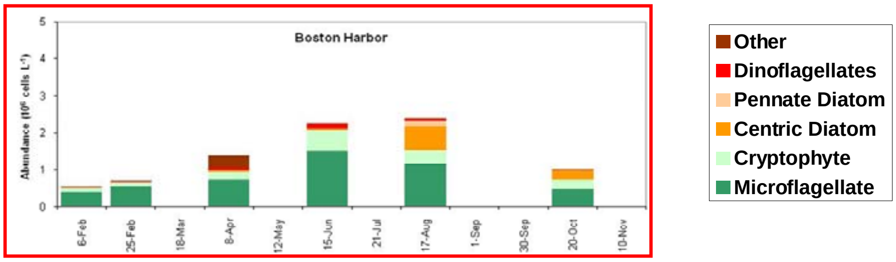


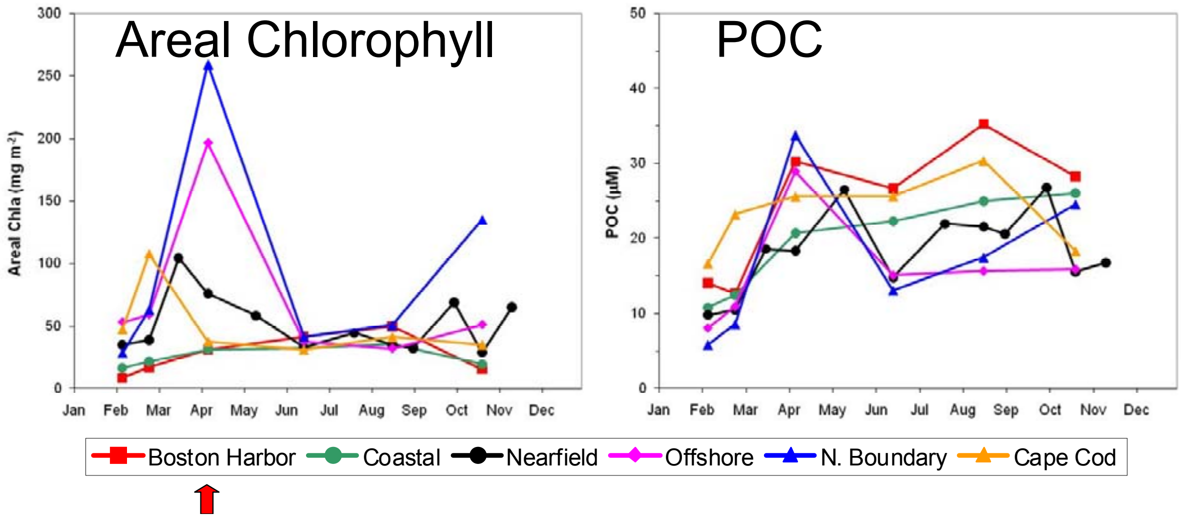
2009 Phytoplankton at the Northern Boundary 9



2009 Phytoplankton in Boston Harbor

10



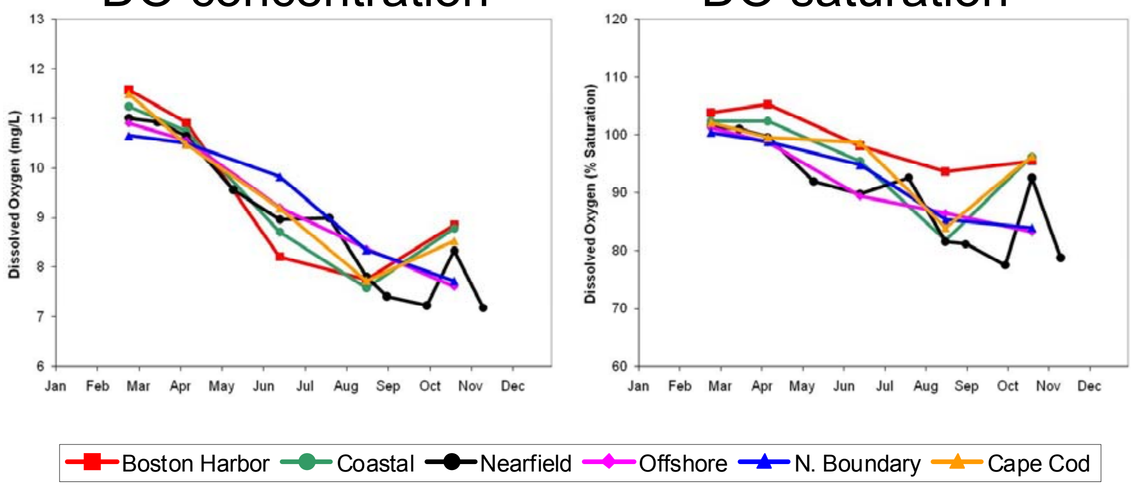


2009 Dissolved Oxygen in bottom waters across regions

11

DO concentration

DO saturation



Threshold Values for DO and Chlorophyll

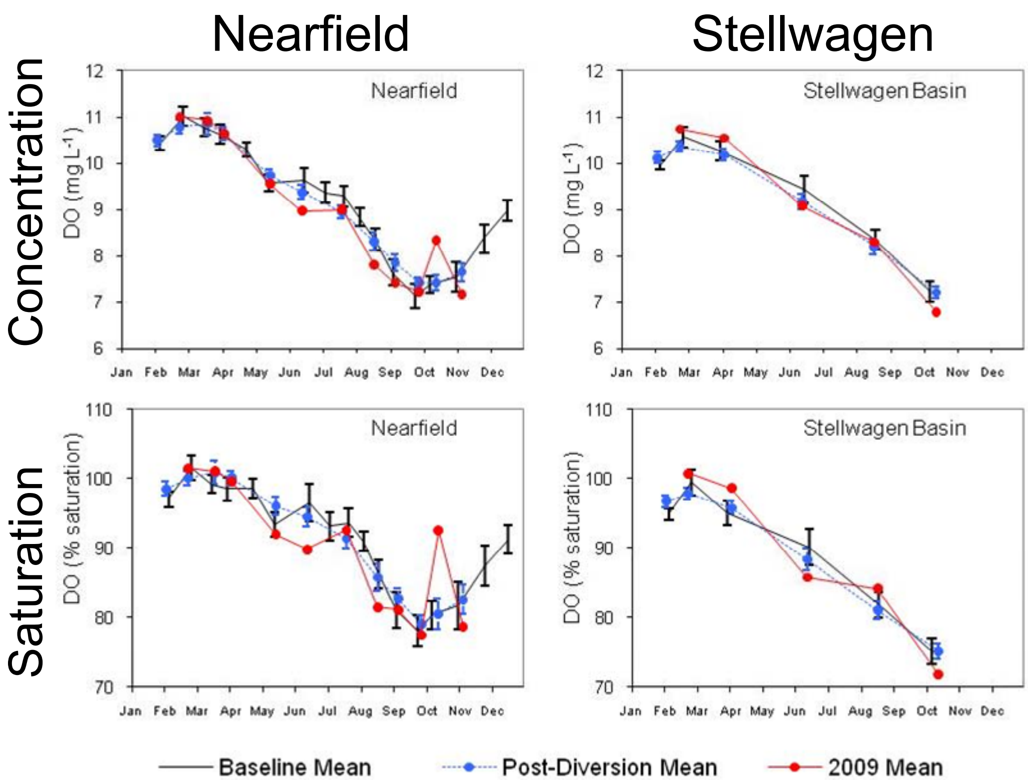
12

Parameter	Time Period	Caution Level	Warning Level	Background	2009
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 Stellwagen 6.2 mg/l	7.23 mg/l 6.79 mg/l
Bottom Water DO %saturation	Survey Mean in June-October	< 80% (unless background lower)	< 75% (unless background lower)	Nearfield - 64.3% Stellwagen - 66.3%	77.5% 71.8%
Bottom Water DO depletion rate	June to October	0.037	0.049		0.010
Chlorophyll	Annual	118 mg/m^2	158 mg/m^2	--	52 mg/m^2
	Winter/spring	238 mg/m^2	--	--	63 mg/m^2
	Summer	93 mg/m^2	--	--	43 mg/m^2
	Autumn	212 mg/m^2	--	--	49 mg/m^2

No exceedances for DO or Chlorophyll in 2009

Bottom DO: Post vs. baseline

13



Threshold Values for Nuisance Species (cells/L)

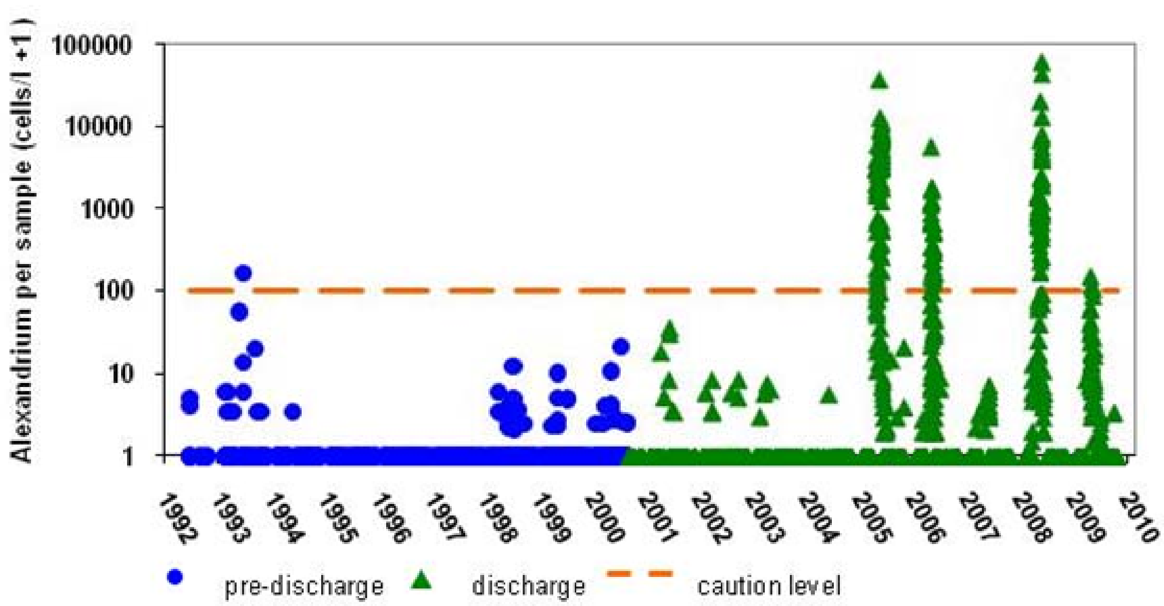
14

Parameter	*Phaeocystis pouchetii*			*Pseudo-nitzschia*			*Alexandrium*
Season or sample unit	Winter/ spring	Summer	Autumn	Winter/ spring	Summer	Autumn	Any near-field sample
Caution Level	2,020,000	357	2,540	21,000	43,100	24,700	100
2001	186,400	0	0	6,620	163	6,030	35
2002	269,000	14,900	0	896	234	3,210	8
2003	482,000	1,700	0	275	84	12,100	7
2004	2,870,000	164,400	0	11	380	660	5
2005	438,500	517	0	147	3,320	45	36,831
2006	383,000	18,000	0	0	0	222	5,668
2007	2,150,000	0	0	78	0	0	7
2008	1,980,000	0	0	0	540	171	60,430
2009	402,000	0t	0	0	0	1,460	151

- No *Phaeocystis* or *Pseudonitzschia* exceedance in 2009
- Exceedance of *Alexandrium* threshold in May 2009

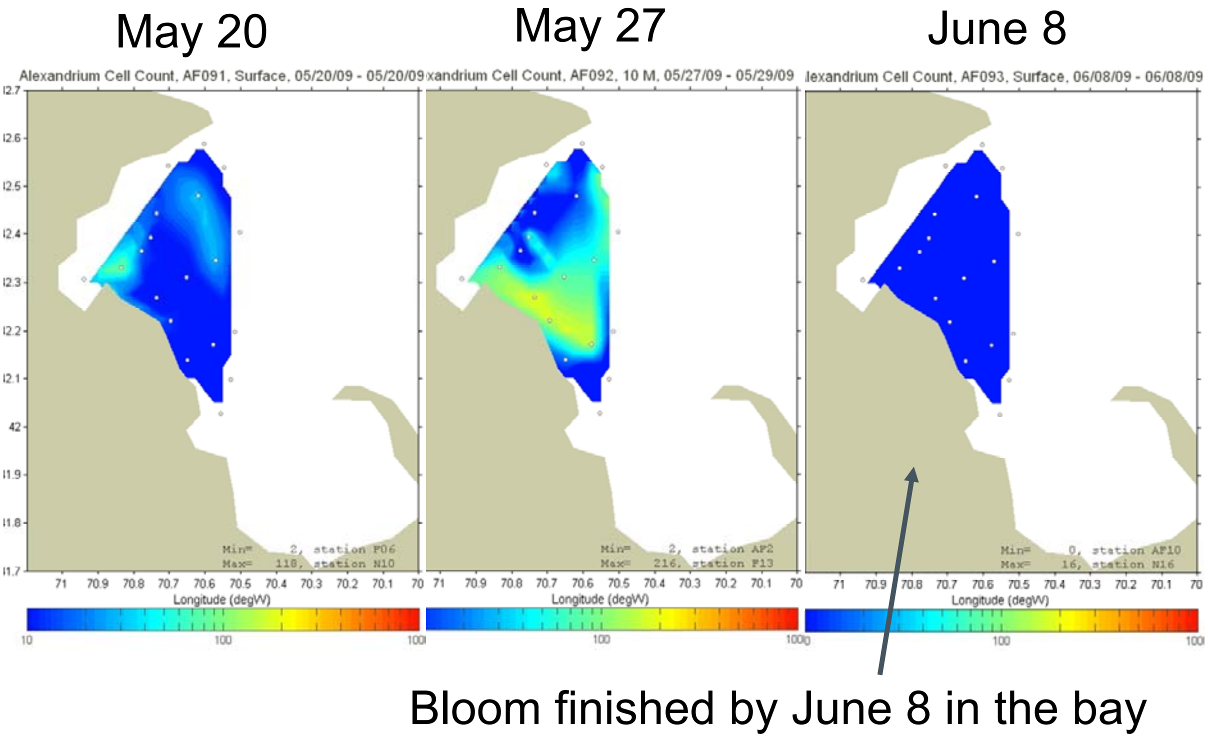
Nearfield *Alexandrium* Abundance

15



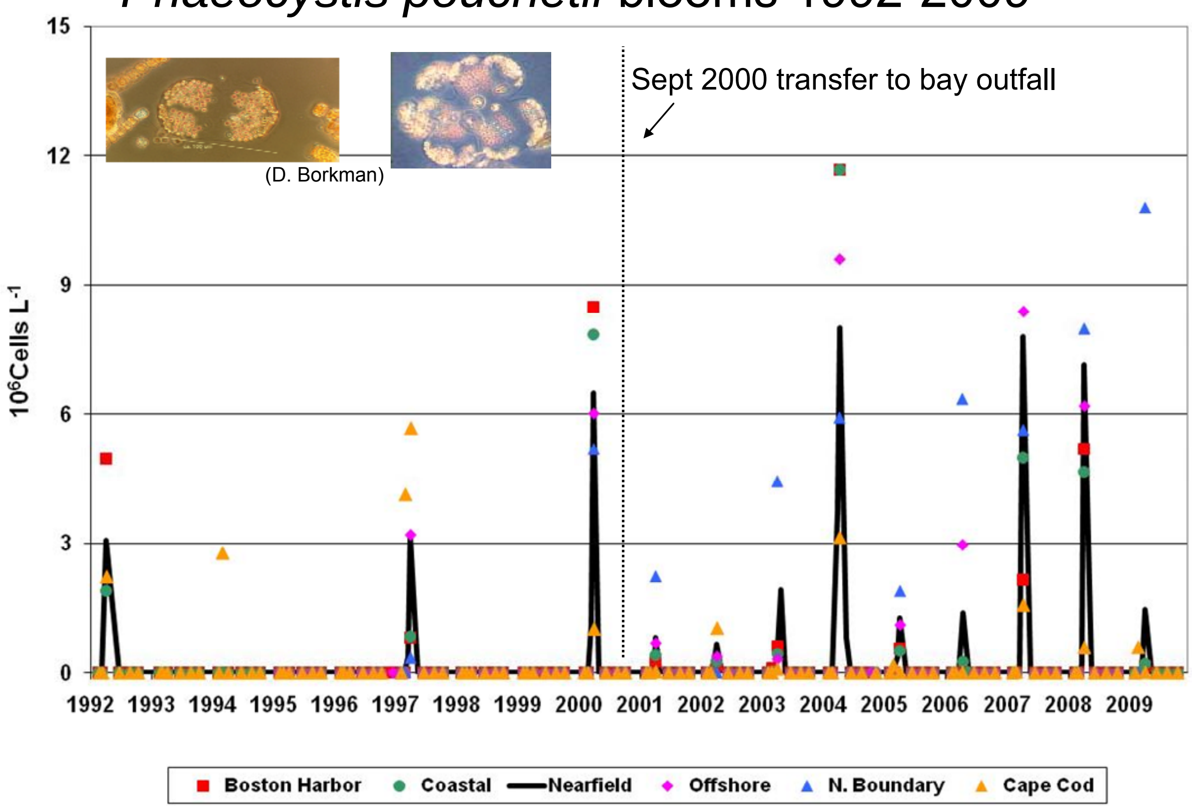
2009 *Alexandrium* bloom in Mass Bay

16



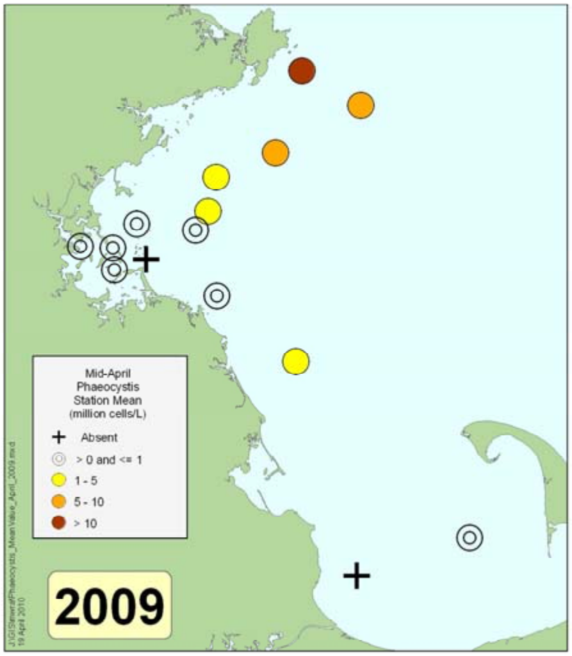
Phaeocystis pouchetii blooms 1992-2009

17



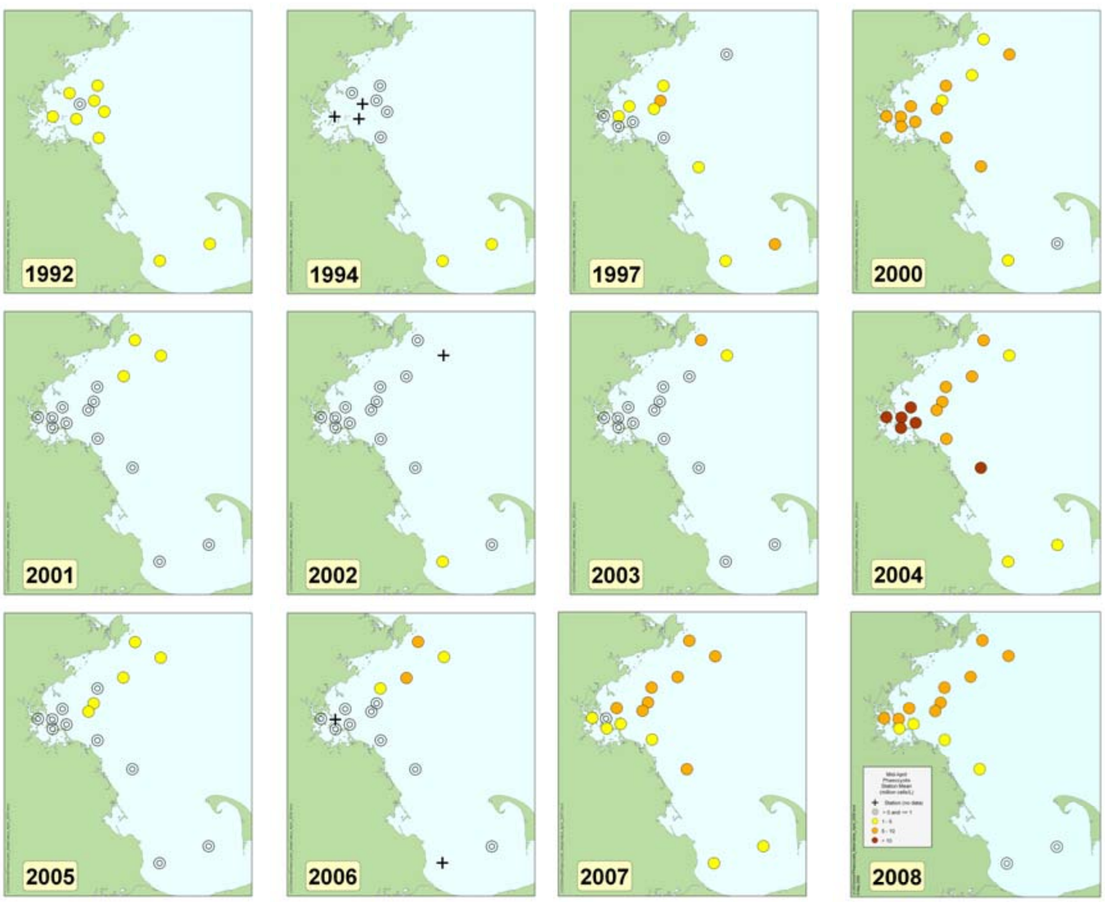
April 2009 Phaeocystis Distribution

18



- Bloom first observed in Cape Cod Bay at station F02 in February (1.5 million cells/L)
- Observed throughout the bays (13 stations)
- Highest levels (>10 million cells/L) observed to the northeast at mid-depth (F26 and F27)
- With a maximum of ~15 million cells/L at F26 at mid-depth
- Similar to many of the past *Phaeocystis* blooms – regional (bays and western Gulf of Maine), but with an early bloom in CCB

19



2009 Summary

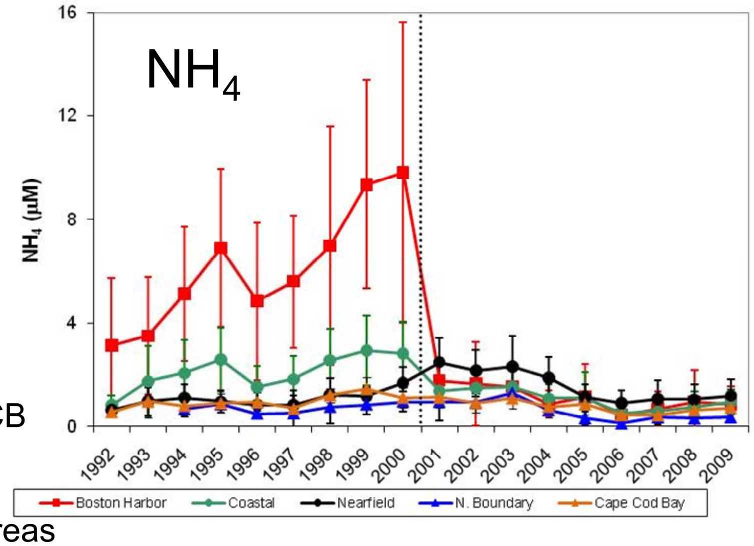
20

- Nutrients
  - High concentrations in February and March with sharp decline (except for SiO_4) coincident with the *Phaeocystis* bloom in MA Bay in April
  - Slightly lower NO_3 and SiO_4 in CCB in February and a sharp decrease in SiO_4 in February, but slight decline in this nutrient from late February to April in CCB (earlier occurrence of *Phaeocystis* bloom)
  - Slight increase from June to August – perhaps related to stormy summer
- Chlorophyll
  - Slightly elevated in CBB in March associated with early *Phaeocystis* bloom
  - Annual peak survey means for chlorophyll and POC in April in the offshore areas of MA Bay due to *Phaeocystis* bloom
  - Highest concentrations associated with peak abundance in boundary and offshore areas
  - Increase in concentrations peaking during August diatom bloom observed in coastal, harbor, and CCB areas
  - Late fall increase in chlorophyll, POC, and diatoms in the nearfield and N. Boundary
- Dissolved Oxygen
  - Slight increase in bottom water DO in July (related to high flow/storms?)
  - Relatively high bottom water DO in 2009 with fall minimum of >7 mg/L in nearfield

Annual Mean Nutrients

21

- Post Diversion
  - Large Decrease in Boston Harbor (red)
  - Decrease in Coastal area (green)
  - Initial doubling in nearfield (black)
  - Unchanged elsewhere MB and CCB

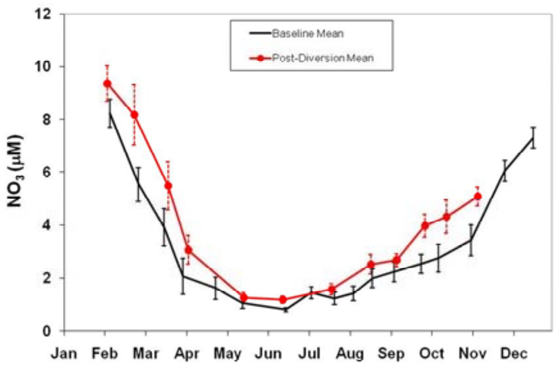


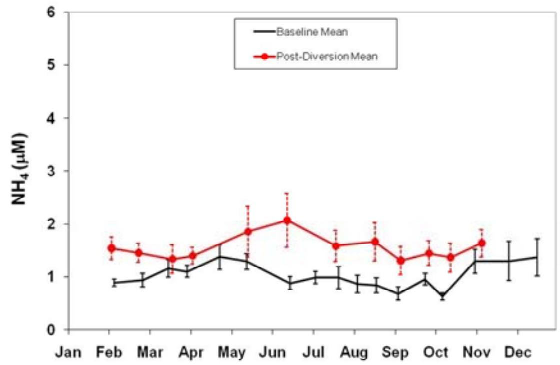
- After 2003
  - Decrease across all areas
  - Current nearfield levels comparable to 90's

- Other nutrients: more interannual variability and no long-term trends

2009 Nutrients: Post vs. baseline (nearfield) 22

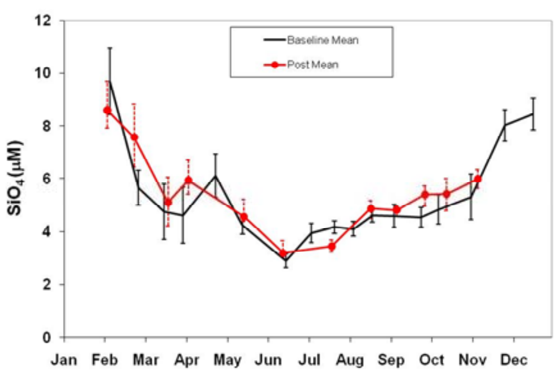
NO_3 NH_4

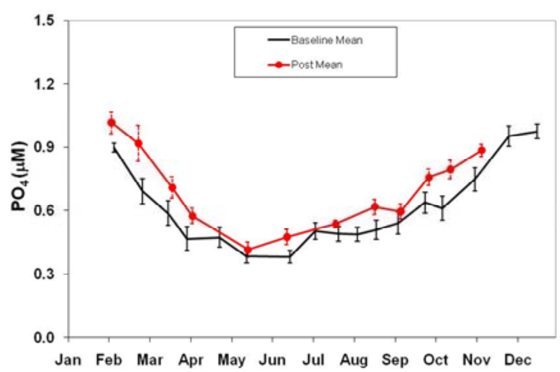




2009 Nutrients: Post vs. baseline (nearfield) 23

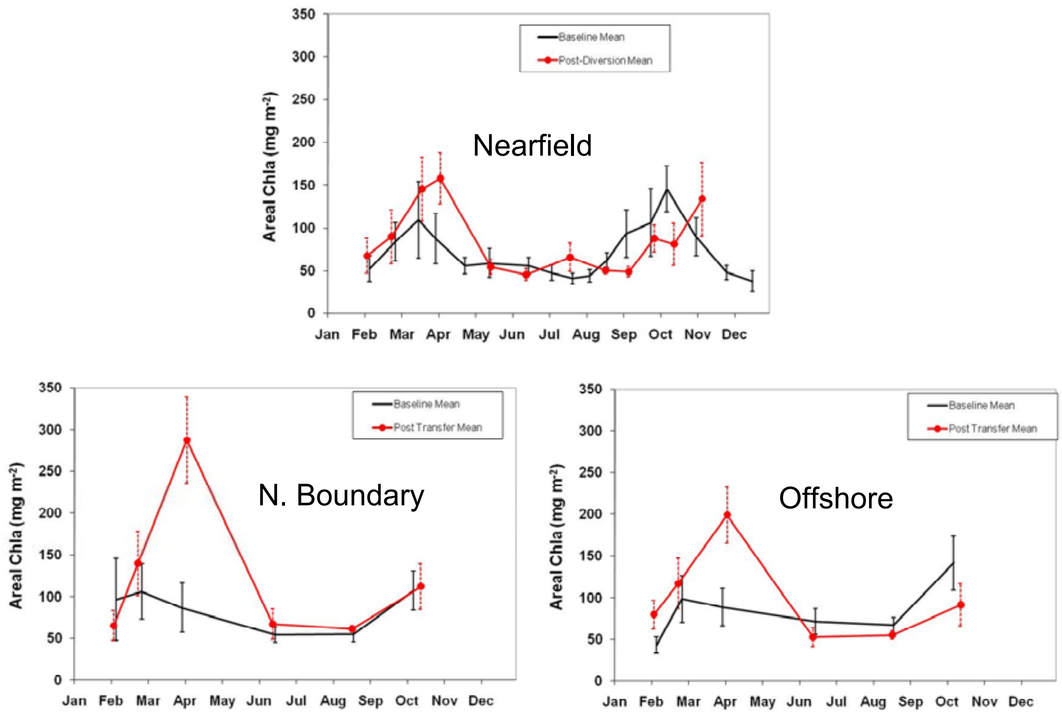
SiO_4 PO_4





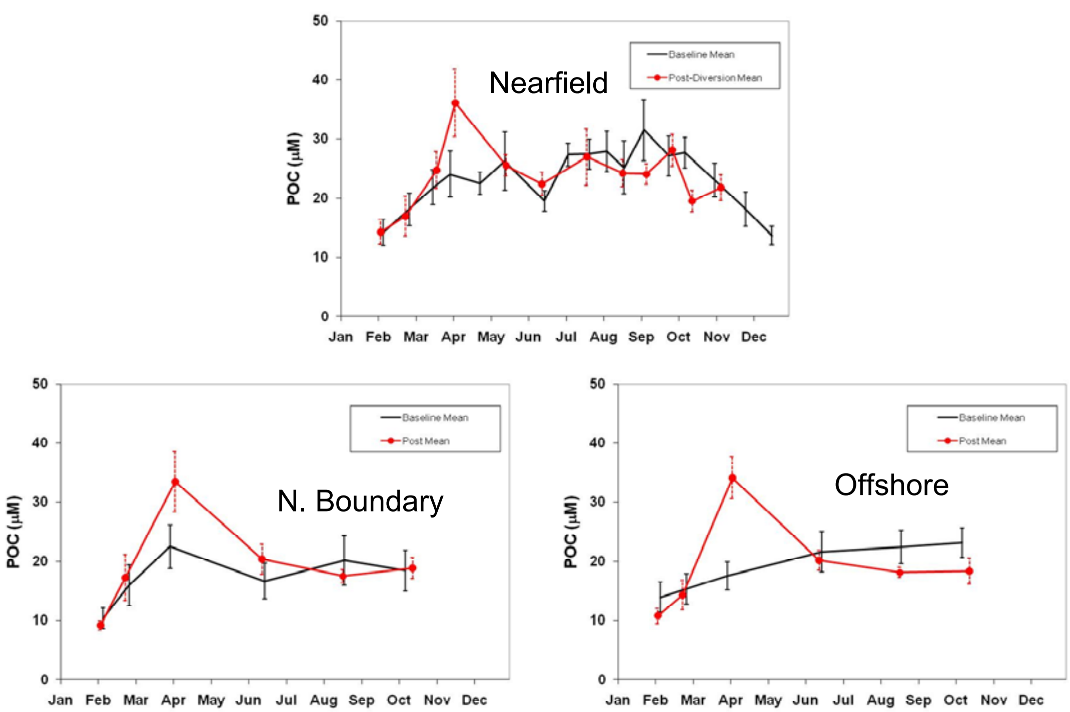
Areal Chlorophyll: Post vs. Baseline

24



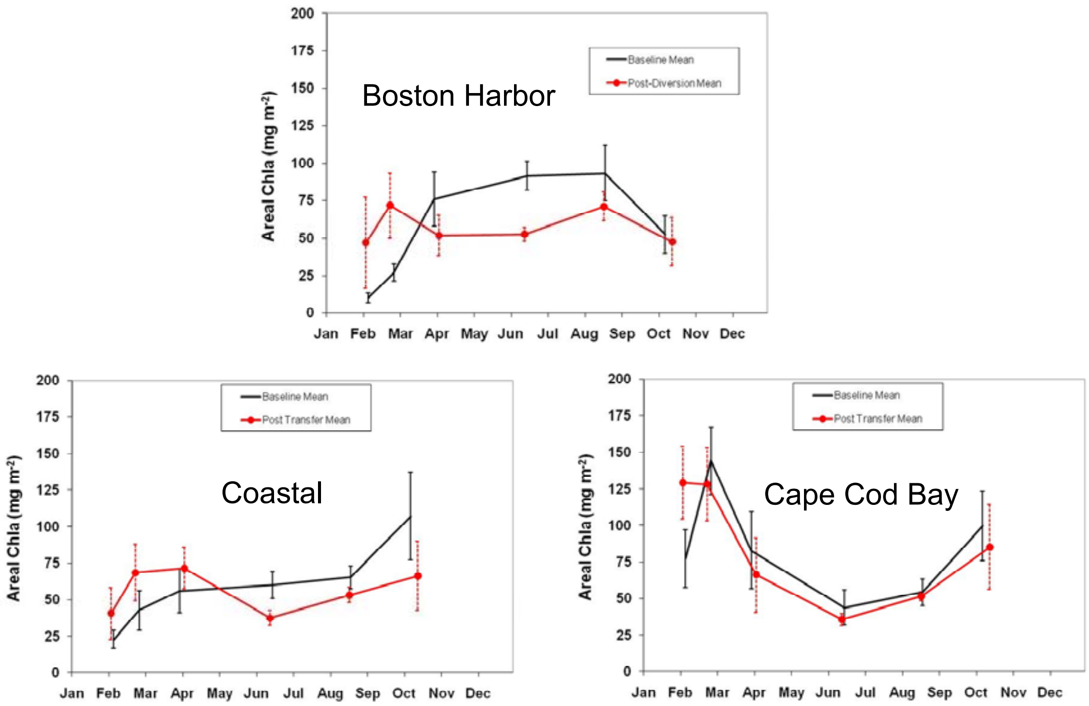
POC: Post vs. Baseline

25



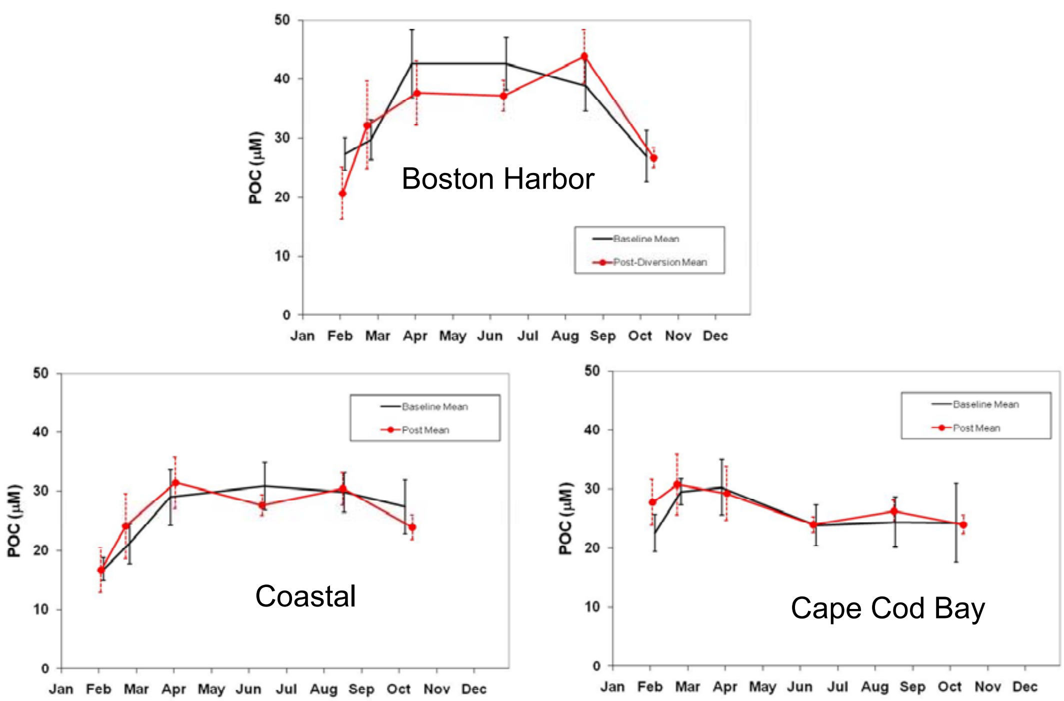
Areal Chlorophyll: Post vs. Baseline

26



POC: Post vs. Baseline

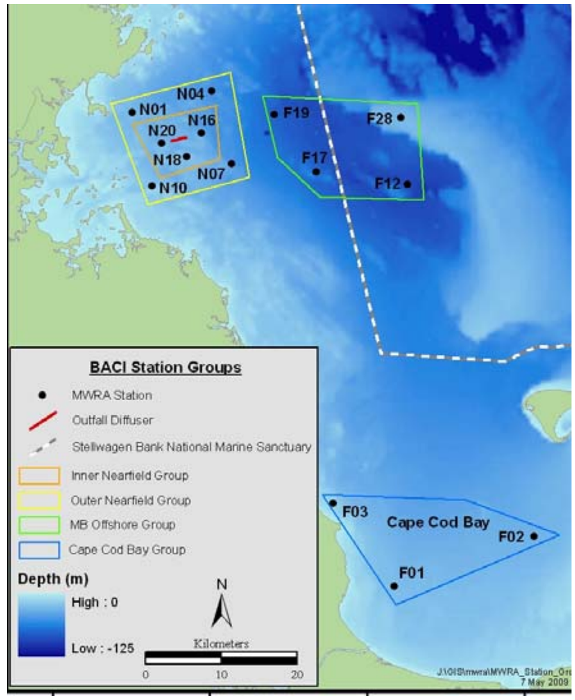
27



BACI Statistical Analysis (1992-2008)

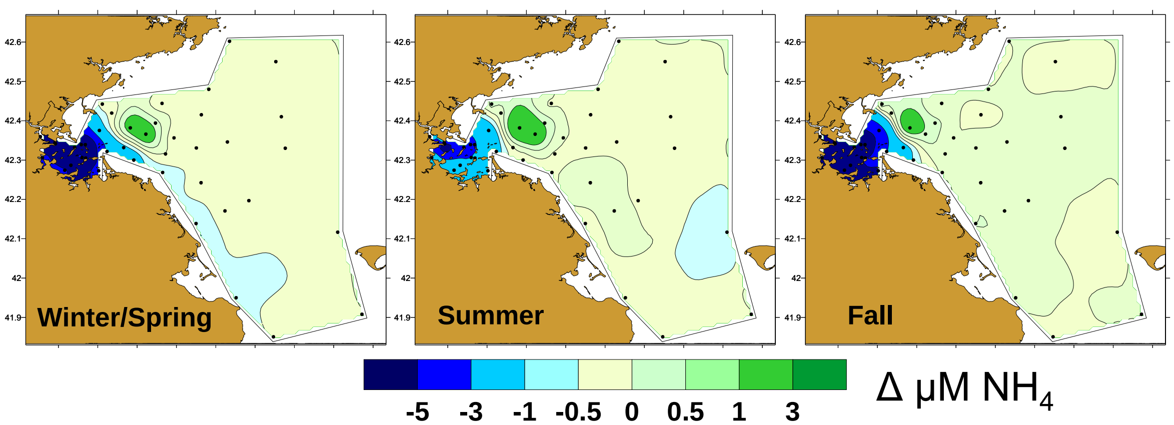
28

- 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



Spatial changes after outfall relocation (2001-2009 minus baseline): NH_4

29

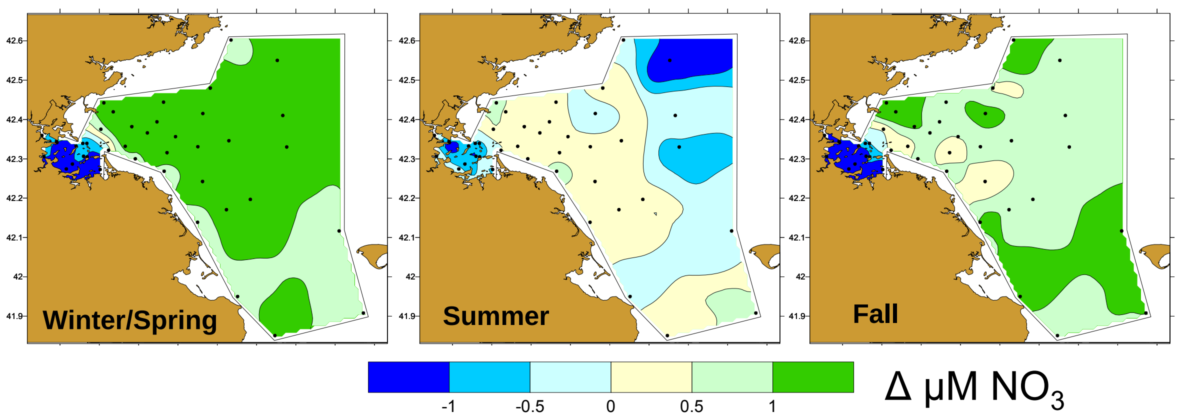


Winter/Spring	Summer	Fall
↑ Inner Nearfield	↑ Inner Nearfield	↑ Inner Nearfield
↓ Outer Nearfield, CCB, and MB Offshore		↓ MB Offshore

BACI analysis indicated increases ($p \leq 0.05$) in NH_4 above baseline levels in the Inner Nearfield compared to all three control areas for each season

Spatial changes after outfall relocation (2001-2009 minus baseline): NO_3

30



Δ μM NO_3

↑ Inner Nearfield, Outer Nearfield, and MB Offshore

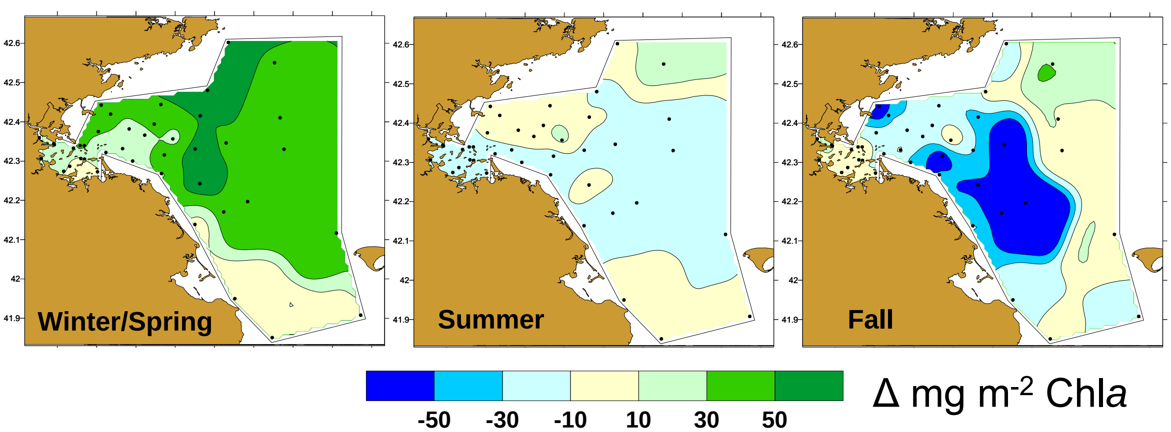
↑ Inner Nearfield

↑ Inner Nearfield, Outer Nearfield, and CCB

All groups trending in the same direction – no change ($p>0.05$) for Inner Nearfield compared to the three control areas for any season

Spatial changes after outfall relocation (2001-2009 minus baseline): Chlorophyll

31



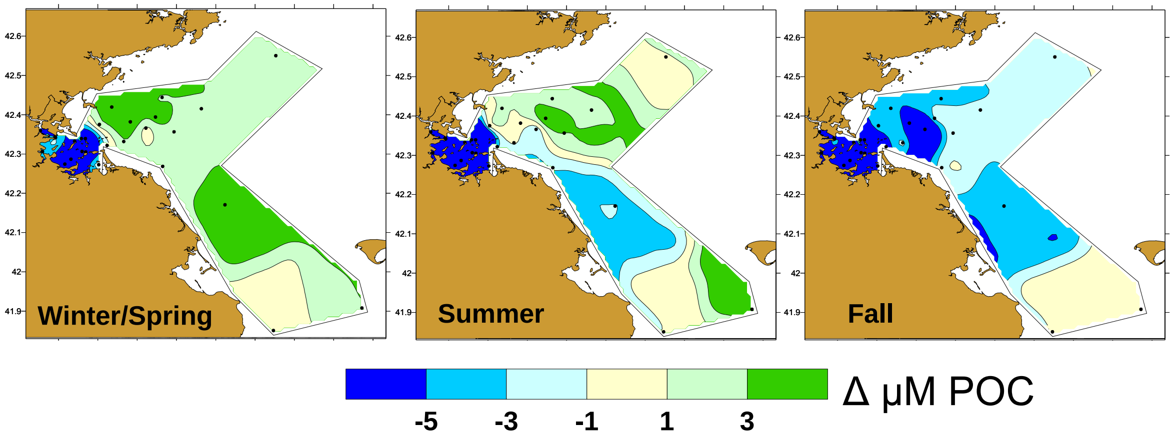
Δ mg m^{-2} Chl*a*

↑ Inner Nearfield, Outer Nearfield, and MB Offshore

All groups trending in the same direction – no change ($p>0.05$) for Inner Nearfield compared to the three control areas for any season

Spatial changes after outfall relocation (2001-2009 minus baseline): POC

32



↑ Inner Nearfield, Outer Nearfield

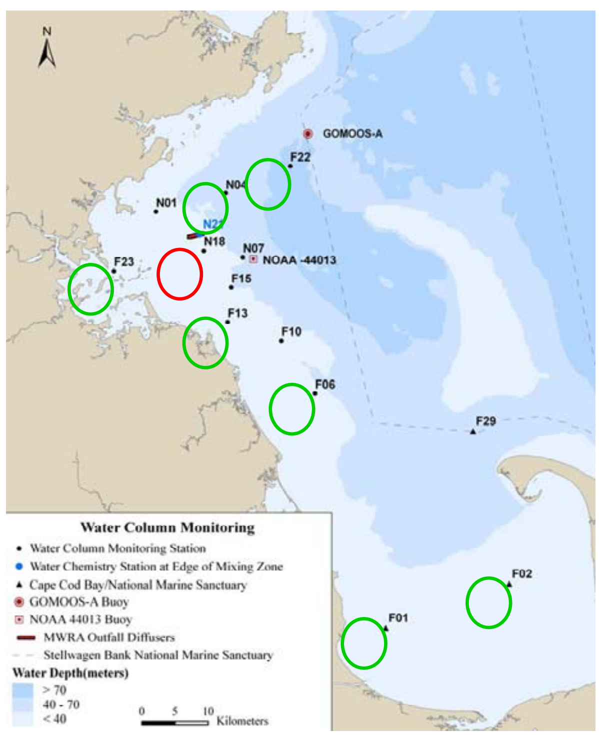
↑ Inner Nearfield

All groups trending in the same direction – no change ($p>0.05$) for Inner Nearfield compared to the three control areas for any season

Updated BACI by stations (1992-2009)

33

- Ran analysis based on proposed AMP revision
- Pre. vs. post station changes
  - Changes for NH_4 only ($p \leq 0.05$)
    - Increase at N18 all seasons
    - Decrease at F23 all seasons
- BACI results
  - Impact vs. Control sites
  - Only changes were for NH_4
    - Increase at N18 ($p \leq 0.05$) relative to nearly all other stations/season groups
    - No differences for N18 in fall vs. F01, F06, F13, F22, and N04



Post vs. Baseline Comparison - Summary

34

- "Typical" patterns observed in both time periods
- Nutrients
  - NH_4 clearly increased in the nearfield. Regional increase in NO_3
  - Overall there has been decrease in NH_4, NO_3, SiO_4, and PO_4 in Boston Harbor and adjacent coastal waters
- 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 (00-09)
    - Have changed April biomass levels in N. Boundary, Offshore and nearfield areas
  - No change in Coastal, CCB or Boston Harbor areas.
- Dissolved Oxygen
  - 2009 levels comparable to baseline in the nearfield and Stellwagen Basin
  - No change in DO (interannual variability driven by regional processes)

Conclusions

35

- 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 trends 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

C. Plankton

Dave Borkman, University of Rhode Island
Jeff Turner, University of Massachusetts Dartmouth

Phytoplankton and zooplankton abundance and community composition were monitored during 2009, the 18th year of MWRA's comprehensive outfall monitoring program. Two nearfield stations were sampled 12 times per year, and an additional 13 farfield stations were sampled six times per year.

C.1. Phytoplankton

At each plankton station, phytoplankton were sampled at two depths: near-surface and chlorophyll maximum (or mid-depth). Part of the sample was preserved in Lugols, the rest was 20-µm-screened to concentrate larger cells and then preserved in formalin. Over the year, 204 whole-water samples and 204 screened-water samples were collected. In the lab, the samples were concentrated by gravity, and then counted using phase contrast light microscopy (250X and 500X).

The 2009 phytoplankton annual cycle was bimodal with winter-spring and late summer abundance peaks: a *Phaeocystis pouchetii* bloom during April (but February in Cape Cod Bay; **Slide 6**) and a *Skeletonema*-dominated summer diatom bloom during August (Boston Harbor & Cape Cod Bay; **Slides 5-6**) through October (Offshore & Boundary regions; **Slide 4**). The 2009 *Phaeocystis* bloom marked the 10th year running that a bloom of >10^6 cells L^{-1} was detected, and marks the 12th of 18 years of monitoring that *Phaeocystis* dominated the winter-spring phytoplankton (**Slide 15**). However, the 2009 *Phaeocystis* bloom was primarily an offshore event, with maximum *Phaeocystis* abundance detected in the Offshore (5.4 x 10^6 cells L^{-1}) and Boundary (14.9 x 10^6 cells L^{-1}) regions. In contrast, the maximum 2009 *Phaeocystis* observation in the Nearfield was 2.8 x 10^6 cells L^{-1}. The gradient from greatest *Phaeocystis* abundance offshore to lowest abundance in the Coastal and Harbor regions suggests an offshore origin for the 2009 *Phaeocystis* bloom. In addition, the timing of the 2009 *Phaeocystis* bloom was regionally variable, with a February peak in Cape Cod Bay and an April peak in all other regions.

While 2009 diatom abundance remained below baseline mean levels through most of the year, a fall diatom bloom that reached a maximum of 2.5 x 10^6 cells L^{-1} in the Nearfield on 30 September 2009 was an important feature of the 2009 phytoplankton annual cycle (**Slides 3 and 11**). This diatom bloom was dominated by *Skeletonema* spp. (formerly identified as *Skeletonema costatum*; see Zingone *et al*. 2005; Kooistra *et al*. 2008) which reached a maximum of 2.2 x 10^6 cells L^{-1} in the Nearfield on 30 September 2009. The summer *Skeletonema*-dominated centric diatom bloom was region-wide, with peaks of 353,000 cells L^{-1} (Coastal region) to 2.48 x 10^6 cells L^{-1} (Nearfield region). The timing of the summer/fall bloom varied from an August peak (Cape Cod Bay and Boston Harbor) to an October peak in the Offshore and Boundary regions and Coastal regions. The summer/fall diatom bloom, while *Skeletonema*-dominated, was also comprised of elevated abundance of other diatoms such as *Dactyliosolen fragilissimus* (179,000 cells L^{-1} in the Nearfield during late September), *Leptocylindrus danicus* (66,000 cells L^{-1} in the Nearfield during late September) and *Guinardia delicatula*, *Guinardia flaccida* and *Cerataulina pelagica* which were each present at ca. 1,000 cells L^{-1} during the 2009 diatom bloom.

Other notable features of the 2009 phytoplankton cycle were elevated abundance, relative to baseline levels, of microflagellates and cryptomonads during March 2009 (**Slides 9-10**). A similar pattern of increased microflagellate and cryptomonad abundance during February and March was noted during 2008. One possible mechanism for this may be an increase in single-celled (rather than colonial) *Phaeocystis* cells that could be inadvertently classified as microflagellates.

Dinoflagellates had below baseline mean abundance levels during most of 2009, continuing the recent pattern of long-term reduced dinoflagellate abundance (**Slide 12**). However, October (41,000 cells L^{-1}) and November (47,000 cells L^{-1}) Nearfield dinoflagellate abundance was elevated to levels that were approximately twice the respective baseline mean levels. Much of this late 2009 dinoflagellate increase was due to elevated *Ceratium tripos* abundance (**Slide 13**). *Ceratium tripos* was present at 2,000 – 2,500 cells L^{-1} during October-November 2009 compared to a long-term mean abundance of 700 cells L^{-1} during October and November. A single nuisance or harmful algae bloom exceedance occurred in 2009. A maximum of 150 *Alexandrium fundyense* cells L^{-1} was recorded during May 2009 in the Nearfield (**Slide 16**). Of note is that low levels (2.5 cells L^{-1}) of *Alexandrium* were also detected in October of 2009. This marks the second year in a row that low levels of *Alexandrium* were detected in autumn. The 2009 winter-spring *Phaeocystis* bloom did not exceed any warning thresholds. Similarly, 2009 levels of *Pseudo-nitzschia* spp. remained at reduced levels (2009 maximum was 12,000 cells L^{-1}) observed since 1998-1999 that did not exceed the warning threshold (**Slide 17**).

2009 phytoplankton patterns generally followed observed long-term trends, including the long-term decline in diatom abundance (**Slides 8 and 11**). No changes in total phytoplankton abundance were detected, but changes in phytoplankton functional groups have been occurring. For example, 2009 mean diatom abundance in the Nearfield (131,400 cell L^{-1}) was one-third the 1992-2008 mean of 368,100 cells L^{-1} (Mann-Whitney U test, $p = 0.0030$). This long-term decline in diatom abundance has been ongoing since 2004, and is largely due to a reduction in winter-spring diatom bloom magnitude during the last decade of *Phaeocystis* dominance of the winter-spring bloom (Libby *et al*. 2009). Another group that appears to be increasing in abundance is cryptomonads which during 2009 had a mean Nearfield abundance level of 185,600 cells L^{-1} compared to a 1992-2008 long-term mean of 127,400 cells L^{-1} (Mann-Whitney U test, $p = 0.0186$).

Patterns and trends assessed by only phytoplankton numerical abundance may obscure changes in the relative contribution of variously sized phytoplankton groups or species to total phytoplankton biomass (expressed as µg phytoplankton carbon L^{-1}). A preliminary investigation of long-term patterns of phytoplankton biomass during 1992-2009 was initiated (see **Slides 20-28**). For the Nearfield, the abundance and biomass observed during the most recent five years (2005-2009) was compared to that observed during the first 13 years of monitoring (1992-2004). These results are summarized in Table 1.

The following observations may be made from the comparison of 1992-2004 versus 2005-2009 biomass and abundance (Table 1):

At the community level:

- Total phytoplankton carbon during 2005-2009 (73 g C L^{-1}) was about 75% of that observed during 1992-2004 (95 µg C L^{-1}).
- Much of this decline was due to a change in mean diatom biomass from 57 µg C L^{-1} (1992-2004) to 43 µg C L^{-1} (2005-2009).

At the cellular level:

- Shifts in the mean cellular carbon of phytoplankton functional groups were detected: diatoms appear to have increased their mean carbon per cell content while dinoflagellates and total phytoplankton have declined in carbon per cell.
- Dominance of winter-spring phytoplankton by small cells (*Phaeocystis*) appears to be driving the decline in mean phytoplankton size.
- Recent summer increases in *Dactyliosolen fragilissimus* and other large diatoms (*Guinardia flaccida*, for example) appear to be driving the long-term increase in mean diatom cellular carbon.

- The decline in dinoflagellate cellular carbon was driven by a decline in large dinoflagellates (*Ceratium* spp.) and a recent increase in smaller species (small *Gymnodinium* spp. and *Heterocapsa rotundatum*).

Table 1. Summary of Nearfield phytoplankton biomass and abundance changes in recent years (2005 – 2009) compared to 1992-2004. Comparisons made using Mann-Whitney test. Surface nearfield observations used; typically n = 182 (1992-2004) and n = 60 (2005-2009). Blue denotes significant decrease; red denotes significant increase.

	1992 - 2004	2005 – 2009	P value
Biomass (ug C L^{-1})			
Total phytoplankton	95	73	0.0023
Diatoms	57	43	0.0008
Dinoflagellates	14	4	0.0040
Abundance (cells L^{-1})			
Total phytoplankton	1.384×10^6	1.334×10^6	0.6699
Diatoms	273,600	167,300	< 0.0001
Dinoflagellates	18,700	34,000	0.0297
Cell Carbon (pg C $cell^{-1}$)			
Total phytoplankton	67	41	<0.0001
Diatoms	268	435	0.0003
Dinoflagellates	1,812	570	<0.0001

C.2. Zooplankton

At each plankton station, zooplankton were sampled using vertical oblique net hauls (102 µm mesh) and preserved in formalin. Over the year, 102 samples were collected. In the lab, the samples were counted using a dissecting microscope.

The 2009 total zooplankton annual cycle in the nearfield featured reduced abundance of < 10,000 animals m^{-3} during February through April followed by an increase to 55,000 to 81,000 animals m^{-3} during May to August and a return to < 40,000 animals m^{-3} during September to November (**Slides 30 and 35**). As in previous years, the zooplankton community was overwhelmingly dominated (90% numerically) by copepods. Meroplankton (barnacle bivalves, gastropod veligers, polychaete larvae) and non-copepod zooplankton such as *Evadne nordmani* and *Oikopleura dioic*a, comprised >10% of total zooplankton during the months of May, August and September. Zooplankton patterns appeared to be regionally coherent (**Slides 31-33**). Some minor regional differences noted include elevated barnacle nauplii abundance during the spring in the Harbor and Coastal regions and elevated (2 × mean) copepod abundance in the North Boundary region during August. In addition, total zooplankton abundance had peak abundance during June in the Coastal, Boston Harbor and Cape Cod Bay regions versus an August peak observed in the Offshore and North Boundary regions.

During 2009 *Oithona similis* continued to be the most abundant copepod, with *Oithona* representing about 33% of total copepods numerically. The 2009 *Oithona* annual cycle featured reduced *Oithona* levels (100s to 2,400 m^{-3}) during February to April followed by an increase to 16,000 – 28,000 m^{-3} during May through early September and a return to *Oithona* levels of <10,000 m^{-3} from late September through November 2009. The summer *Oithona* levels were above the *Oithona* baseline mean levels (**Slide 38**).

Calanus finmarchicus comprised 0% (November) to 27% (March) of nearfield total zooplankton during 2009. While not numerically dominant, *Calanus* is an important food resource for endangered Right Whales (Mayo &

Marx 1990). 2009 *Calanus finmarchicus* abundance was elevated relative to the mean baseline level (**Slide 39**). For example, *Calanus* abundance during May 2009 (14,378 animals m^{-3}) was 15-times the baseline May level (960 animals m^{-3}) and June 2009 nearfield *Calanus* abundance (5,988 animals m^{-3}) was twice the baseline mean level of 3,079 animals m^{-3} (**Slide 39**). May 2009 *Calanus* abundance included the second greatest individual *Calanus* abundance seen and the greatest Nearfield averaged *Calanus* abundance recorded in 18 years of monitoring. Also of note is that the 2009 *Calanus* annual cycle appears to continue the post-diversion shift from double annual peaks (April & June, baseline) to a single May annual *Calanus* peak (post diversion).

Overall, 2009 zooplankton levels were near the long-term mean levels for most groups. This represents a return to near mean levels during 2006-2009 following reduced zooplankton abundance during 2002-2005 (**Slide 43**). This return to near mean levels appears to have been led by a rebound in copepod abundance, particularly an increase in *Oithona* abundance to above the long-term mean level since 2007 (**Slides 44-45**). Nearfield *Calanus finmarchicus* attained elevated abundance during 2009 (**Slide 46**), featuring the greatest nearfield average abundance levels recorded during 18 years of monitoring.

C.3. REFERENCES

Kooistra, W.C.H.F., Sarno, D., Balzano, S., Gu, H., Andersen, R.A., Zingone, A., 2008. Global diversity and biogeography of *Skeletonema* species (Bacillariophyta). Protist 159, 177–193.

Libby PS, Anderson DM, Borkman DG, Geyer WR, Keller AA, Oviatt CA, Turner JT. 2009. 2008 Water Column Monitoring Results. Boston: Massachusetts Water Resources Authority. Report 2009-12. 31p. plus appendices.

Mayo, C. A. & M. K. Marx. 1990. Surface foraging behavior of the North Atlantic right whale, *Eubalaena glacialis*, and associated zooplankton characteristics. Can. J. Zool. 68: 2214-2220.

Zingone, A., Percopo, I., Sims, P.A., Sarno, D., 2005. Diversity in the genus *Skeletonema* (Bacillariophyceae). I. A re-examination of the type material of *S. costatum* with the description of *S. grevillei* sp. nov. J. Phycol. 41, 140–150.

1

2009 Plankton Overview

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2010 Science Meeting *29 April 2010*

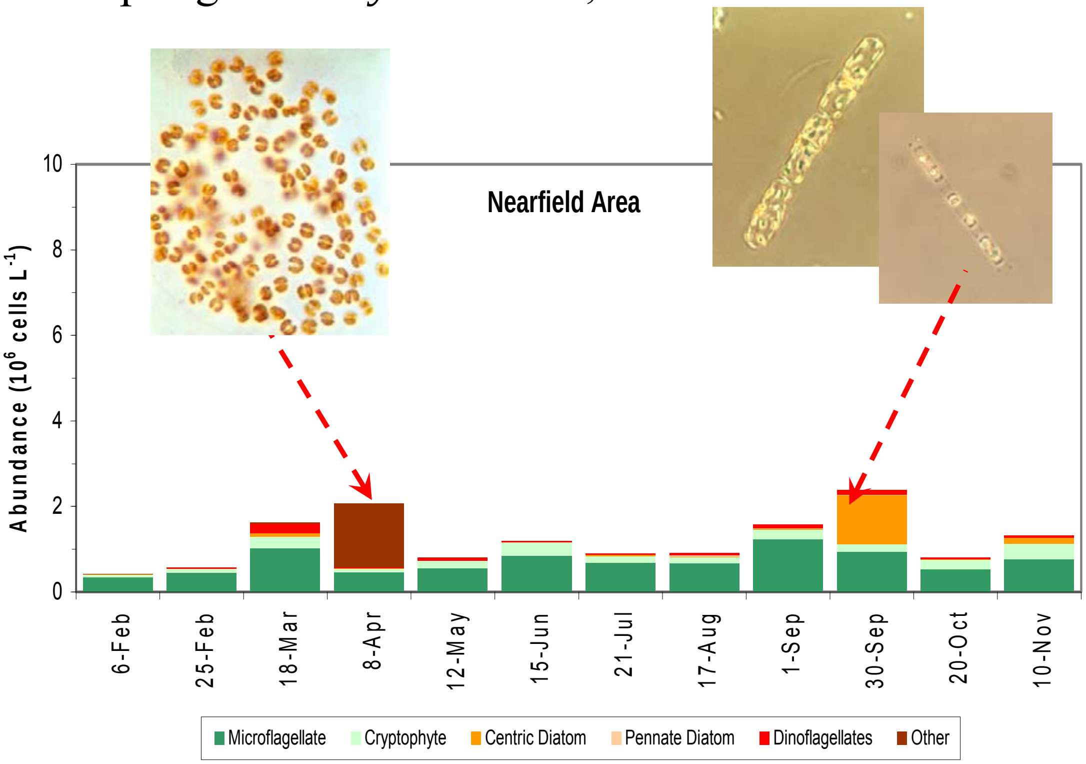
2

2009 Plankton Overview

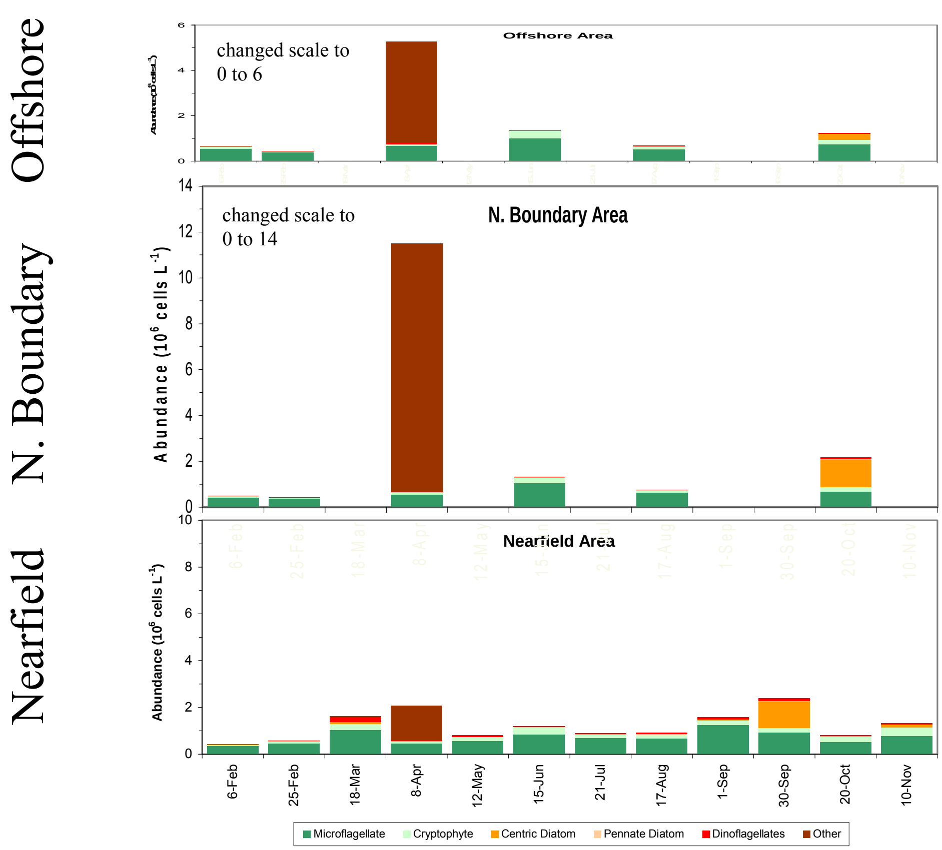
- Phytoplankton and Zooplankton Monitoring
  - 2 nearfield stations are visited 12 times/y
  - 13 farfield stations are visited 6 times/y
  - Phytoplankton sampled using nisken bottles at the surface and at the mid-depth (or at chlorophyll-max). A portion is also 20-um screened for large rare dinoflagellates.
  - Zooplankton sampled using vertical-oblique hauls of a flow-metered 102-um mesh net
- Samples are enumerated for species and abundance
- Results are used to
  - Test contingency plan thresholds
  - Compare across years and regions
  - Look for long-term patterns & trends
  - Understand phytoplankton growth and predation
  - Understand nuisance algal blooms

3

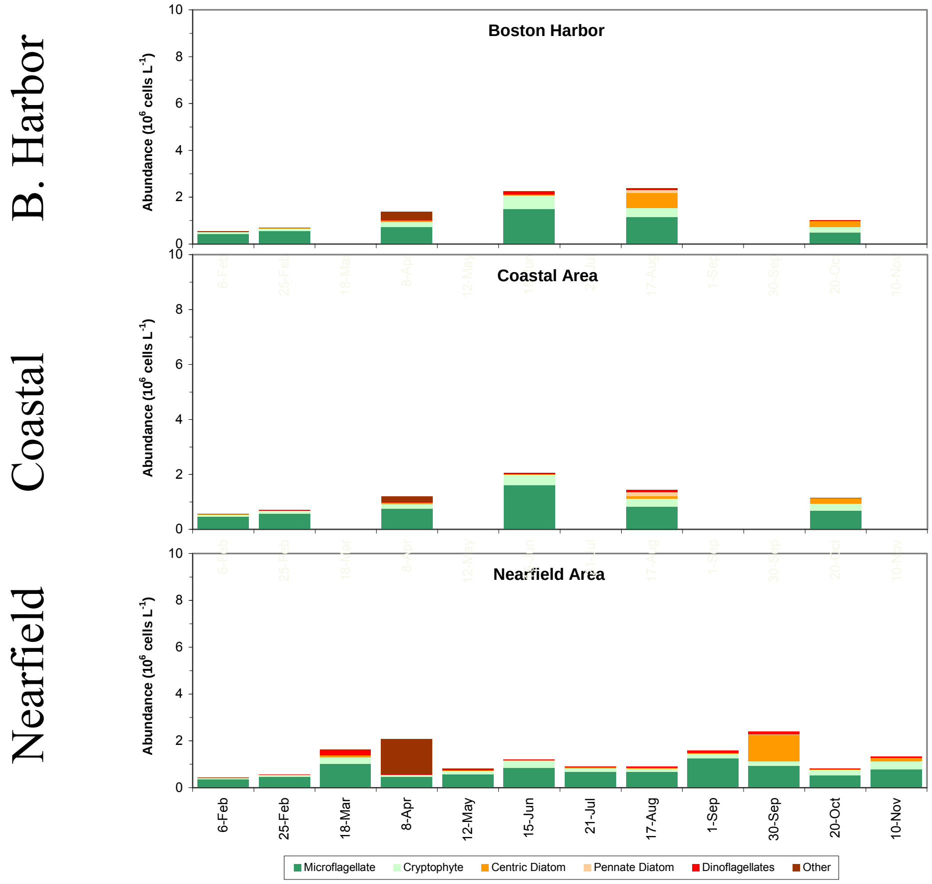
Spring *Phaeocystis* bloom; autumn diatom bloom



4

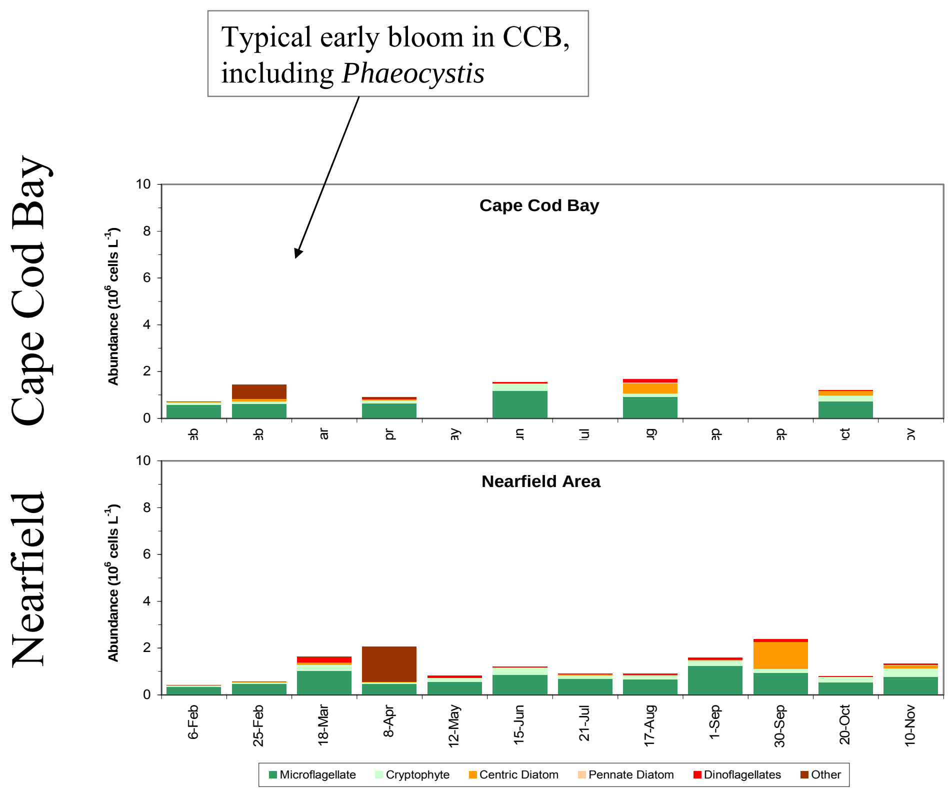


5



B. Harbor
Coastal
Nearfield
Boston Harbor
Coastal Area
Nearfield Area
Abundance (10^6 cells L^-1)
0
2
4
6
8
10
6-Feb
25-Feb
18-Mar
8-Apr
12-May
15-Jun
21-Jul
17-Aug
1-Sep
30-Sep
20-Oct
10-Nov
Microflagellate
Cryptophyte
Centric Diatom
Pennate Diatom
Dinoflagellates
Other

6



Typical early bloom in CCB, including *Phaeocystis*
Cape Cod Bay
Nearfield
Cape Cod Bay
Nearfield Area
Abundance (10^6 cells L^-1)
0
2
4
6
8
10
6-Feb
25-Feb
18-Mar
8-Apr
12-May
15-Jun
21-Jul
17-Aug
1-Sep
30-Sep
20-Oct
10-Nov
Microflagellate
Cryptophyte
Centric Diatom
Pennate Diatom
Dinoflagellates
Other

7

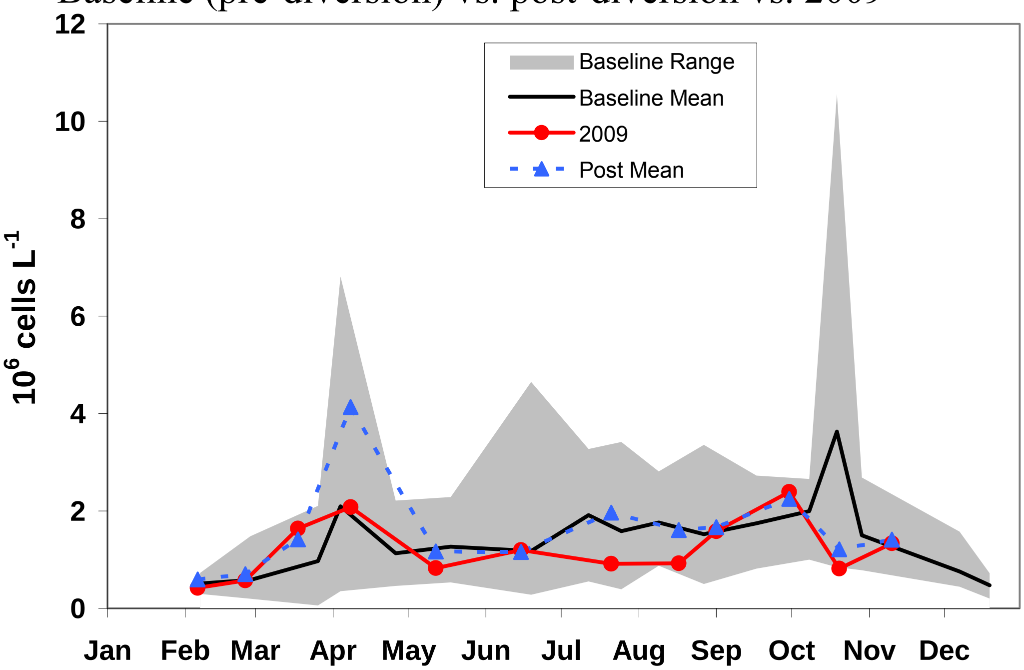
Regional phytoplankton composition patterns

- Microflagellate ‘baseline’ varies seasonally with temperature
- Phaeocystis
  - 2009 was another “*Phaeocystis* year,” marking the 10th consecutive year with samples having more than a million cells per liter. Before 2000, it was only seen every 2 or 3 years.
  - Blooms in April, but earlier (February) in Cape Cod Bay.
  - Mainly Offshore and Boundary in 2009
- Diatoms
  - Summer-Autumn bloom dominant in 2009
  - August: *Skeletonema* and *Dactyliosolen* in Harbor & Cape Cod Bay
  - September: *Skeletonema* and *Dactyliosolen* in Nearfield
  - October: *Skeletonema* and *Dactyliosolen* in Offshore and Boundary
- Dinoflagellates
  - Small cells (*Gymnodinium*, *Heterocapsa*) in spring
  - *Ceratium* elevated in October and November

8

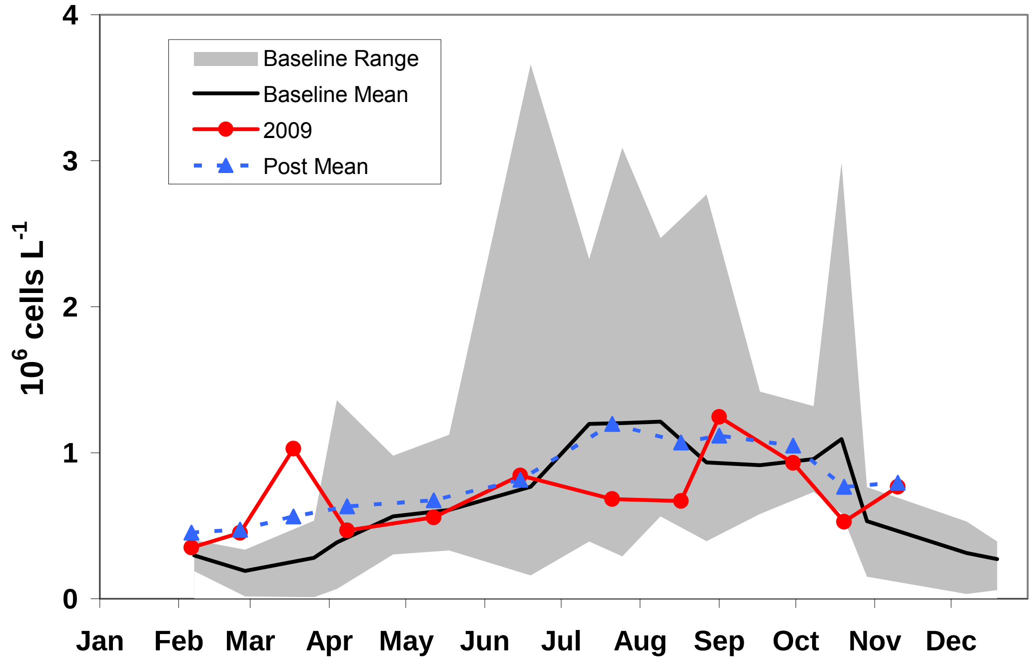
Total phytoplankton – nearfield

Baseline (pre-diversion) vs. post-diversion vs. 2009



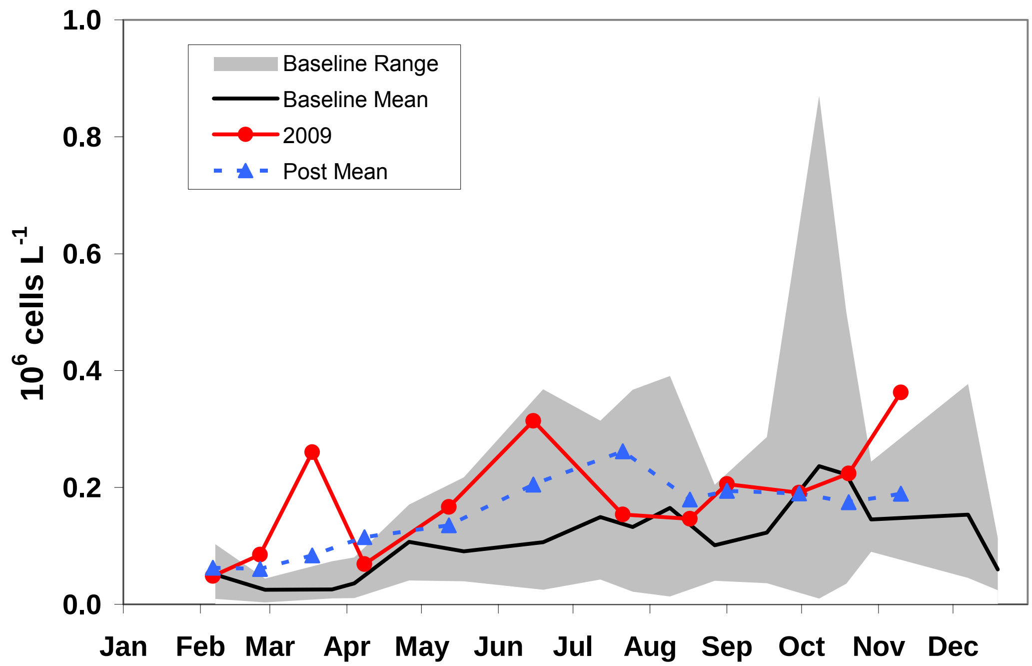
9

Microflagellates – nearfield



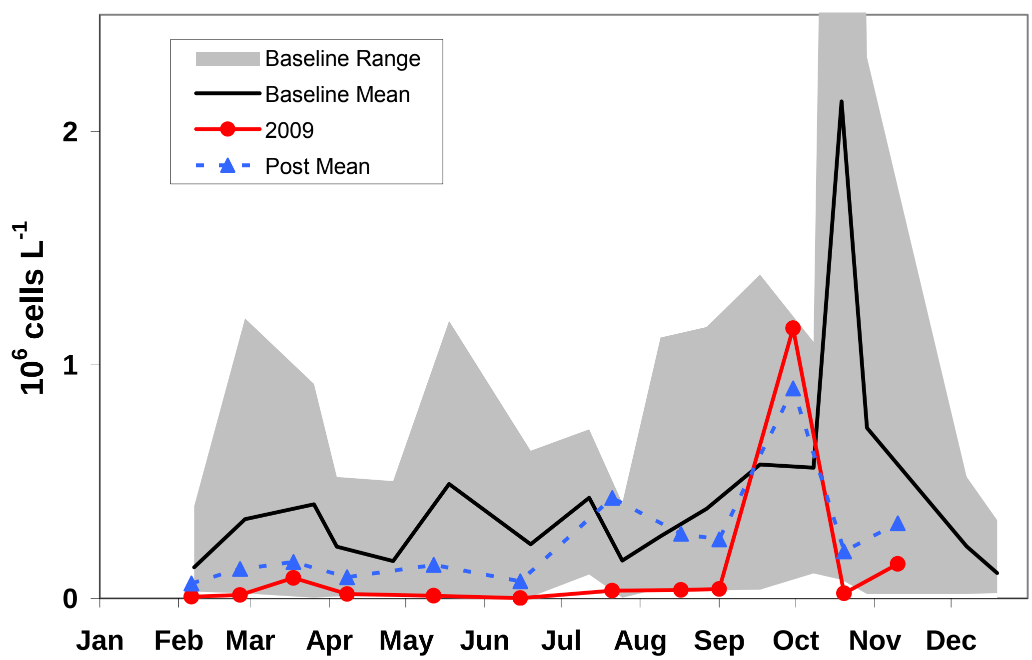
10

Cryptophytes – nearfield



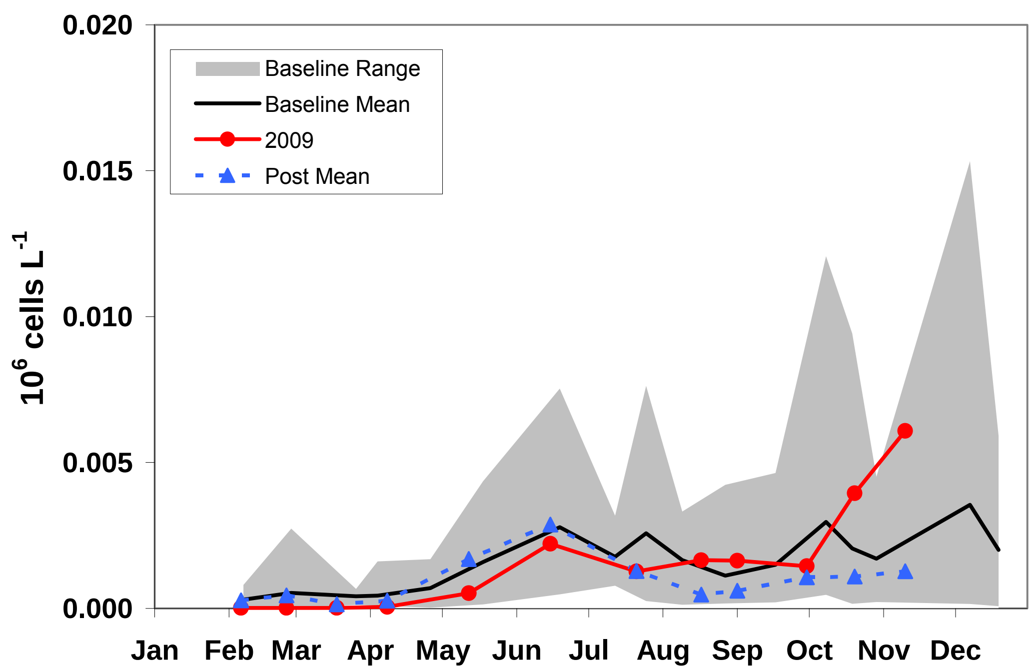
Diatoms – nearfield

11



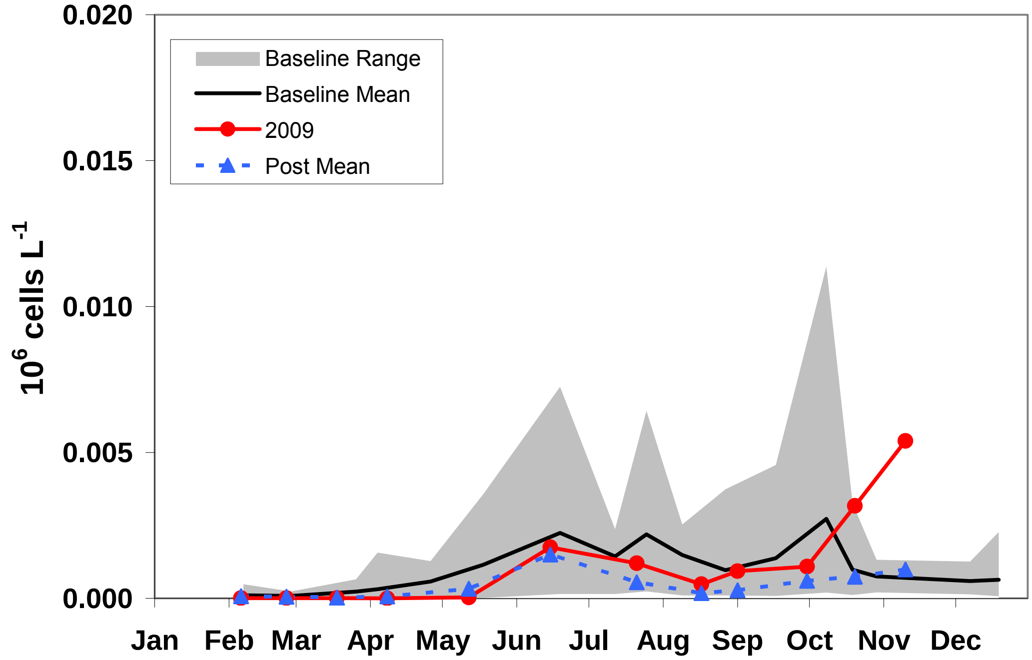
Dinoflagellates (20-uM screened) – nearfield

12



13

Ceratium (a subset of the previous slide) – nearfield



14

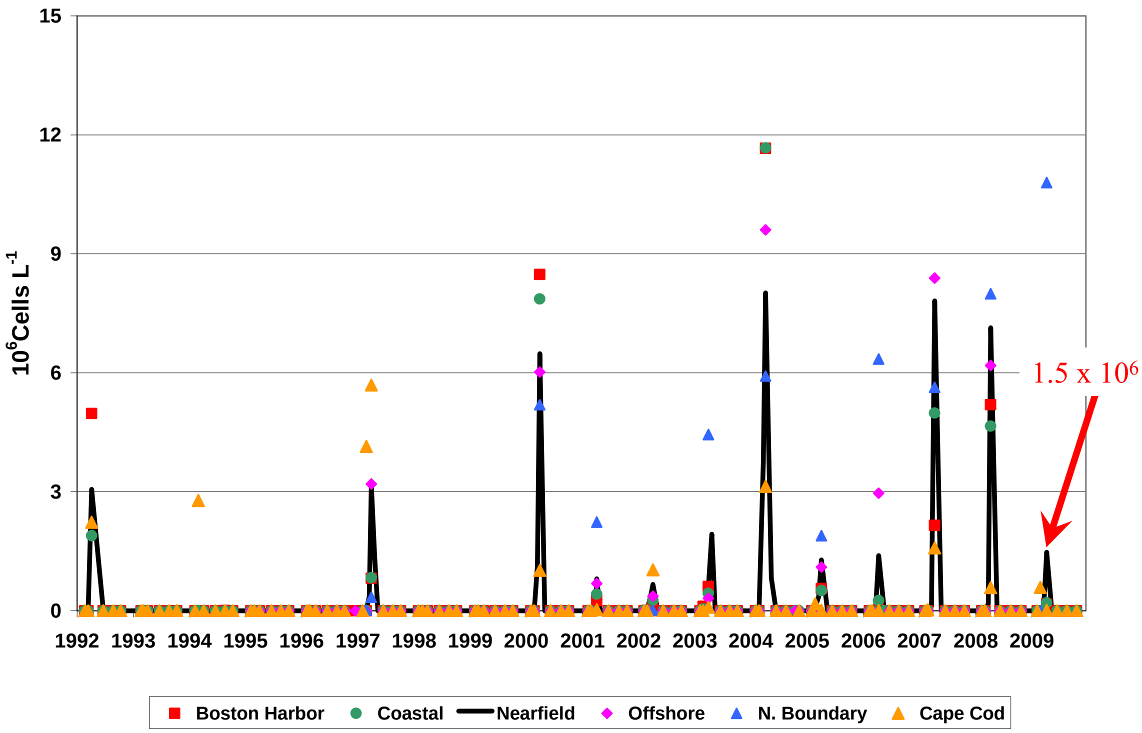
2009 nearfield phytoplankton annual cycle

- Total phytoplankton
  - bimodal annual cycle
  - elevated March & April (*Phaeocystis*)
  - reduced July, August, October
  - elevated in September (diatoms)
- Microflagellates
  - elevated in March
  - reduced in July-August & October
- Diatoms
  - reduced Winter-Spring bloom (March)
  - generally reduced except September (*Skeletonema* & *Dactyliosolen*)
- Cryptophytes
  - elevated during March
  - reduced during November
- Dinoflagellates
  - reduced in Feb-May; near long-term mean in June-September
  - elevated in October and November (*Ceratium*)

14

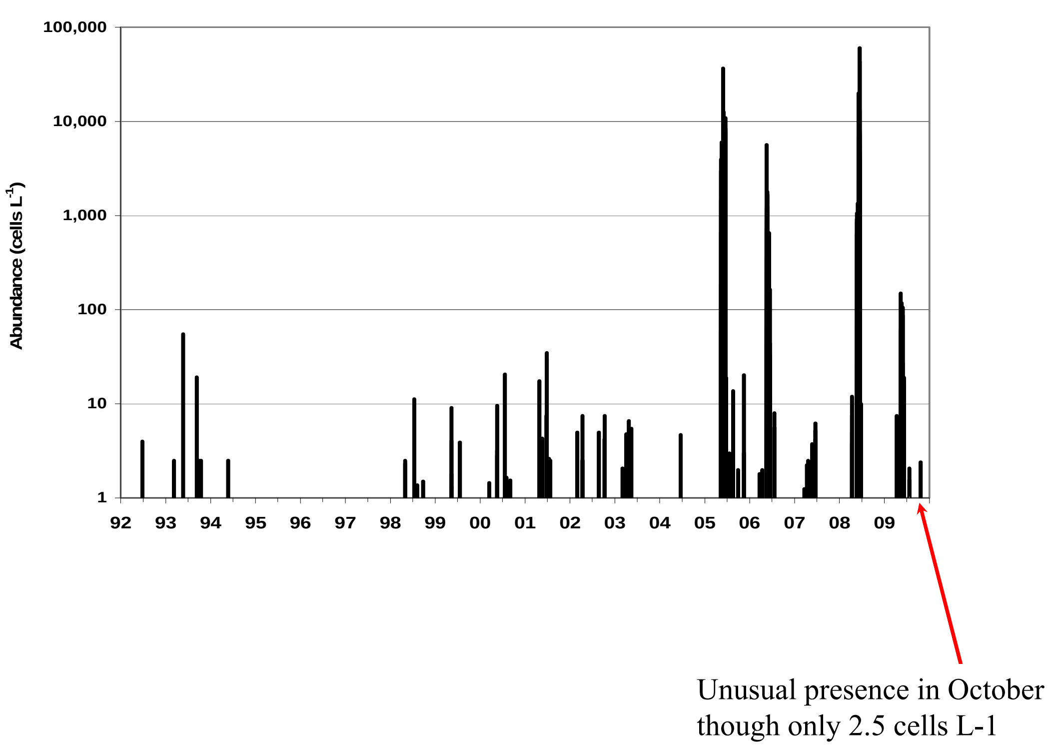
15

Harmful and nuisance algae: *Phaeocystis*



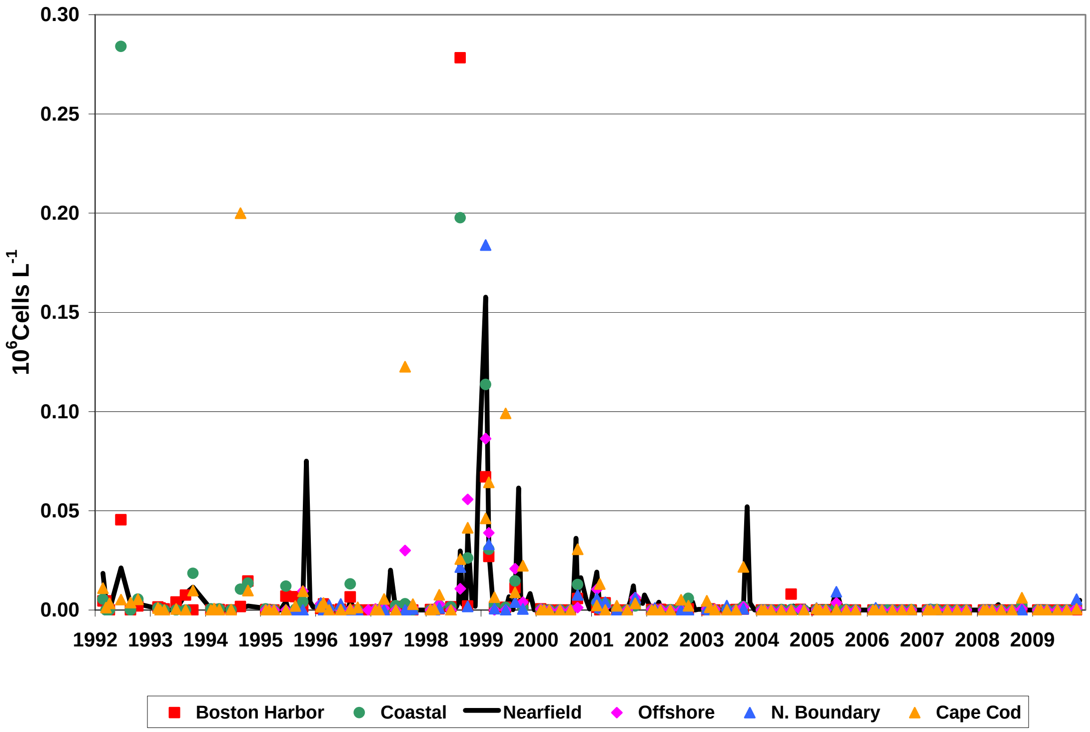
16

Alexandrium – nearfield



17

Pseudo-nitzschia continues to be low



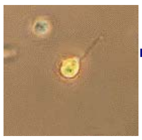
18

2009 nuisance and harmful species summary

- Another *Phaeocystis* bloom year (< 2007, 2008)
  - Most abundant well offshore, peaking at 14.9 x 10^6 cells/L
  - Only moderate levels in the nearfield (1.5 x 10^6 cells/L)
- Weak *Alexandrium* bloom
  - Nearfield peaked at only 150 cells/L
  - April-May bloom; but cells also present in October
- *Pseudo-nitzschia* continued to be low since 1999
  - Peaked at 12,000 cells/L at the Boundary in October

19

Phytoplankton cell biomass varies 5000-fold



Microflagellate
5 um sphere

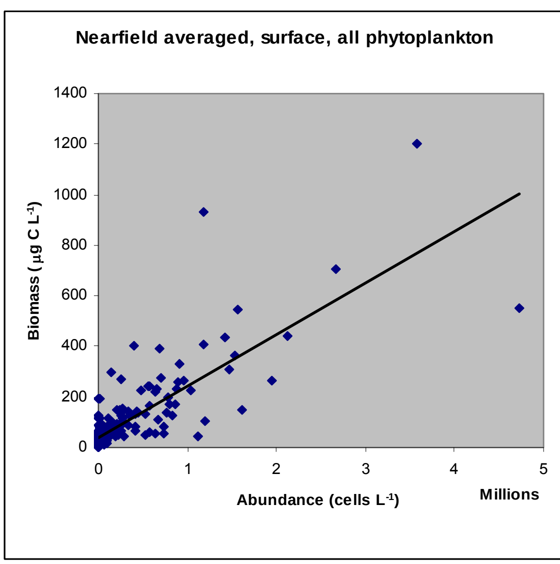
< 10 pg C/cell

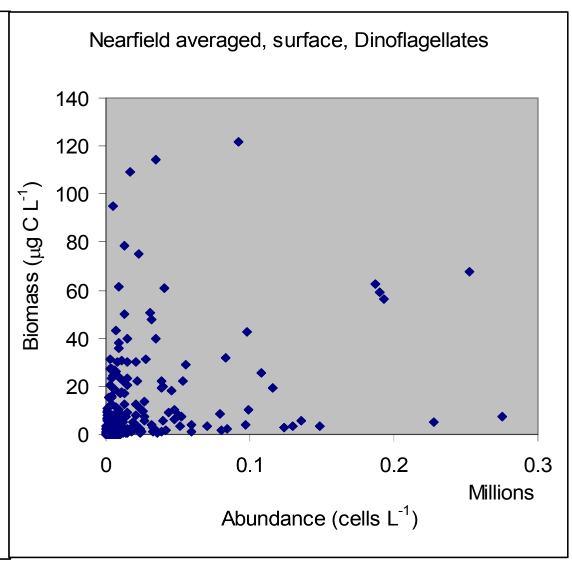
Dactyliosolen fragilissimus
10-70 um diameter,
40-300 um length
332 pg C/cell

Ceratium tripos
60-90 um width,
200-400 um length
10,000 pg C/cell
50,000 pg C/cell max

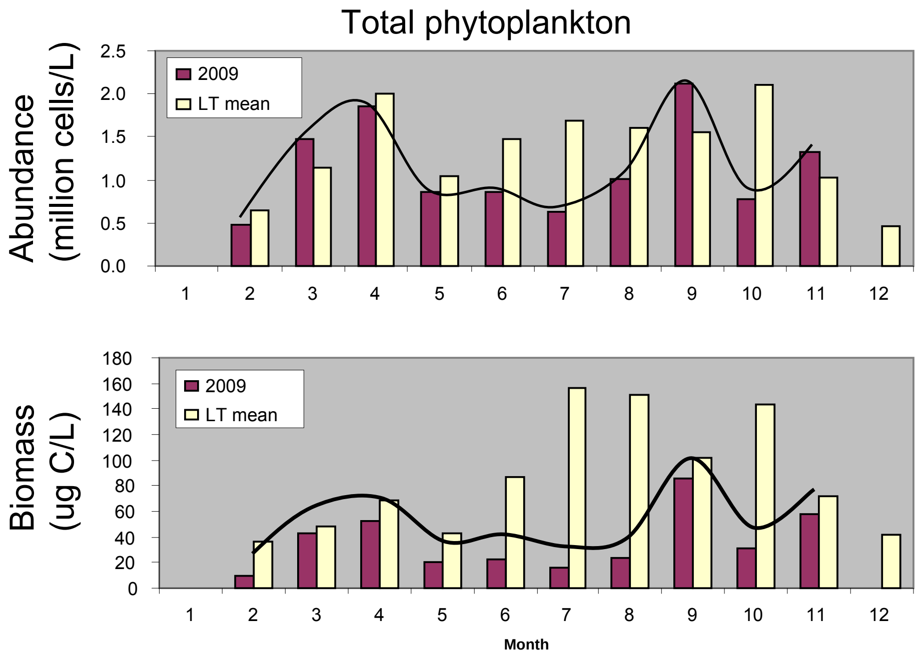
20

Biomass/L = abundance/L * biomass/cell. The latter term can be important



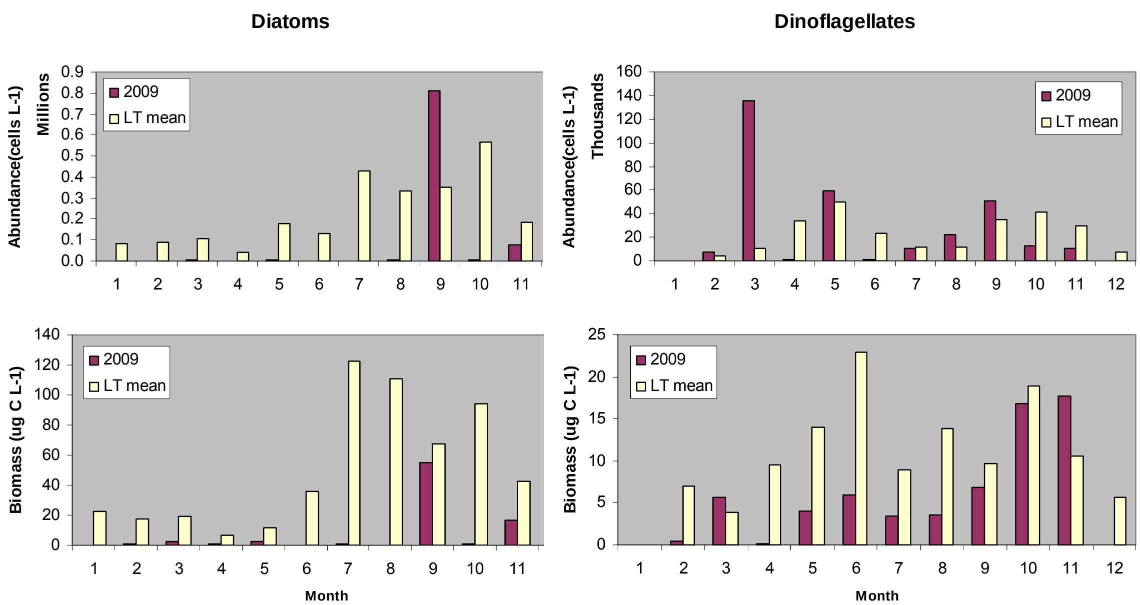


21



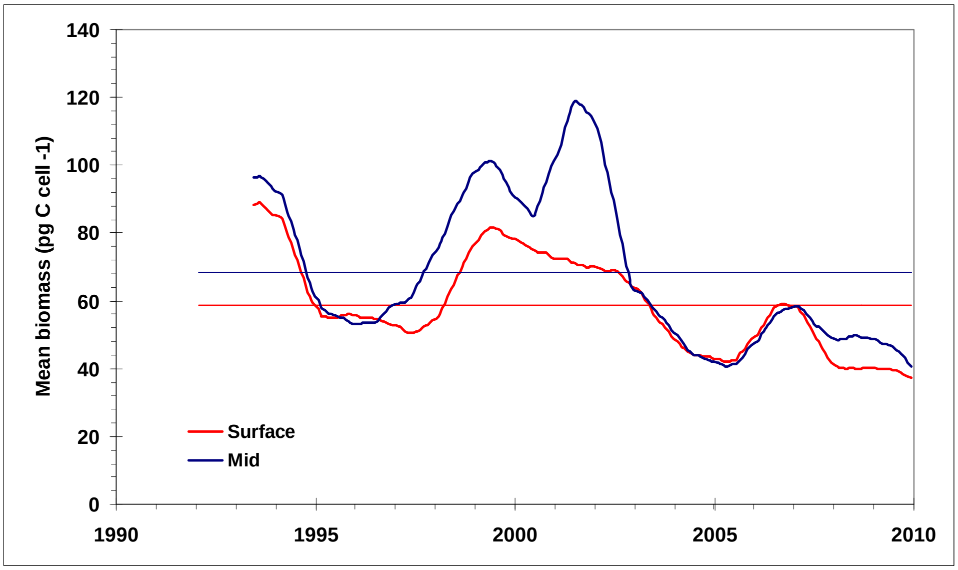
22

Abundance vs. carbon biomass interpretation.
Biomass bloom of diatoms in summer.
Abundance bloom of dinoflagellates in March.



23

Carbon per cell – total phytoplankton



Total phytoplankton

– trend towards smaller cells (*Phaeocystis, Cryptomonads*)

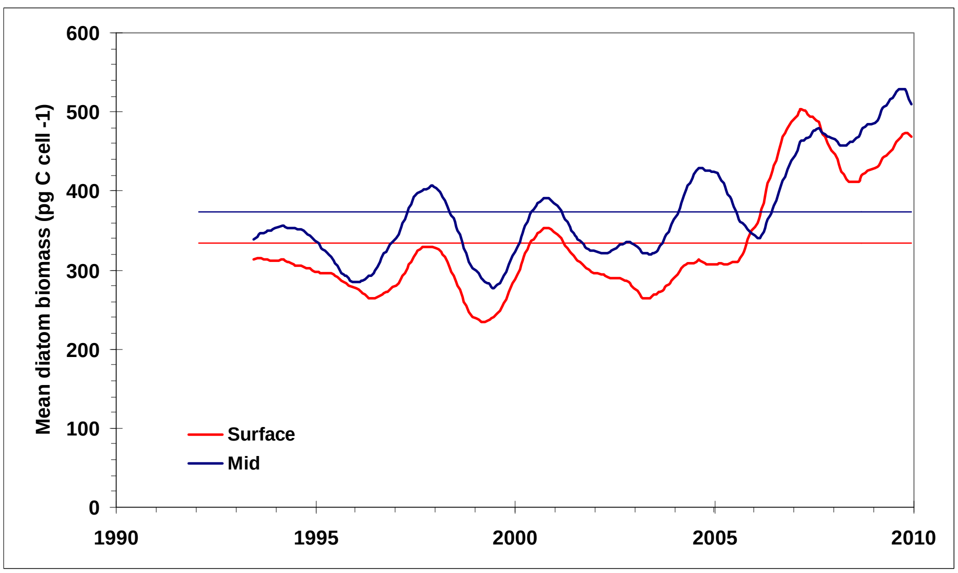
1992-2004 mean = 67 pg C $cell^{-1}$

2005-2009 mean = 40 pg C $cell^{-1}$

(surface, Mann-Whitney test , $p < 0.0001$)

24

Carbon per cell – diatoms
Trend towards larger cells (*Dactyliosolen*, others?)



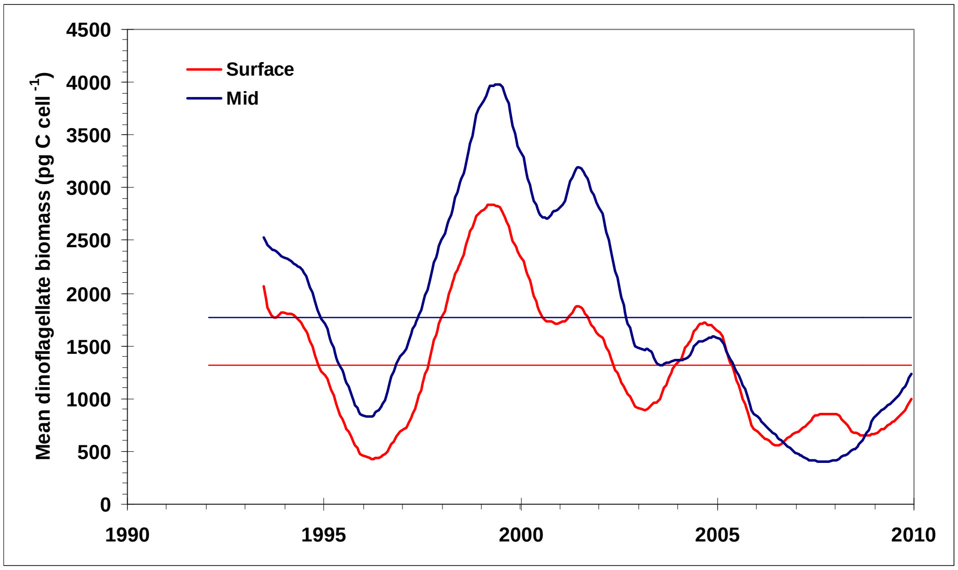
1992-2004 mean = 265 pg C $cell^{-1}$

2005-2009 mean = 398 pg C $cell^{-1}$

(surface, Mann-Whitney test , $p = 0.0027$)

25

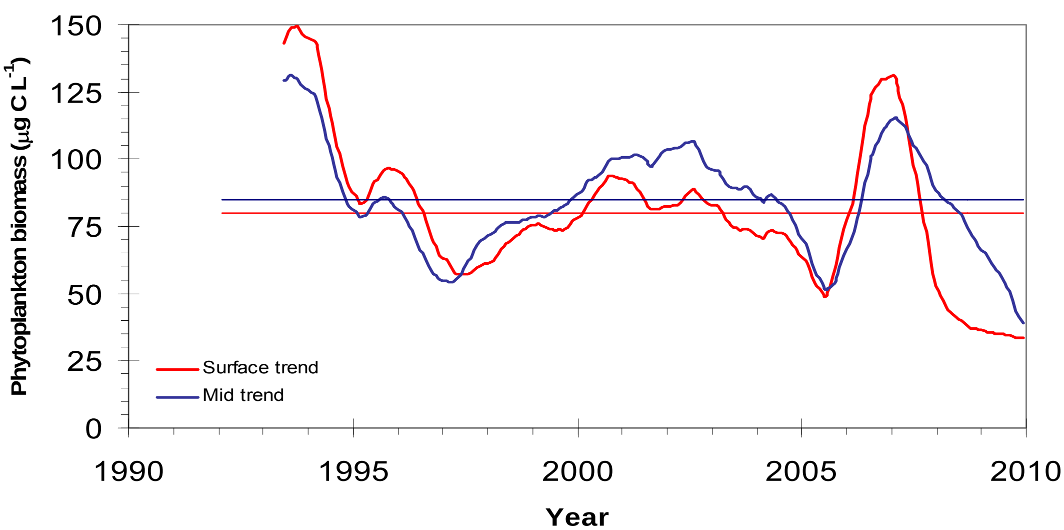
Carbon per cell – diatoms
Trend towards smaller cells (*Gymnodinium, Heterocapsa*)



1992-2004 mean = 1,885 pg C cell $^{-1}$
2005-2009 mean = 637 pg C cell $^{-1}$
(surface, Mann-Whitney test , $p = 0.0002$)

26

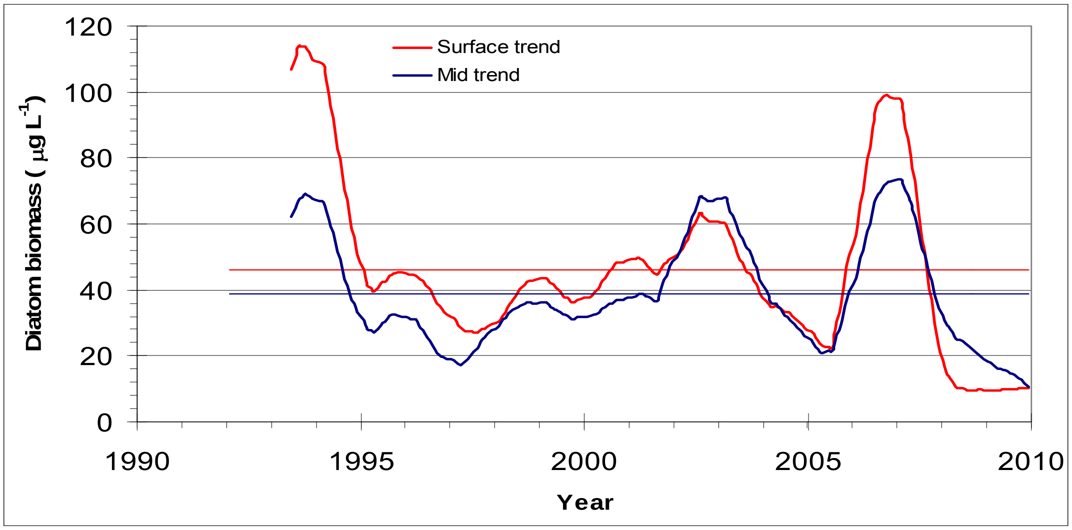
Biomass (carbon per liter) – total phytoplankton



Long-term phytoplankton biomass pattern
2004-2005 *Ceratium* decline
2006 *Dactyliosolen* bloom
marked decline in 2007, low since

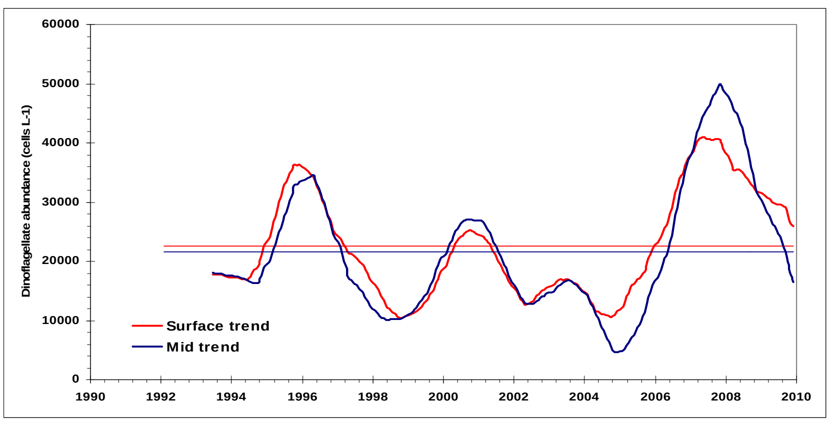
27

Biomass (carbon per liter) - diatoms

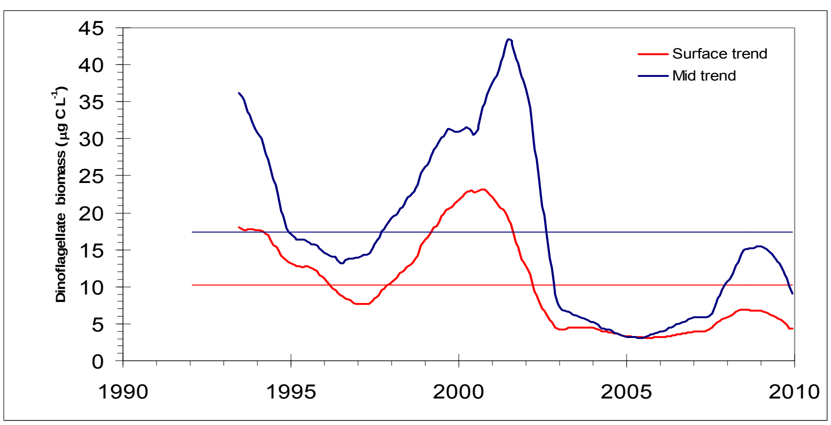


Long-term phytoplankton biomass pattern
2006 *Dactyliosolen* bloom
marked decline in 2007, low since

28



Dinoflagellate abundance



Dinoflagellate biomass

-these abundance and biomass patterns diverge due to changes in species composition.

Phytoplankton Biomass and Abundance Summary

29

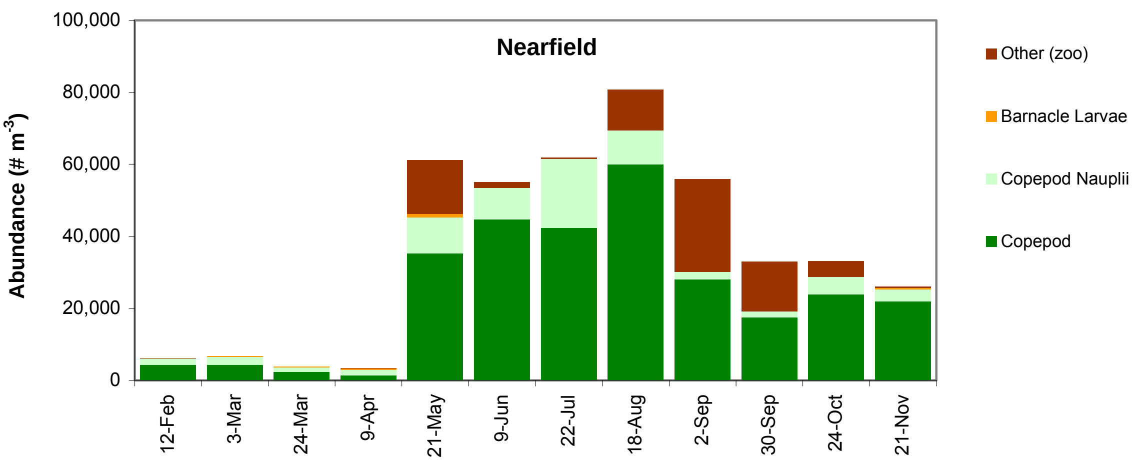
- Larger diatoms, but smaller dinoflagellates and total phytplankton.
  - Smaller total phytoplankton, diatoms, and dinoflagellates.
- Fewer diatoms, more dinoflagellates.
- Decline in biomass of total phytoplankton dinoflagellates. Increase in diatom biomass.
- Dinoflagellate changes complex and reflect community composition changes
  - Abundance increased (+80%); Biomass declined (-70%)

Table: Phytoplankton abundance changes in recent years (2005 – 2009) compared to 1992-2004. Comparisons made using Mann-Whitney test. Surface nearfield observations used; typically n = 182 (1992-2004) and n = 60 (2005-2009).

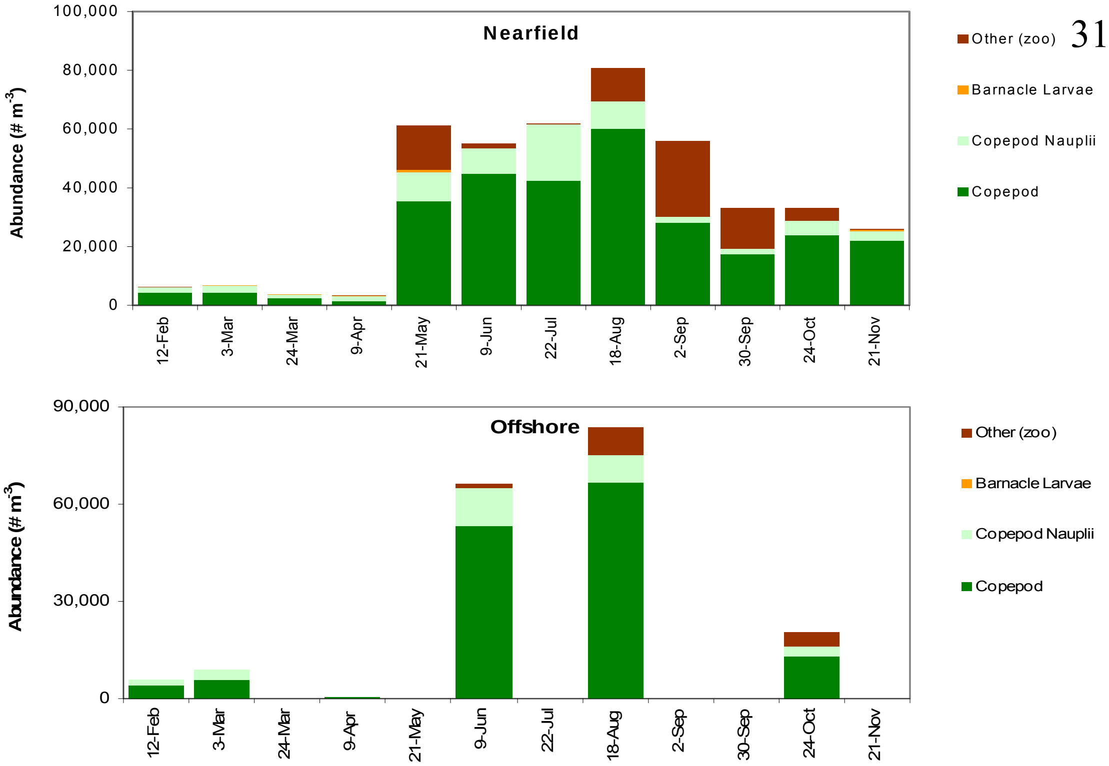
	1992 - 2004	2005 - 2009	change	P value
Biomass (µg C L^{-1})				
Total phytoplankton	95	73	- 22	0.0023
Diatoms	57	43	- 14	0.0008
Dinoflagellates	14	4	- 10	0.0040
Abundance (cells L^{-1})				
Total phytoplankton	1.384×10^6	1.334×10^6		0.6699
Diatoms	273,600	167,300	- 106,300	< 0.0001
Dinoflagellates	18,700	34,000	15,300	0.0297
Cell Carbon (pg C $cell^{-1}$)				
Total phytoplankton	67	41	- 26	<0.0001
Diatoms	268	435	167	0.0003
Dinoflagellates	1,812	570	- 1,242	<0.0001

2009 Zooplankton

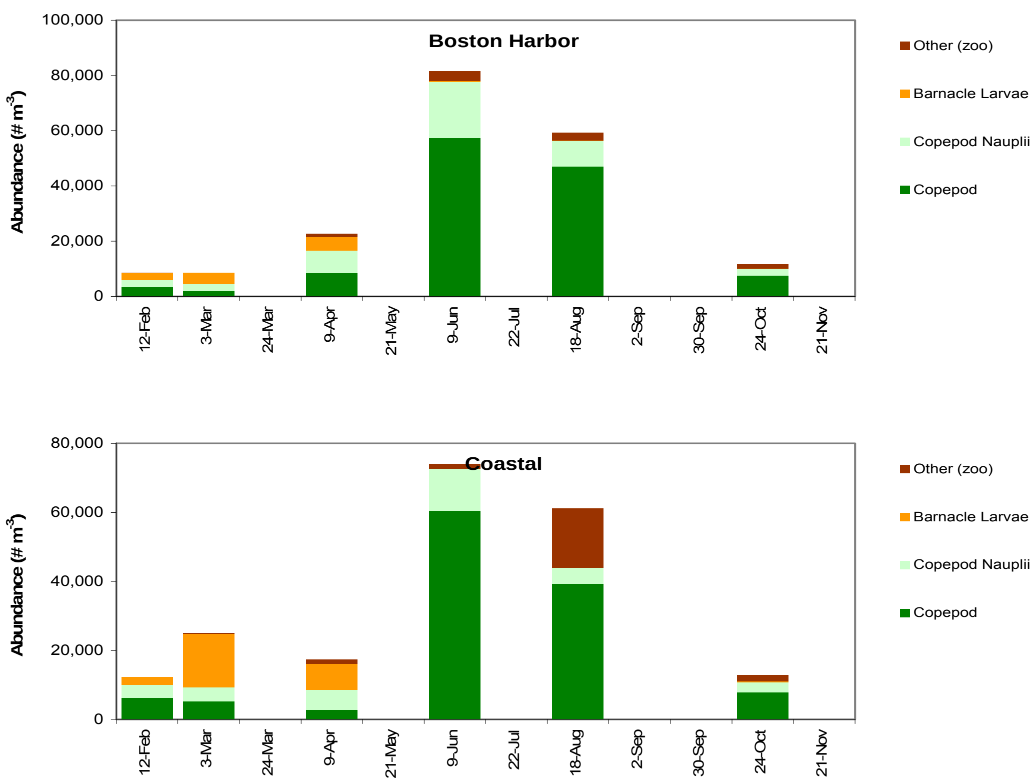
30

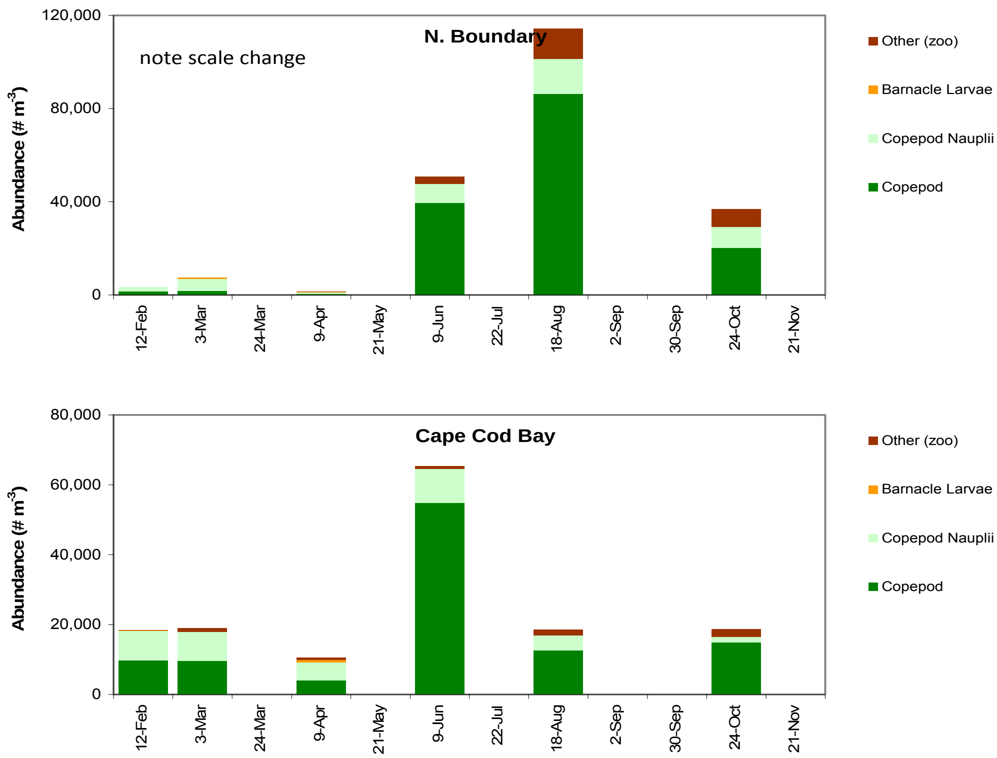


31

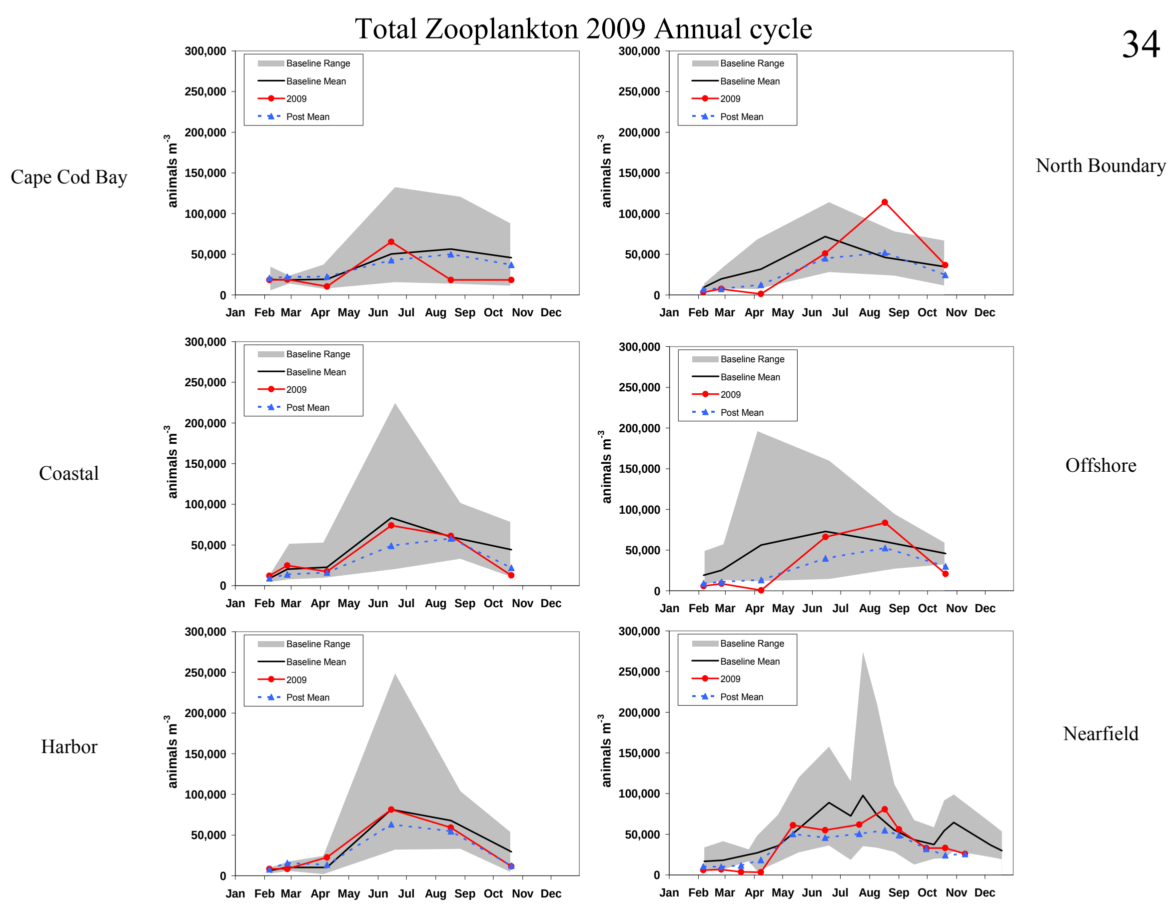

Nearfield
Abundance (# m^{-3})
100,000
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod
Offshore
Abundance (# m^{-3})
90,000
60,000
30,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod

32


Boston Harbor
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
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

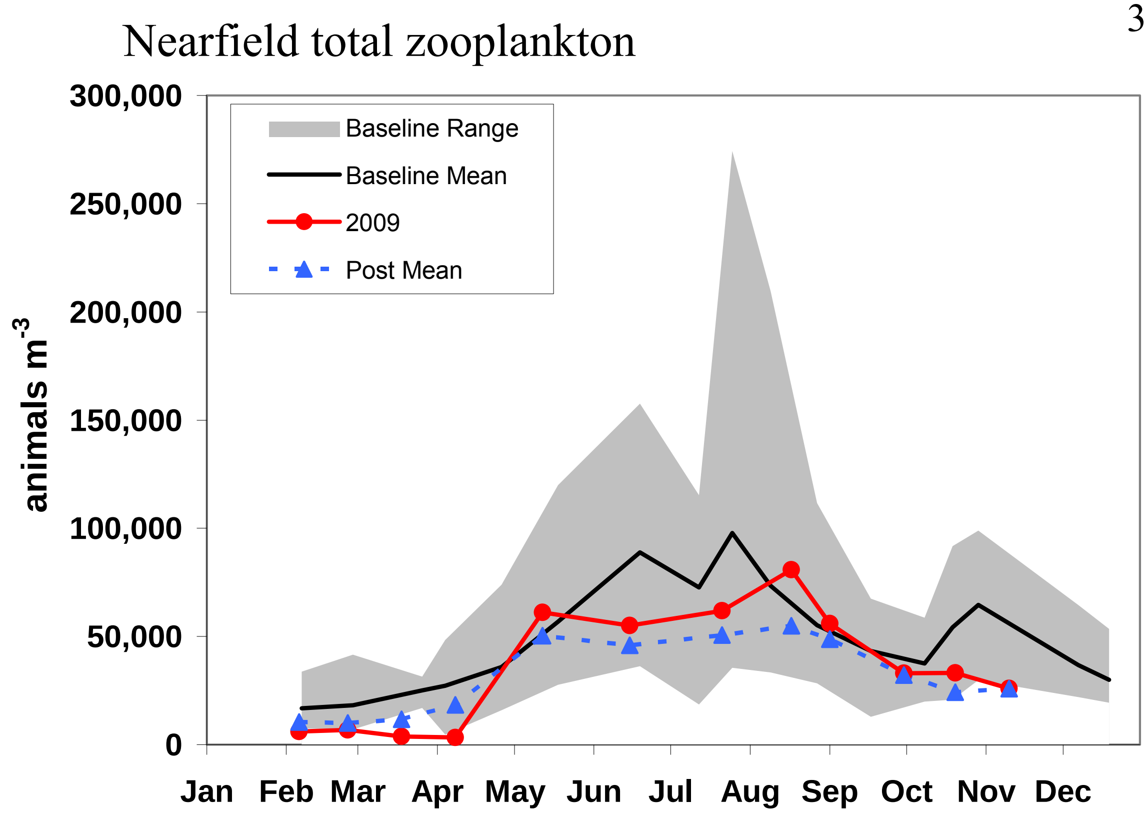

N. Boundary
note scale change
Abundance (# m-3)
120,000
80,000
40,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod
Cape Cod Bay
Abundance (# m-3)
80,000
60,000
40,000
20,000
0
12-Feb
3-Mar
24-Mar
9-Apr
21-May
9-Jun
22-Jul
18-Aug
2-Sep
30-Sep
24-Oct
21-Nov
Other (zoo)
Barnacle Larvae
Copepod Nauplii
Copepod

33

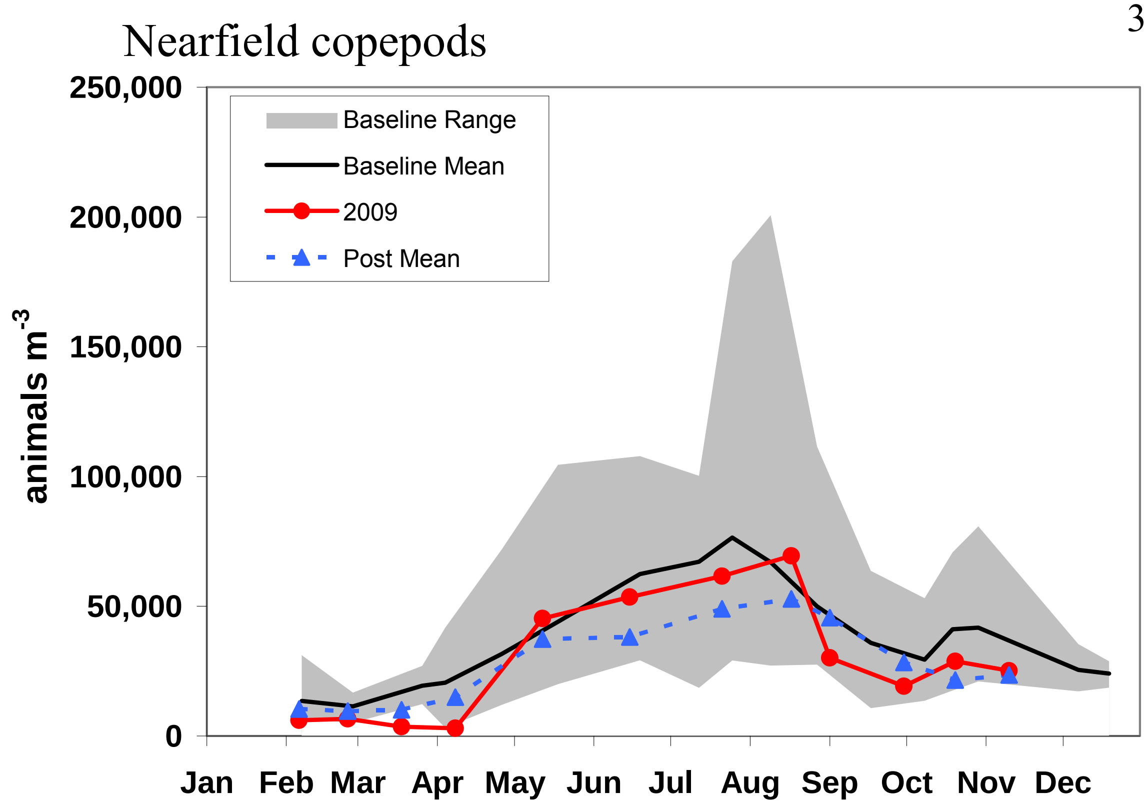

Total Zooplankton 2009 Annual cycle
Cape Cod Bay
North Boundary
Coastal
Offshore
Harbor
Nearfield
animals m-3
300,000
250,000
200,000
150,000
100,000
50,000
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Baseline Range
Baseline Mean
2009
Post Mean

34

35

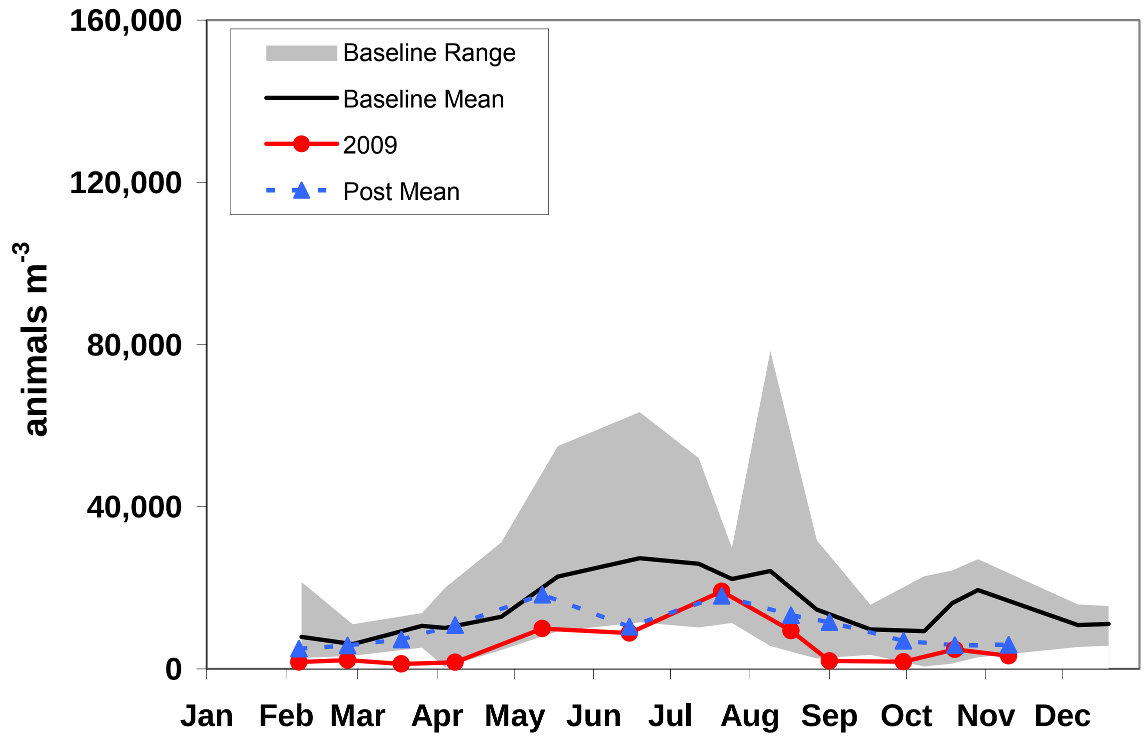

Nearfield total zooplankton
300,000
250,000
200,000
150,000
100,000
50,000
0
animals m-3
Baseline Range
Baseline Mean
2009
Post Mean
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

36


Nearfield copepods
250,000
200,000
150,000
100,000
50,000
0
animals m-3
Baseline Range
Baseline Mean
2009
Post Mean
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

37

Nearfield copepod nauplii



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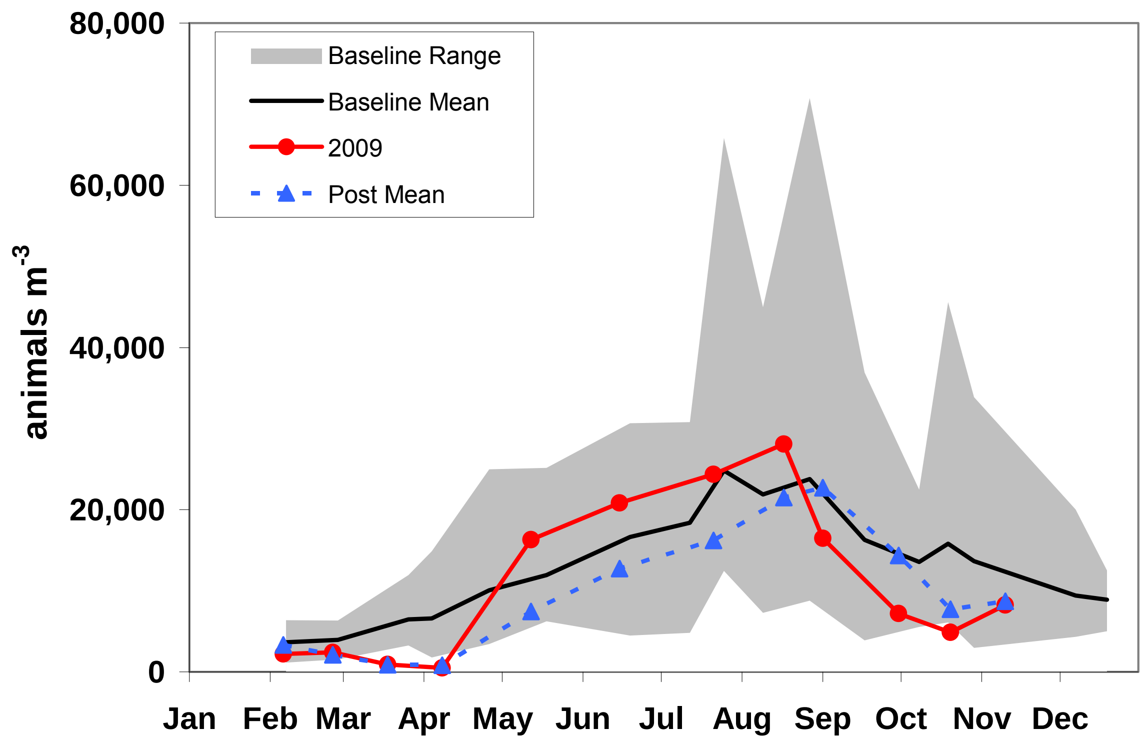
Nearfield *Oithona spp.* total



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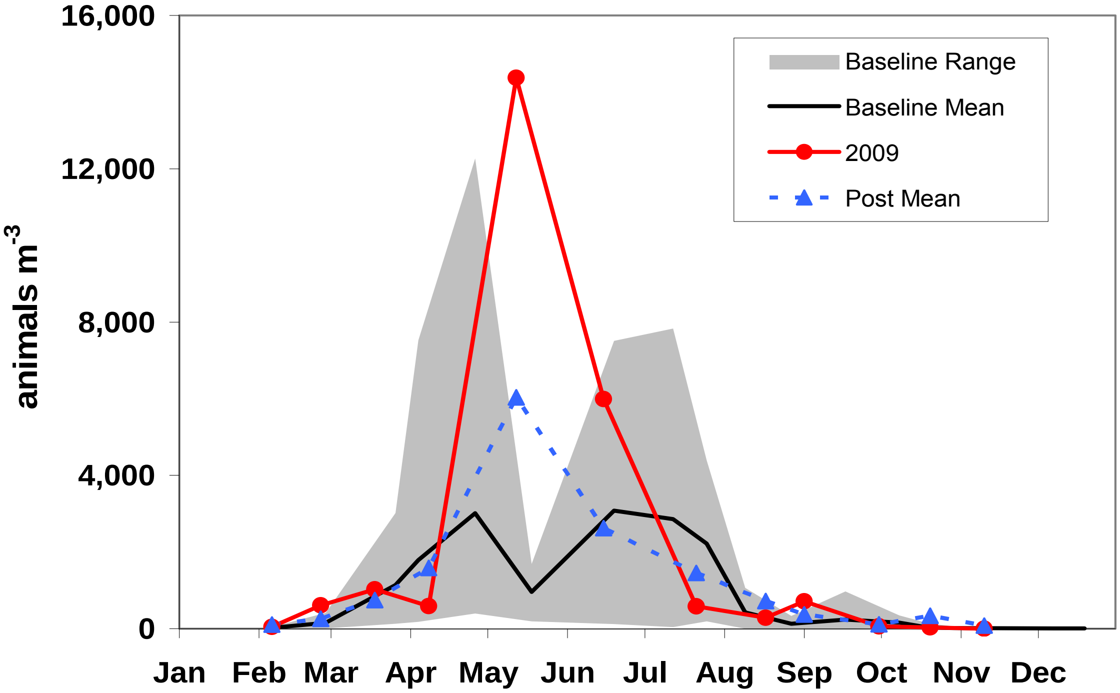
Nearfield *Calanus finmarchicus*



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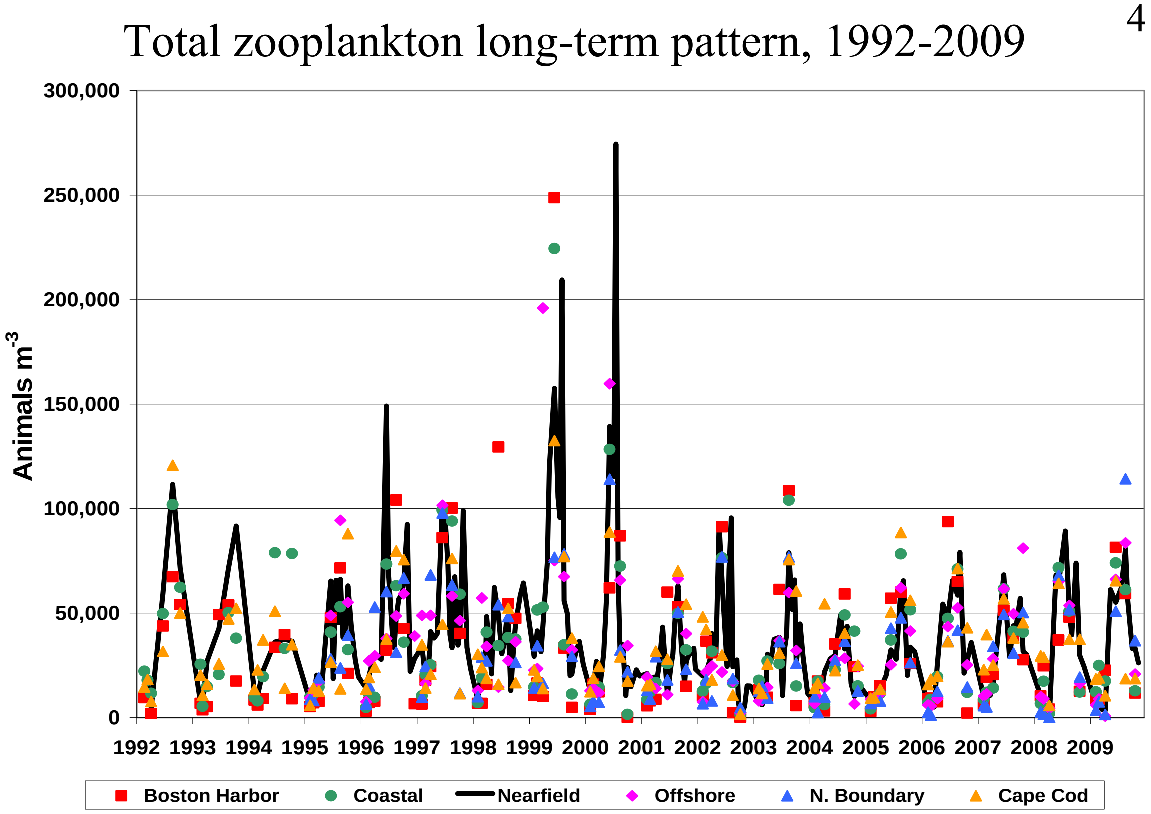
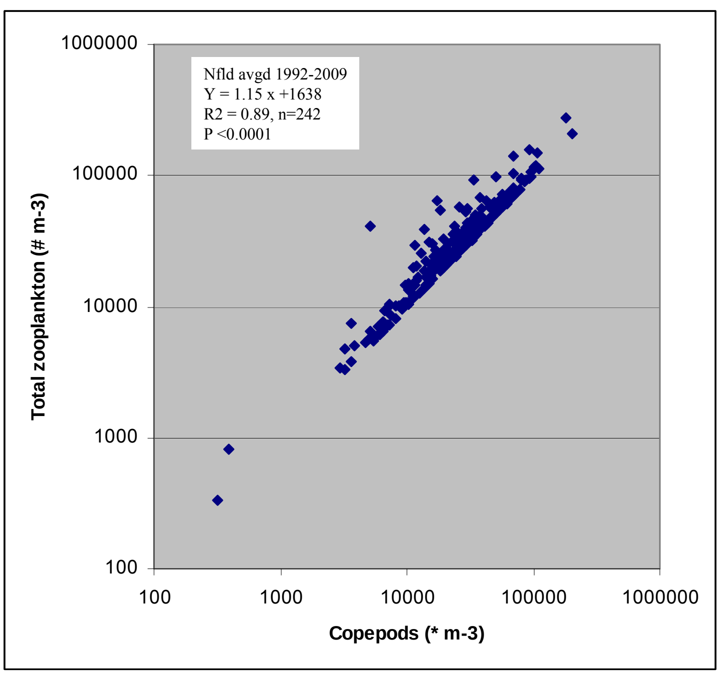
2009 Zooplankton Annual Pattern

- Regional
  - Generally regionally coherent
  - Elevated Spring barnacle abundance in Harbor and Coastal regions
  - Elevated (ca. 2X mean) copepod abundance North Boundary during August
- 2009 Zooplankton Annual Cycle
  - June zooplankton peak in Cape Cod, Coastal and Harbor regions
  - *Oithona* abundance reduced March and April; above baseline May-August
  - August zooplankton peak in North Boundary and Offshore regions
  - Increased total zooplankton led by increased *Oithona* abundance
  - *Calanus finnmarchicus*
    - Elevated May abundance (14,000 m^{-3}; 2^{nd} greatest Nearfield avg)
    - Shift from bimodal (April and July peaks) to unimodal (May peak)?

41



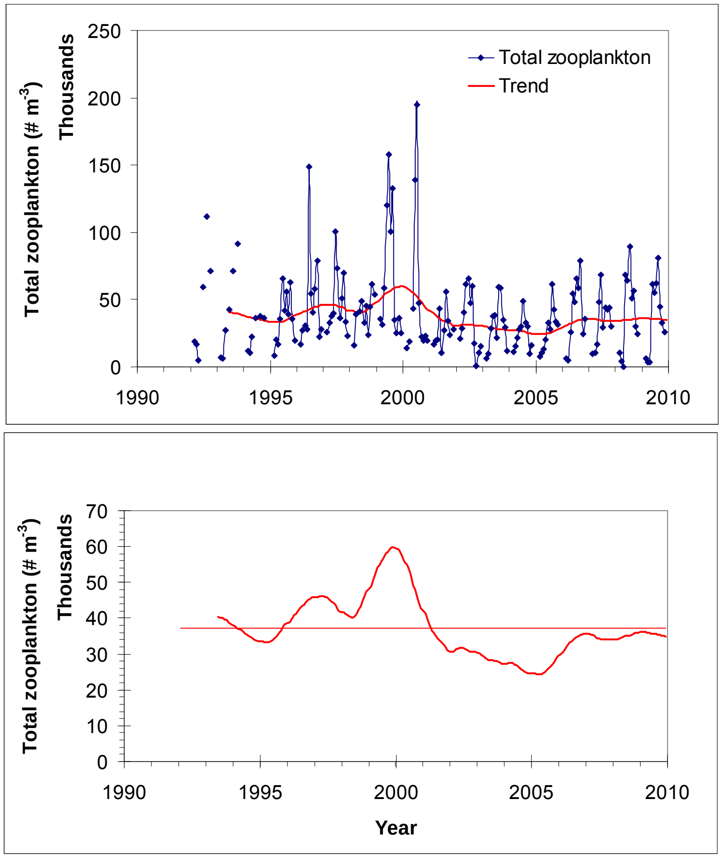
42



- Copepods comprise ca. 90% of total zooplankton abundance

-*Oithona* comprises ca. 33% of copepod abundance

-Examine long-term trends in Nearfield
  - Total Zooplankton
  - Copepods
  - *Oithona spp.*
  - *Calanus finmarchicus*



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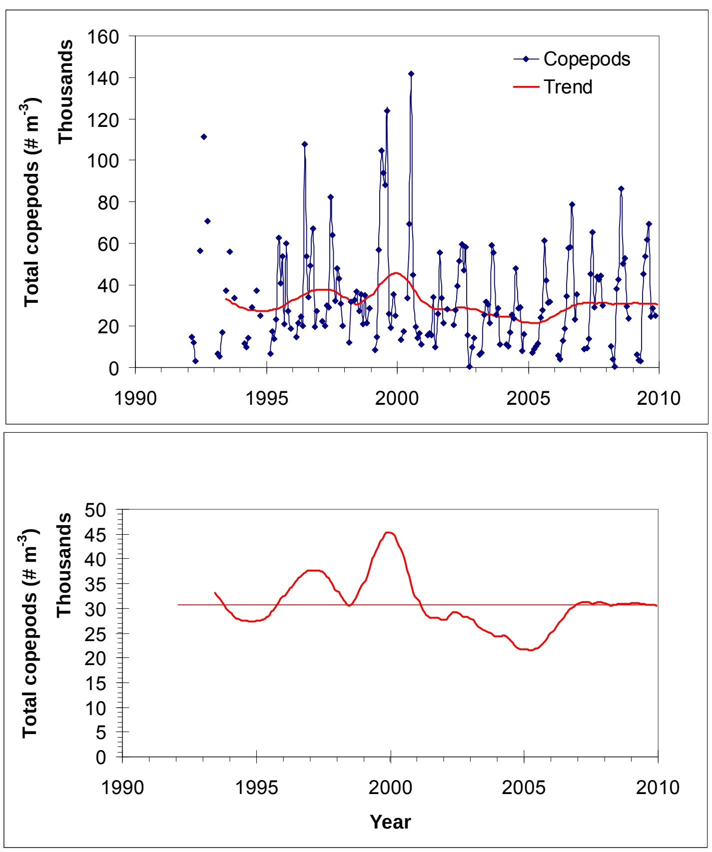
Total zooplankton

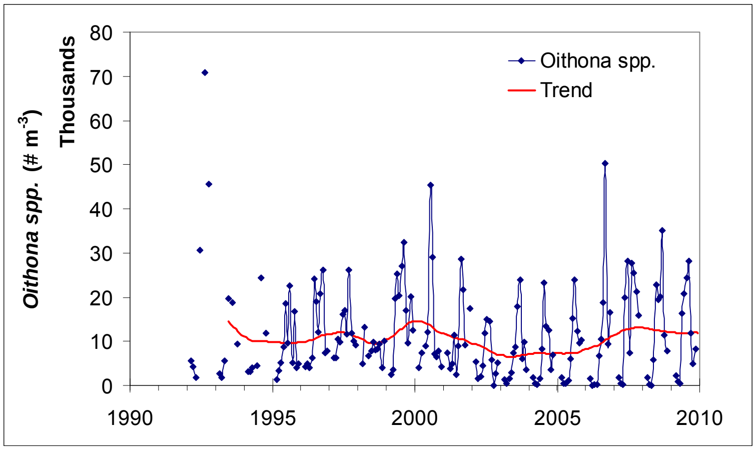
- return to near mean levels 2006-2009

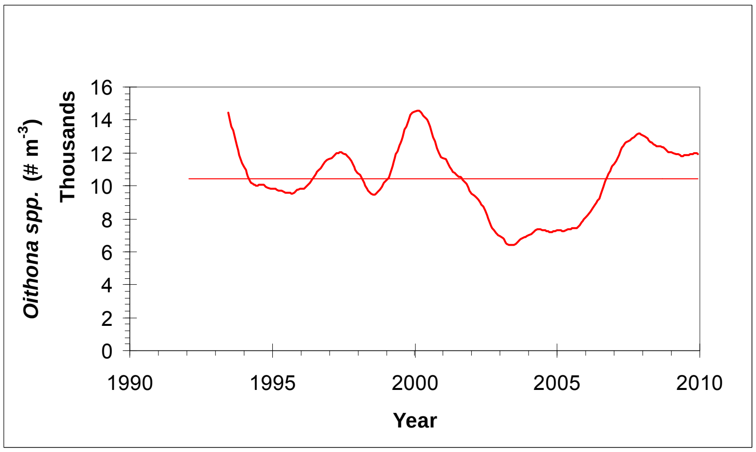


44

Total copepods

- return to near mean levels 2006-2009





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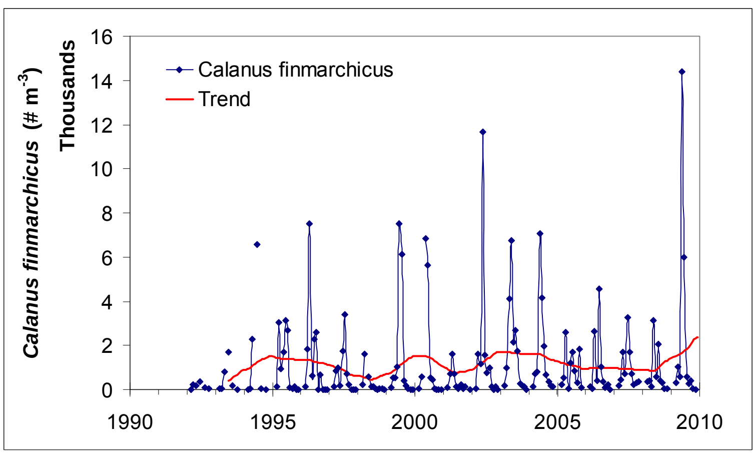
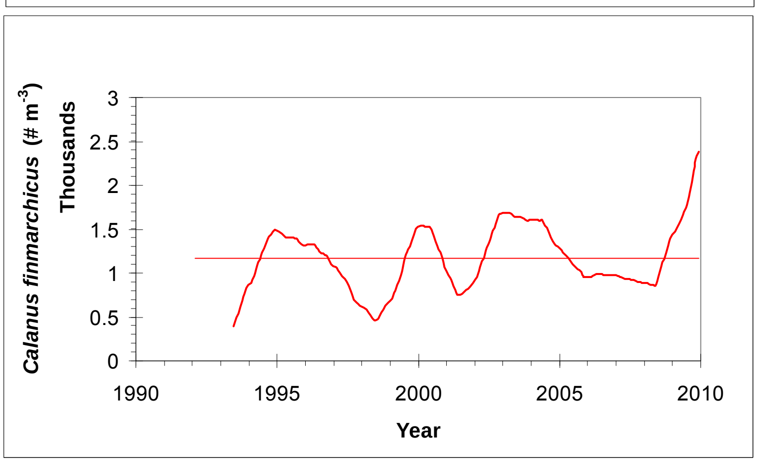
Oithona

- above mean levels 2006-2009





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Calanus finmarchicus

- increase to above mean levels 2008 -2009

D. *Alexandrium* Bloom

The 2009 *Alexandrium* bloom and the forecast for 2010
Don Anderson, Woods Hole Oceanographic Institution
Scott Libby, Battelle

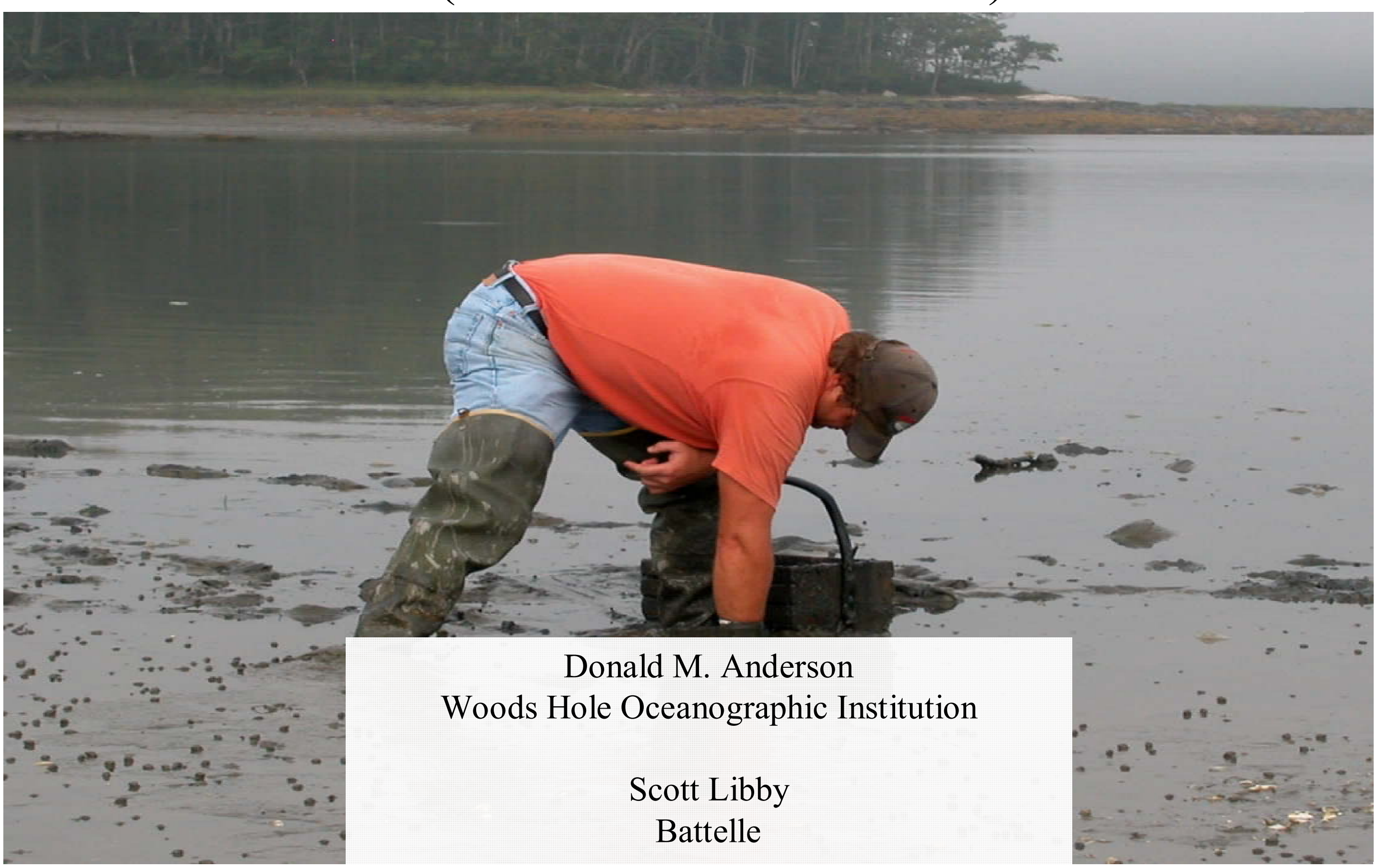
In 2009 there was a moderate regional red tide in Massachusetts, with toxicity in Mass Bay and Boston Harbor. This was consistent with predictions based on last year's data.

More noteworthy was a severe red tide in Maine – the worst in many years.

Cysts were very abundant later in the year, and closer than usual to Massachusetts Bay. Their later germination may cause a severe bloom in 2010.

1

The 2009 red tide bloom in Massachusetts Bay
(and the forecast for 2010)



2

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
  - MWRA has conducted *Alexandrium* focused sampling the last five years, often in conjunction with efforts of WHOI/GOMTOX and PCCS
- So what happened in 2009?
  - A moderate regional red tide in Massachusetts, with toxicity in Mass Bay and Boston Harbor
  - A severe red tide in Maine –the worst in many years.

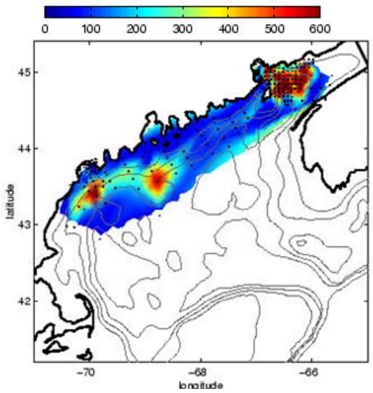
3

The 2009 forecast

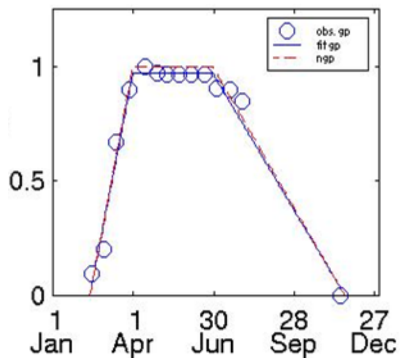
Alexandrium Population Dynamics Model

4

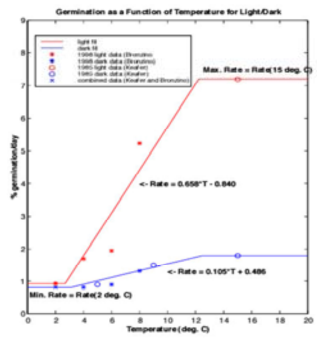
Cyst Dist. (# / cm^2)



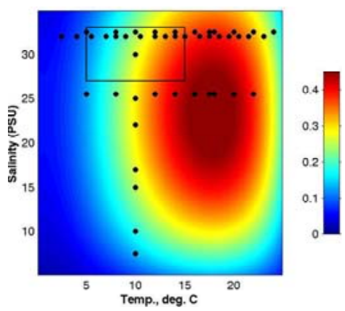
Endogenous Clock



Germ. rate (% / day)



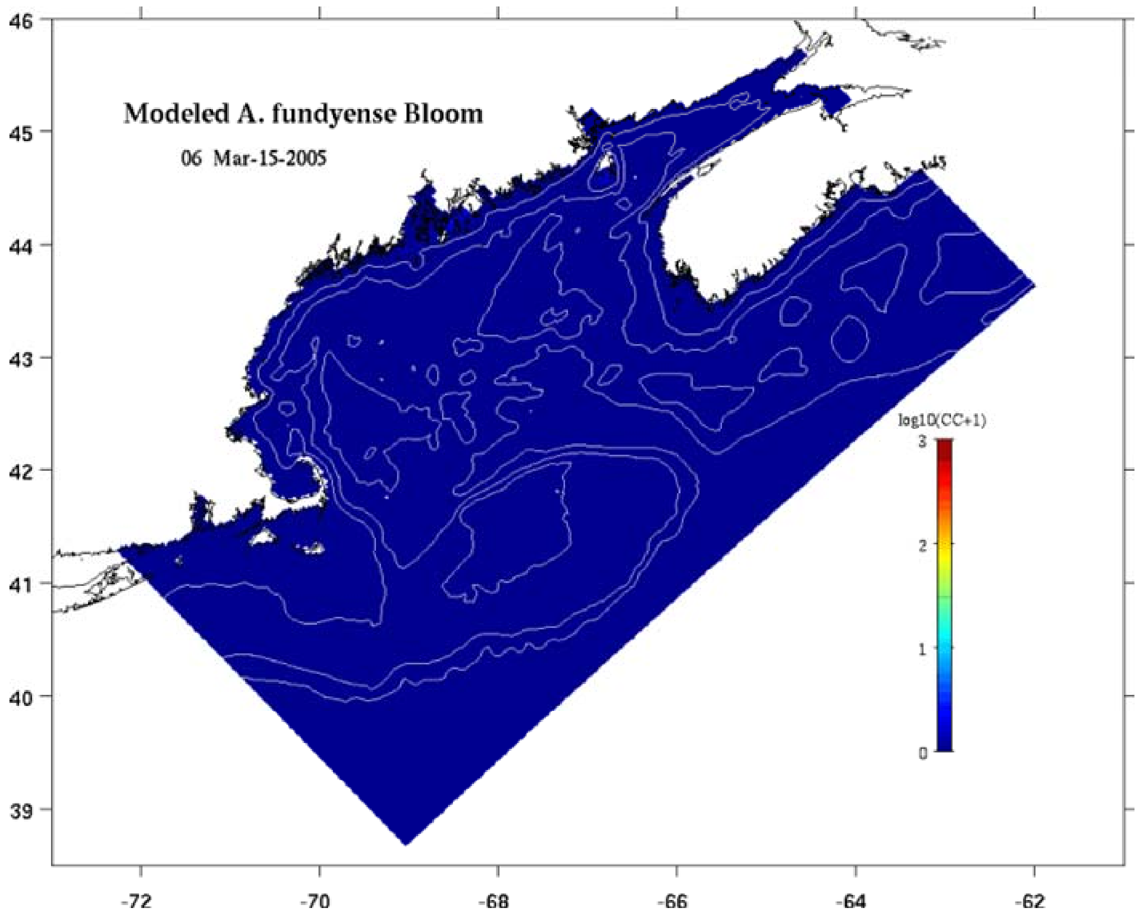
Growth (per day)



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

Upward swimming 10 m/day

"Mortality" = 0.1 per day, with a temperature dependence



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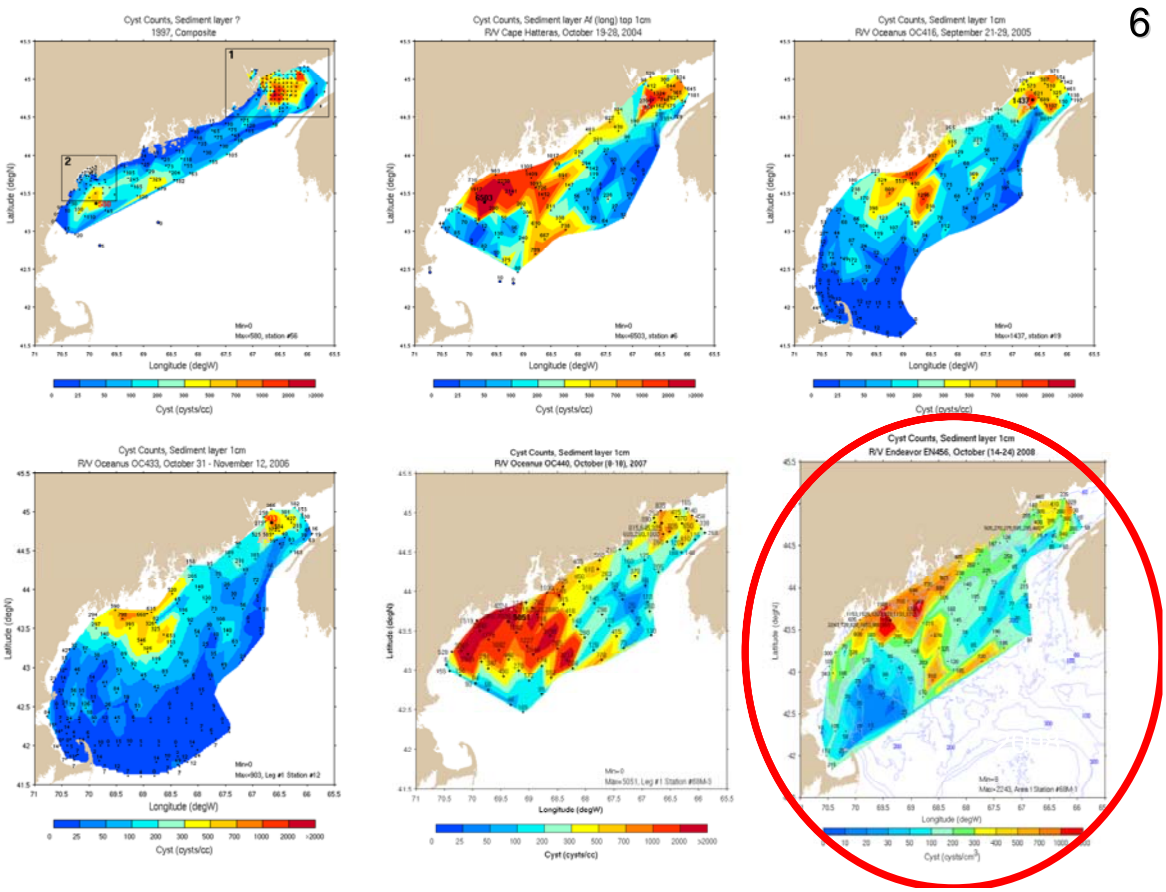


6

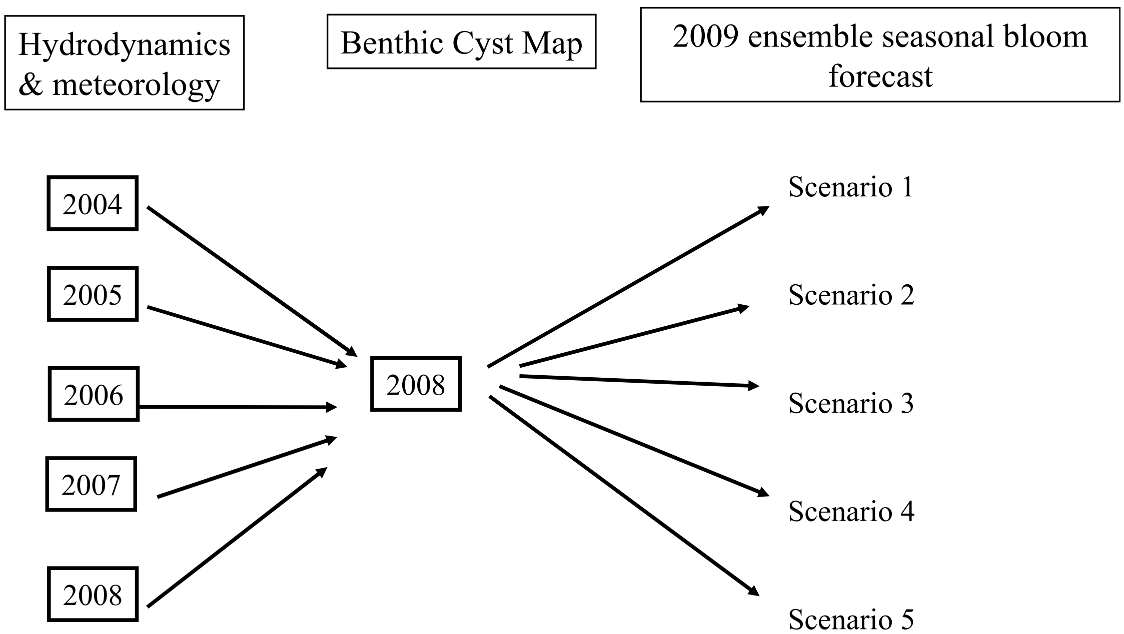
7

Total cyst abundances (# of cysts x 10^{16}) and % change relative to 1997 for the Gulf of Maine (GOM) and Bay of Fundy (BOF) subdomains

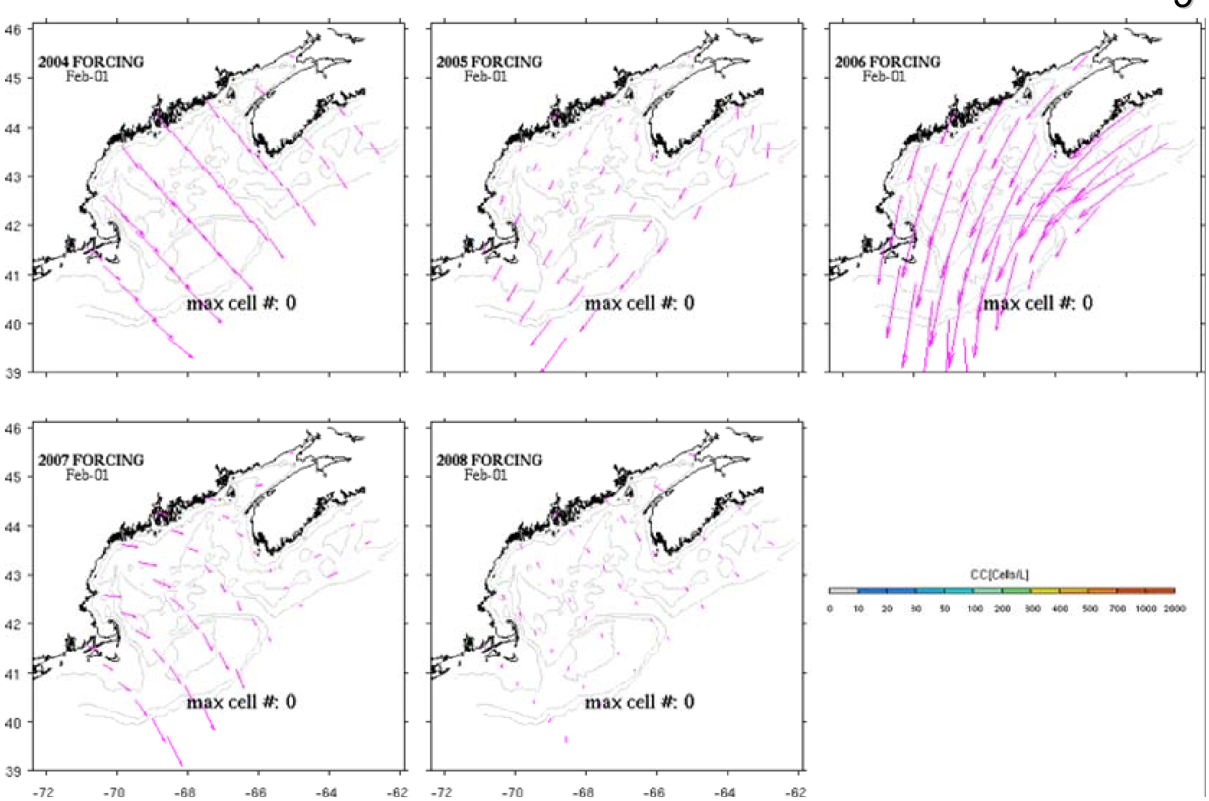
Year	GOM	% change GOM	BOF	% change BOF	Total (GOM + BOF)
1997 domain comparison (top 1 cm)					
1997	2.5	100	2.8	100	5.3
2004	21.6	878	6.7	235	28.3
2005	9.9	404	3.7	130	13.6
2006	7.8	317	2.4	82	10.2
2007	28.2	1147	4.0	140	32.2
2008	11.8	478	2.1	75	13.9
1997 domain comparison (1-3 cm)					
1997	4.4	100	1.0	100	5.4
2004	20.4	461	5.5	576	25.9
2005	41.2	931	20.0	2100	61.2
2006	15.4	348	6.7	703	22.1
2007	21.5	486	5.2	548	26.7
2008	17.2	389	4.2	442	21.4
1997 domain comparison (0-3 cm)					
1997	6.88	100	3.8	100	10.7
2004	42.0	610	12.2	321	54.1
2005	52.1	757	23.7	624	74.8
2006	23.2	337	9.1	240	32.3
2007	49.7	722	9.2	243	58.9
2008	29.0	421	6.3	167	35.3

3.38 x 10 ^14 cm^2 **BOF area = 0.95 x 10^14 cm^2**

8


Hydrodynamics & meteorology
Benthic Cyst Map
2009 ensemble seasonal bloom forecast
2004
2005
2006
2007
2008
2008
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5

9


2004 FORCING
Feb-01
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2007 FORCING
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2008 FORCING
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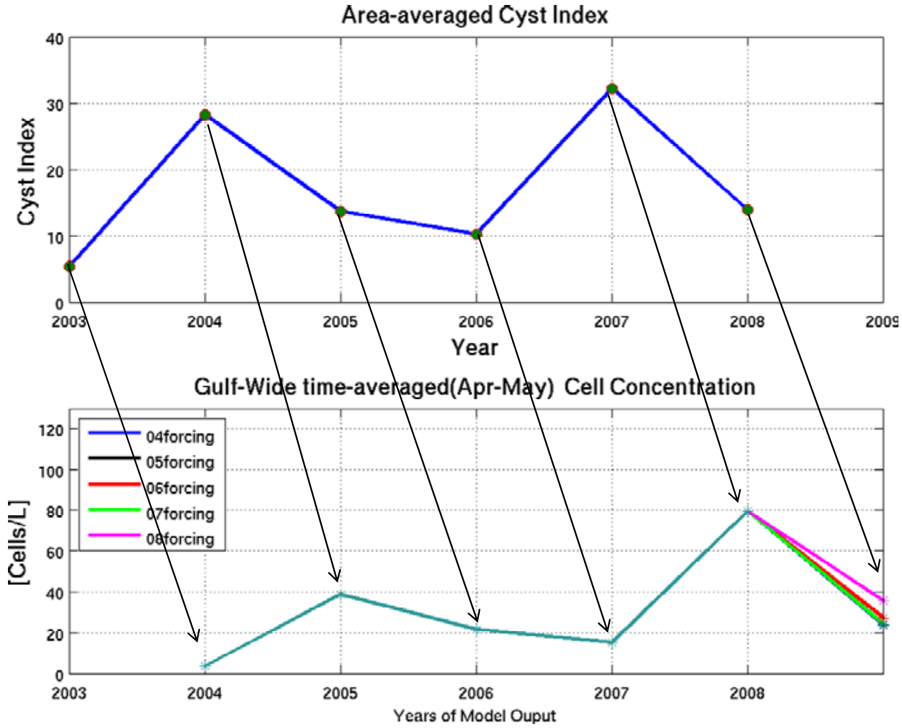
CC[Cells/L]
0 10 20 30 50 100 200 300 400 500 700 1000 2000

10

Impact of cyst abundance on the next year's bloom



News release: Potential for 'moderately large' red tide in 2009

11


News Release : Researchers Report Potential for 'Moderately Large' Red Tide Outbreak in the Gul - Windows Internet Explorer

http://www.whoi.edu/page.do?pid=7545&tid=282&cid=56567&ct=162

Woods Hole Oceanographic Institution

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News Release : Researchers Report Potential for 'Moderately Large' Red Tide Outbreak in the Gulf of Maine Region for 2009

Toxic bloom expected to be smaller than last year, but still significant

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

April 22, 2009
Media Relations Office
93 Water Street MS #16
Woods Hole Oceanographic Institution

April 22, 2009
Source: Media Relations

The potential for an outbreak of the phenomenon commonly called "red tide" is expected to be "moderately large" this spring and summer, according to researchers with the Woods Hole Oceanographic Institution (WHOI) and North Carolina State University (NCSU).

This advisory is based in part on a regional seafloor survey of quantities of *Alexandrium fundyense* — the algae 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. The survey maps are used with computer models that simulate different scenarios of weather and oceanographic conditions to indicate where and in what abundance the toxic cells might be expected in 2009.

The researchers found concentrations of *Alexandrium* cysts — the dormant seed-like stage of the algae's life cycle — in the Gulf of Maine to be 40 percent lower than the historically high levels observed prior to last year's bloom, but still higher than the level preceding a major regional bloom in spring 2006 that closed shellfish beds from Canada to Massachusetts Bay.

Enlarge Image

CYST CONCENTRATIONS - Maps of the Gulf of Maine reveal the concentration of *Alexandrium* cysts buried in seafloor sediments, as detected by WHOI-led surveys in the fall of 1997, 2004, 2005, 2006, 2007, and 2008. The cyst distribution maps

The 2009 *Alexandrium fundyense* bloom

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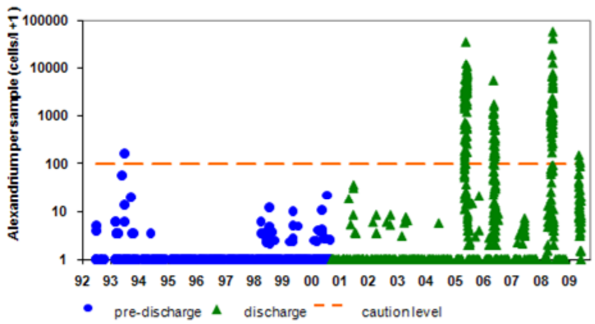
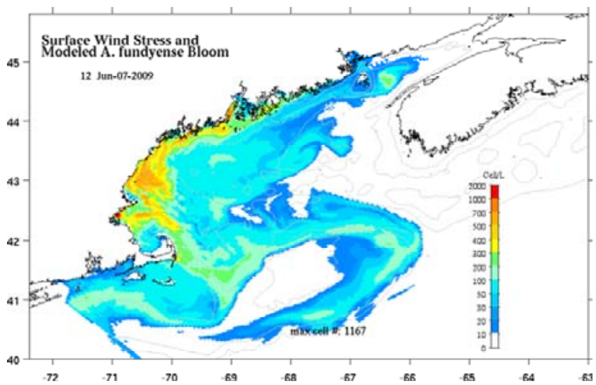
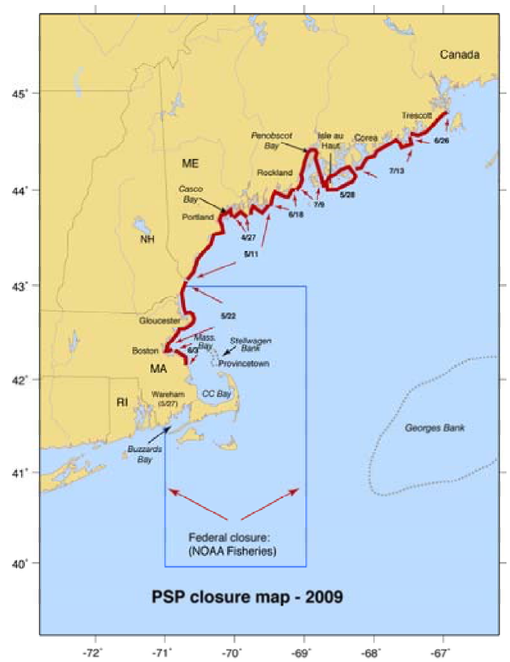
- This shows that the prediction was correct. The closures were moderate across most of Massachusetts Bay, but not down into CCB similar to 2006; and the abundances were lower than 2006 higher than 2007







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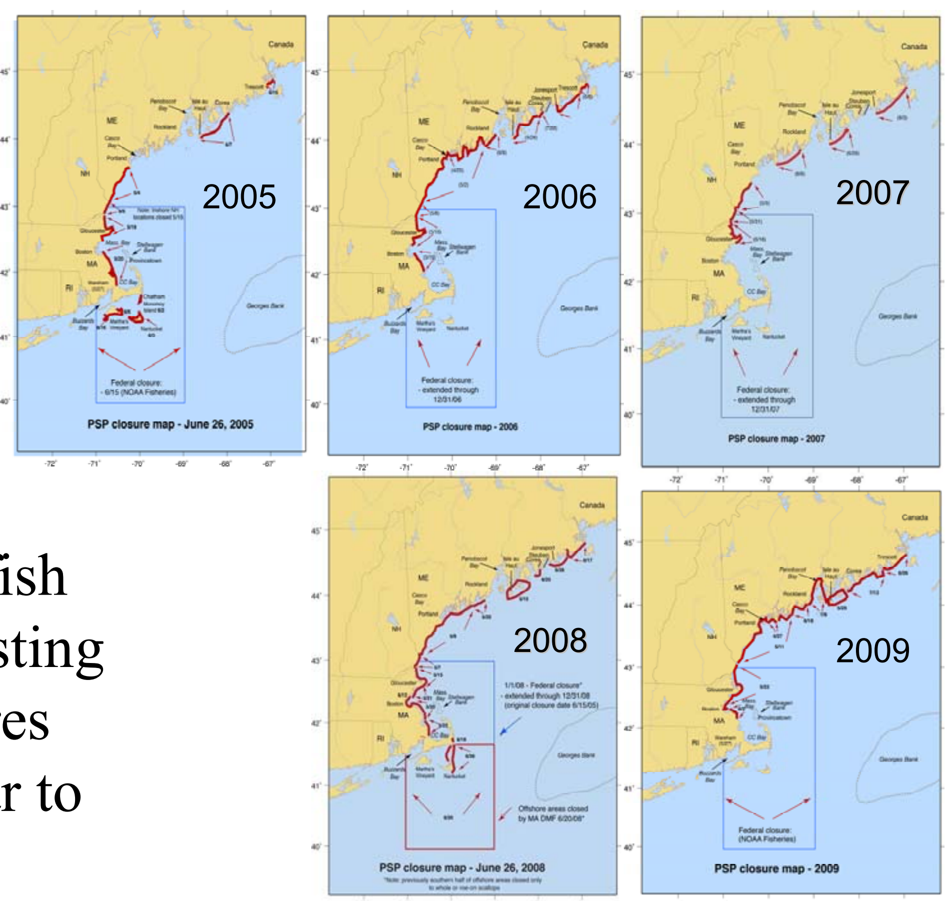

Shellfish harvesting closures similar to 2006

14

2009 *Alexandrium* chronology

- March 24 – WHOI releases 2008 cyst data and predicts "moderately large" red tide event for 2009 – comparable to 2006
- April 17 – Nauset system PSP toxicity closure
- Late April - early May PSP toxicity observed in Maine and NH
- May 7 – High PSP approaching closure levels at Star Island, NH
- May 12th MWRA sampled for *Alexandrium* on regular nearfield survey (150 cells/L at N18)
- MWRA conducted three ARRS surveys and a harbor survey over the following 4 weeks
  - Abundances reached a maximum of 356 cells/L in late May – coincident with highest PSP toxicity
  - Bloom ended by June 8th survey

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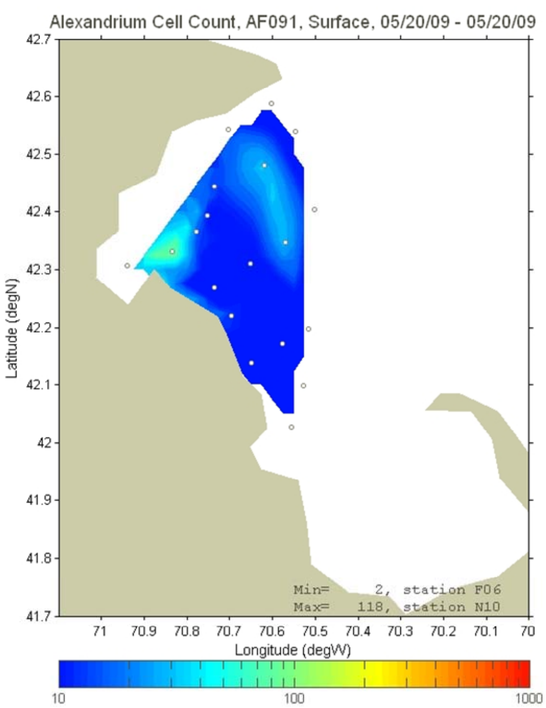
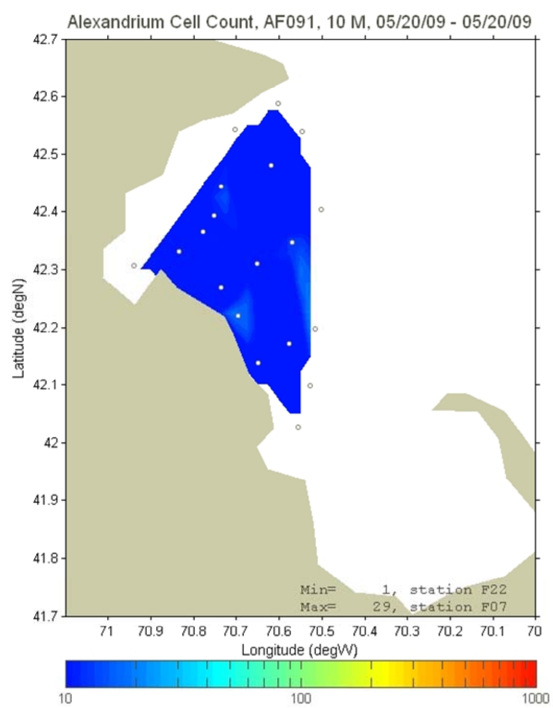
May 20, 2009





May 29, 2009

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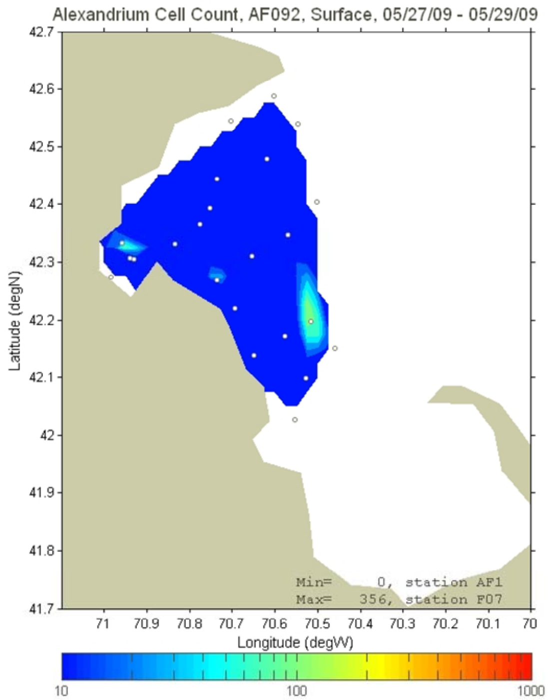
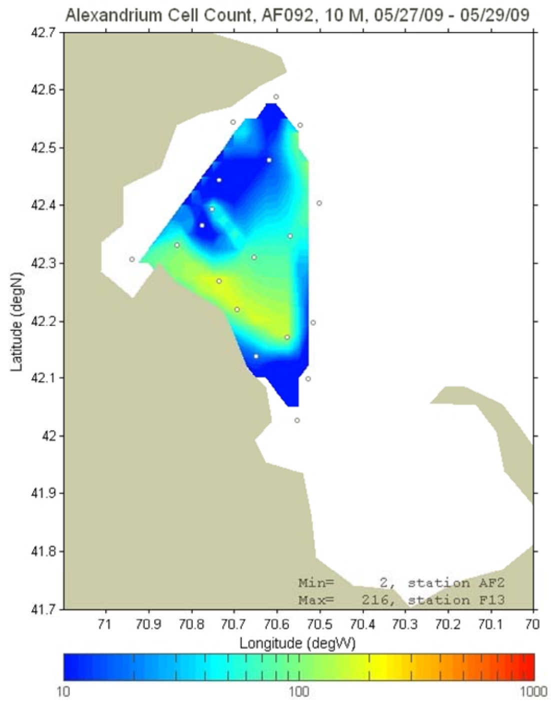
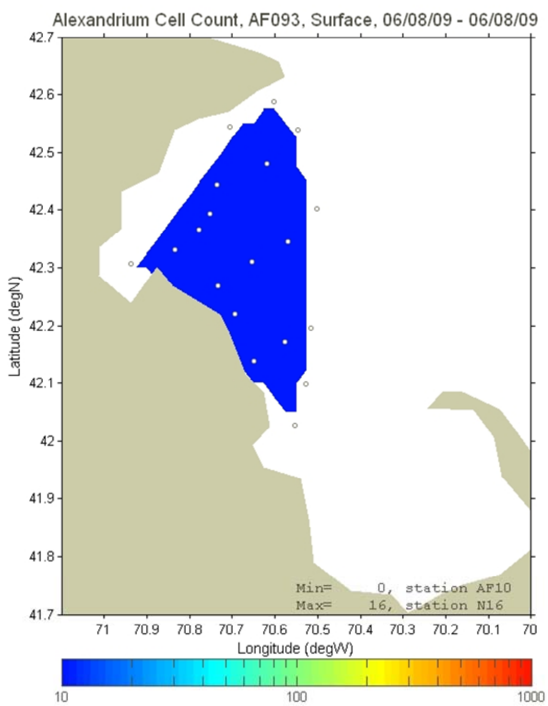
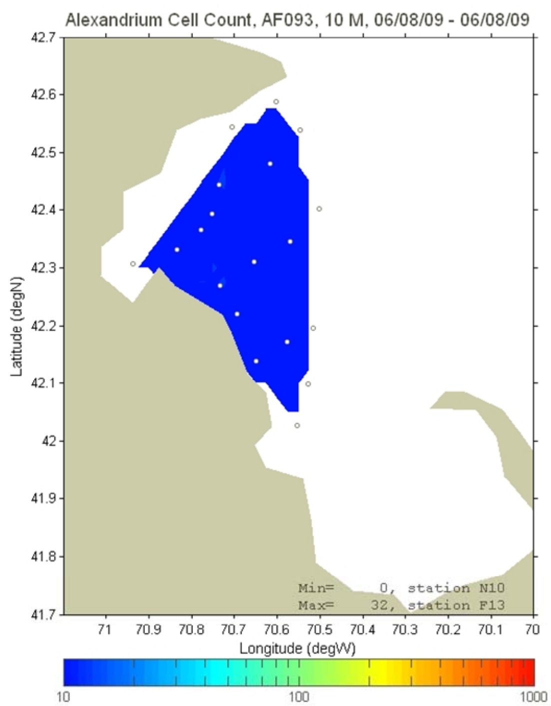




June 8, 2009 – bloom over

17





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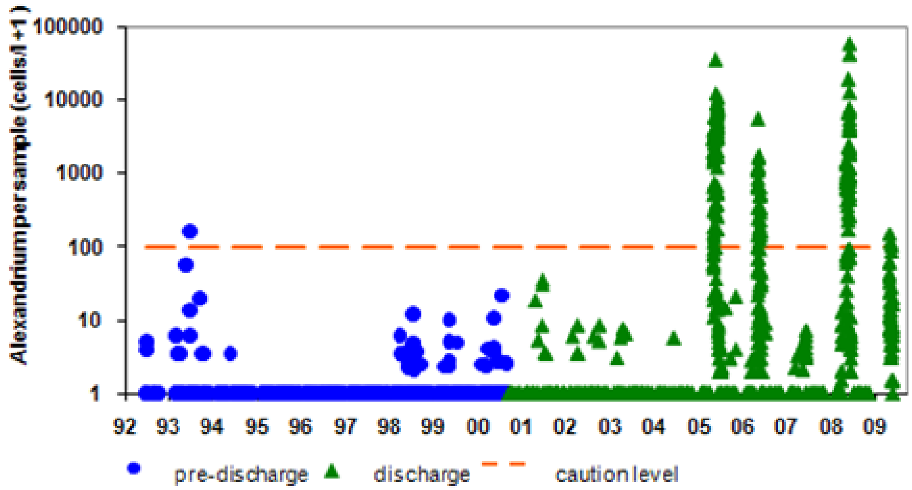
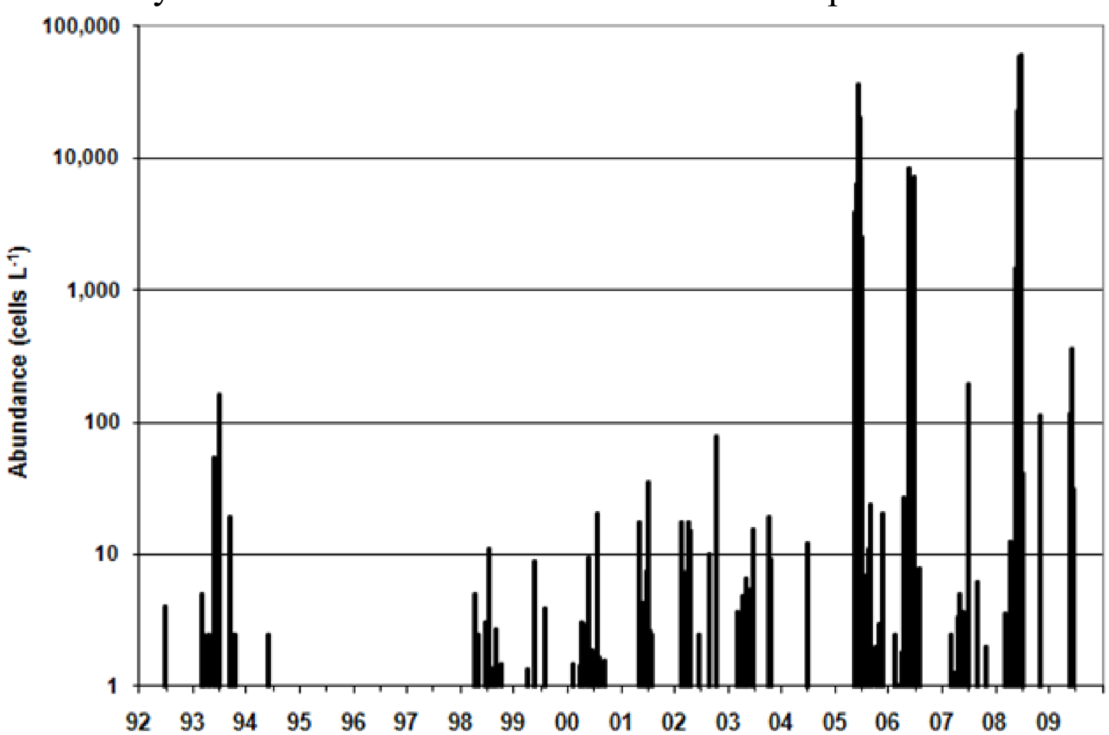
Alexandrium abundance – MWRA nearfield area



Contingency Plan Threshold Exceedance:
>100 cells/L from May 12th to 29th (≤150 cells/L)

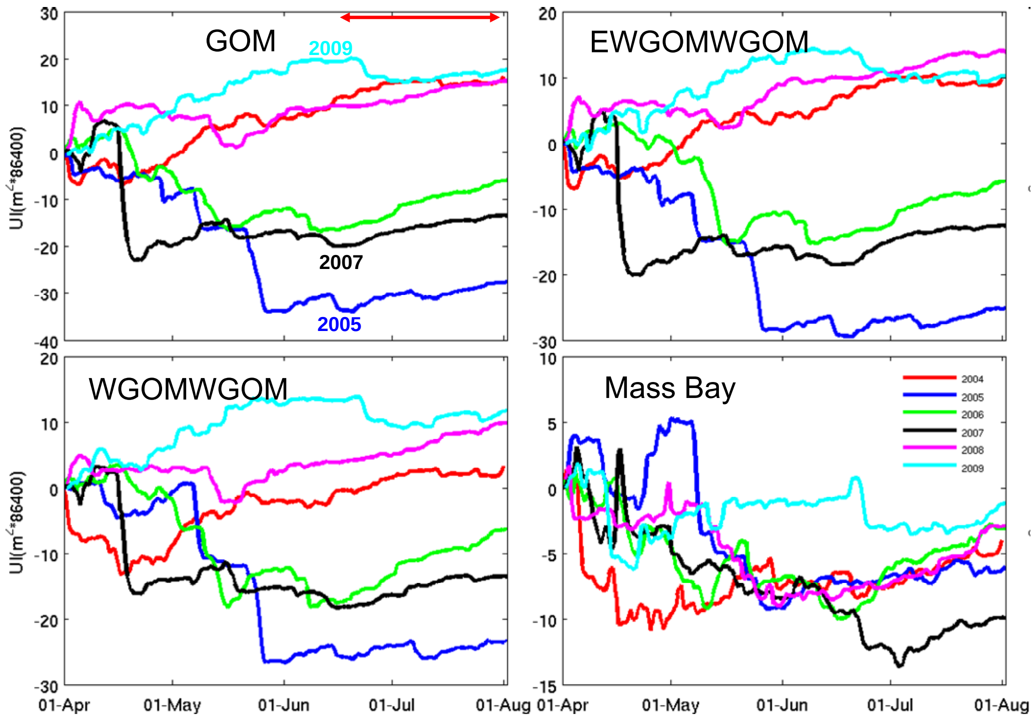
19

Baywide *Alexandrium* Abundance 2009 comparable to 2007



20

1. Overall, downwelling favorable winds in 2009 were not as strong as those in 2005 and 2007
2. Yet the cumulative index was falling during June-July period in 2009 (downwelling), but rising in all the other years (upwelling) except in Mass Bay in 2007



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Summary 2009

- *Alexandrium* population dynamics model & cyst abundance were good predictors of the magnitude of the 2009 bloom
  - This follows the 2008 bloom forecast that was the first prediction of a major regional red tide
- May/June 2009 bloom cell abundance in Mass Bay was relatively low – lower than the 2005, 2006 and 2008 blooms, comparable to 2007
- Unlike 2007 the cells that entered Massachusetts Bay resulted in PSP closures (comparable in extent to 2006)
- Early May winds transported the bloom into Massachusetts Bay, but unlike previous years, there were not subsequent storms and the bloom petered out
- Persistent northeast and east winds in June and July caused a resurgence of toxicity in eastern and western Maine

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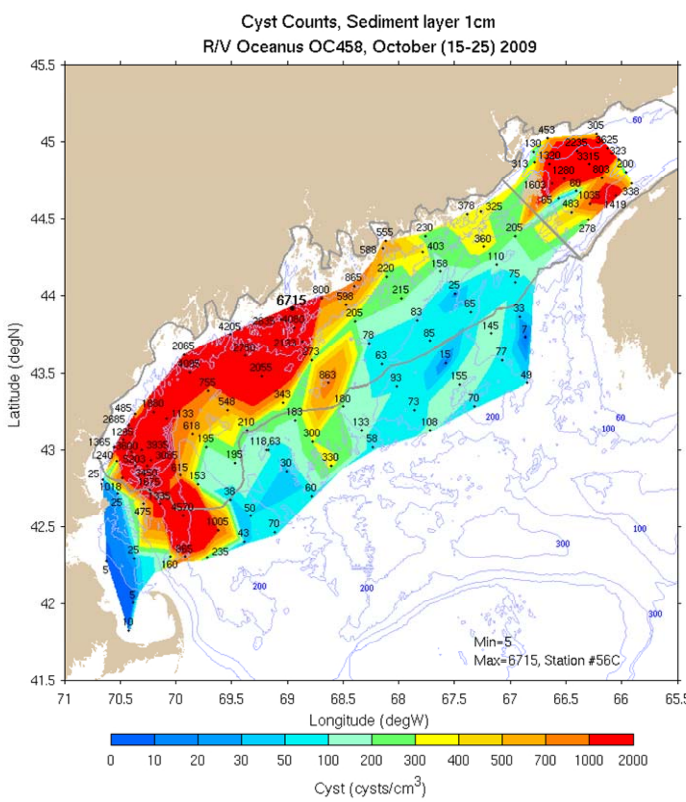
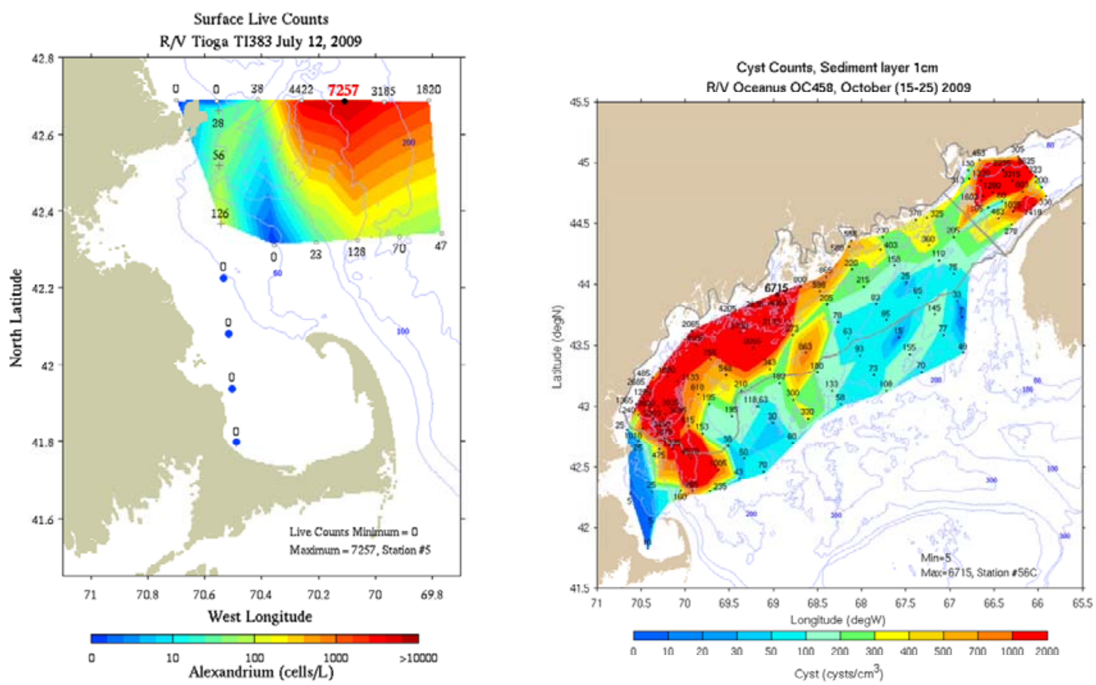
What about 2010?

23

2009 cyst abundance



Probable cause of cyst seedbed extension in western GOM – red water near Portsmouth and Cape Ann 24



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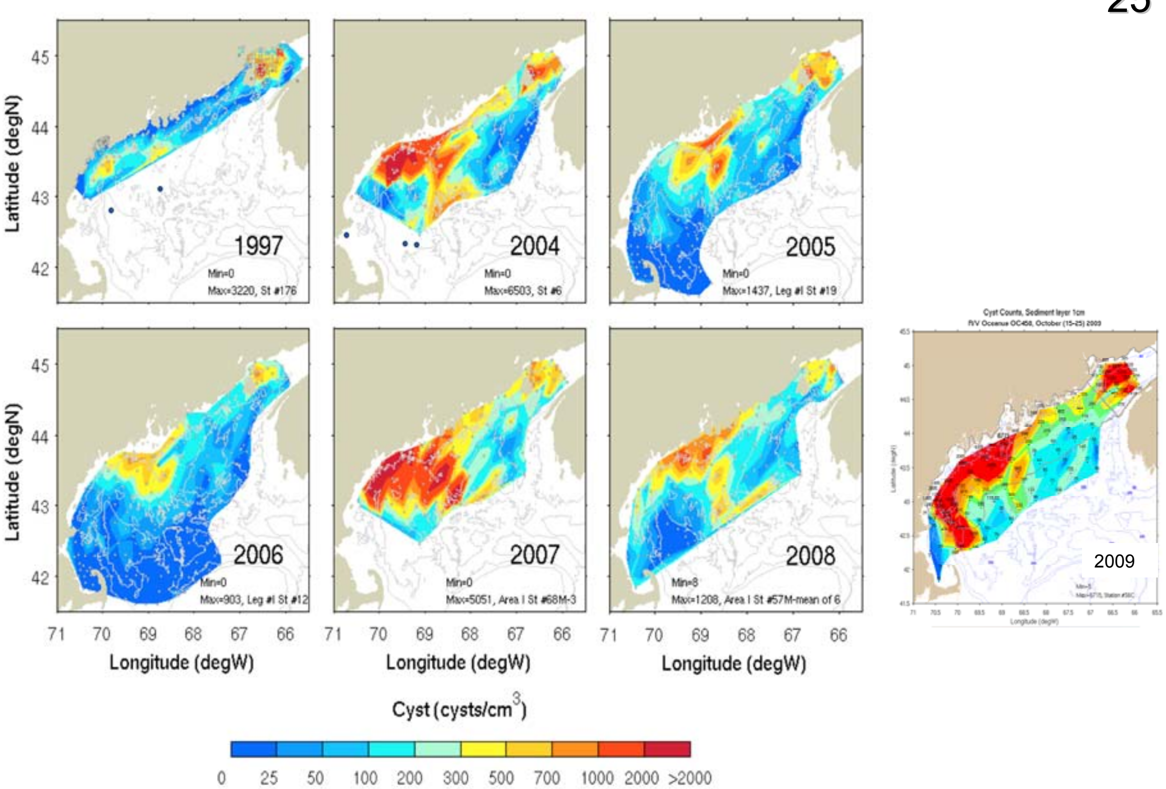

Total cyst abundances (# of cysts x 10^{16}) and % change relative to 1997 for the Western Gulf of Maine (WGOM) and Bay of Fundy (BOF) subdomains. 26

Year	GOM	% change GOM	BOF	% change BOF	Total (GOM + BOF)
1997 domain comparison (top 1 cm)					
1997	2.5	100	2.8	100	5.3
2004	21.6	878	6.7	235	28.3
2005	9.9	404	3.7	130	13.6
2006	7.8	317	2.4	82	10.2
2007	28.2	1147	4.0	140	32.2
2008	11.8	478	2.1	75	13.9
2009	35.6	1448	9.4	331	45.0
1997 domain comparison (1-3 cm)					
1997	4.4	100	1.0	100	5.4
2004	20.4	461	5.5	576	25.9
2005	41.2	931	20.0	2100	61.2
2006	15.4	348	6.7	703	22.1
2007	21.5	486	5.2	548	26.7
2008	17.2	389	4.2	442	21.4
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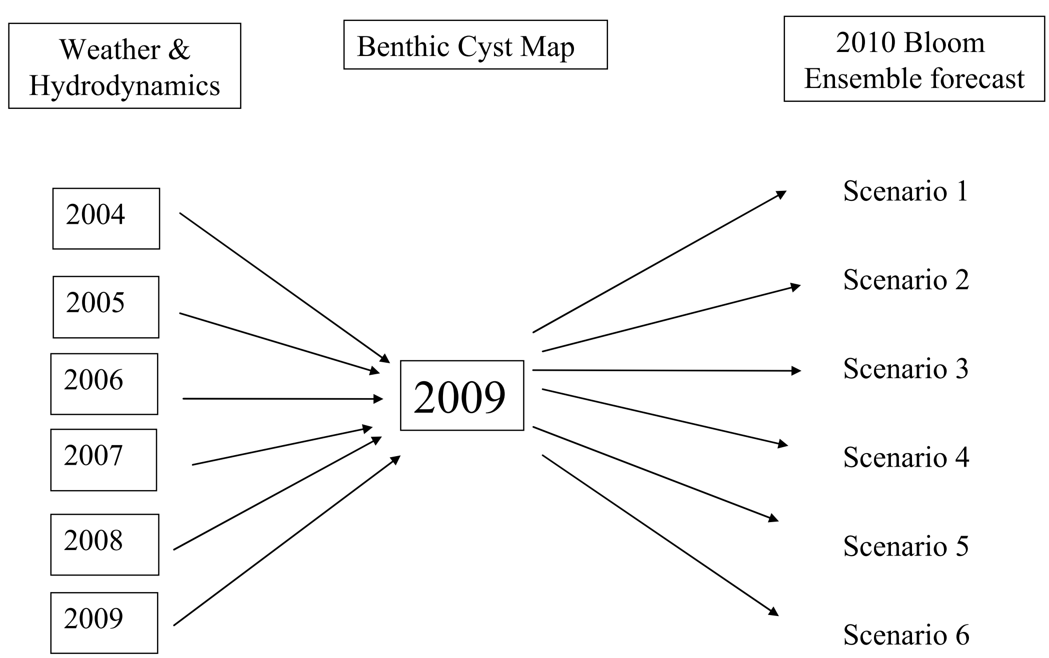
2005	52.1	757	23.7	624	74.8
2006	23.2	337	9.1	240	32.3
2007	49.7	722	9.2	243	58.9
2008	29.0	421	6.3	167	35.3

3.38 x 10 ^14 cm^2 BOF area = 0.95 x 10^14 cm^2

Seasonal Ensemble Forecast for 2010 27



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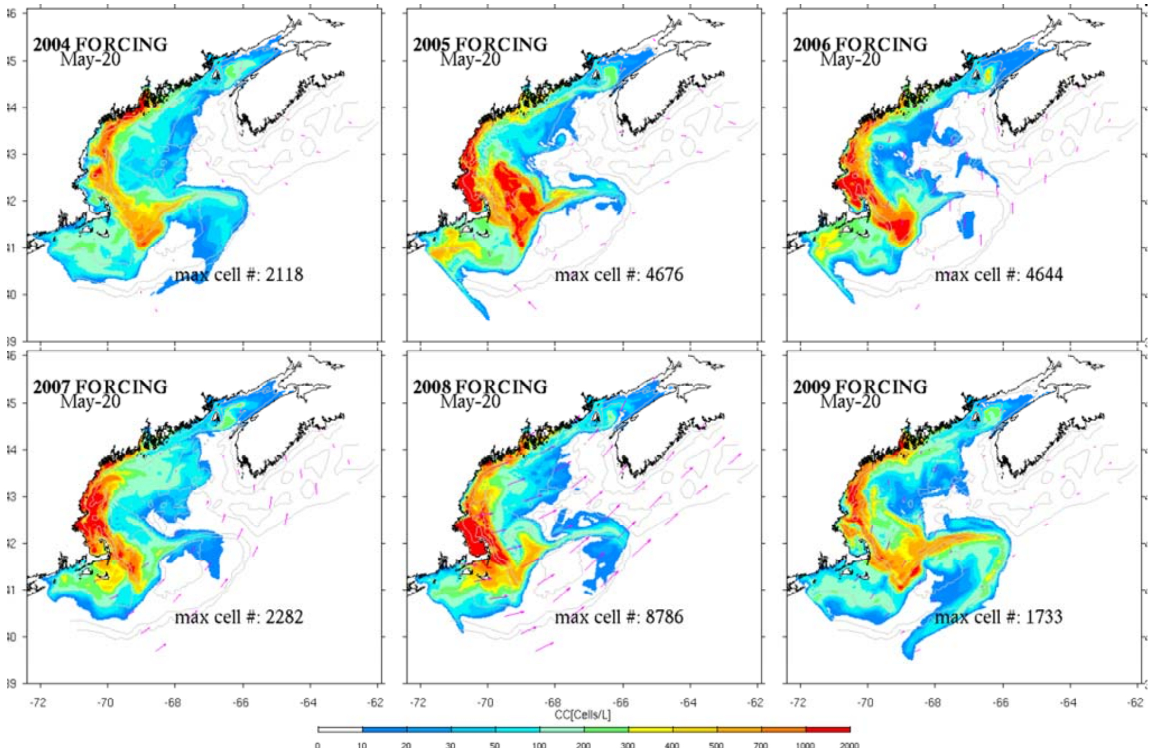
Online animation:
http://omglnx3.meas.ncsu.edu/yli/10ensemble_2d/dino_10ensemble.htm



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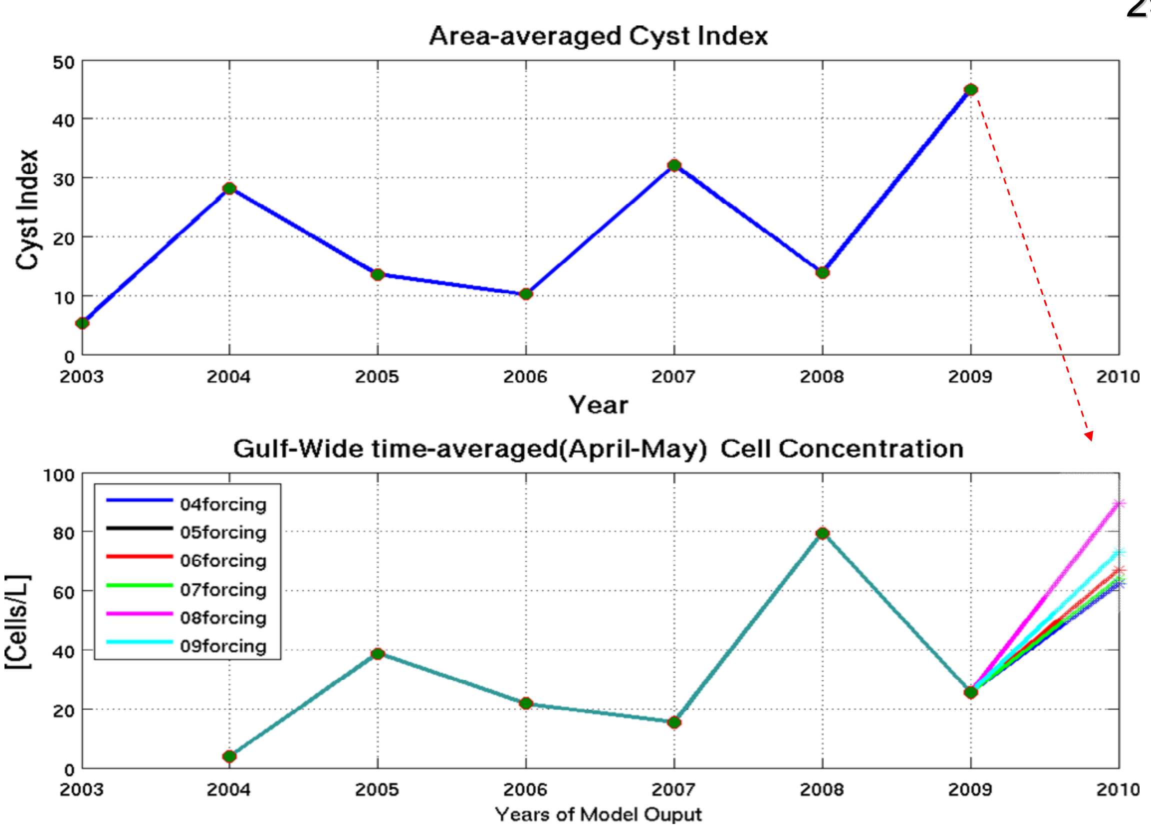
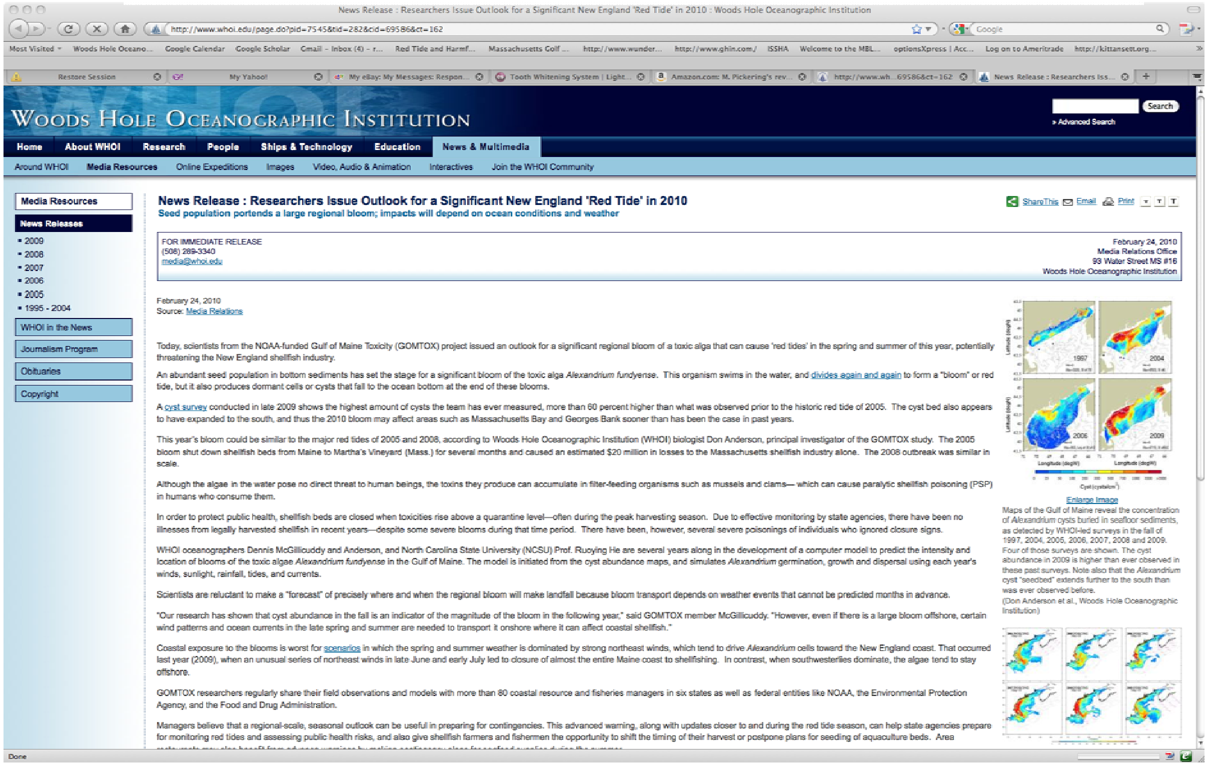


News release: Outlook for a significant red tide in 2010

30



News Release : Researchers Issue Outlook for a Significant New England 'Red Tide' in 2010

Seed population portends a large regional bloom; impacts will depend on ocean conditions and weather

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

February 24, 2010
Media Relations Office
93 Water Street MS #16
Woods Hole Oceanographic Institution

February 24, 2010
Source: Media Relations

Today, scientists from the NOAA-funded Gulf of Maine Toxicity (GOMTOX) project issued an outlook for a significant regional bloom of a toxic alga that can cause 'red tides' in the spring and summer of this year, potentially threatening the New England shellfish industry.

An abundant seed population in bottom sediments has set the stage for a significant bloom of the toxic alga *Alexandrium fundyense*. This organism swims in the water, and divides again and again to form a "bloom" or red tide, but it also produces dormant cells or cysts that fall to the ocean bottom at the end of these blooms.

A cyst survey conducted in late 2009 shows the highest amount of cysts the team has ever measured, more than 60 percent higher than what was observed prior to the historic red tide of 2005. The cyst bed also appears to have expanded to the south, and thus the 2010 bloom may affect areas such as Massachusetts Bay and Georges Bank sooner than has been the case in past years.

This year's bloom could be similar to the major red tides of 2005 and 2008, according to Woods Hole Oceanographic Institution (WHOI) biologist Don Anderson, principal investigator of the GOMTOX study. The 2005 bloom shut down shellfish beds from Maine to Martha's Vineyard (Mass.) for several months and caused an estimated $20 million in losses to the Massachusetts shellfish industry alone. The 2008 outbreak was similar in scale.

Although the algae in the water pose no direct threat to human beings, the toxins they produce can accumulate in filter-feeding organisms such as mussels and clams— which can cause paralytic shellfish poisoning (PSP) in humans who consume them.

In order to protect public health, shellfish beds are closed when toxicities rise above a quarantine level—often during the peak harvesting season. Due to effective monitoring by state agencies, there have been no illnesses from legally harvested shellfish in recent years—despite some severe blooms during that time period. There have been, however, several severe poisonings of individuals who ignored closure signs.

WHOI oceanographers Dennis McGillicuddy and Anderson, and North Carolina State University (NCSU) Prof. Ruoying He 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. The model is initiated from the cyst abundance maps, and simulates *Alexandrium* germination, growth and dispersal using each year's winds, sunlight, rainfall, tides, and currents.

Scientists are reluctant to make a "forecast" of precisely where and when the regional bloom will make landfall because bloom transport depends on weather events that cannot be predicted months in advance.

"Our research has shown that cyst abundance in the fall is an indicator of the magnitude of the bloom in the following year," said GOMTOX member McGillicuddy. "However, even if there is a large bloom offshore, certain wind patterns and ocean currents in the late spring and summer are needed to transport it onshore where it can affect coastal shellfish."

Coastal exposure to the blooms is worst for scenarios in which the spring and summer weather is dominated by strong northeast winds, which tend to drive *Alexandrium* cells toward the New England coast. That occurred last year (2009), when an unusual series of northeast winds in late June and early July led to closure of almost the entire Maine coast to shellfishing. In contrast, when southwesterlies dominate, the algae tend to stay offshore.

GOMTOX researchers regularly share their field observations and models with more than 80 coastal resource and fisheries managers in six states as well as federal entities like NOAA, the Environmental Protection Agency, and the Food and Drug Administration.

Managers believe that a regional-scale, seasonal outlook can be useful in preparing for contingencies. This advanced warning, along with updates closer to and during the red tide season, can help state agencies prepare for monitoring red tides and assessing public health risks, and also give shellfish farmers and fishermen the opportunity to shift the timing of their harvest or postpone plans for seeding of aquaculture beds. Area

Enlarge Image

Maps of the Gulf of Maine reveal the concentration of *Alexandrium* cysts buried in seafloor sediments, as detected by WHOI-led surveys in the fall of 1997, 2004, 2005, 2006, 2007, 2008 and 2009. Four of those surveys are shown. The cyst abundance in 2009 is higher than ever observed in these past surveys. Note also that the *Alexandrium* cyst "seedbed" extends further to the south than was ever observed before.
(Don Anderson et al., Woods Hole Oceanographic Institution)

Time series of simulated *A. fundyense* cell concentration near the Mass Bay outfall

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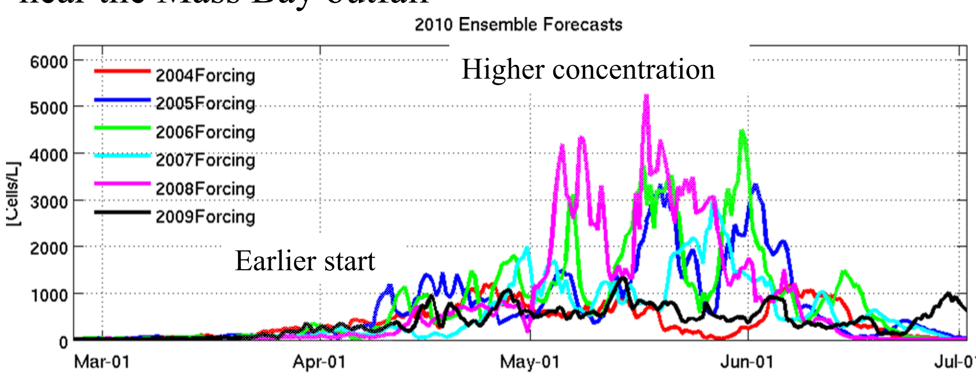
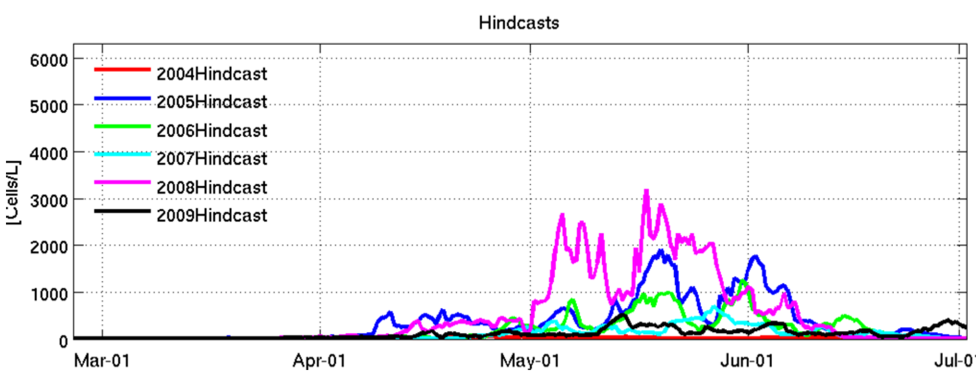
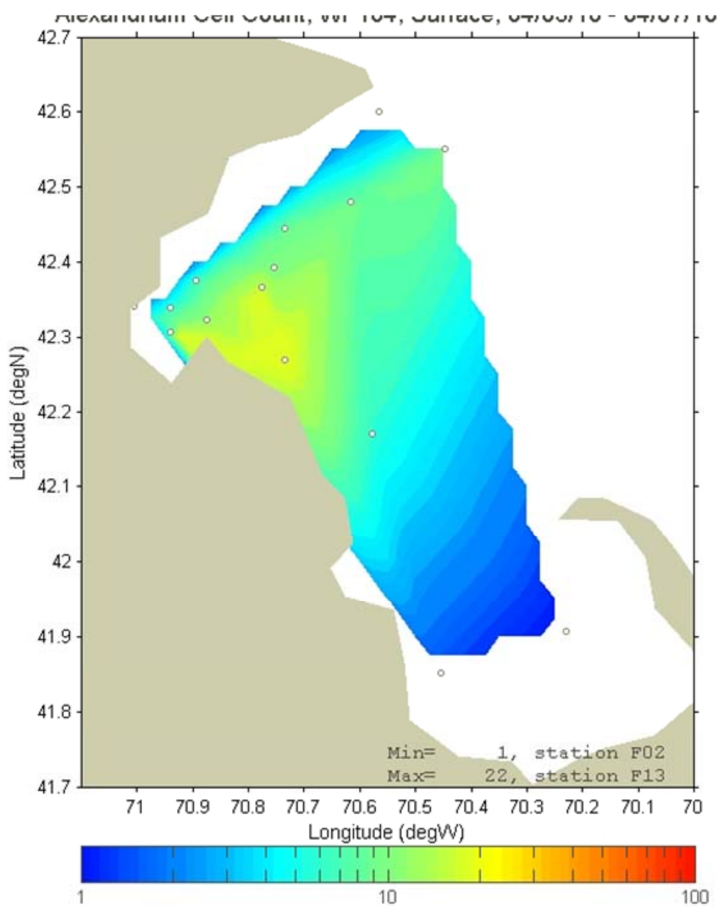




HOM survey
4-7 April, 2010



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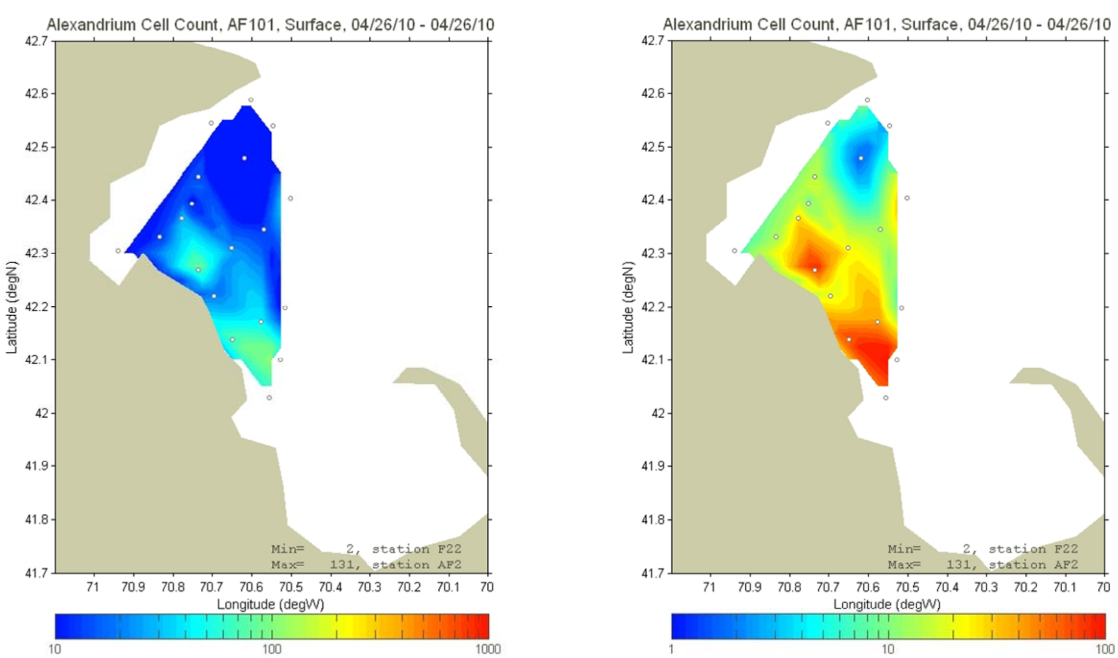
ARRS survey 26 April, 2010



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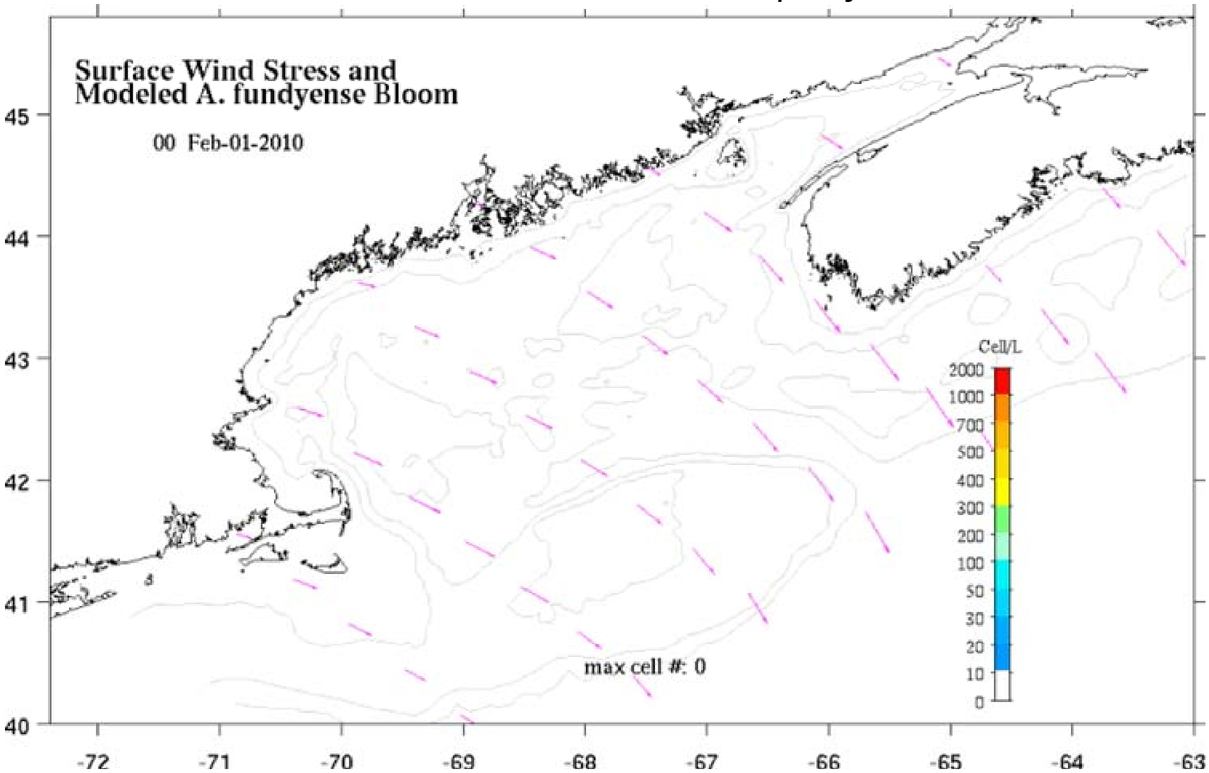
Animation: wind stress and modeled *A. fundyense* bloom



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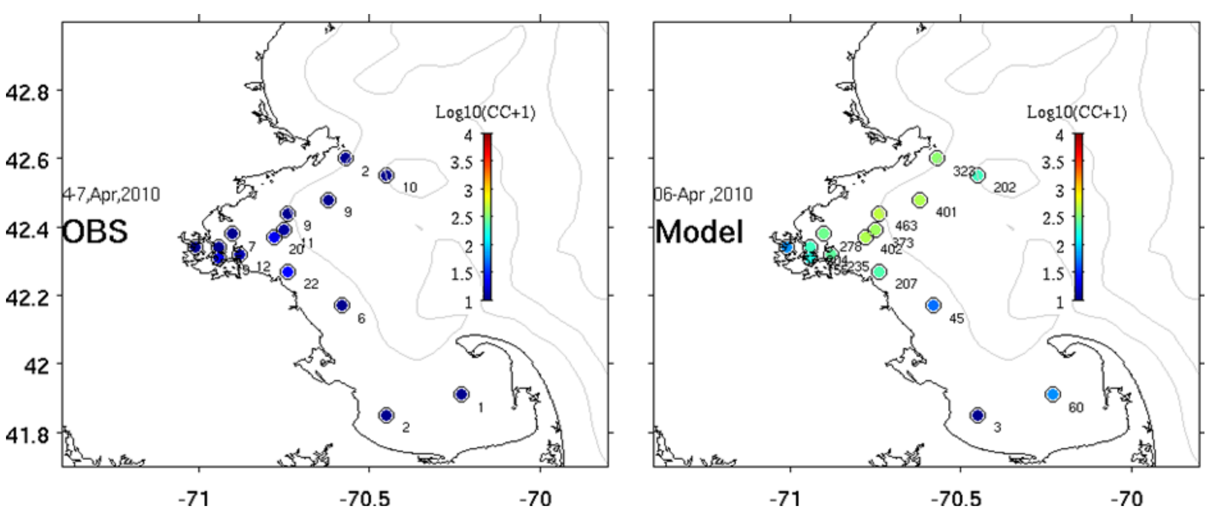

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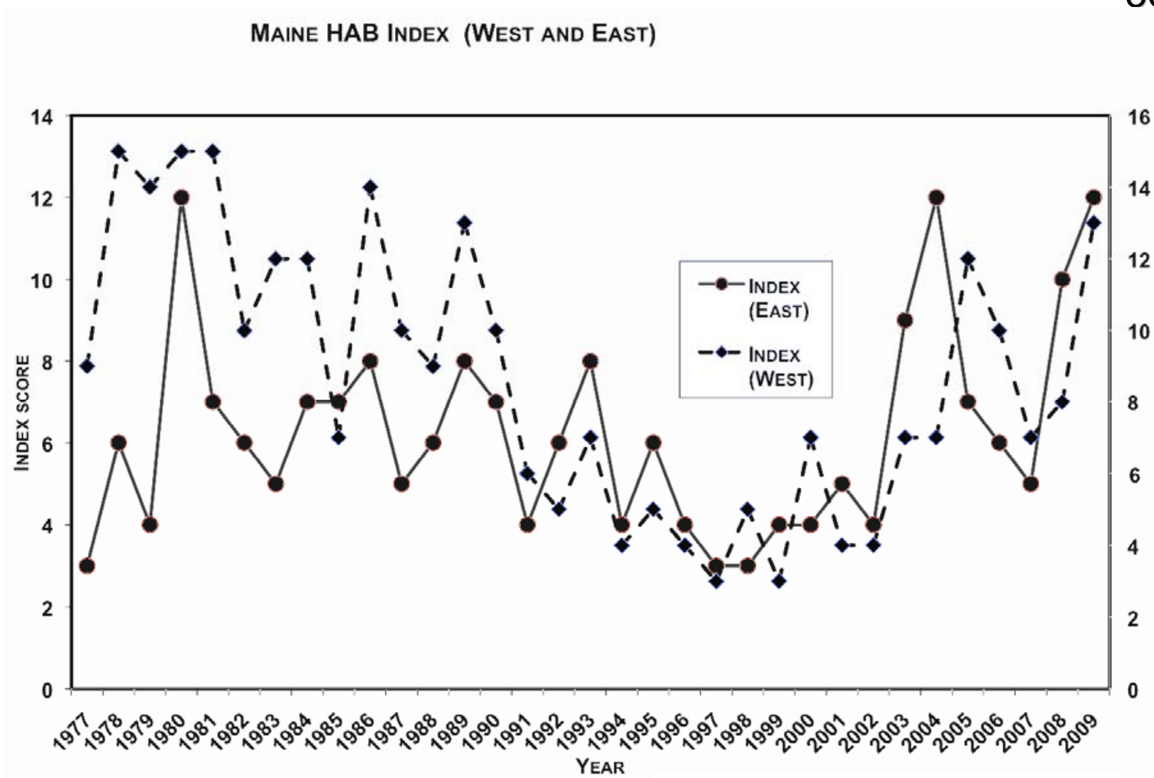

Source: Darcie Couture, Maine DMR

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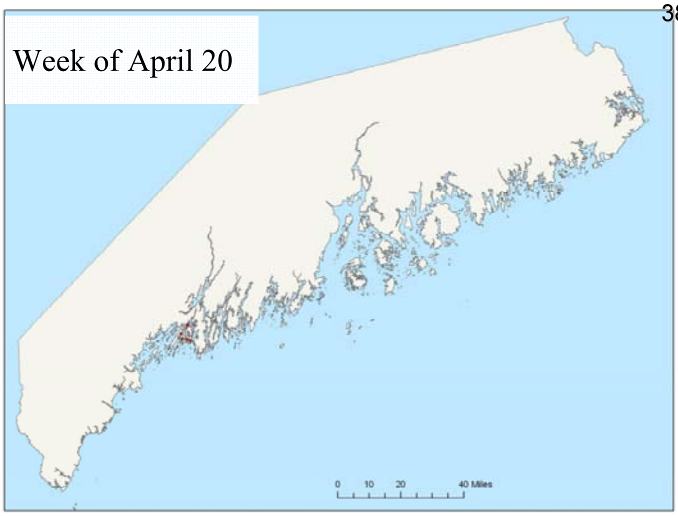
Acknowledgements

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

- MWRA/Battelle HOM6 and HOM7 teams
- 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

38



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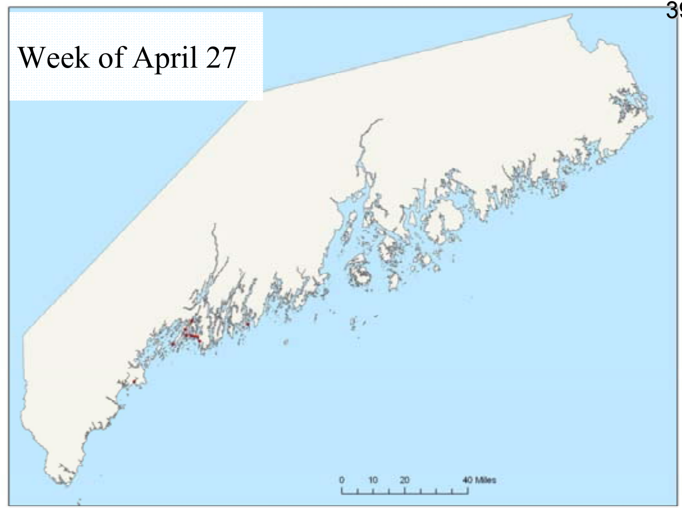

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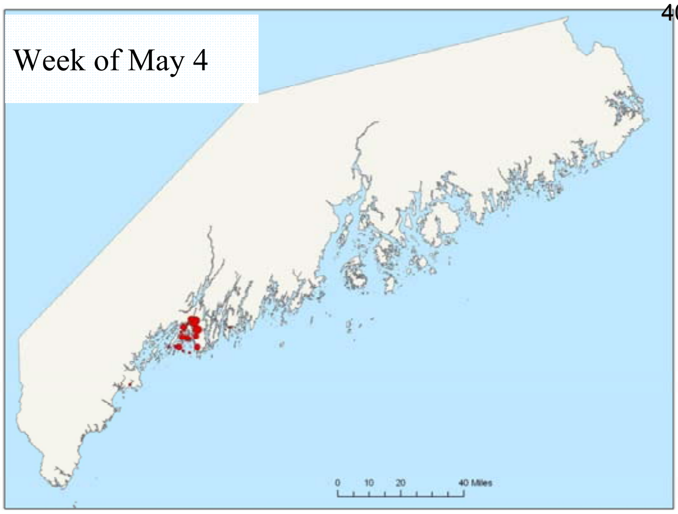

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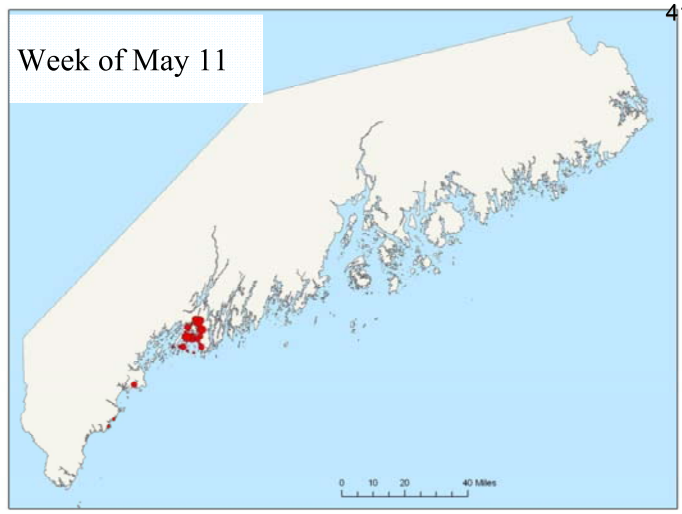

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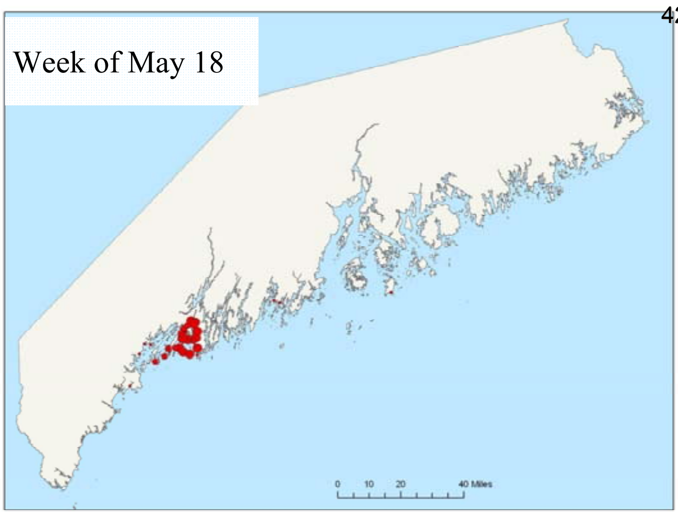

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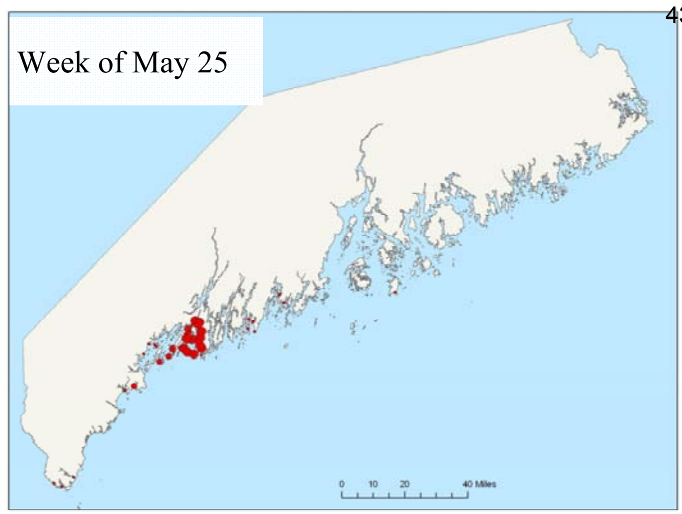
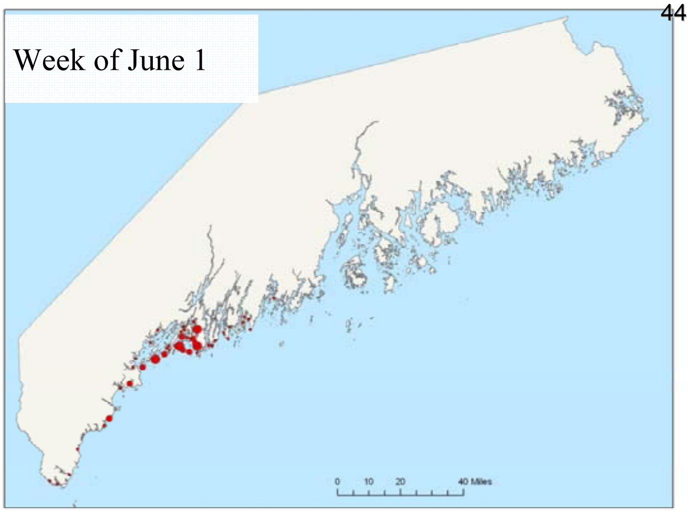
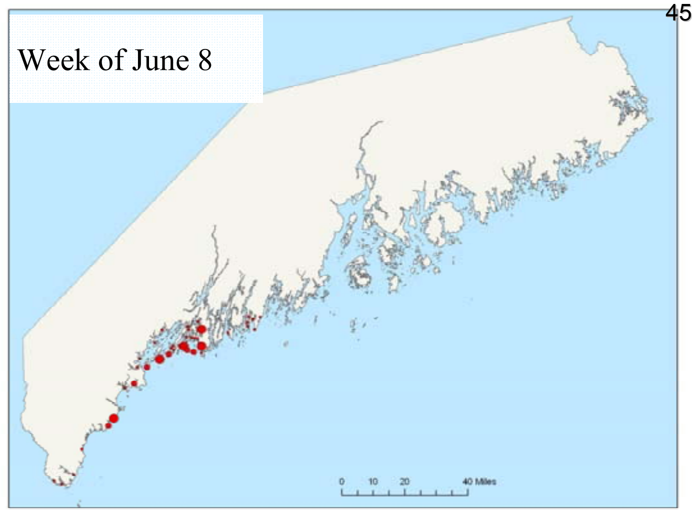
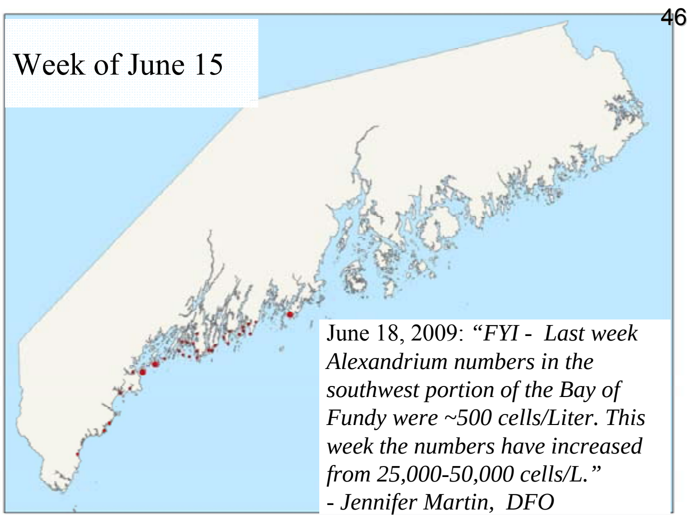
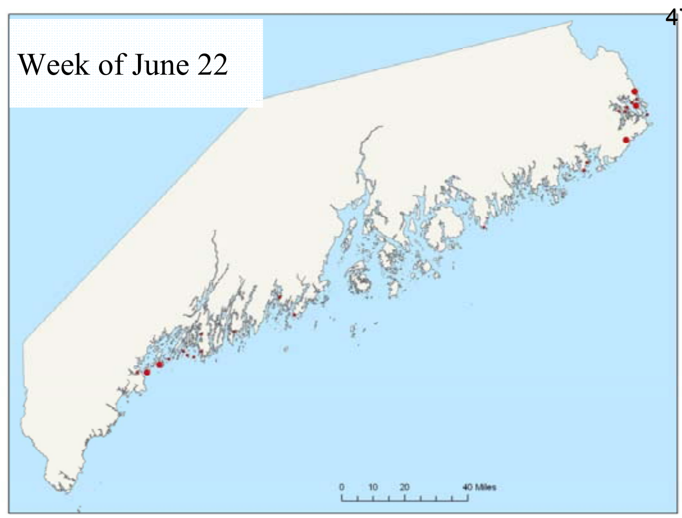
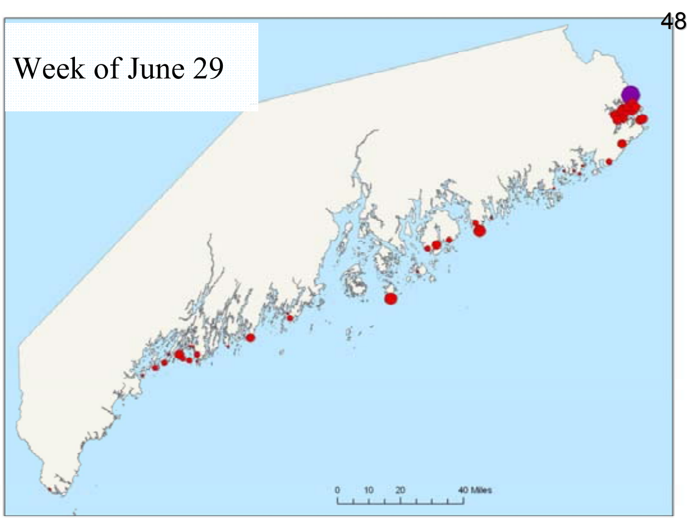


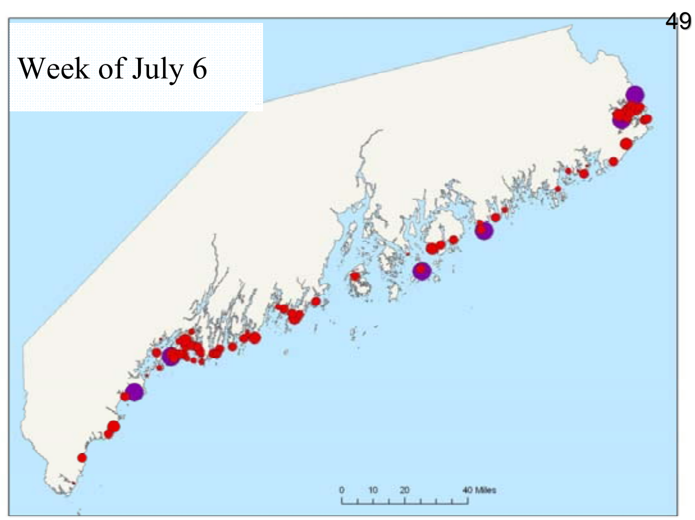

44
Week of June 1
0 10 20 40 Miles

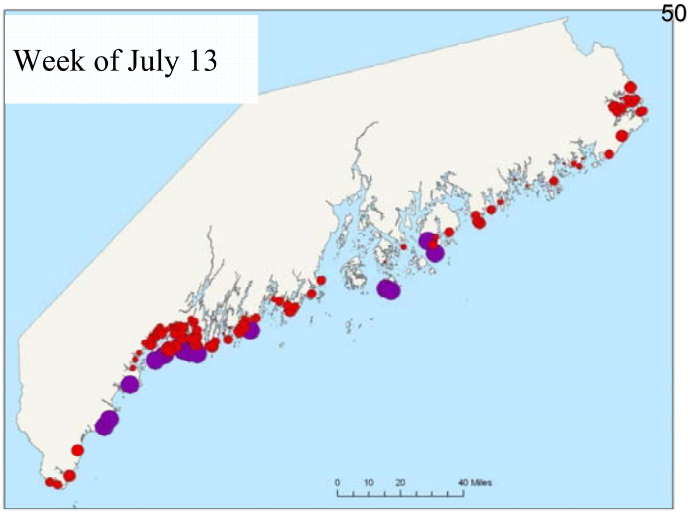

45
Week of June 8
0 10 20 40 Miles

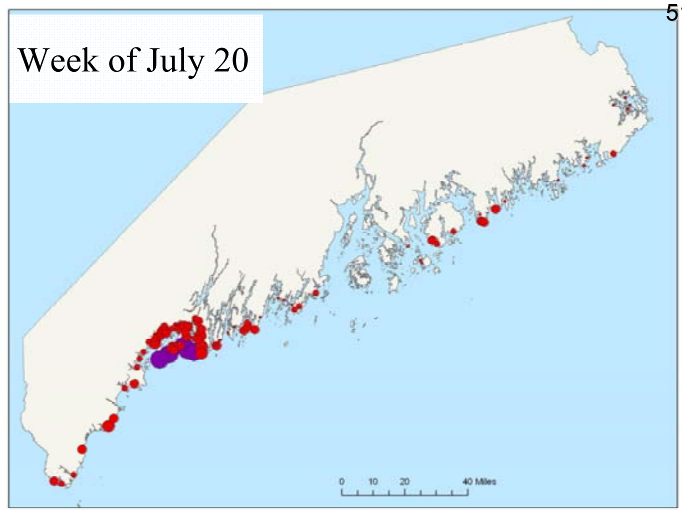

46
Week of June 15
June 18, 2009: *"FYI - Last week Alexandrium numbers in the southwest portion of the Bay of Fundy were ~500 cells/Liter. This week the numbers have increased from 25,000-50,000 cells/L."*
- Jennifer Martin, DFO

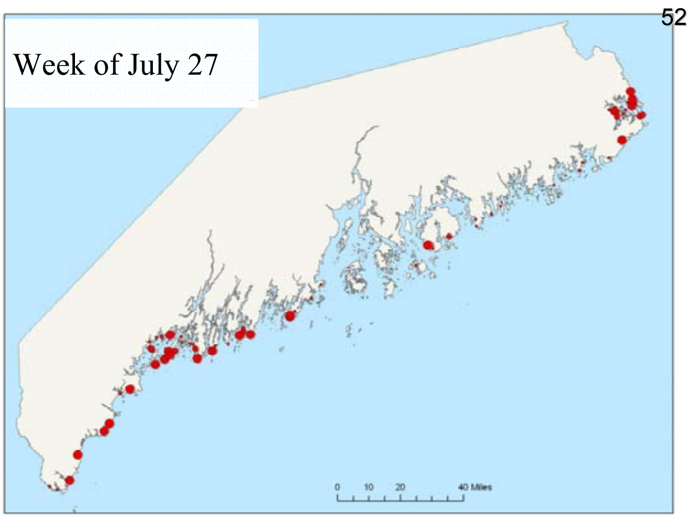

47
Week of June 22
0 10 20 40 Miles

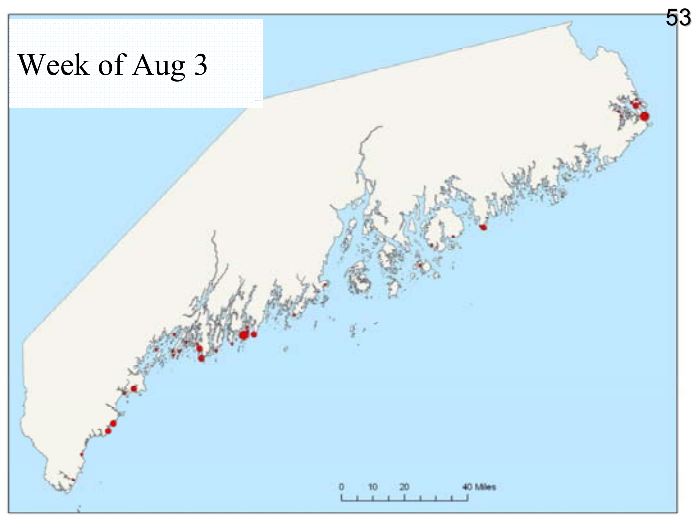

48
Week of June 29
0 10 20 40 Miles


49
Week of July 6
0 10 20 40 Miles


50
Week of July 13
0 10 20 40 Miles


51
Week of July 20
0 10 20 40 Miles


52
Week of July 27
0 10 20 40 Miles


53
Week of Aug 3
0 10 20 40 Miles

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