2010 Water Column Monitoring Results

Massachusetts Water Resources Authority
Environmental Quality Department
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Submitted to

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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 2010 data represent the tenth 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. Note that 2010 was the final year of water column monitoring following the plan outlined in the Ambient Monitoring Plan Revision 1 (MWRA 2004). In coordination with EPA, MWRA revised the Ambient Monitoring Plan for 2011 (MWRA 2010) to focus more closely on the nearfield and nearby farfield stations during a synoptic one day survey (with Center for Coastal Studies sampling in Cape Cod Bay in the same timeframe). The updated plan and 2011 sampling efforts will be summarized in the 2011 report.

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 from primary 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
2005	Improved removal of TSS etc due to more stable process
2010	Major repairs and upgrades to primary and secondary clarifiers

Twelve water column monitoring surveys were conducted in 2010. 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 2010 results in the context of the seasonal patterns and the annual cycle of ecological events in Massachusetts and Cape Cod Bays. The 2010 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 2011 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.* 2010). The survey objectives, station locations and tracklines, instrumentation and vessel information, sampling methodologies, and staffing were documented in a survey plan prepared for each survey. A survey report was prepared after each survey summarized the activities 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. Analytical results 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 2010 (**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 was sampled once per survey except station N16 which was sampled twice during each combined nearfield/farfield survey. 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 were sampled for phytoplankton and zooplankton. Two additional zooplankton stations (F32 and F33) in Cape Cod Bay were 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). Subsets of the data have been grouped for 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 for calculation of chlorophyll, *Phaeocystis*, and *Pseudo-nitzschia* Contingency Plan thresholds. 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. Comparison 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 2010. Year 2000 data are not used for calculating annual means as the year spans both periods, but are included in plots and analyses broken out by survey and season. Specific details on how the 2000 data are treated are included in the captions and text.

Table 1-2. Water column surveys for 2010. The nearfield day is underlined.

Survey	Type of Survey	Survey Dates
WF101	Nearfield/Farfield	February 2, <u>3</u>, 4
WF102	Nearfield/Farfield	February 22, <u>23</u>, 24
WN103	Nearfield	March <u>19</u>
WF104	Nearfield/Farfield	April 5, 6, <u>7</u>
WN106	Nearfield	May <u>11</u>
WF107	Nearfield/Farfield	June 14, <u>15</u>, 16
WN109	Nearfield	July <u>20</u>
WF10B	Nearfield/Farfield	August 9, <u>10</u>, 11
WN10C	Nearfield	August <u>30</u>
WN10D	Nearfield	September <u>29</u>
WF10E	Nearfield/Farfield	October <u>18</u>, 19, 20
WN10F	Nearfield	November <u>15</u>

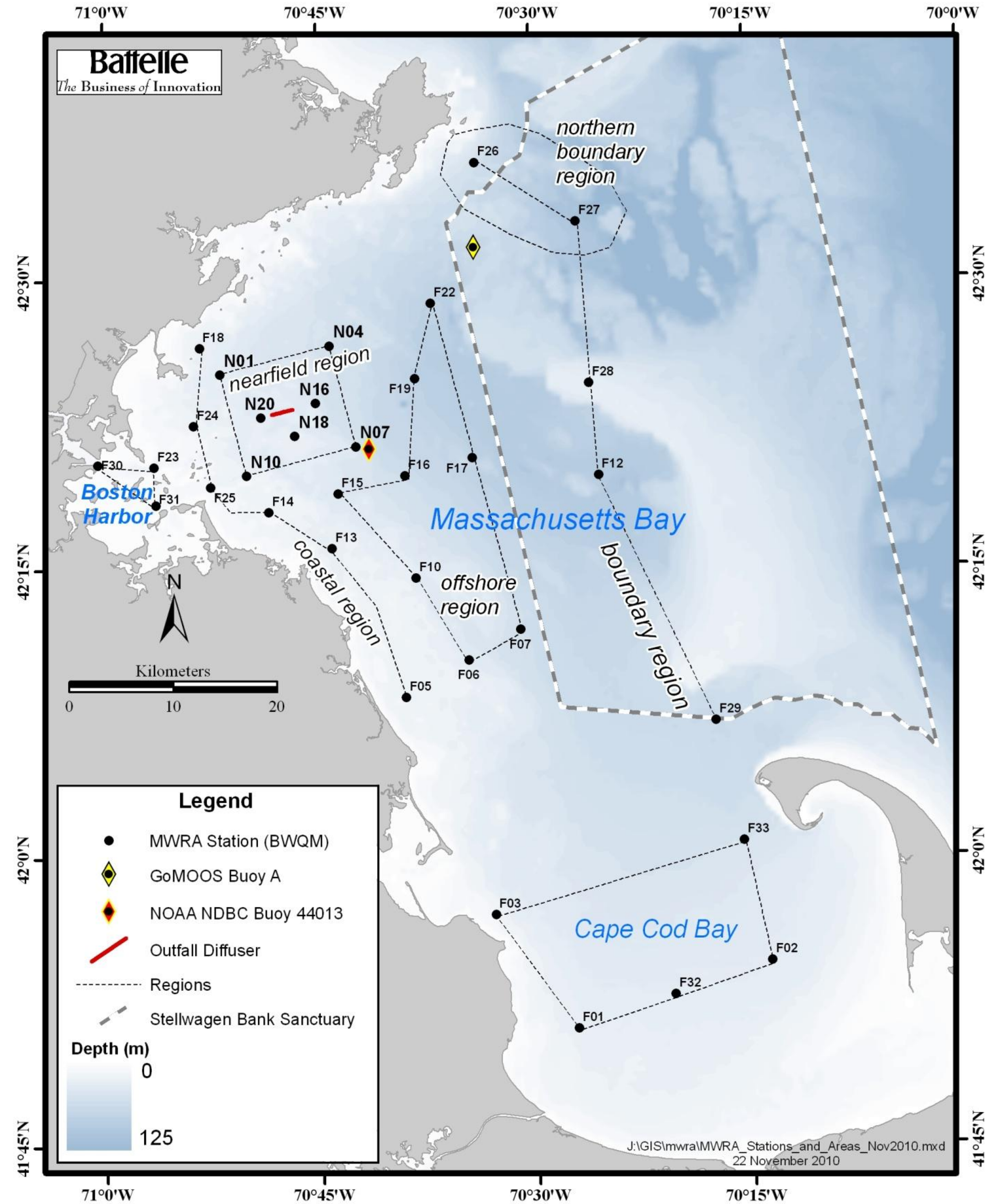

Figure 1-1. MWRA stations and their regional groupings. Also shown are the MWRA outfall and instrumented buoys operated by GoMOOS and NOAA's NDBC.

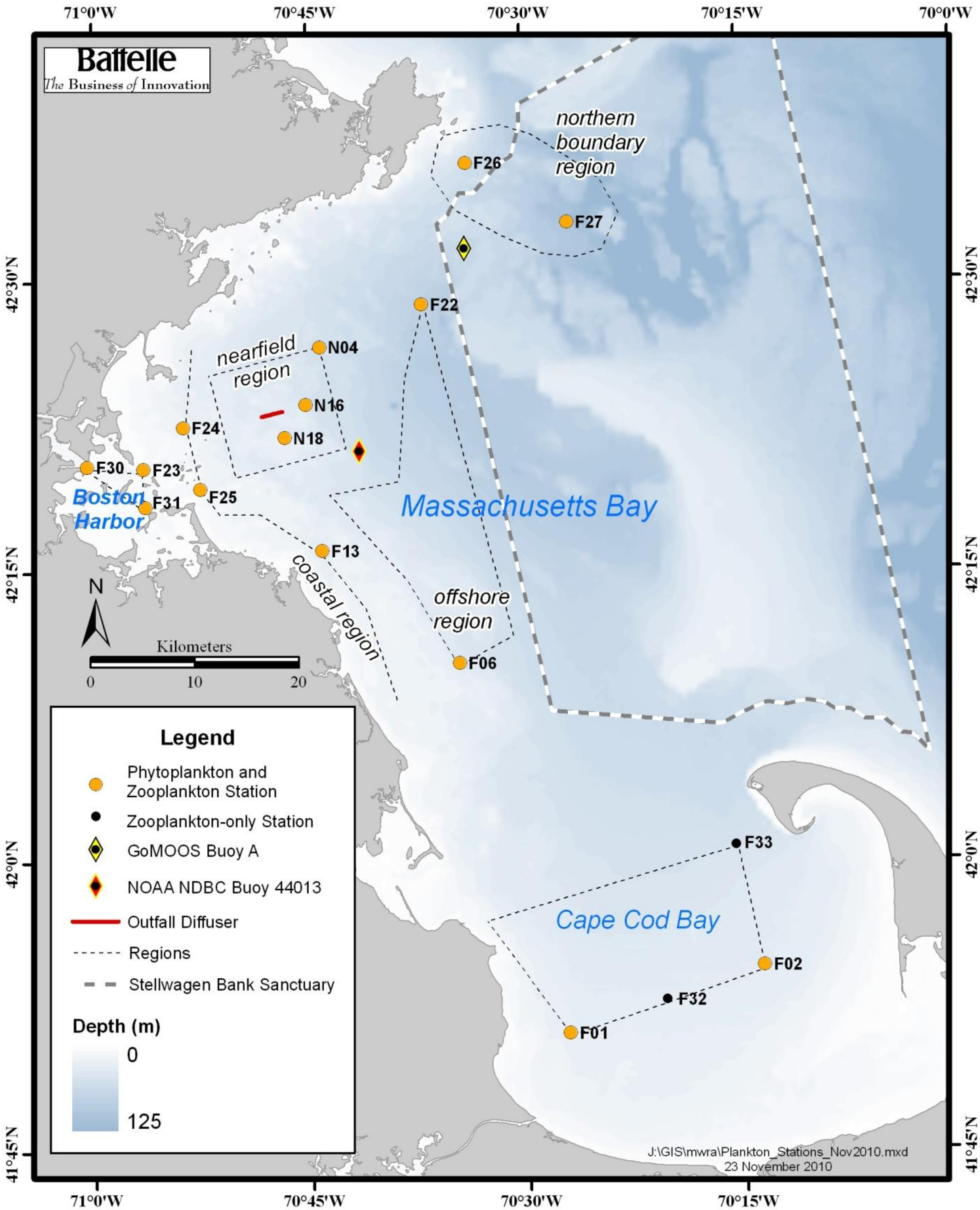

Figure 1-2. MWRA plankton stations (regional groupings shown for reference).

2 MONITORING RESULTS

The seasonal pattern of water column events expected for this latitude has been observed in the HOM program data from Massachusetts and Cape Cod Bays. The general pattern is evident although the timing and intensity of the events are variable. 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 followed by a bloom of *Phaeocystis pouchetii* in April. The water column transitions from well-mixed to stratified conditions in the late spring. 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. As temperatures cool in the fall 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 water column overturn – usually in October. By late fall or early winter, the water column is well mixed and resets to winter conditions, when nutrients are available but waters are too dark and cold to support rapid phytoplankton growth. The major features in 2010 and differences from previous years are discussed below.

2.1 2010 RESULTS

Overall, the physical, water quality, and biological conditions in 2010 followed the seasonal patterns observed previously in the monitoring program (1992-2009). The mean annual and mean seasonal values of winds, temperature, stratification, nutrients, phytoplankton biomass, dissolved oxygen and zooplankton abundance and community structure for 2010 were close to the averages over all years. The most notable characteristics of the physical environment in 2010 were the record-setting precipitation in March accompanied by stormy conditions and associated high river flow, and then the very dry summer, both of which were record levels (high and low river flow) for the 1992-2010 period (**Figure** 2-1). The fall was also unusually stormy. The wet spring provided additional nutrients and increased stratification in March. The dry summer combined with relatively high water temperatures led to lower than usual dissolved oxygen levels in nearfield bottom waters in late September. The stormy fall contributed to the seasonal turnover of the water column and ended the seasonal DO decline.

Nutrient concentrations (**Figure** 2-2) were higher in February than the rest of the year (as has been found for the past 20 years), but were lower than typically observed and much lower than the February 2008 and 2009 levels. A bay wide presence of diatoms in February likely contributed to these lower nutrient levels. While not as consistent as seen in other years, nutrient levels generally declined from February to June coincident with March and April diatom and *Phaeocystis* blooms although the timing of occurrence and magnitude of these blooms varied by area in the bays. With the exception of Cape Cod Bay, nutrient concentrations were lowest in the summer and increased and became quite variable in the fall. The main features of the pattern of phytoplankton biomass were the winter/spring diatom and *Phaeocystis* blooms, as well as inshore diatom blooms in summer (observed in the harbor, coastal, and nearfield regions) and in fall throughout the bays to varying degrees (**Figure** 2-3). Chlorophyll and particulate organic carbon (POC) concentrations peaked in most areas during the February to April blooms, except for the harbor where these parameters reached maxima in June. There were no Contingency Plan caution threshold exceedances in 2010. A forecast[1] of a major *Alexandrium* bloom for 2010 based on fall 2009 cyst distributions did not materialize; only low abundances of *Alexandrium* were observed in the bay (see Appendix B) and no paralytic shellfish poison (PSP) toxicity closures occurred in Massachusetts Bay in 2010. A chronological synopsis of the 2010 results is provided below and additional details are presented in Appendices A-D.

[1] http://www.whoi.edu/page/live.do?pid=51334&tid=282&cid=69586&ct=162 for details on WHOI forecast for 2010.

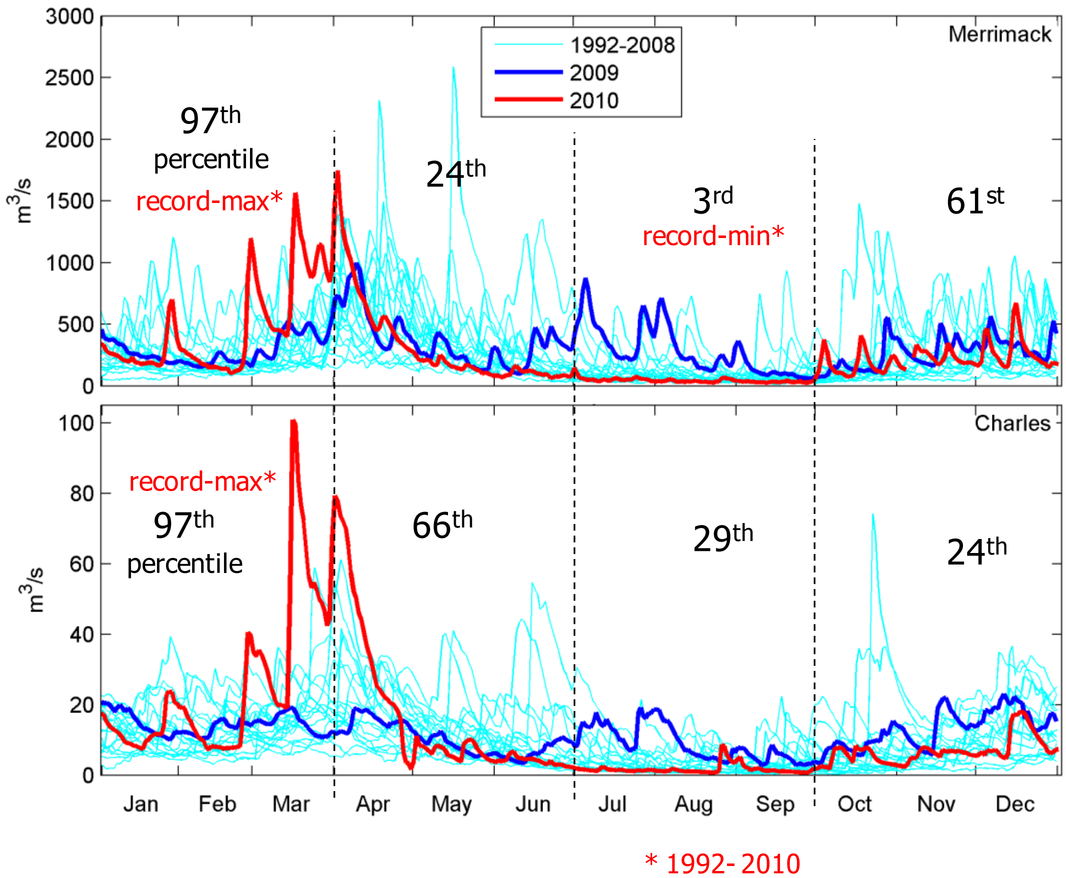

Figure 2-1. Comparison of the 2010 discharge of the Charles and Merrimack Rivers (solid red curve) with the observations from 2009 (solid blue curve) and 1992-2008 (light blue lines). Percentile of flow in 2010 relative to other years is presented for each river/season. Note record maxima for the 1992-2010 monitoring period, largely due to the rainy July.

Nutrient concentrations were low in Massachusetts and Cape Cod Bays in February 2010 (**Figure** 2-2) relative to prior years (Appendix B Slides 31 and 32). Nitrate (NO_3) and silicate (SiO_4) levels in Cape Cod Bay were slightly lower than those in Massachusetts Bay consistent with the elevated chlorophyll and POC concentrations associated with the early diatom (*Thalassiosira* and *Chaetoceros* spp.) and *Phaeocystis* blooms, respectively, in Cape Cod Bay (**Figure** 2-3 and **Figure** 2-4). Elevated chlorophyll concentrations were also observed at the offshore, nearfield, and northern boundary stations in late February coincident with slight increases in abundances of diatoms and *Phaeocystis*. Chlorophyll levels were much lower at the coastal and Boston Harbor stations in February compared to the other bay stations. There was an increase in NO_3, SiO_4, and phosphate (PO_4) concentrations in the nearfield from February to March that was coincident with the high river flows observed and a decrease in chlorophyll levels.

Nutrient concentrations throughout the bays in April were comparable to or just slightly lower than those observed in February. The April nearfield nutrient concentrations decreased sharply from March levels; the decrease was coincident with a relatively large spring diatom bloom (dominated by *Thalassiosira decipiens*) that reached seasonal peak chlorophyll concentrations and annual peak POC and productivity levels (**Figure** 2-3, 2-4, and 2-5). Chlorophyll also peaked at the coastal stations. POC levels also reached their annual maxima at coastal, offshore and Cape Cod Bay stations in April (**Figure** 2-3). Silicate concentrations increased slightly from February to April in the offshore and northern boundary areas in April. These were the only stations where *Phaeocystis* were observed in April 2010 (**Figure** 2-6). Although *Phaeocystis* often peaks in April, it was present throughout the bays in February, albeit at abundances that were quite low. The highest abundance for the year was 1.65 million cells L^{-1} at station F02 in Cape Cod Bay in late February. In the nearfield, the 2010 *Phaeocystis* levels were the lowest since 2000, approaching the low levels seen during the baseline period (Appendix B Slide 16).

By May, chlorophyll, POC and phytoplankton levels had all decreased sharply in the nearfield (**Figure** 2-3 and 2-4). Similar decreases were observed in Cape Cod Bay and offshore areas of Massachusetts Bay from April to June. In coastal waters and Boston Harbor, levels remained elevated or increased due to a June bloom of diatoms in the harbor and coastal waters. Similarly to the summer of 2009, the diatom bloom in these near shore waters was dominated by *Skeletonema* and *Dactyliosolen fragilissimus*. The June bloom resulted in annual maximum chlorophyll, POC concentrations, and productivity in Boston Harbor (**Figure** 2-3 and 2-5) and corresponding nutrient minima.

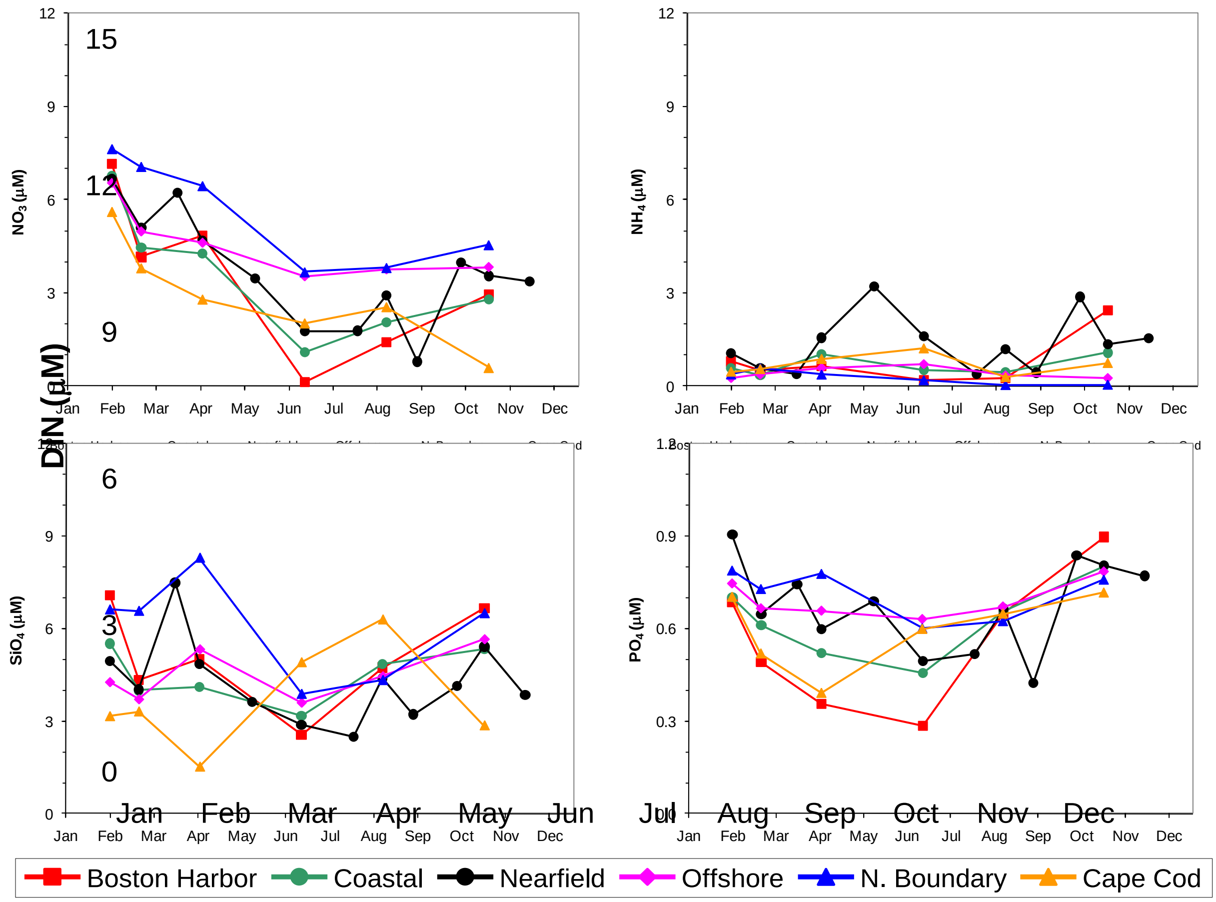

Figure 2-2. **Time-series of survey mean nutrient concentrations (µM) in Massachusetts and Cape Cod Bays. Mean concentrations over depths and stations within each region in 2010.**

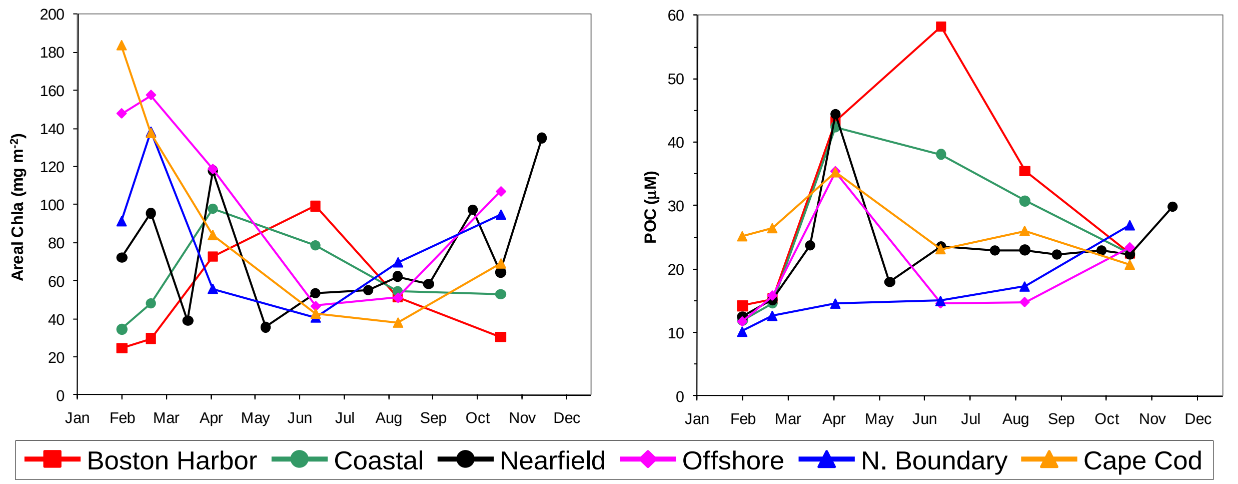

Figure 2-3. Time-series of survey mean areal chlorophyll (mg m^{-2}) and POC (µM) in Massachusetts and Cape Cod Bays. Mean concentrations over all stations and all depths for POC within each region in 2010 (chlorophyll is already depth-integrated).

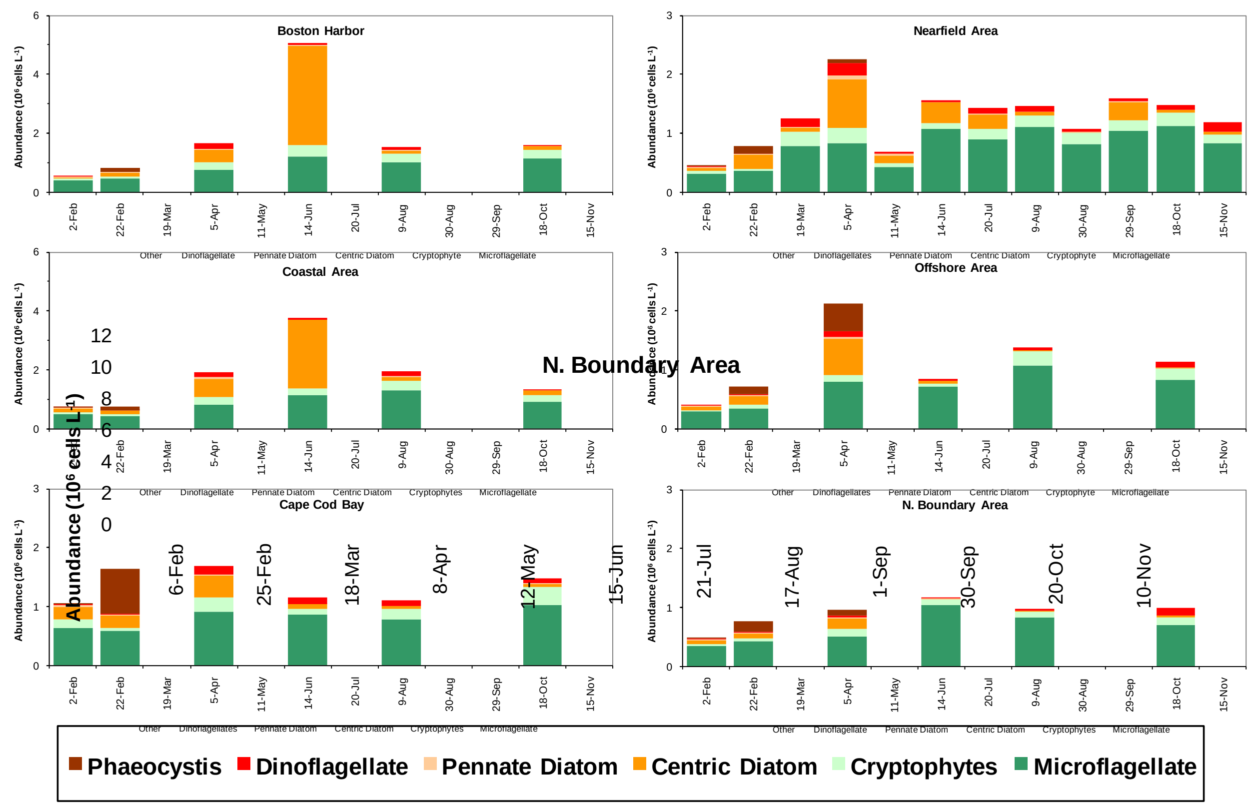

Figure 2-4. Phytoplankton abundance by major taxonomic group in all six areas for 2010. Note different scale for Boston Harbor and coastal areas.

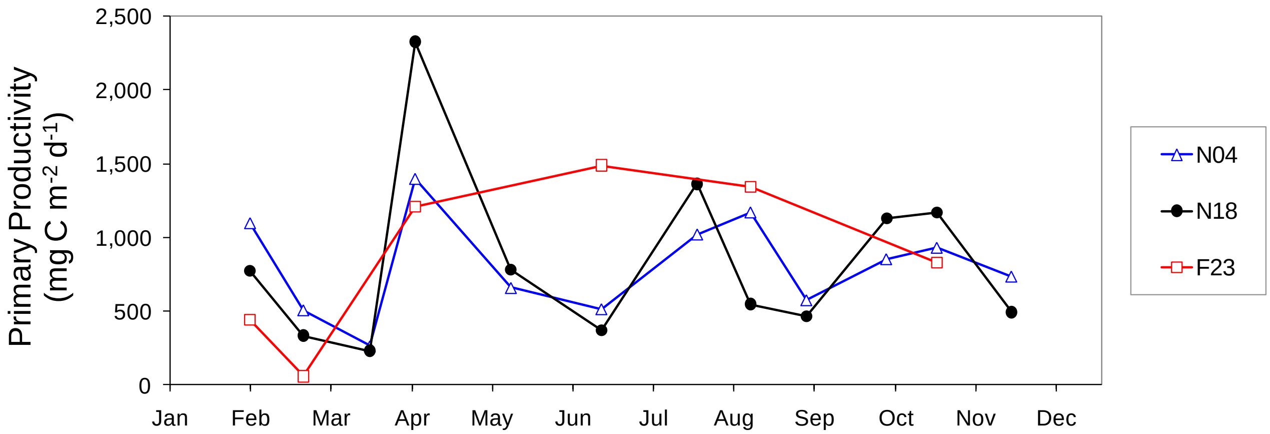

Figure 2-5. Potential areal productivity (mg C m^{-2} d^{-1}) in 2010 at stations F23, N18, and N04.

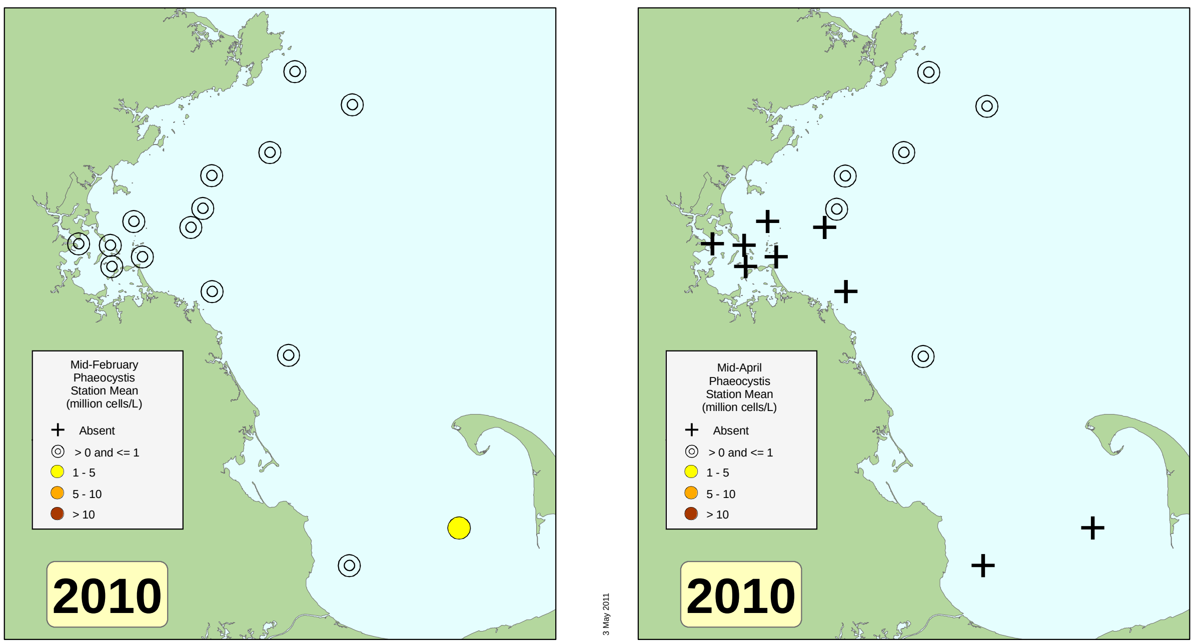

Figure 2-6. Station mean *Phaeocystis* abundance (million cells L^{-1}) in February and April 2010.

A bloom of the toxic dinoflagellate species *Alexandrium fundyense* occurred in the southwestern Gulf of Maine in April/May 2010. This has occurred every year since 2005. The model forecast for a major *Alexandrium* bloom led to MWRA requesting additional sampling for *Alexandrium* during the early April 2010 farfield survey. The survey data verified that *Alexandrium* was present at all 15 plankton station sampled but at low abundances (<25 cells L^{-1}). Measurable PSP toxicity was first reported in New Hampshire waters on April 15 and in Massachusetts Bay (Gloucester, Cohasset, and Scituate) on April 21st (emails via NH Department of Environmental Services and MA Division of Marine Fisheries, respectively), which triggered initiation of the *Alexandrium* Rapid Response Surveys (Libby 2006). A series of three rapid response surveys were conducted on April 26, May 3, and May 21 and additional sampling for *Alexandrium* was also conducted during the May 11 nearfield and June 14 farfield surveys to characterize the 2010 bloom. *Alexandrium* abundances peaked at 79 cells L^{-1} in the nearfield on the May 3 survey; the highest observed abundance was found at station AF4 just offshore of Cohasset, MA on May 11 (285 cells L^{-1}). Abundances had decreased to <35 cells L^{-1} by May 21, and had essentially disappeared from the bay (present at 1 or 2 cells L^{-1} in only 1/3 of the samples collected; see Appendix B Slides 23-25 for data) by mid June.

The model predictions were vastly higher relative to these field data. This disagreement between the 2010 model and observations is being examined in detail by WHOI researchers who are focusing on mesoscale water mass characteristics in the Gulf of Maine and timing of *Alexandrium* germination in 2010 (McGillicuddy *et al.* 2011). In addition to the low *Alexandrium* levels in the Gulf of Maine, another factor for the lack of a large bloom in Massachusetts Bay was that only one, relatively weak, northeasterly storm occurred in early May, and unlike previous years no additional storms occurred in April - June 2010 (Appendix A Slide 14).

In June, nutrient concentrations were relatively low throughout the area and remained low in July in the nearfield. Nearfield chlorophyll concentrations remained low from May through September. The June diatom bloom in the harbor and coastal waters was followed by a decrease in chlorophyll concentrations and phytoplankton abundance and a coincident increase in nutrients by August.

Bottom water dissolved oxygen (DO) concentrations generally declined throughout the system from late February to August (**Figure** 2-7). Strong water column stratification in March and April (**Figure** 2-8) led to an early decrease in bottom water DO concentrations. After a decrease in stratification and mixing of the water column from April to May, the rate of DO decline leveled off from May to July. A sharp decline in nearfield bottom water DO concentrations occurred after the July survey, resulting in an unusually low minimum DO value (6.36 mg L^{-1}) in late September. These lower than usual DO levels in nearfield bottom waters likely resulted from the dry conditions during the summer combined with relatively high water temperatures (Appendix A Slides 23 and 24). Stormy conditions then contributed to the seasonal turnover of the water column in the fall and an increase in bottom water DO levels. The observed fall values (average Sept-Nov) were consistent with the regression model developed by Geyer et al. (2002) (Appendix A Slide 25). The empirical model shows that low DO is correlated with warm salty water.

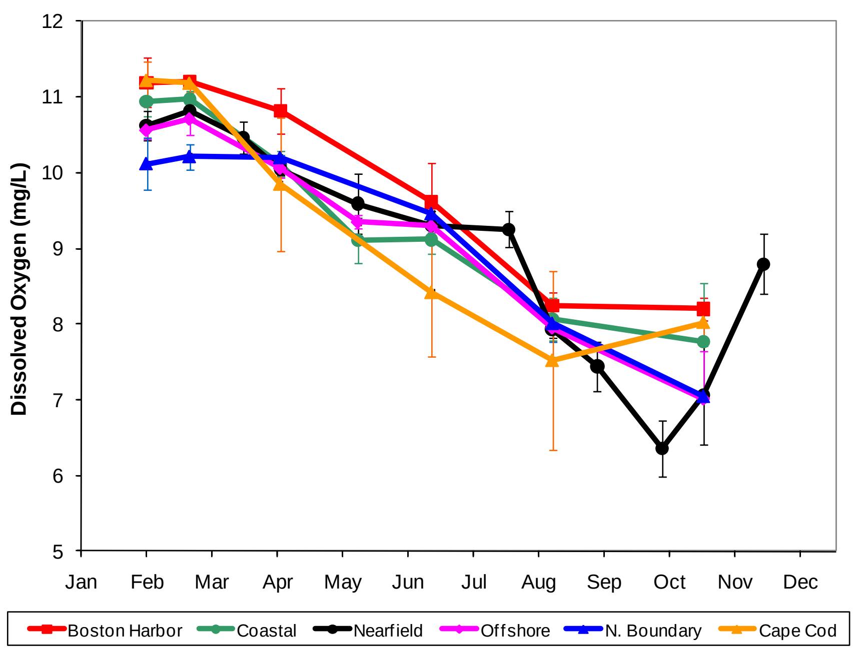

Figure 2-7. Time-series of survey-average bottom dissolved oxygen concentration in Massachusetts and Cape Cod Bays in 2010. Average represents the bottom values from all stations in each region. Error bars represent ±1 standard deviation. The additional farfield data in May were obtained during the special sampling for *Alexandrium*.

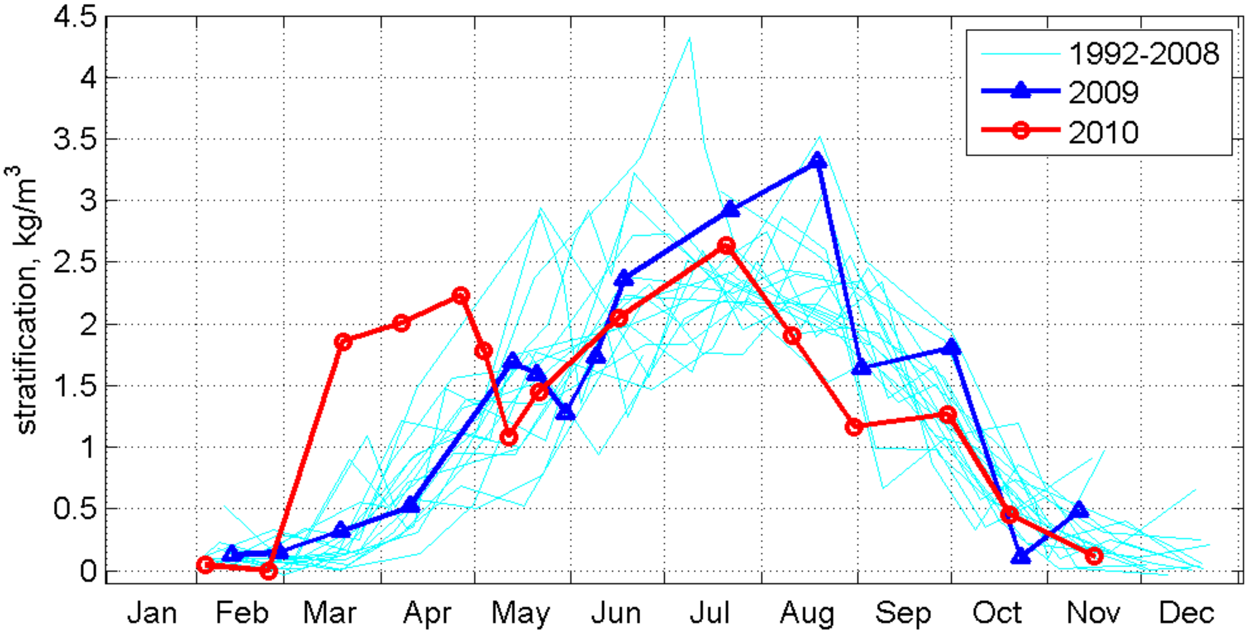

Figure 2-8. Stratification near the outfall site (nearfield stations N16, N18 and N20) for 2010 (red line) compared to 2009 (dark blue line) and the previous 16 years of observations (1992-2008; light blue).

In summer 2010, the phytoplankton community was dominated by typical seasonal increase in microflagellate and dinoflagellates (*Ceratium* spp.) abundance (up to a million cells L^{-1}), but as observed in 2009, there was also an increase in diatoms with *Dactyliosolen fragilissimus* and *Skeletonema* spp. dominant during both years. Nearfield diatom abundances increased to about 300,000 cells L^{-1} in June and July 2010, while the diatom bloom in Boston Harbor and coastal waters reached levels of 2 to 3.4 x 10^6 cells L^{-1} in June (**Figure** 2-4). Harbor productivity peaked at ~1,500 mg C m^{-2} d^{-1} during this summer bloom, but remained relatively low at the nearfield stations (**Figure** 2-5). Productivity did increase to comparable levels at station N18 by July.

Nutrient and chlorophyll concentrations were low during the summer (**Figure** 2-2 and **Figure** 2-3). From early to late August, there was a sharp drop in nearfield NO_3 and PO_4 concentrations, but by late September nutrient concentrations had increased substantially. Fall storms and associated mixing (Appendix A Slide 16) likely contributed to these changes. The increase in nutrients also supported a late September diatom bloom in the nearfield (dominated by *Skeletonema* spp. and *Leptocylindrus danicus*), which led to increased chlorophyll concentrations. By October, chlorophyll levels at coastal and harbor stations had decreased to low levels comparable to those seen in these areas in February.

Fall peaks in chlorophyll were observed in the offshore and northern boundary areas coincident with an unusual increase in dinoflagellate abundance (mixed assemblage dominated by *Ceratium* spp. and *Prorocentrum micans*). The autumn bloom of *P. micans* continued into November with abundances of >15,000 cells L^{-1} observed in nearfield samples. This autumn *P. micans* bloom was extraordinary in both its timing (dinoflagellate annual abundance usually peaks in summer) and in its magnitude. November 2010 dinoflagellate abundance was more than 10 times the baseline and post-diversion November dinoflagellate mean levels (see **Figure** 2-20). This unusual autumn dinoflagellate bloom led to both 2010 annual maximum nearfield survey mean chlorophyll concentration and POC concentration occurrences in the autumn of 2010 (**Figure** 2-3).

Zooplankton abundance and species composition in 2010 were generally similar to previous years. The 2010 total zooplankton annual cycle in the nearfield featured reduced abundance of ≤30,000 animals m^{-3} during February through April followed by an increase in May and June (**Figure** 2-9). The nearfield annual peak abundance of 86,000 animals m^{-3} was observed in July before abundances decrease in August and returned to lower levels (<40,000 animals m^{-3}) during September to November. Zooplankton patterns and overall abundances appeared to be regionally coherent.

As in previous years, the zooplankton community was overwhelmingly dominated (90% numerically) by copepods (nauplii + copepodites + adults). *Oithona similis* continued to be the most abundant copepod and followed the seasonal trend of increasing abundance in July and August. *Calanus finmarchicus* peaked earlier in March in the nearfield than in previous years, but had lower abundances for the rest of the year. While not numerically dominant, *Calanus* is an important food resource for endangered Right Whales (Mayo & Marx 1990). Also in the nearfield, meroplankton (barnacle nauplii, bivalve and gastropod veligers, polychaete larvae) and non-copepod zooplankton such as *Evadne nordmani*, *Podon polyphemoides* and *Oikopleura dioic*a, comprised >10% of total zooplankton in the nearfield during the months of March, April, July, and September. Elevated barnacle nauplii abundance was observed in February through April in the nearfield, harbor and coastal regions. Overall, 2010 zooplankton levels were near the long-term mean levels for most zooplankton groups in most regions.

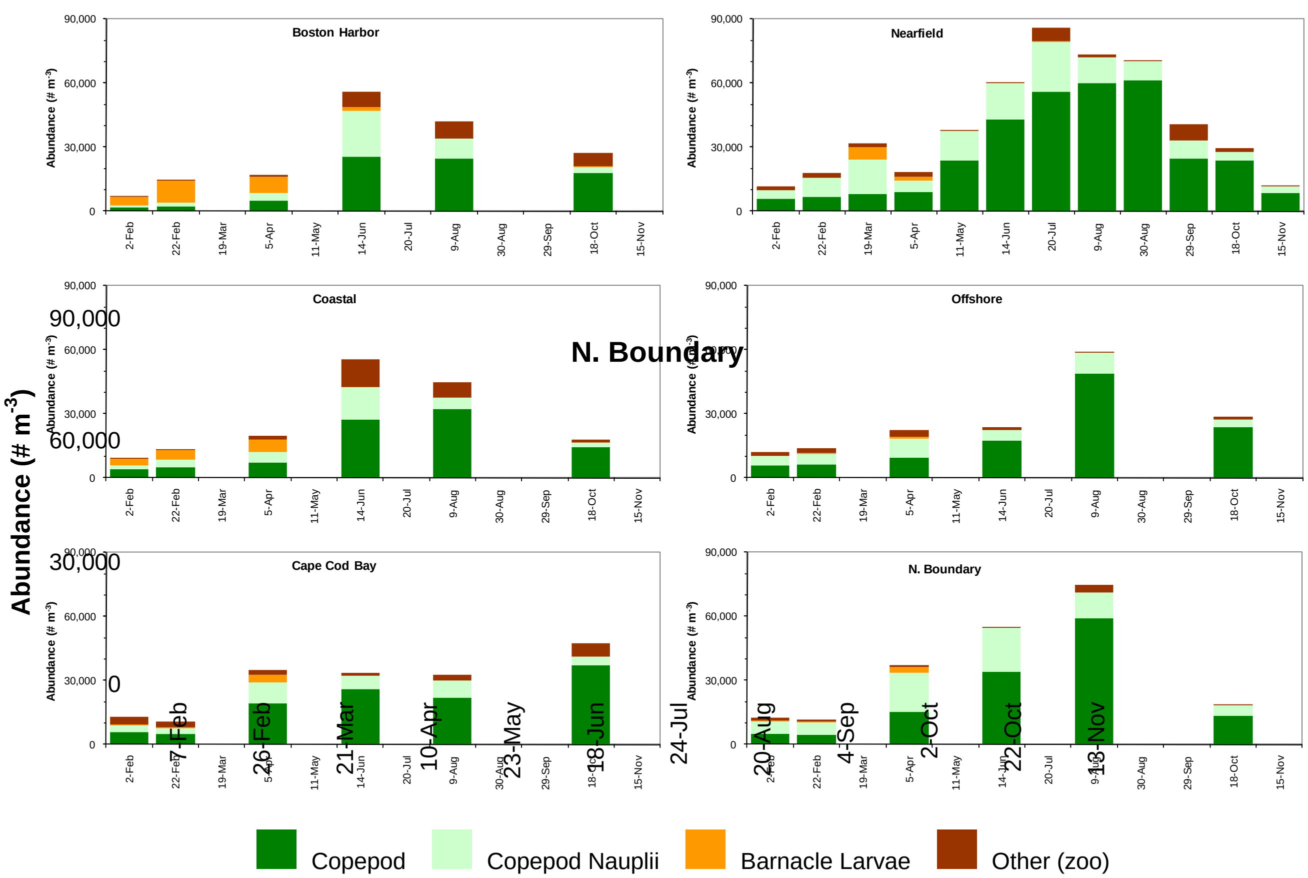

Figure 2-9. Zooplankton abundance by major taxonomic group in six areas during 2010.

2.2 CONTINGENCY PLAN THRESHOLDS FOR 2010

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 survey 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 includes both non-toxic *P. pungens* as well as the domoic-acid-producing species *P. multiseries*; these appear identical under a light microscope. Since distinguishing between these two species requires scanning electron microscopy or molecular probes, all P. *pungens* and *Pseudo-nitzschia* unidentified within the genus are included in the threshold. For A. *fundyense*, each individual sample value is compared against the threshold of 100 cells L^{-1}. There were no water column threshold exceedances in 2010.

Table 2-1. Contingency plan threshold values for water column monitoring in 2010. There were no exceedances in 2010.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2010
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: 6.36 SW Basin min: 6.67
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: 69.3% SW Basin min: 71.2%
Bottom Water DO rate of decline (Nearfield, mg L^{-1} d^{-1})	Seasonal June-October	0.037	0.049	0.024	0.024
Chlorophyll (Nearfield mean, mg m^{-2})	Annual	118	158	79	74
	Winter/spring	238	--	62	81
	Summer	93	--	51	53
	Autumn	212	--	97	99
Phaeocystis pouchetii (Nearfield mean, cells L^{-1})	Winter/spring	2,020,000	--	468,000	53,300
	Summer	357	--	72	Absent
	Autumn	2,540	--	317	Absent
Pseudo-nitzschia pungens (Nearfield mean, cells L^{-1})	Winter/spring	21,000	--	6,200	610
	Summer	43,100	--	14,600	54
	Autumn	24,700	--	9,940	1,160
Alexandrium fundyense (Nearfield, cells $L^{-1)}$	Any nearfield sample	100	--	Baseline Max 163	79

As described earlier, DO concentrations in 2010 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 pattern in the nearfield and Stellwagen Basin (**Figure** 2-10). As described previously, the 2010 bottom water DO concentration minimum was quite low in the nearfield; atypically low values were also measured in Stellwagen Basin relative to most baseline and post-diversion means. As in the past these low values were still well above the DO warning level thresholds and background. Minimum DO concentrations and % saturation in the 2010 nearfield and Stellwagen Basin data were generally slightly lower than the baseline and post-diversion means, especially in the summer and fall months. This is partially explained by the high river runoff in March 2010 which led to early, strong stratification in the nearfield and contributed to the lower DO levels in March/April. Mixing and relaxation of stratification in May-June led to relatively consistent bottom water DO levels during those months. As considered previously, the dry warm summer months likely led to warmer, more saline bottom waters and the low DO levels observed. The consistency of these results with prior data again demonstrate that the 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.* 2009a).

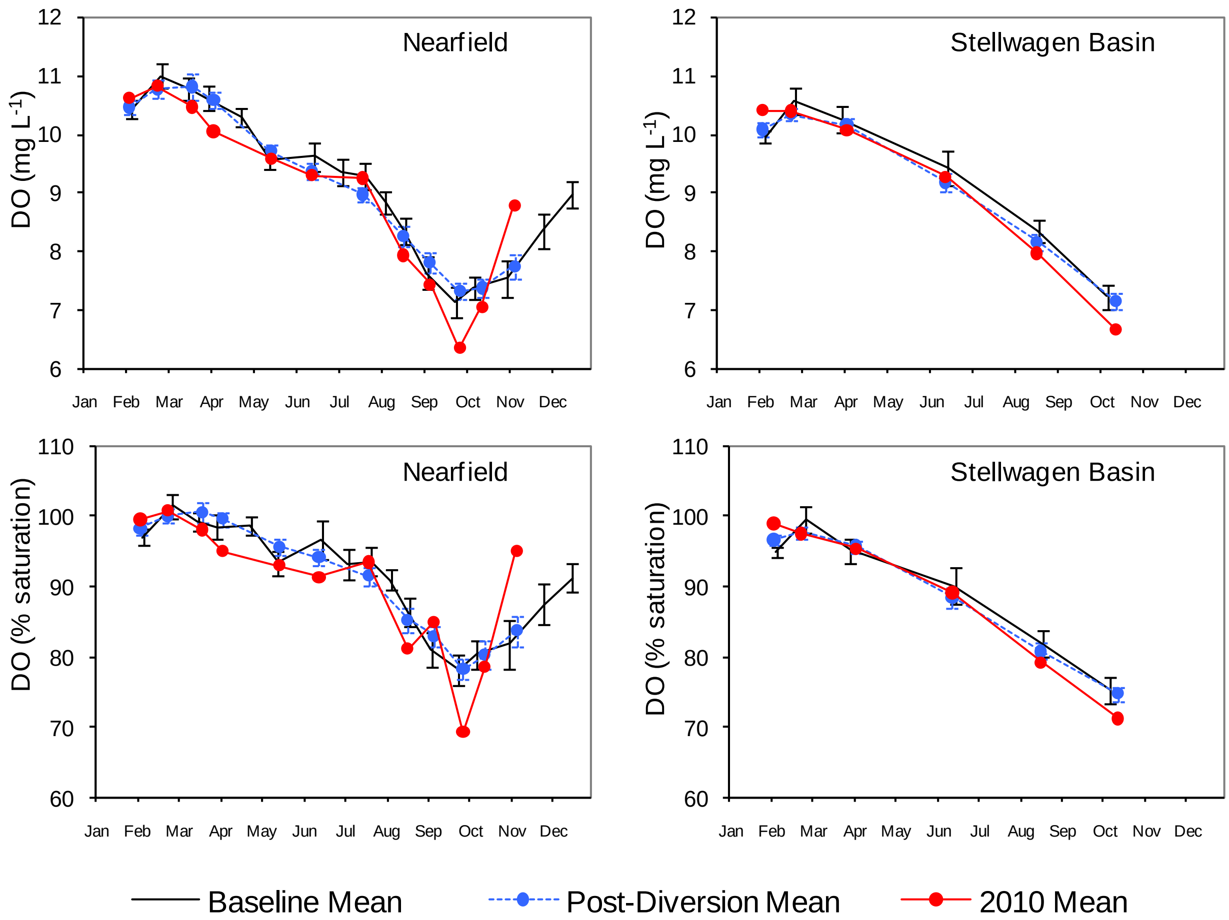

Figure 2-10. Time-series of survey mean bottom water DO concentration (top) and percent saturation (bottom) in the nearfield (left) and Stellwagen Basin (right) during baseline (black), post-diversion (blue), and 2010 (red). Data for Stellwagen Basin collected from stations F12, F17, F19, and F22. Error bars represent ± SE.

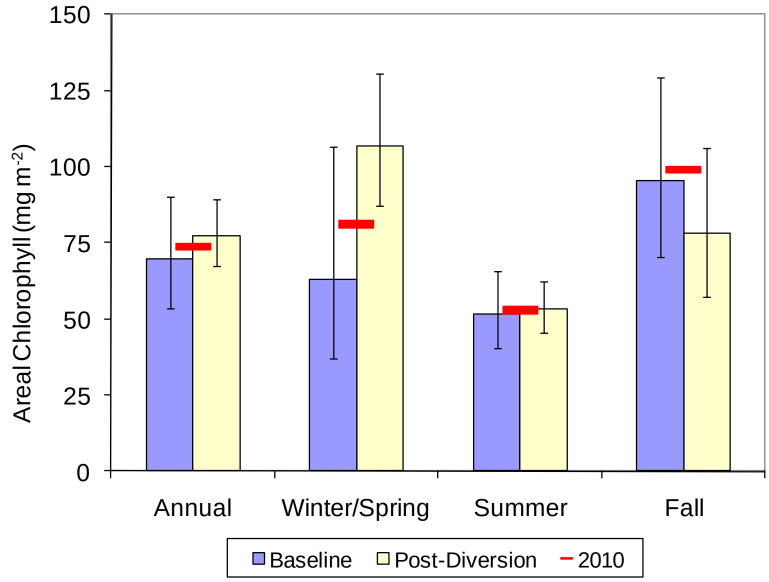

Figure 2-11. Comparison of baseline and post-diversion seasonal and annual mean areal chlorophyll (mg m^{-2}) in the nearfield. Error bars represent ± SE.

The seasonal and annual nearfield mean areal chlorophyll levels for 2010 were comparable to background levels and well below Contingency Plan threshold values (**Table** 2-1). The large April diatom bloom led to a winter/spring mean value of 81 mg m^{-2}, which is greater than the baseline mean, but well below the post-diversion mean when major *Phaeocystis* blooms have dominated the winter/spring seasonal chlorophyll signal (**Figure** 2-11). The summer, fall, and annual 2010 nearfield areal chlorophyll means were also quite low compared to the thresholds and comparable to the baseline and post-diversion means.

Each of the harmful or nuisance phytoplankton species included in the Contingency Plan thresholds (*Phaeocystis pouchetii, Pseudo-nitzschia* spp., and *Alexandrium fundyense*) were observed in 2010; none of the threshold levels were exceeded (**Table** 2-1). As discussed previously, *Phaeocystis* abundance was relatively low in 2010 peaking in late February in Cape Cod Bay (**Figure** 2-6). Nearfield levels were very low (53,300 cells L^{-1} winter/spring mean; **Figure** 2-12) and were higher in February than April (actually absent from the March samples). *Pseudo-nitzschia* was present in very low abundances during each season, as has been the case during the post-diversion period, (Appendix B Slide 19). 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. 2010 *Alexandrium* abundances were also quite low reaching a maximum in the nearfield of 79 cells L^{-1} (**Figure** 2-13). A large *Alexandrium* bloom in Massachusetts Bay in 2010 had been predicted, based on high fall 2009 cyst abundances and the presence of cysts in sediments east of Stellwagen Bank. It is unclear why there was such a big disagreement between the model predictions and actual observations, but current thinking is that the water characteristics in the Gulf of Maine were outside of the range that the model was built upon (McGillicuddy *et al.* 2011). The 2010 *Alexandrium* event in Massachusetts Bay was small, of short duration, and did not lead to any shellfishing closures.

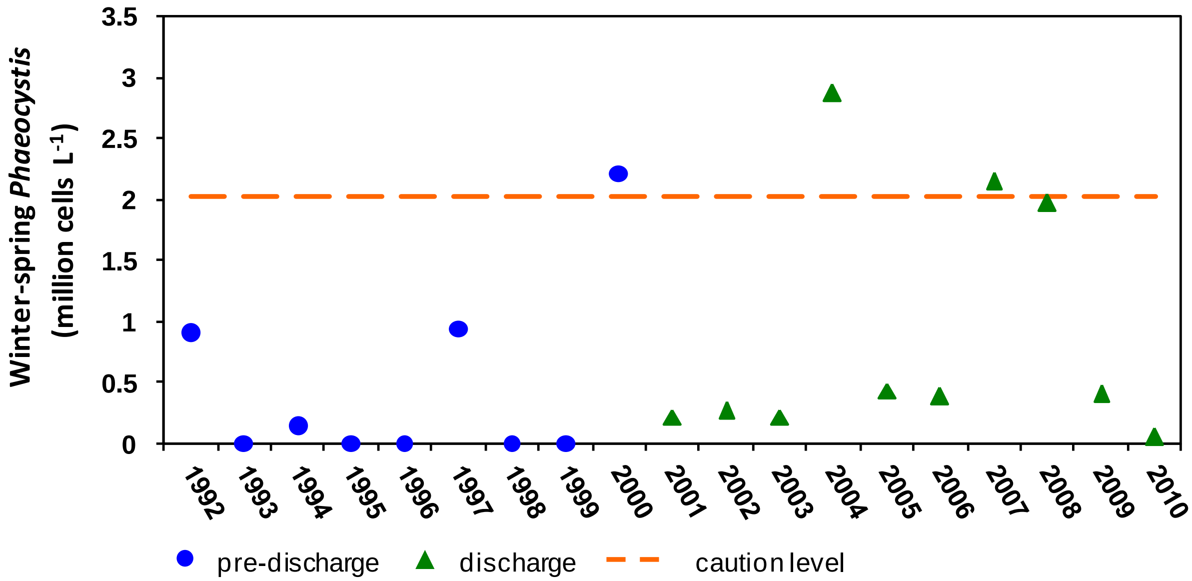

Figure 2-12. Winter/spring seasonal mean nearfield *Phaeocystis* abundance (million cells L^{-1}) for 1992 to 2010. Contingency Plan threshold value shown as dashed line.

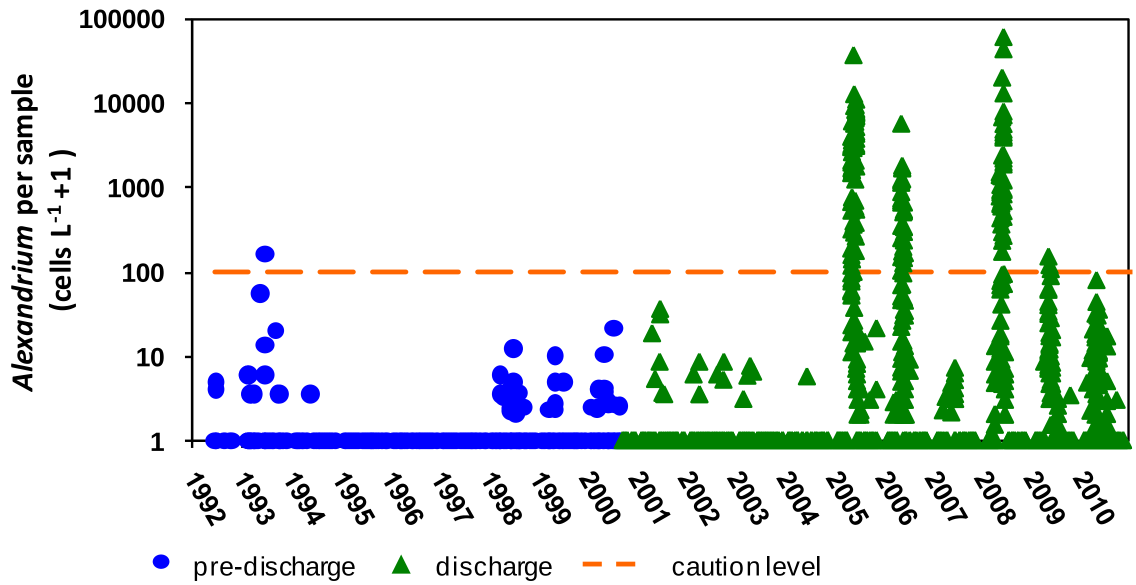

Figure 2-13. Nearfield *Alexandrium* abundance for individual samples (cells L^{-1}; note log axis). Contingency Plan threshold value shown as dashed line.

2.3 INTERANNUAL TRENDS

2.3.1 **Nutrients and Biomass**

The post diversion changes in the nutrient regimes remain clear and consistent with model predictions (Libby *et al.* 2009a, Signell *et al.* 1996). Ammonium (NH_4) dramatically decreased in Boston Harbor and nearby coastal waters and remained low through 2010. The initial increase in nearfield annual mean NH_4 (~1 µM) was much smaller than the decrease in the harbor (~8 µM) due to increased dilution and transport at the bay outfall (**Figure** 2-14). The increase in nitrogen loading to the nearfield area has been observed as elevated NH_4 concentrations above background levels of 1-2 µM up to >10 µM, which have been attributed to sampling within the effluent plume. The NH_4 signature of the plume has generally been observed within 10-20 km of the outfall (**Figure** 2-15) for the past 10 years. One feature of interest is the overall decrease since 2003 in annual mean NH_4 concentrations across the bay, including the nearfield, to levels comparable to the 1990's. The nearfield since diversion has averaged about 1 µM above background (northern boundary) values.

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*. 2009a). Winter/spring chlorophyll has been higher in most of Massachusetts Bay including the nearfield area (**Figure** 2-15 and Appendix B Slides 33 and 35) resulting from regional *Phaeocystis* blooms which have occurred every year since 2000. However, in 2010, the *Phaeocystis* bloom was relatively minor and a large diatom bloom (and elevated chlorophyll) was observed in April.

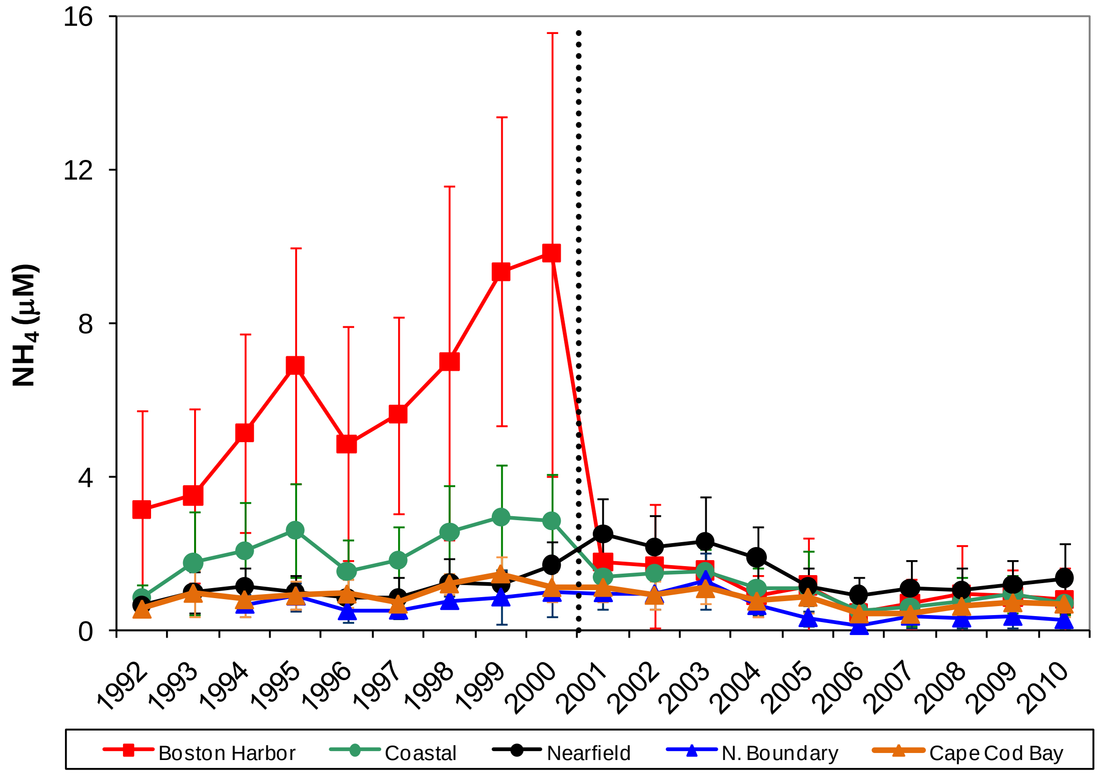

Figure 2-14. Time-series of annual mean NH_4 concentrations (µM) by area. Data collected from all depths and all stations sampled in each area. Error bars represent ±1 standard deviation.

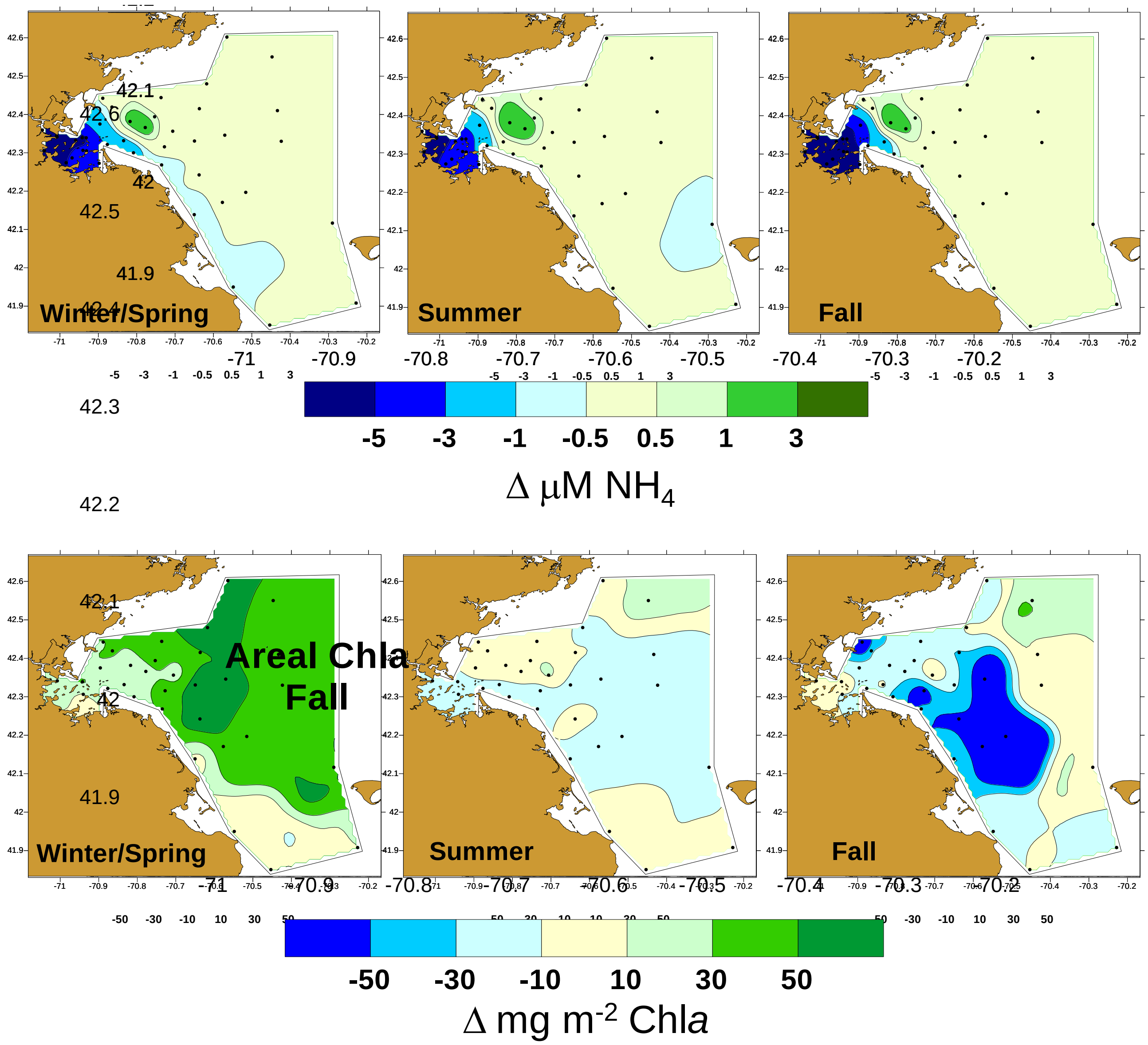

Figure 2-15. Change in seasonal NH_4 concentrations (µM; top row) and areal chlorophyll (mg m^{-2}; bottom row) from baseline to post-diversion. Change calculated as the difference in means over all depths for each season from each station.

A "Before-After, Control-Impact" (BACI) statistical analyses on 1992-2007 NH_4, chlorophyll, and POC 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*. 2009a). NH_4 was higher in the inner nearfield ($p<0.05$). Chlorophyll and POC did not differ ($p>0.05$) 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. As predicted, there was an increase in NH_4 in the nearfield relative to the baseline and also relative to the regional background concentrations (Signell *et al*. 1996). The signature levels of NH_4 in the effluent plume are generally confined to an area within 10-20 km of the outfall. The annual occurrence of consistently large *Phaeocystis* or diatom blooms since 2000 have caused elevated chlorophyll and POC in spring, but those blooms are regional and not caused by the outfall.

2.3.2 Productivity

Data from 2010 marked the completion of the productivity study. Annual production at the Boston Harbor station F23 has decreased by 48% since diversion to the bay outfall ($p<0.05$; **Figure** 2-16). A similar decrease was also observed at nearfield station N18 (30%; $p<0.05$), which is just south of the bay outfall. No change in annual productivity was noted for station N04. Decreases in productivity rates associated with peak seasonal blooms have decreased at similar levels, but the only statistically significant change was a 28% decrease at station N18 for the fall peak productivity ($p<0.05$). **Figure** 2-16 shows apparent decreases in seasonal peak productivity of ~50% for the Boston Harbor station, but the change is not significant due to the high degree of interannual variability in bloom peak production in the harbor.

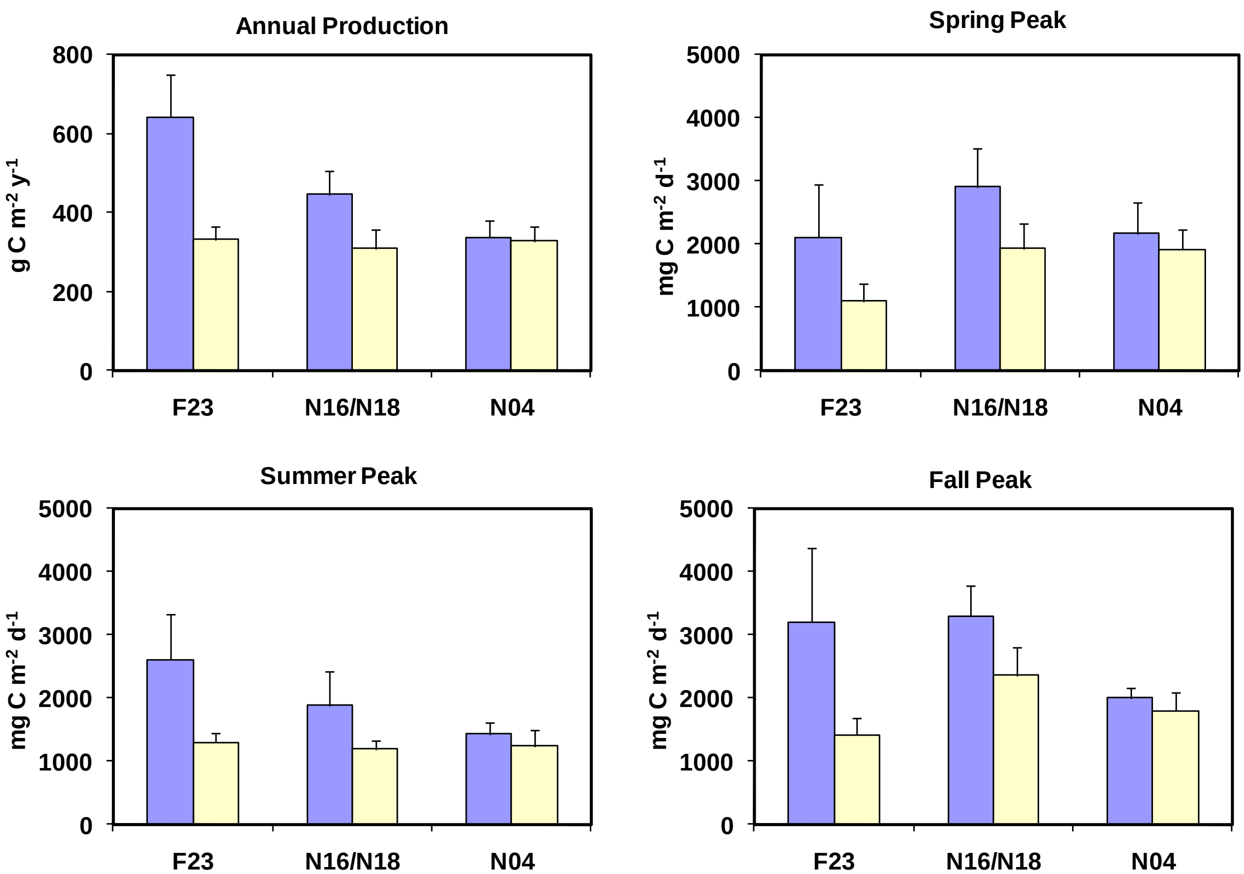

Figure 2-16. Primary productivity for baseline (blue) and post-diversion (yellow): annual production (gC m^{-2} y^{-1}) and seasonal peak productivity for spring, summer, and fall (mgC m^{-2} d^{-1}). The error bars represent +1 standard error.

Although the decrease in annual production at the Boston Harbor station might be expected, the decrease at station N18 is not consistent with the expected response from additional nutrients discharged to the nearfield. A closer look at the data suggests that there is a natural trend in the data with elevated production from 1995 to 2002 and lower levels from 2003 to 2010 (**Figure** 2-17). A comparison of 1995-2002 vs. 2003-2010 annual productivity indicates that there has been a decrease in primary production ($p<0.05$) at all three stations over this time period (50% at F23, 52% at N18, and 34% at N04). There has also been a decrease in peak winter/spring production of 51% at nearfield station N18 and decreases of about 50% in fall peak production at all three stations ($p<0.05$). These decreases 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 similar decreases in productivity at the nearfield stations suggest that a decrease in nutrients in the harbor was not the only factor in the dramatic differences in harbor productivity as the slight increase in NH_4 concentration in the nearfield was expected to increase rather than decrease productivity in this area.

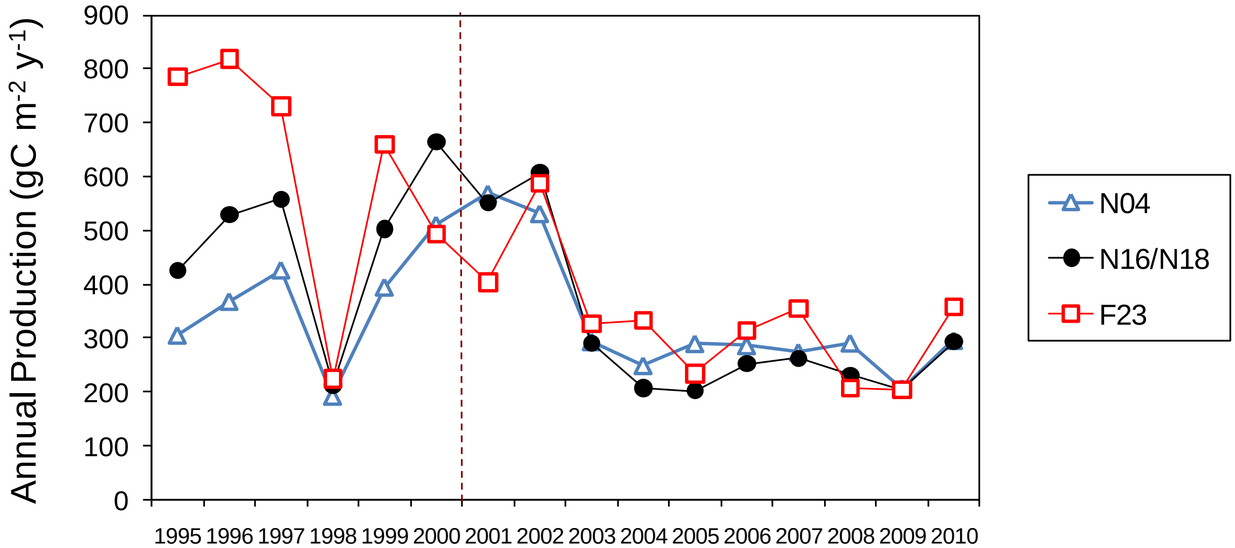

Figure 2-17. Potential annual production (g C m^{-2} y^{-1}) for stations F23, N16/N18, and N04.

Keller *et al.* (2001) note that environmental conditions may play a role in primary productivity with reduced wind speeds contributing to lower productivity in both the harbor and nearfield areas. Examination of the entire data set for all three stations shows the primary production is positively correlated with average summer wind speed and with average summer wind gusts with r^2 values of 0.32 or greater (Appendix C Slides 18 and 19). The mean summer wind speed and the summer average wind gusts were lower in the period 2003 to 2010 compared to the period 1995 to 2002 (Appendix C Slide 21). Overall, both summer wind and gust speed averages have decreased since 1995, but this relationship over time was weaker (r^2 = 0.10 for both; Appendix C Slide 20) when 2010 is added to the correlation analysis. This is apparently due to unusually high wind and gust speeds in 2010; 2010 has the highest speeds seen at NOAA buoy 44013 over the 1995-2010 period. These analyses support Keller et al. (2001) assertions that winds, meteorological, and other environmental factors influence the regional trends observed in primary production in Massachusetts Bay.

Overall, since outfall relocation, the Boston Harbor station has shown a dramatic decrease in productivity consistent with reduced sewage effluent nutrient loading to this station (**Figure** 2-17). The nearfield stations in the vicinity of the new outfall in Massachusetts Bay showed no clear increase or decrease in primary productivity associated with outfall relocation. Years prior to and after relocation had a similar range of productivity. A decrease in productivity in 1998 and since 2003 at the nearfield stations and to some extent at the Boston Harbor station is correlated with climate related reduced wind intensities during these years. The enhanced stratification due to lighter winds has prevented the mixing of subsurface nutrients to fuel primary production during all seasons.

2.3.3 Plankton

The 2010 phytoplankton patterns generally followed observed long-term trends with one notable difference – an increase in winter/spring diatom abundance reversing a long trend of decreasing diatom abundance (**Figure** 2-18 and **Figure** 2-19). Total phytoplankton abundance in the nearfield region of Massachusetts Bay has fluctuated by +/- 20% around the long-term mean level of 1.4 x 10^6 cells L^{-1} during 19 years of monitoring (Appendix D Slide 20). Total phytoplankton levels have been below the long-term mean since 2008, but increased towards long-term mean in 2010. Much of this increase appears to be due to an increase in diatom abundance in 2010 (**Figure** 2-18). 2010 diatom abundance was buoyed by the prolonged and abundant winter-spring bloom and a relatively large and prolonged summer diatom bloom (**Figure** 2-19). These diatom blooms brought 2010 diatom abundance up to the long-term mean of ~300,000 cells L^{-1}.

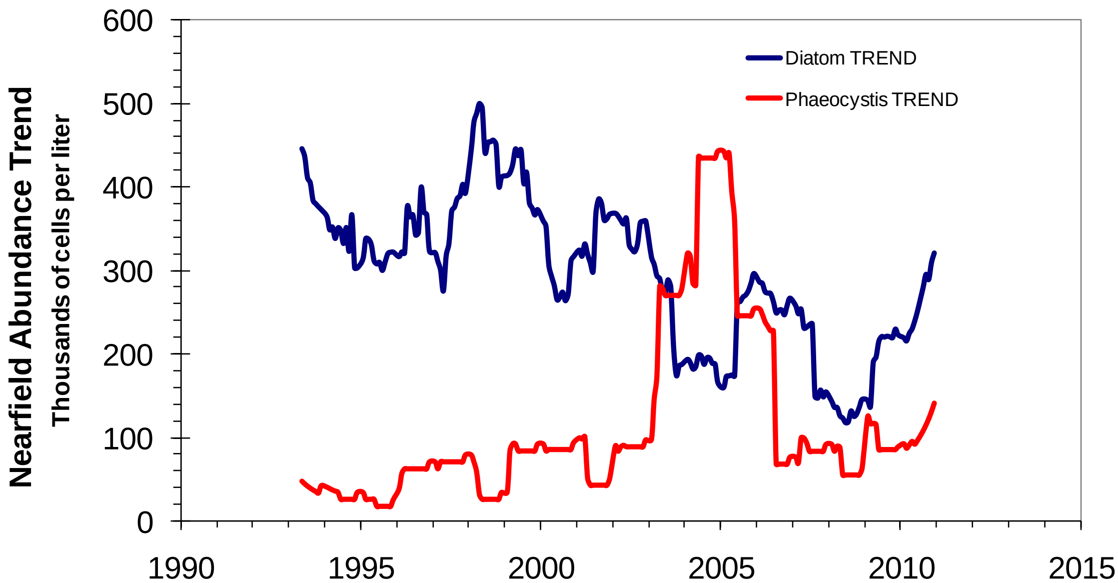

Figure 2-18. Long-term trends (1992-2010) in total diatom and *Phaeocystis* abundance in the nearfield derived from time series analysis. Pearson r value of two trends was -0.47 (p =0.005).

Diatoms displayed oscillations and a long-term decline during the late-1990s through 2008. During 2009 and 2010 diatom abundance appears to rebound to near long-term mean. Moreover, the trends in long-term diatom abundance are inversely correlated to changes in *Phaeocystis* abundance in the nearfield (Pearson's correlation coefficient -0.47, p=0.005; **Figure** 2-18). The decline in diatom abundance from 2004 to 2008 was 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*. 2009b).

Another trend that has been observed since 2006 is that dinoflagellates have been relatively abundant and remained above the long-term mean level (>50,000 cells L^{-1}) during 2010 (Appendix D Slide 24). The recent dinoflagellate increase relative to the long-term mean level appears to be driven by increases in the abundance of smaller dinoflagellates (*Heterocapsa rotundatum*, *Heterocapsa triquetra*, *and Gymnodinium* spp.) and large blooms such as the *Prorocentrum micans* bloom in November 2010 (**Figure** 2-20). A return to increased abundances of C*eratium* spp. during the summer months appears in the in 2009 and 2010 data.

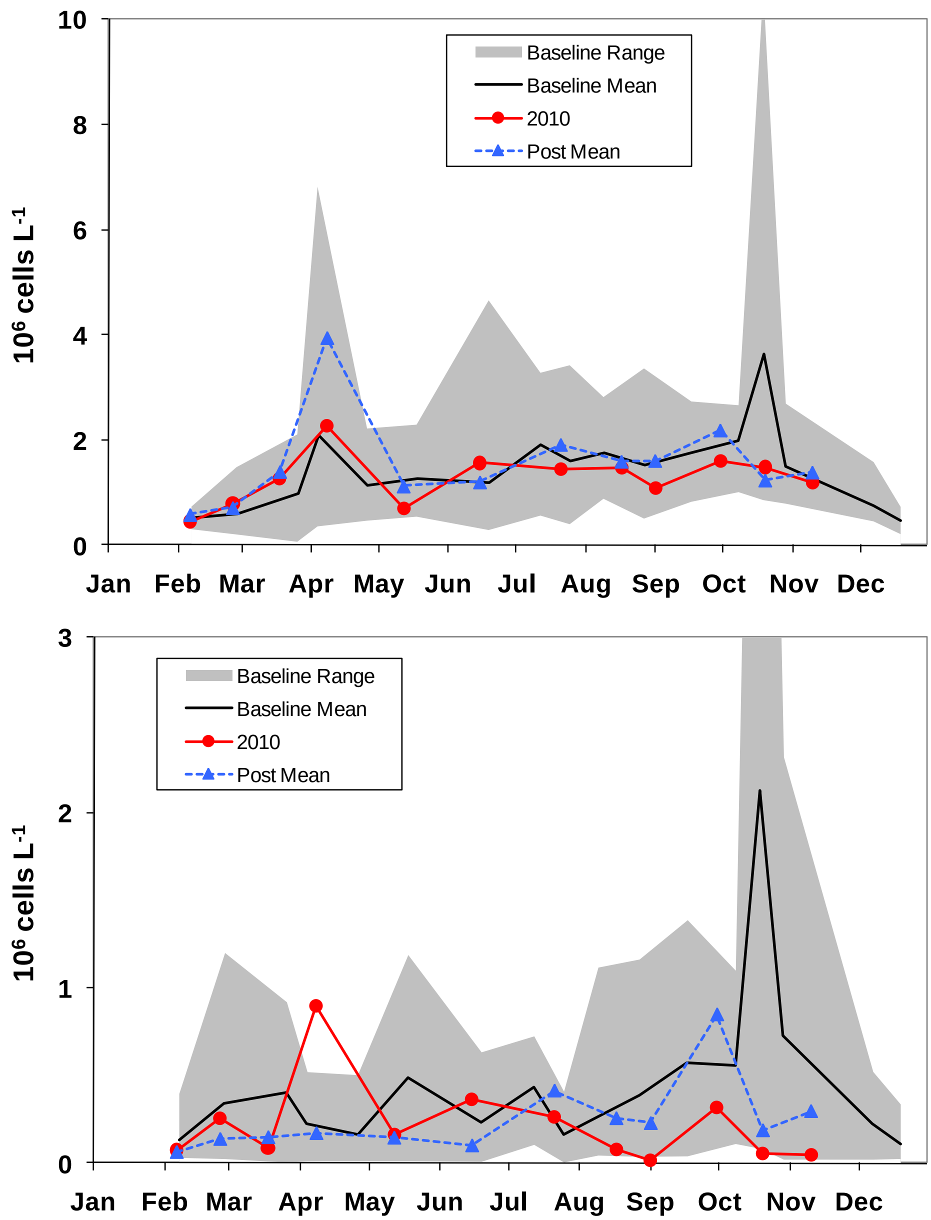

Figure 2-19. Time-series of survey mean total phytoplankton (top) and diatom (bottom) abundance (10^6 cells L^{-1}) in the nearfield in 2010 compared against the baseline range, baseline mean and post-diversion mean.

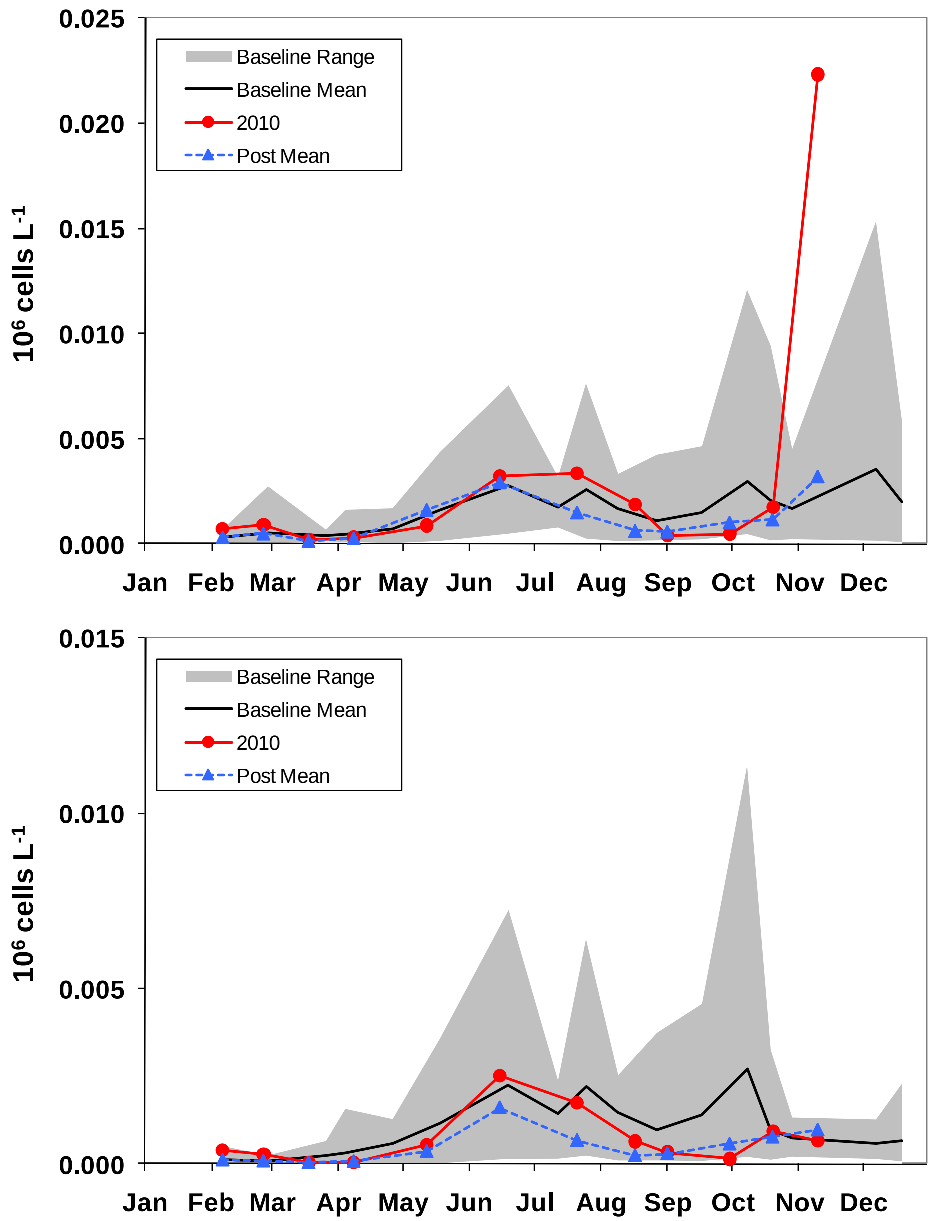

Figure 2-20. Time-series of survey mean total dinoflagellates (top) and *Ceratium* spp. (bottom) abundance (10^6 cells L^{-1}) in the nearfield in 2010 compared against the baseline range, baseline mean and post-diversion mean.

Shifts within the phytoplankton community assemblage associated with above long-term, regional trends have been noted previously (Hunt *et al.* 2010). This long-term data set has enabled observation that diatom and *Phaeocystis* abundance fluctuate in an inverse pattern over periods of multiple years. Dinoflagellates have gone through periods of decreasing and increasing abundance over the course of the monitoring program for the first ten years (1992 – 2003) these trends were also consistent with changes in the relative proportion of large and small dinoflagellates – dominated by fewer, but larger species (e.g. C*eratium* spp.) vs. more plentiful, smaller species (e.g. *Heterocapsa rotundatum*, *Heterocapsa triquetra*, *Gymnodinium* spp., *Prorocentrum micans*). There is no plausible outfall-related link or causality associated with these shifts as they occur over large spatial scales; such long term trends in the phytoplankton community 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 1992-2010 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** 2-21).

Time series analysis indicated that there had been a substantial long-term decline in the total zooplankton abundance in the nearfield from 2001-2006 due to a long-term decline in total copepods (Libby *et al*. 2009a). Total zooplankton and copepod abundances have rebounded somewhat over the last few years (Libby *et al*. 2010) and in 2010 were close to the baseline means for most of the year (**Figure** 2-22). The recent increase in zooplankton/copepod abundance appears to have been led by a rebound in *Oithona* abundance, which in 2010 was well above baseline and post-diversion means for the summer months (**Figure** 2-23). Post-diversion *Calanus finmarchicus* abundances have been at or above baseline levels for the nearfield and continued this trend in early 2010 before decreasing to very low abundances from June –November 2010 (**Figure** 2-23). There is no clear cause for the fluctuations that have been observed in total zooplankton, copepod, or copepod species abundances over 1992-2010. The timing of the decline from 2000 to 2001 (**Figure** 2-21) 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 the decline have emerged from recent studies in the Gulf of Maine and shelf waters of the western North Atlantic which hypothesize that the changes may relate to large-scale climatic phenomena such as freshening of the Northwest Atlantic due to Arctic melting (Greene and Pershing 2007; Pershing *et al*. 2005).

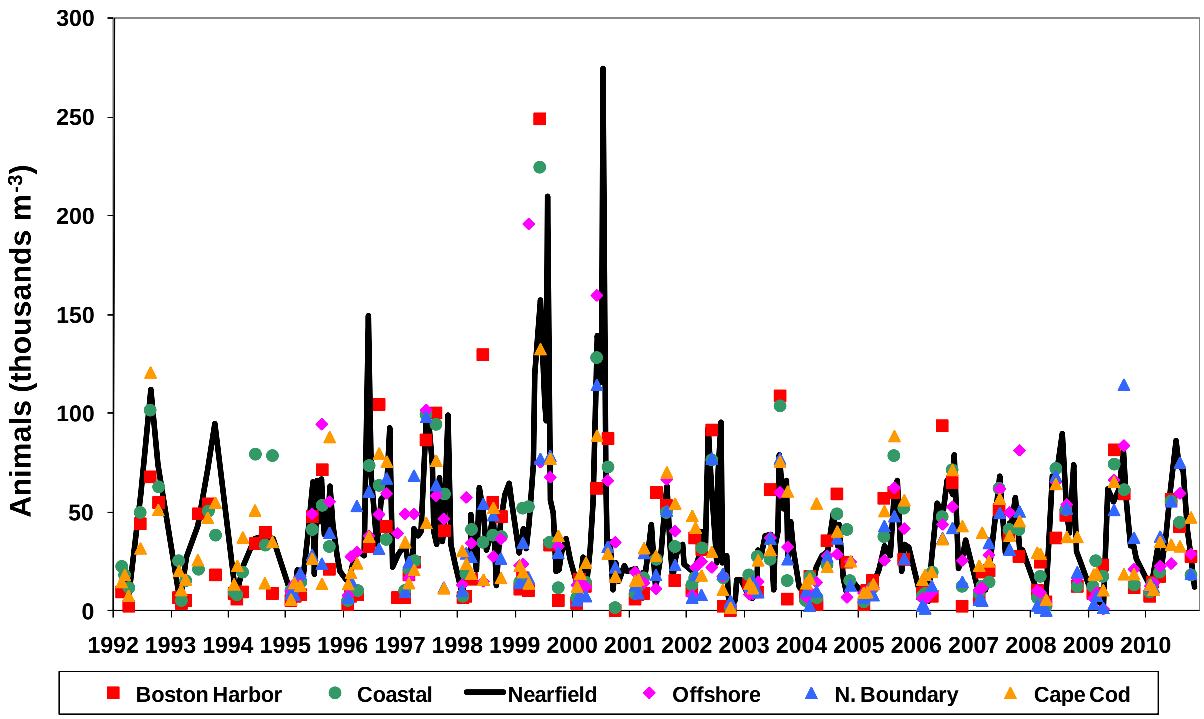

Figure 2-21. Time series of total zooplankton abundance by area (1992- 2010).

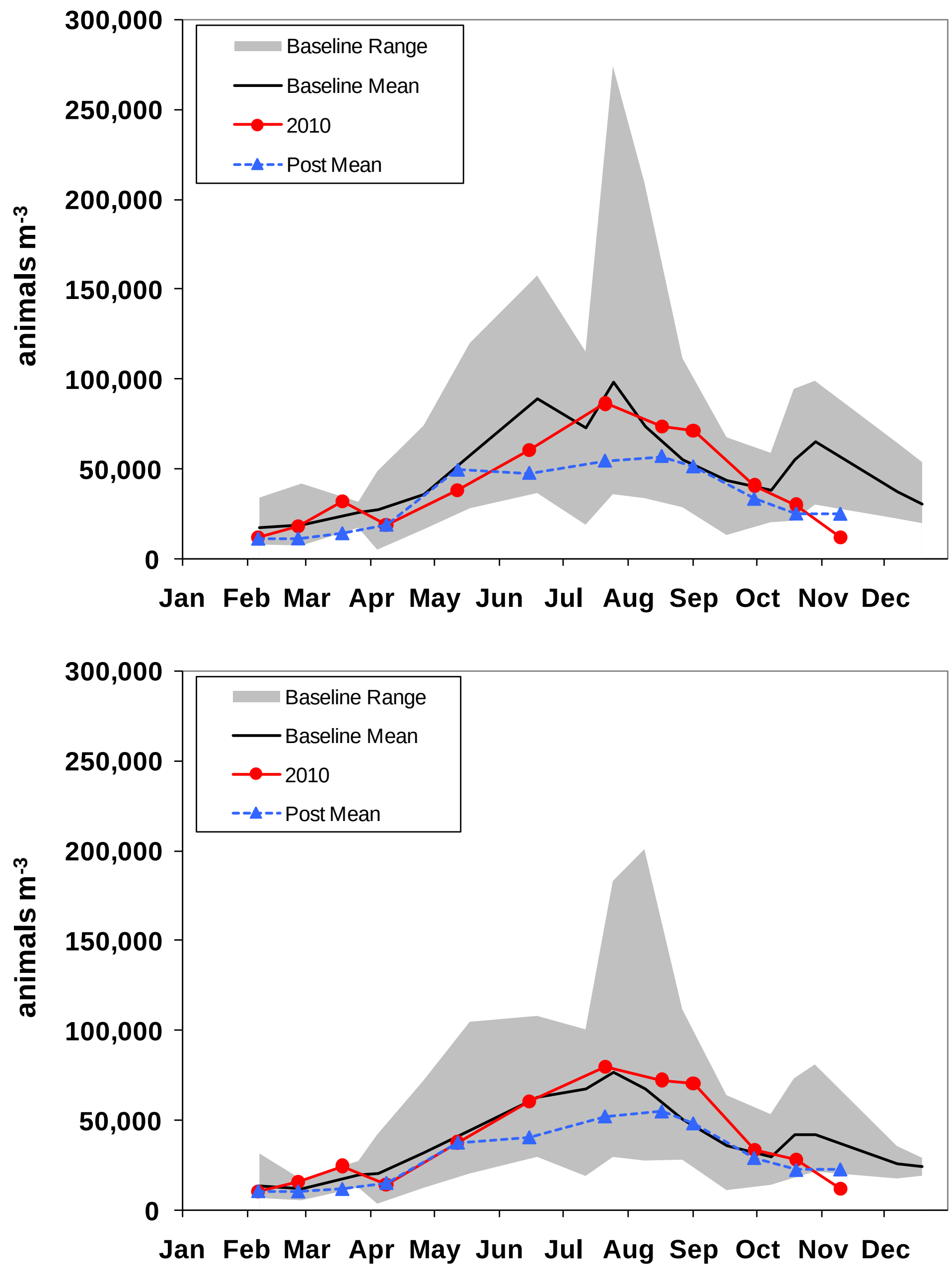

Figure 2-22. Time-series of survey mean total zooplankton (top) and total copepods (bottom) abundance (animals m^{-3}) in the nearfield in 2010 compared against the baseline range, baseline mean and post-diversion mean.

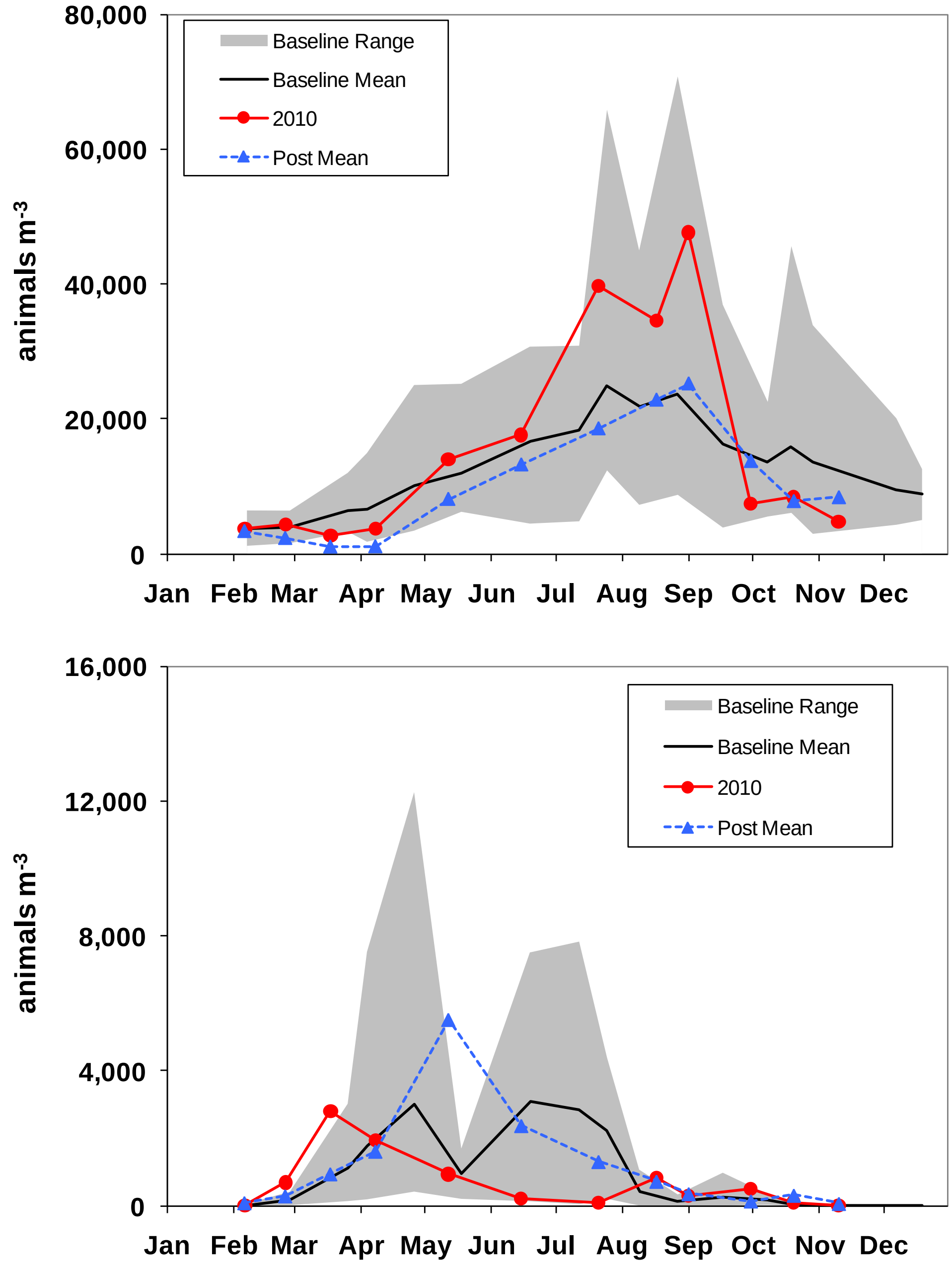

Figure 2-23. Time-series of survey mean *Oithona similis* (top) and *Calanus finmarchicus* (bottom) abundance (animals m^{-3}) in the nearfield in 2010 compared against the baseline range, baseline mean and post-diversion mean.

3 SUMMARY

In general, water column conditions in 2010 exhibited typical seasonal patterns observed over the course of the monitoring program (1992-2009). Mean annual and mean seasonal values of many variables for 2010 were close to the averages over all years including: winds, temperature, nutrients, phytoplankton biomass, dissolved oxygen and zooplankton abundance and community structure. The most notable characteristics of the physical environment in 2010 were the record-setting precipitation in March accompanied by stormy conditions and associated high river flow, and then the very dry summer period, both of which were record levels (high and low river flow) for the 1992-2010 period. The fall was also unusually stormy. The wet spring contributed additional nutrients to the system in March/April. The dry conditions in the summer combined with relatively high water temperatures led to lower than usual dissolved oxygen levels in nearfield bottom waters in late summer/early fall. Stormy conditions contributed to the seasonal turnover of the water column in the fall ending the seasonal DO decline.

As usual, nutrient concentrations were at a maximum in February, but were lower than typically observed and much lower than February 2008 and 2009 levels. The bay wide presence of diatoms in February likely contributed to these low levels of nutrients. There was a decline in nutrient levels from February to June coincident with March and April diatom and *Phaeocystis* blooms although the timing of occurrence and magnitude of these blooms varied by area in the bays. Nutrient concentrations were lowest in the summer and then increased in the fall. The main features of the phytoplankton biomass pattern were the winter/spring diatom and *Phaeocystis* blooms, as well as inshore diatom blooms in summer (observed in the harbor, coastal, and nearfield 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 blooms, except for the harbor where these parameters reached maxima in June. There were no Contingency Plan caution threshold exceedances in 2010. There had been a forecast of a major *Alexandrium* bloom for 2010 based on fall 2009 cyst distributions, but the large bloom did not materialize and only low abundances of *Alexandrium* were observed in the bay and no paralytic shellfish poison (PSP) toxicity closures occurred in Massachusetts Bay in 2010. Overall, the water column characteristics in 2010 were comparable to those observed during the baseline and post-diversion periods.

There are clear changes in the nutrient regimes following diversion – NH_4 concentrations have dramatically decreased in Boston Harbor and nearby coastal waters while increasing slightly in the nearfield (the changes are consistent with model predictions made during the planning process). The signature levels of NH_4 in the effluent plume are generally confined to an area within 10-20 km of the outfall. The higher nearfield NH_4 concentrations, however, have not been manifested as 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). Since diversion, the harbor has often exhibited patterns in these parameters (and productivity) that are comparable to those observed in the nearfield and other temperate coastal waters (Libby *et al.* 2009a). Overall, the decreases in nutrients appear to be associated with a decrease in biomass and productivity in Boston Harbor; for the bay the association between observed nutrient and phytoplankton biomass changes is not as clear.

Before-After-Control-Impact statistical analyses based on stations and groups of stations has shown 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 seasons (Libby *et al*. 2009a). 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.

Annual productivity has decreased at both Boston Harbor station F23 and nearfield station N18 from baseline levels by 48% and 30%, respectively. Although the decrease in annual production at the harbor station might be expected given the decrease in nutrient loading, the decrease at station N18 is not consistent with the anticipated effect of providing additional nutrients to the nearfield. This statistical analysis was conducted on data showing a long term trend with a large decrease in production from 2002 to 2003 a few years after the bay outfall went online. A comparison of 1995-2002 vs. 2003-2010 productivity data indicated decreases in annual production at all three stations(34-52%), peak winter/spring production at station N18 (51%), and peak fall production at all three stations (50%). Although the reduced nutrient loading to Boston Harbor has likely played a role in the decreased productivity measured at station F23, similar decreases in productivity at the nearfield stations suggest that other environmental factors, local or regional, may be driving these patterns in primary production in Massachusetts Bay.

There have been shifts within the phytoplankton community assemblage that are associated with long-term, regional trends. It appears that diatom and *Phaeocystis* abundance fluctuate in an inverse pattern over periods of multiple years. Dinoflagellates have gone through periods of decreasing and increasing abundance from 1992-2010 and for the first ten years these trends were also consistent with changes in the relative proportion of large and small dinoflagellates – dominated by fewer, but larger species (e.g. C*eratium* spp.) vs. more plentiful, smaller species (e.g. *Heterocapsa rotundatum*, *Heterocapsa triquetra*, *Gymnodinium* spp., *Prorocentrum micans*). 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.

There was a general decline in total zooplankton (mainly copepods) in the nearfield and Massachusetts Bay from 2001 to 2006 followed by a rebound in 2007-2010. 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).

APPENDICES

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APPENDICES

A. Summary of Physical Processes Influencing Massachusetts Bay, 2010

Rocky Geyer, Woods Hole Oceanographic Institution

A.1. Overview

The notable conditions in 2010 were record-setting rains in the Boston area during March, followed by very low precipitation in the summer. The high precipitation was accompanied by stormier than usual conditions in March. The fall was also unusually stormy. The dissolved oxygen got lower than usual, due both to warmer than usual bottom temperatures and saltier than normal bottom water. The high salinity is in part due to the dry conditions during the summer.

A.2. Forcing variables

Air temperature (**slide 3**) followed the normal seasonal pattern. Some large fluctuations in the spring and fall were related to passage of storms. Approximately one month of data was missing from the NOAA Massachusetts Bay buoy (44013), so this interval was patched with data from the GOMOOS A buoy. The two data sets are highly correlated for overlapping time periods.

River flow (**slide 4**) was record-setting (for the interval 1992-2010) for the months Jan-Mar for both the Merrimack and the Charles. Most of this precipitation came in three storms, in the beginning, middle and end of March. The flow levels dropped off rapidly after the last March storm, and the months of Jul-Sep were exceptionally dry. The fall was normal. The timeseries of river discharge (**slide 6**) shows that the peak in discharge of the Charles of 100 m^3/s was the highest observed during the monitoring program. The long-term plot of annual-average precipitation (**slide 7**) indicates that we may be at the end of the wet period that peaked between 2005 and 2008, based on the Merrimack discharge. The Charles is smaller, so its interannual variability is noisier.

Winds showed strong downwelling in the early spring and fall (**slide 8**), in association with the storminess during those periods. Persistent, weak upwelling occurred during the summer. Only one weak northeasterly storm occurred during May (**slide 14**). This means that the Alexandrium cells would probably not enter the bay in large numbers.

Waves were larger than normal during March, in association with the storms during that period (**slide** 9). There were also a number of significant fall storms that resulted in intervals of rough conditions from September to December.

A.3. Water properties

Note that all MWRA water column data presented and discussed in this abstract are based on the averages of near surface or near bottom sampling depths from stations N16, N18 and N20 (stations closest to the bay outfall).

Surface water temperature (**slides 11** and **12**) showed warmer than normal near-bottom temperatures at the end of the stratified period. In fact these are the highest near-bottom temperatures recorded during the monitoring program. The continuous NOAA data (**slide 13**) showed the typical variability, although it was warmer than normal during the spring, with considerable variability associated with storm passage (**slide 14**).

The warm bottom water temperature observed during the late August observations (**slide 12**) might be explained by the intense downwelling event that occurred around August 25 (**slide 15**).

Salinity was substantially lower than average during March and April (**slide** 1**8**), due to the record freshwater inflow. The salinity still did not get as low as in 1998, which recorded the lowest salinities of the record.

Stratification was established early and became anomalously strong during March and April (**slides 19** and **20**) due to the freshwater input. It dropped off early due to the strong storm at the end of August.

Dissolved oxygen got down to nearly 6 mg/l at the end of September in the near-field bottom water (**slide 22**, **23**). This is the fourth lowest dissolved oxygen observed during the monitoring program. The low dissolved oxygen is explained in part by the warm near-bottom waters (**slide 23**) and high salinity (**slide 24**), which have been shown to be correlated with low near-bottom dissolved oxygen in prior years. The regression model (**slide 25**) indicated that both temperature and salinity should have generated negative anomalies, but the observed DO anomaly is almost twice as large as predicted. Apparently some other factor also contributed to the low dissolved oxygen in 2010.

The timeseries data from the GOMOOS A buoy provide short-timescale resolution of the deep dissolved oxygen at the mouth of Massachusetts Bay (**slide 26**). The only notable feature of the seasonal decrease in DO was how steady it was. Comparing 2010 to 2009 (**slide 27**), the rates were similar, but there were fewer upticks in 2010 during early fall mixing events, so the minimum DO was lower in 2010. The differences in forcing and in overall DO levels were quite small.

slide 1

Massachusetts Bay
Physics 2010

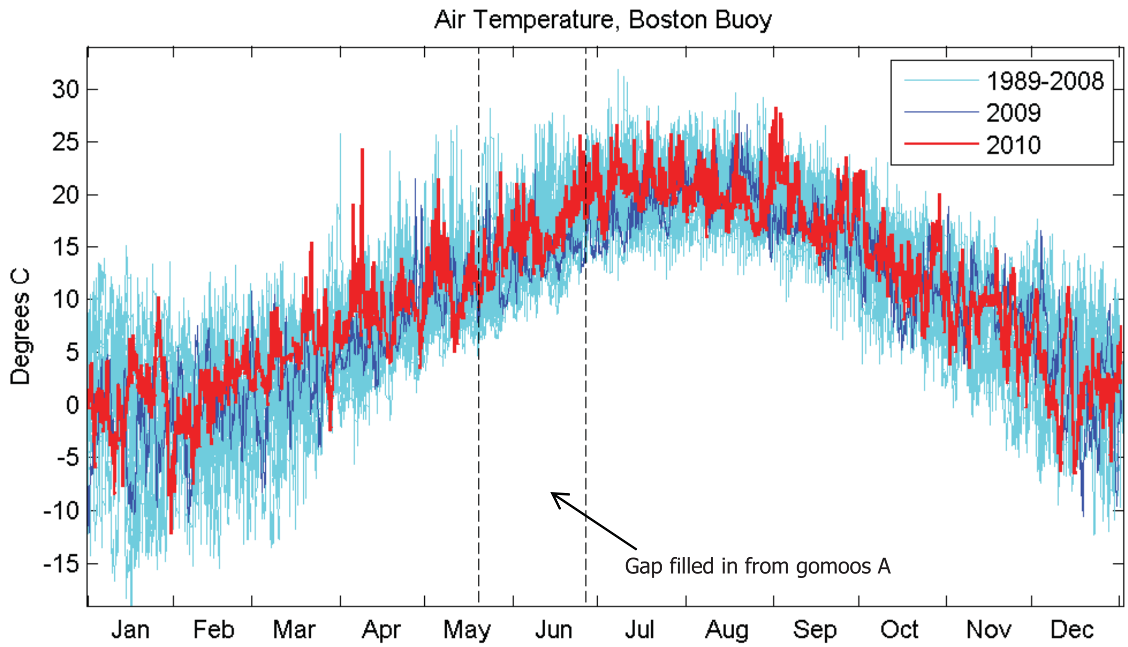
Rocky Geyer

Woods Hole Oceanographic Institution

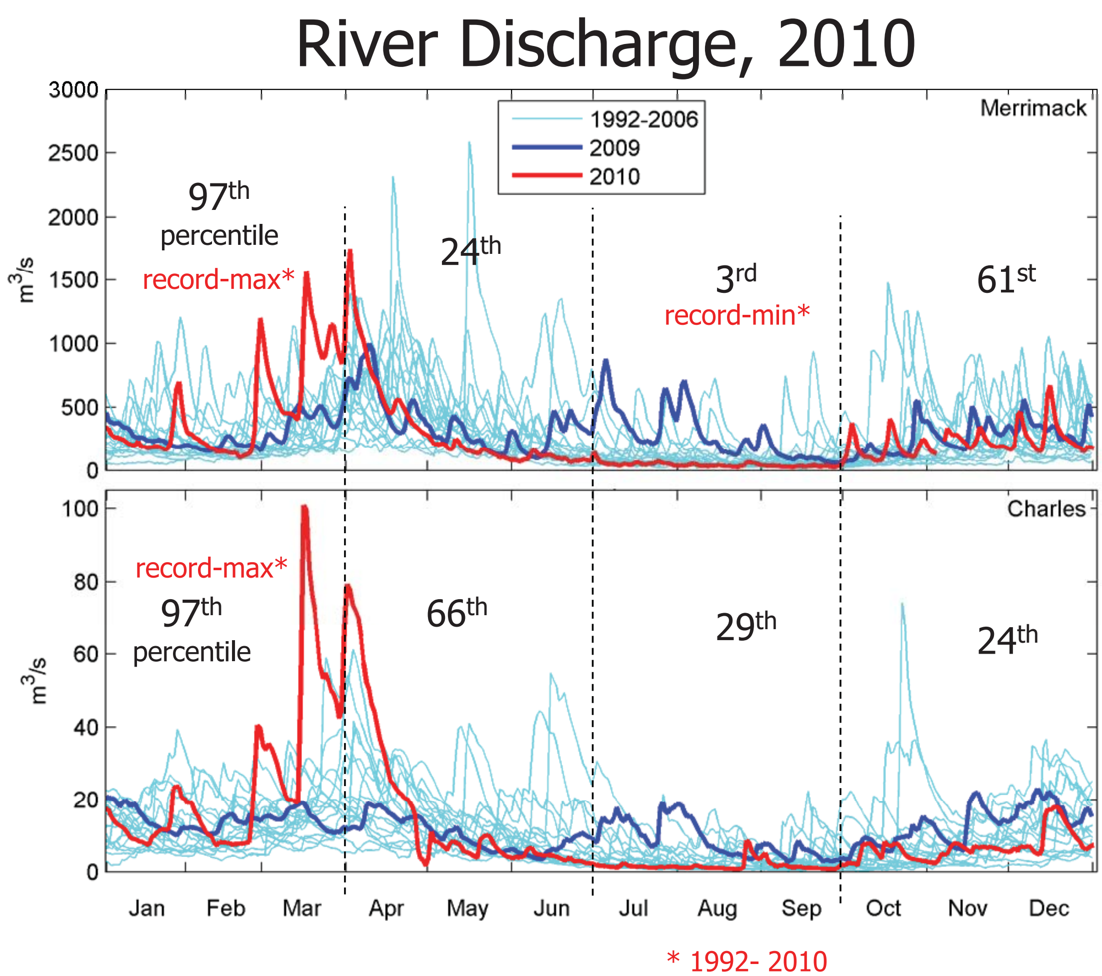
slide 2

forcing conditions

slide 3



slide 4



slide 5

A record-setting March

In the span of a few weeks, March brought New England two storms that slammed the region with record amounts of rainfall, causing flooding, evacuations, and much damage.

(Wendy Maeda/Globe Staff)

Dana Knight and his daughter, Emily, 2, surveyed the waters surrounding their home in Framingham.

MARCH 29-31

Obama thanks flood workers as area waits for waters to recede

Governor Patrick briefed President Obama during a visit to flood-fighting headquarters in Framingham. Obama also thanked relief workers for their efforts. (Boston Globe, 4/2/10)

- Rain abates, but rivers continue to rise
- IRS deadline eased for flood victims
- Freetown regroups | Quincy offers relief
- In Fall River, Clinton, hope sinks
- As waters rise, state gets federal aid
- GRAPHIC Flood recovery | Wettest March
- Wading through crisis: Storm wreaks havoc

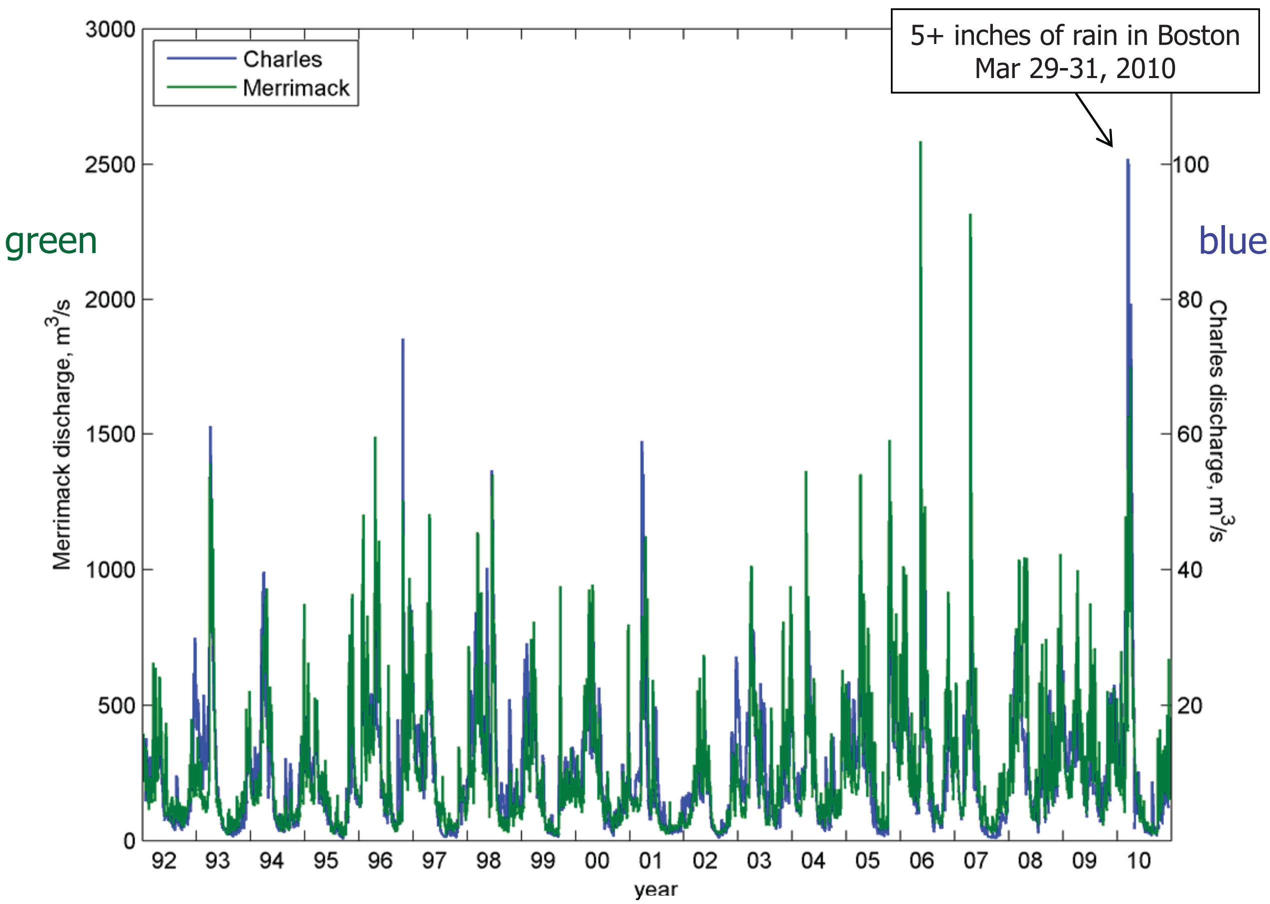
MARCH 13-15

A deluge of misery

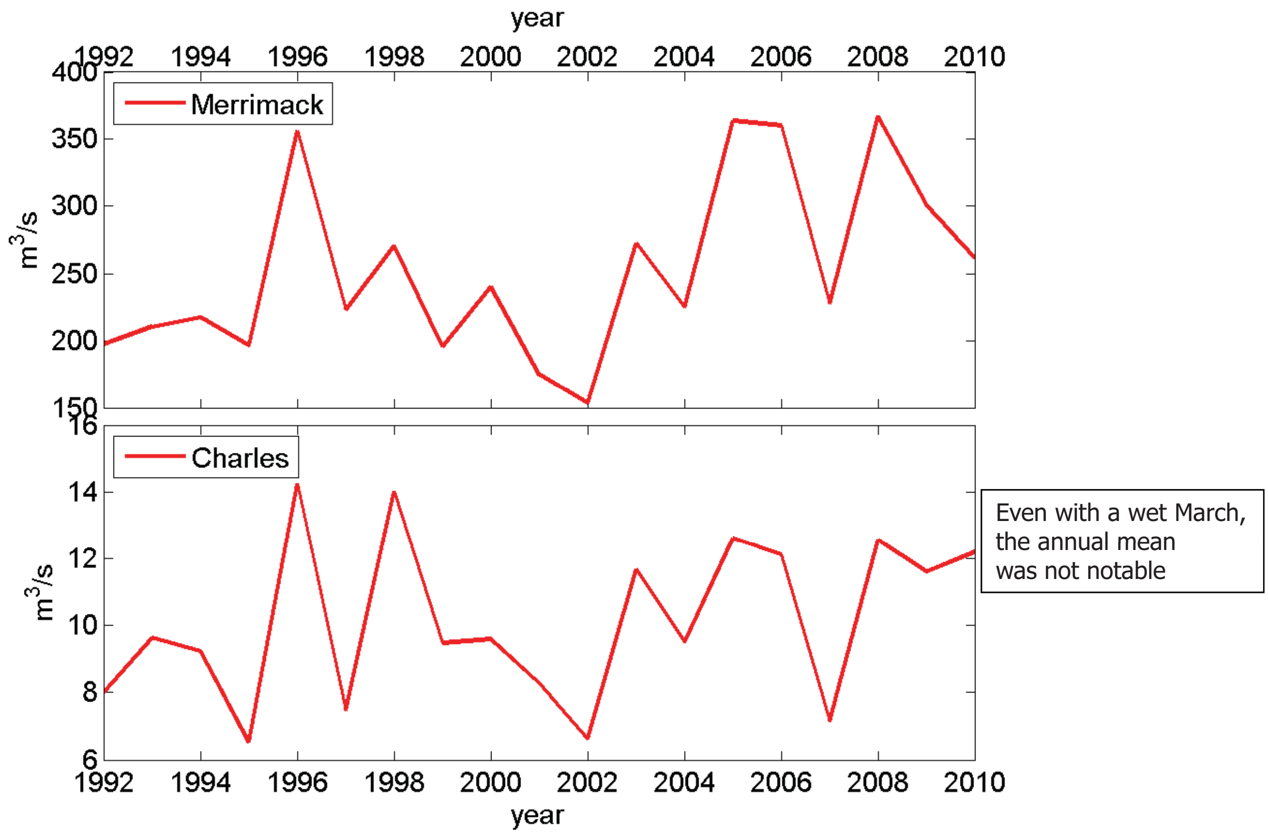
The unusually persistent late-winter storm dropped more than 10 inches of rain on Boston over a 72-hour span and prompted a release of untreated sewage into Quincy Bay. (Boston Globe, 3/16/10)

- Sewage release brings calls for answers
- Cleanup from flooding to be slow
- Many must fend for themselves
- After deluge, mop-up continues
- Waltham museum damaged
- Newton City Hall damaged, files lost

slide 6

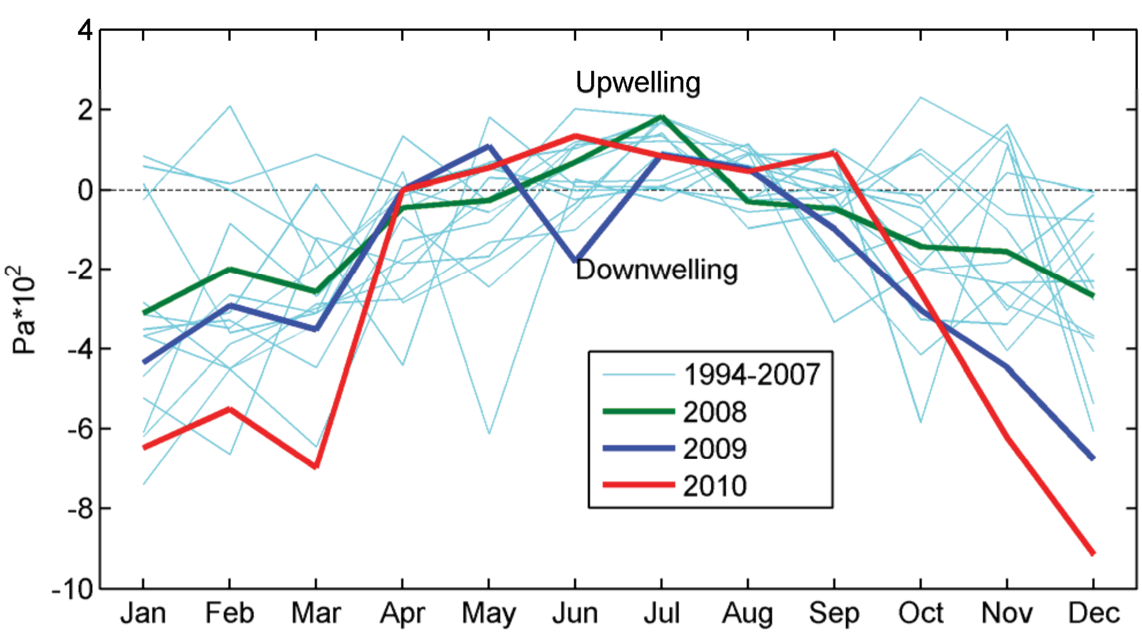


slide 7



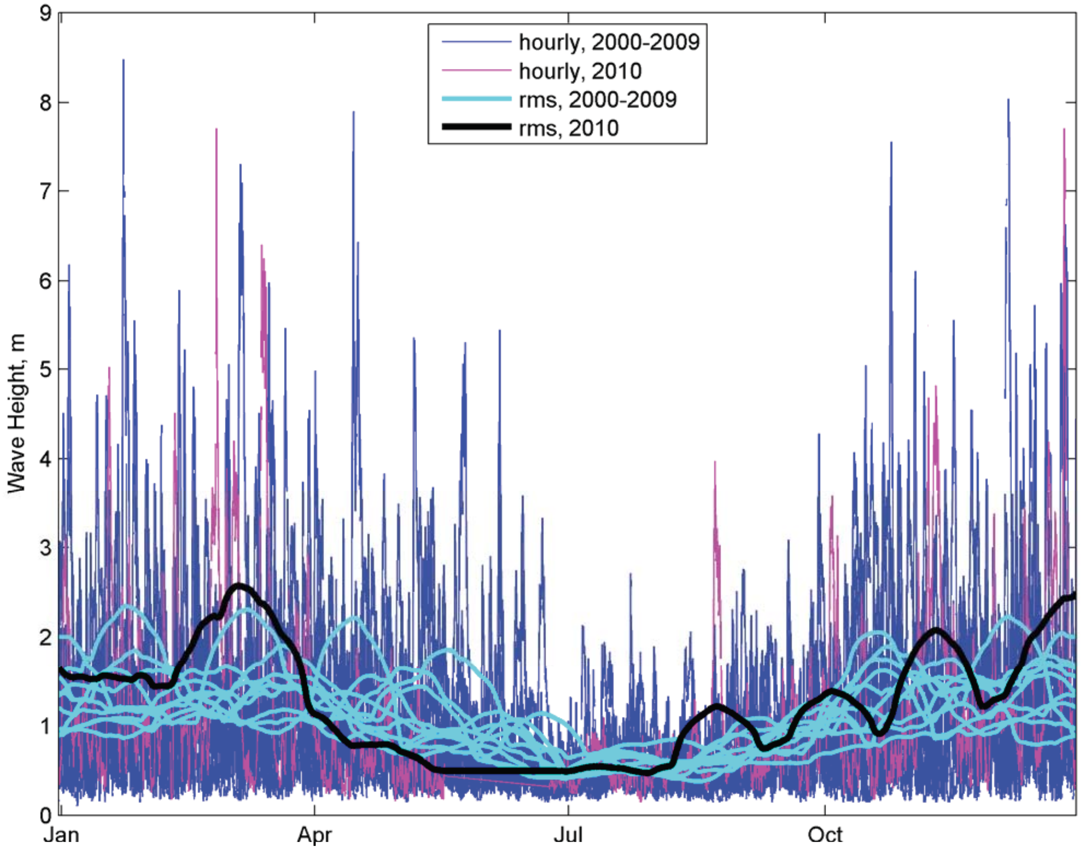
slide 8

Upwelling index, 2010



Wave Height

slide 9

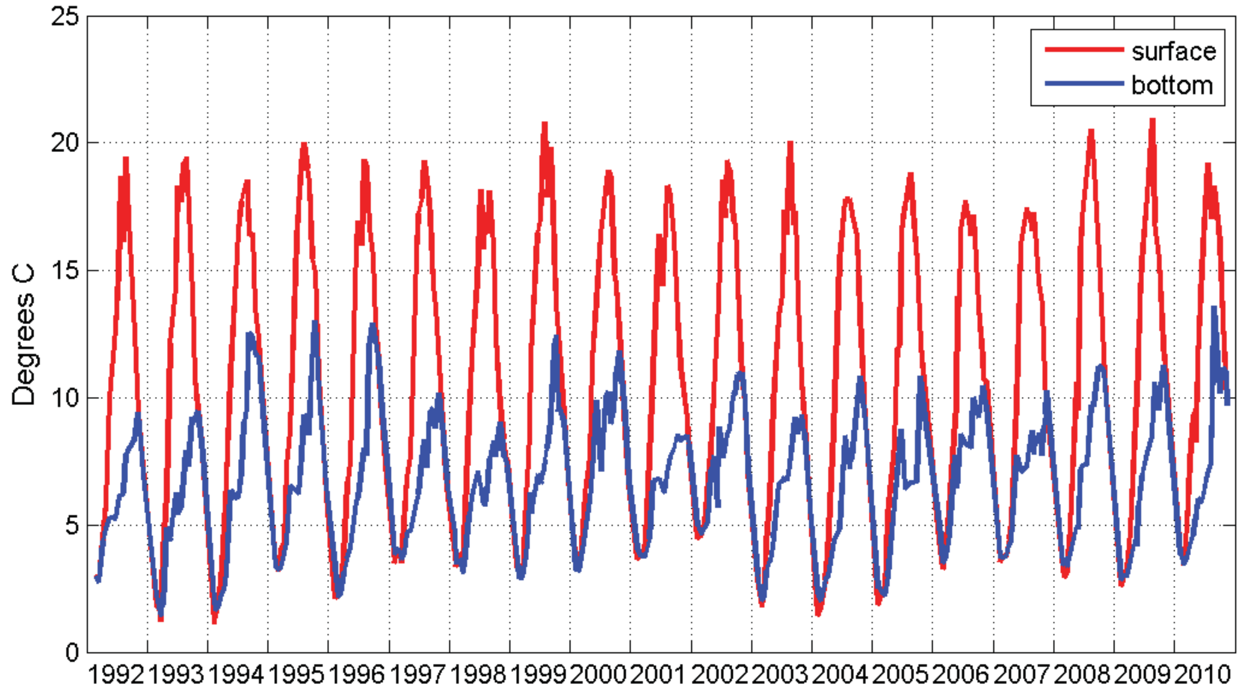


slide 10

water properties

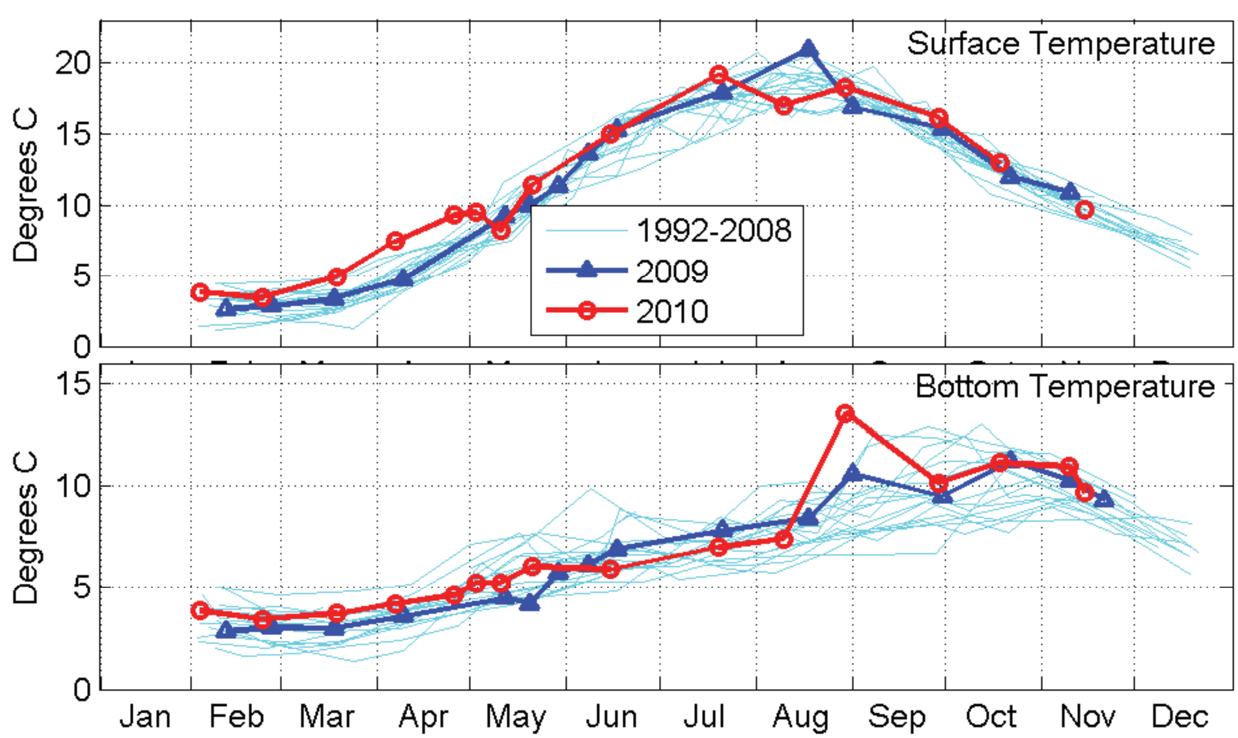
slide 11

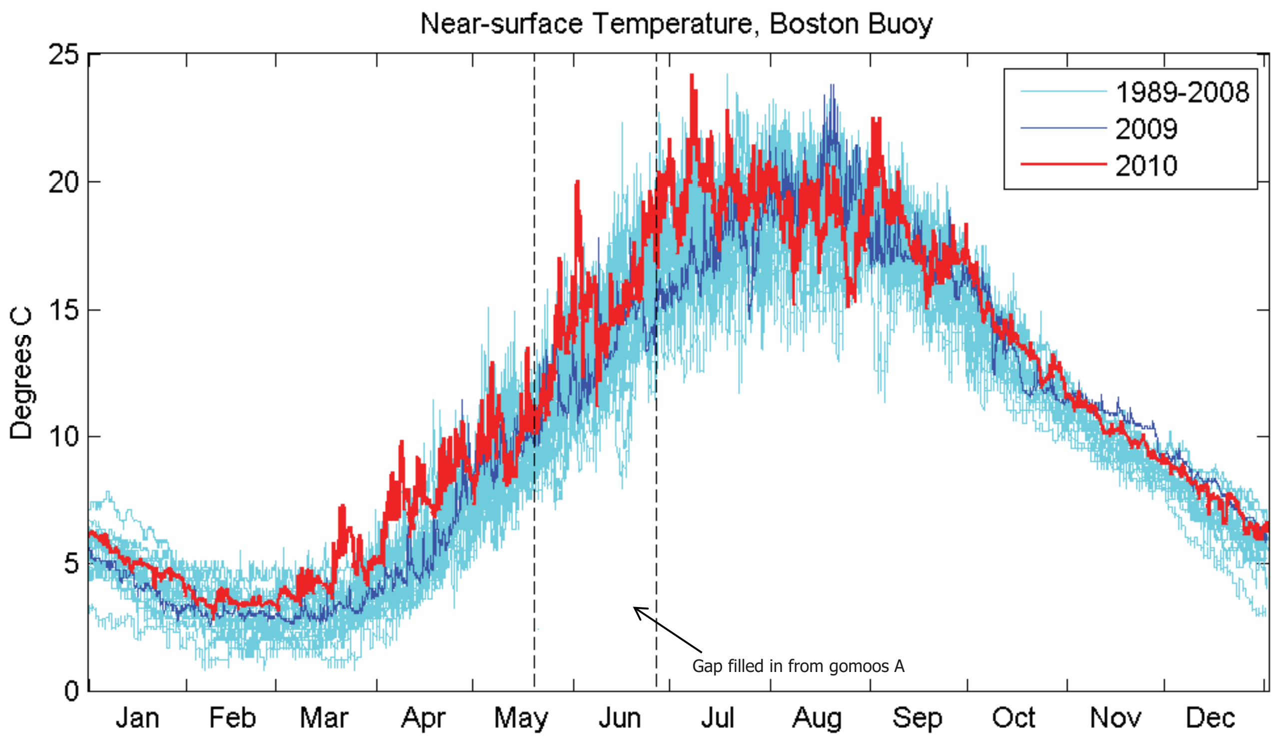
water temperature



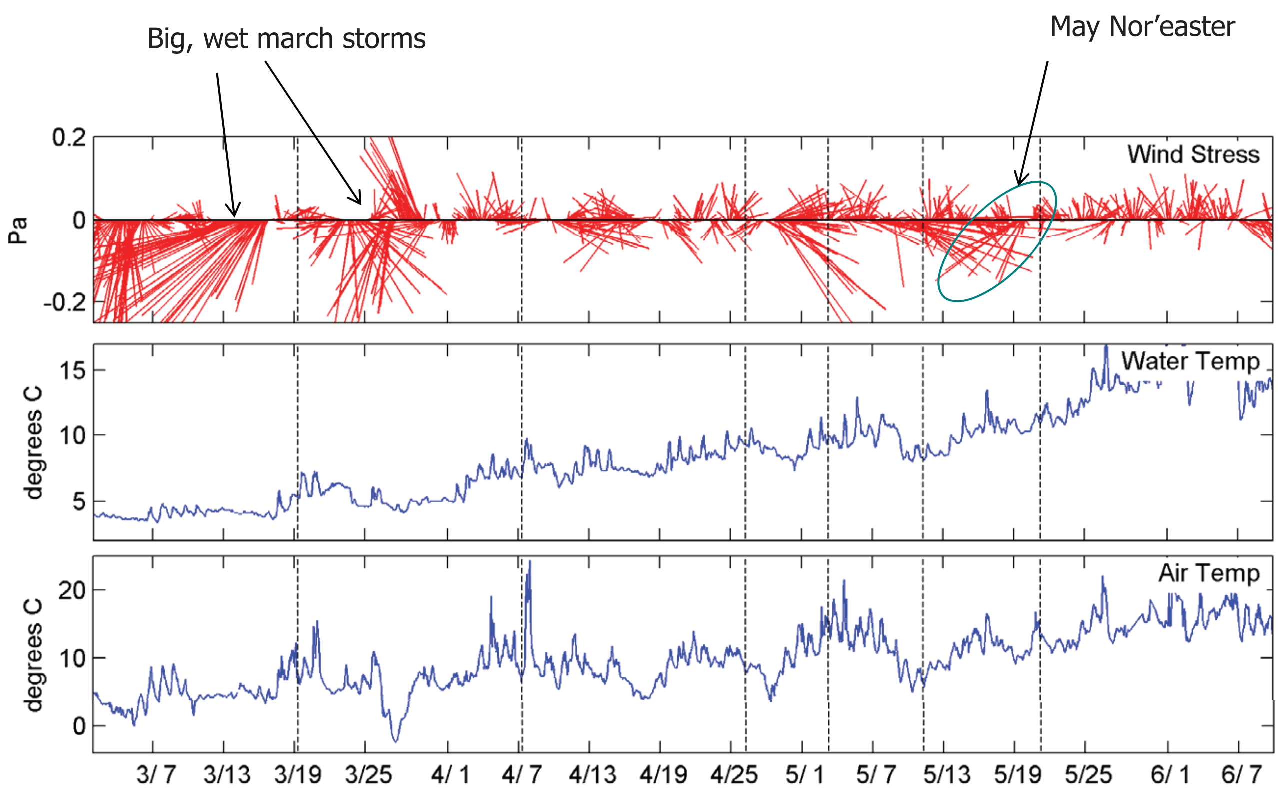
slide 12

water temperature



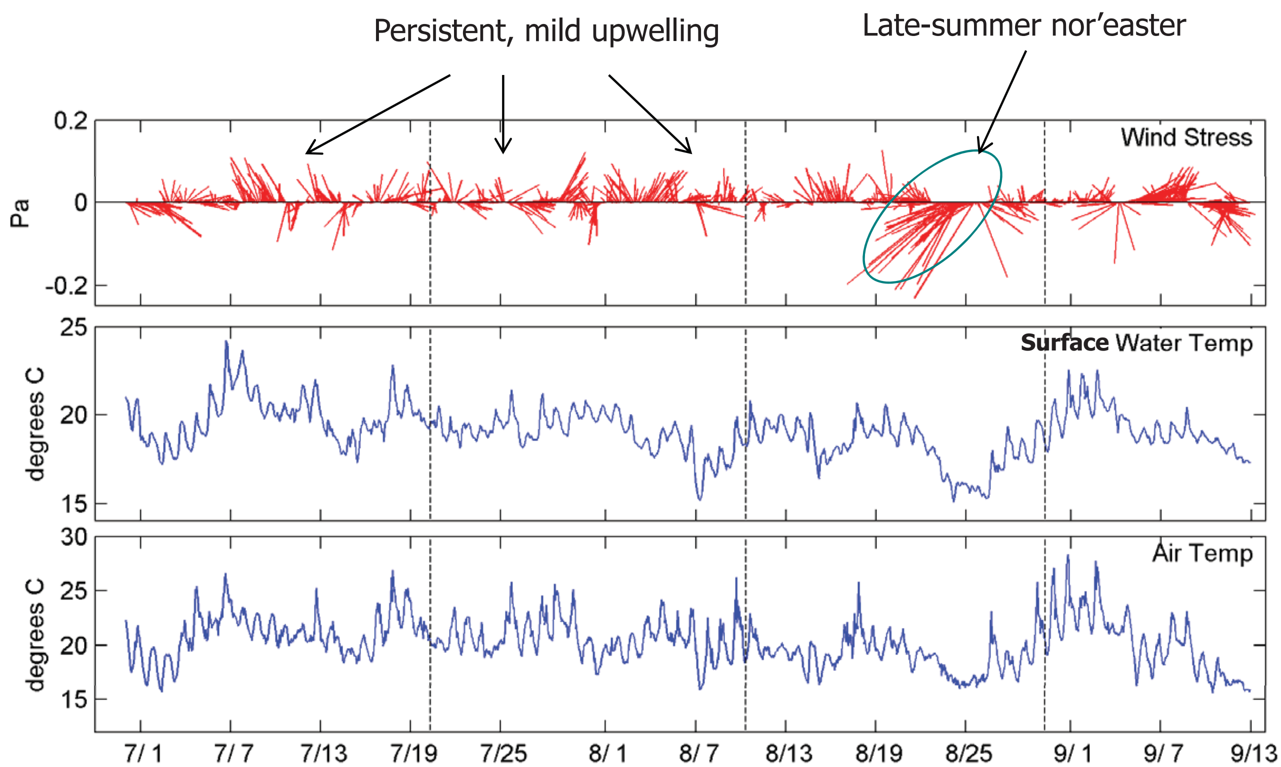


spring winds and water temperature



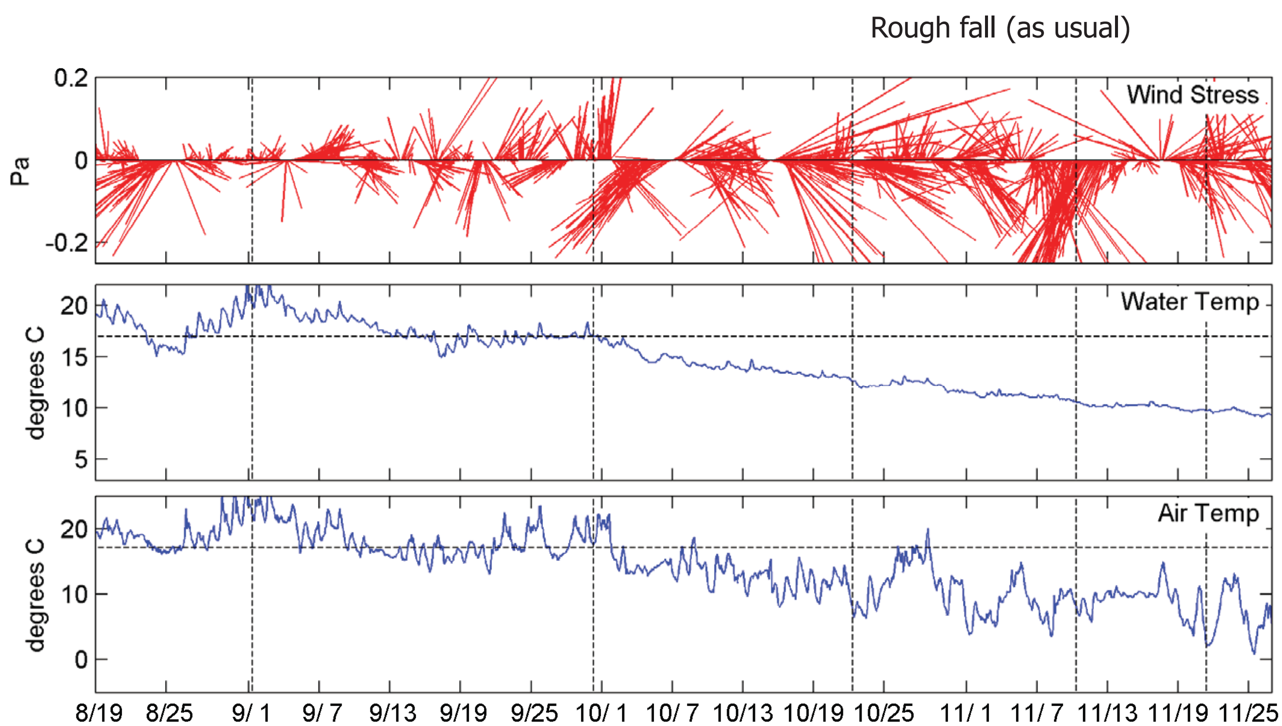
slide 15

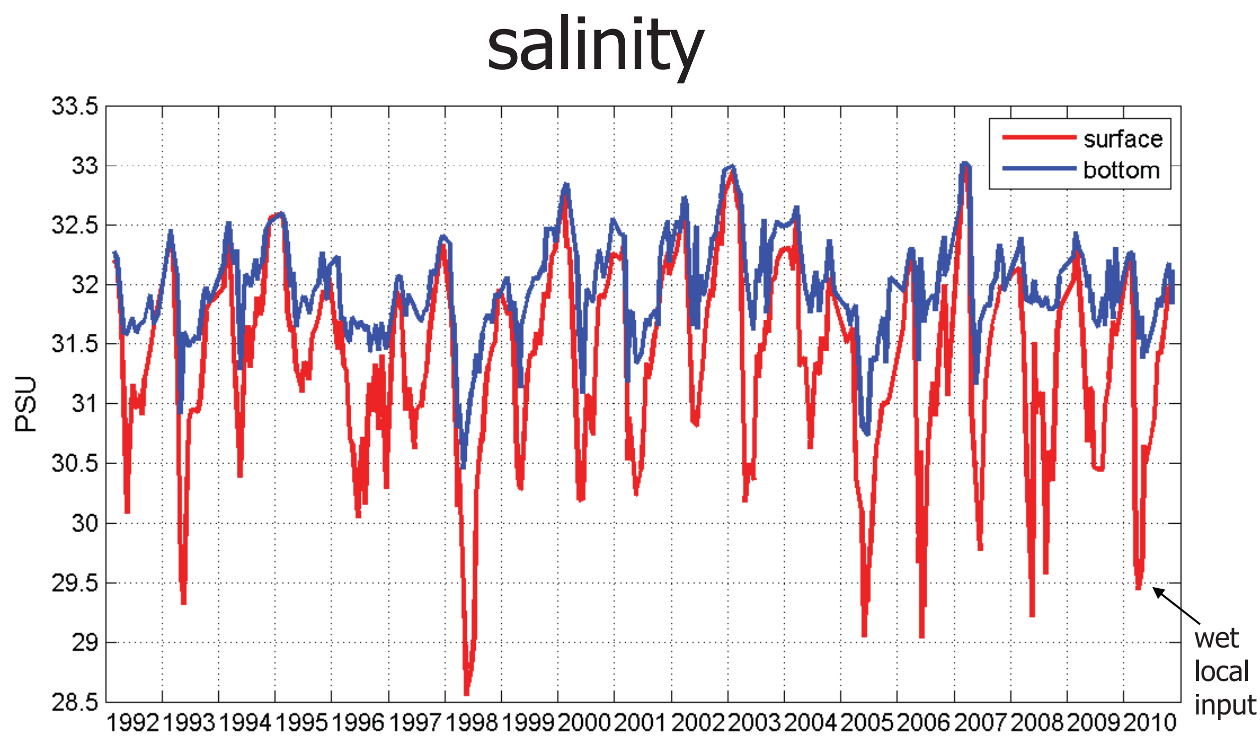
summer winds and water temperature



slide 16

fall winds and water temperature

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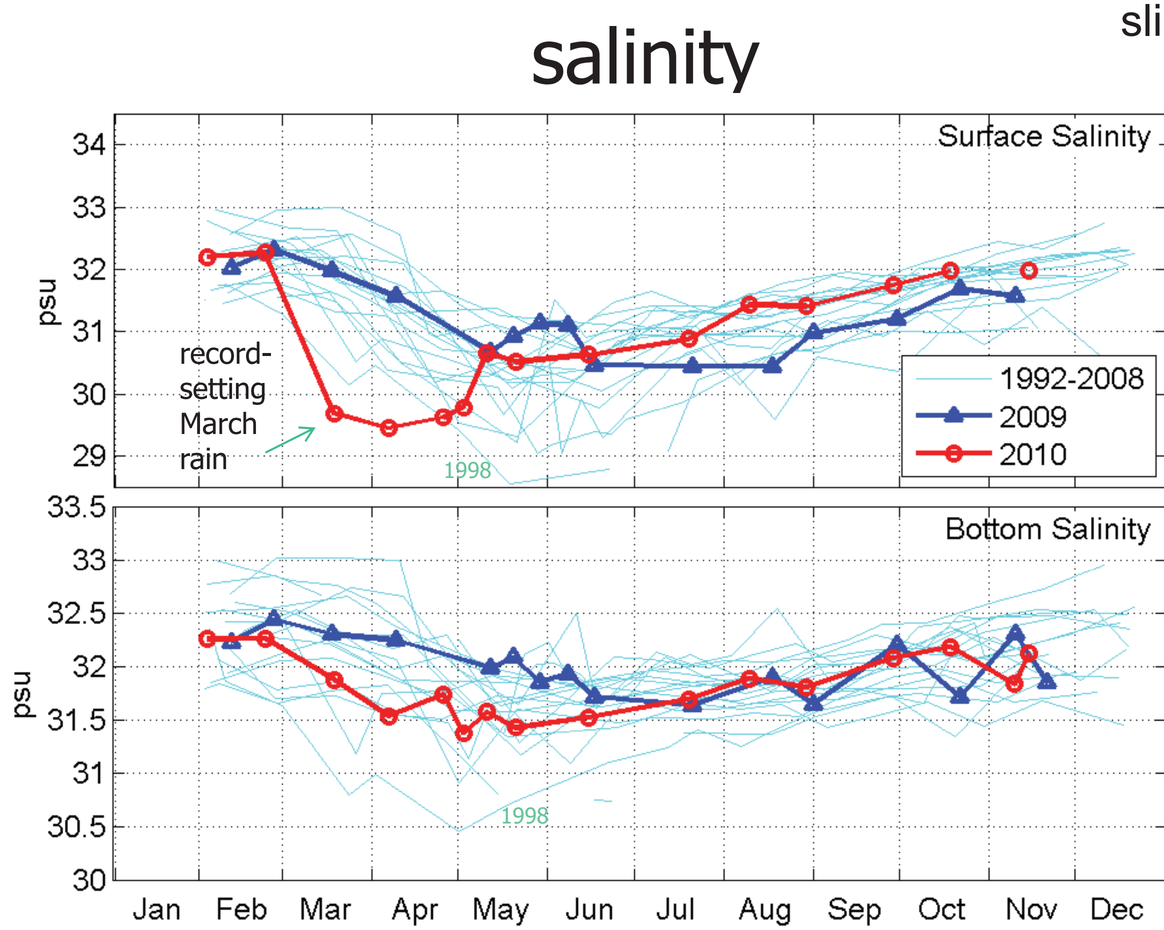
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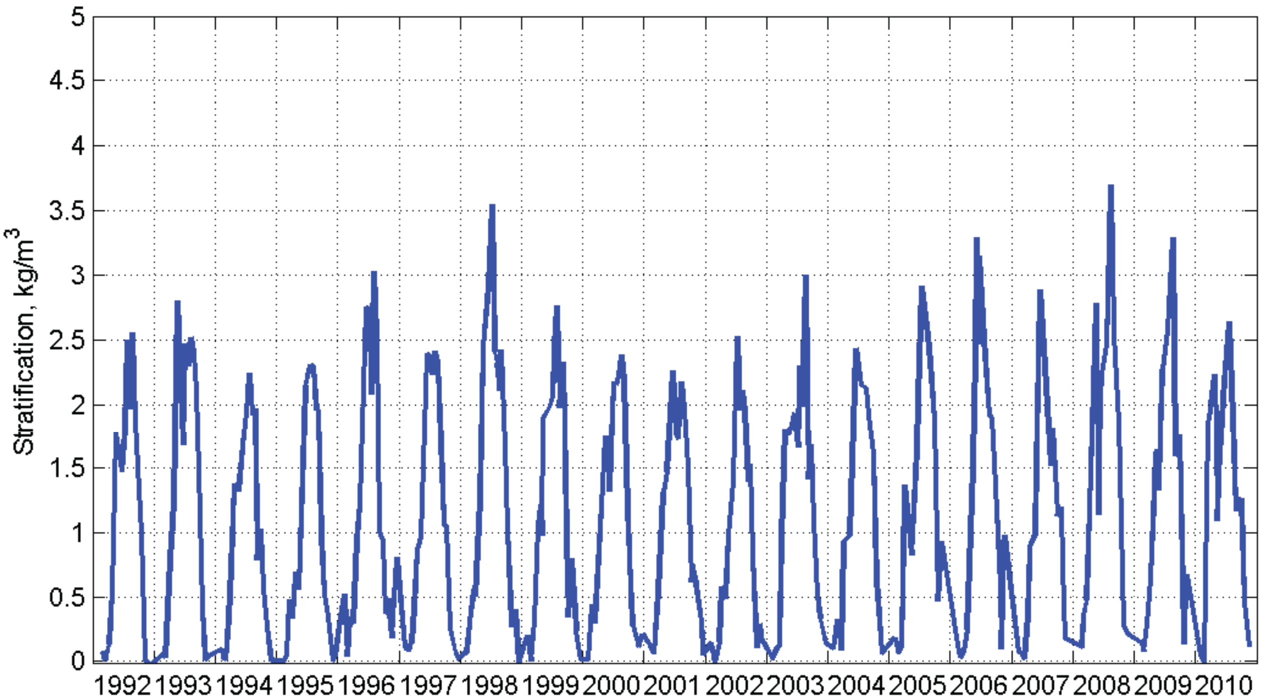
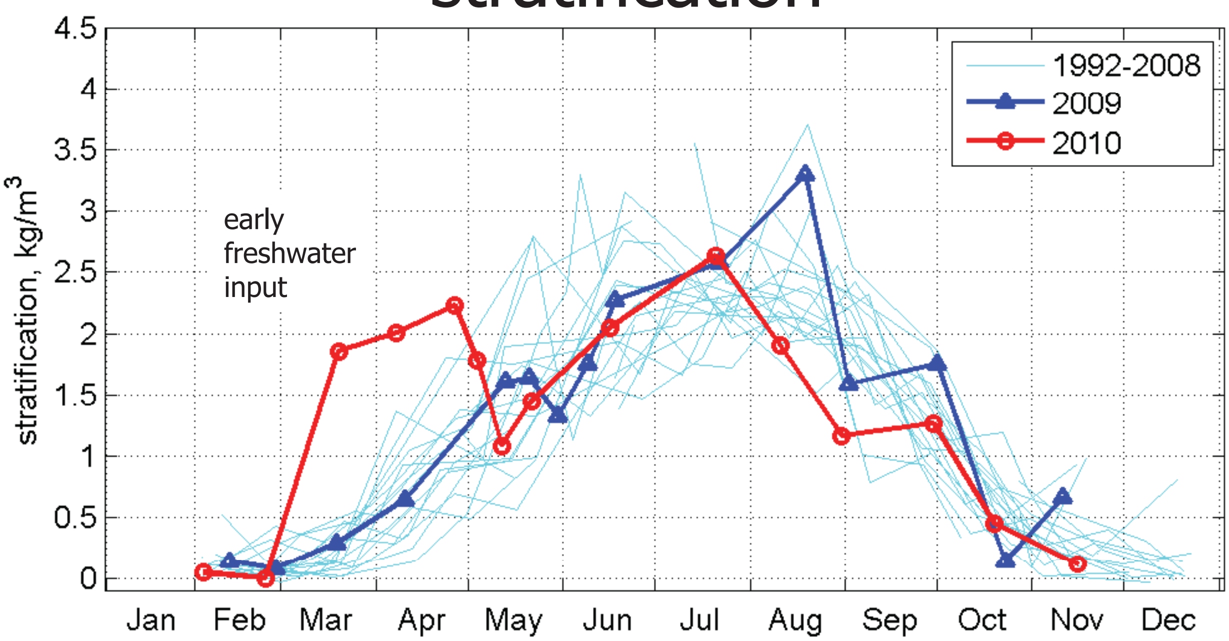
stratification

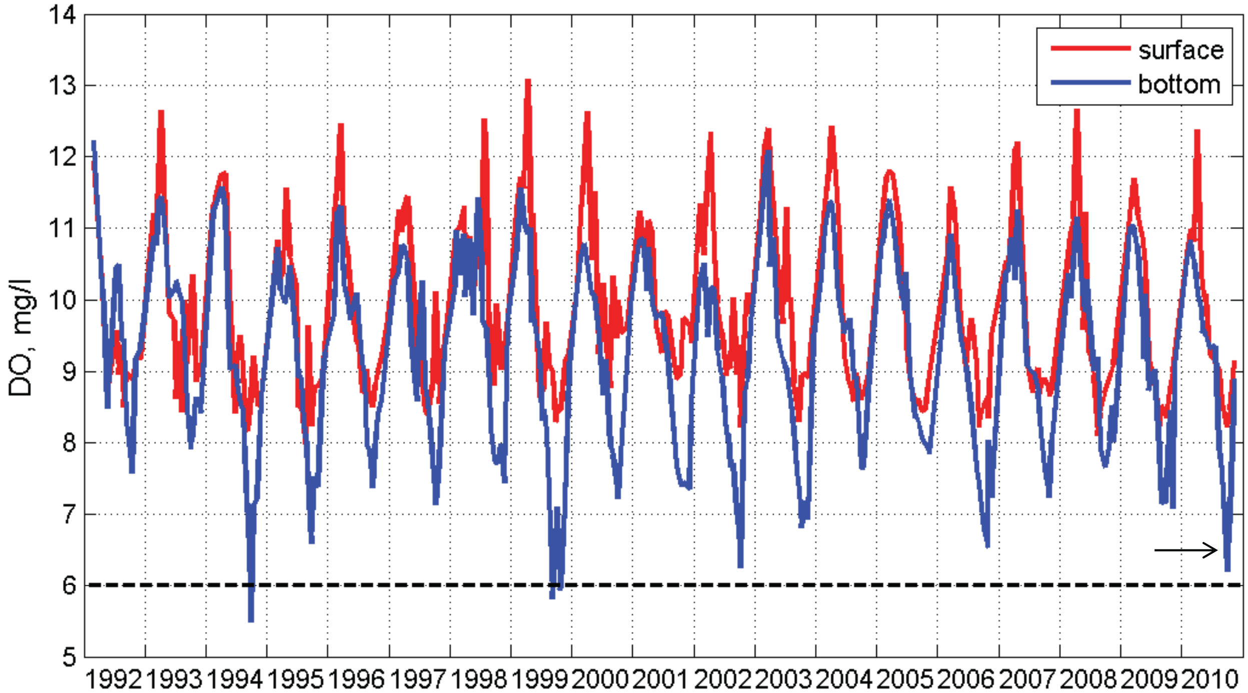


stratification



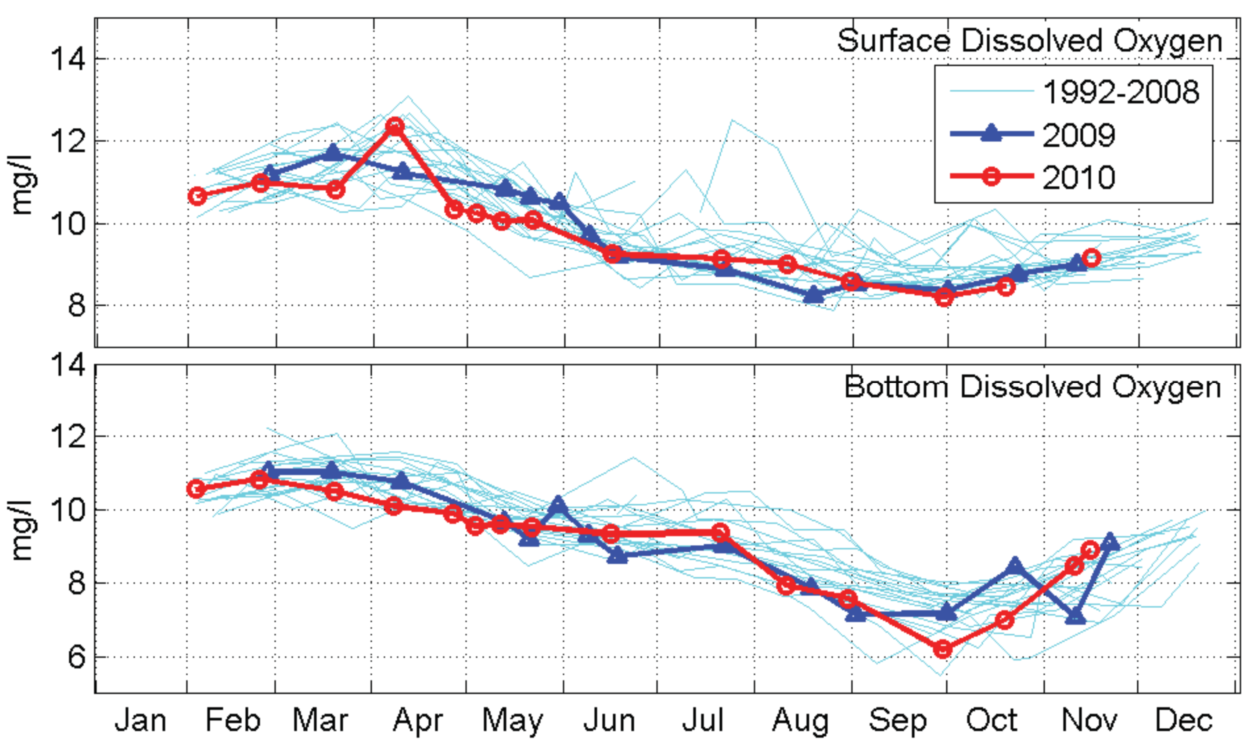
slide 21

dissolved oxygen



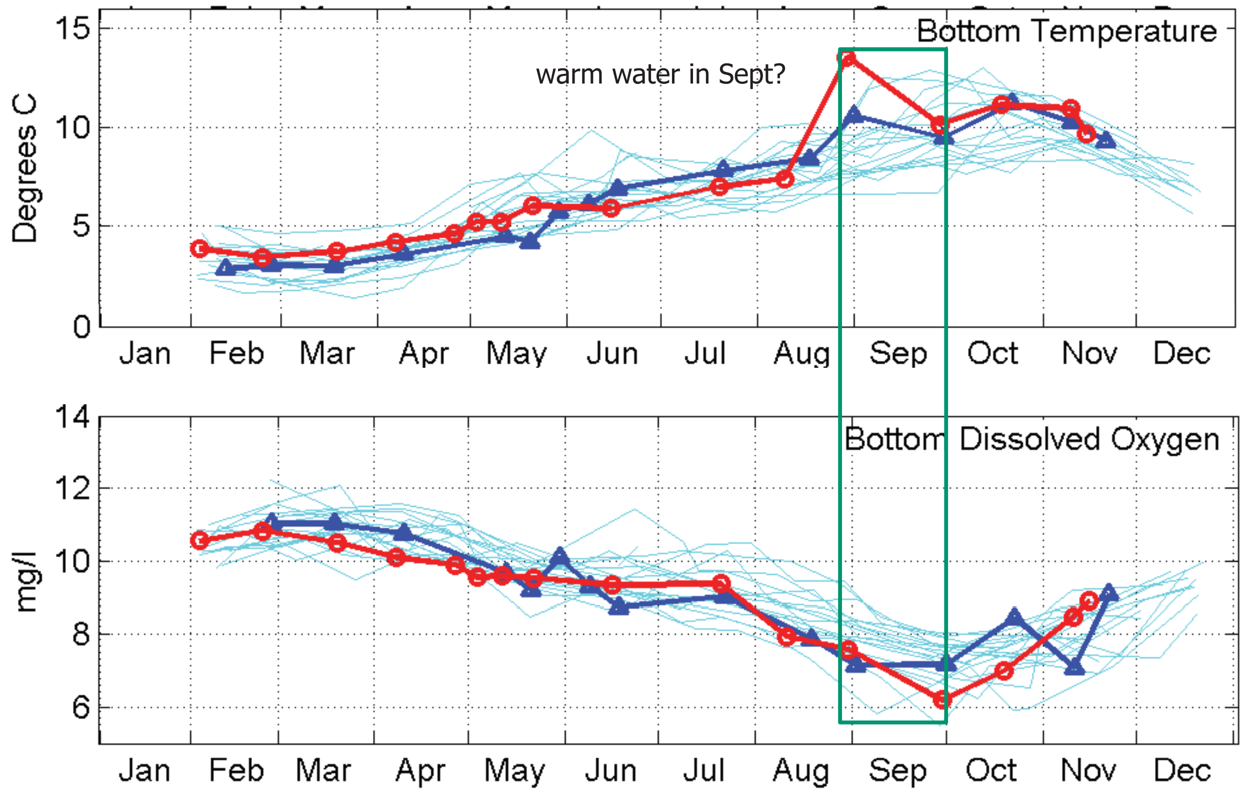
slide 22

dissolved oxygen



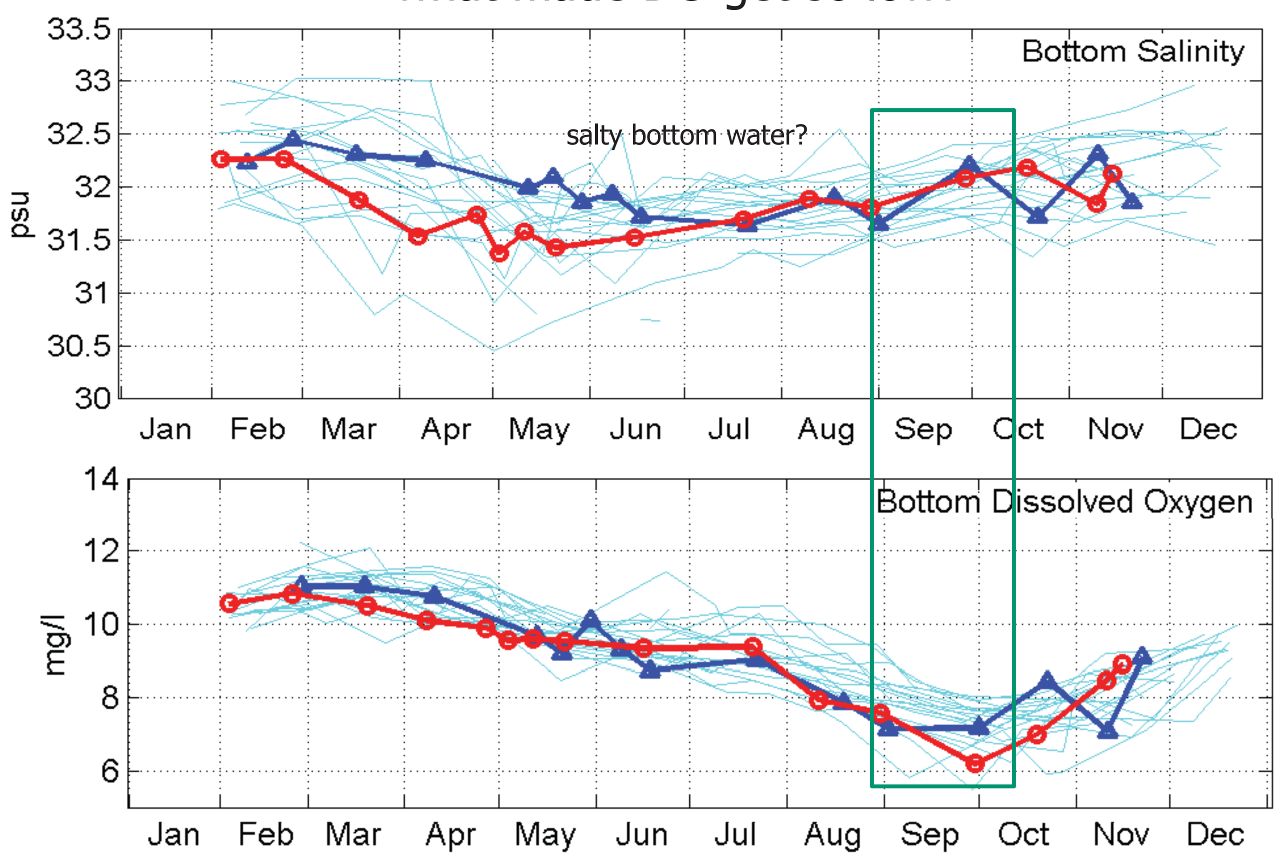
slide 23

what made DO get so low?



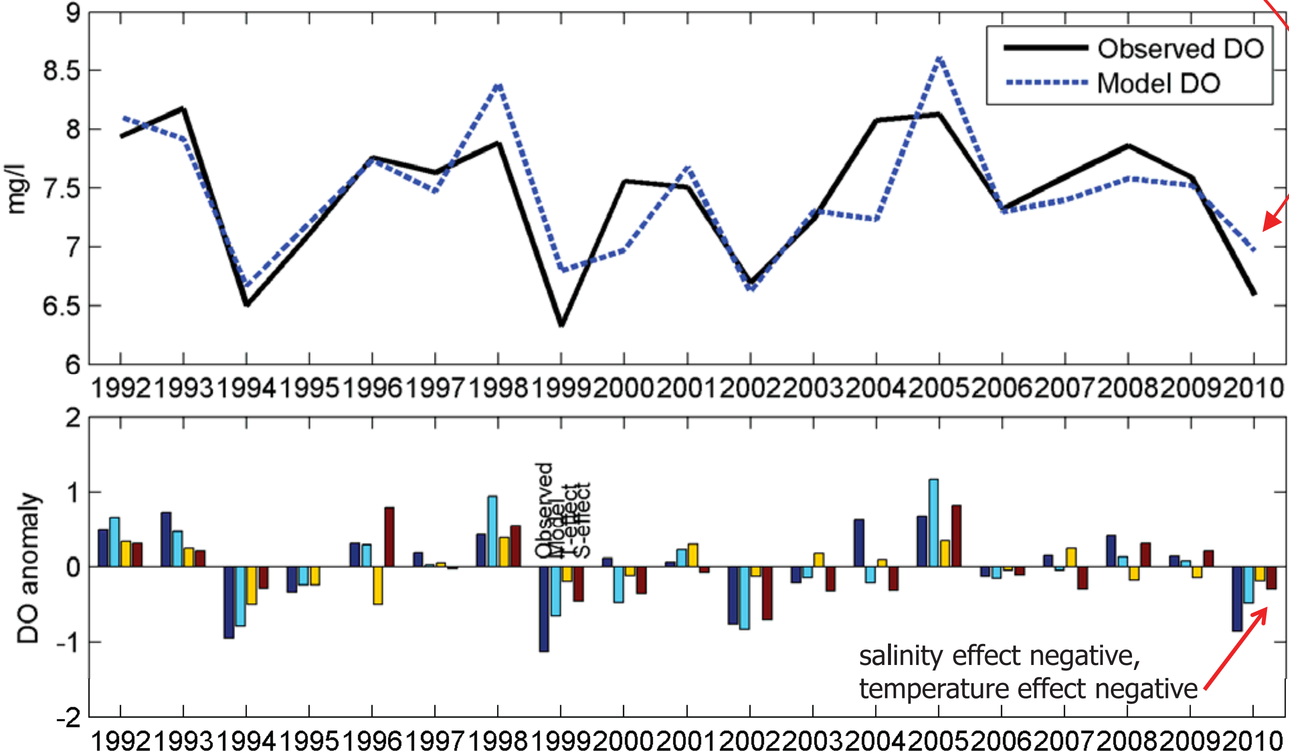
slide 24

what made DO get so low?



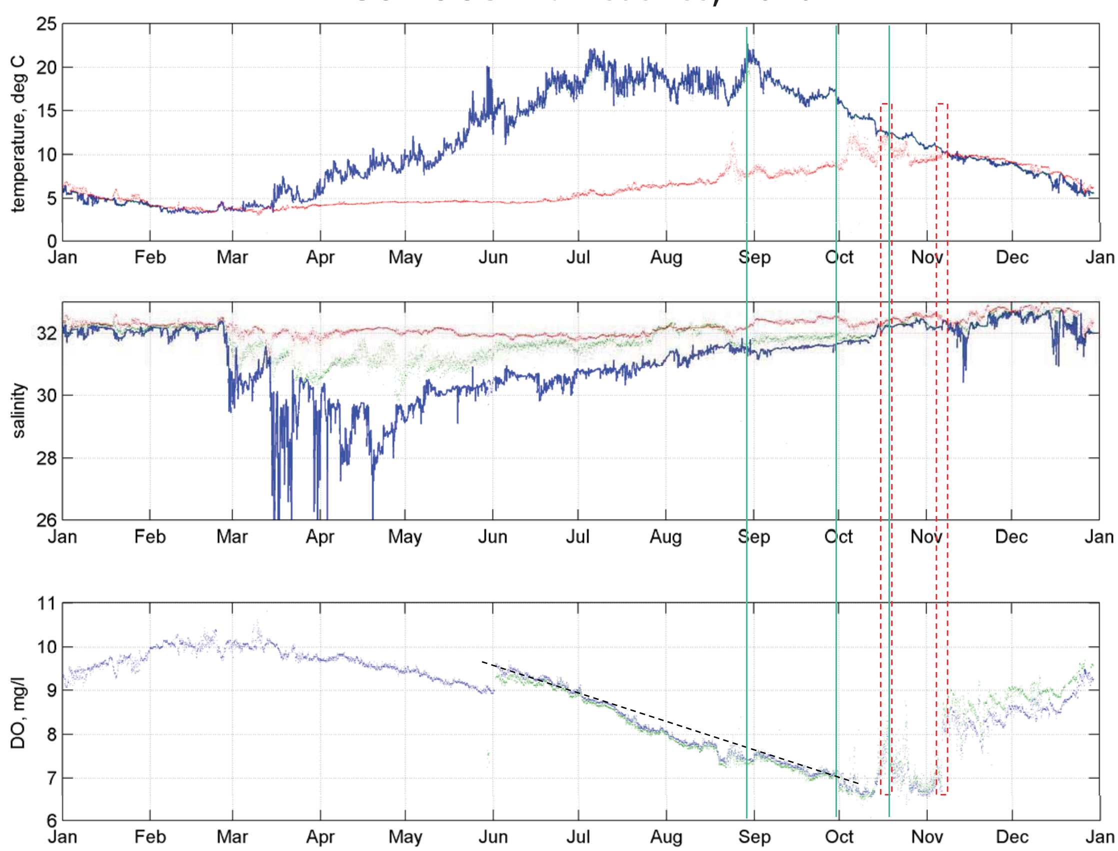
slide 25

DO model predicts low near-bottom DO for 2010

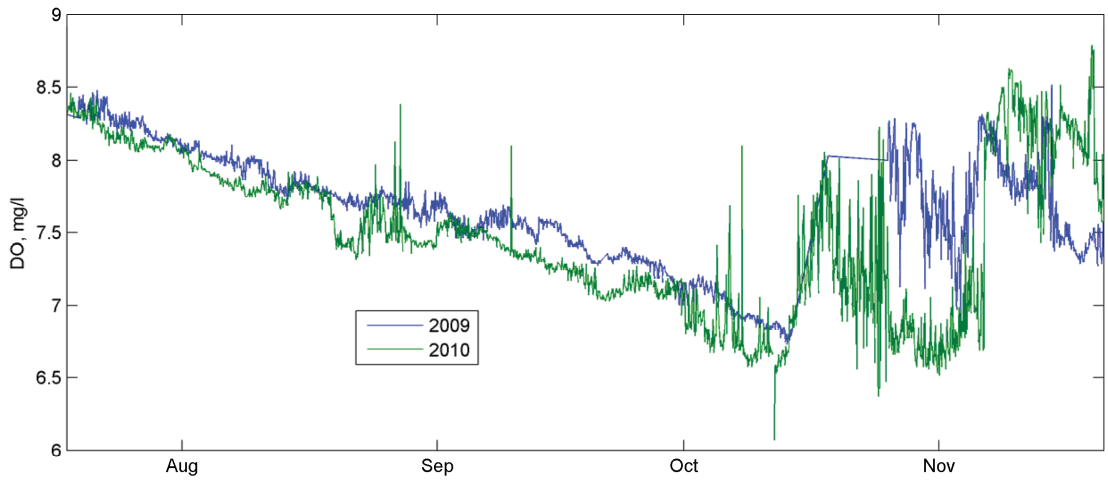


slide 26

GOMOOS A timeseries, 2010



GOMOOS A DO comparison, 2009 vs. 2010



summary

- Very wet March
- upwelling was typical
- Big nor'easter at end of August warmed up bottom water and advected in high salinity offshore water.
- Low DO is associated with higher near-bottom water temperatures and higher than average salinities.

B. 2010 Water Column Overview

Scott Libby, Battelle

Over the course of the HOM program, a general seasonal sequence of water quality events is apparent from the data collected in Massachusetts and Cape Cod Bays. The events are evident each year even though their timing and intensity 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 of 2010 compared to the typical seasonal pattern are discussed below.

B.1. Chronological pattern

Nutrient concentrations were relatively low in Massachusetts and Cape Cod Bays in February 2010 (**Slides 4** and **5**) compared to other years (**Slides 31** and **32**). Nitrate (NO_3) and silicate (SiO_4) levels in Cape Cod Bay were slightly lower than those in Massachusetts Bay consistent with the elevated chlorophyll and POC concentrations associated with the early February diatoms and late February diatom plus *Phaeocystis* bloom, respectively, in Cape Cod Bay (**Slides 6** and **7**). Elevated chlorophyll concentrations were also observed at the offshore, nearfield, and northern boundary stations in February where elevated abundances of diatoms were also seen (**Slides 6**, **8**, and **9**). Chlorophyll levels were much lower at the coastal and Boston Harbor stations in February compared to the other bay stations. There was an increase in NO_3, SiO_4, and phosphate (PO_4) concentrations in the nearfield from February to March that was coincident with a decrease in chlorophyll levels.

Nutrient concentrations in April were comparable or just slightly lower to those observed in February throughout the bays. In the nearfield, the April concentrations were a sharper decrease from March levels and coincident with a relatively large spring diatom bloom that achieved seasonal peak chlorophyll concentrations and annual peak POC levels (**Slides 6** and **8**). Chlorophyll also peaked at the coastal stations, while POC levels reached their annual maxima at coastal, offshore and Cape Cod Bay stations in April (**Slide 6**). There was a small increase in SiO_4 concentrations in the offshore and northern boundary areas in April. These were the only stations where *Phaeocystis* was present in April 2010 (**Slide 18**). Although *Phaeocystis* often peaks in April, it was present throughout the bays in February, albeit at abundances that were quite low. The highest abundance for the year was 1.65 million cells L^{-1} at station F02 in Cape Cod Bay in late February. In the nearfield, the 2010 *Phaeocystis* levels were the lowest since 2000, approaching the low levels seen during the baseline period (**Slide 16**).

By May, chlorophyll, POC and phytoplankton levels had all decreased sharply in the nearfield (**Slide 8**). Similar decreases were observed in Cape Cod Bay and offshore areas of Massachusetts Bay from April to June. In coastal waters and Boston Harbor, the trend was opposite with a large increase in each associated with a June bloom of diatoms. As also observed during the summer of 2009, the diatom bloom in these near shore waters was dominated by *Skeletonema* and *Dactyliosolen fragilissimus* (**Slide 10**). The June bloom resulted in annual maximum concentrations of chlorophyll and POC in Boston Harbor and corresponding nutrient minima (**Slides 4** and **5**).

Nutrient concentrations were relatively low throughout the area in June and remained low in July in the nearfield. Nearfield chlorophyll and POC concentrations remained low from May through September. Following the June diatom bloom in the harbor and coastal waters there was a decrease in chlorophyll concentrations and phytoplankton abundance with a commensurate increase in nutrients in August. Additionally, bottom water dissolved oxygen (DO) concentrations generally declined from late February to August (**Slide 11**). However, in the nearfield, DO concentrations were unchanged from June to July though there were no indications in the physical forcing data to suggest why the trend leveled off during this early summer period. Following the July survey, there was a sharp decline in nearfield bottom water DO concentrations, which reached a minimum of 6.36 mg L^{-1} in late September.

Nutrient and chlorophyll concentrations were quite variable in the nearfield in the fall of 2010 (**Slides 4**, **5**, and **6**). From early to late August, there was a sharp drop in nearfield nutrient concentrations, but by late September concentrations had increased substantially. Fall storms and associated mixing (see Phys-O abstract) likely contributed to these changes. The increase in nutrients also supported a late September diatom bloom in the nearfield (**Slide 8**) which led to increased chlorophyll concentrations. By October, chlorophyll levels at coastal and harbor stations had decreased to low levels comparable to those seen in these areas in February.

Fall peaks in chlorophyll were observed in the offshore and northern boundary areas coincident with an unusual increase in dinoflagellate abundance (mixed assemblage dominated by *Ceratium* spp. and *Prorocentrum micans*). The autumn 2010 bloom of *P. micans* continued into November with abundances of >15,000 cells L^{-1} observed in nearfield samples. This autumn *P. micans* bloom was extraordinary in both its timing (dinoflagellate annual abundance usually peaks in summer) and in its magnitude. November 2010 dinoflagellate abundance was more than 10 times the baseline and post-diversion November dinoflagellate mean levels (**Appendix D slide 13**). This unusual autumn dinoflagellate bloom led to both 2010 annual maximum nearfield survey mean chlorophyll concentration and POC concentration occurrences in the autumn of 2010.

In 2010, seasonal and annual chlorophyll levels were well below threshold values (**Slide 12**) and although 2010 bottom water DO levels were quite low in the nearfield and Stellwagen Basin compared to baseline and post-diversion means (**Slide 13**), both nearfield and Stellwagen DO levels were above the DO thresholds. There were no threshold exceedances for water quality or nuisance species in 2010. As mentioned previously, *Phaeocystis* abundance in the bays was relatively low in 2010 peaking in late February in Cape Cod Bay (**Slide 17**). Nearfield levels were very low (53,300 cells L^{-1} winter/spring mean) and were higher in February than April (actually absent from the March samples). *Pseudo-nitzschia* were present in very low abundances during each season, but as has been the case during the post-diversion period, were well below thresholds (**Slide 19**). *Alexandrium* abundances were quite low reaching a maximum in the nearfield of only 79 cells L^{-1}, which is below the 100 cells L^{-1} threshold. Predictions had suggested that there would be a large *Alexandrium* bloom in Massachusetts Bay in 2010 based on fall 2009 cyst abundances being very high and present in the sediments to the east of Stellwagen Bank (**Slides 21** and **22**). It is unclear why a large bloom did not occur, but current thinking is that the water characteristics in the Gulf of Maine were outside of the range that the model was built upon (**Slides 26** and **27**; McGillicuddy et al. 2011).

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 30**). 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 33** and **34**), but this appears to be related to regional processes governing the consistent annual blooms of *Phaeocystis* in March-April since 2000. While the 2010 *Phaeocystis* bloom was minor relative to recent years, the large diatom bloom observed in April 2010 contributed to the post-diversion winter/spring chlorophyll signal of peak chlorophyll levels in April.

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 have indicated 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 (Libby *et al*. 2008).

B.2. REFERENCES

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2010 Water Column Overview

MWRA Annual Technical Meeting May 9, 2011

Scott Libby and Don Anderson

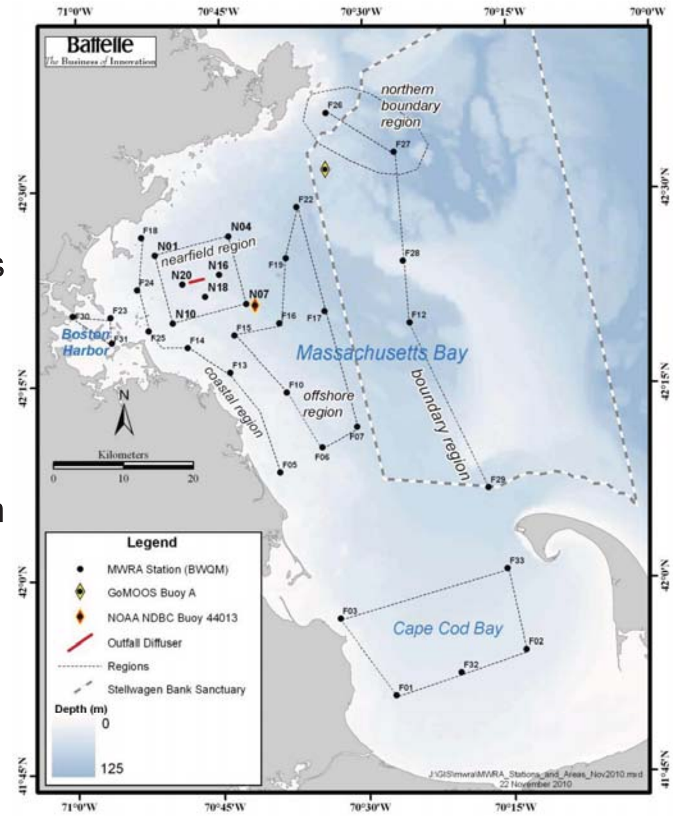
Presentation Overview

- 2010 nutrient, chlorophyll, and DO results
  - "Typical" trends generally observed in these parameters
  - Contingency Plan threshold results
    - No water column exceedances in 2010
    - *Phaeocystis* bloom (not this year…..)
    - *Alexandrium* bloom (smaller than predicted…..)

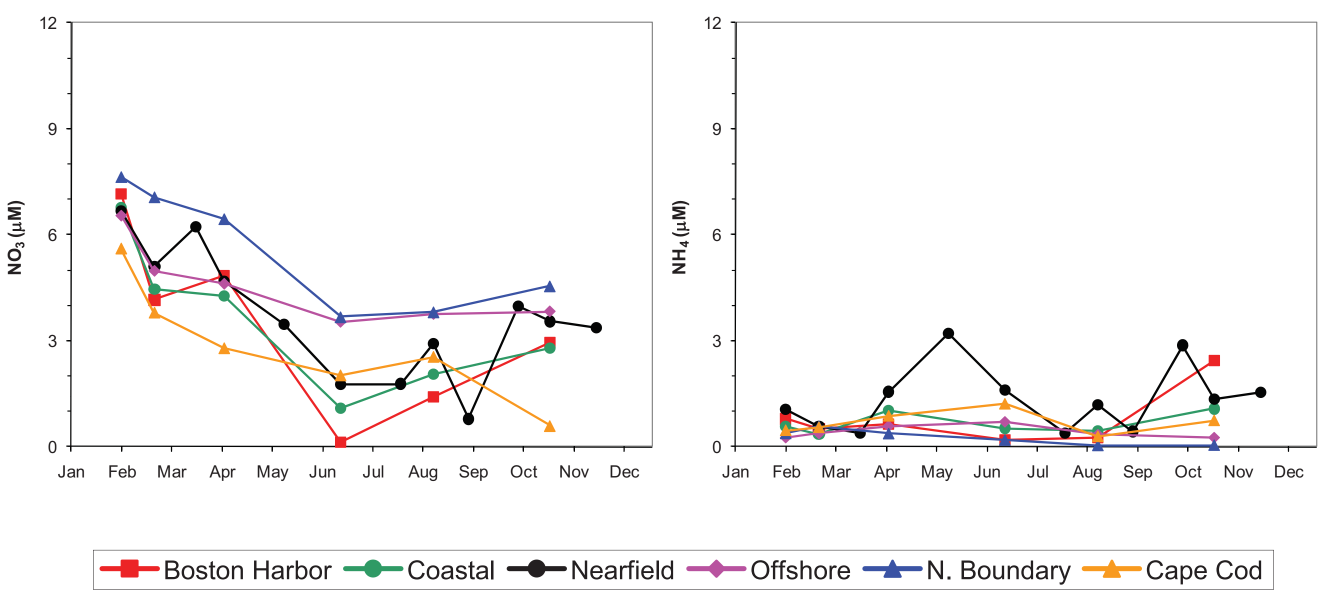
- Compare post transfer years and baseline
  - Have nutrients changed near the outfall or in the farfield? **Yes**
  - Has phytoplankton biomass changed? **Yes, but regionally**
  - Has dissolved oxygen changed? **No**

2010 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

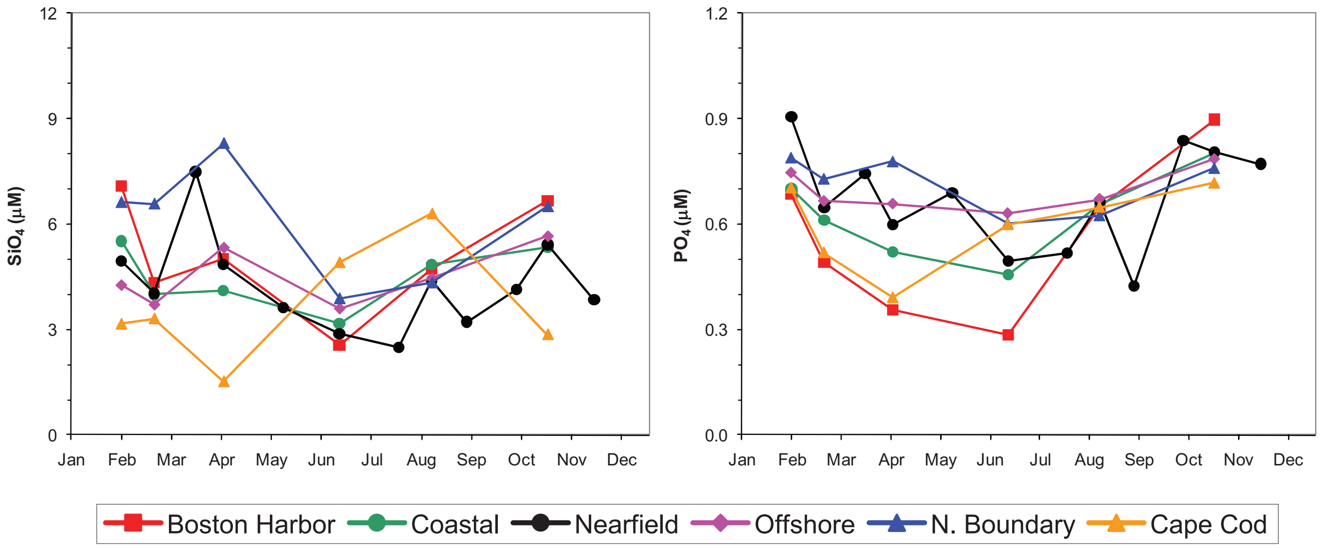


2010 Nutrients – NO_3 & NH_4



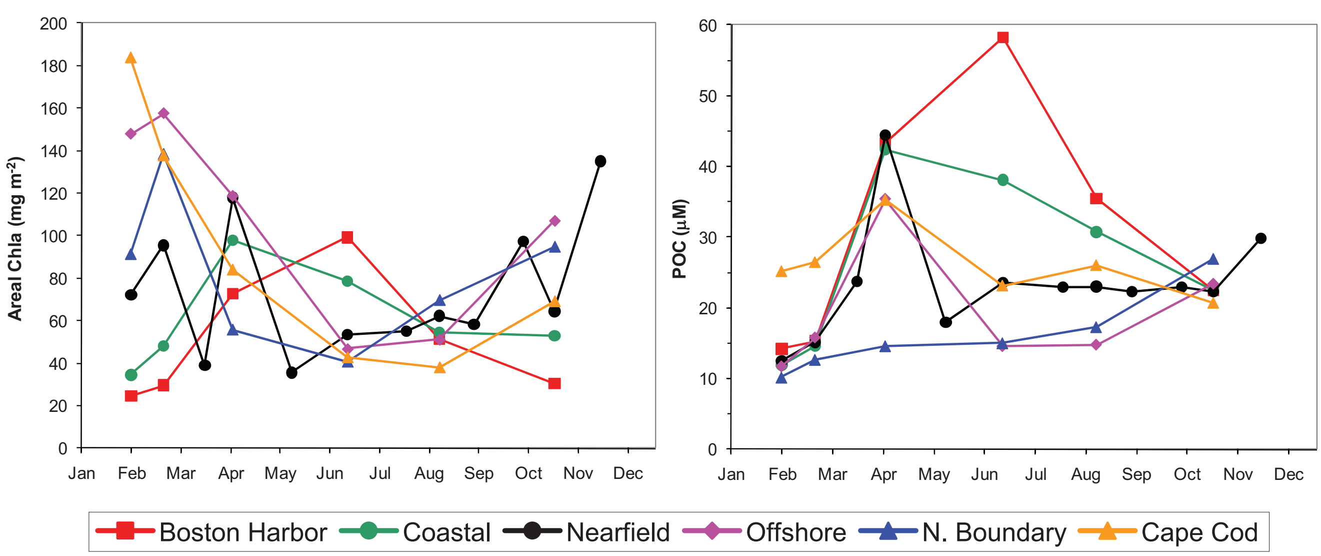
slide 5

2010 Nutrients – SiO_4 & PO_4



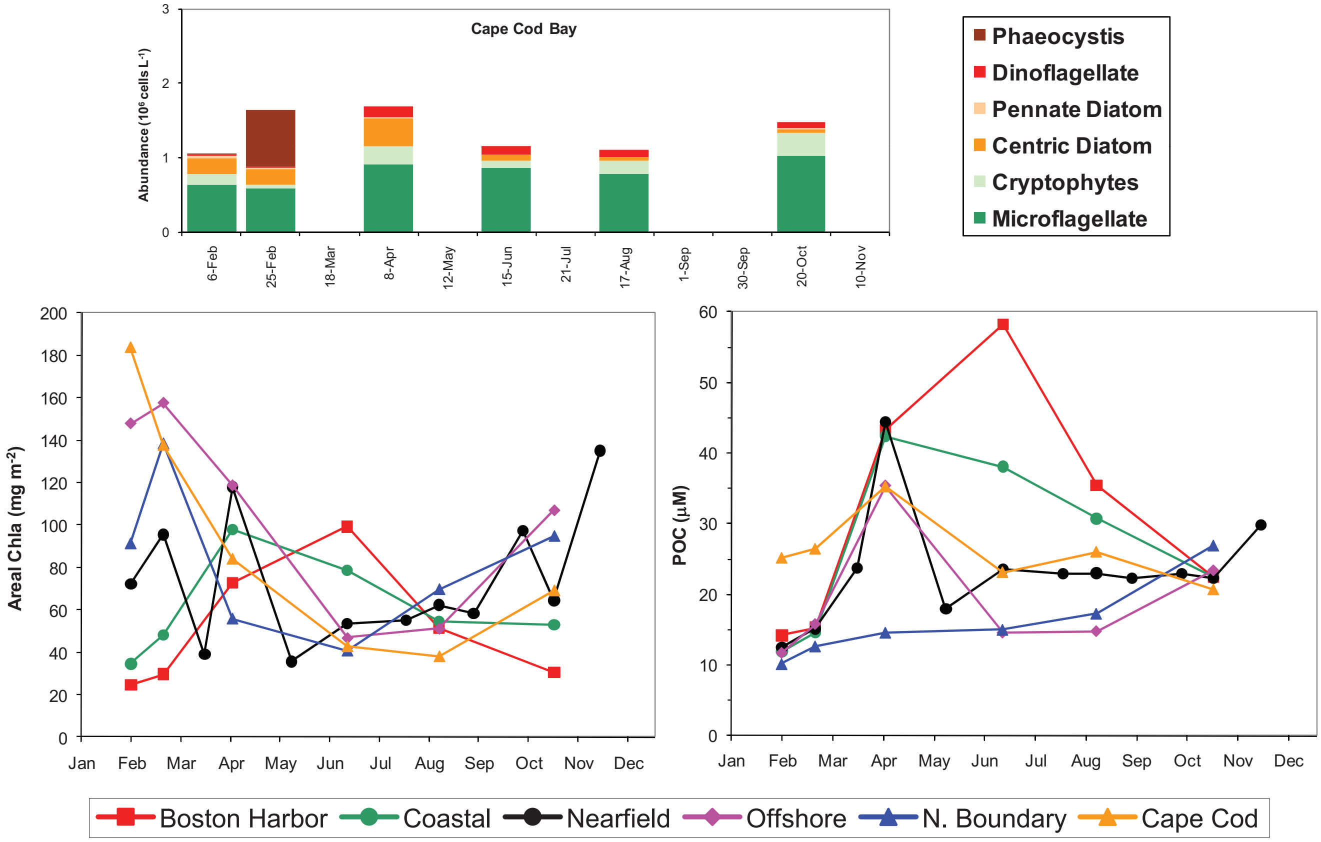
slide 6

2010 Areal Chlorophyll & POC



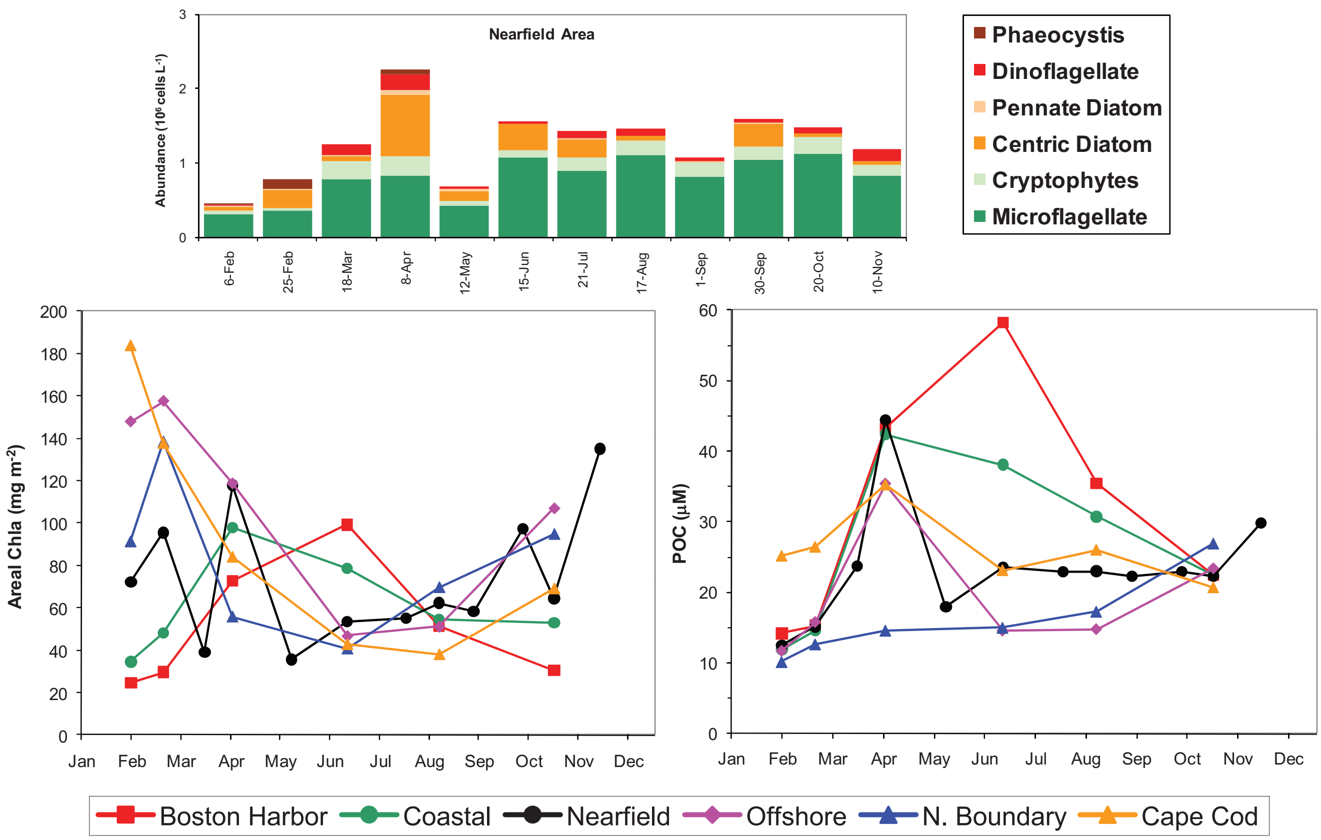
slide 7

2010 Areal Chlorophyll & POC



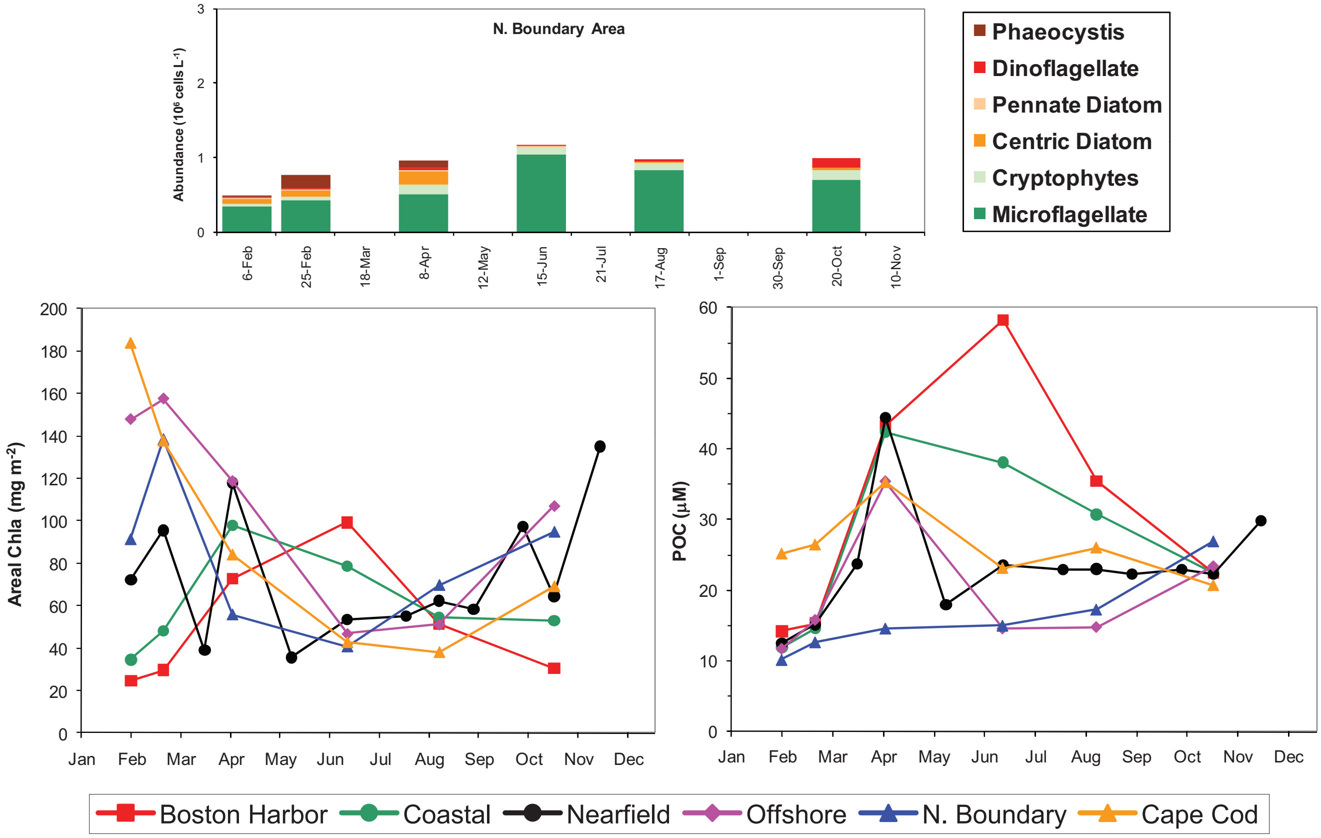
slide 8

2010 Areal Chlorophyll & POC



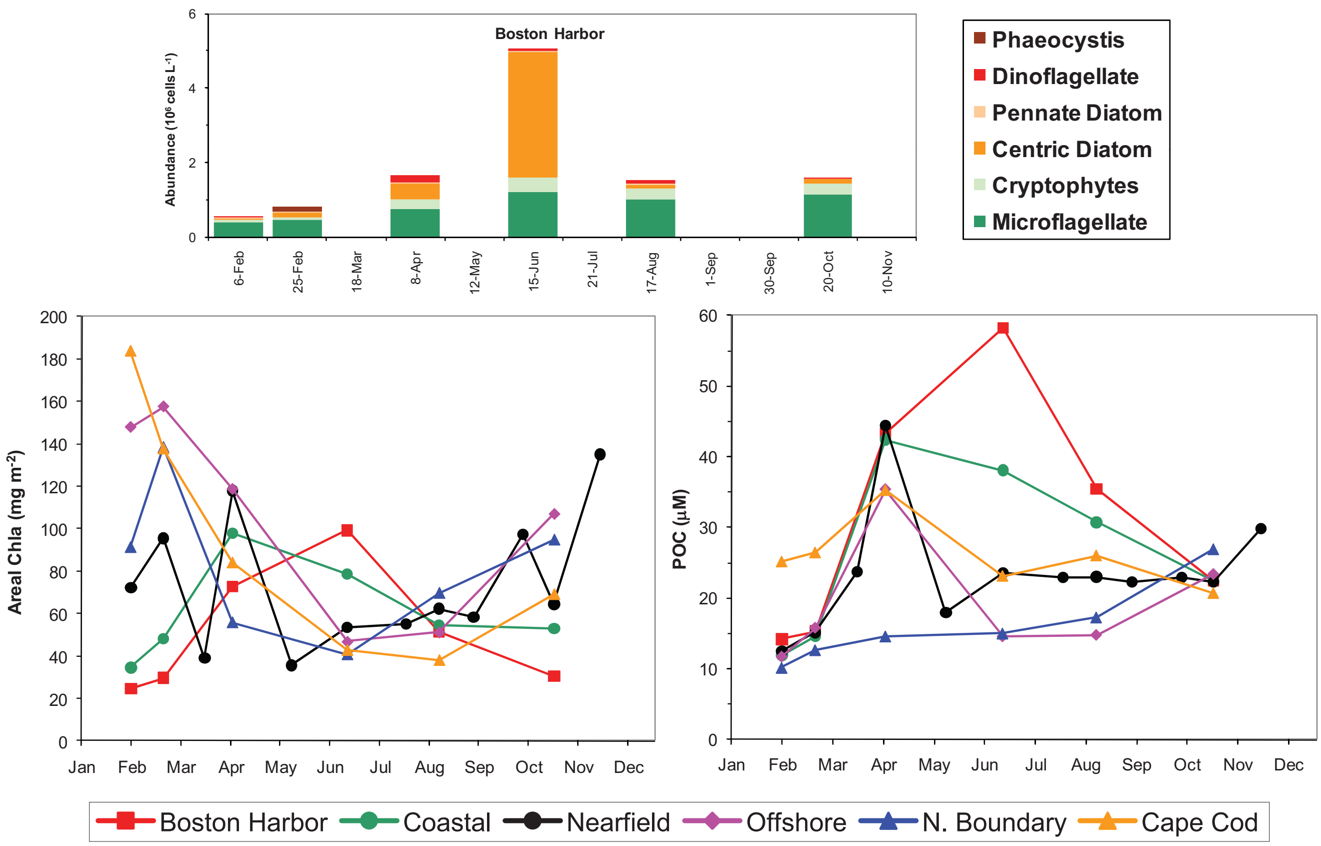
slide 9

2010 Areal Chlorophyll & POC

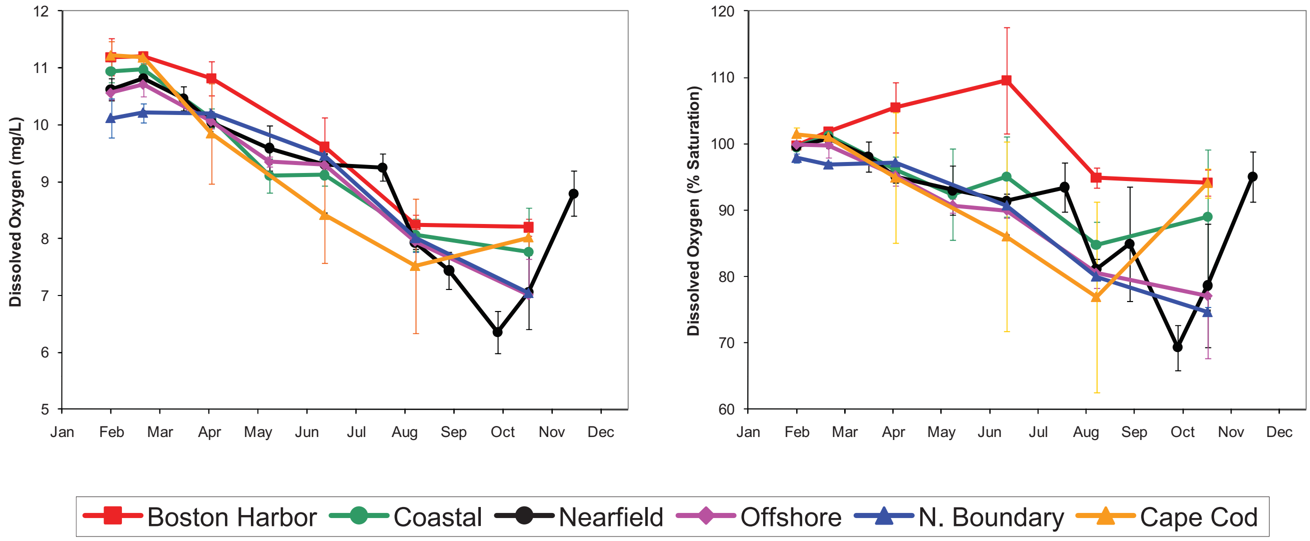


slide 10

2010 Areal Chlorophyll & POC



2010 – Bottom Water DO



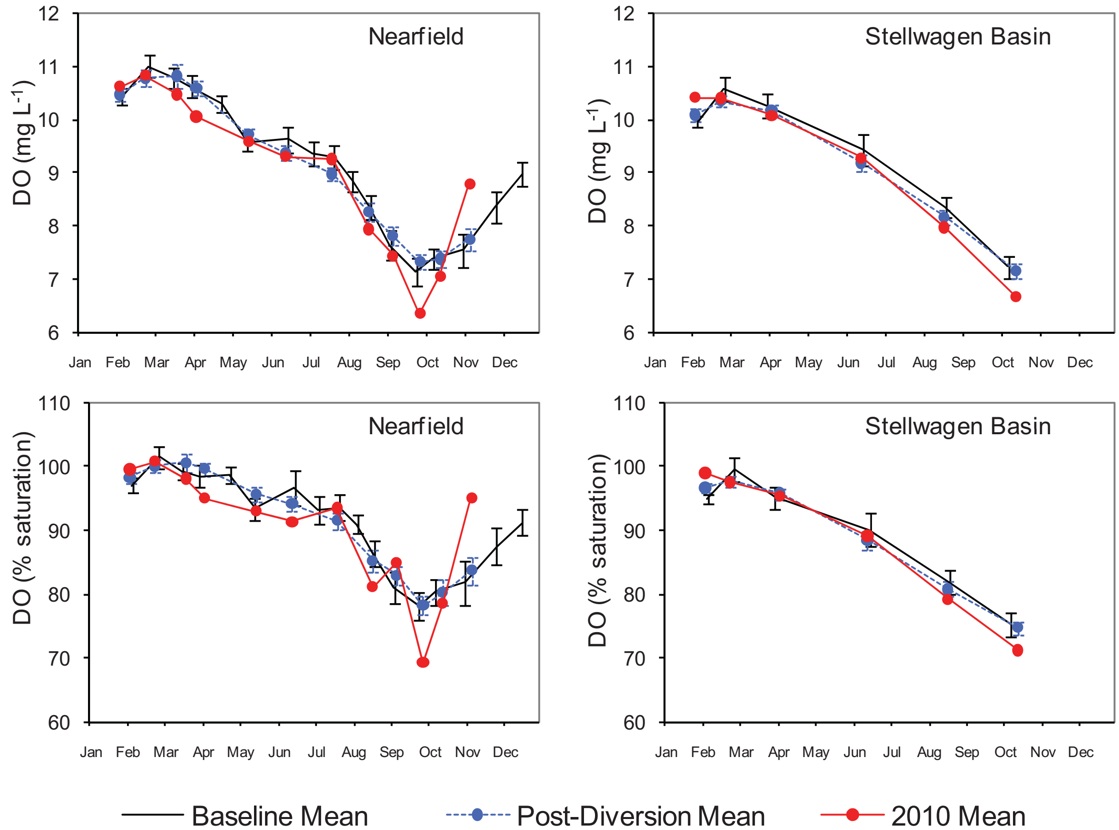
Threshold Values for DO and Chlorophyll

Parameter	Time Period	Caution Level	Warning Level	Background	2010
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	6.36 mg/l 6.67 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%	69.3% 71.2%
Bottom Water DO depletion rate	June to October	0.037 mg/l/d	0.049 mg/l/d		0.024 mg/l/d
Chlorophyll	Annual	118 mg/m^2	158 mg/m^2	--	74 mg/m^2
	Winter/spring	238 mg/m^2	--	--	81 mg/m^2
	Summer	93 mg/m^2	--	--	53 mg/m^2
	Autumn	212 mg/m^2	--	--	99 mg/m^2

No DO or Chlorophyll threshold exceedances in 2010

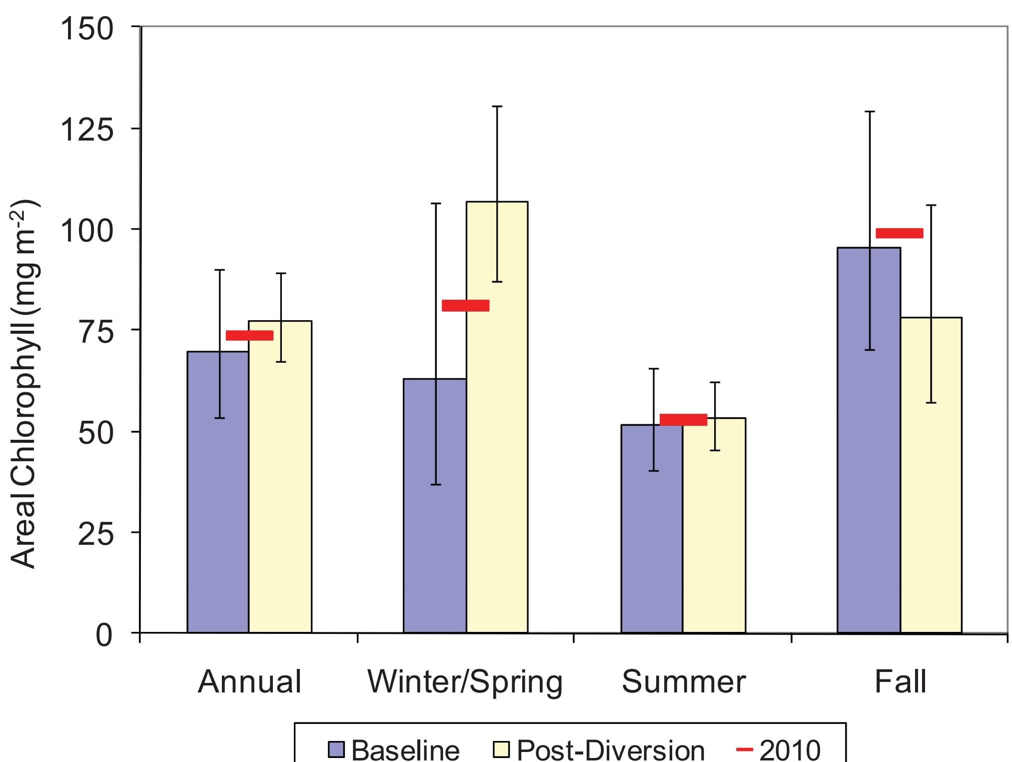
slide 13

Baseline vs. Post-discharge – Bottom DO Nearfield & Stellwagen



slide 14

Baseline vs. Post-discharge – Nearfield Areal Chlorophyll

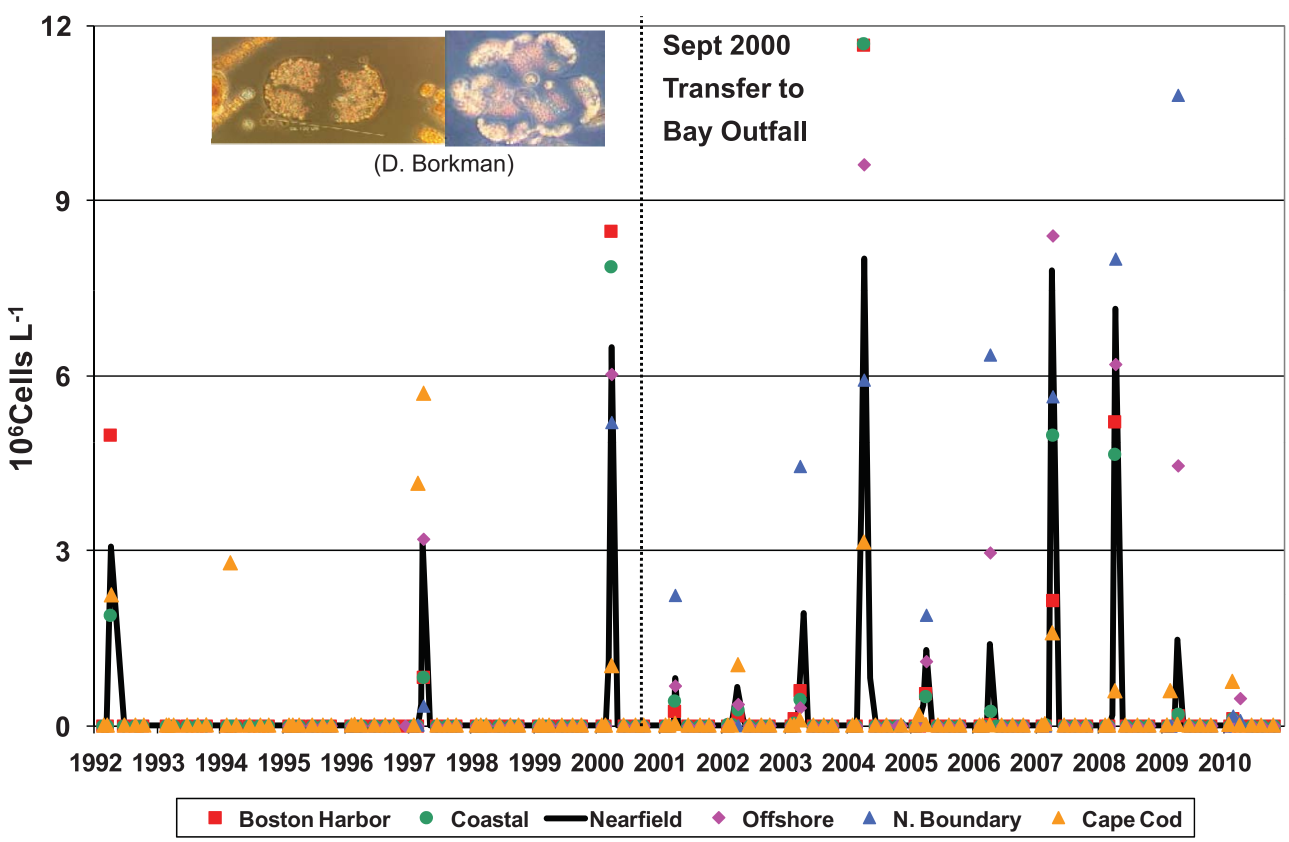


Threshold Values for Nuisance Species

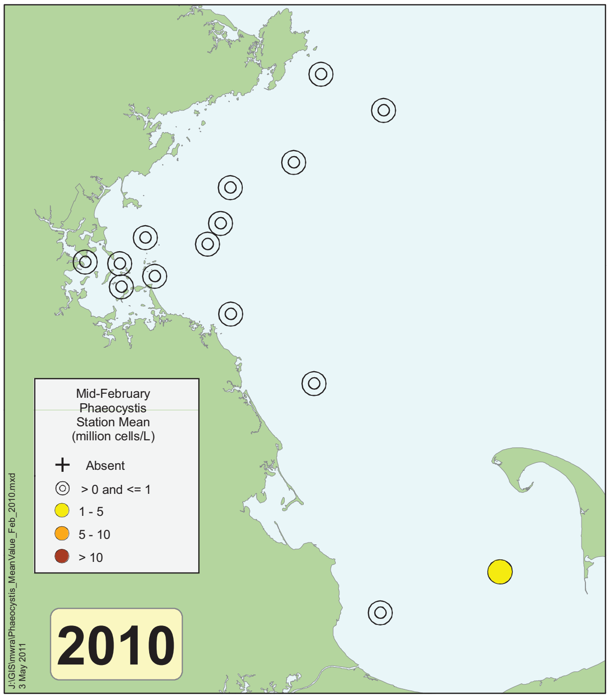
Parameter	Time Period	Caution Level	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Phaeocystis pouchetii (cells L^{-1})	Winter/ spring	2,020,000	186,400	269,000	482,000	**2,870,000**	438,500	383,000	**2,150,000**	1,980,000	402,000	53,300
	Summer	357	absent	**14,900**	**1,700**	**164,400**	**517**	**18,000**	absent	absent	absent	absent
	Autumn	2,540	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent
Pseudo-nitzschia (cells L^{-1})	Winter/ spring	21,000	6,620	896	275	11.3	147	absent	77.5	absent	absent	610
	Summer	43,100	163	234	83.5	380	3,320	absent	absent	540	absent	54
	Autumn	24,700	6,030	3,210	12,100	660	44.7	222	absent	171	1,460	1,160
Alexandrium	Any nearfield sample	100	35	8	7	5	**36,831**	**5,668**	7.2	**60,430**	**151**	79

No nuisance species threshold exceedances in 2010

Phaeocystis pouchetii blooms 92-10

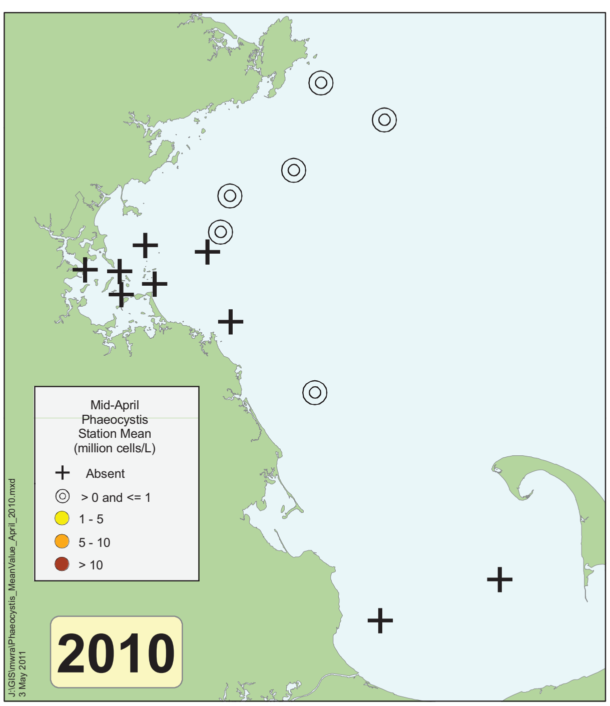


2010 Phaeocystis Distribution



- Observed throughout the bays (all 15 stations) in late February
- Peak abundance in Cape Cod Bay at station F02 (~1.5 million cells/L)
- Much lower (<0.3 million cells/L) everywhere else

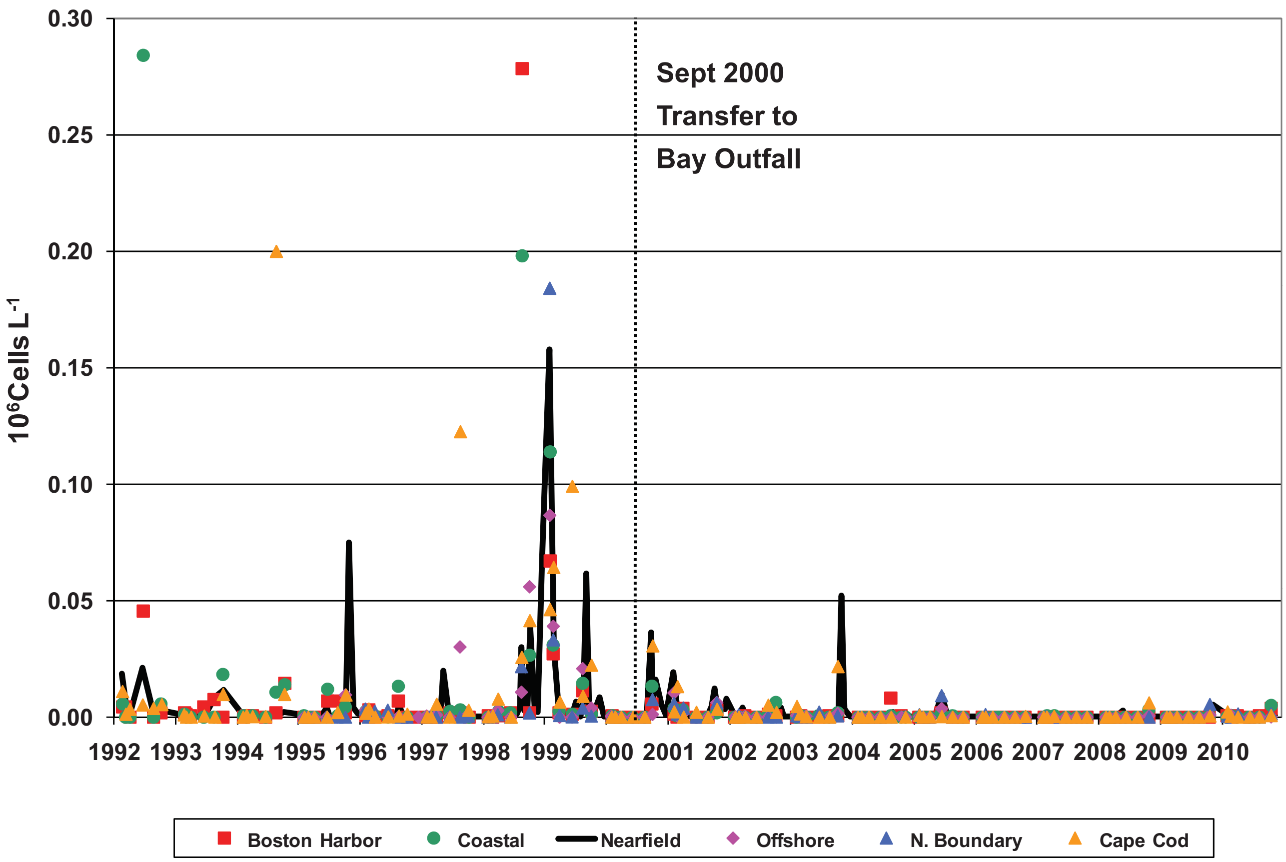
2010 Phaeocystis Distribution



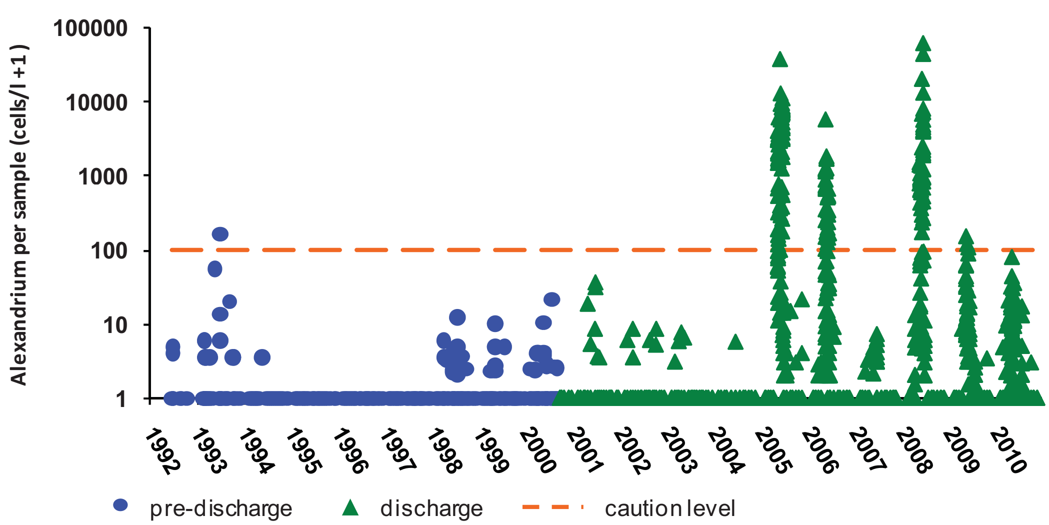
- Observed throughout the bays (all 15 stations) in late February
- Peak abundance in Cape Cod Bay at station F02 (~1.5 million cells/L)
- Much lower (<0.3 million cells/L) everywhere else

- In April, limited to MA Bay and very low abundances
- Similar to baseline years when *Phaeocystis* blooms were sparse or not observed

Pseudo-nitzschia blooms 92-10



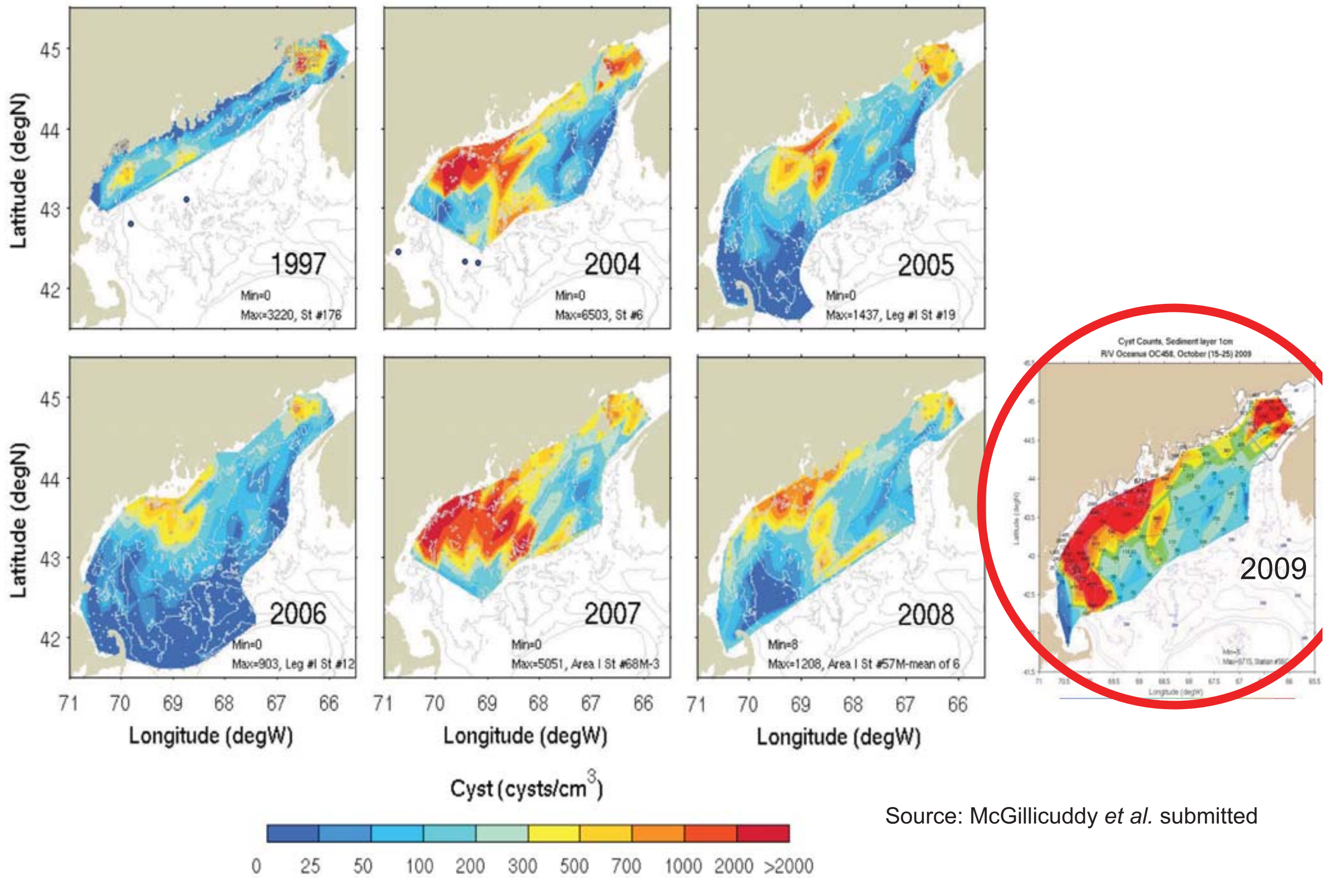
Nearfield *Alexandrium* Abundance



Minor bloom for 2010 in Massachusetts Bay – but a major bloom had been forecast

slide 21

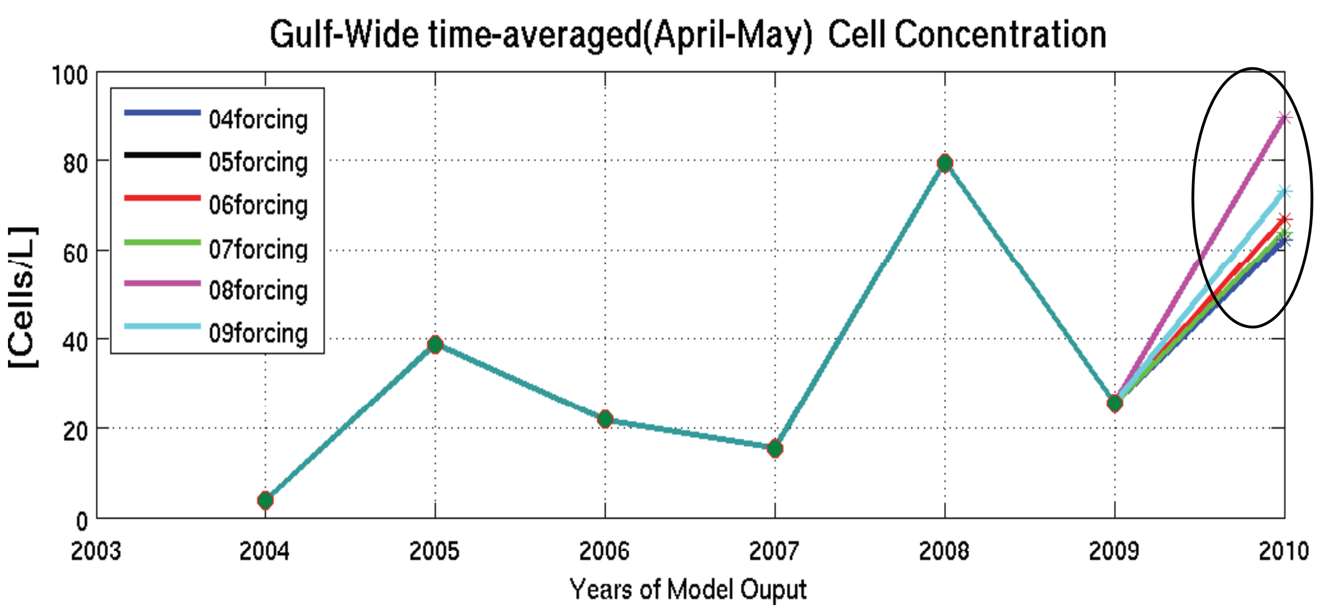
2010 Forecast – Cyst Maps



Source: McGillicuddy *et al.* submitted

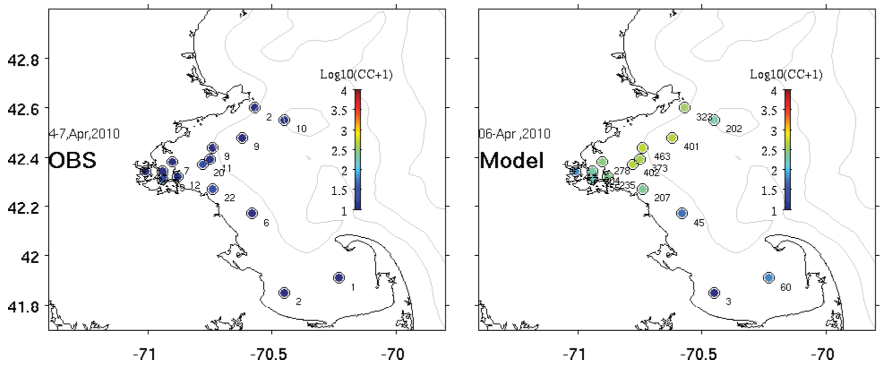
slide 22

2010 ensemble forecast



Source: McGillicuddy *et al.* submitted

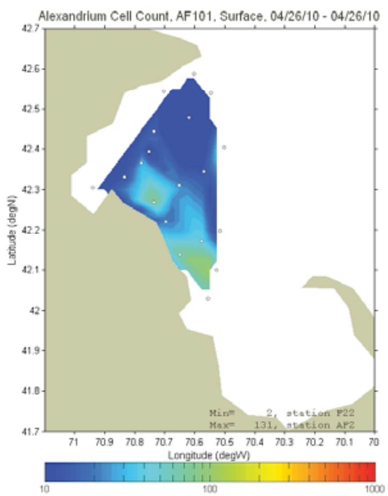
2010 *Alexandrium* "Bloom"

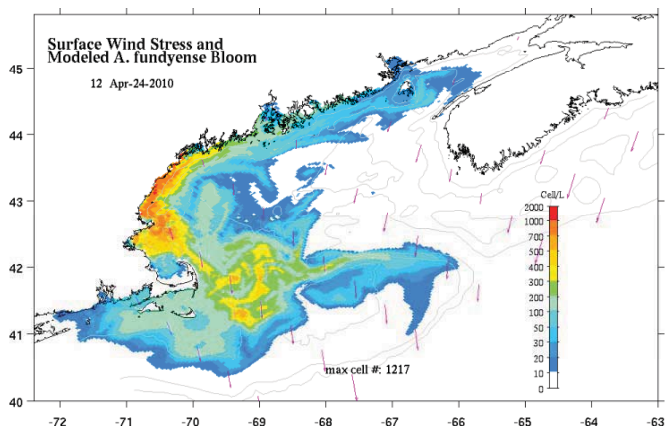


Disconnect between observations and model:

- early April (WF104, top)

- late April (AF101, bottom)

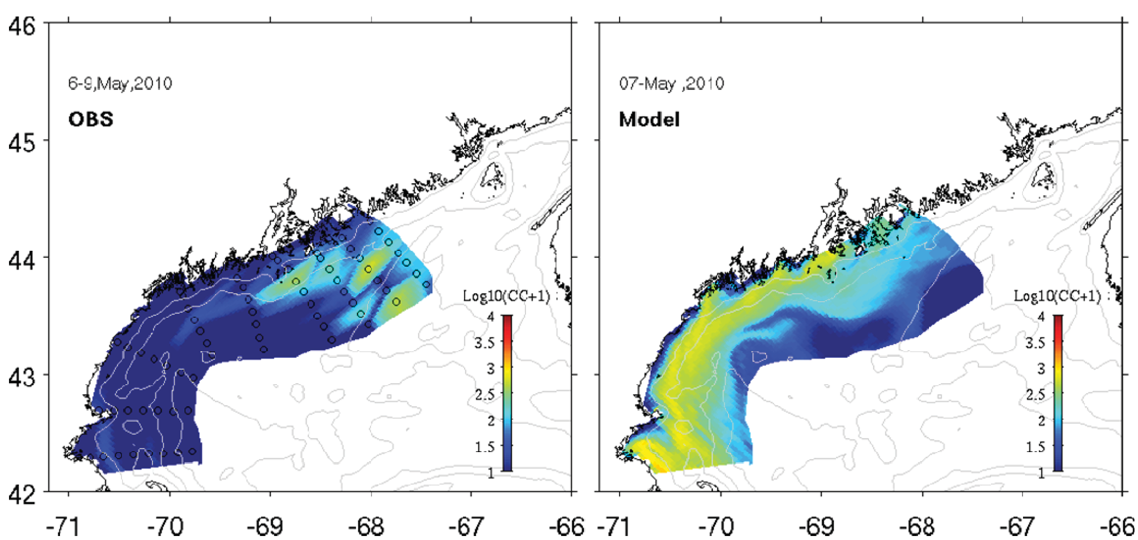




Source: R. He

2010 *Alexandrium* "Bloom"

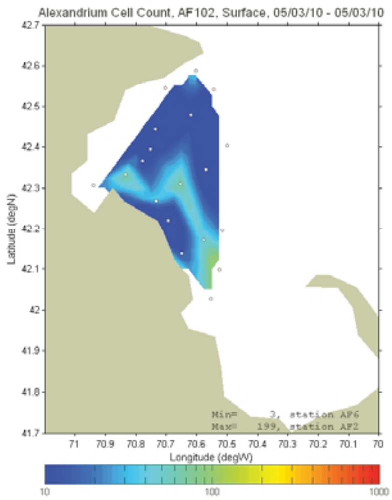
Oceanus Survey vs. Model Results
May 6-9, 2010



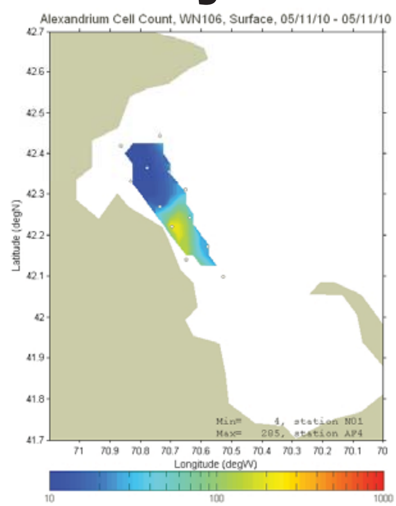
Source: McGillicuddy *et al.* submitted

2010 *Alexandrium* "Bloom" in the Bay

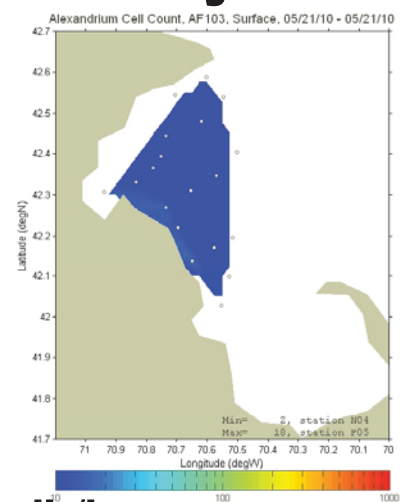
May 3



May 11



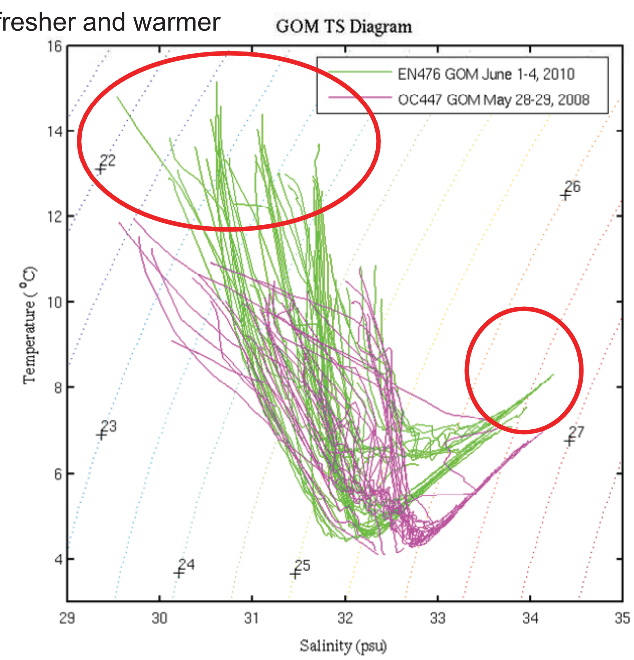
May 21



- **Nearfield peak abundance May 3 at N10 – 79 cells/l**
- **Maximum abundance May 11 at AF4 – 285 cells/l**
- **Minor *Alexandrium* event in Massachusetts Bay and Gulf of Maine**

So what happened? Why was the forecast so wrong?

- Working hypothesis:
  - A mesoscale Gulf of Maine water mass change occurred that was outside the envelope of observations from the last six years used as the basis of the 2010 ensemble forecast.
    - Surface and deep waters were fresher and warmer than previous years

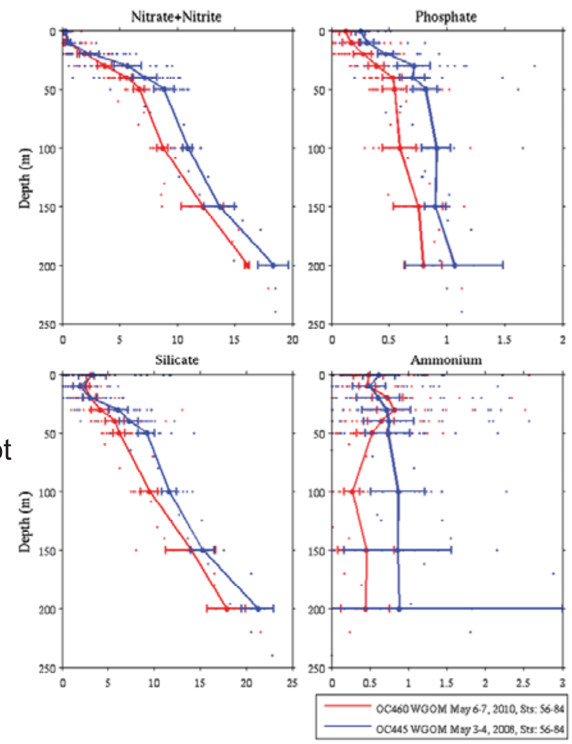


Source: McGillicuddy *et al.* submitted

slide 27

So what happened? Why was the forecast so wrong?

- <u>Working hypothesis</u>:
  - A mesoscale Gulf of Maine water mass change occurred that was outside the envelope of observations from the last six years used as the basis of the 2010 ensemble forecast.
    - Surface and deep waters were fresher and warmer than previous years
    - Nutrient concentrations slightly lower
    - Spring 2010 phytoplankton bloom started earlier, was more intense and crashed earlier than usual
    - GOMTOX cruise data are being used to assess this hypothesis and these factors.
  - *Alexandrium* cysts germinated into conditions not supportive of “normal” growth (i.e. the endogenous clock that regulates germination was out of synch with the environment in 2010).
- Indications are that similar water mass conditions are present in 2011



Source: McGillicuddy *et al.* submitted

slide 28

2010 Summary

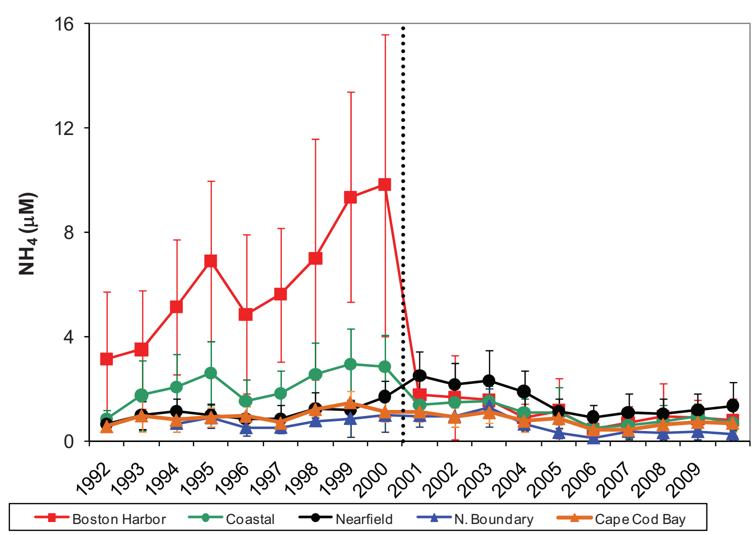
- Nutrients
  - Lower concentrations in February with early diatom and *Phaeocystis* ‘blooms’
  - Lower NO_3 and SiO_4 in CCB in February and a decrease in SiO_4 from late February to April in CCB (earlier occurrence of *Phaeocystis* bloom shifting to April diatom bloom)
  - Relatively low during summer with increasing concentrations and variability into the fall
- Chlorophyll
  - High chlorophyll in CBB and offshore waters of MB in February with annual maxima in CCB, offshore, and northern boundary areas associated with early *Phaeocystis* and diatom blooms
  - Annual peak survey means for chlorophyll and POC in April in the nearfield and coastal areas and POC peaks in CCB and offshore areas all coincident with April diatom bloom
  - Boston Harbor peak survey means for chlorophyll and POC observed in June coincided with peak phytoplankton abundance during large diatom bloom (also elevated in coastal waters)
  - Increase in nearfield chlorophyll in late September during a fall diatom bloom
  - Late fall increase in chlorophyll and POC in the nearfield, offshore and northern boundary areas coincident with a large dinoflagellate bloom

2010 Summary

- Dissolved Oxygen
  - Slight increase in bottom water DO in July in the nearfield
  - Relatively low bottom water DO in 2010 with fall minimum of <6.5 mg/L in nearfield
- Contingency Plan Thresholds - no exceedances in 2010
  - Low seasonal and annual chlorophyll vs. thresholds – though close to baseline and post-diversion means
  - Relatively low DO concentrations and percent saturation in both nearfield and Stellwagen Bank bottom waters, but above baseline background
  - *Phaeocystis* present in the bays in February-April, but at low abundances (lowest since 1999 when it was absent)
  - *Pseudo-nitzschia* abundance continues 10+ year trend of low abundances
  - *Alexandrium* observed early in 2010, but only a minor bloom in Massachusetts Bay (and Gulf of Maine)

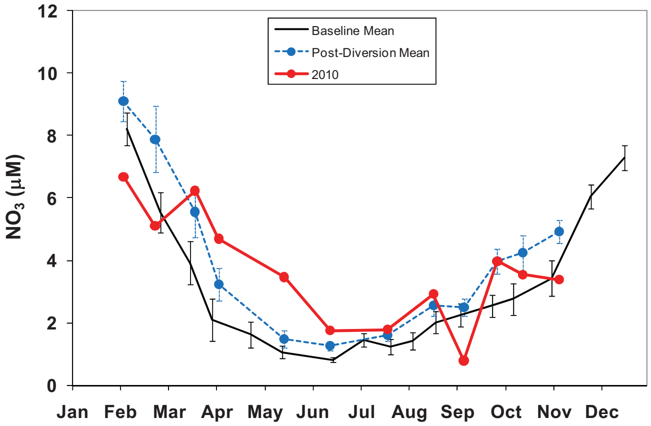
Annual Mean Nutrients – NH_4

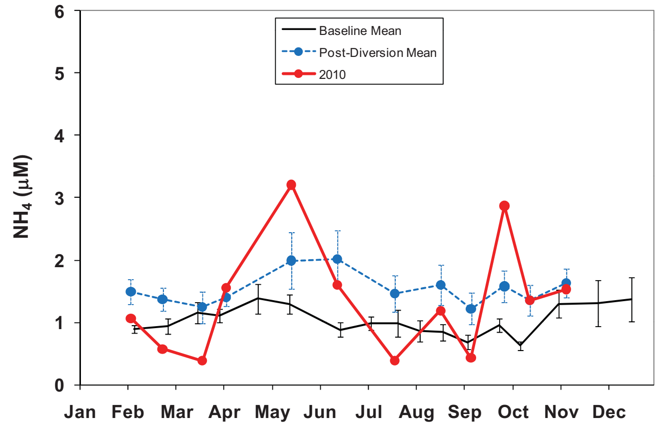
- Post Diversion
  - Large Decrease in Boston Harbor (red)
  - Decrease in Coastal area (green)
  - Initial doubling in nearfield (black)
  - Unchanged elsewhere MB and CCB
- After 2003
  - Decrease across all areas
  - Current nearfield levels comparable to 90’s



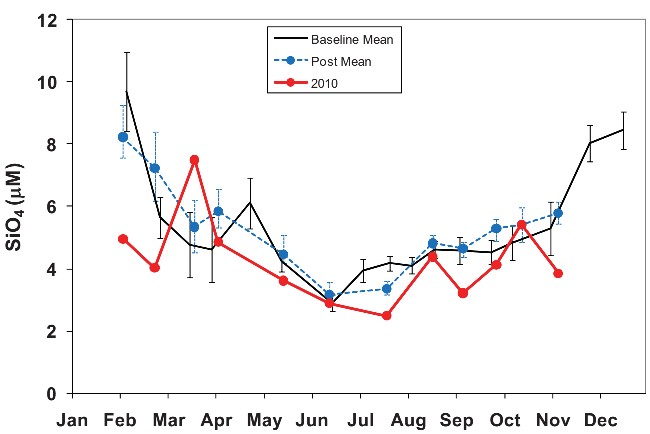
- Other nutrients more interannual variability and no long-term trends (except for decreases in all nutrients in Boston Harbor)

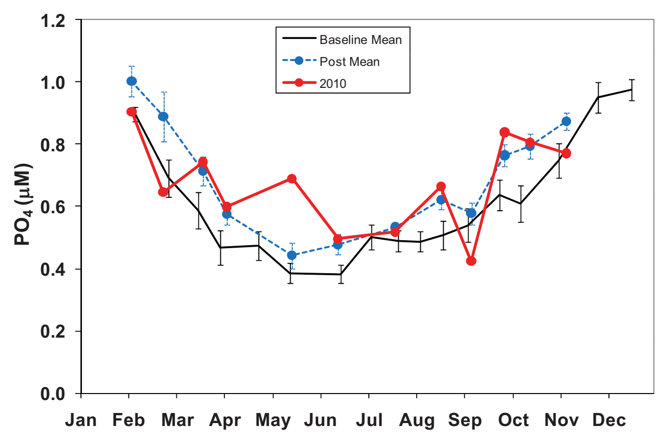
Nearfield – NO_3 & NH_4





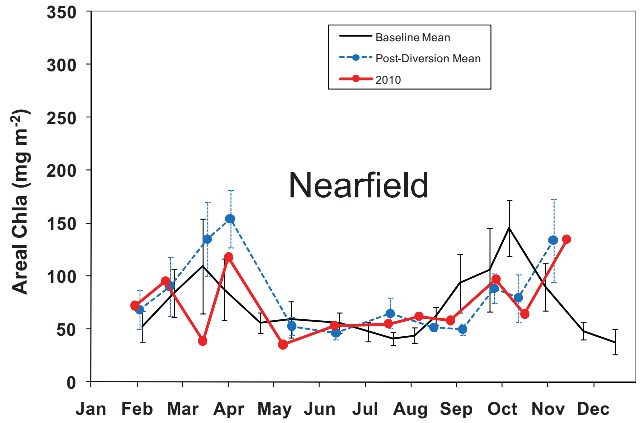
Nearfield – SiO_4 & PO_4

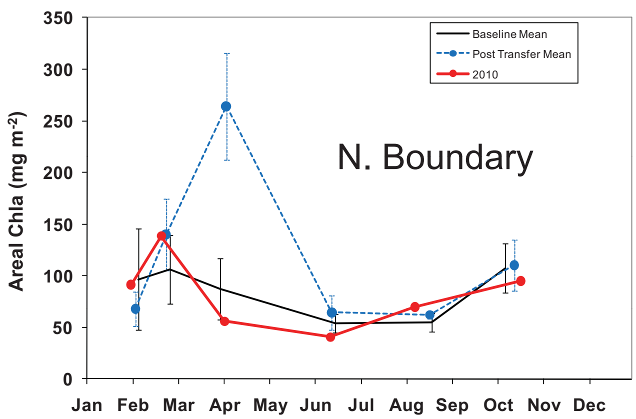


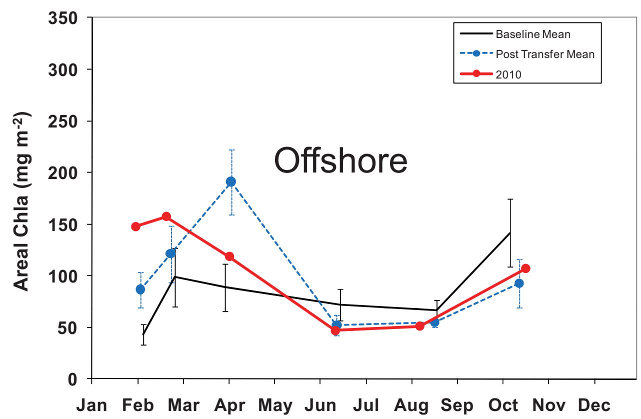


slide 33

Areal Chlorophyll – Post vs. Baseline

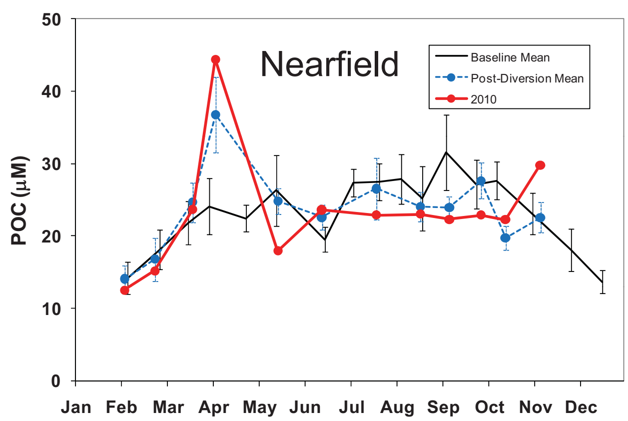


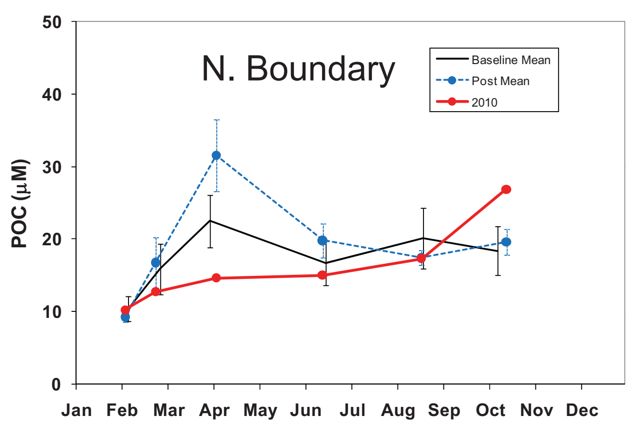


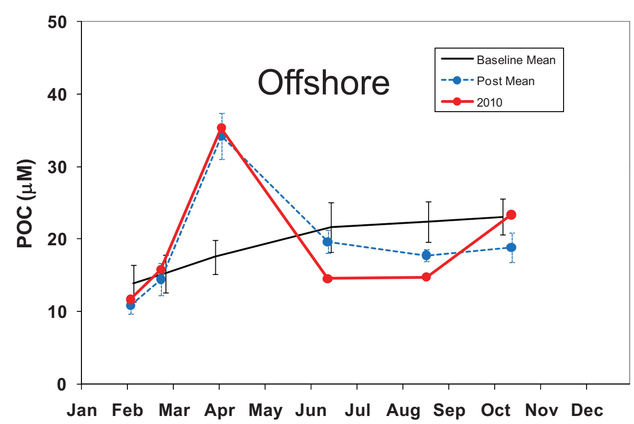


slide 34

POC – Post vs. Baseline

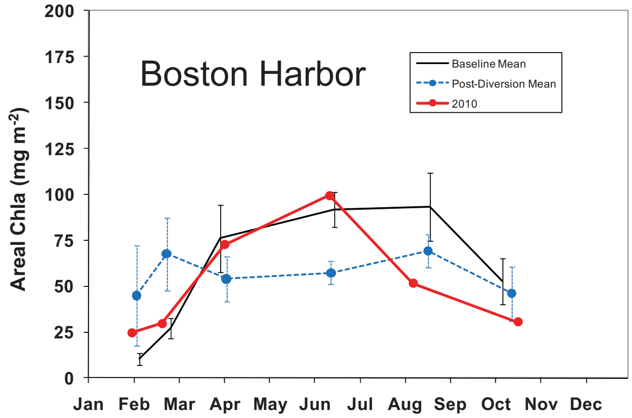


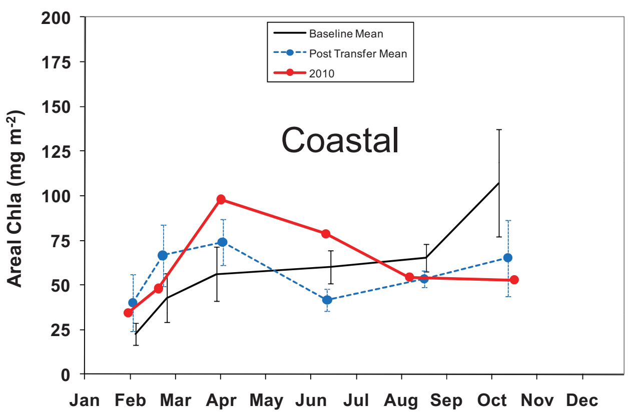


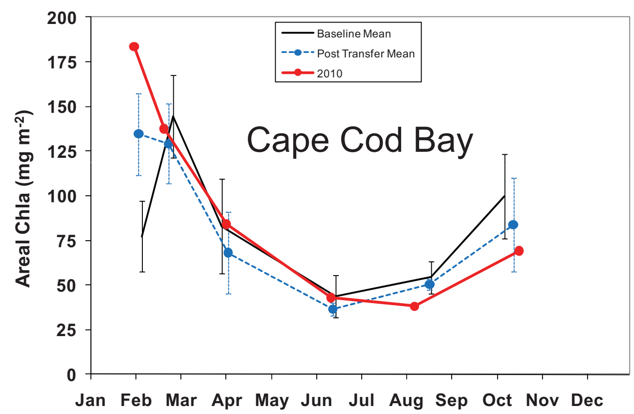


slide 35

Areal Chlorophyll – Post vs. Baseline

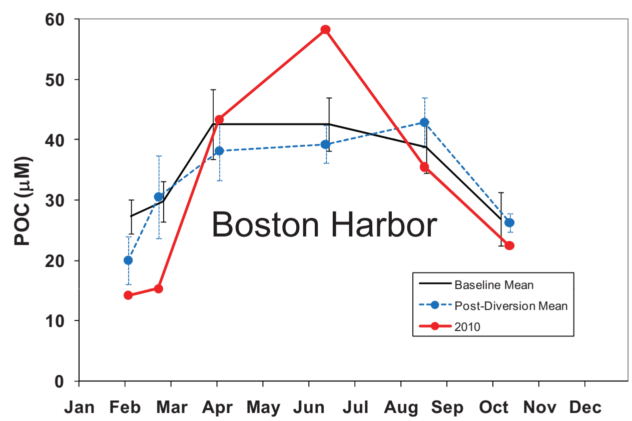


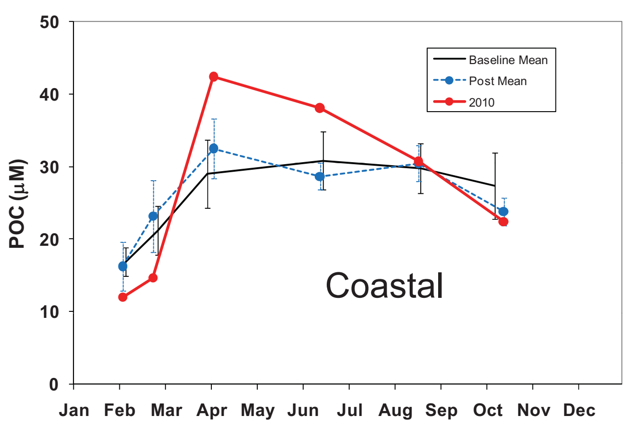


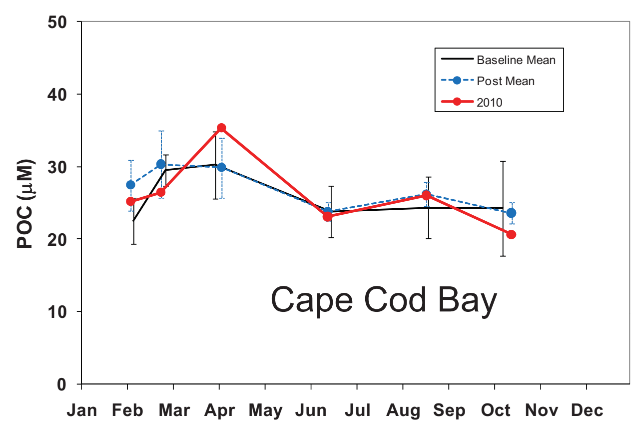


slide 36

POC – Post vs. Baseline

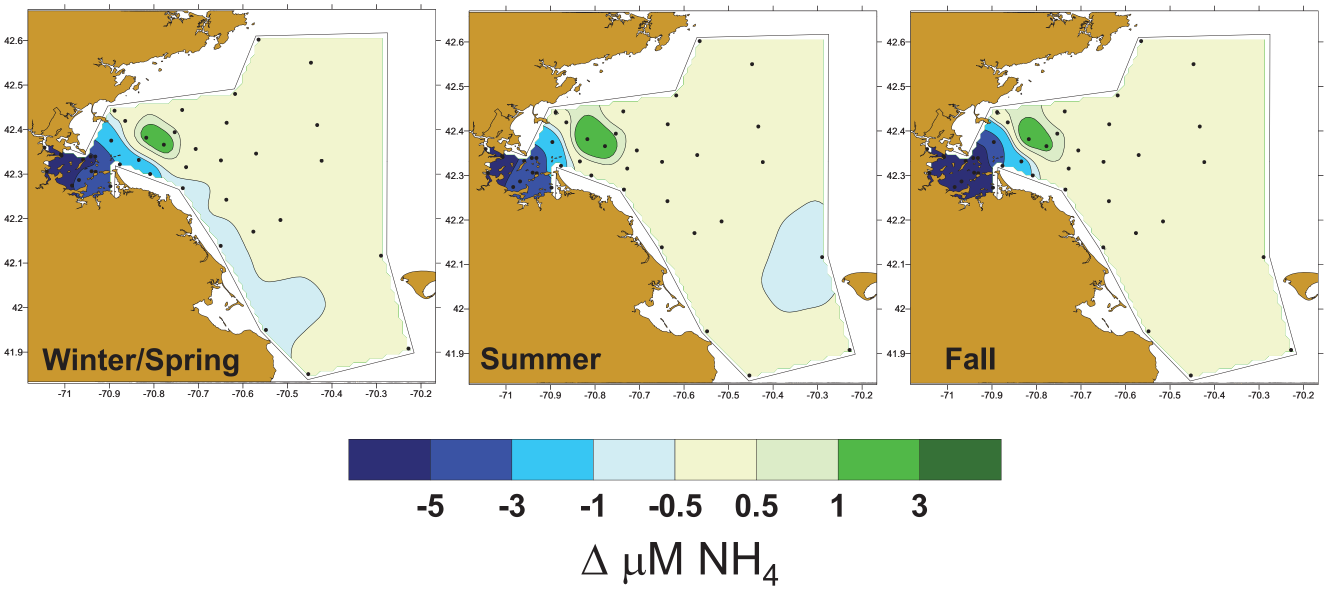






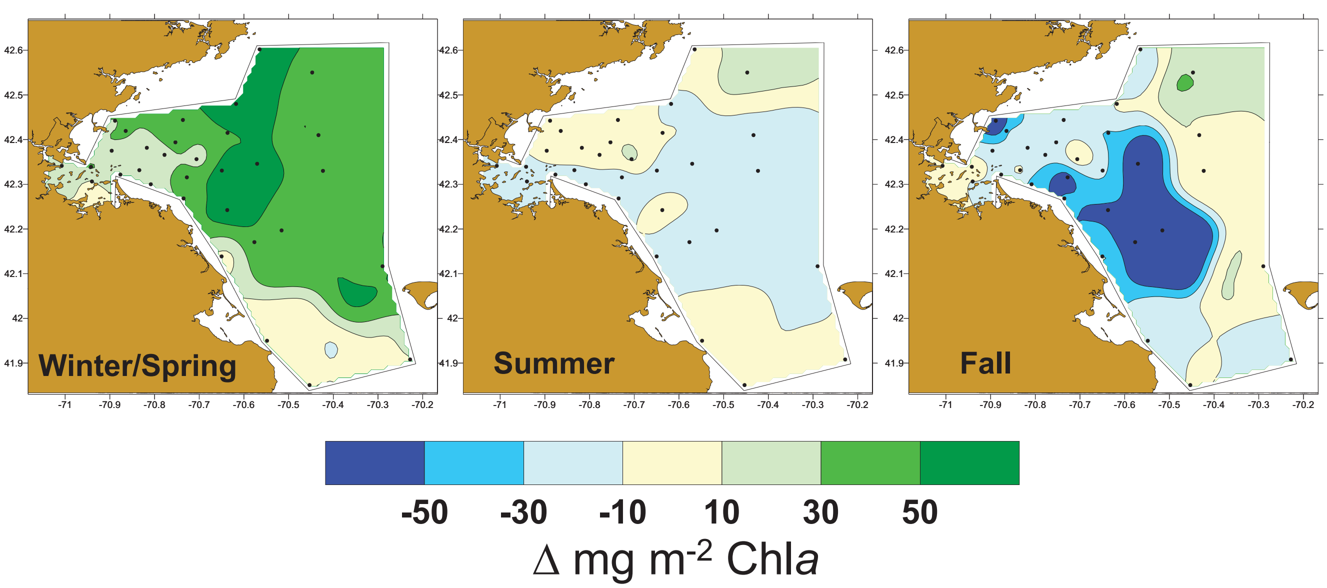
Nutrient Distribution – Pre-Post changes

Ammonium – Baseline vs. 2001-2010



Chlorophyll Distribution – Pre-Post changes

Areal Chl*a* – Baseline vs. 2001-2010



Baseline Comparison Summary

- "Typical" trends generally observed in comparison to baseline
- Nutrients
  - Increase in nearfield NH_4 in vicinity of the outfall
  - Overall there has been decrease in NH_4, NO_3, SiO_4, and PO_4 in Boston Harbor and adjacent coastal waters and a slight increase in NO_3 offshore
- Chlorophyll
  - Trends in Nearfield compared to baseline
    - Higher in winter/spring with March/April (*Phaeocystis* – due to diatoms in 2010)
    - Summer levels comparable
    - Early fall levels have decreased while late fall levels have increased vs. baseline
  - 2000-2009 spring *Phaeocystis* blooms were regional events that contributed to a change in trends for winter/spring biomass levels in northern boundary, offshore and nearfield areas (April vs. February/March peak)
  - No change in coastal, CCB or Boston Harbor areas.
- Dissolved Oxygen
  - 2010 levels comparable to baseline in the nearfield and Stellwagen Basin
  - No change in DO (interannual variability driven by regional processes)

slide 40

Conclusions

- Changes in the nutrient regimes following diversion are unambiguous.
  - Ammonium has dramatically decreased in Boston Harbor (80%) and nearby coastal waters while increasing to a lesser degree in the nearfield (though comparable to baseline levels since 2005) - 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….
  - Only significant change was the increase in NH_4 concentrations
  - Analyses have not found statistically significant changes in chlorophyll
  - The chlorophyll and phytoplankton changes have been regional in nature – occurring throughout Massachusetts Bay and further offshore in the western Gulf of Maine

C. Primary Productivity in Massachusetts Bay, 2010

Candace Oviatt, Aimee Keller, and Conor McManus, Graduate School of Oceanography, URI

The 2010 potential primary production was again much lower than for years prior to 2003 (except for 1998 - the year without a spring bloom), although greater than the production in 2008 and 2009 for all sites (**Slide 2**). The harbor station had higher annual productivity than the nearfield stations. The annual potential productivity for the harbor station, and nearfield stations N04 and N18 were 357, 296 and 293 g C $m^{-2}y^{-1}$ respectively (**Slide 3**).

The Boston Harbor station reached its greatest potential productivity of roughly 1500 mg C $m^{-2}d^{-1}$ during the summer diatom bloom. The productivity increased in April and began to decrease in August and into the fall. Station N18 had peaks in productivity in April, August and October, with the highest peak (in April) reaching to 2326 mg C $m^{-2}d^{-1}$. At station N04, there were peaks in productivity in each season, however, none of them greater than 1400 mg C $m^{-2}d^{-1}$. The peaks are consistent with timing of the blooms in their respective seasons (**Slide 3**).

With the exceptions of blooms, all three stations areal productivities were lower than the baseline means. At the harbor station, the spring bloom productivity increased toward the baseline mean, but never made it above the baseline mean at any point throughout the year (**Slide 4**). The spring and summer blooms at station N04 were slightly higher than the baseline means for those respective dates (**Slide 5**). The natural logarithm of the areal productivity at station N04 displayed similar results (**Slide 6**). At nearfield station N18, the spring bloom greatly exceeded the baseline mean, while the summer bloom was only slightly greater. At other times of the year productivity at station N18 was at the lower end of the baseline, and occasionally below it (**Slide 7**).

Since 2002, there has been a decrease in spring bloom peak areal productivity. However, while the spring bloom at station N04 had a marginal increase from 2009 to 2010, the N18 spring bloom peak was the greatest at that station since 2002, reaching 2326 mg C $m^{-2}d^{-1}$ (**Slide 8**). The fall bloom peaks in areal productivity experienced opposite trends, for the productivity decreased at both sites from 2009 to 2010. The station N04 fall bloom peak areal productivity decreased by roughly 161 mg C $m^{2}d^{-1}$, whereas the fall bloom peak areal productivity at station N18 decreased by 1552 mg C $m^{-2}d^{-1}$ (**Slide 9**.)

With the inclusion of 2010 data, the average areal production at the Harbor station post-relocation was still less than it was before the movement, most notably in the warmer months (April-September). The post-relocation areal production at this site was greater than before the relocation in the winter months, but only by a small margin (**Slide 10**). The error bars on the means represent standard errors. The chlorophyll-specific areal production at the harbor station was below the baseline mean and below the lower end of baseline range in February and March. This was true except for in November, where chlorophyll-specific areal production exceeded the upper end of the baseline range (**Slide 11**). The chlorophyll-specific areal production at station N04 was also at or below the lower end of the baseline range excluding late August through September, where the production was above the baseline mean (**Slide 12**). Station N18 experienced chlorophyll-specific areal production outside the low end of baseline range from February-May, mid June-mid July and in November. The peaks in production at station N18 (in May, late July and October) almost reached their respective baseline means (**Slide 13**). Overall, with the exceptions of areal production peaks, the chlorophyll seemed to be relatively inactive with low levels of productivity in 2010.

Spring bloom peak areal productivity has decreased since the relocation of the sewage outfall for both the harbor and nearfield stations. The nearfield stations decreased by about 500 mg C $m^{-2}d^{-1}$ and the harbor station experienced an even greater decrease of about 1000 mg C $m^{-2}d^{-1}$ (**Slide 14**). The larger decrease at the harbor station could be due to decreased surface nutrient concentrations following outfall relocation. The pooled nearfield stations still has a higher post-relocation-average of spring bloom areal productivity peaks than the harbor station. The areal productivity in summer bloom peaks also decreased for both the harbor and nearfield stations after the relocation effort. The Boston Harbor station saw a larger decrease in areal productivity than the nearfield stations, and both now are very similar (**Slide 15**). The fall bloom areal productivity peaks also decreased from pre to post relocation, but now the nearfield stations have greater fall peaks than the harbor station (**Slide 16**). All stations' annual productivity decreased after the relocation effort, however now the productivity at all three stations are very similar, whereas before the relocation there were large differences between all three (**Slide 17**).

It is plausible that the reduced nutrient loading at the Boston Harbor station has played a role in its decreased productivity, but for the somewhat smaller decreases in productivity at the nearfield stations we suggest that a decrease in surface nutrients was not the only factor in the differences in productivity before and after the relocation of the sewage outfall. It appears that reduced wind and gust speeds could also be playing a role in the reduced productivity. At all three stations, primary production was positively correlated with average summer wind and gust speeds, with r^2 values of 0.32 or greater (**Slides 18** and **19**). The wind data were obtained from the NOAA buoy station 44013 in Massachusetts Bay. Over an average summer wind range of about 3.90 to 4.67 m s^{-1} annual production values increased from roughly 200 to 532 g C m^{-2} y^{-1} at nearfield stations and to higher values at the harbor station (**Slide 18**). Over an average summer gust range of 4.58 to 5.53 m s^{-1} a similar increase in production occurred (**Slide 19**). Overall, both wind and gust summer speed averages have decreased since 1995. However, the correlations between wind speed and time and gust speed and time are decreased due to the unusually high wind and gust speeds of 2010, the highest seen at this wind station over the 1995-2010 period (r^2 = 0.10 for both; **Slide 20**). **Slide 21** shows that wind speed and gust speed summer averages decreased by 0.14 and 0.17 m/s respectively from 1995-2002 to 2003-2010, the periods showing the decrease in potential productivity (**Slide 3**). The error bars are one standard deviation.

In summary, since outfall relocation, the Boston Harbor station has shown a dramatic decrease in productivity consistent with reduced sewage effluent nutrient loading to this station (**Slide 3**). The nearfield stations in the vicinity of the new outfall in Massachusetts Bay showed no clear increase or decrease in primary productivity associated with outfall relocation. Years prior to and after relocation had a similar range of productivity. A decrease in productivity in 1998 and since 2003 at the nearfield stations and to some extent at the Boston Harbor station can be correlated with climate related reduced wind intensities during these years. The enhanced stratification due to lighter winds has prevented the mixing of sub surface nutrients to fuel primary production during all seasons.

Primary Production in Massachusetts Bay, 2010

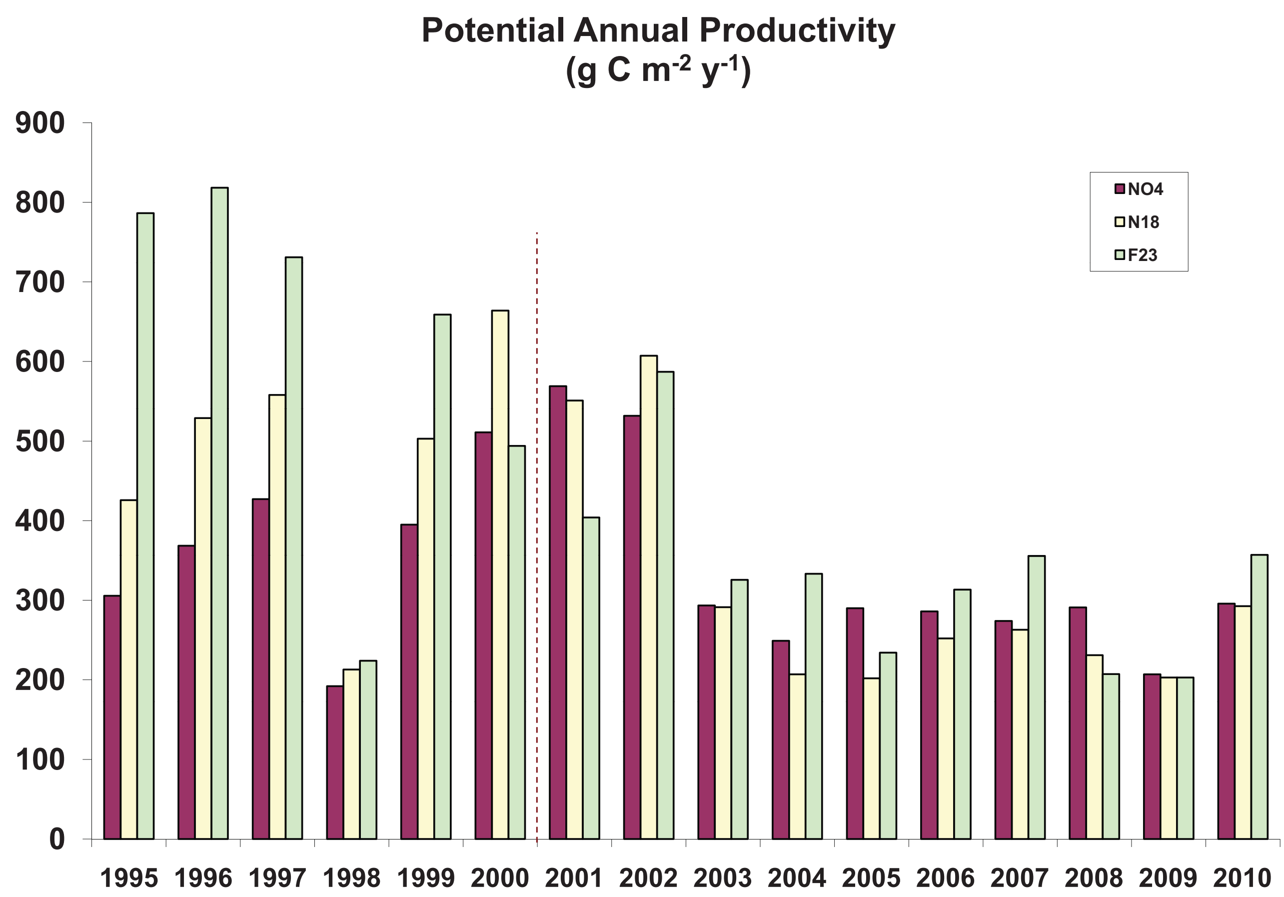
Candace Oviatt

Aimee Keller

Conor McManus

May 9, 2011

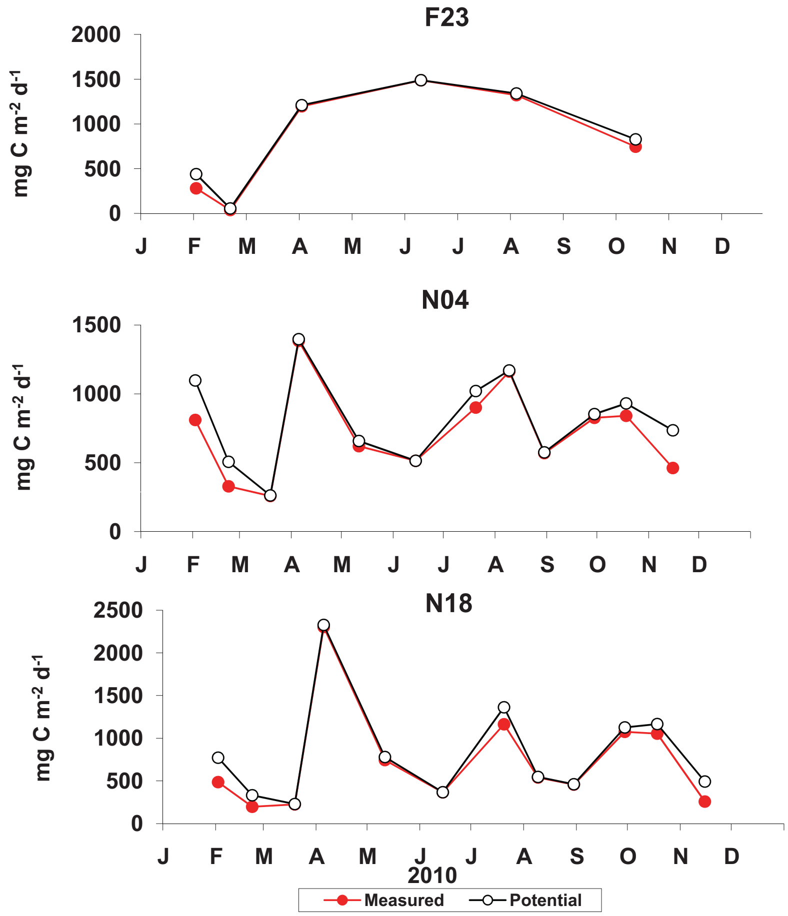
slide 2



slide 3

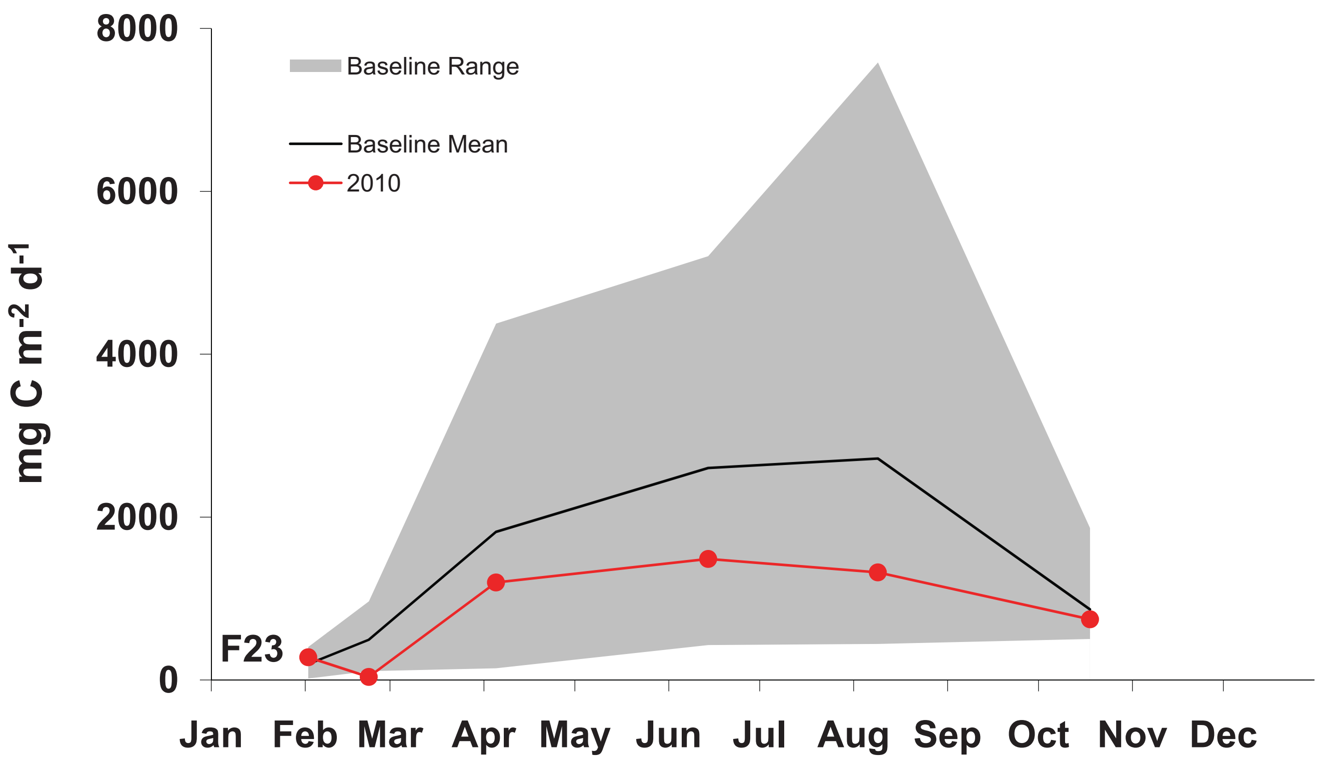
year	N04	N16-18	F23
2010	296	293	357

g C m^{-2}y^{-1}

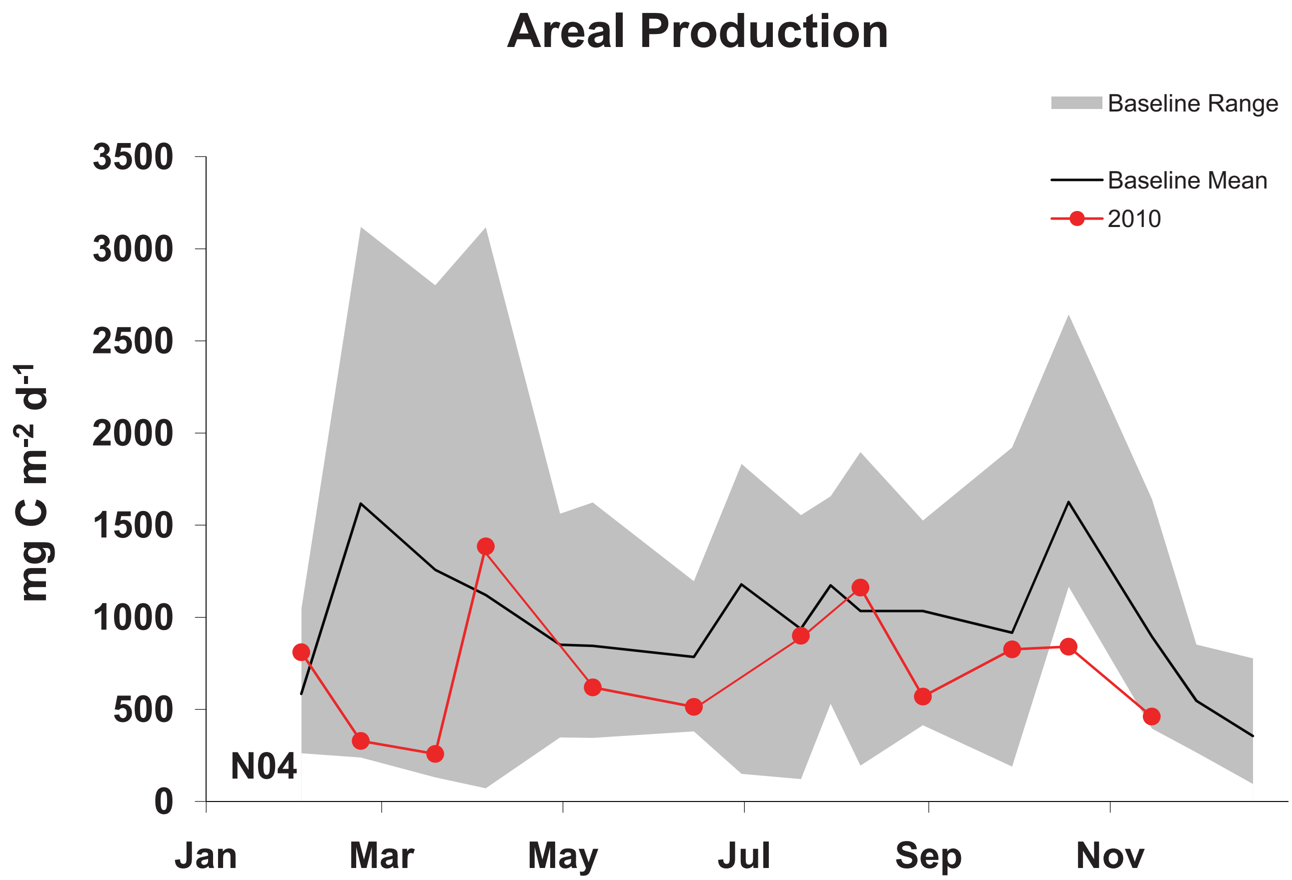


slide 4

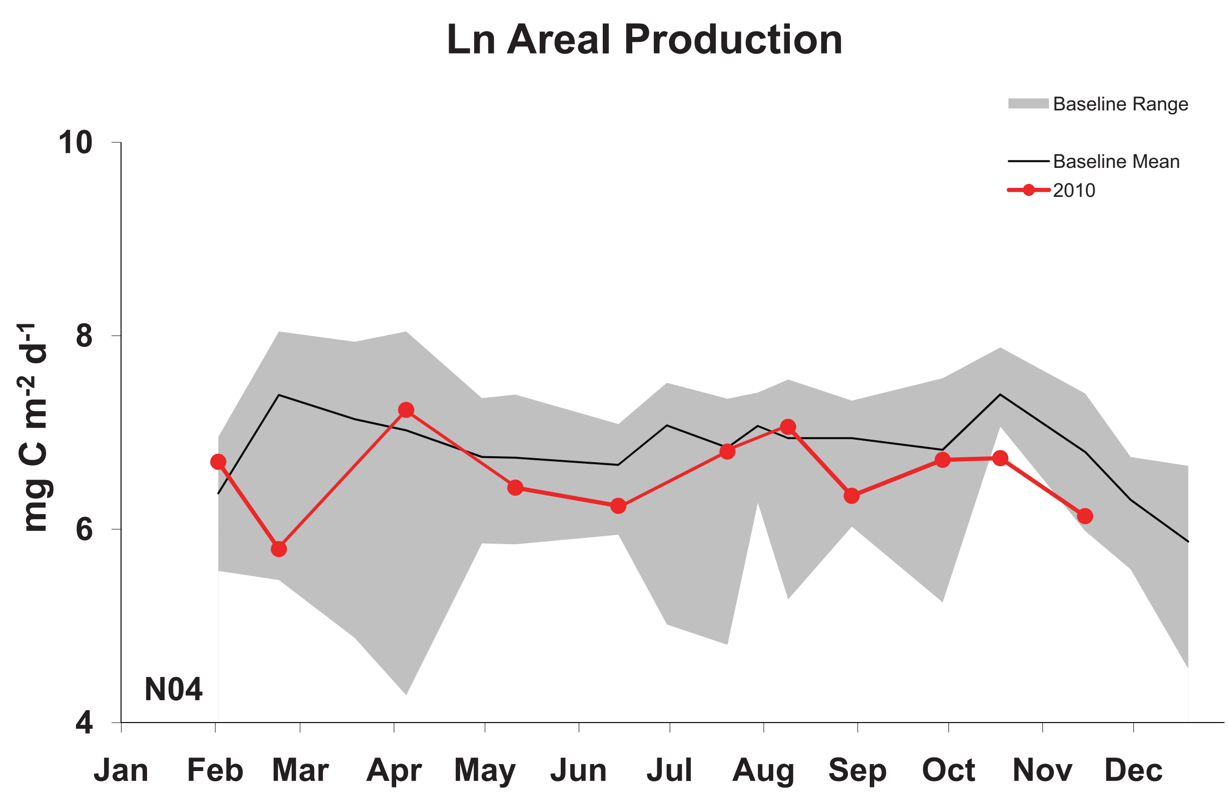
Areal Production



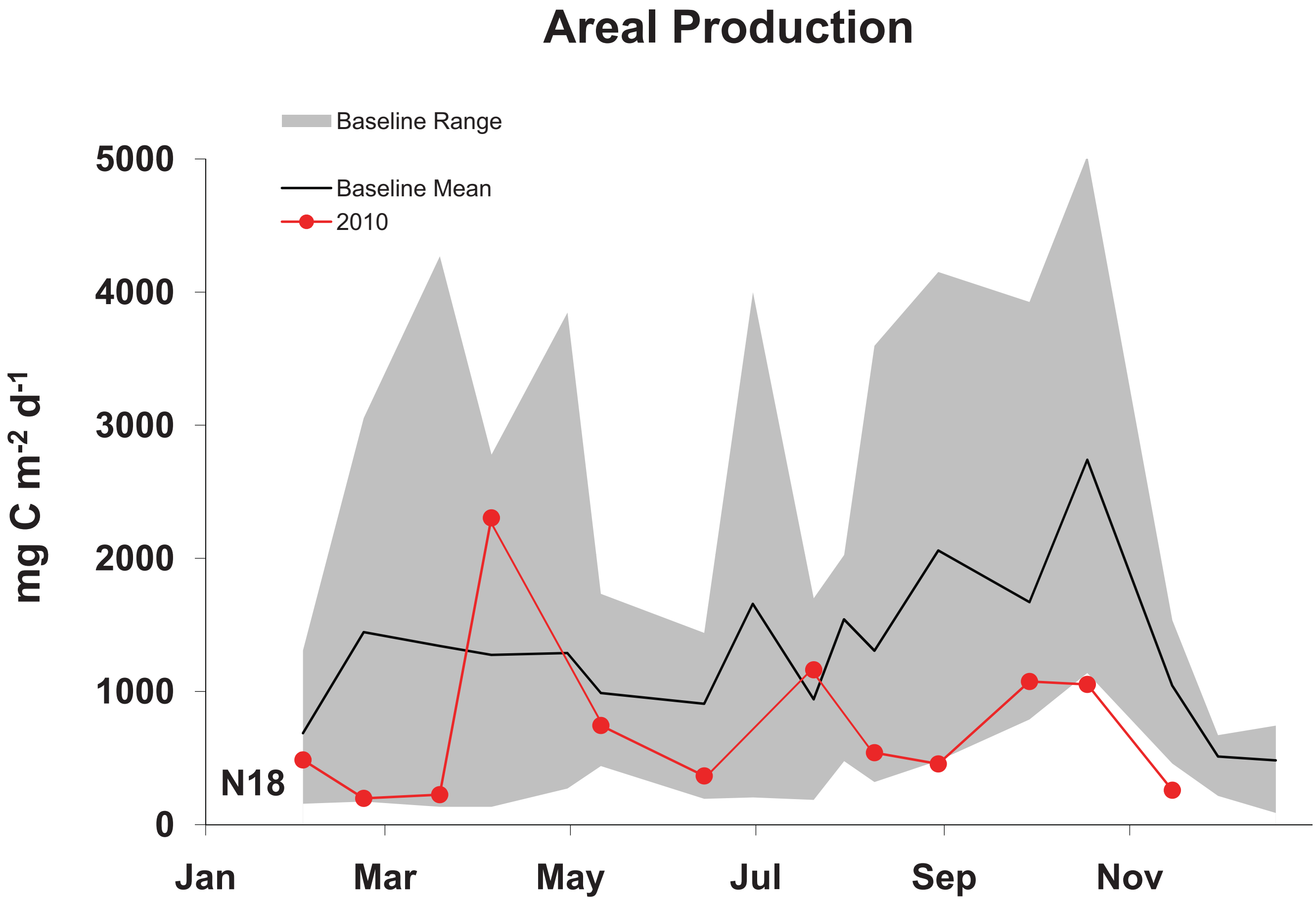
slide 5



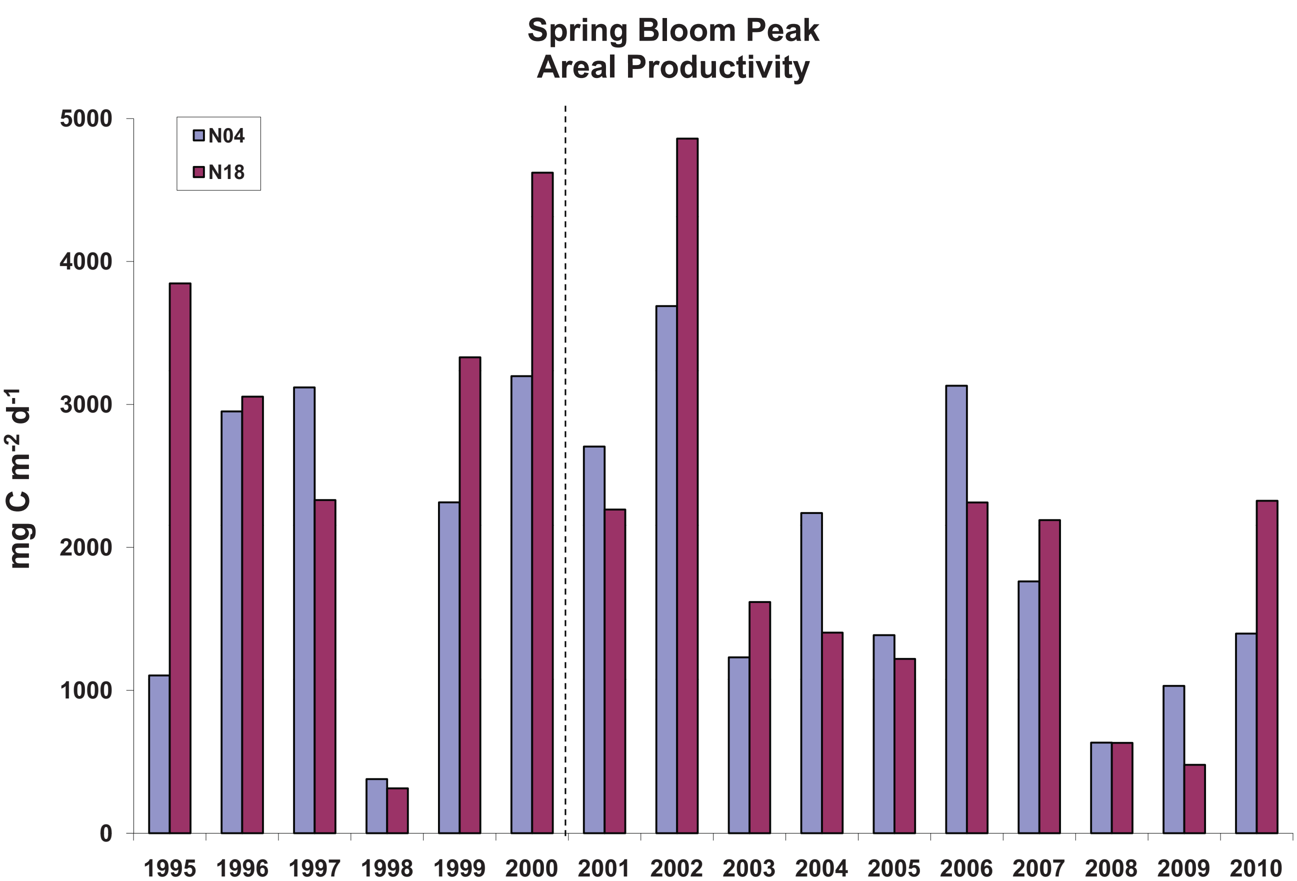
slide 6

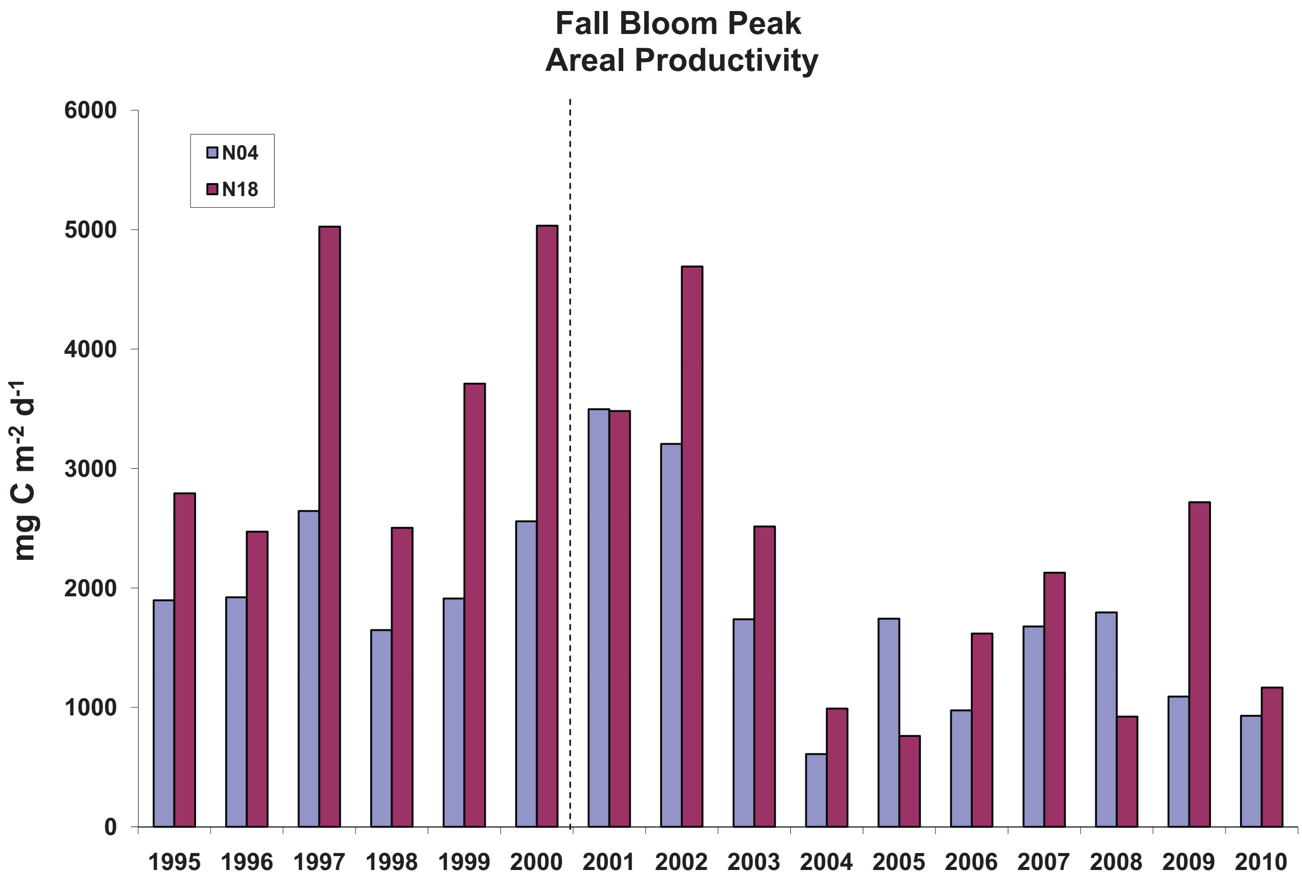


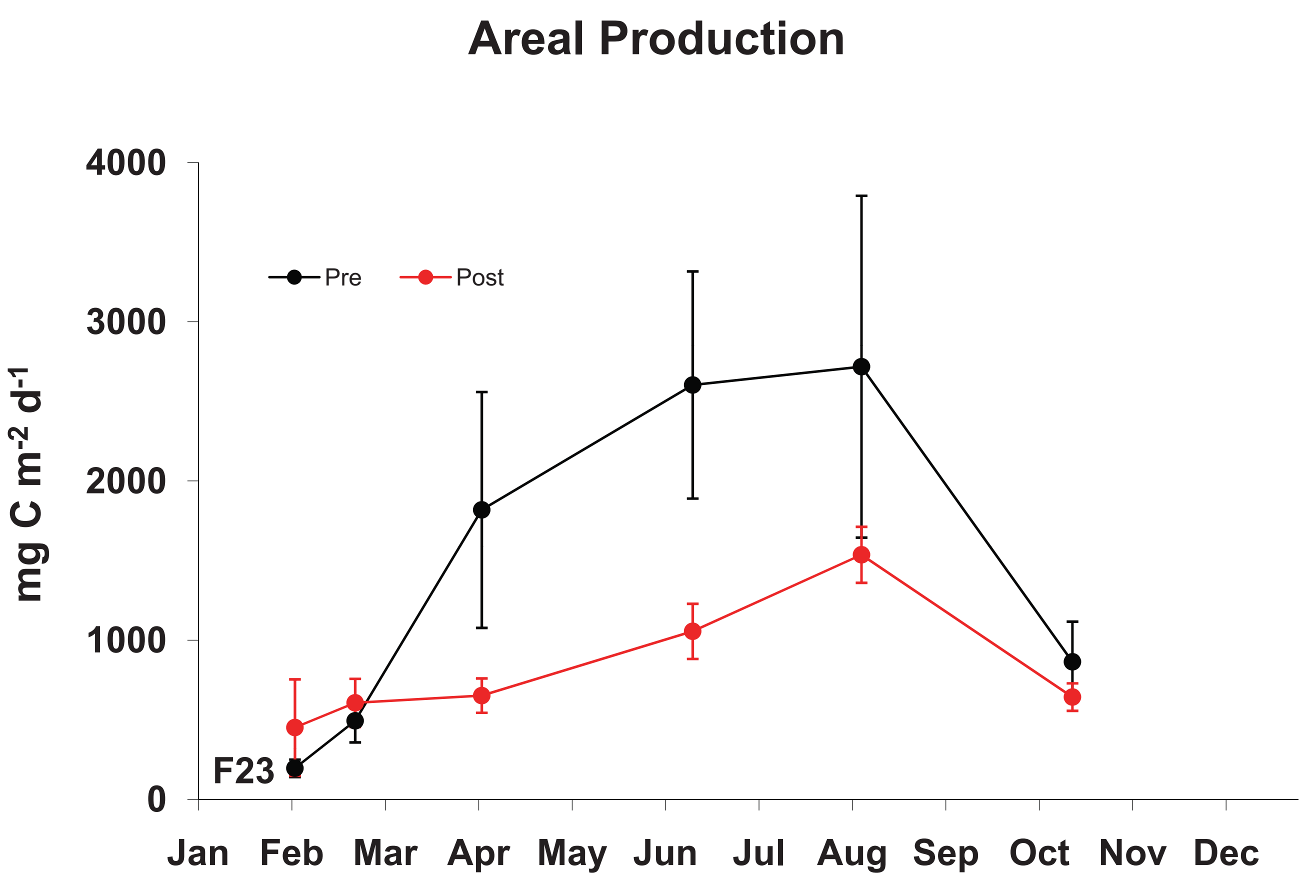
slide 7



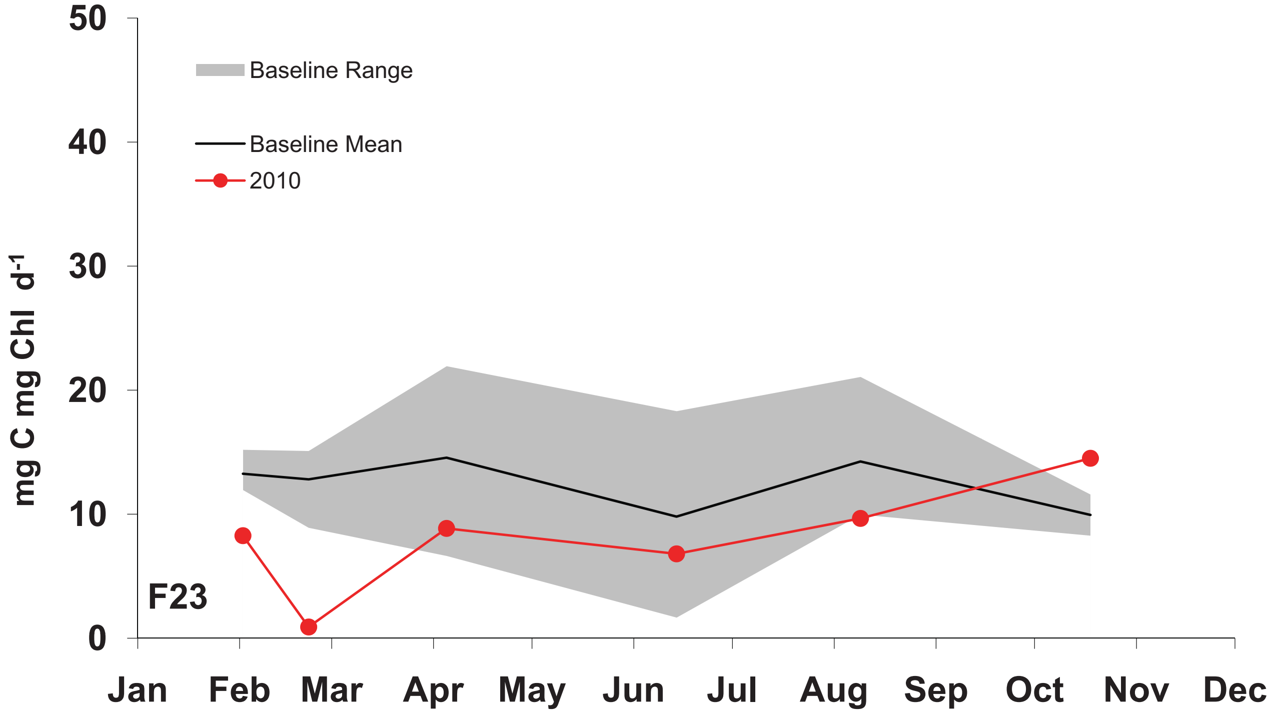
slide 8




Fall Bloom Peak
Areal Productivity
N04
N18
mg C m-2 d-1
6000
5000
4000
3000
2000
1000
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

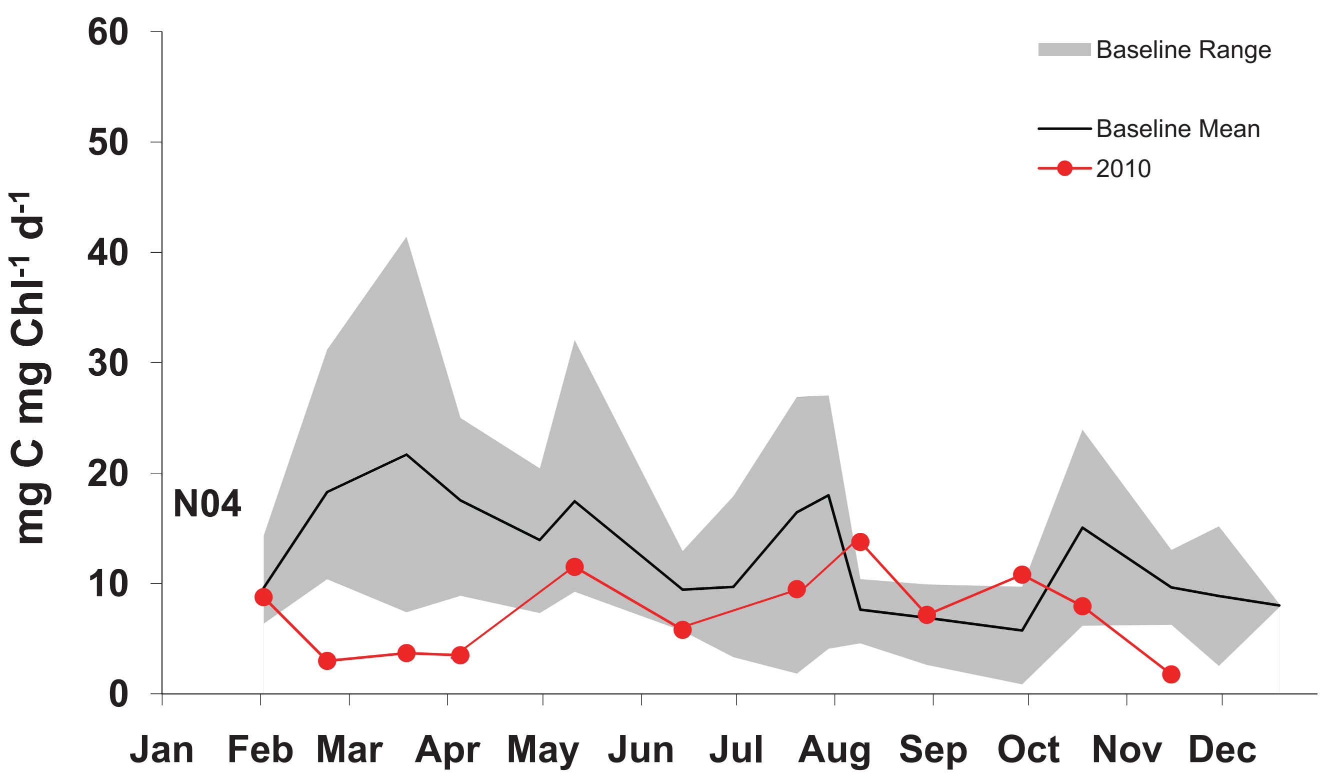

Areal Production
Pre
Post
mg C m-2 d-1
4000
3000
2000
1000
0
F23
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Chlorophyll-Specific Areal Production

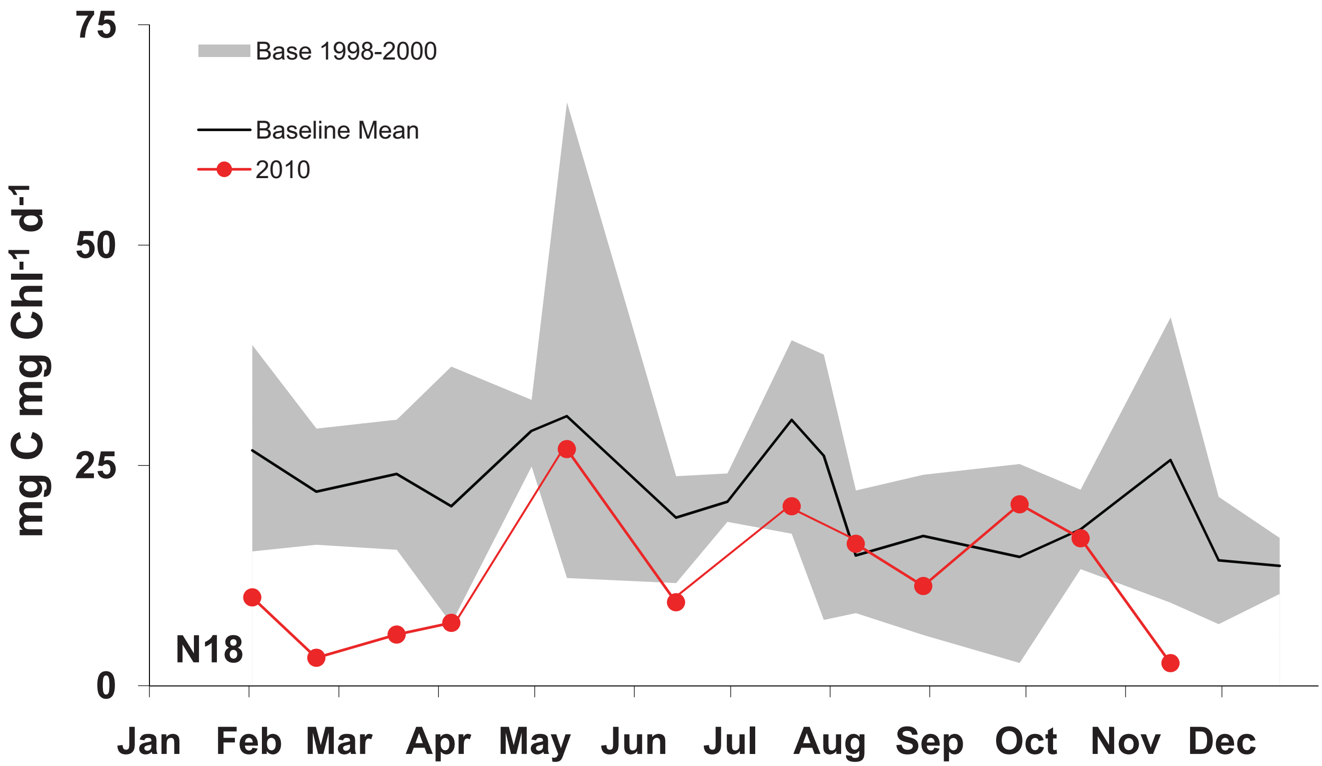


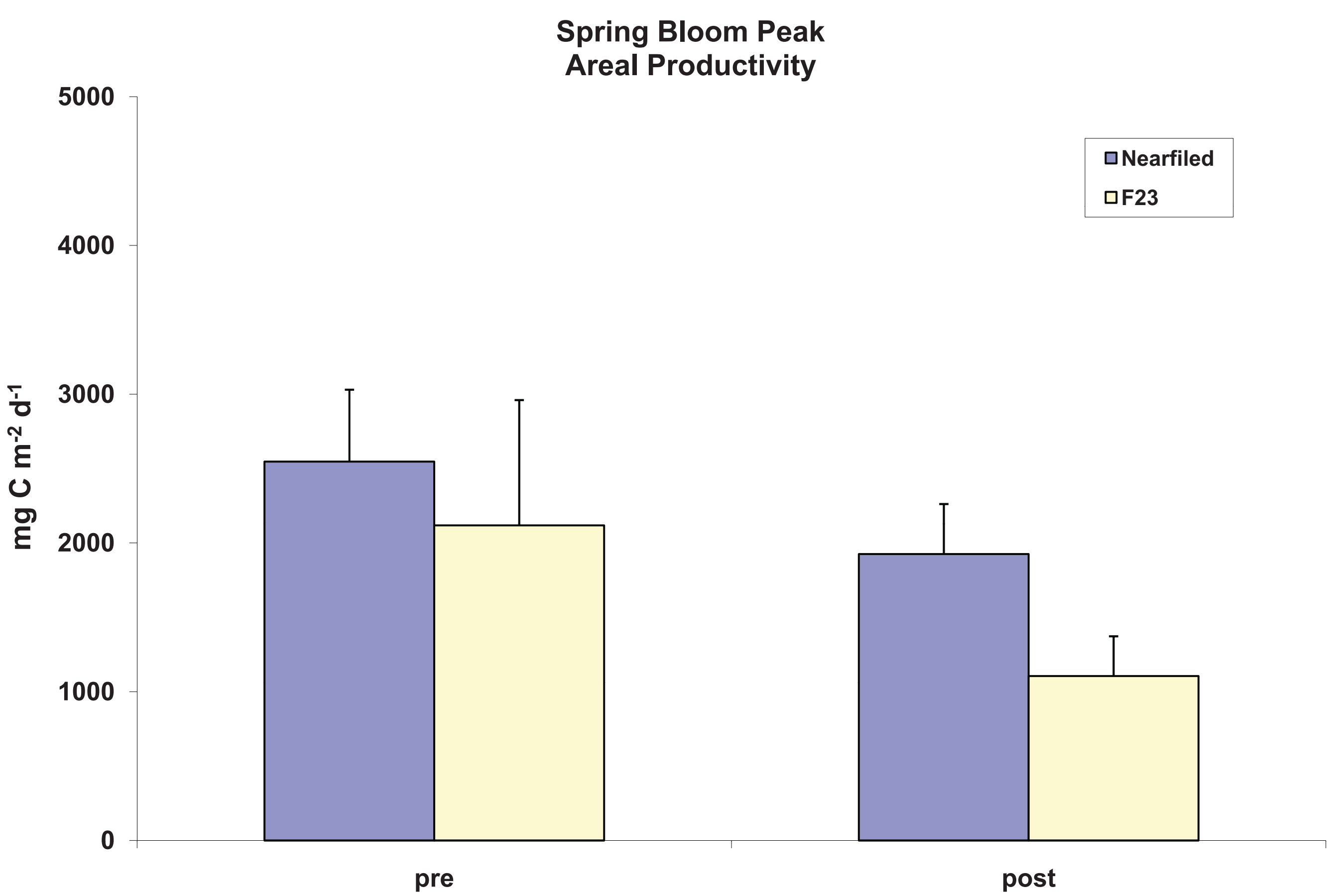
slide 12

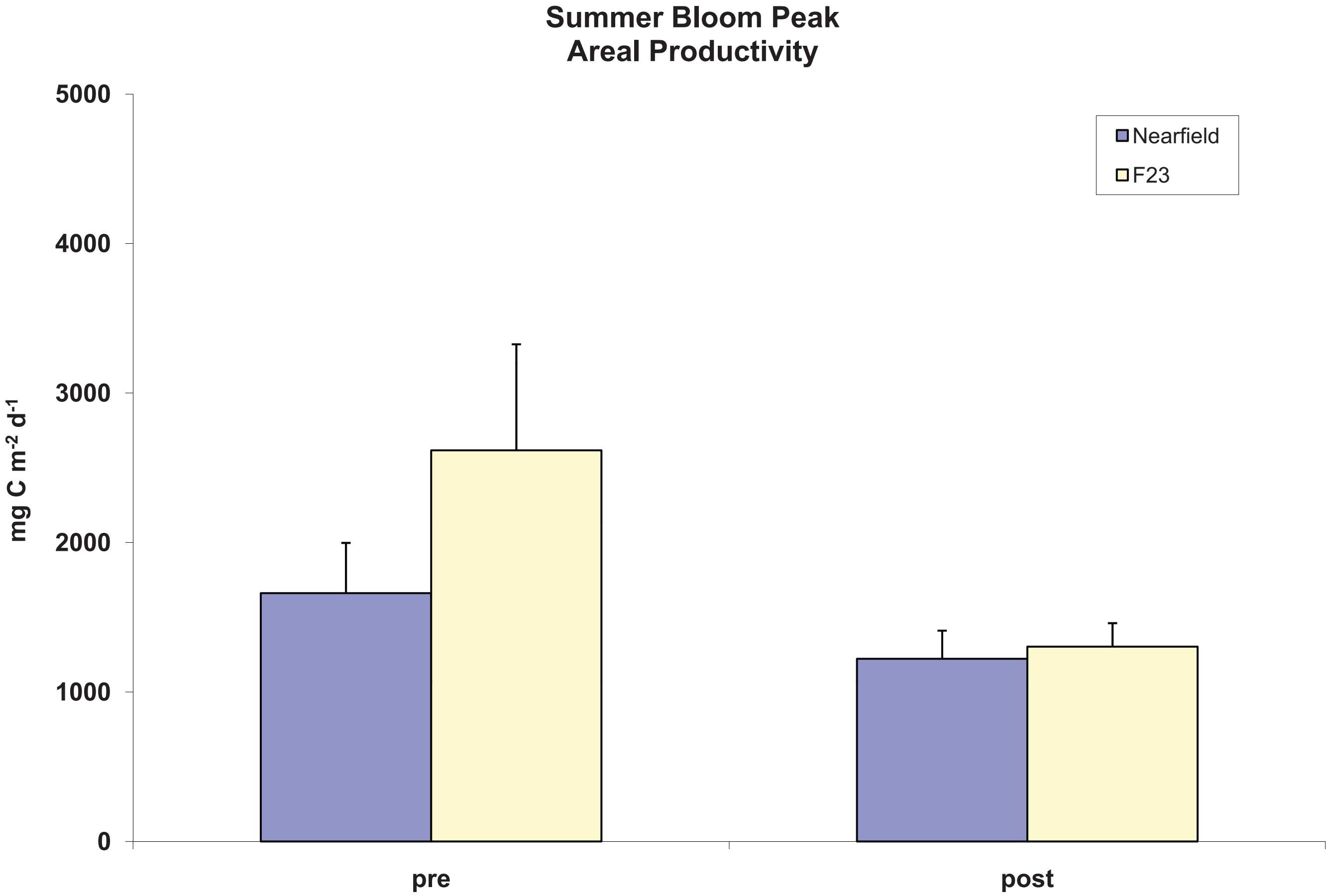
Chlorophyll-Specific Areal Production

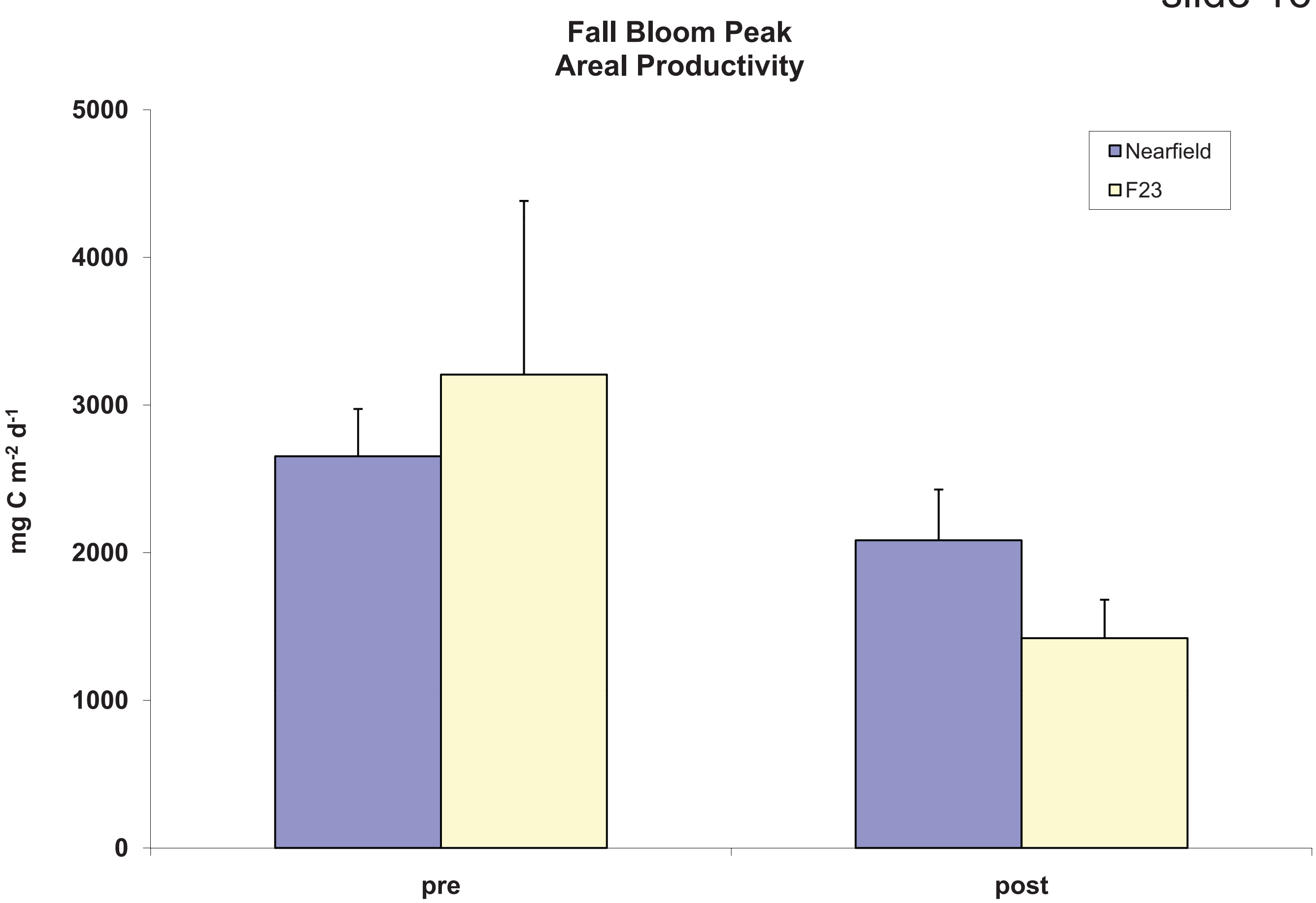


Chlorophyll-Specific Areal Production

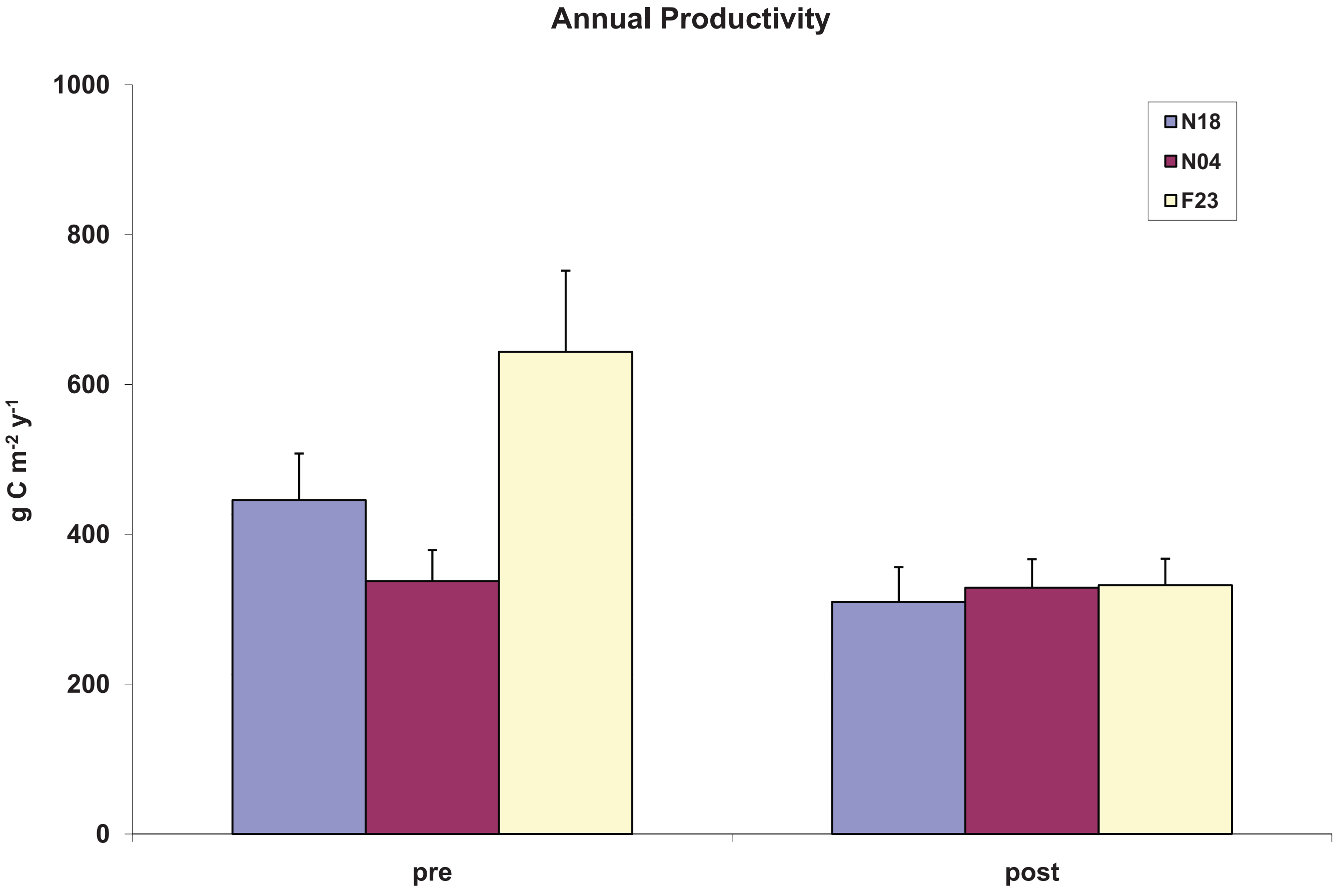




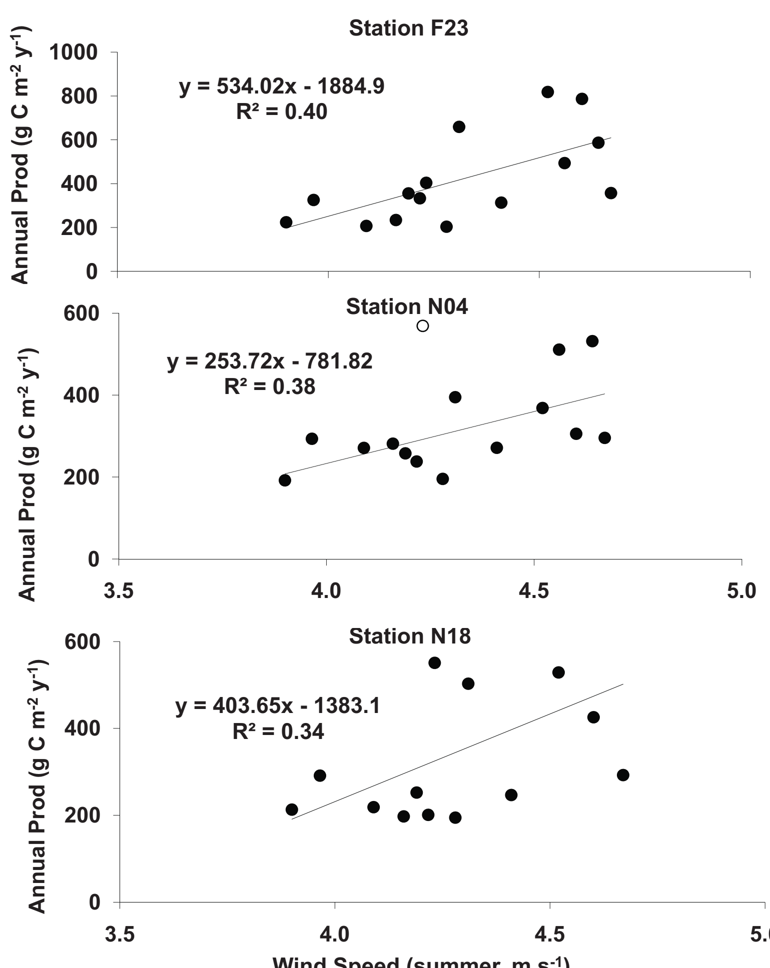

Summer Bloom Peak
Areal Productivity
mg C m-2 d-1
5000
4000
3000
2000
1000
0
Nearfield
F23
pre
post


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

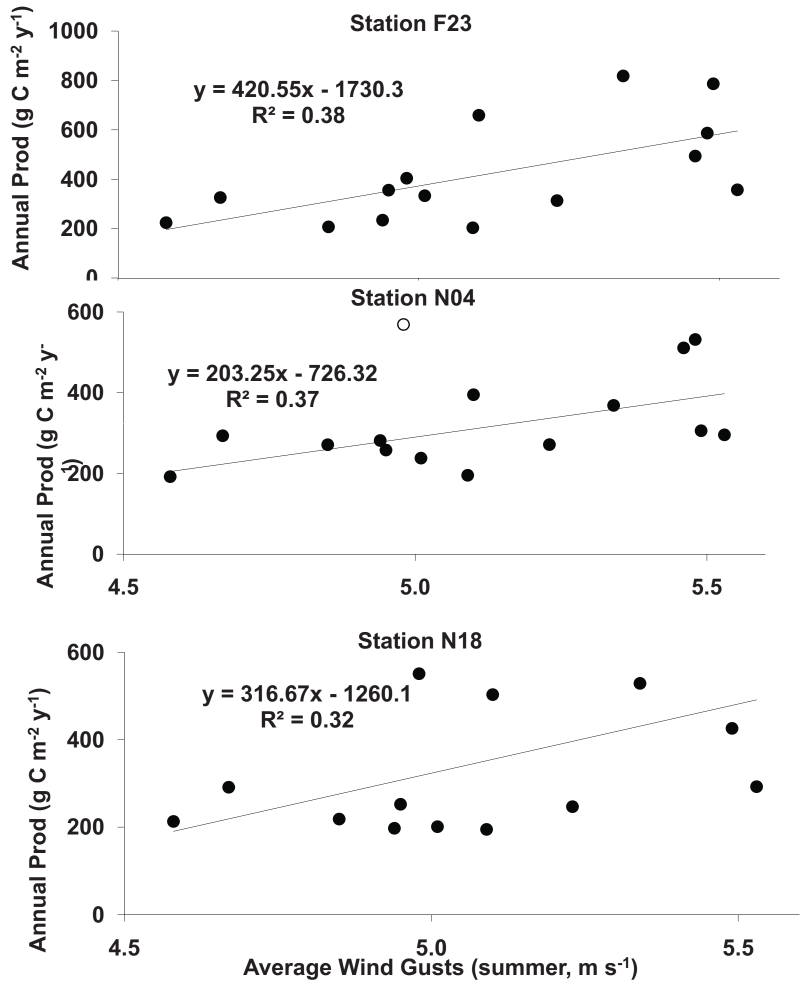
slide 17



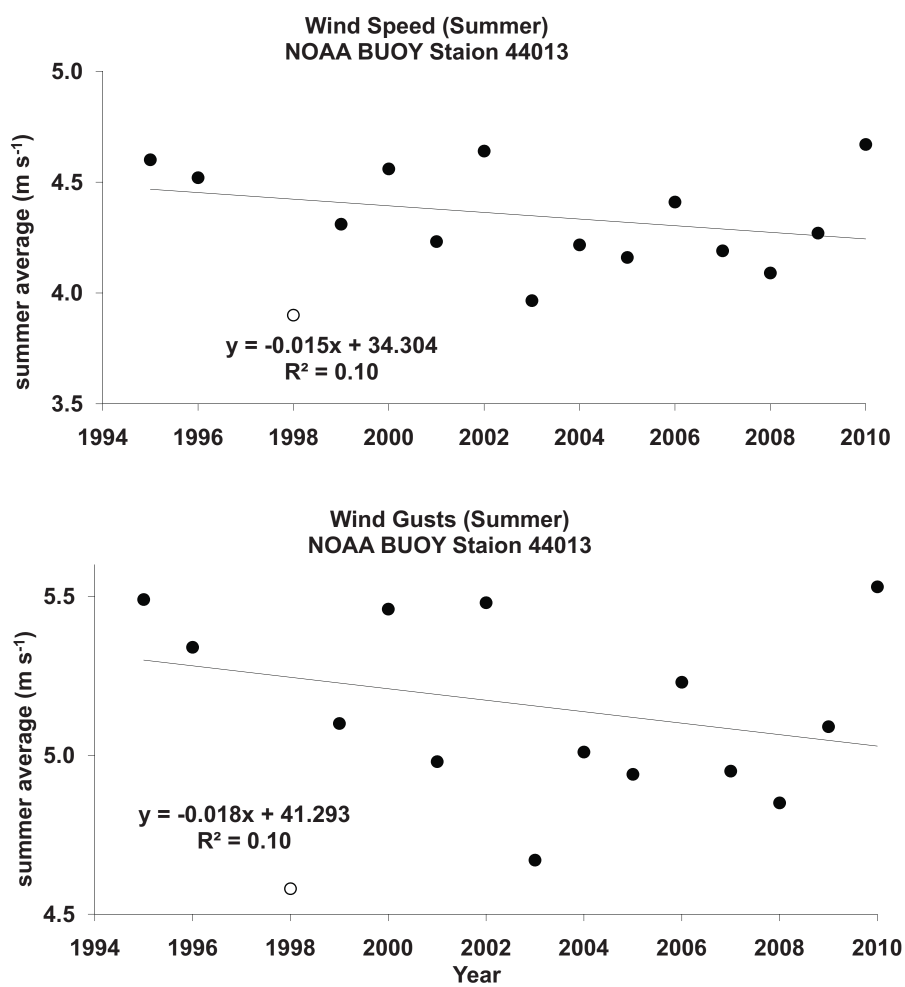
slide 18



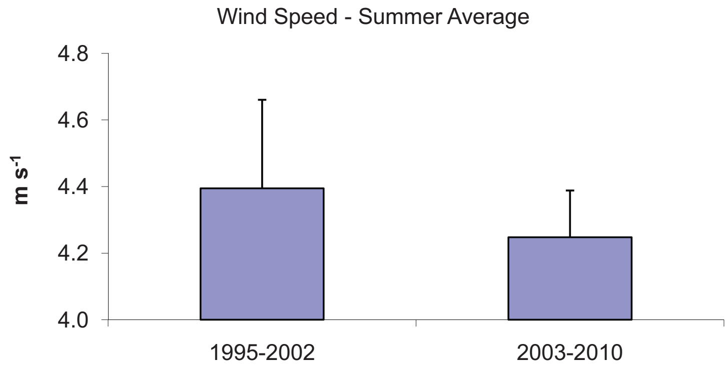
slide 19

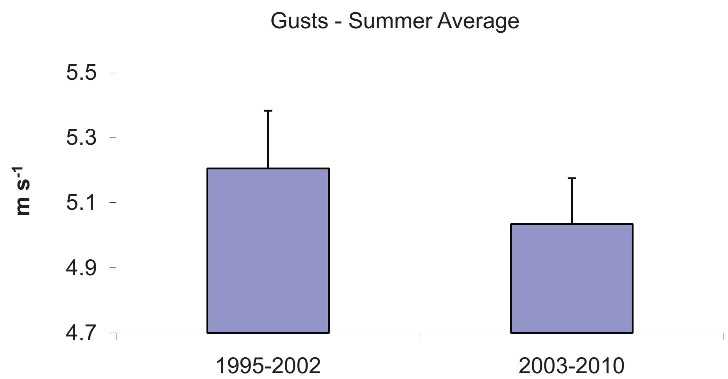


slide 20



slide 21





slide 22

In summary, since outfall relocation,
the Harbor station has shown a decrease
in productivity consistent with reduced
sewage effluent nutrient loading to this station.

By contrast, the near field area
of the new sewage out fall in
Massachusetts Bay showed no increase
or decrease in primary productivity
associated with outfall relocation.

D. 2010 MWRA Plankton Monitoring Summary

David Borkman, University of Rhode Island and Jeff Turner, University of Massachusetts Dartmouth

Plankton monitoring was conducted as part of the 2010 MWRA comprehensive water column monitoring program. All phytoplankton and zooplankton analyses were conducted according to procedures described in Libby *et al.* (2010). Phytoplankton abundance and species composition were assessed *via* quantitative phytoplankton counts using phase contrast light microscopy (250X and 500X) of whole-water (Lugol's preserved) and >20 um size-fractionated (formalin preserved) phytoplankton samples. Near-surface and chlorophyll maximum (or mid-depth) samples were analyzed from each of the phytoplankton stations. Zooplankton abundance and community composition was monitored during 2010 as part of the MWRA's comprehensive outfall monitoring program. The zooplankton community was assessed *via* vertical oblique net hauls (102 am mesh). Plankton samples were collected at two nearfield stations (N04 and N18) 12 times per year and at an additional 13 farfield stations in Massachusetts Bay and Cape Cod Bay six times per year (February, March, April, June, August, and October). 2010 was the 19th consecutive year of monitoring (1992-2010).

D.1. 2010 Phytoplankton Annual Cycle

Total phytoplankton in 2010 followed an annual pattern similar to that of other years in the post-transfer period, although there were some notable anomalies in the 2010 annual cycles of some phytoplankton functional groups (**Slide 3**; notably dinoflagellates). The 2010 phytoplankton annual cycle was dominated by a winter-spring bloom. The winter-spring bloom featured a modest diatom (*Thalassiosira* and *Chaetoceros* spp.) bloom in early February, a moderate (maximum of 1.6 x 10^6 cells L^{-1}; in Cape Cod Bay **Slide 6**) *Phaeocystis pouchetii* bloom in late February followed by a larger diatom bloom (dominated by *Thalassiosira decipiens* at a million cells L^{-1}) in late April (**Slide 3**). This was followed by a period of relatively low phytoplankton abundance in May 2010 as the phytoplankton community made a transition from small cells (*Phaeocystis*, *Chaetoceros socialis*, *Thalassiosira decipiens*) to larger cells (*Ceratium* spp., *Dactyliosolen fragilissimus*) in the summer (**Slide 3**). This small cell (winter) to larger cell size (summer) transition is a reliable feature of the Massachusetts Bay phytoplankton annual succession, although the species that become dominant in each year vary. The transition period is likely associated with the onset of seasonal stratification in the bay.

In summer 2010, the phytoplankton community was marked by a seasonal increase in microflagellate abundance (to a million cells L^{-1}), an increase in dinoflagellate abundance to several thousand cells per liter and diatom (*Dactyliosolen fragilissimus* and *Skeletonema* spp. dominated) increases to about 400,000 cells L^{-1} during June and July 2010 (**Slides 4**, **5** and **6**). August phytoplankton was microflagellate-dominated, followed by decline in total phytoplankton, especially a decline in diatoms, in early September (**Slide 3**). By late September a modest diatom bloom (~300,000 cells L^{-1}) dominated by *Skeletonema* spp. and *Leptocylindrus danicus* developed. By late October this bloom had disappeared and the phytoplankton community was again microflagellate-dominated with an increase in dinoflagellate abundance.

The 2010 phytoplankton showed a pattern of elevated microflagellate abundance in the spring (March, April) and autumn (early November). Early November featured an unusual bloom (>15,000 cells L^{-1}) of the dinoflagellate *Prorocentrum micans* in the nearfield. The *P. micans* bloom pushed November 2010 survey mean dinoflagellate abundance to 22,322 cells L^{-1}. This was the highest level of autumn dinoflagellate abundance recorded in 19 years of monitoring, and represents a dinoflagellate abundance level in November 2010 that was ca. 10-fold greater than the baseline and post-transfer mean level of autumn dinoflagellate abundance (2,000 cells L^{-1}) in the nearfield (**Slide 13**).

The 2010 phytoplankton annual cycle can be summarized by the following highlights:

- Microflagellate abundance typically follows temperature - lowest in March and highest in September.
  - Elevated (March, April); Less autumn decline in 2010
- *Phaeocystis* varies greatly between years. When it does bloom the peak is typically in April.
  - A moderate "*Phaeocystis* year" for Cape Cod Bay, minor in Massachusetts Bay
  - *Phaeocystis* present 14 of 19 years
  - *Phaeocystis* blooms (>10^6 cells L^{-1}) in past 11 years running
  - early and larger bloom in Cape Cod Bay (February) & Offshore (April)
- Diatoms typically bloom in spring and in the fall as the water is stratifying and later destratifying.
  - Winter-spring bloom (April) dominant in 2010
  - Winter-spring: *Thalassiosira decipiens* bloom
  - Summer (*Skeletonema, Dactyliosolen fragilissimus*) in Harbor & Coastal
- Dinoflagellates. Larger species flourish in the stratified waters of summer, Smaller species occur at any time.
  - Small cells (*Gymnodinium, Heterocapsa*) in spring
  - Transition to larger forms (*Ceratium)* June - August 2010
  - *Prorocentrum micans* bloom in November 2010

D.2. 2010 Phytoplankton Regional Patterns

Phytoplankton patterns in other monitored regions (Boston Harbor, coastal, northern boundary, offshore, and Cape Cod Bay) generally followed the same patterns of species composition and abundance levels as the nearfield (**Slides 4**, **5**, and **6**). Statistical analysis of regional differences in 2010 mean abundance levels of phytoplankton functional groups are presented in Table 1. The only statistically significant regional difference noted in 2010 was for the *Phaeocystis pouchetii* bloom which was initially a Cape Cod Bay (February) and later an offshore event (April). There was no difference for the winter/spring period (Feburary-April) mean *Phaeocystis* abundance across regions, but when individual months were examined Phaeocystis abundance was significantly greater (ANOVA, $p < 0.05$) in the Cape Cod Bay (381,900 cells L^{-1}) in February and offshore (200,400 cells L^{-1}) in April than in the other regions where levels ranged from zero to 90,000 cells L^{-1} (Table 1; see **Appendix B Slides 17** and **18**). Also, while not statistically significant, the abundance of diatoms tended to be elevated in the harbor and coastal regions relative to the nearfield region. This was driven by summer 2010 *Skeletonema* spp. and *Dactyliosolen fragilissimus* blooms which were about 10-fold more abundant in the harbor and coastal regions than those observed in the nearfield. For example, June 2010 region averaged diatom abundance was 2.33 x 10^6 cells L^{-1} and 3.39 x 10^6 cells L^{-1} in the coastal and Boston Harbor regions, respectively, compared to a level of 0.36 x 10^6 cells L^{-1} in the nearfield. This pattern of elevated summer diatom abundance in the harbor and coastal waters continues a post-discharge trend. However, the regional differences in diatom abundance described above did not drive mean annual diatom abundance levels to be significantly different by region (Table 1).

Table 1: Summary of 2010 mean annual (except Phaeocystis, monthly means as indicated) regional abundance of main phytoplankton groups. Differences in regional abundance tested by ANOVA or KW test. Units are cells L^{-1}.

Group	*Cape Cod Bay*	*Harbor*	*Coastal*	*Offshore*	*North Bndry.*	*Nearfield*	*P value*
Ttl. Phytoplankton	1.36×10^6	1.88×10^6	1.75×10^6	1.11×10^6	0.90×10^6	1.27×10^6	NS
Microflagellates	801,300	834,900	854,400	679,700	643, 100	800,200	NS
Diatoms	182,600	719,900	602,000	160,900	71,820	217,100	NS
Dinoflagellates	75,170	68,860	73,760	48,160	40,800	78,280	NS
Phaeocystis (February– April)	254,580	43,582	38,140	200,400	89,310	53,330	NS
Phaeocystis (February)	381,900	65,370	57,200	65,370	86,980	61,920	0.0445
Phaeocystis (April)	0	0	0	470,300	93,970	71,710	0.0044

D.3. 2010 Nuisance Phytoplankton Blooms

No threshold exceedances of any harmful of nuisance phytoplankton species were recorded in 2010. As described above, 2010 was a modest *Phaeocystis pouchetii* bloom year, with the bloom mainly confined to the offshore and Cape Cod Bay regions. *Alexandrium fundyense* was observed in nearfield samples in April and May 2010, but maximum abundance was low at only 78 cells L^{-1} in 2010. Low numbers (<10 cells L^{-1}) of *Alexandrium* spp. cells were also observed in September 2010, marking the third year in a row that some *Alexandrium* was observed in the autumn. *Pseudo-nitzschia* spp. continue to be in a period of reduced abundance in Massachusetts Bay with a maximum *Pseudo-nitzschia* observation of 13,300 cells L^{-1} observed in the coastal region in October 2010.

D.4. Long-term Phytoplankton Trends: 2010 Update

Total phytoplankton abundance in the nearfield region of Massachusetts Bay has fluctuated by +/- 20% around the long-term mean level of 1.4×10^6 cells L^{-1} during 19 years of monitoring (**Slide 20**). Total phytoplankton levels have been below long-term mean level since 2008, but in 2010 total phytoplankton abundance increased towards long-term mean levels. Much of this increase appears to be due to a 2010 increase in diatom abundance. 2010 diatom abundance was buoyed by the prolonged and abundant winter-spring bloom and a relatively large and prolonged summer diatom bloom. Together, these 2010 diatom blooms brought 2010 diatom abundance up to the long-term mean level of ~300,000 cells L^{-1} (**Slide 22**). Diatoms have displayed oscillations and a long-term decline during the late-1990s through 2008. During 2009 and 2010 it appears that diatom abundance is rebounding to near long-term mean levels. Dinoflagellates have been relatively abundant since 2006 and remained above the long-term mean level (50,000 cells L^{-1}) during 2010 (**Slide 24**). The recent dinoflagellate increase relative to the long-term mean level appears to be driven by increases in the abundance of smaller dinoflagellates (*Heterocapsa rotundatum*, *Heterocapsa triquetra*, *and Gymnodinium* spp.) and a 2009-2010 return of summer *Ceratium* spp. abundance.

D.5. 2010 Zooplankton Annual Cycle

Zooplankton abundance and species composition in 2010 were generally similar to previous years. Total zooplankton abundance in the nearfield increased through winter, spring, and early summer to maxima in July, with continued high values in August, followed by progressive declines through fall (**Slide 28**). The 2010 total zooplankton annual cycle in the nearfield featured reduced abundance of <30,000 animals m^{-3} during February through April followed by an increase to 35,000 to 85,000 animals m^{-3} during May to August and a return to <40,000 animals m^{-3} during September to November. As in previous years, the zooplankton community was overwhelmingly dominated (90% numerically) by copepods (nauplii + copepodites + adults). Meroplankton (barnacle nauplii, bivalve and gastropod veligers, polychaete larvae) and non-copepod zooplankton such as *Evadne nordmani*, *Podon polyphemoides* and *Oikopleura dioic*a, comprised >10% of total zooplankton during the months of March, April, July, and September.

Zooplankton patterns appeared to be regionally coherent (**Slides 29**, **30**, and **31**). Some minor regional differences noted include elevated barnacle nauplii abundance during the winter and spring in the nearfield, harbor and coastal regions and elevated copepod abundance in most regions during summer and fall. In addition, total zooplankton abundance peaked during the summer in all regions. The 2010 means for total zooplankton abundance by area were generally at the low end of the baseline range, similar to baseline and post-discharge means, except for November when the 2010 nearfield mean was below the baseline range (**Slide 32**).

Various zooplankton taxa exhibited somewhat different patterns. Nearfield abundance of barnacle nauplii in March generally exceeded the baseline range and all previous means (**Slide 38**). During 2010 *Oithona similis* continued to be the most abundant copepod. The 2010 *Oithona* annual cycle in the nearfield featured reduced *Oithona* levels (100s to <20,000 m^{-3}) during February to June followed by an increase to approximately 40,000 – 50,000 m^{-3} during July and August, with a return to *Oithona* levels of <10,000 m^{-3} from September through November (**Slide 36**). All nearfield *Oithona* levels were within the *Oithona* baseline range levels. *Calanus finmarchicus* peaked earlier in March in the nearfield than in previous years, with levels slightly higher than the baseline range, but then had lower values than the baseline and post-discharge means for the rest of the year (**Slide 37**). While not numerically dominant, *Calanus* is an important food resource for endangered Right Whales (Mayo & Marx 1990). Overall, 2010 zooplankton levels were near the long-term mean levels for most zooplankton groups in most regions.

D.6. REFERENCES

Libby PS, Fitzpatrick MR, Buhl RL, Lescarbeau GR, Leo WS, Borkman DG, Turner JT, Oviatt CA. 2010. Quality Assurance Project Plan (QAPP) for water column monitoring 2010: Tasks 4-9 and 13. Boston: Massachusetts Water Resources Authority. Report 2010-02. 105 p.

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.

2010 Plankton Overview

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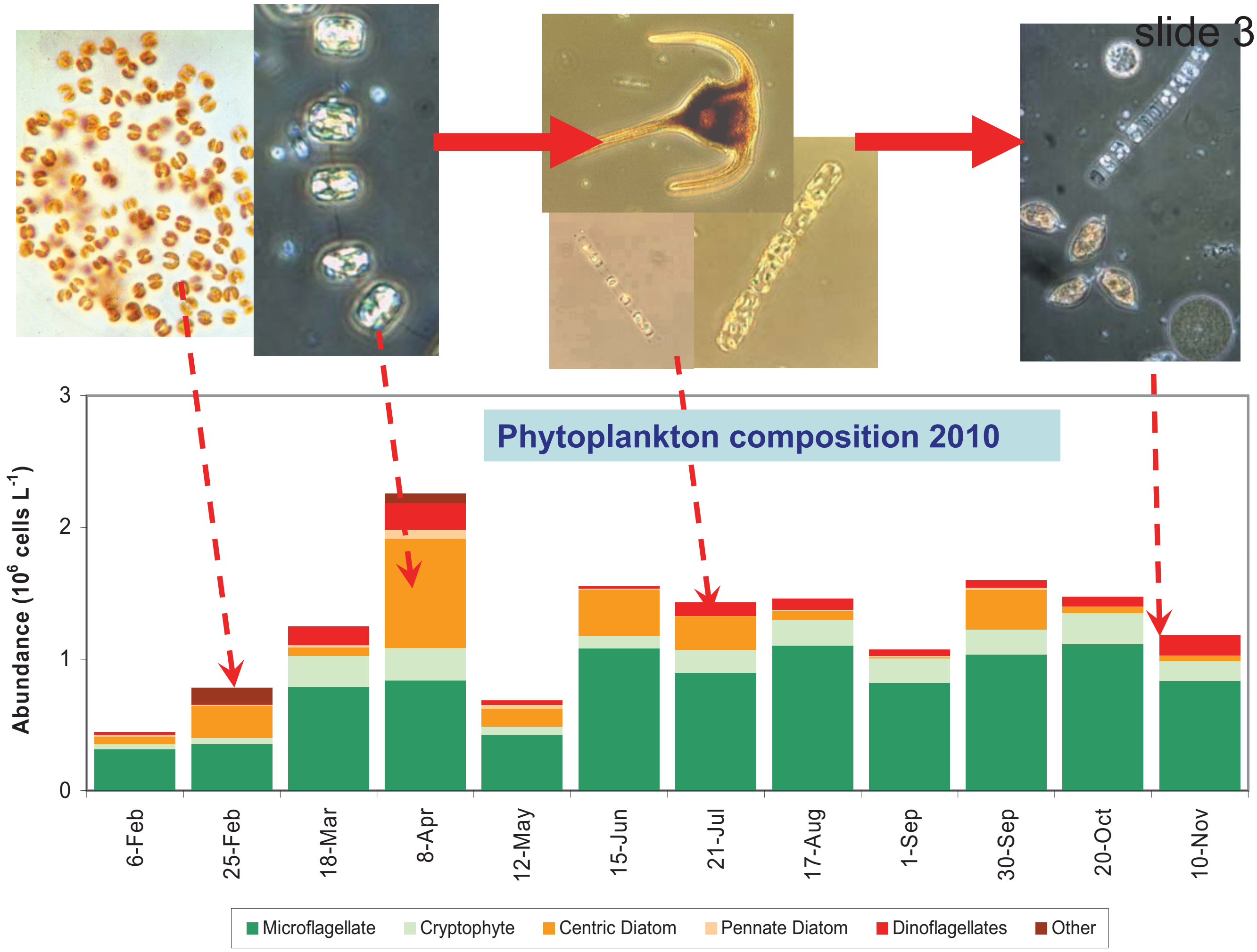
2011 Science Meeting *9 May 2011*

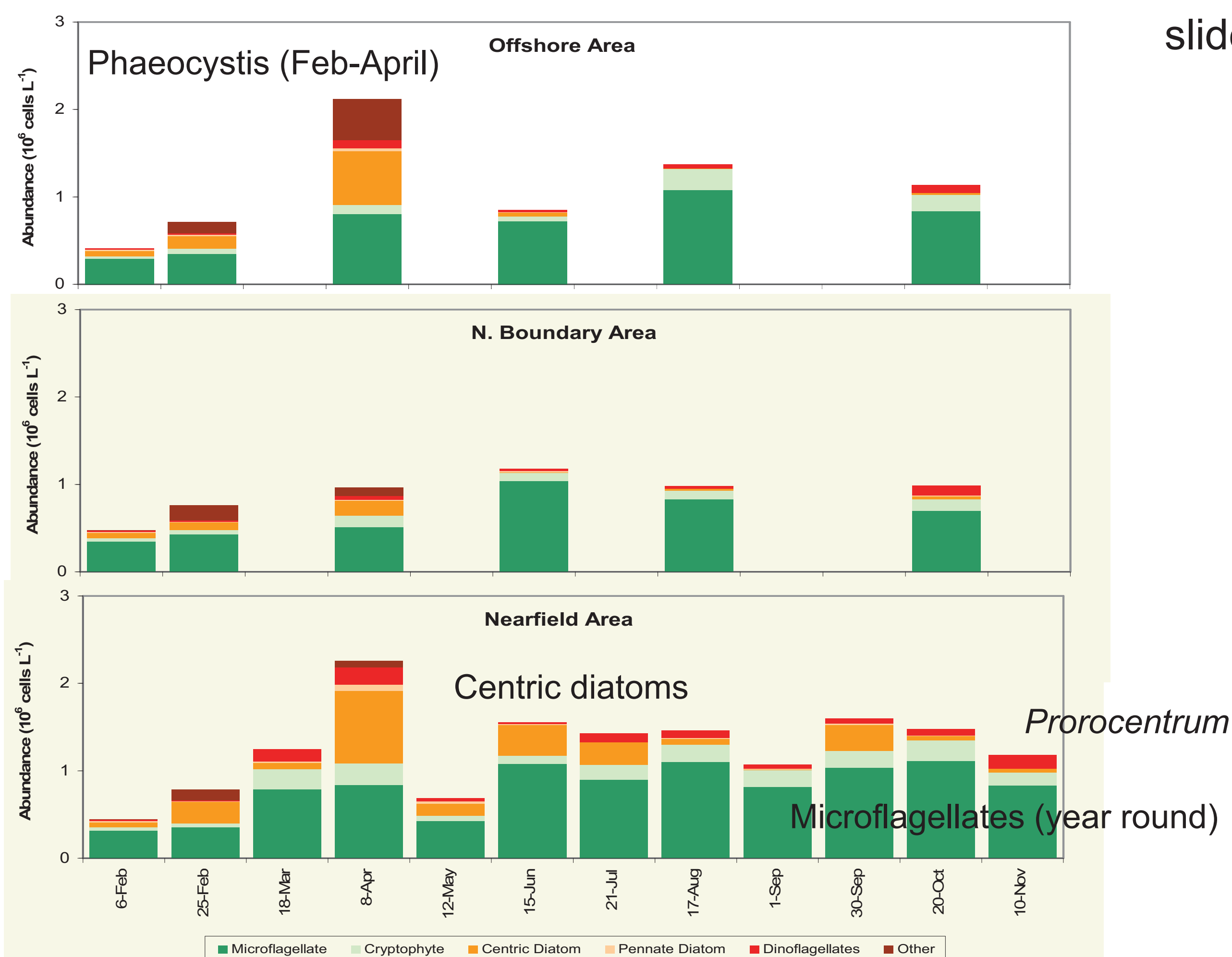
Plankton Overview

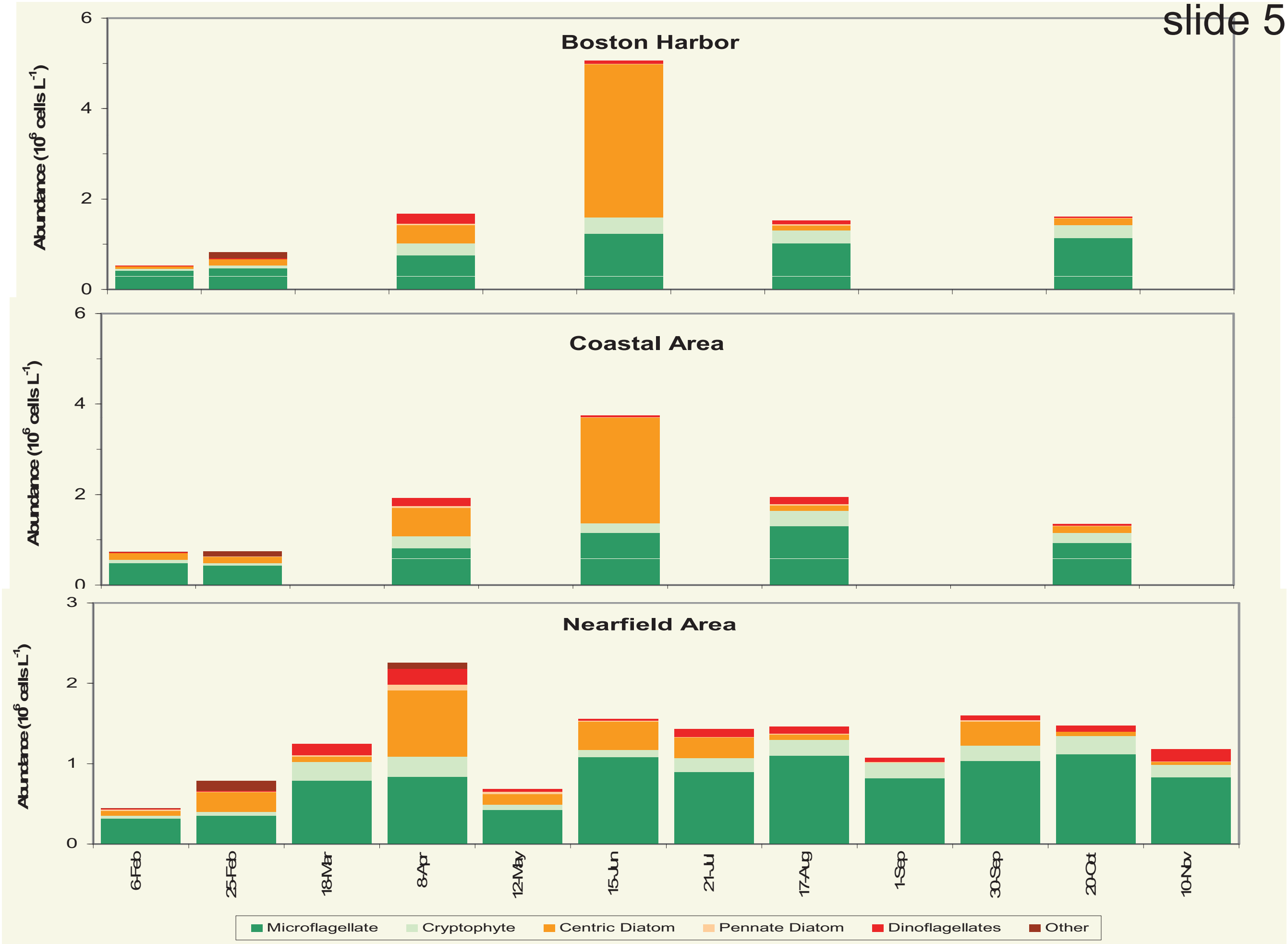
- **Phytoplankton Monitoring**
  - **Species and abundance**
  - **2 stations (NFLD), 12 times annually**
  - **13 stations (FFLD), 6 times annually**
  - **Surface and mid-depth (or CHL max) samples (phytoplankton)**
- **2010 annual pattern**
  - **Species composition**
  - **Abundance levels**
  - **Nuisance phytoplankton species**
- **Long-term patterns & trends**

slide 3



slide 4




slide 5
Boston Harbor
Coastal Area
Nearfield Area
Abundance (10^6 cells L^-1)
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


slide 6
Cape Cod Bay
Nearfield Area
Abundance (10^6 cells L^-1)
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
Cryptophytes
Cryptophyte
Centric Diatom
Pennate Diatom
Dinoflagellates
Other

Table 1: Summary of 2010 mean annual (except Phaeocystis, monthly means as indicated) regional abundance of main phytoplankton groups. Differences in regional abundance tested by ANOVA or KW test. Units are cells L^{-1}.

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Microflagellates	801,300	834,900	854,400	679,700	643, 100	800,200	NS
Diatoms	182,600	719,900	602,000	160,900	71,820	217,100	NS
Dinoflagellates	75,170	68,860	73,760	48,160	40,800	78,280	NS
Phaeocystis (February– April)	254,580	43,582	38,140	200,400	89,310	53,330	NS
Phaeocystis (February)	381,900	65,370	57,200	65,370	86,980	61,920	0.0445
Phaeocystis (April)	0	0	0	470,300	93,970	71,710	0.0044

In 2010, Cape Cod Bay and Offshore had elevated *Phaeocystis* relative to other regions in February and April, respectively.

Regionally coherent phytoplankton composition pattern (mostly….)

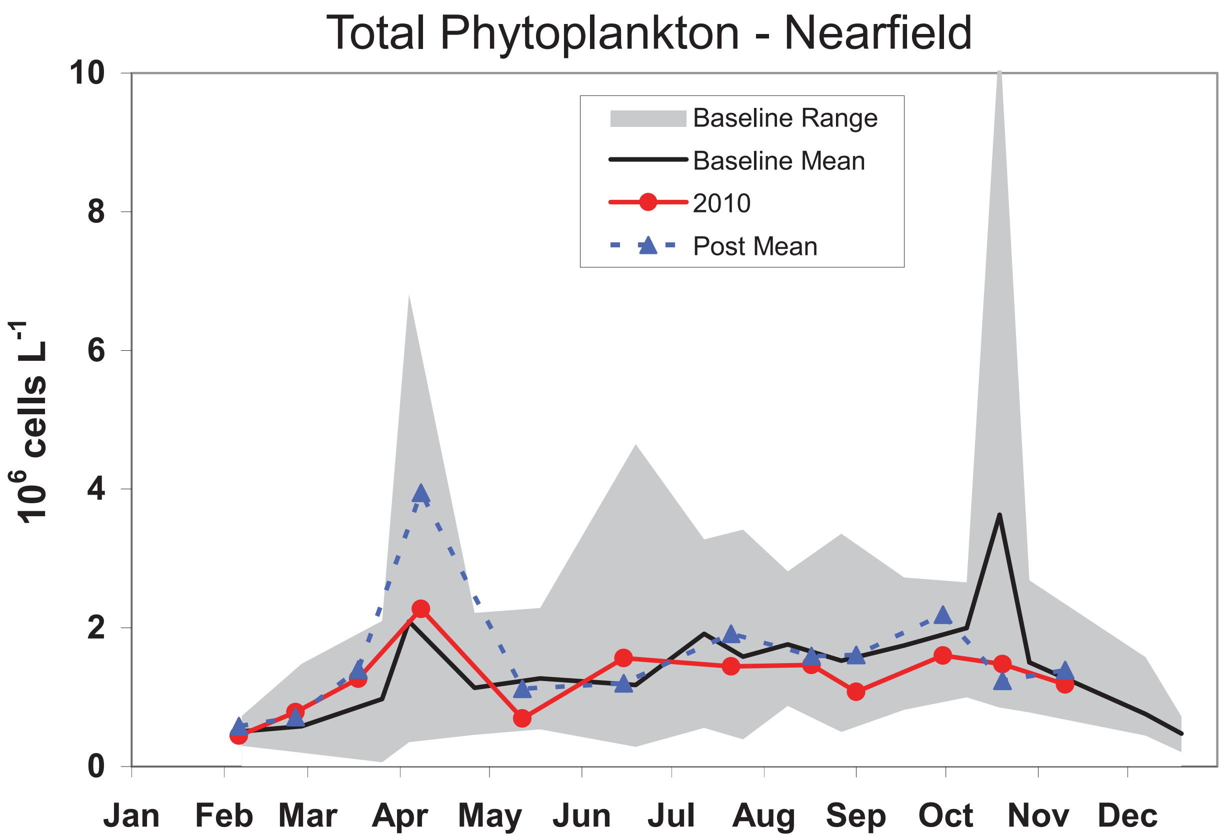
Microflagellate ‘baseline’ varies seasonally.
- Less autumn decline in 2010?

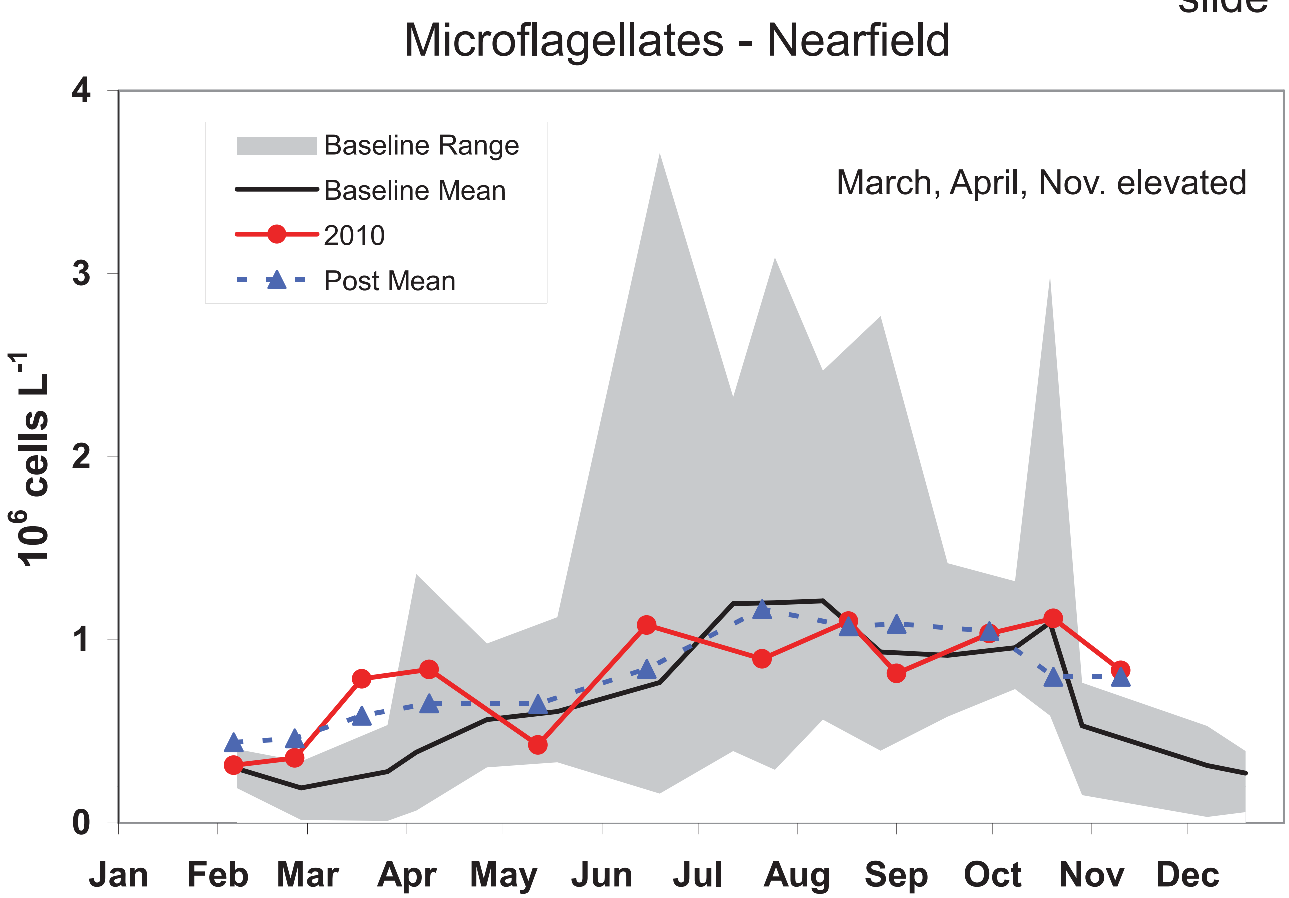
Phaeocystis
- A moderate “*Phaeocystis* year”; 14 of 19 years and *Phaeocystis* blooms (>10^6 L^{-1}) in past 11 years running
- early (Feb.) and larger bloom in CC Bay & Offshore (April)
- mainly Offshore and Boundary in 2010

Diatoms
- Winter-spring bloom (April) dominant in 2010
- Winter-spring: *Thalassiosira decipiens* bloom
- Summer (*Skeletonema, Dactyliosolen fragillisima*) in Harbor & Coastal

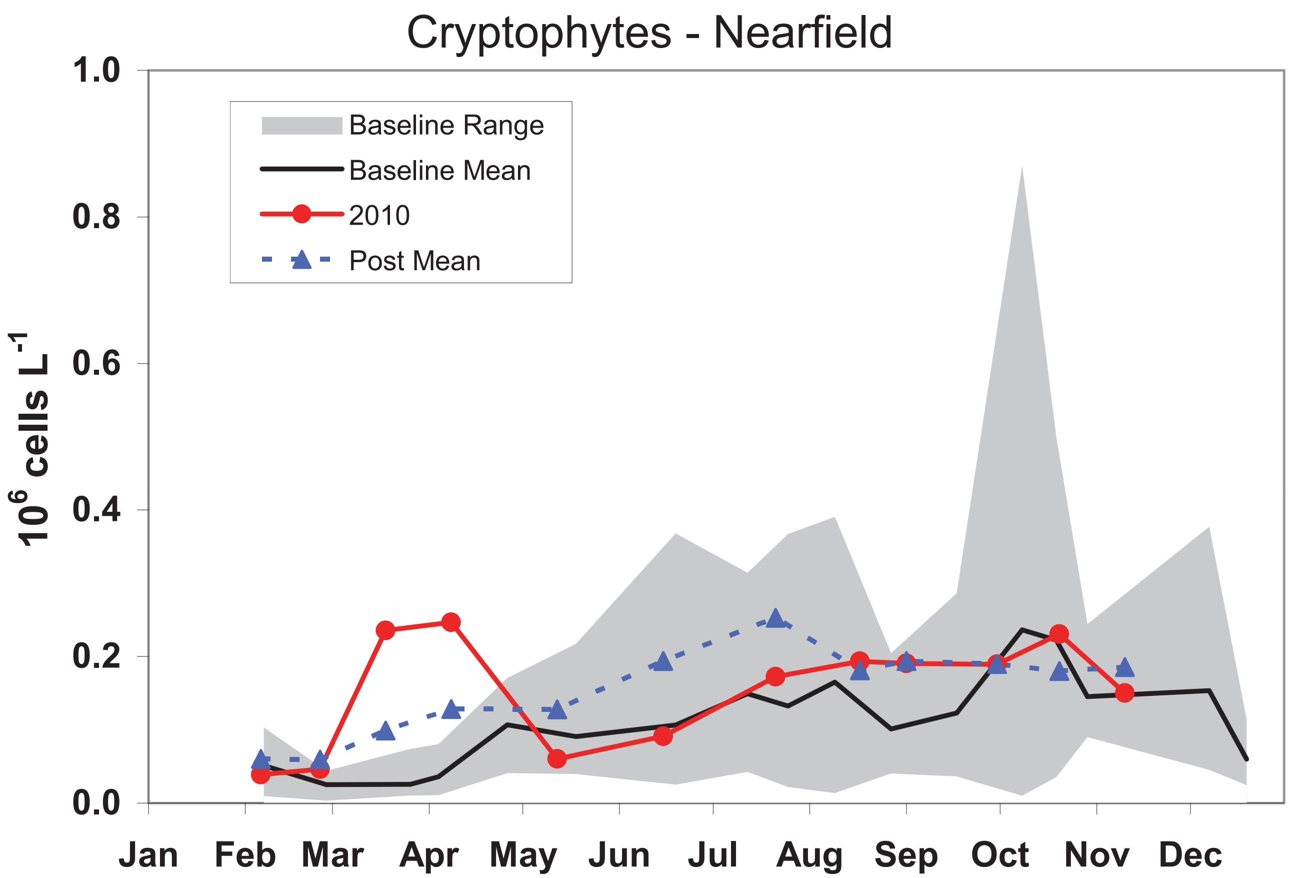
Dinoflagellates
- Small cells (*Gymnodinium, Heterocapsa*) in spring
- Transition to larger forms (*Ceratium)* June - August 2010
- *Prorocentrum micans* bloom in November 2010 (max of 15,000 cell L^{-1})

Annual nearfield patterns of dominant phytoplankton groups 2010 versus pre- and post-diversion levels





slide 11



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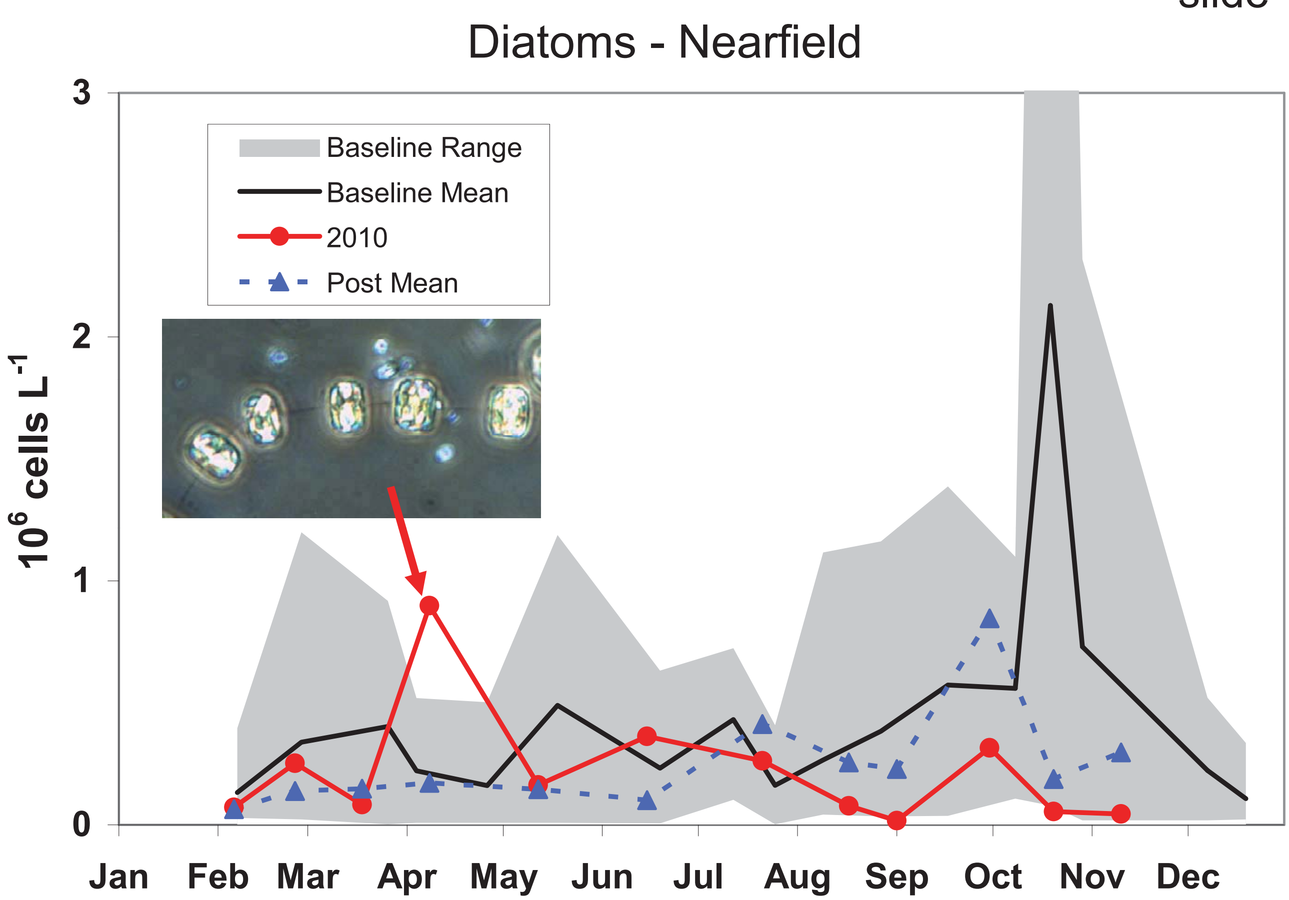

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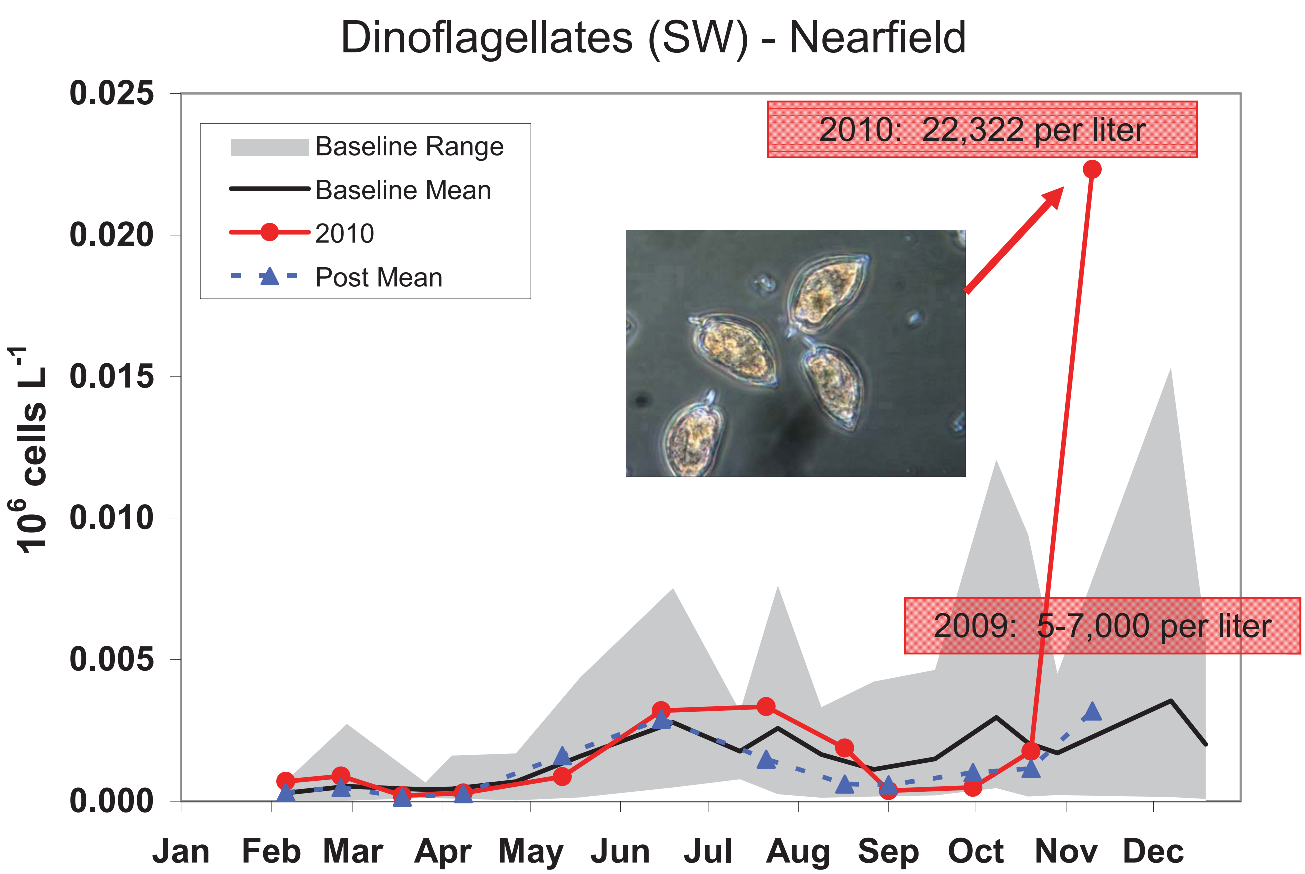

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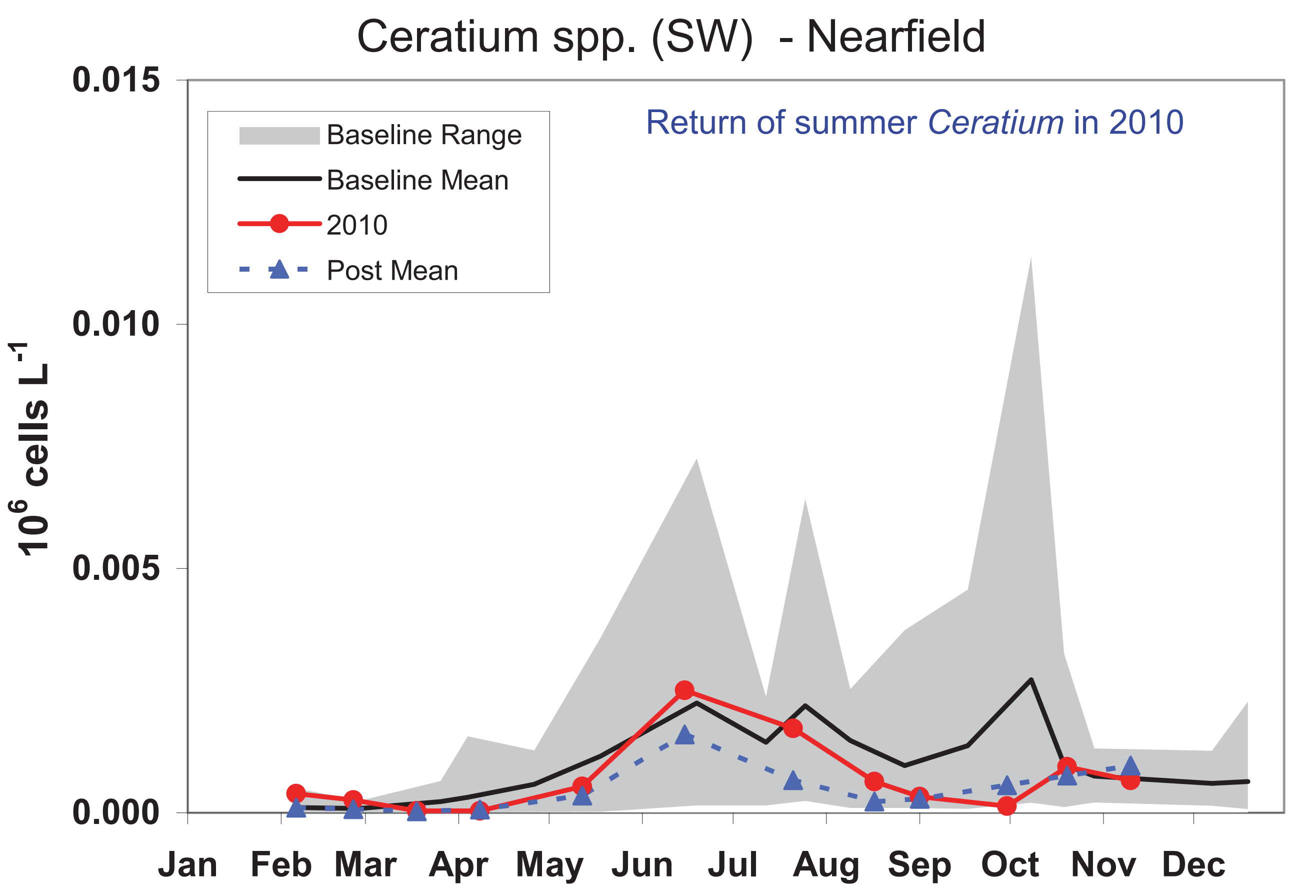


2010 Nearfield Phytoplankton Annual cycle:

Relative to baseline ranges:

Total phytoplankton
- Winter-spring bloom dominated annual cycle
- elevated March (*Phaeocystis*) and April (*Thalassiosira decipiens*)
- near baseline mean rest of year

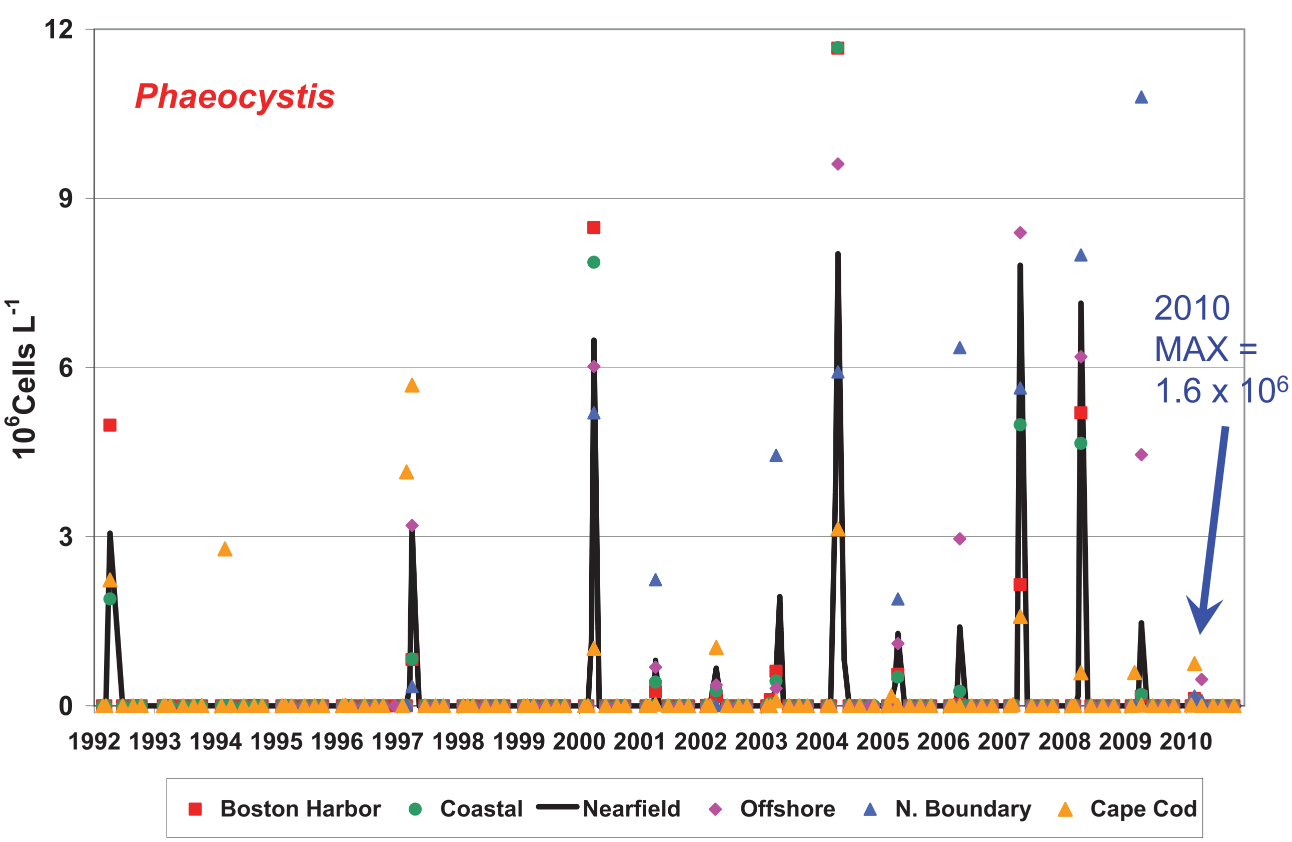
Microflagellates
- elevated in March, April & November

Diatoms
- Winter-Spring bloom (*T. decipiens*) in April
- WS peak ~1 month later than baseline
- reduced August – November 2010 (*Skeletonema & Dactyliosolen*)

Cryptophytes
- elevated during March & April

Dinoflagellates
- Near baseline levels most of year (*Ceratium* return)
- *Prorocentrum micans* (15,000 per liter) bloom in November 2010

Harmful and Nuisance Phytoplankton 2010



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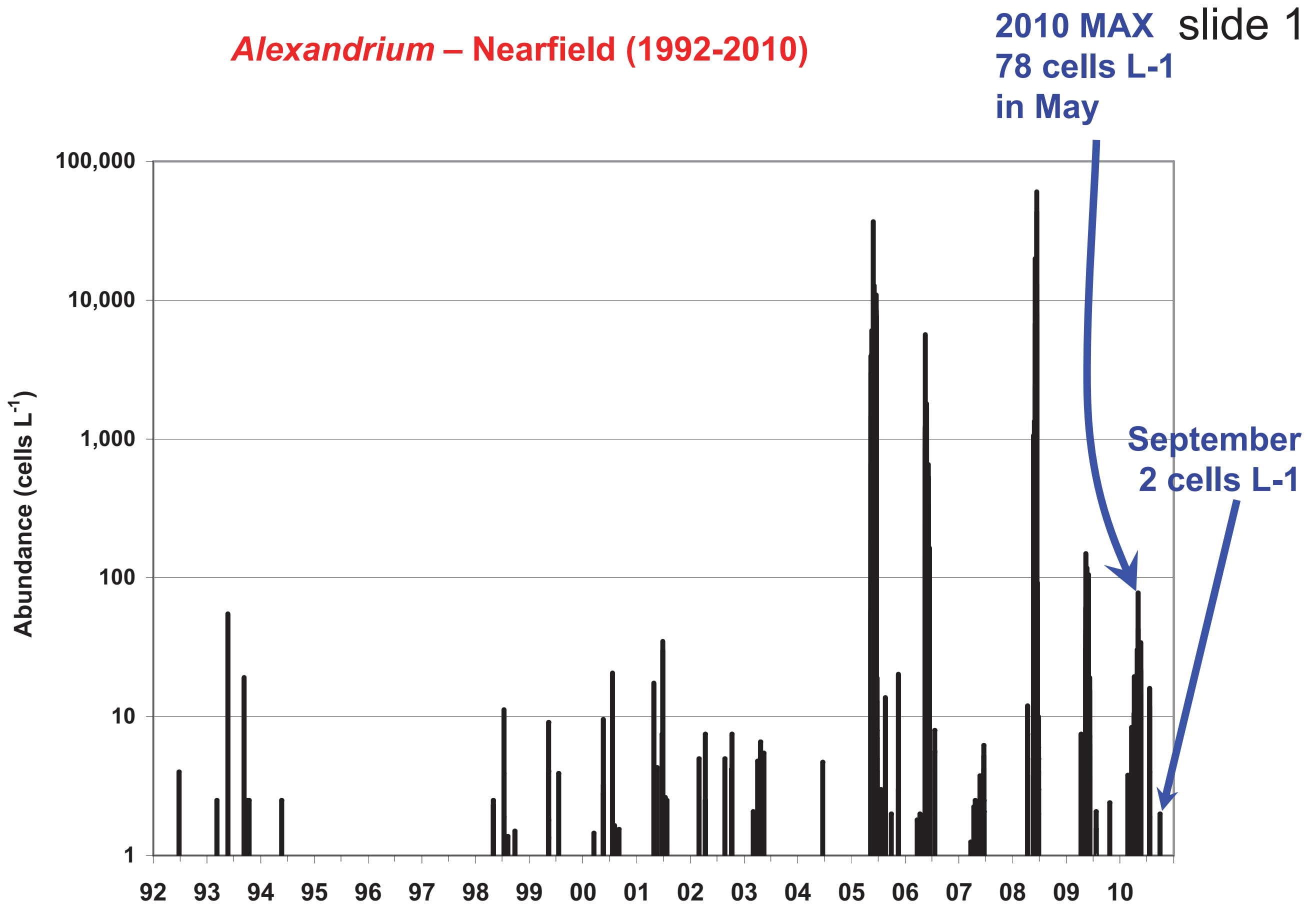

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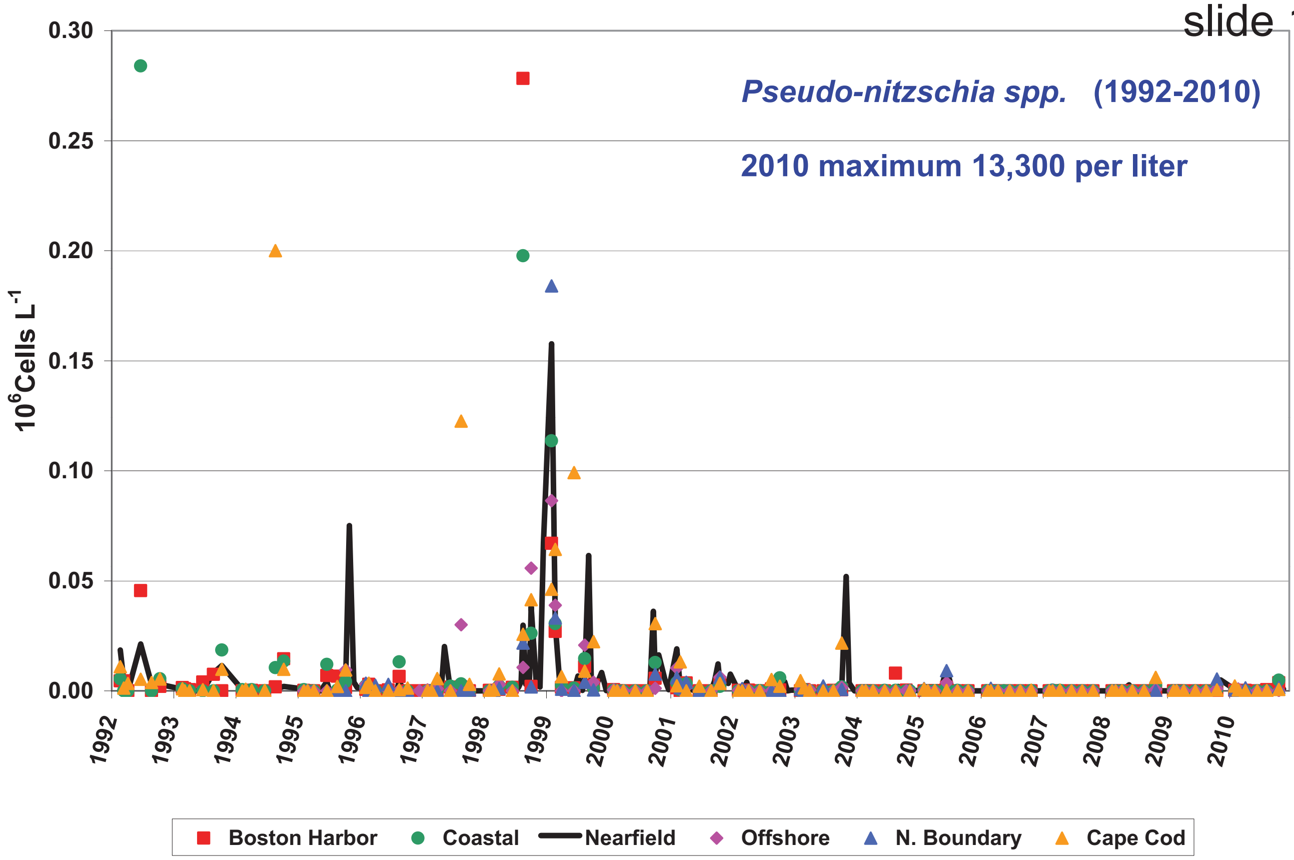


Consistently reduced *Pseudo-nitzschia* spp. abundance since 1998-1999 - far below 21,000 (w-s) to 43,000 (summer) cell L^{-1} threshold

2010 Nuisance and Harmful Species Summary:

Modest *Phaeocystis* bloom year

- maximum of 1.65 x 10^6 cells L^{-1} in late February, Cape Cod Bay
- only ca. 0.12 x 10^6 cells L^{-1} maximum in Nearfield
- lowest observations since 1999

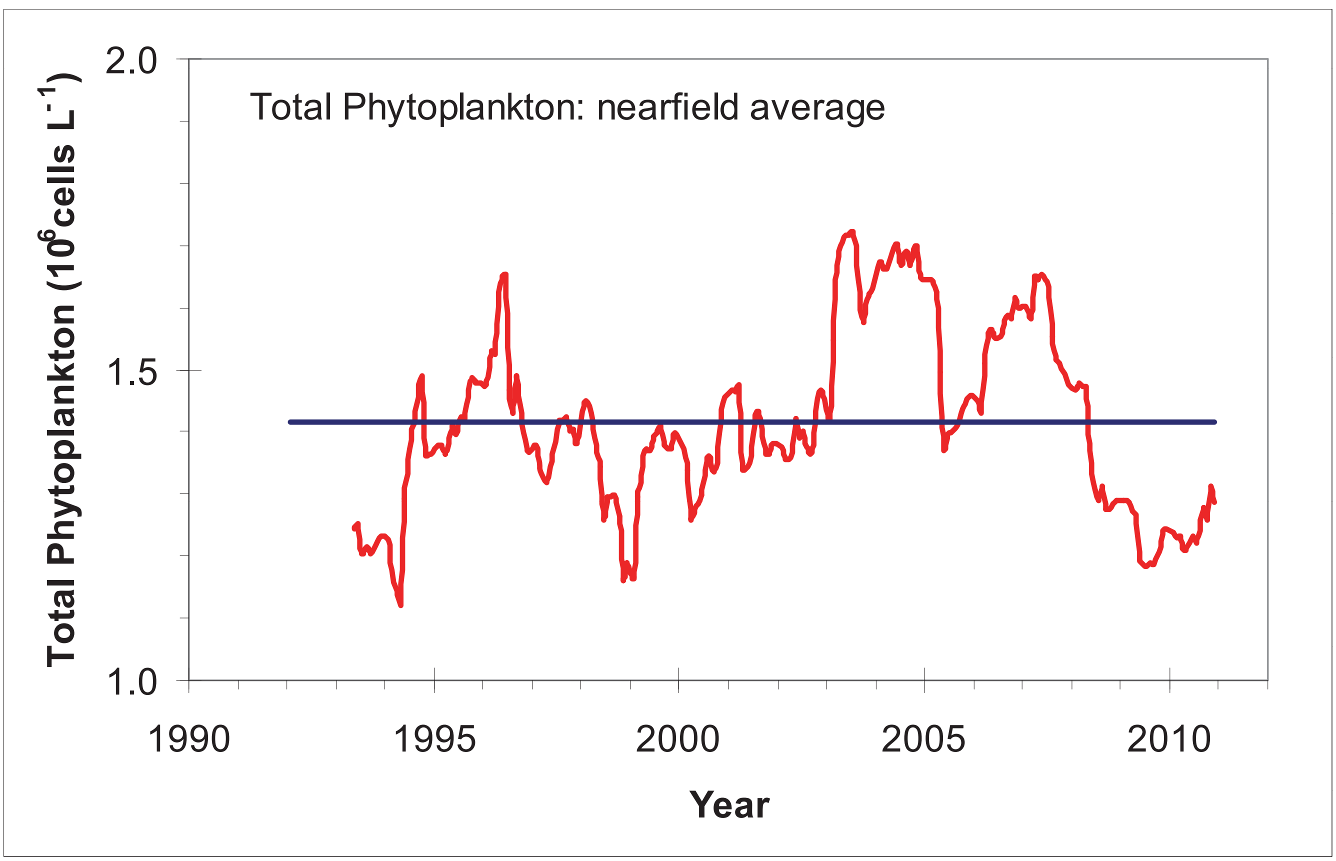
2010 *Alexandrium* bloom (78 cells L^{-1} Nearfield max)

- April - May bloom; also present in September

Reduced *Pseudo-nitzschia* (10^3 cells L^{-1})

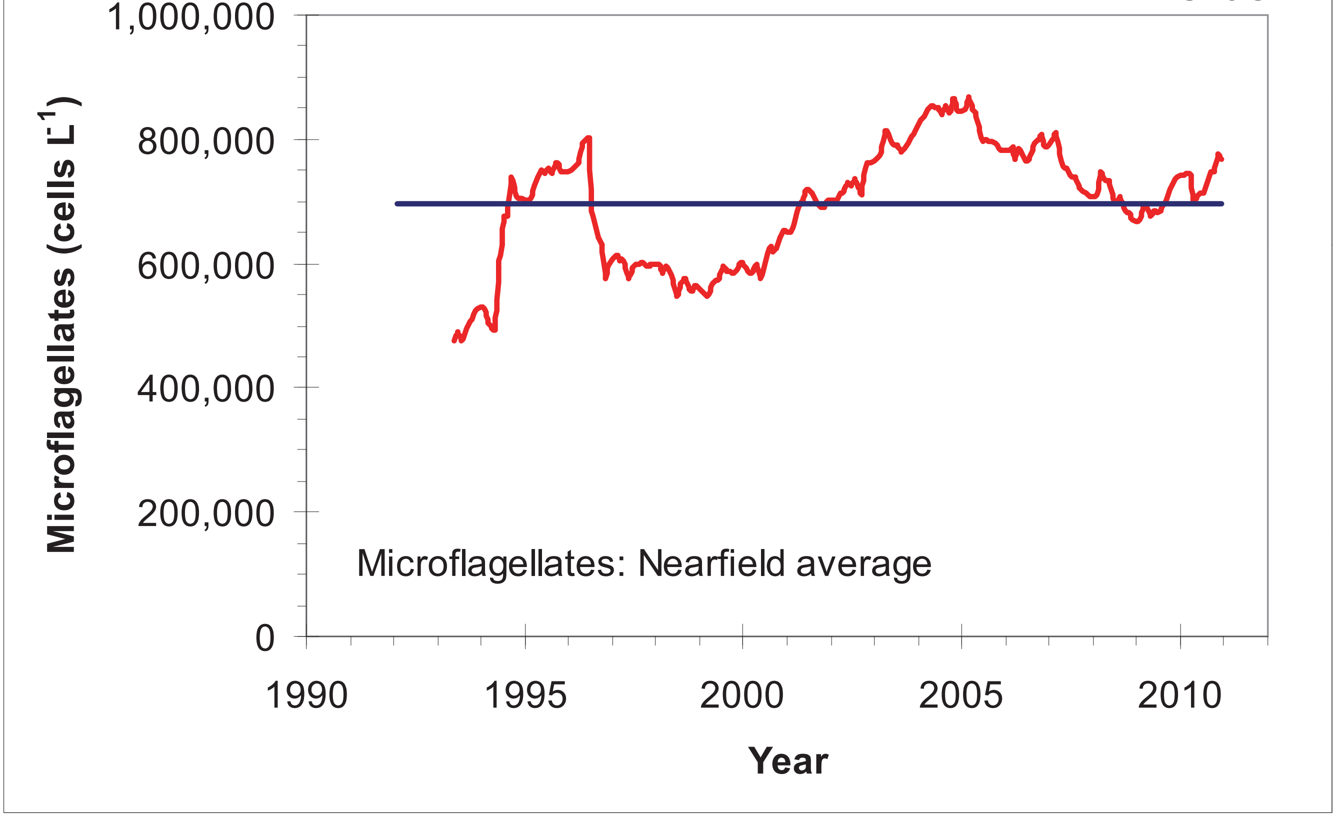
(2010 peak = 13,300 cells L^{-1}, Coastal Region in October)

Phytoplankton Trends 1992-2010 (time series analysis)



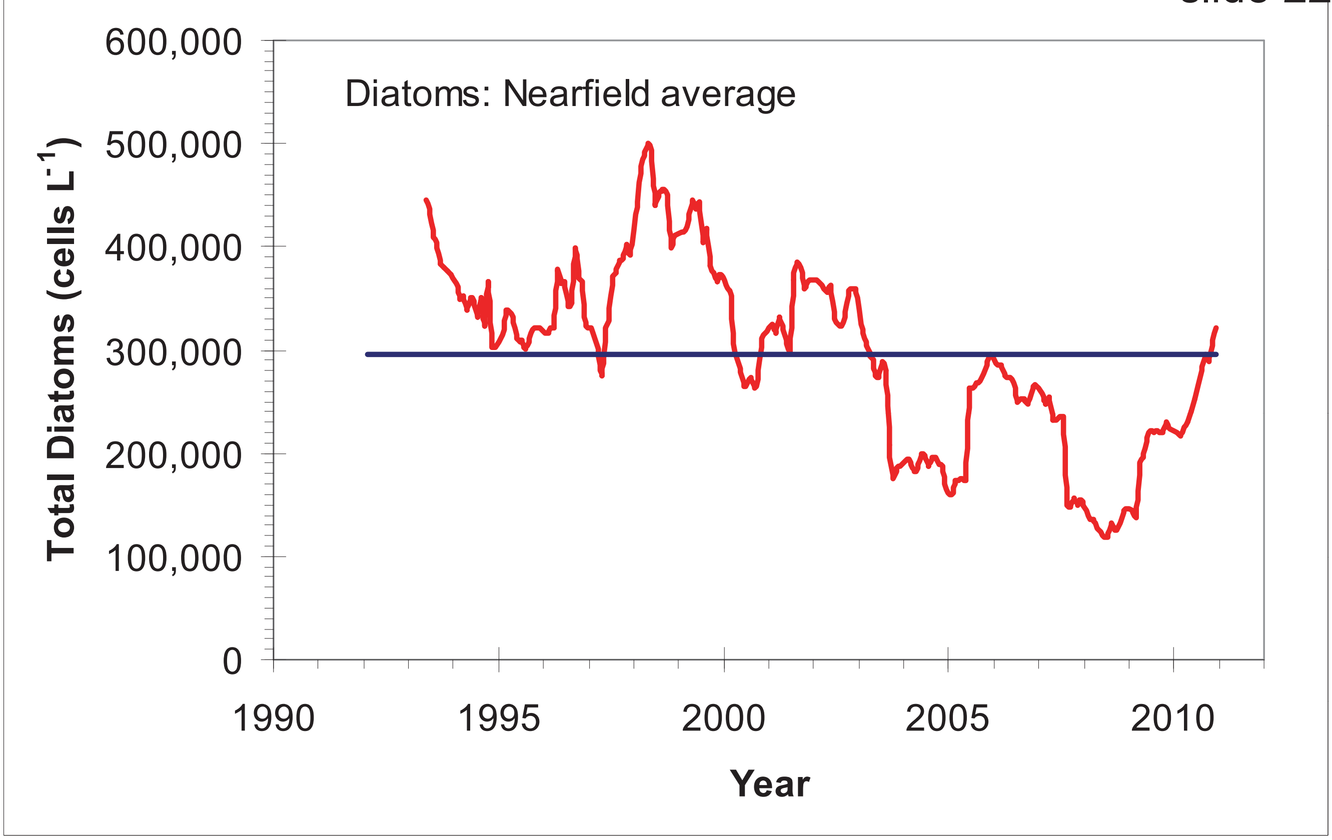
Fluctuations +/- 20% of LT mean; 2009-2010 relative low period

slide 21

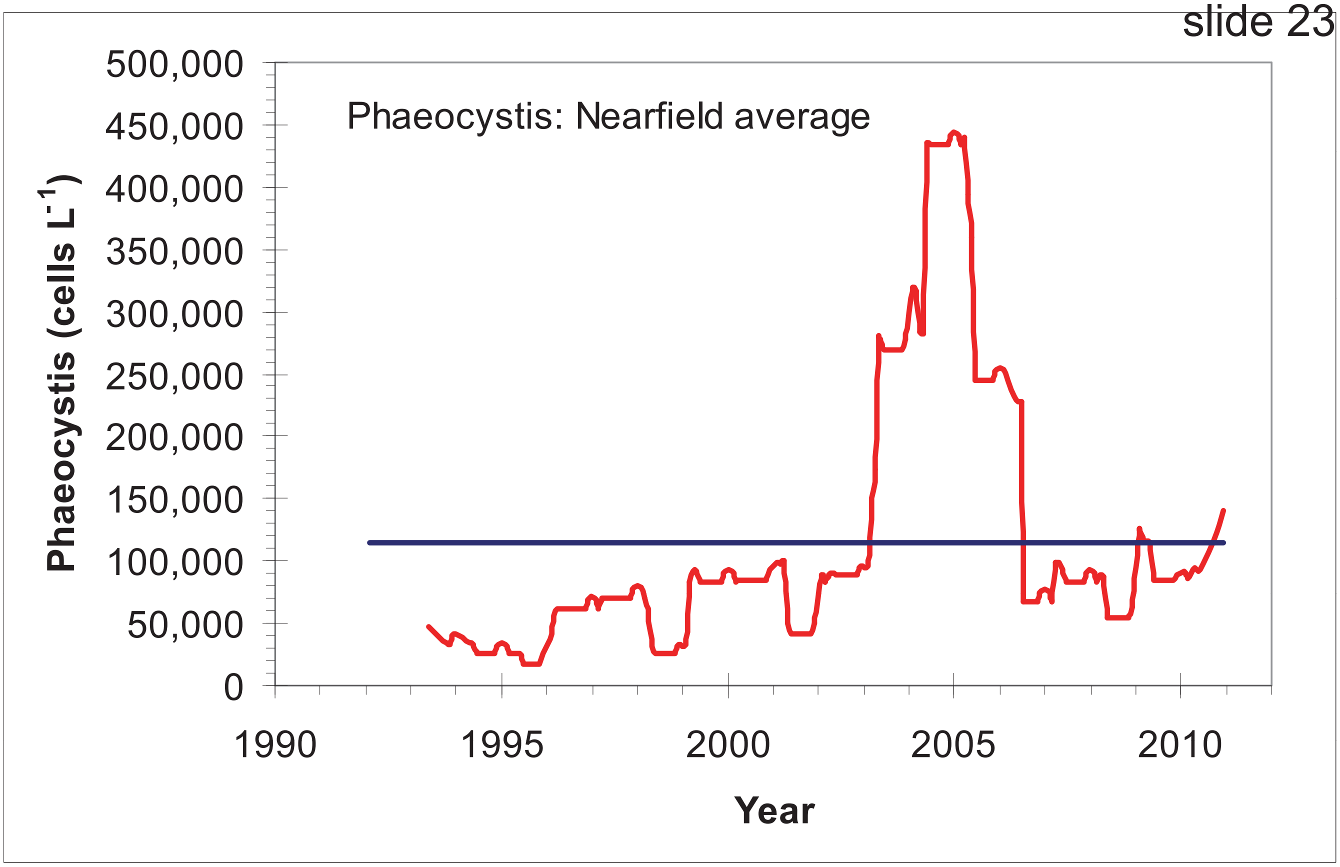


Fluctuations +/- 30% of LT mean; 2009-2010 increasing

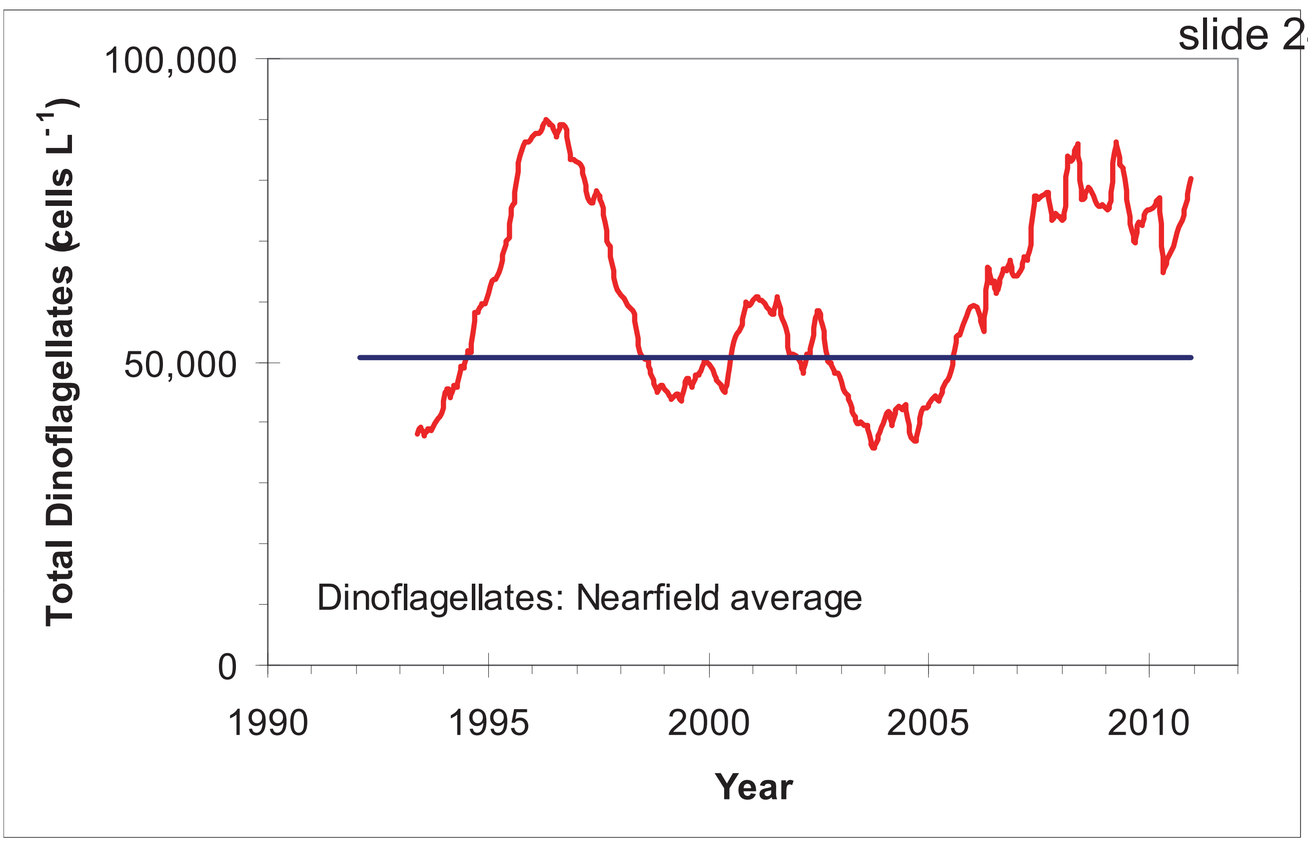
slide 22



Diatoms: cyclic (weather, *Phaeocystis*?), increasing (2010 WS bloom)

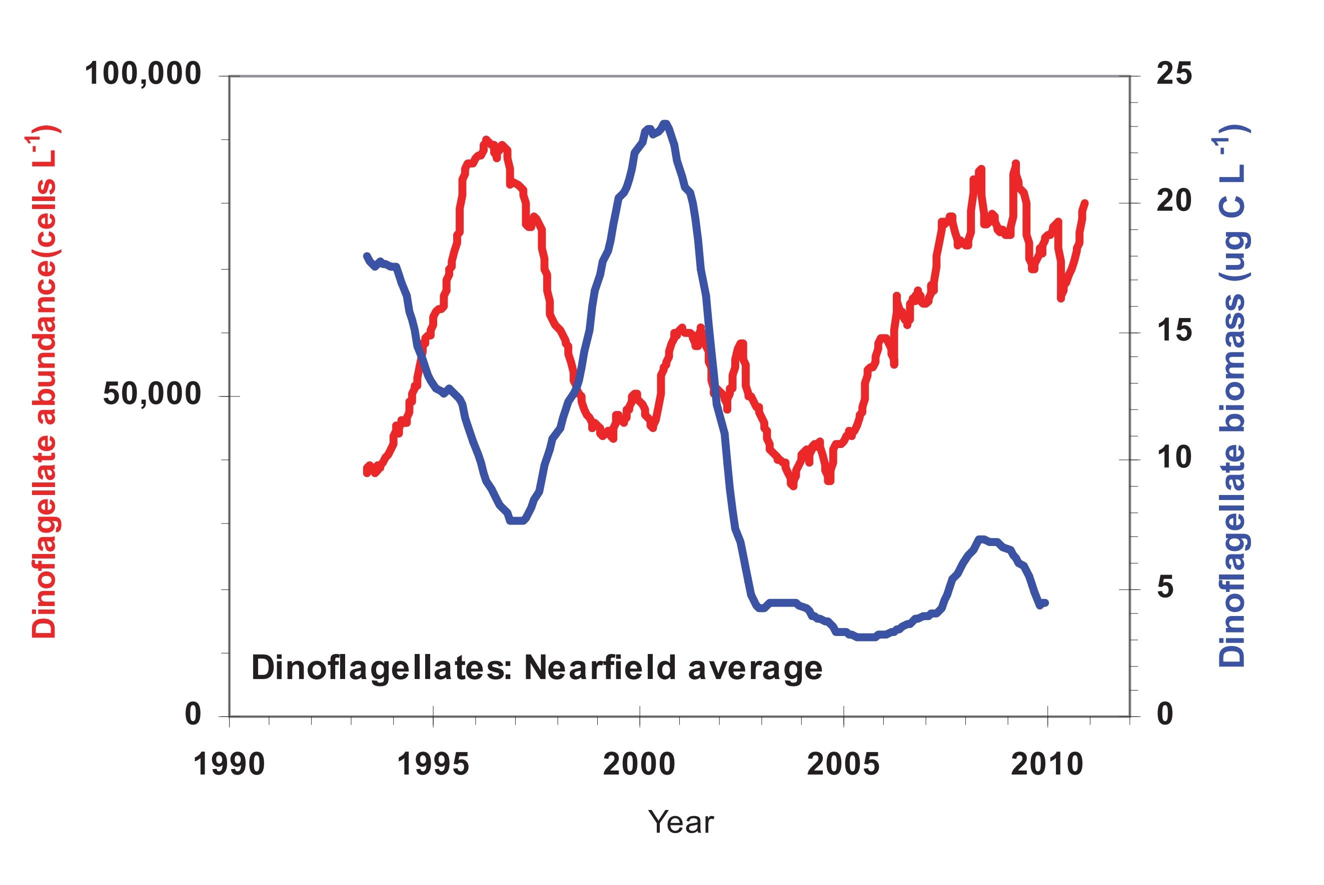


***Phaeocystis*: out of the mid-2000s *Phaeocystis* period**



Dinoflagellates: at elevated levels 2009-2010; prevalence of small forms (*Heterocapsa, Gymnodinum*) in spring, *Ceratium* return in summer(2010 WS diatom bloom). Contrast with biomass pattern……………..

slide 25



slide 26

Phytoplankton Abundance Trends Summary

-Total phytoplankton in a low period 2009-2001 (1.25×10^6 cells L^{-1}) relative to long-term mean (1.4×10^6 cells L^{-1})

-Microflagellates near long-term mean level of ca. 700,000 cells L^{-1}

-Diatoms increasing 2009-2010, return to long term mean levels (300,000 cells L^{-1})

-Out of elevated Phaeocystis period

-Dinoflagellates in relative elevated period with 2009-2010 levels (70,000 cells L^{-1}) that are above the long-term mean level (50,000 cells L^{-1}). Shift to small spp.

-How rare are unusual events?

  -Still seeing 'new' things after 19 years!

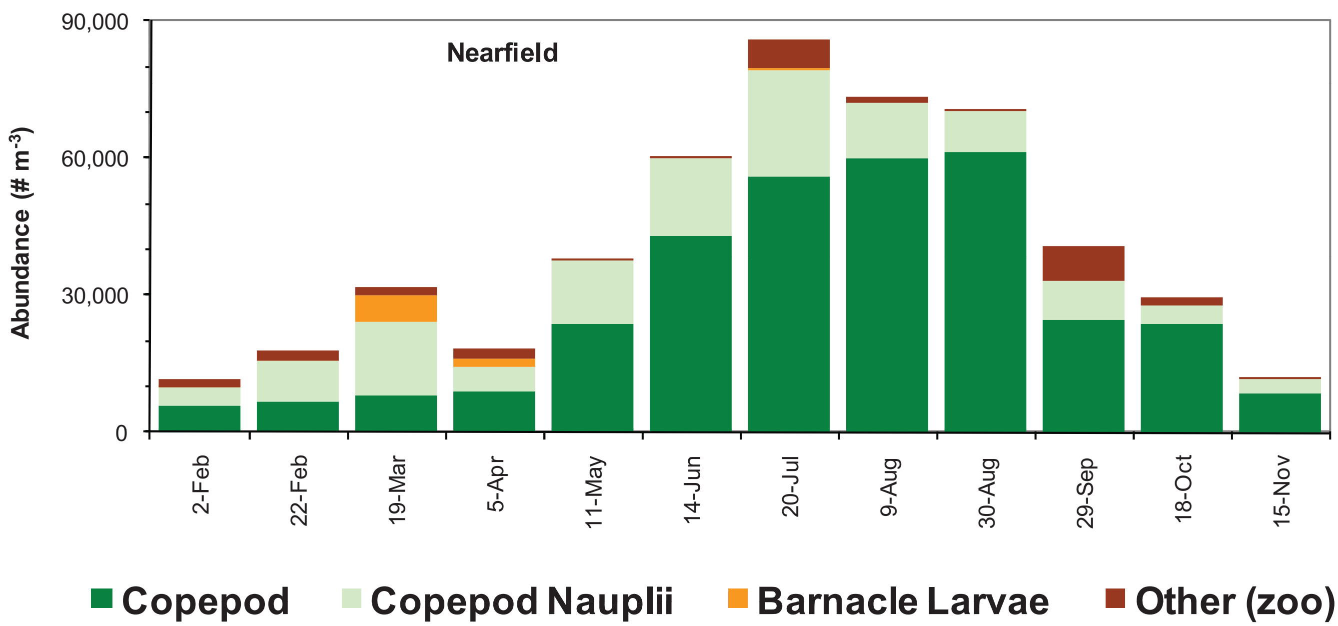
  -Notable 2010 observations:

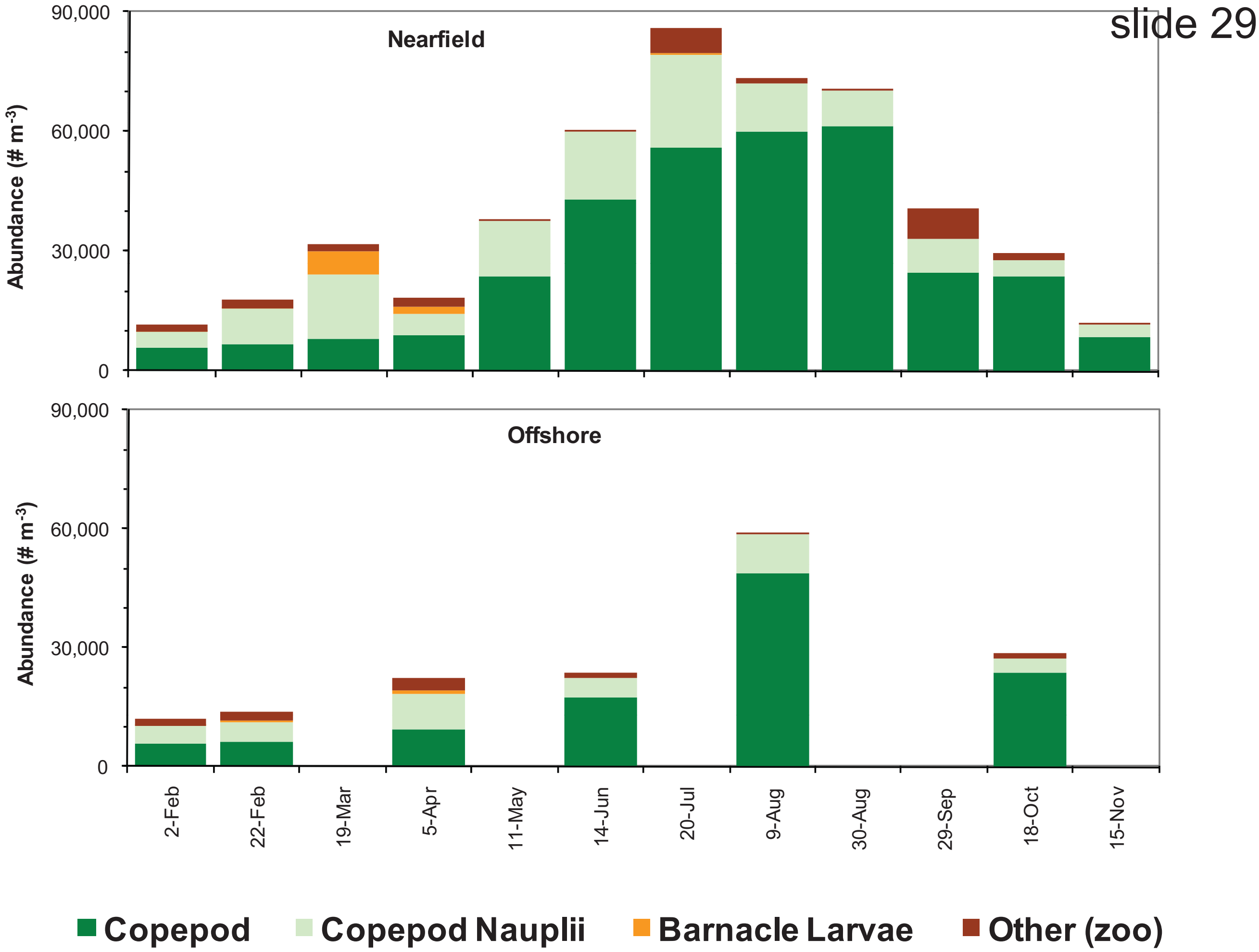
    -*Thalassiosira decipiens* dominated WS bloom
    -Increasing dinoflagellate dominance in Autumn
    -*Prorocentrum micans* bloom (to 15,000 cells L^{-1}) in November
    -Microflagellates and Cryptomonads elevated in March & April
    -Microflagellates remain elevated in November

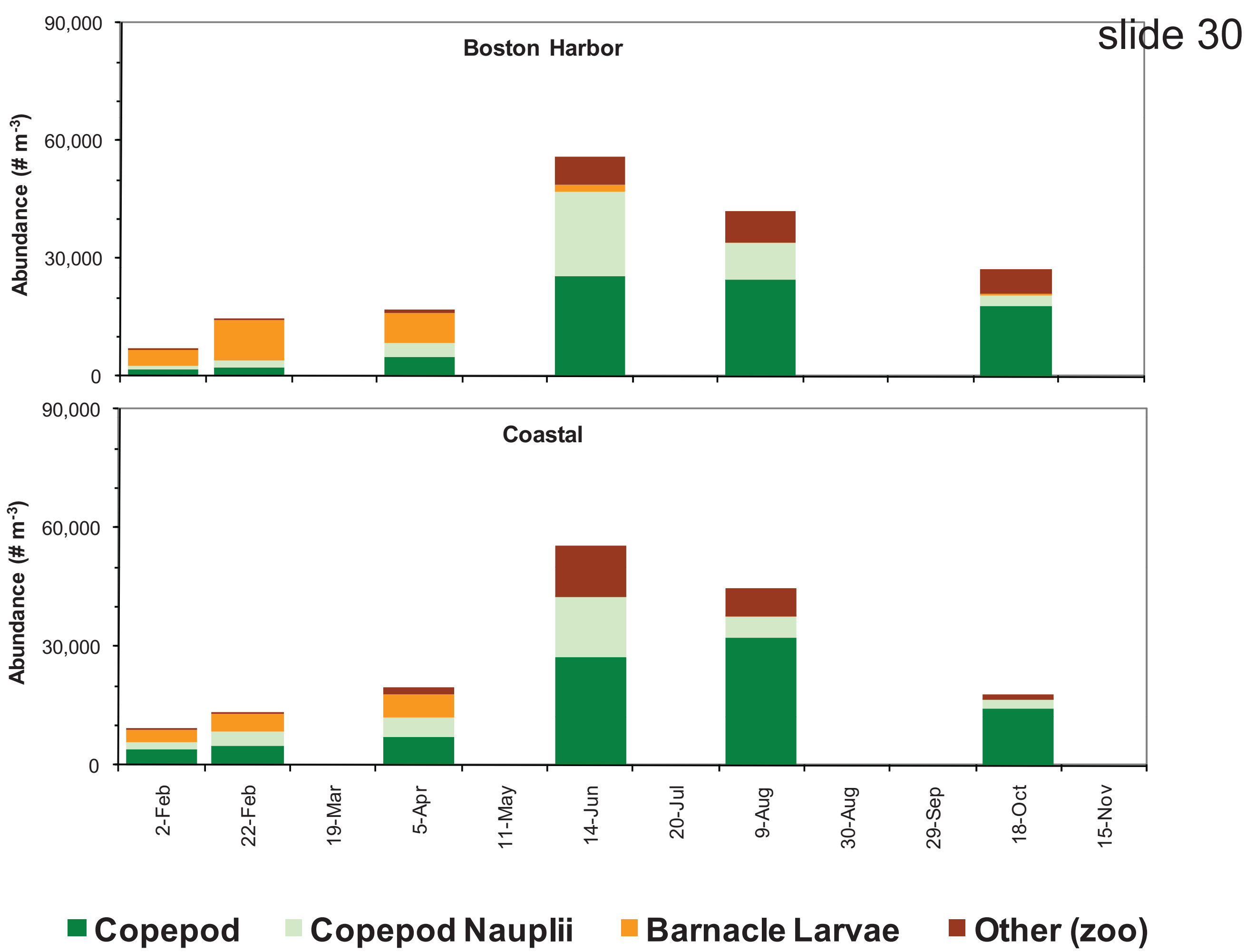
2010 Zooplankton Overview

- **Zooplankton Monitoring**
  - **Species and abundance**
  - **2 stations (NFLD), 12 times annually**
  - **13 stations (FFLD), 6 times annually**
  - **Vertical oblique net hauls, 102 μm mesh net (zooplankton)**
- **2010 annual pattern**
  - **Species composition**
  - **Abundance levels**
- **Long-term patterns & trends**

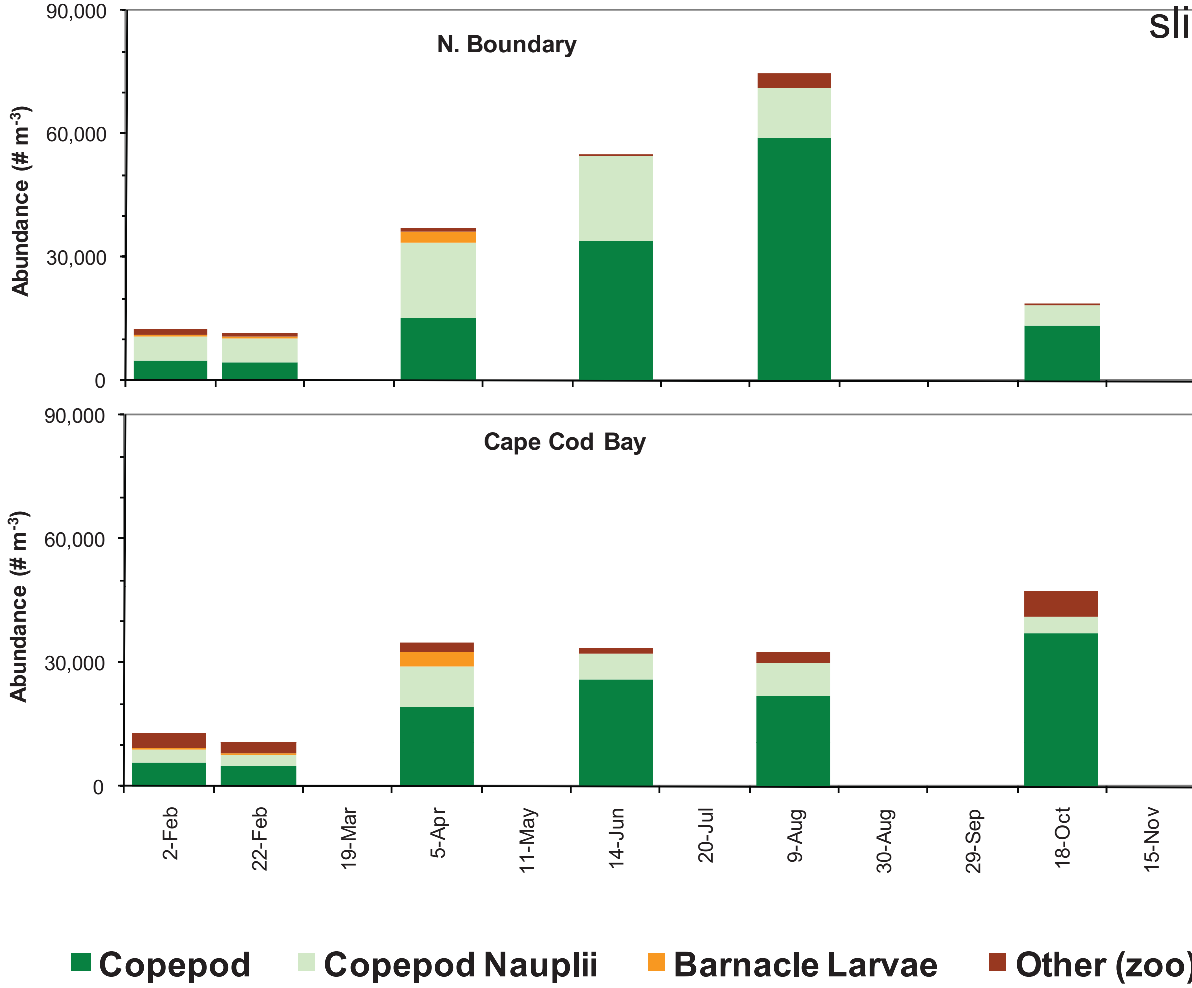
2010 Zooplankton




slide 29
Nearfield
Offshore
Abundance (# m-3)
90,000
60,000
30,000
0
2-Feb
22-Feb
19-Mar
5-Apr
11-May
14-Jun
20-Jul
9-Aug
30-Aug
29-Sep
18-Oct
15-Nov
Copepod
Copepod Nauplii
Barnacle Larvae
Other (zoo)

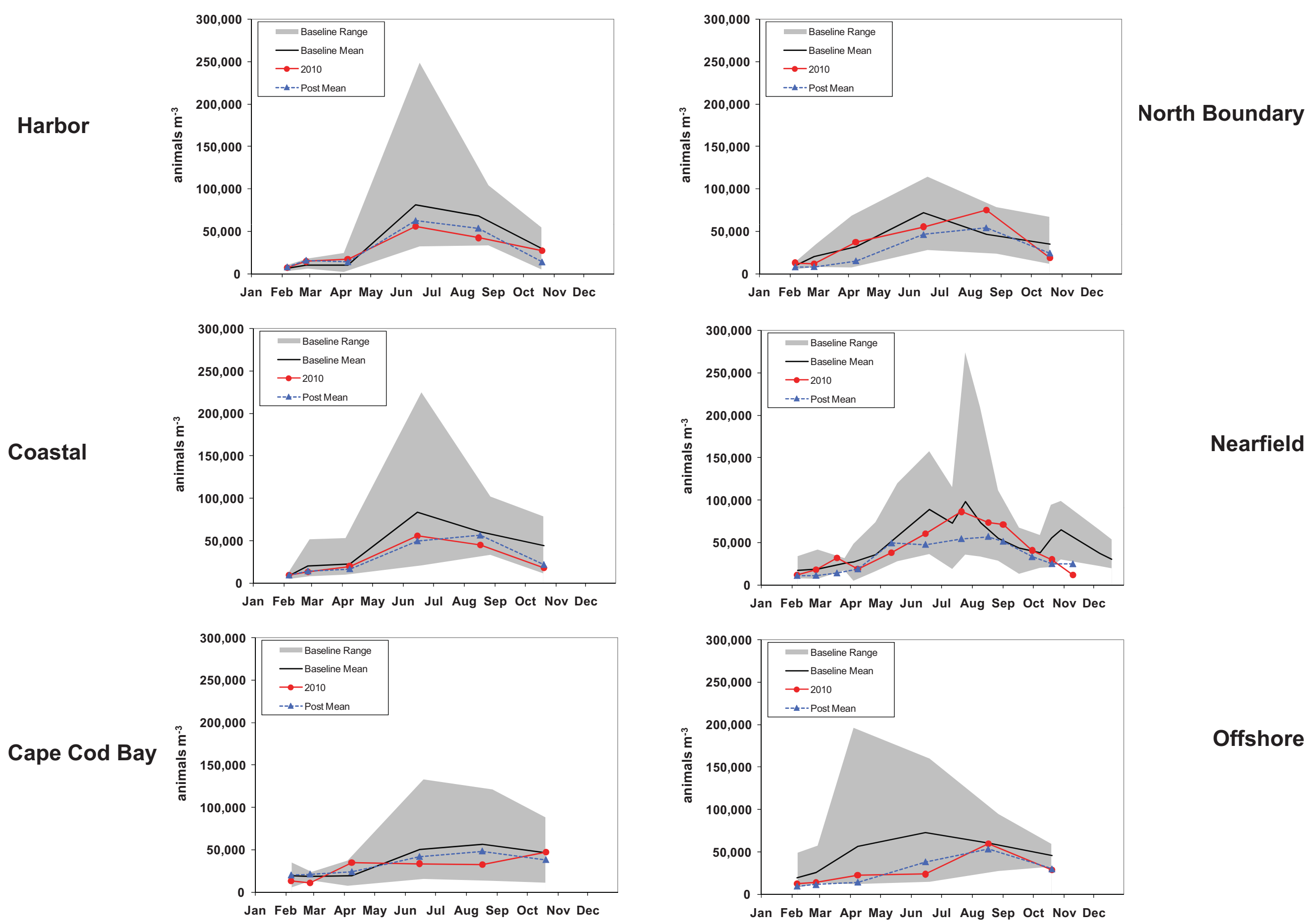

slide 30
Boston Harbor
Coastal
Abundance (# m-3)
90,000
60,000
30,000
0
2-Feb
22-Feb
19-Mar
5-Apr
11-May
14-Jun
20-Jul
9-Aug
30-Aug
29-Sep
18-Oct
15-Nov
Copepod
Copepod Nauplii
Barnacle Larvae
Other (zoo)

slide 31

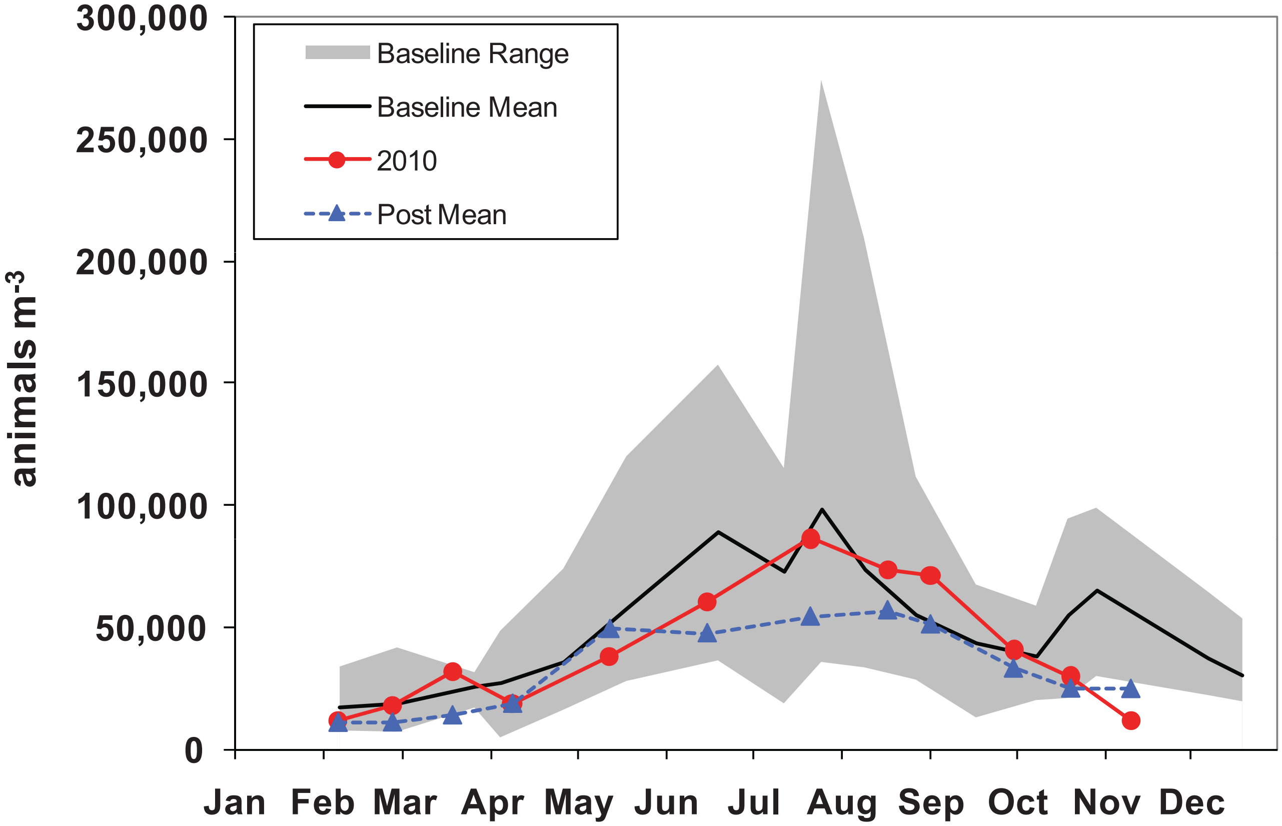


slide 32

Total Zooplankton 2010 Annual cycle

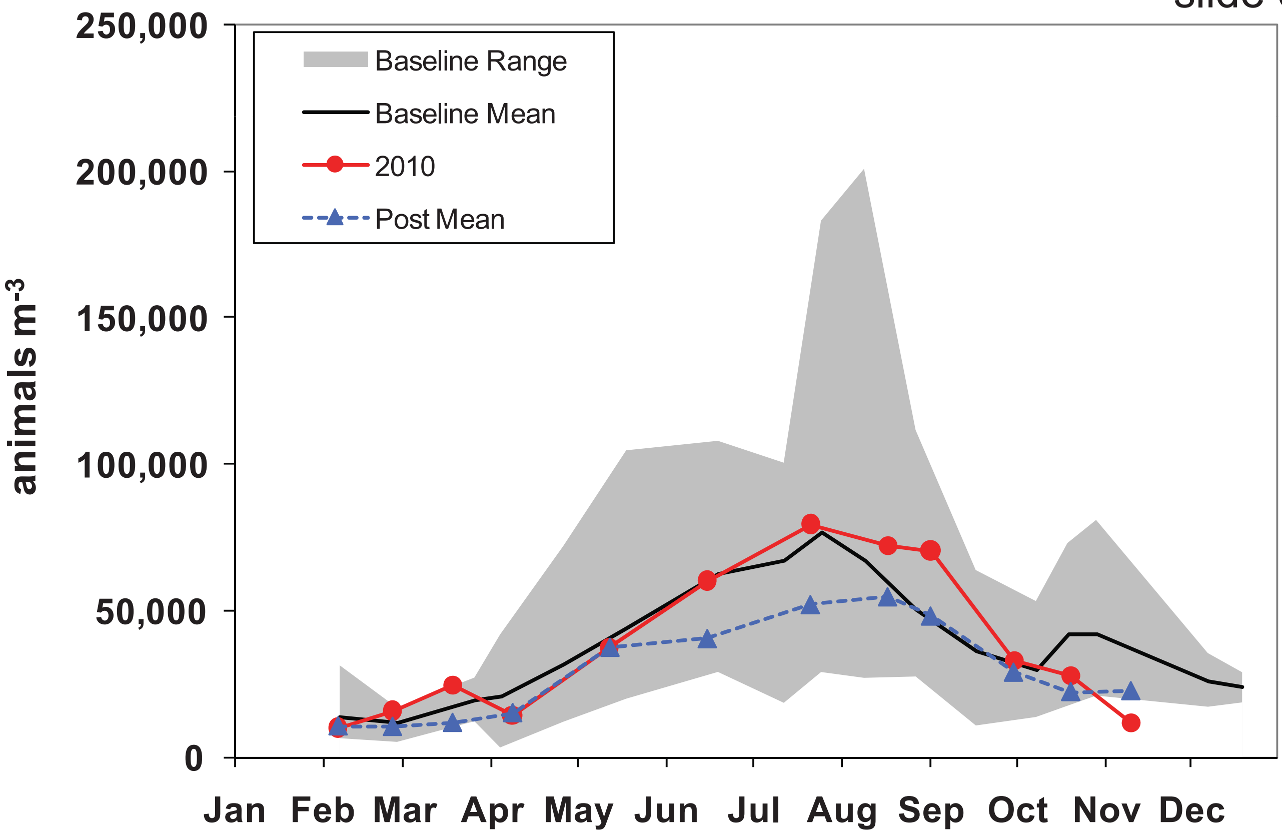


slide 33



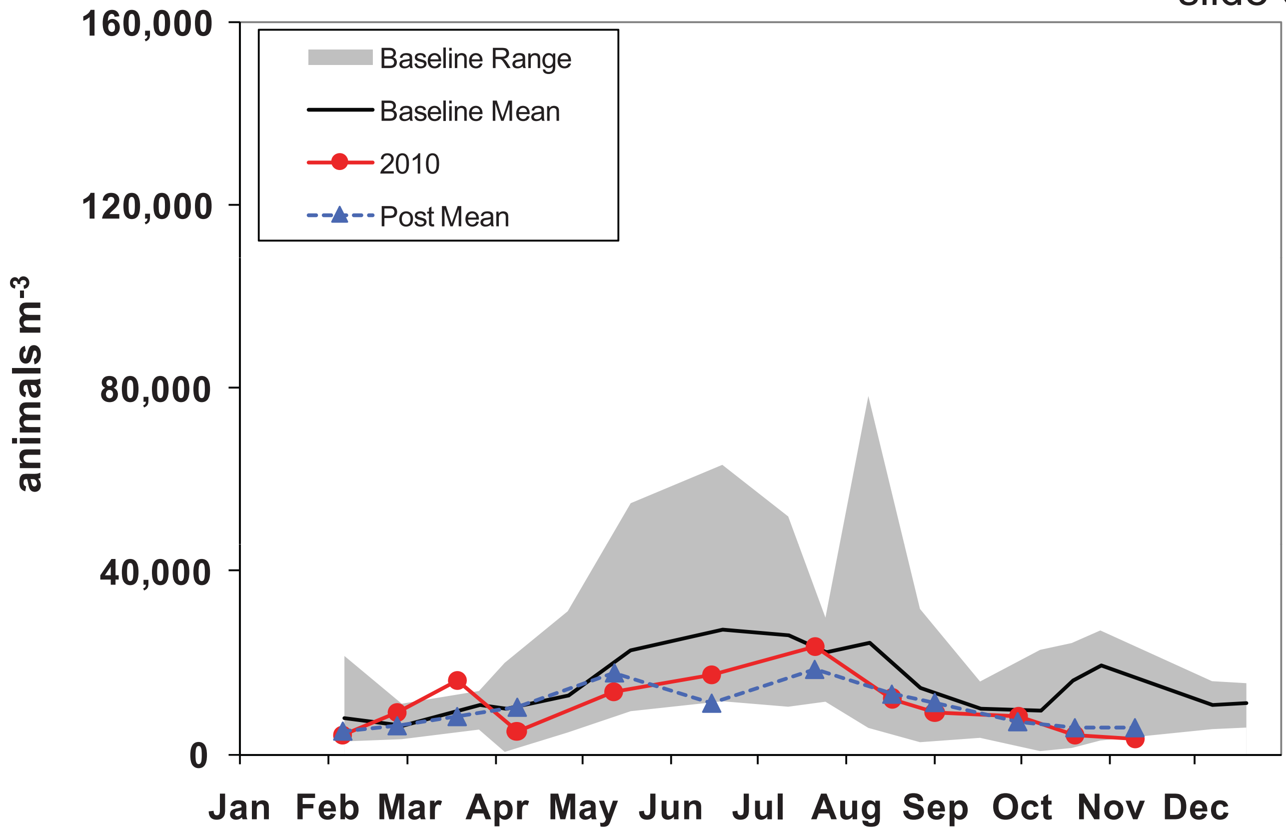
Nearfield total zooplankton

slide 34



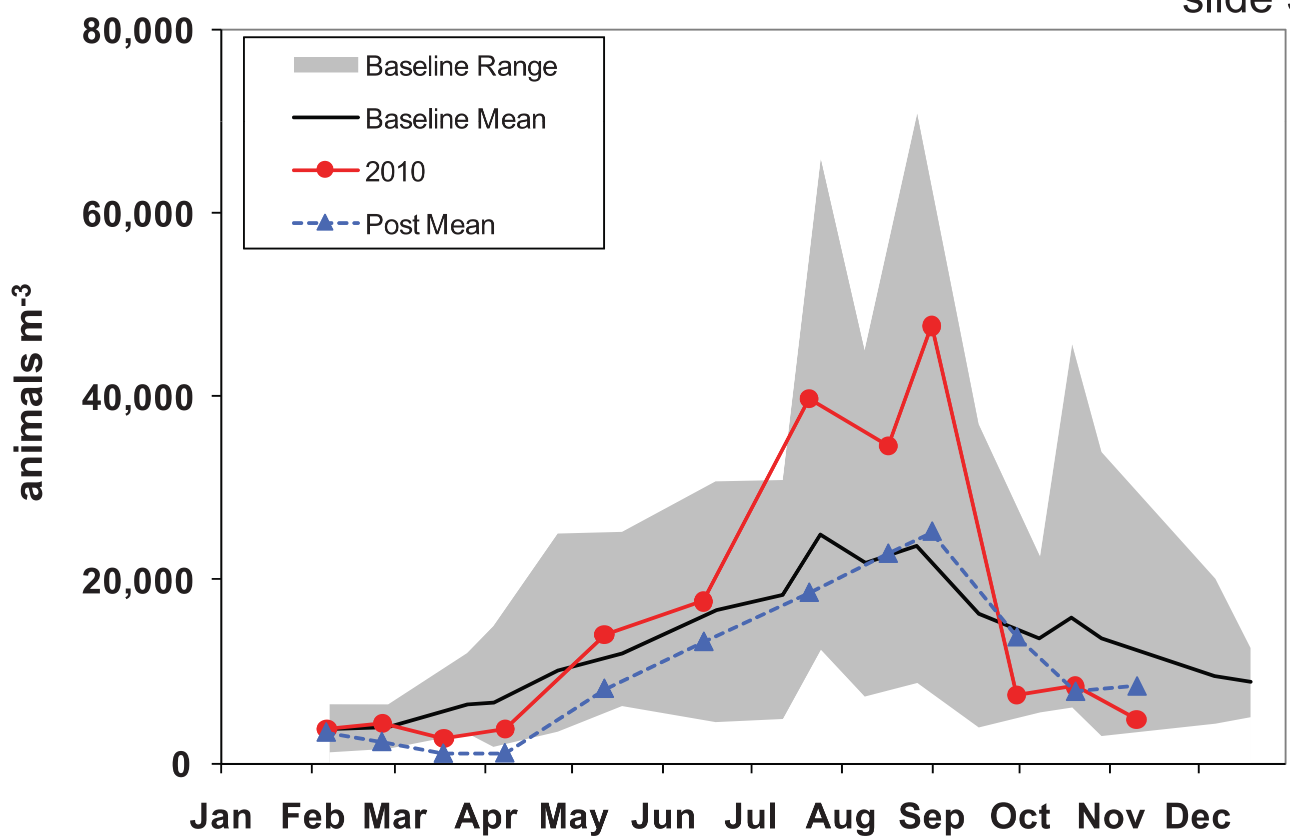
Nearfield copepods

slide 35



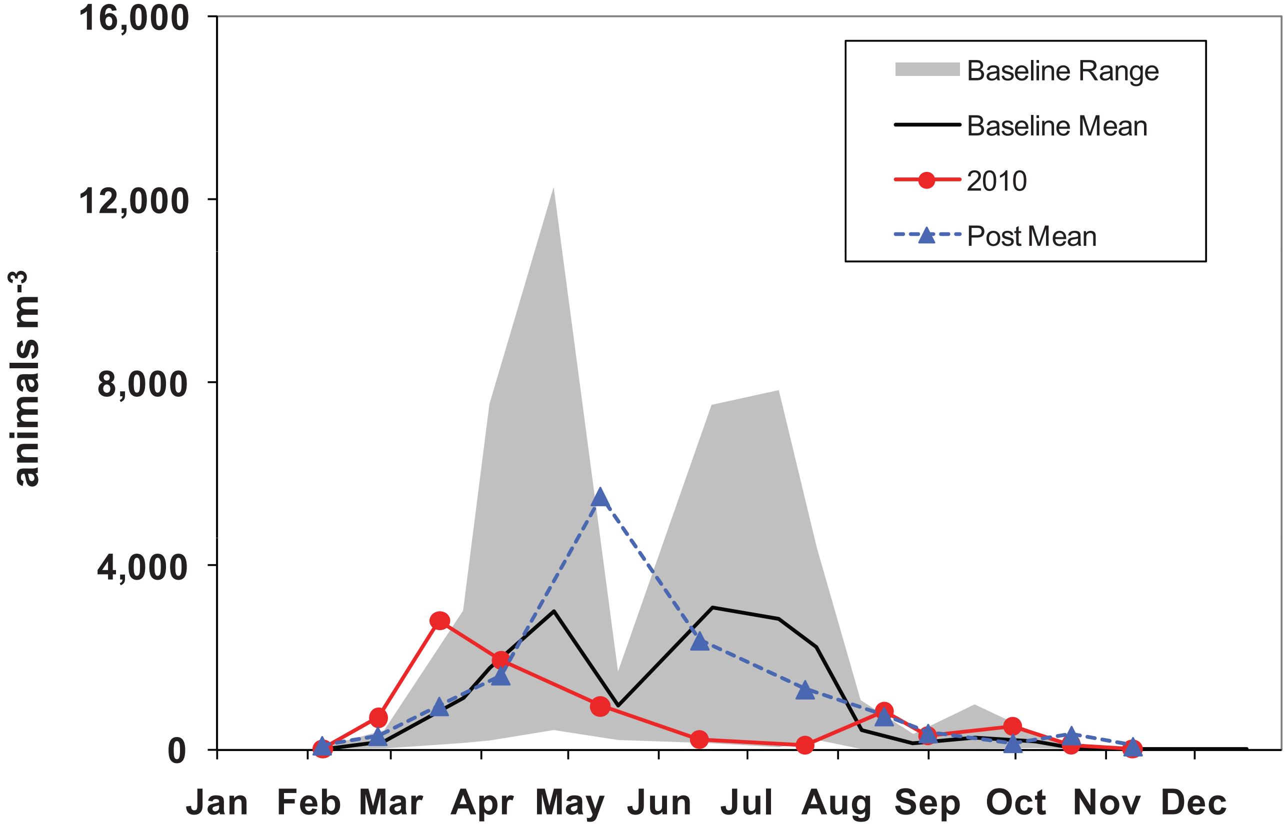
Nearfield copepod nauplii

slide 36



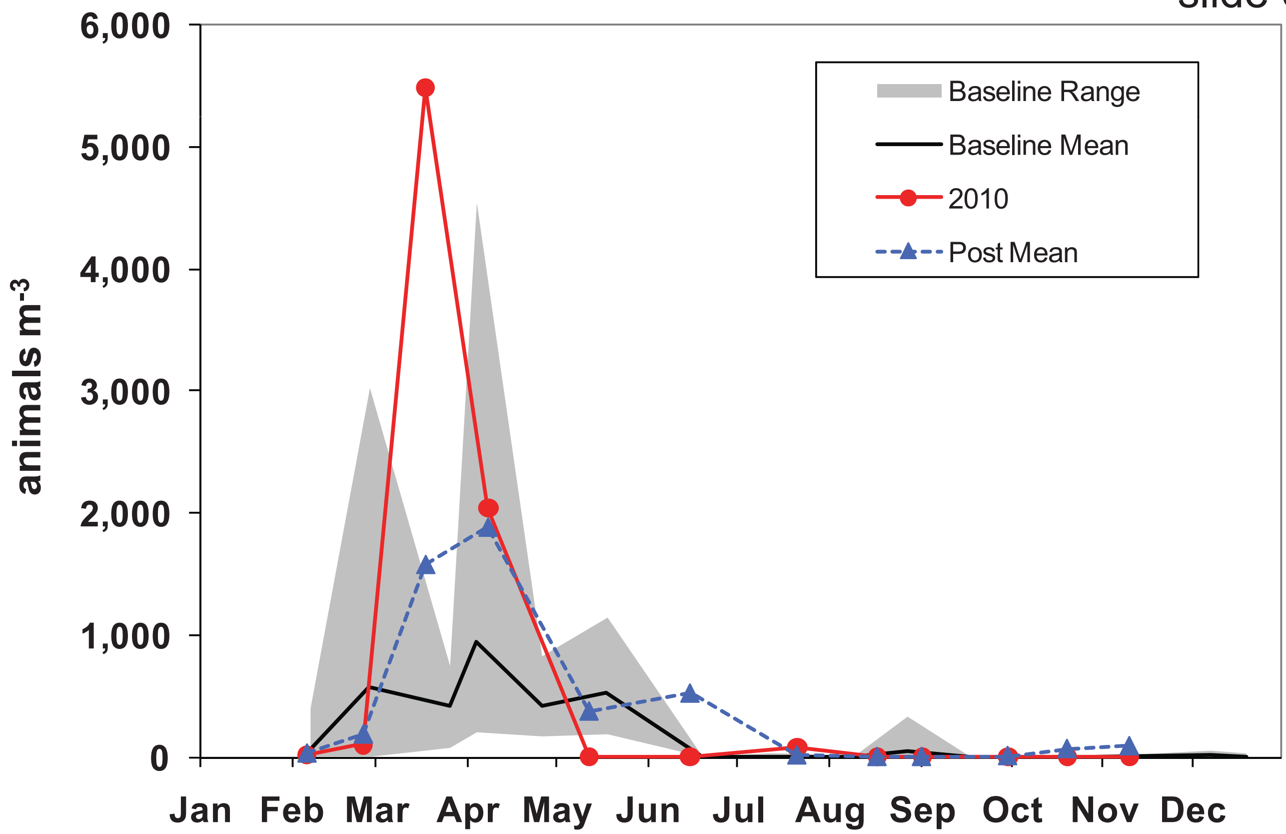
Nearfield *Oithona spp.* total

slide 37



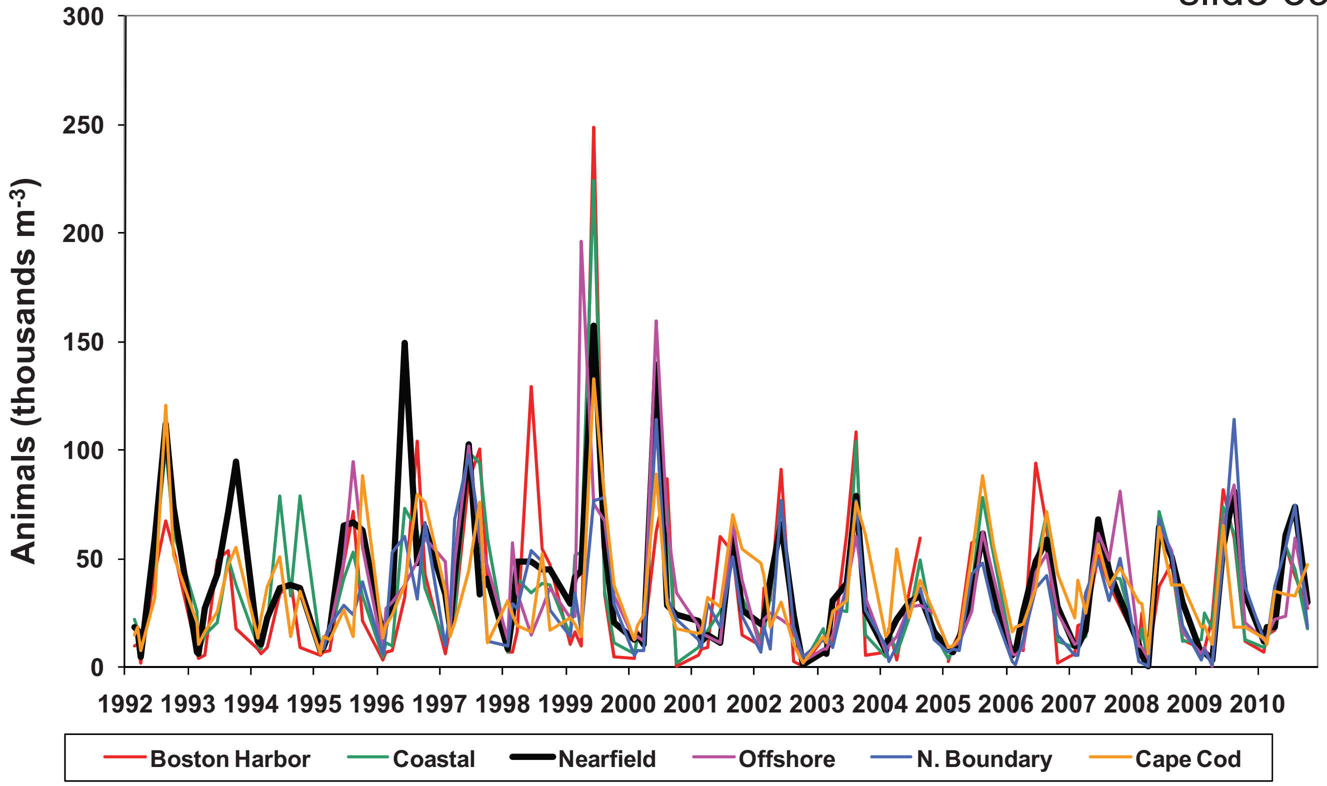
Nearfield *Calanus finmarchicus*

slide 38



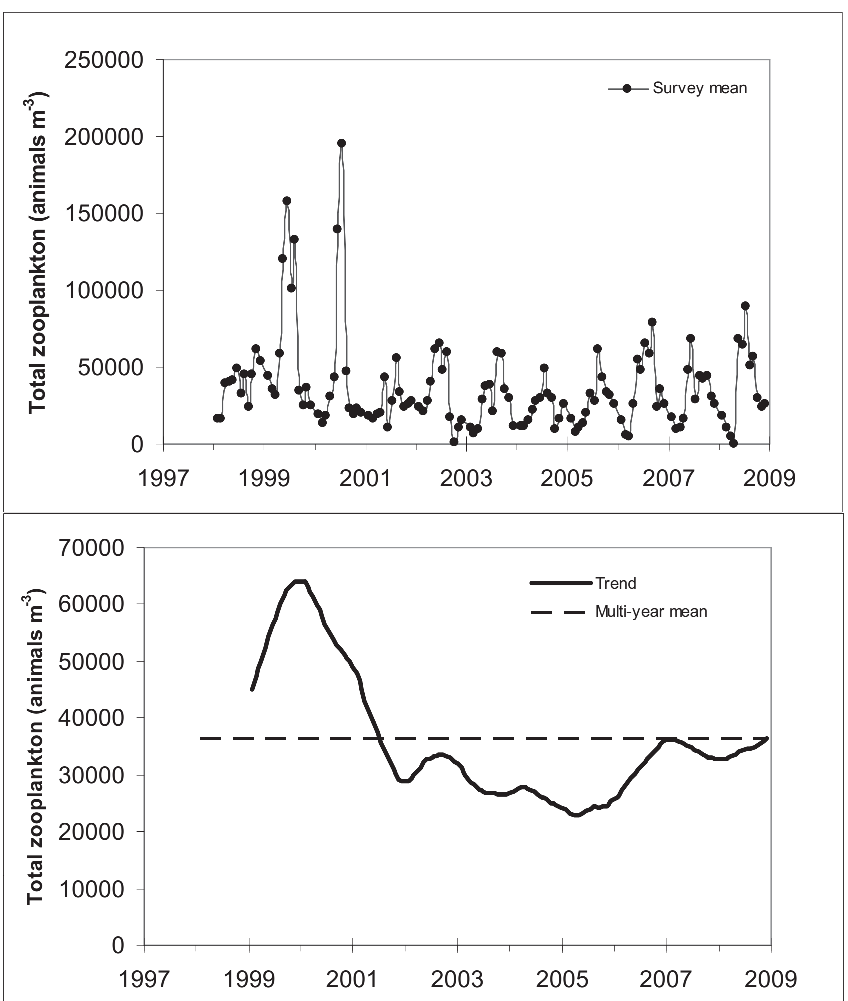
Nearfield Barnacle Larvae

slide 39



Total zooplankton long-term pattern, 1992-2010
Farfield surveys only

slide 40



Total Zooplankton Trend

1998 – 2009

2010 Zooplankton Summary

- Zooplankton abundance and species composition were generally similar to previous years.
- Total zooplankton abundance increased through winter, spring, and early summer to maxima in July, with continued high values in August, followed by progressive declines through the fall.
- Dominant taxa were copepods, primarily *Oithona similis* (copepodites), and copepod nauplii.
- Non-copepods exhibiting sporadic abundance included marine cladocerans (*Podon polyphemoides* and *Evadne nordmani*), *Oikopleura dioic*a, and meroplankters such as barnacle nauplii (March), bivalve and gastropod veligers, and polychaete larvae July and August).
- 2010 means for total zooplankton abundance by area were generally at the low end of the baseline range, similar to baseline and post-discharge means, except for November when the 2010 mean was below the baseline range.
- Nearfield abundance of barnacle nauplii in March greatly exceeded the baseline range and all previous means for previous years.
- *Calanus finmarchicus* peaked earlier in March than in previous years, with levels slightly higher than the baseline range, but then had lower values then the baseline and post-discharge means for the rest of the year.

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