

2011 Water Column Monitoring Results

Massachusetts Water Resources Authority

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1 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) conducts a long-term ambient outfall 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 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 outfall discharge periods (MWRA 2004, 2010). The 2011 data complete eleven years of monitoring since outfall start-up on September 6, 2000. **Table 1-1** shows the timeline of major upgrades to the MWRA wastewater treatment system.

Table 1-1. Major upgrades to the MWRA treatment system.

Date	Upgrade
December 1991	Sludge discharges ended
January 1995	New primary plant 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

MWRA's Effluent Outfall Ambient Monitoring Plan (AMP) was revised in 2010 (MWRA 2010); 2011 was thus the first year of monitoring according to the new design. The 2010 AMP revision builds on the scientific understanding gained over the past 20 years—the monitoring is now focused on the nearfield, stations potentially affected by the discharge, and reference stations in Massachusetts Bay. There are nine synoptic one-day surveys per year (**Table 1-2**). The Provincetown Center for Coastal Studies (PCCS) monitors Cape Cod Bay in the same timeframe.

This annual report summarizes the 2011 results as seasonal patterns and in the context of the annual cycle of ecological events in Massachusetts and Cape Cod Bays, and with respect to Contingency Plan thresholds (MWRA 2001). Long-term inter-annual patterns are also analyzed. Appendices A-F provide abstracts and presentations from the May 2012 Annual Technical meeting showing physical, chemical, and biological data in Massachusetts and Cape Cod Bays, and results of the Bays Eutrophication Model runs for 2011.

1.1 DATA SOURCES

The details of field sampling procedures and equipment, sample handling and custody, sample processing and laboratory analysis, instrument performance specifications and the program's data quality objectives are given in the Quality Assurance Project Plan (Libby *et al.* 2011a). The survey objectives, station locations and tracklines, instrumentation and vessel information, sampling methodologies, and staffing were

documented in the survey plan prepared for each survey. A survey report prepared after each survey summarizes the activities accomplished, details on any deviations from the methods described in the QAPP, the actual sequence of events and tracklines, the number and types of samples collected, and a preliminary summary of *in situ* water quality data. This includes the results of a rapid analysis of >20 µm phytoplankton species abundance in one sample, whale watch information, and any deviations from the survey plan. Electronically gathered and laboratory-based analytical results are tabulated in data reports.

1.2 WATER COLUMN MONITORING PROGRAM OVERVIEW

The new AMP (MWRA 2010) which began in 2011 changed the number of surveys and sampling locations. Previously, there were 12 “nearfield” surveys and six “farfield” surveys. Now all sampling locations (**Figure 1-1**) are visited during nine surveys annually; 2011 sampling dates are in **Table 1-2**. There are five stations sampled in the nearfield (previously seven) and nine stations in the farfield from (previously 27). All stations are sampled for a comprehensive suite of water quality parameters including plankton (except N21). The 11 stations in Massachusetts Bay were sampled synoptically during one-day surveys; the three Cape Cod Bay stations were sampled by PCCS on the same dates except in May and July. There were three *Alexandrium* Rapid Response Surveys (ARRS), AF111-AF113; those dates are in **Table 1-2**.

Table 1-2. Water column surveys for 2011.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Corresponding Harbor Monitoring survey dates
WN111	February 1	February 1	--
WN112	March 15	March 15	--
WN113	April 7	April 7	April 7
WN114	May 20	May 14	--
AF111	May 25	--	--
AF112	June 1	--	--
AF113	June 8	--	--
WN115	June 16*	June 16	June 13
WN116	July 19	July 20	--
WN117	August 18	August 18	August 17
WN118	September 12	September 12	September 9
WN119	October 18	October 18	October 18

*Five additional stations were sampled on June 16 survey as part of red tide monitoring.

PCCS collects samples at three MWRA stations (**Figure 1-1**), and has an ongoing water quality monitoring program at eight other stations in Cape Cod Bay.¹ Nutrient data from all the Cape Cod Bay stations are included in this report. MWRA monitors 10 stations in Boston Harbor [Boston Harbor Water Quality Monitoring, (BHWQM)];² BHWQM data collected within 5 days of an AMP survey are included in this report.

In addition to sampling surveys, this report includes MODIS-Aqua satellite imagery provided by NASA, and continuous monitoring data from the NOAA National Data Buoy Center (NDBC) Buoy 44013 and the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) Buoy A. NDBC Buoy 44013 is located ~10 km southeast of the outfall, near station N07; NERACOOS Buoy A is

¹ PCCS station map available at <http://www.coastalstudies.org/what-we-do/cc-bay-watch/stations.htm>

² BHWQM station map available at http://www.mwra.state.ma.us/harbor/graphic/bostonharbor_850.gif

located in the northwestern corner of Stellwagen Bank National Marine Sanctuary and ~5km northeast of MWRA station F22 (**Figure 1-1**). The satellite imagery provides information on regional-scale patterns; the buoys collect data at high temporal frequency.

The data are grouped by season for calculation of chlorophyll, *Phaeocystis*, and *Pseudo-nitzschia* Contingency Plan thresholds. Seasons are defined as the following 4-month periods: winter/spring is from January through April, summer from May through August, and fall from September through December. Comparison of baseline and outfall discharge period data are made for a variety of parameters. The baseline period is February 1992 to September 6, 2000 and the outfall discharge period is September 7, 2000 through December 2011.³

³ 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.

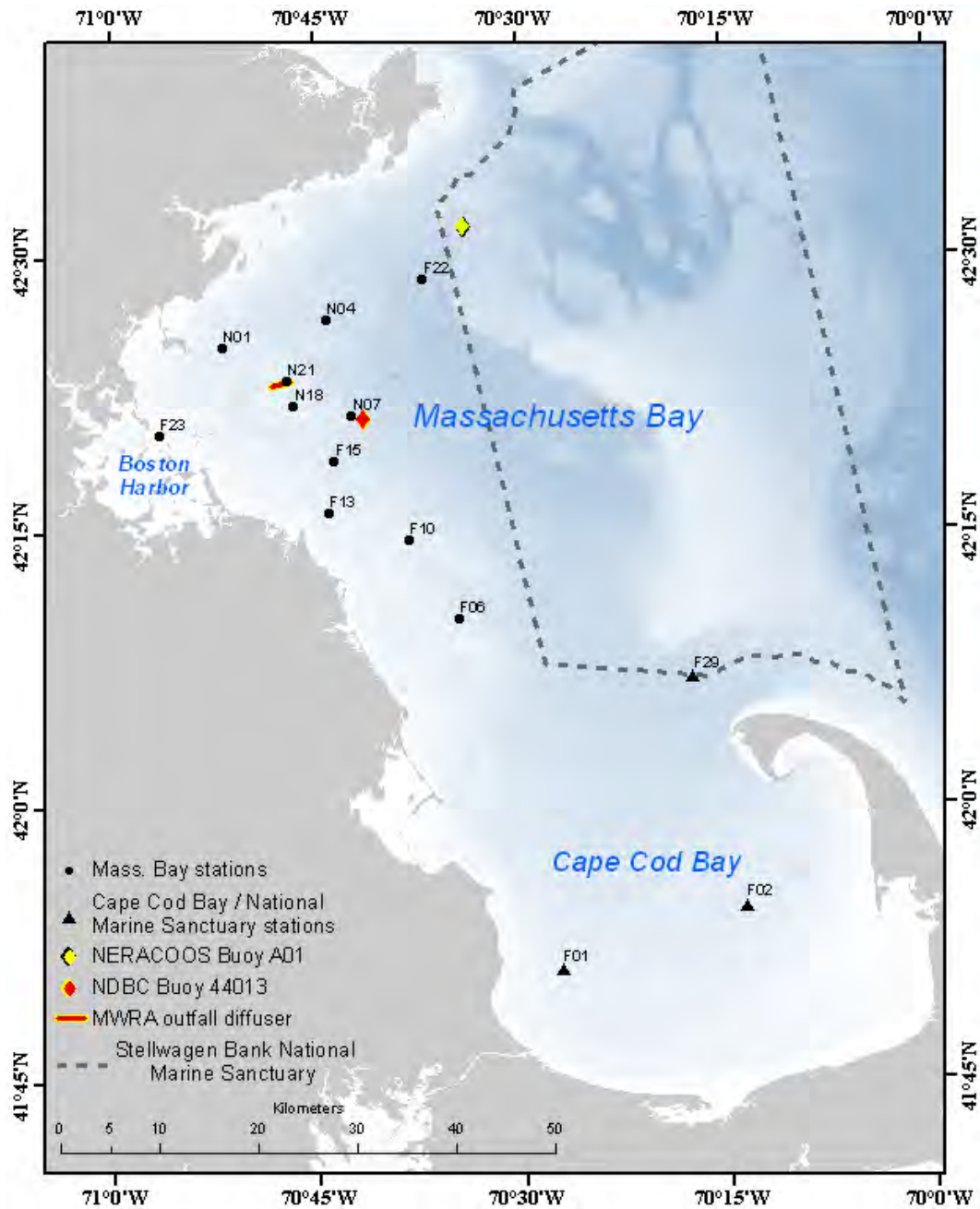


Figure 1-1. Water column monitoring locations.

2 MONITORING RESULTS

As expected the 2011 results follow the typical seasonal sequence of water quality events in Massachusetts Bay. A typical winter/spring phytoplankton diatom bloom developed as light became more available, temperatures increased, and nutrients were readily available. In line with previous observations, the 2011 winter/spring diatom bloom was followed by a bloom of *Phaeocystis pouchetii* in April. The water column transitioned from well-mixed to stratified conditions in the late spring with concomitant cut-off of the nutrient supply to surface waters terminating the spring bloom. The summer period was strongly stratified, with depleted surface water nutrients, and a relatively stable mixed-assemblage phytoplankton community. The normal fall cooling, initial vertical mixing and return of the nutrient supply to surface waters was evident as well as the associated development of a fall phytoplankton bloom. Previous observations showed that the lowest observed dissolved oxygen concentrations for the year can be found in bottom waters just prior to the complete fall overturn of the water column. In 2011, the return of the system to well-mixed winter conditions was not observed in the survey data because there were no strong fall storms until after the final survey in October. The details of the major features observed and differences noted in 2011 relative to the previous 19 years of monitoring are considered below.

2.1 2011 RESULTS

The physical, water quality, and biological conditions in 2011 followed the seasonal patterns observed from 1992 through 2010. The most notable characteristic of the physical environment was that 2011 was very wet throughout the year with river discharges well above the 50th percentile (compared to 1992-2010) for nearly all of the year (**Figure 2-1**). Although the overall river discharges were elevated, there were no major river discharge events, even though strong Northeaster storms occurred in May and Hurricane Irene's impact was felt in August. The river runoff provided additional nutrients and supported both an April *Phaeocystis* bloom and a bloom of centric diatoms and dinoflagellates in May. Hurricane Irene's winds led to strong upwelling in August. Even though mixing during this event was confined to the near surface waters, there was a strong temperature and river discharge signal associated with the storm. In contrast, the weather was calm in September and October and the water column was still stratified by the final survey for 2011 in mid-October. Bottom water DO may have continued to decline until a strong storm in late October. A chronological synopsis of the 2011 results is provided below and additional details are presented in Appendices A-F.

Nutrient concentrations were highest in Massachusetts Bay in February and March [see map of surface and bottom water nitrate + nitrite ($\text{NO}_3 + \text{NO}_2$) in **Figure 2-2** and **Figure 2-3**] (additional plot by month in Appendix B slides 5 and 6). $\text{NO}_3 + \text{NO}_2$ and phosphate (PO_4) levels in Cape Cod Bay were about one-half those in Massachusetts Bay in February and surface nutrients in Cape Cod Bay were nearly depleted by March. The lower nutrients levels were consistent with the elevated chlorophyll concentrations (**Figure 2-4** and **Figure 2-5**) associated with the winter/spring centric diatom bloom of *Chaetoceros* spp. and *Thalassiosira* spp. and elevated microflagellate abundances observed in Cape Cod Bay during and between the first two surveys. In March, the effluent plume (as delineated by elevated ammonium (NH_4) concentrations) was evident in the nearfield surface waters (**Figure 2-6**). Stratification at that time was too weak to prevent the plume from surfacing; the stratified case is shown in **Figure 2-9**.

From March to April, there was a very sharp decrease in nutrients throughout Massachusetts Bay. Surface NO_3 concentrations were depleted at all but the harbor stations by April (**Figure 2-2**); silicate (SiO_4) levels also decreased but remained somewhat elevated relative to NO_3 (Appendix B slide 6). In fact, NO_3 concentrations were low throughout the upper 30 m of the water column. The decreases in nutrients were coincident with increases in chlorophyll associated with an April bloom; the relatively greater decrease in NO_3 vs. SiO_4 is consistent with that bloom being dominated by *Phaeocystis* as that phytoplankton species does not utilize SiO_4 .

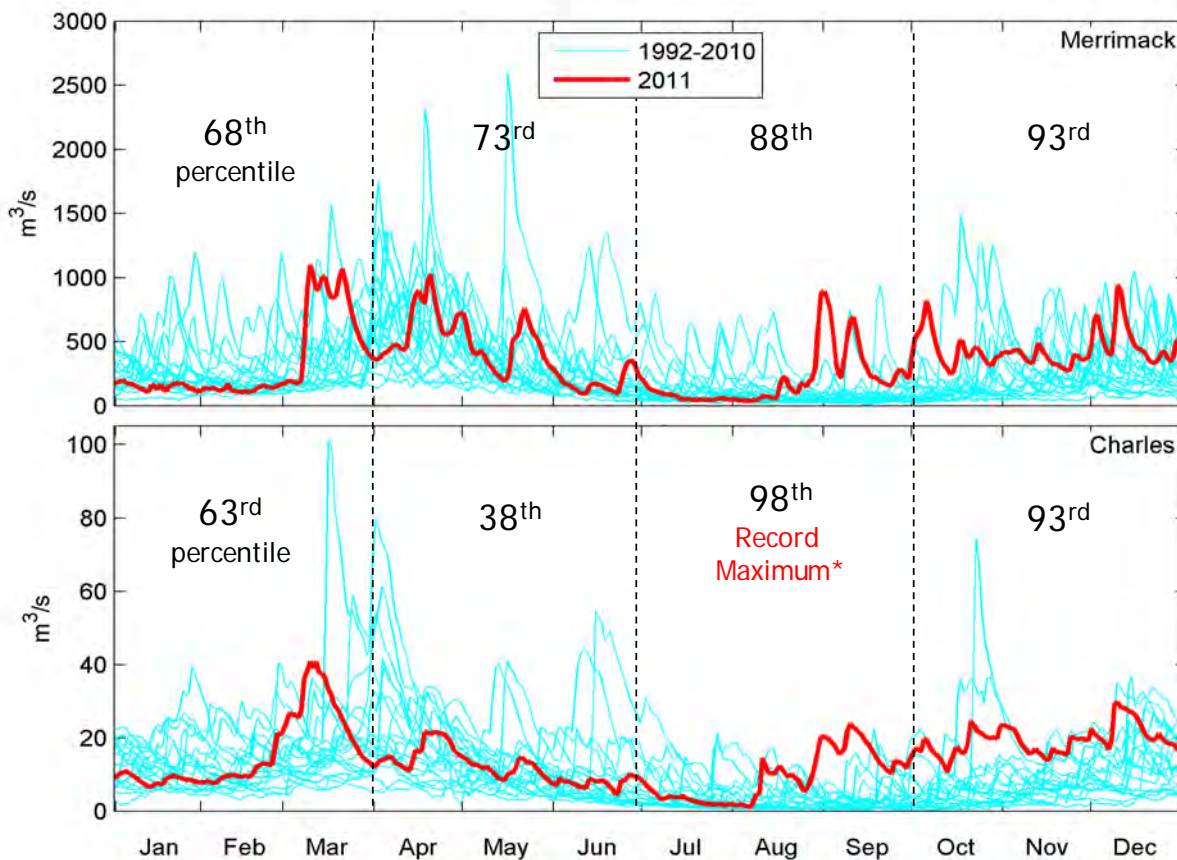


Figure 2-1. Comparison of the 2011 discharge of the Charles and Merrimack Rivers (solid red curve) with 1992-2010 (light blue lines). Percentile of flow in 2011 relative to other years is presented for each river/season.

The 2011 *Phaeocystis* bloom was modest with elevated abundances (>1 million cells L^{-1}) observed in Massachusetts Bay (maximum abundance of >2 million cells L^{-1} measured at station N18). Abundances of the pennate diatom *Pseudo-nitzschia delicatissima* cells were elevated in April with the majority associated with, observed on, or embedded in, *Phaeocystis pouchetii* colonies. The blooms of these two species led to an overall increase in phytoplankton abundance (**Figure 2-7**). Despite the increase in phytoplankton abundance, surface chlorophyll levels during the April survey were not very high with a $2.7 \mu g L^{-1}$ maximum in the nearfield (**Figure 2-4**). The MODIS imagery from late March suggests the bloom peaked (at least in chlorophyll concentrations) in mid to late March (**Figure 2-5**) between the March and April surveys. Elevated *in situ* fluorescence levels were observed near the pycnocline in April, which is often indicative of a senescent bloom, and the *in situ* fluorescence signal was noisy (Appendix B slide 16) indicative of large particulates, such as *Phaeocystis* colonies, passing through the fluorometer.

From April to May, chlorophyll and POC concentrations continued to increase in Massachusetts Bay especially in the surface waters (**Figure 2-4** and **Figure 2-8**), coinciding with an increase in centric diatoms and smaller dinoflagellates. Surface nutrient concentrations increased slightly over this time period (Appendix B slides 5 and 6) likely due to freshwater inputs during April and May storms. The higher riverine nutrient input also likely supported the May increase in centric diatoms (primarily *Skeletonema* and *Thalassiosira* spp.) and small dinoflagellates. Dinoflagellate abundance reached an annual peak in May (maximum of $\sim 375,000$ cells L^{-1}) dominated by a variety of small dinoflagellates such as *Heterocapsa triquetra*, *Heterocapsa rotundata*, *Gymnodinium* spp. and *Prorocentrum minimum*. The May dinoflagellate community also included the toxic dinoflagellate *Alexandrium fundyense* with abundances peaking during

the May 20 survey at ~2,500 cells L⁻¹ at station N07 in the nearfield. The levels were above the 100 cells L⁻¹ trigger for *Alexandrium* rapid response surveys (ARRS). A three week series of ARRSs was conducted from May 25 to June 8 which documented a moderate bloom that impacted shellfishing across most of Massachusetts Bay. The 2011 bloom led to an exceedance of the MWRRA Contingency Plan Threshold for *Alexandrium*. The 2011 bloom is discussed in detail in section 2.2.

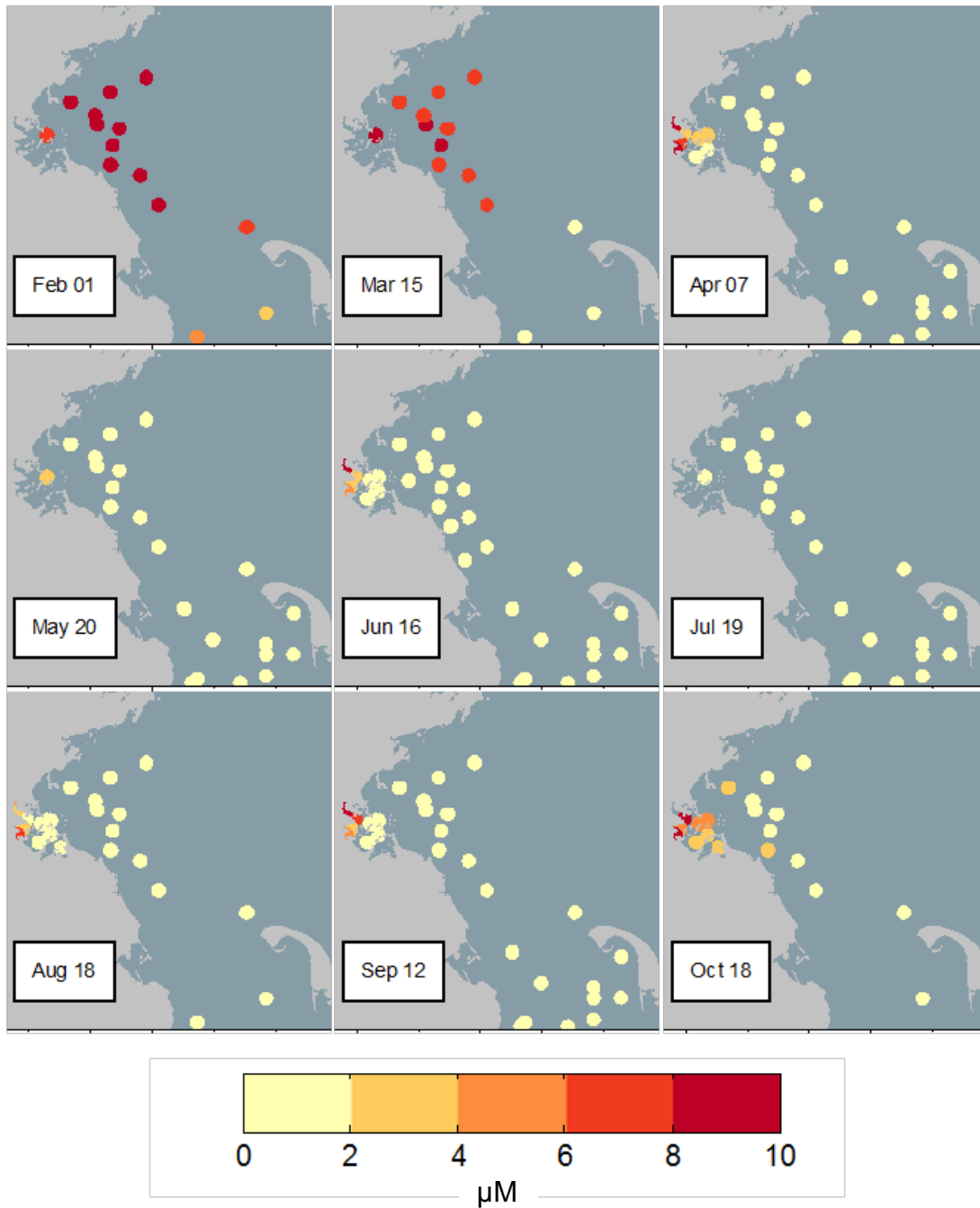


Figure 2-2. Surface water nitrate + nitrite (NO₃ + NO₂, µM) by station in Massachusetts and Cape Cod Bays.

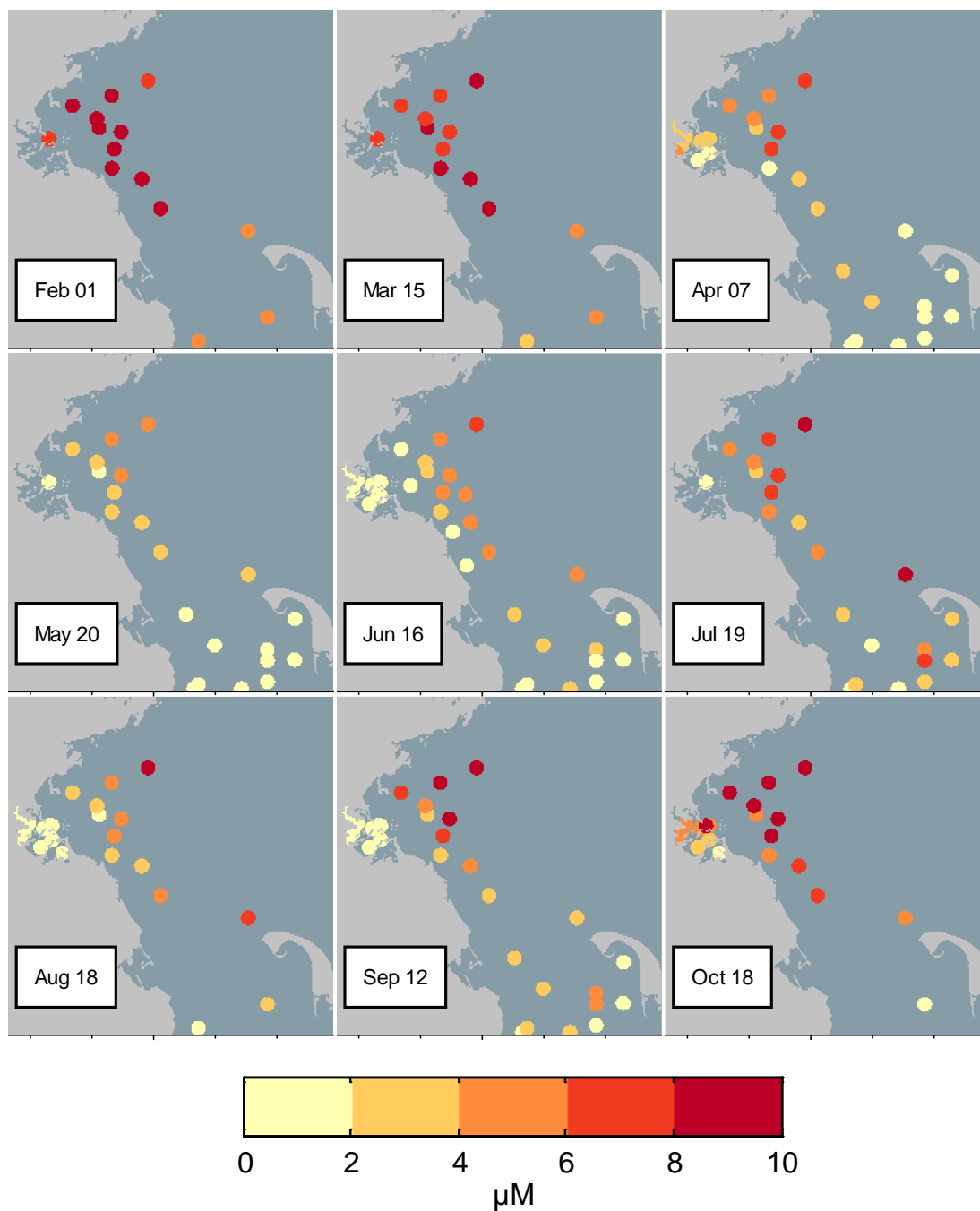


Figure 2-3. Bottom water $\text{NO}_3 + \text{NO}_2$ (μM) by station in Massachusetts and Cape Cod Bays.

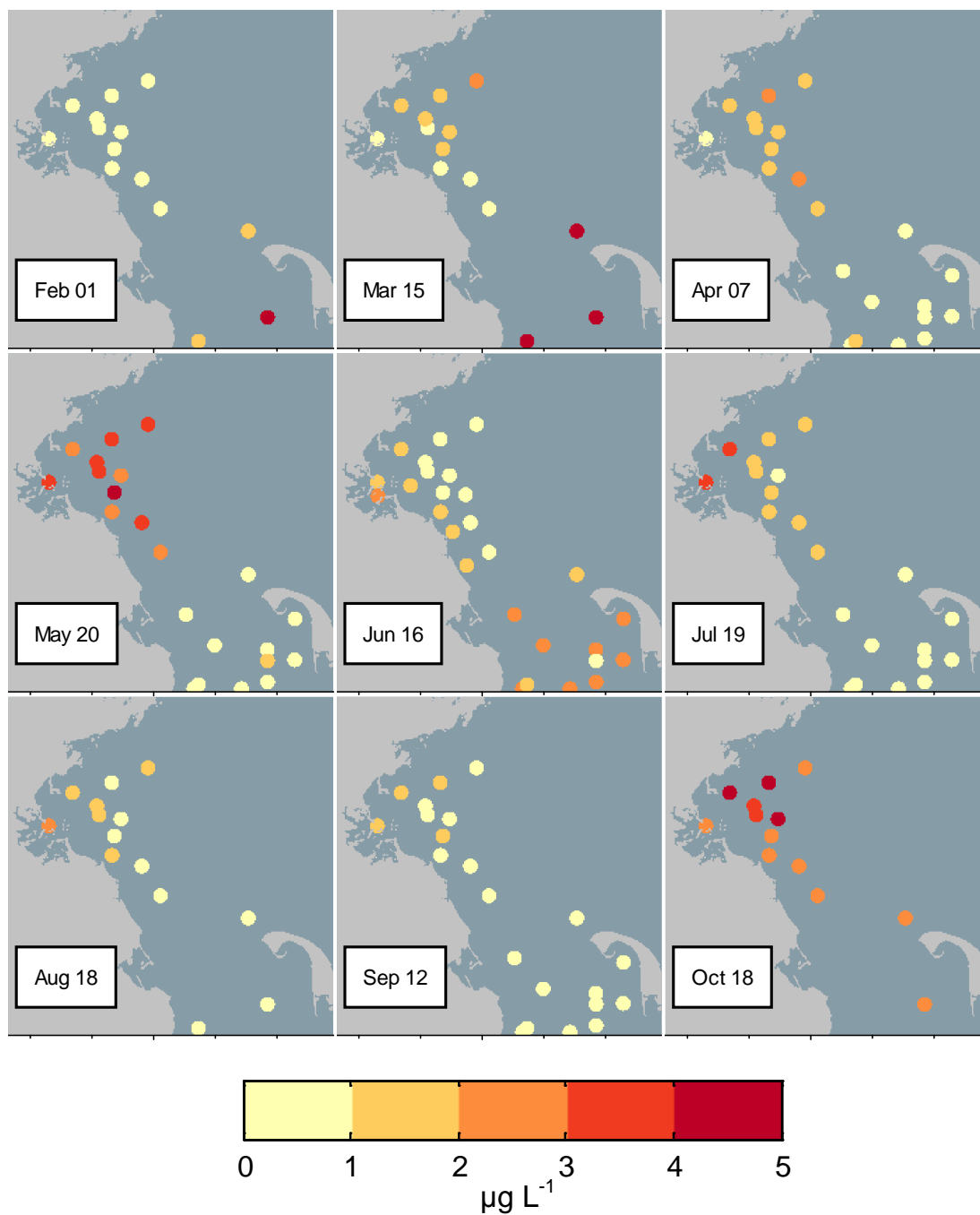


Figure 2-4. Surface water *in situ* chlorophyll fluorescence ($\mu\text{g L}^{-1}$) by station in Massachusetts and Cape Cod Bays.

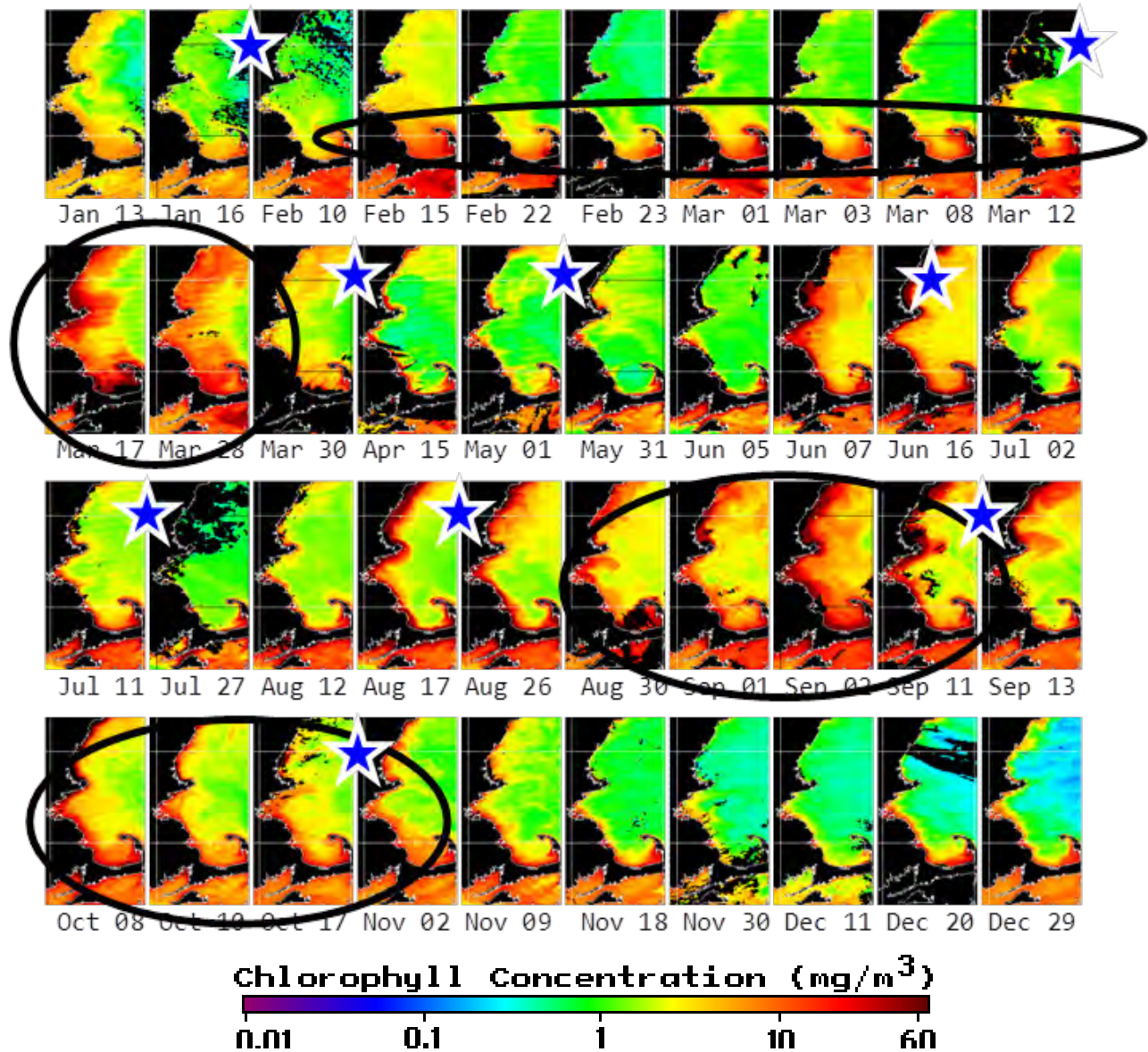


Figure 2-5. MODIS imagery of surface chlorophyll concentrations (mg m⁻³) in 2011. The circles highlight specific blooms: 2nd row – region-wide *Phaeocystis* bloom in March; 3rd row – post Hurricane Irene *Skeletonema* and microflagellate blooms in late August and early September; and 4th row – microflagellate and *Prorocentrum* blooms in October. (Note that these images are heavily weather dependent and do not represent consistent intervals of time; for example, only two images were available over the two-month period between March 30 and May 31. The stars on the image correspond to the nine MWRA surveys.)

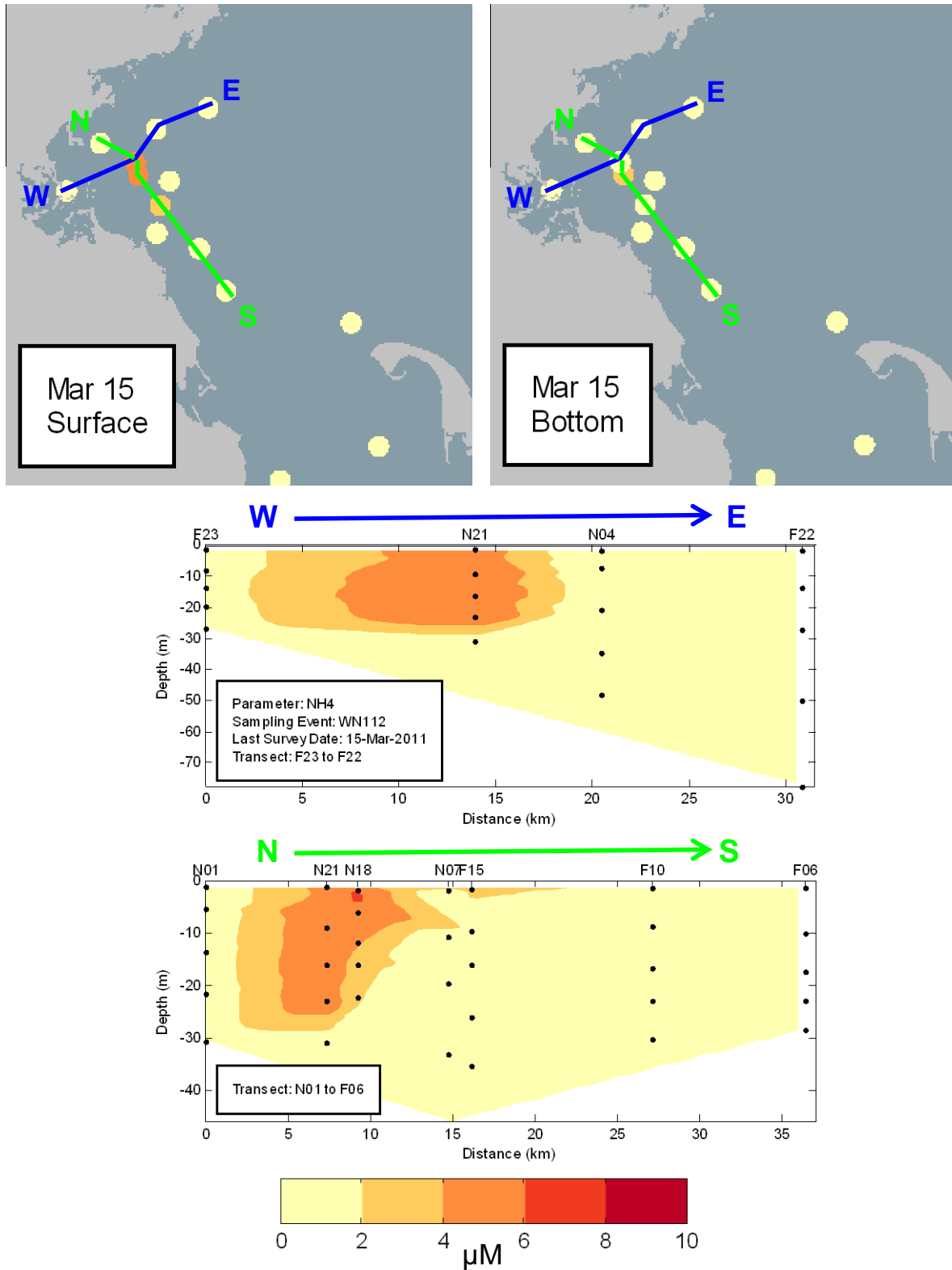


Figure 2-6. Surface and bottom water ammonium (NH₄, μM) by station and along two vertical transects in Massachusetts and Cape Cod Bays on March 15, 2011.

By the June 16th survey there was a decrease in nutrients, chlorophyll and POC throughout Massachusetts Bay and the *Alexandrium* bloom had ended. A diatom bloom in Cape Cod Bay in June resulted in higher chlorophyll concentrations relative to those measured to the north in Massachusetts Bay (**Figure 2-4**). The water column had become stratified by mid-June and nutrients were confined below the pycnocline including NH₄ levels associated with the effluent plume (**Figure 2-9**). The effluent plume, detected as elevated NH₄ concentrations, was confined to station N21 along the E-W transect and extended from station N21 to station F06 (~25 km south of the outfall) along the N-S transect. The elevated NH₄ concentrations at nearfield stations N18 and N21 persisted from June through September as seasonal stratification confined the plume to the bottom waters (Appendix B slide 5). This has been a consistent pattern in the nearfield since diversion of the outfall September 2000 (Libby *et al.* 2011b).

A month later (July) surface water nitrogen levels were depleted throughout Massachusetts Bay including the Boston Harbor station F23 (**Figure 2-2** and Appendix B slide 5). This lack of nitrogen was coincident with annual peaks of chlorophyll and POC at the harbor station and increasing levels in adjacent coastal waters (**Figure 2-4** and Appendix B slide 13). The high chlorophyll and POC were due to a summer bloom of the centric diatom *Dactyliosolen fragilissimus* at the shallower, inshore stations (**Figure 2-7**). This is the third year in a row that a bloom of this species has been observed in the shallow harbor and coastal waters.

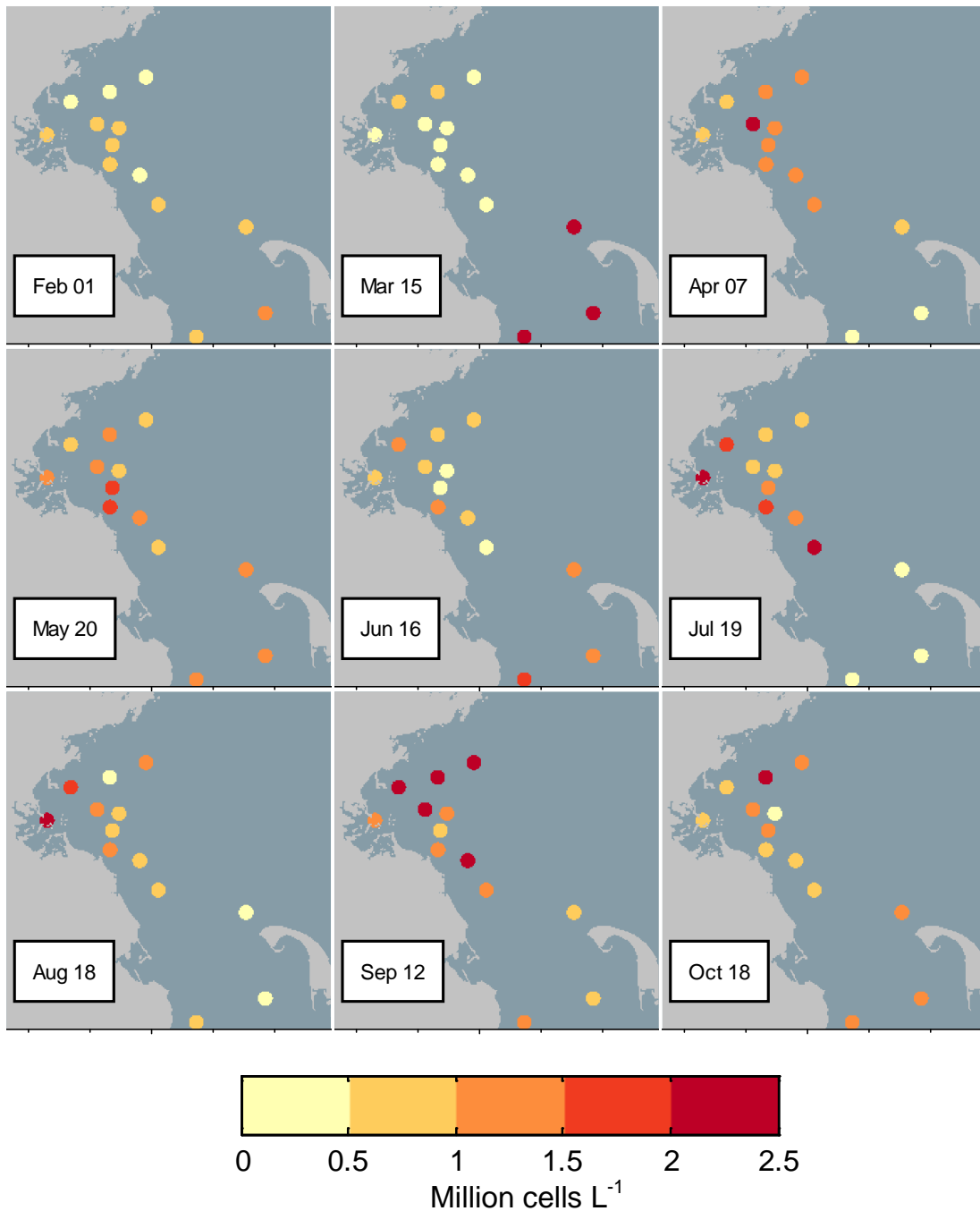


Figure 2-7. Average phytoplankton abundance (million cells L⁻¹) by station in Massachusetts and Cape Cod Bays for 2011.

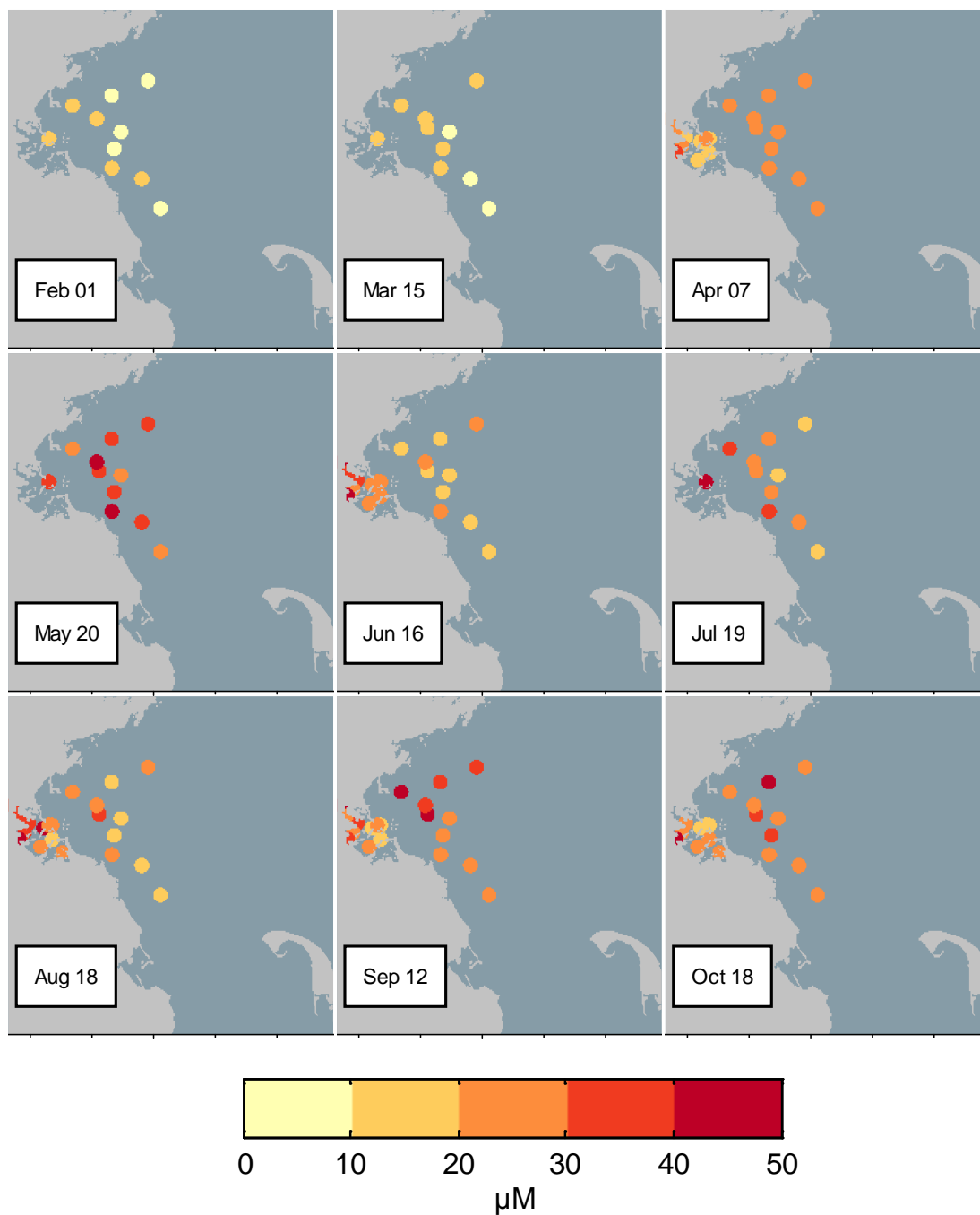


Figure 2-8. Surface water particulate organic carbon (POC, μM) by station in Massachusetts Bay (not measured in CCB).

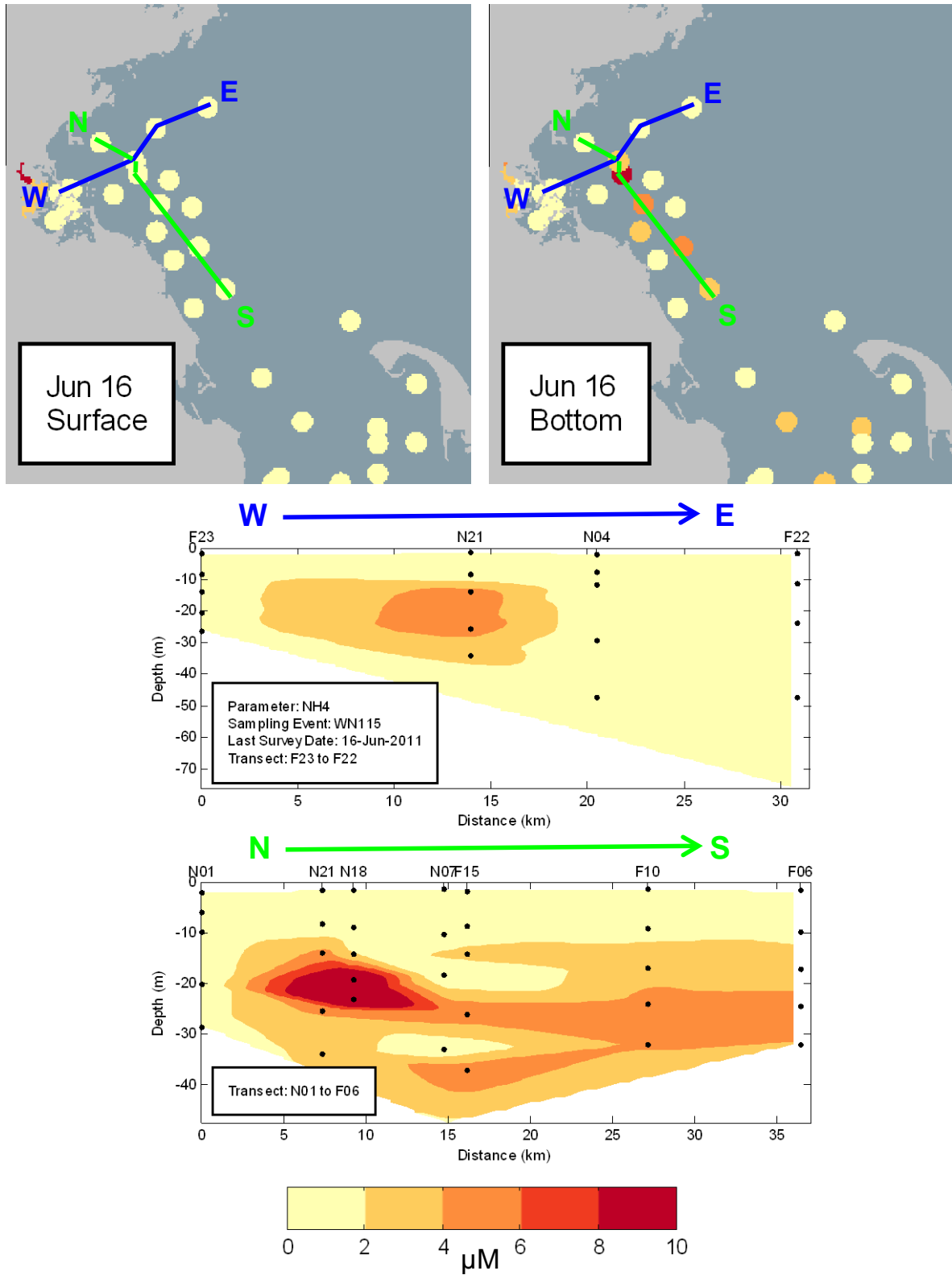


Figure 2-9. Surface and bottom water NH_4 (μM) by station and along two vertical transects in Massachusetts and Cape Cod Bays on June 16, 2011.

Cryptomonad abundance was also elevated in July: about 650,000 cells L⁻¹ at station F06 offshore of Scituate (Appendix C slide 16). This is three-fold higher than the long-term mean and approximately twice the highest July observations made during the 20 years of monitoring in this region.

Reports of ‘purple water’ in Massachusetts Bay were received by MWRA from the US Coast Guard in early August 2011. Samples collected by MWRA staff on August 2 off Nahant from “blood red water” showed about 4.5 million cells L⁻¹ of *Myrionecta rubra*, a phototrophic aloricate ciliate. The June AMP survey documented elevated *M. rubra*, with station mean abundances up to 3,300 cells L⁻¹ (Appendix C slide 18), about twice that of the long-term mean level for the bay and the highest abundances observed to date in the harbor and northern offshore stations.

Elevated cryptomonad and *M. rubra* are not a concern for human health or seafood safety. However, these species form part of a complex biological interaction that involves potentially toxic dinoflagellates. *M. rubra* is an obligate phototroph that ‘steals’ plastids (aka kleptoplasty) from its cryptomonad prey (Johnson *et al.* 2007). The kleptoplasty does not end there. *Dinophysis* spp. (dinoflagellates), including potentially toxic species are also kleptoplastic, containing cryptomonad plastids. However, *Dinophysis* do not take plastids directly from the cryptomonads; instead relying on *Myrionecta* as an intermediary, and harvest the cryptomonad plastids from *M. rubra* (Wisecaver and Hackett 2010). The first two components of this serial kleptoplastic sequence, elevated cryptomonad and *M. rubra* abundance, were observed in summer 2011. However the third and potentially harmful component of this sequence, an increase in abundance of toxic *Dinophysis fortii*, was not observed.

By August, the chlorophyll and POC concentrations in the harbor and coastal waters had decreased from the July peaks, but remained elevated compared to offshore waters due to a near-shore increase in *Skeletonema* (Figures 2-4, 2-7, & 2-8 and Appendix C slide 11). The summer dinoflagellate flora, dominated by large *Ceratium* spp., were relatively sparse, continuing a post-2000 pattern of reduced *Ceratium* abundance. While nutrient levels were low during the mid-August survey, they may have increased in late August due to the heavy precipitation, upwelling, and river discharge from Hurricane Irene (Figure 2-1 and Appendix A slide 13) fueling the increased phytoplankton abundances observed in September. There was a substantial drop in sea surface temperatures (~3 °C) from August 26 to September 2, 2011 (Appendix B slide 4) and an increase in chlorophyll fluorescence (Figure 2-5). By mid-September, surface water nutrients were low in the bay, though there was an increase in surface water concentrations in Boston Harbor (Appendix B slide 5). The satellite imagery and observed increase in *Skeletonema* abundance throughout Massachusetts Bay in September suggest that the hurricane may have provided the nutrients to the surface waters to fuel this bloom. Oddly, by the September 13 survey, not only were surface nutrients low, but there was no clear increase in chlorophyll. However, there was a clear increase in POC and phytoplankton abundance by September 13 (Figures 2-7 & 2-8). The MODIS imagery suggests that this *Skeletonema* bloom may have reached peak chlorophyll levels in early September (Figure 2-5).

By October, the last survey of 2011, surface water nutrient concentrations had increased at near shore stations, although nitrogen levels remained depleted at the more offshore stations in Massachusetts Bay (Figure 2-2 and Appendix B slides 5, 6, and 12). This was connected with elevated chlorophyll levels and, for the second year in a row, an increase in large dinoflagellates. The October dinoflagellate increase was largely due to *Prorocentrum micans*, especially in the northern offshore and nearfield stations (Appendix C slide 14). The MWRA survey results are consistent with dense *Prorocentrum* populations found off of Portsmouth, NH in October 2011 during a NOAA rapid response survey (D. Anderson pers. com.). This survey was conducted by WHOI researchers in response to reports of dead seals and shore birds and the possibility that it might be related to observed “red water” containing high *Prorocentrum* concentrations. The investigation did not implicate *Prorocentrum* or other toxic species in the seal mortality event, but did show that the bloom was a widespread, regional event.

The late autumn increase in *P. micans* has been observed for the past two years. A late autumn annual peak in microflagellate abundance was also observed in October 2011 (and 2010) at nearfield and northern stations. The increases in dinoflagellates and microflagellates may be related to warmer water temperature late in the season (Appendix A slide 10) and a delay in seasonal water column de-stratification.

The annual minima in dissolved oxygen (DO) were observed, as is typical, throughout the survey area during October. Bottom water DO concentrations generally declined from March/April to October (**Figure 2-10**). The bottom water minima were moderate compared to past years with nearfield mean and Stellwagen Basin station F22 minima of 6.78 and 7.21 mg L⁻¹, respectively. A slight increase at the harbor and coastal station bottom water DO was measured from August to September and is likely due to upwelling and shallow water mixing associated with Hurricane Irene, but the lowest DO for 2011 was observed at Boston Harbor station F23 (6.30 mg L⁻¹) in October.

Time series data from NERACOOS Buoy A showed bottom water DO levels continuing to decrease into late October dipping below 6 mg/l (**Figure 2-11**). The lack of major fall storms until late October likely delayed destratification of the water column and recovery of bottom water DO concentrations. A regression between temperature and DO (Appendix A slide 22) also demonstrates that temperature is the dominant factor resulting in low DO, although it is not the only factor, and it is consistent with past annual calculations. Another potential factor is the persistence of onshore currents (Appendix A slide 23), which appear to cause DO to drop as well. The summer and fall of 2011 had unusually strong and persistent onshore flow, which may partially explain the low DO in the fall of 2011.

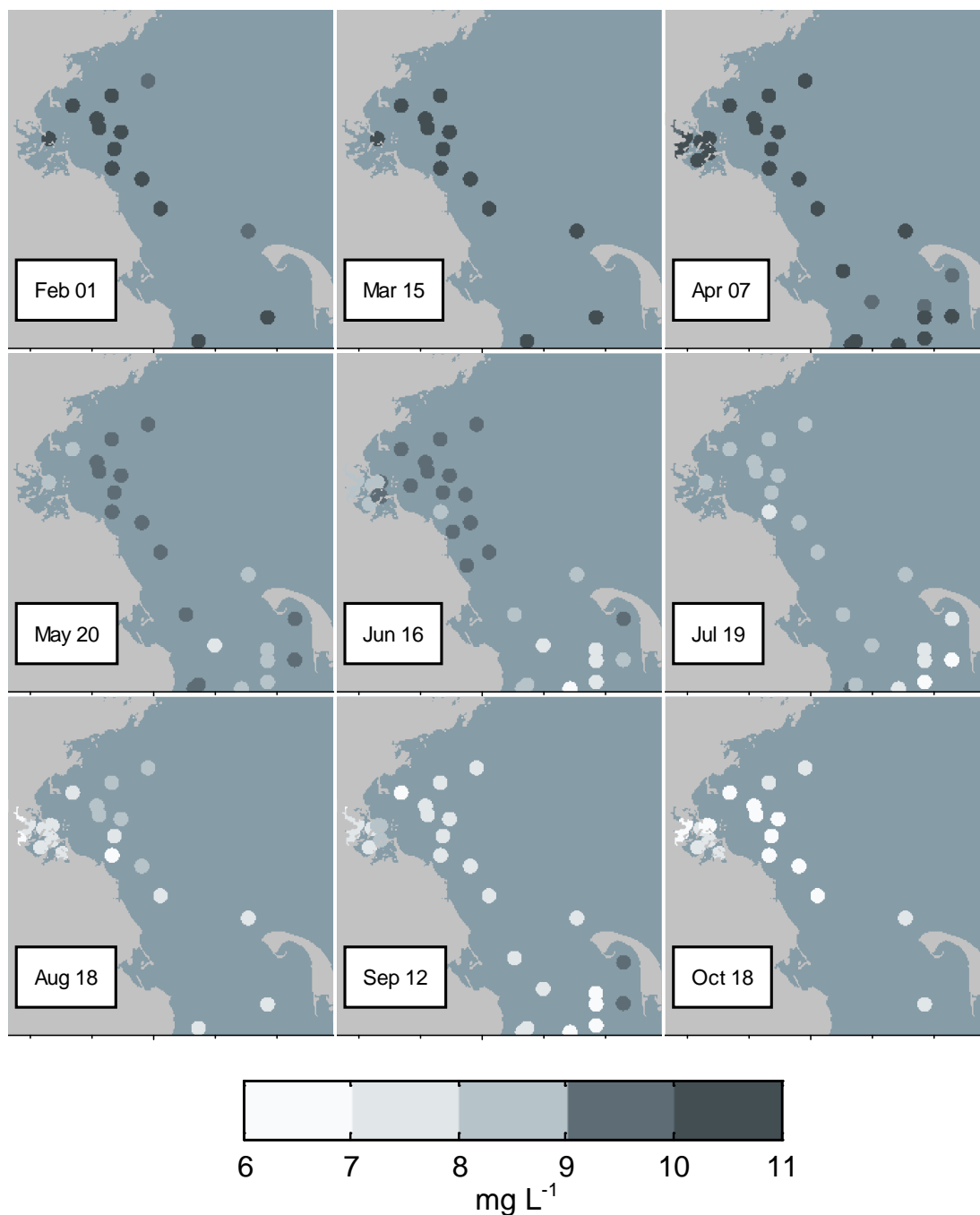


Figure 2-10. Bottom water dissolved oxygen (DO) concentration (mg L⁻¹) at stations in Massachusetts and Cape Cod Bays in 2011.

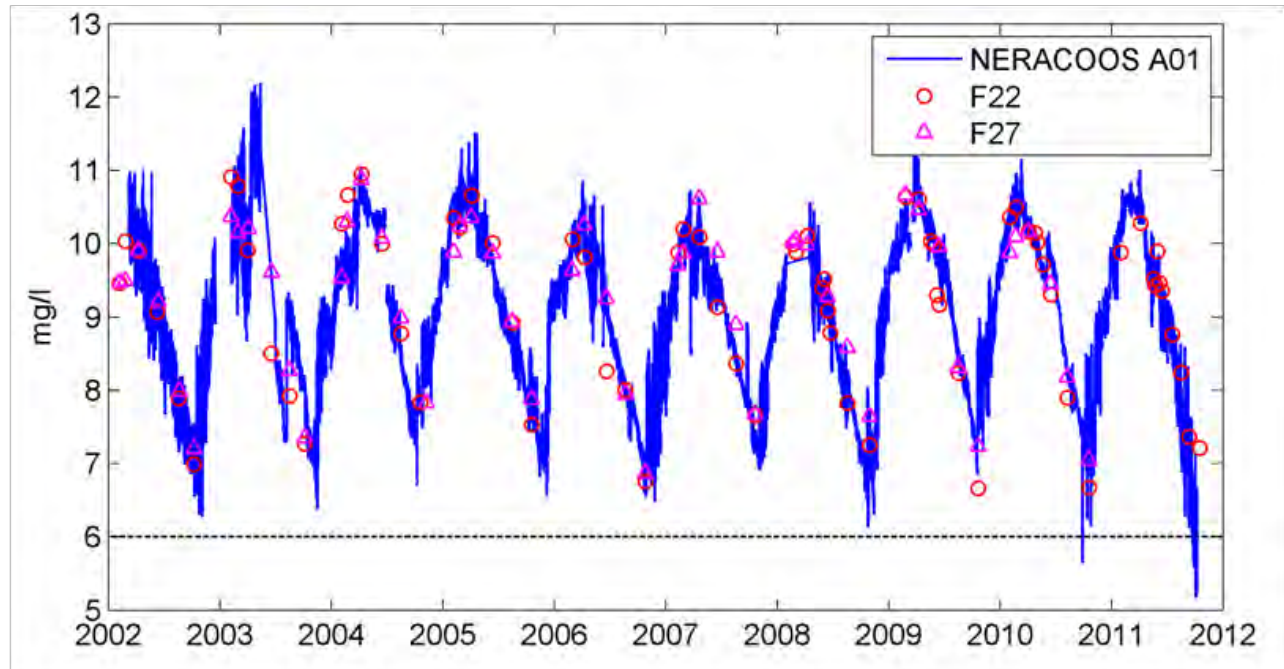


Figure 2-11. Bottom water DO concentrations (mg L^{-1}) at NERACOOS Buoy A01 and nearby MWRA stations F22 and F27. Note that station F27 was dropped from the monitoring program in 2011.

The year 2011 was a typical for zooplankton community composition and seasonal patterns. Total zooplankton were dominated by copepod nauplii and *Oithona similis* copepodites and adults and the dominant zooplankton species varied by season. Total zooplankton abundance increased from the winter through the spring to peak in the summer, and declined in late summer with an interesting September peak in the fall (**Figure 2-12**). There was more temporal than spatial variability in total zooplankton abundance.

Calanus finmarchicus and barnacle nauplii tended to peak earlier in the spring, with *Calanus* abundances peaking at $>15,000$ individuals m^{-3} in April and comprising over 20% of total zooplankton at station N07 (Appendix D slide 5). *Acartia* peaked in May with 21,000 individuals m^{-3} at Boston Harbor station F23 and similarly high counts at other inshore and nearfield stations (Appendix D slide 6). High *Acartia* abundances in the nearfield area in May are unusual (see **Figure 2-21**) and may have been due to the large influx of fresher waters observed in May 2011 (Appendix A slides 15 and 16). Unlike total zooplankton, which seemed to vary more temporally than spatially, *C. finmarchicus* was most abundant offshore and *Acartia* spp. was most abundant inshore. Total zooplankton abundance and its primary constituents copepods (adults + copepodites), copepod nauplii and *O. similis* all had similar seasonal increases through winter and spring into summer with declines in August, but then peaked again in September perhaps in response to the increase in phytoplankton following Hurricane Irene (**Figure 2-12** and Appendix D slide 7). Overall, 2011 zooplankton levels were near the long-term mean levels for most zooplankton groups in most regions.

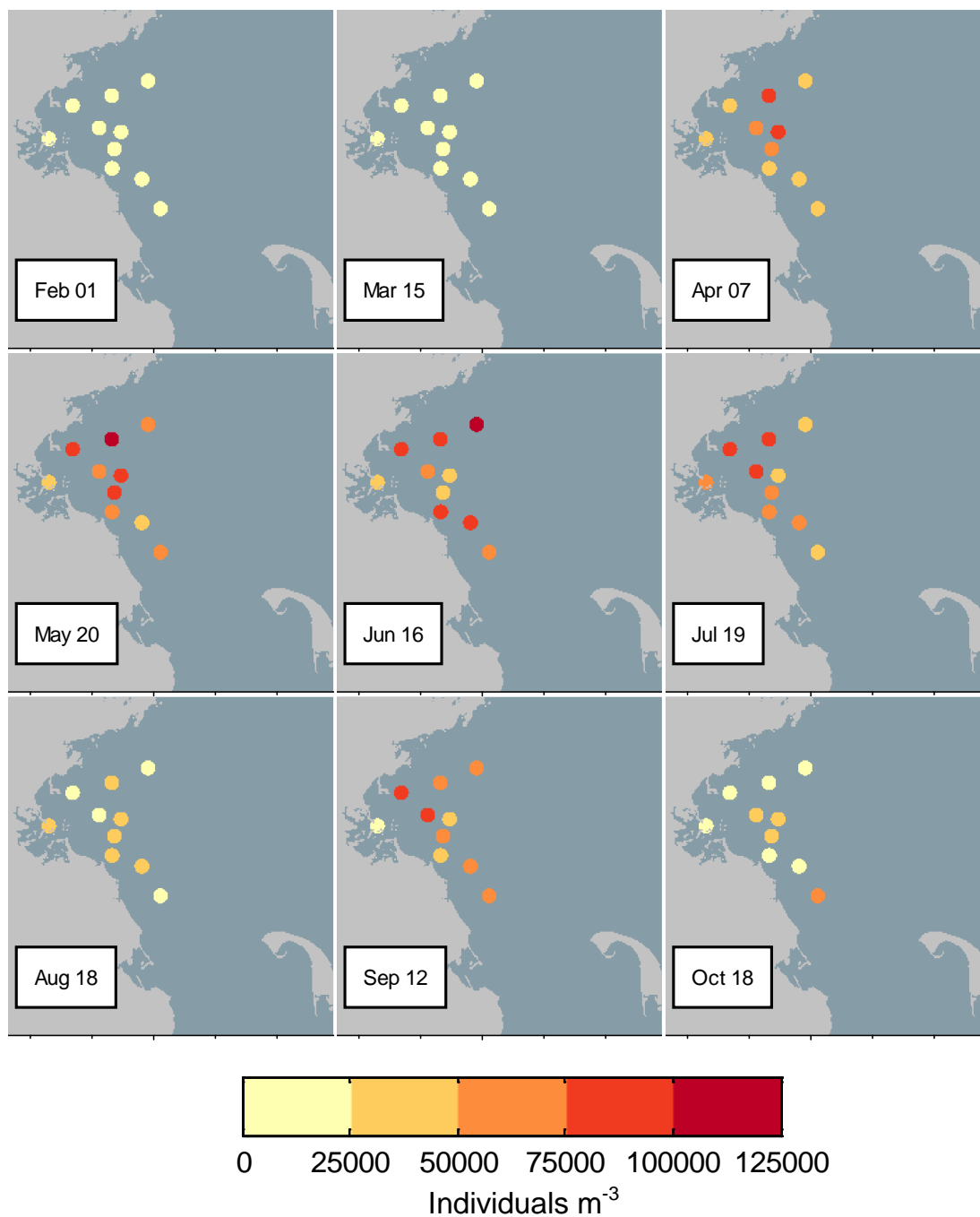


Figure 2-12. Total zooplankton abundance (individuals m⁻³) at each station in Massachusetts Bay during 2011.

2.2 CONTINGENCY PLAN THRESHOLDS FOR 2011

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 thresholds have been recalculated based on the monitoring design in the revised AMP.

Table 2-1. Contingency plan threshold values for water column monitoring in 2011. The highest nearfield value is shown for the *Alexandrium* exceedance.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2011
Bottom Water DO concentration (mg L ⁻¹)	Survey Mean June-October	<6.5 (unless background lower)	<6.0 (unless background lower)	Nearfield: 6.05 SW Basin: 6.23	Nearfield min: 6.78 SW Basin min: 7.21
Bottom Water DO percent saturation (%)	Survey Mean June-October	<80% (unless background lower)	<75% (unless background lower)	Nearfield: 65.3% SW Basin: 67.2%	Nearfield min: 74.4% SW Basin min: 76.5%
Bottom Water DO rate of decline (Nearfield, mg L ⁻¹ d ⁻¹)	Seasonal June-October	0.037	0.049	0.024	0.021
Chlorophyll (Nearfield mean, mg m ⁻²)	Annual	108	144	72	49
	Winter/spring	199	--	50	44
	Summer	89	--	51	48
	Autumn	239	--	90	56
<i>Phaeocystis pouchetii</i> (Nearfield mean, cells L ⁻¹)	Winter/spring	2,860,000	--	622,000	338,000
	Summer	357	--	79	Absent
	Autumn	2,960	--	370	Absent
<i>Pseudo-nitzschia pungens</i> (Nearfield mean, cells L ⁻¹)	Winter/spring	17,900	--	6,735	Absent
	Summer	43,100	--	14,635	660
	Autumn	27,500	--	10,500	1,240
<i>Alexandrium fundyense</i> (Nearfield, cells L ⁻¹)	Any nearfield sample	100	--	Baseline Max 163	2,453

The DO values compared against thresholds are calculated based on the survey means of bottom water values for surveys conducted through October. The nearfield bottom water mean is an average of the five nearfield stations: N01, N04, N07, N18, and N21. The Stellwagen Basin DO value is from station F22. The seasonal rate of nearfield bottom water DO decline is calculated from June to October. The chlorophyll values are calculated as nearfield 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. multiseriis*; 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} . The only water column threshold exceedance in 2011 was for *A. fundyense*, which has consistently been present in the bay in May/June since the extraordinary bloom of 2005.

Bottom water DO concentrations in 2011 were consistent with past trends: highest in winter, decreasing over the summer stratified period, and reaching the annual minimum in October. The bay outfall has not caused a detectable change in the pattern or rate of DO decline in the nearfield or Stellwagen Basin (**Figure 2-13**). Although DO was still relatively low in October of 2011 this has been observed previously. Overall, the DO minima in 2011 were only moderately low and well within the range of levels observed from 1992-2010 and well above the state minimum DO standard. Bottom water DO levels in the bays are primarily driven by regional physical oceanographic processes and have been unaffected by the outfall (Geyer *et al.* 2002).

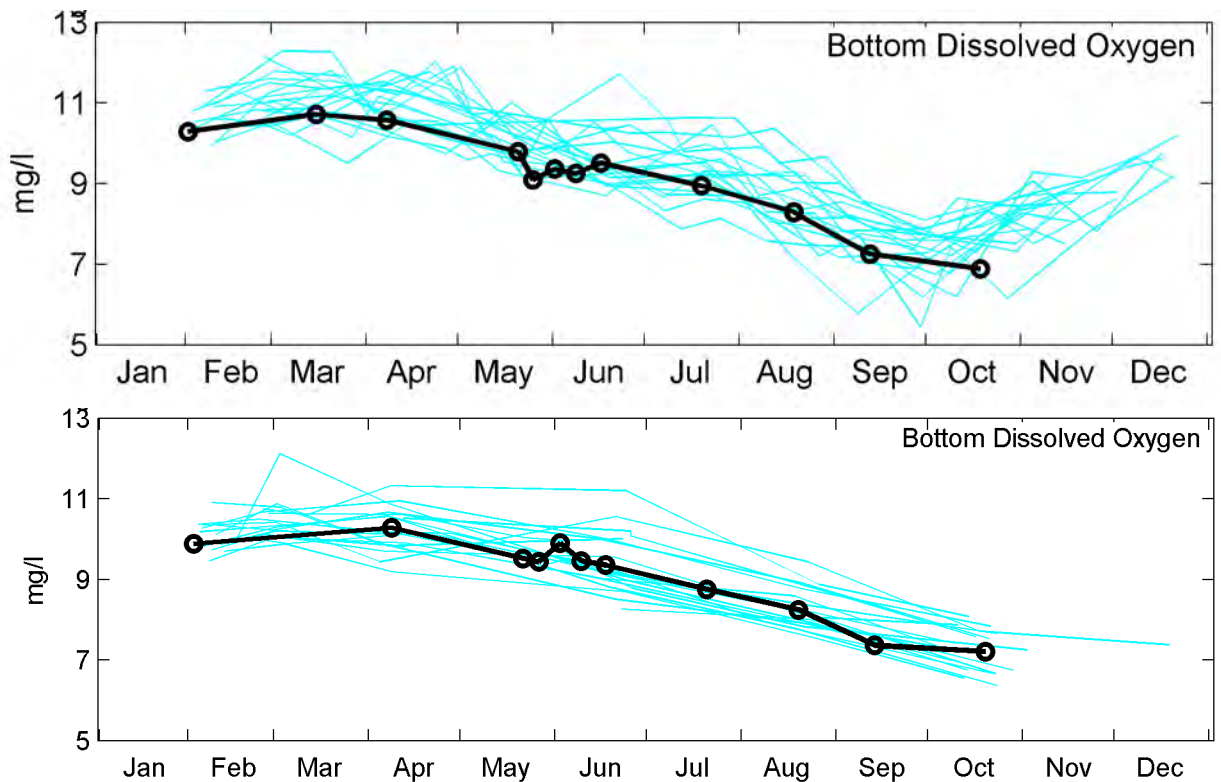


Figure 2-13. Time-series of bottom water DO concentration ($mg L^{-1}$) in the nearfield (station N18; top) and Stellwagen Basin (station F22; bottom) for 2011 (black) compared to the previous 19 years of observations (1992-2010; light blue).

The seasonal and annual nearfield mean areal chlorophyll levels for 2011 were comparable to background levels and well below Contingency Plan threshold values (**Table 2-1**). The moderate *Phaeocystis* bloom and various diatom and dinoflagellate blooms over the summer and fall did not lead to elevated chlorophyll concentrations and the seasonal and annual means were 25 to 50% of the threshold values. The relatively low chlorophyll values for 2011 are evident when directly compared to those observed in the past at nearfield station N18 (**Figure 2-14**). The winter/spring and fall chlorophyll peaks in 2011 are well below those observed during major blooms of past years.

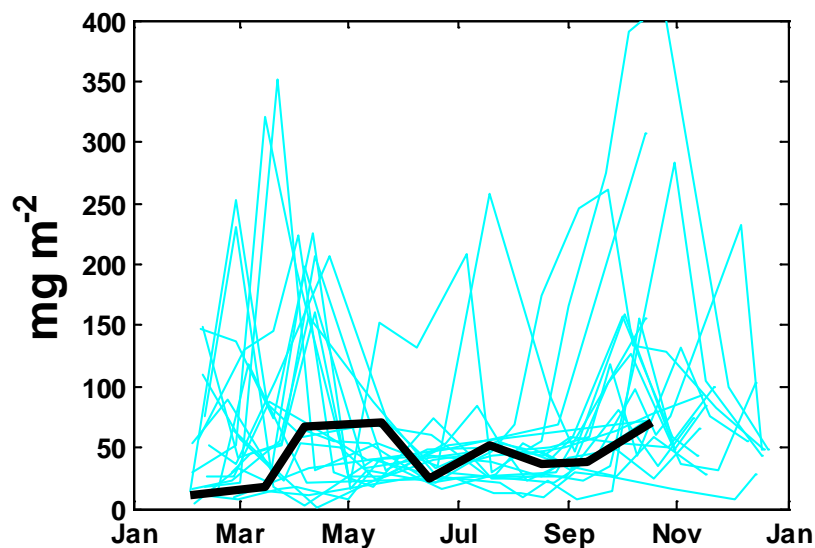


Figure 2-14. Areal chlorophyll (mg m^{-2}) near the outfall site (nearfield station N18) for 2011 (black line) compared to the previous 19 years of observations (1992-2010; light blue).

Phaeocystis abundance was moderate in 2011 relative to the prior years, peaking in late April in Massachusetts Bay, with 1.4 and 2.8 million cells L^{-1} in the surface and mid-depth samples respectively, at station N18; abundances at the other nearfield stations ranged from 0.3 to 0.93 million cells L^{-1} . MODIS imagery suggests that the bloom didn't begin until mid-March and seemed to be declining by the time of the April survey (**Figure 2-5**). February and March *Phaeocystis* abundances were low, with a nearfield winter/spring mean abundance of 338,000 cells L^{-1} , (**Figure 2-15**), about half the baseline.

Pseudo-nitzschia counts were elevated in April 2011, with 130,000 cells L^{-1} maximum in the surface water at station N18. However the cells were *Pseudo-nitzschia delicatissima*, a non-toxic species that is not counted in the *Pseudo-nitzschia* spp. threshold grouping. The potentially toxic forms of *Pseudo-nitzschia* spp. continued the trend since 2000 of very low abundances, and were well below the Contingency Plan threshold and levels that would cause amnesic shellfish poisoning.

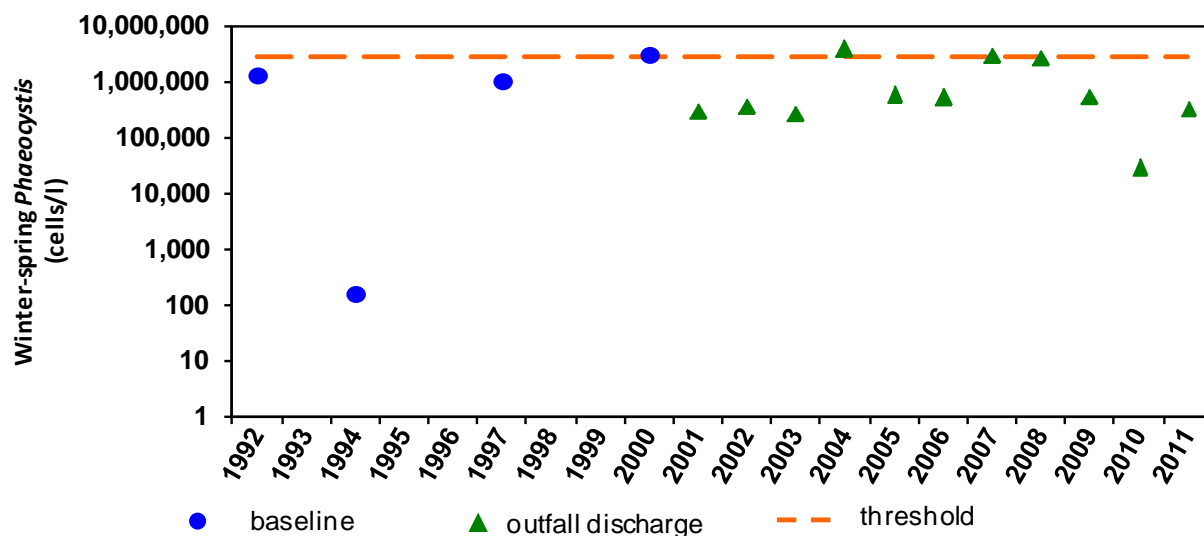


Figure 2-15. Winter/spring seasonal mean nearfield *Phaeocystis* abundance (cells L⁻¹; note log axis) for 1992 to 2011. Contingency Plan threshold value shown as dashed line.

The dinoflagellate abundance peak in May included a moderate bloom of *Alexandrium fundyense*. *Alexandrium* were present at very low numbers (<25 cells L⁻¹) in the nearfield in April 2011 (**Figure 2-16**). Massachusetts Division of Marine Fisheries shellfish toxicity testing showed low levels of PSP toxicity at their Gloucester station on May 3 and levels remained low for the following week before increasing in Gloucester and spreading to other north shore stations on May 17 (emails from MA DMF). Woods Hole Oceanographic Institution scientists estimated *Alexandrium* abundance about 100 cells L⁻¹ using a novel *in situ* sensor moored off of Portsmouth, NH (Environmental Sample Processor (ESP); B. Keafer pers. com.). On May 19, MA DMF closed the north shore to shellfishing due to PSP toxin levels. On May 20, *Alexandrium* abundances were elevated across most of the survey area, with a maximum of 2,453 cells L⁻¹, at station N07 (**Figure 2-16** and **Figure 2-17**). The 100 cells L⁻¹ Contingency Plan threshold was exceeded, triggering MWRA's *Alexandrium* rapid response study surveys (ARRS). Three weekly ARRS surveys were conducted from May 25 to June 8. *Alexandrium* abundances were elevated in the nearfield during each of these surveys, but did not increase after May 20. The peak abundance seen in 2011, 2,931 cells L⁻¹, was at station AF2 off Marshfield at 10 m on May 25; the bloom was over by the June 16 survey when only a few *Alexandrium* cells observed (**Figure 2-16**). In 2011 the moderate red tide in Massachusetts Bay caused closed shellfish beds due to PSP toxicity from Duxbury to Cape Ann (Appendix B slide 26).

In contrast to prior years of high *Alexandrium* abundance (e.g. 2005) when onshore winds drove the offshore *Alexandrium* bloom into Massachusetts Bay (Anderson *et al.* 2007), the 2001 bloom was moderate and relatively short-lived perhaps limited by the strong upwelling event in late May/early June (Appendix A slide 11). For example, two major northeaster storms conducive to transporting *Alexandrium* cells into Massachusetts Bay passed through the area prior to the May 20 survey. The timing of these storms and the rapid increase in both *Alexandrium* abundance and subsequent PSP toxicity in the bay suggests that the winds and associated downwelling was yet again responsible for the transport of upstream, established blooms into the area in May 2011. However, the winds became upwelling favorable (Appendix A slide 11) after May 20, and this is clearly seen in both temperature and stratification in the nearfield (Appendix A slide 10 and **Figure 2-18**, respectively). This is the condition that Csanady (1977) refers to as "full upwelling," in which the near-bottom water gets all the way to the surface, weakening or eliminating stratification in the near-shore region (inshore of the upwelling front). This unusually strong upwelling event likely pushed the surface water and the inshore *Alexandrium* bloom offshore. Furthermore, upwelling generally diverts

“upstream” populations along the NH coast to a more offshore trajectory and prevents them from being transported into the bay. Thus, the wind event may have mitigated the potential for a larger bloom from occurring in Massachusetts Bay in May/June 2011.

The WHOI researchers predicted a moderate *Alexandrium* bloom for Massachusetts Bay in 2011, based on moderate cyst abundances in coastal sediments in the fall of 2010,⁴ which were lower than those measured prior to the major red tides events of 2005 and 2008. The 2011 bloom was in fact moderate, lower than 2005 and 2008 and similar to 2006 (**Figure 2-17**). Near real-time model predictions (Ruoying He, North Carolina State University) generally agreed with MWRA field observations for the 2011 *Alexandrium* bloom (Appendix B slide 29). The model captured the initiation of the bloom, timing of peak abundances and their relative magnitude, and the ending of the bloom.

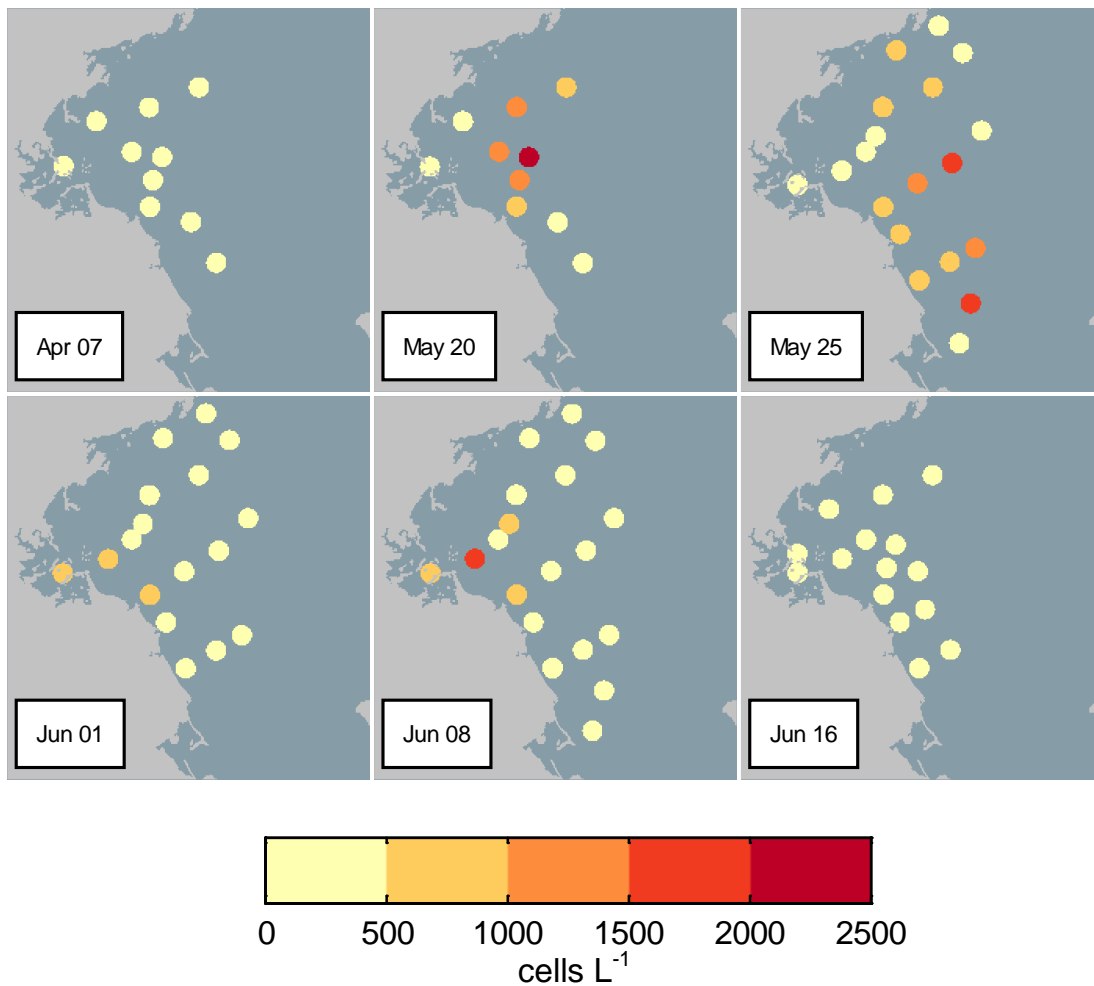


Figure 2-16. Surface *Alexandrium* abundance (cells L⁻¹); for individual samples during the April to June 2011 surveys.

⁴ See <http://www.whoi.edu/page.do?pid=83338&tid=3622&cid=96609&c=2> for article

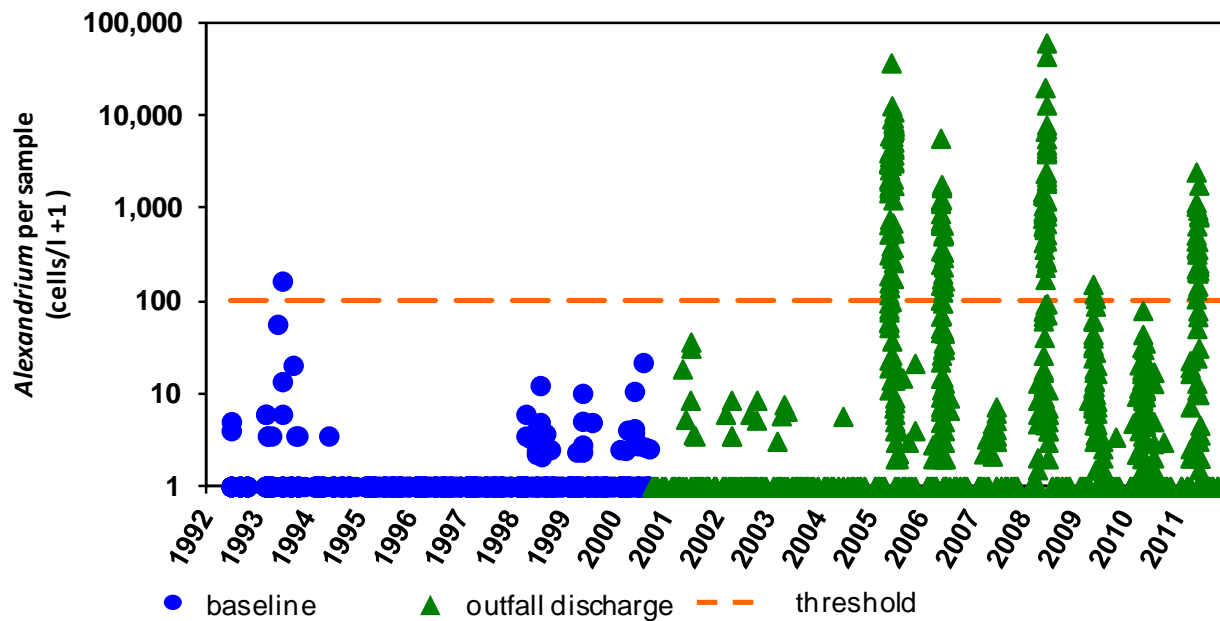


Figure 2-17. Nearfield *Alexandrium* abundance for individual samples (cells L⁻¹; note log axis). Contingency Plan threshold value shown as dashed line.

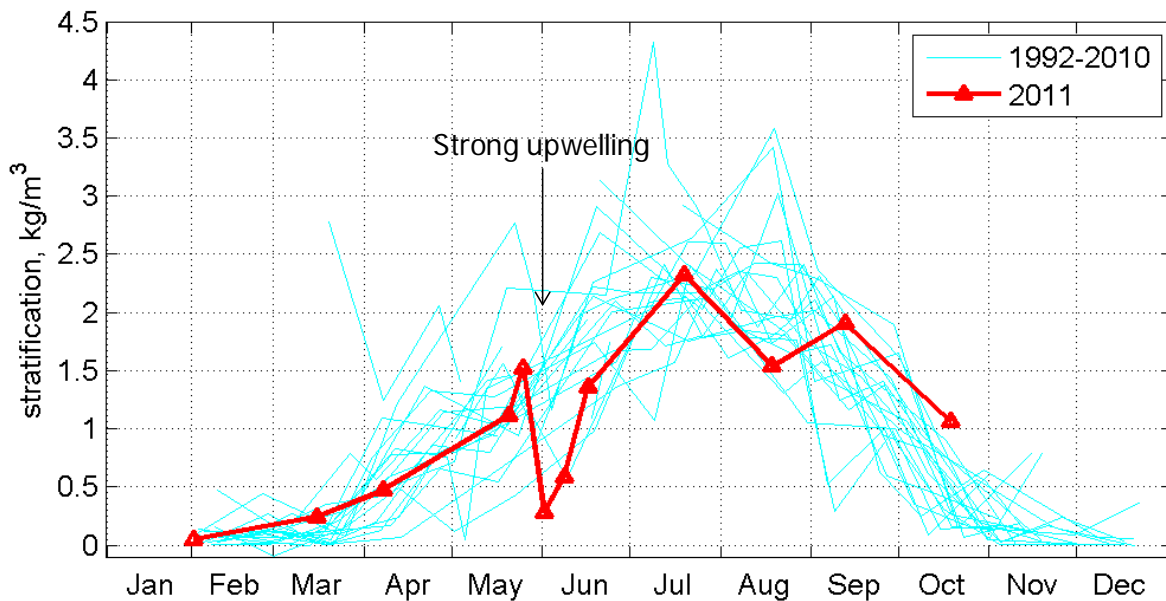


Figure 2-18. Stratification near the outfall site (nearfield station N18) for 2011 (red line) compared to the previous 19 years of observations (1992-2010; light blue).

2.3 HISTORICAL COMPARISONS

The 2011 data were consistent with the general trends and patterns observed during both the baseline (1992-2000) and outfall discharge (2001-present) time periods. Trends in nutrients at station N18, just south of the outfall, are similar for NO_3 and SiO_4 since 1992 and for NH_4 and PO_4 since September 2000, when the outfall came on-line and elevated concentrations of these latter nutrients became noticeable in the nearfield (**Figure 2-19**). High survey-to-survey variability is especially evident in the SiO_4 concentrations over time. This nutrient in 2011 was greatly affected by freshwater inputs (May 2011) or major species-specific blooms (decrease with diatoms and only minor changes with *Phaeocystis* relative to decreases in NO_3 during both blooms). Elevated NH_4 concentrations associated with the effluent plume surfacing in the winter months (February and March 2011) and being confined below the pycnocline under stratified summer conditions (June through August 2011) were again clearly evident in 2011 (Appendix B slide 5). An increase in summer PO_4 concentrations was also observed in 2011, associated with elevated PO_4 in the effluent.

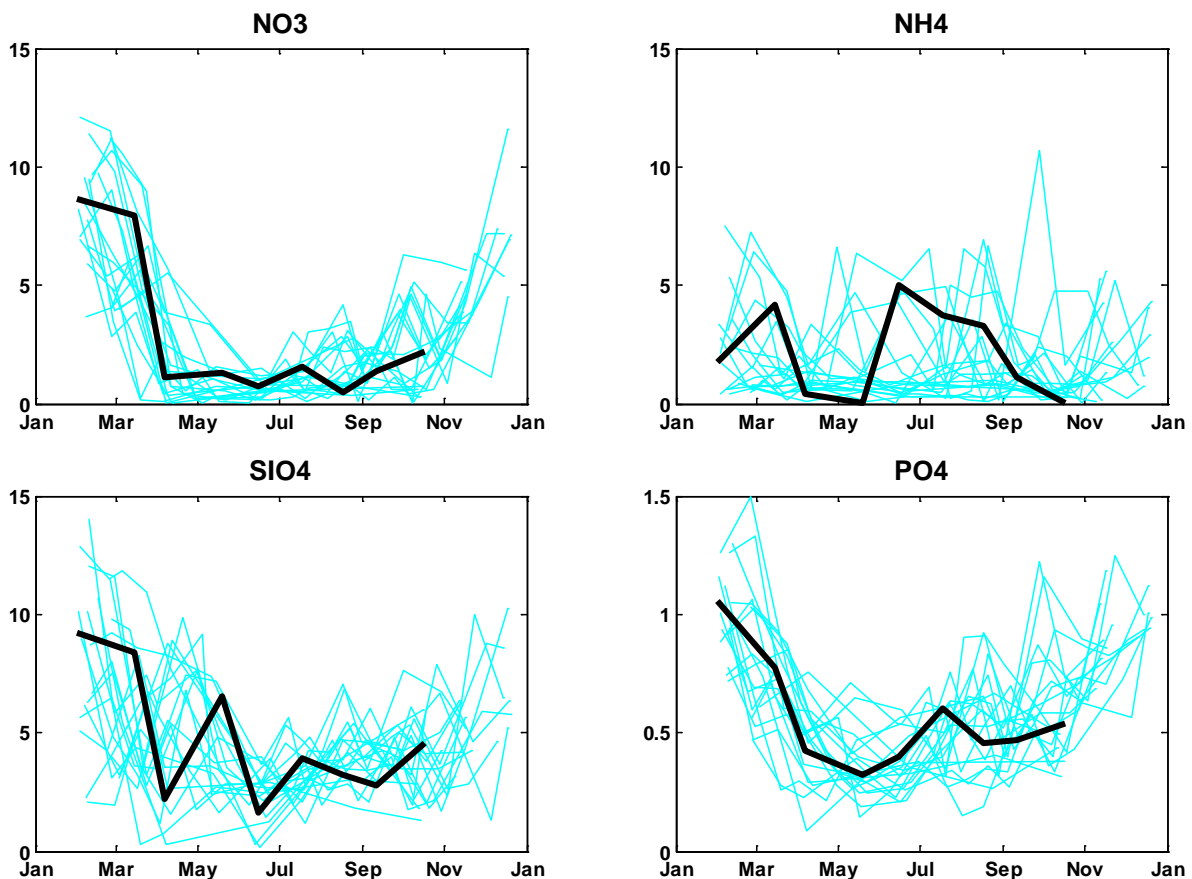


Figure 2-19. Station average nutrient concentrations (μM) near the outfall site (nearfield station N18) for 2011 (black line) compared to the previous 19 years of observations (1992-2010; light blue). Note change in scale for PO_4 plot.

Although increases in NH_4 and PO_4 associated with the effluent plume have been observed in the nearfield, no related changes or increases in phytoplankton biomass in this region have been observed. Biomass (as measured by chlorophyll and POC) and total nitrogen in 2011 vs. historic values shows the levels were low relative to prior years at both nearfield station N18 (**Figure 2-20**) and across the range of stations sampled under the revised monitoring plan (Appendix B slides 21 and 22). Although the trend of elevated NH_4 is represented in the 2011 total nitrogen plot for nearfield station N18, the total nitrogen values were quite low compared to historic values (**Figure 2-20**, Appendix B slide 23).

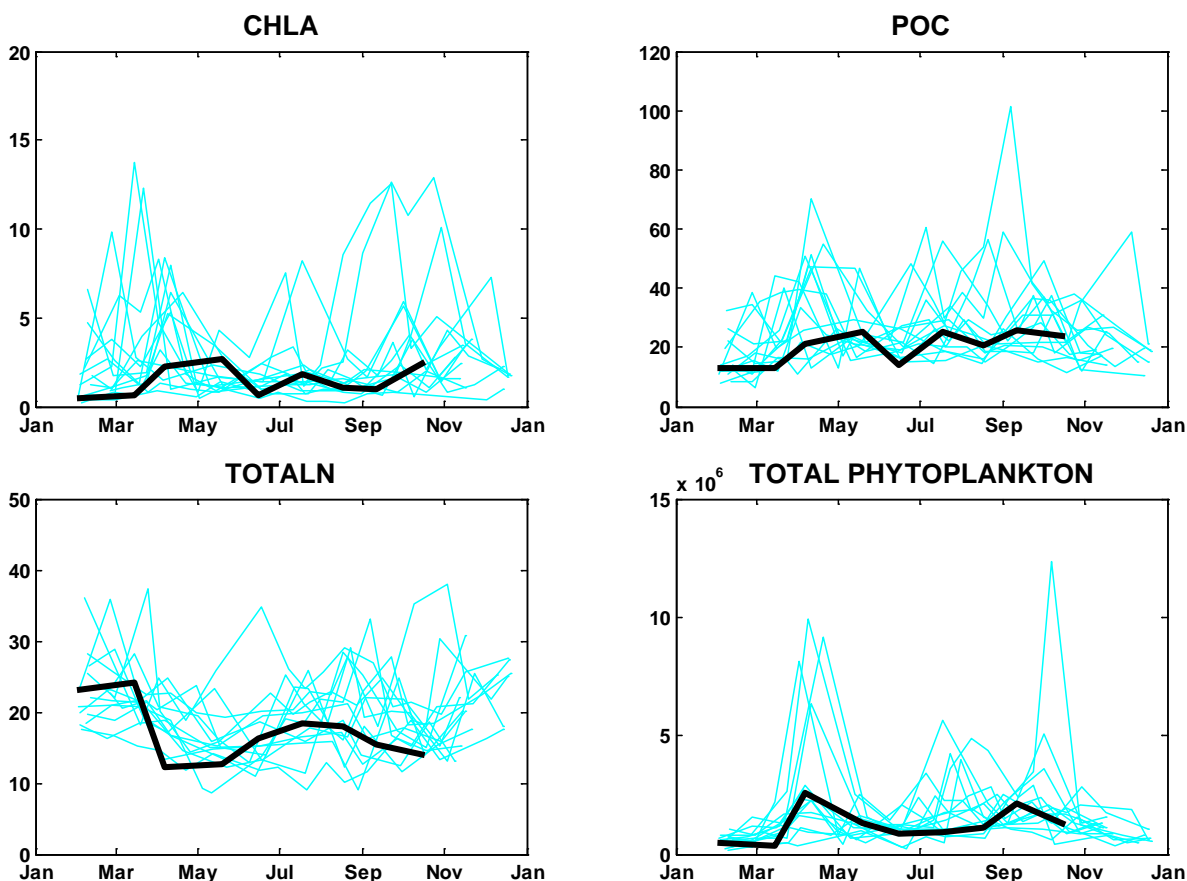


Figure 2-20. Station average chlorophyll ($\mu\text{g L}^{-1}$), POC (μM), total nitrogen (μM), and total phytoplankton (million cells L^{-1}) near the outfall site (nearfield station N18) for 2011 (black line) compared to the previous 19 years of observations (1992-2010; light blue).

Total phytoplankton as well as the various phytoplankton groups and species measured in 2011 were present at relatively low to moderate abundances. Similarly, bloom peaks were well below those observed during previous monitoring years (**Figure 2-20**). Comparison of the main phytoplankton groups' abundances measured in 2011 to the long-term (1992-2010) levels using a Mann-Whitney test demonstrated a decline in total phytoplankton abundance in 2011 (mean of 1.04×10^6 cells L^{-1}) relative to levels observed in the previous 19 years of monitoring (mean of 1.55×10^6 cells L^{-1} ; $p = 0.0001$; **Table 2-2**). This can largely be related to declines in microflagellates which had a mean 2011 level of 500,000 cells L^{-1} compared to a 1992-2010 mean level of 720,000 cells L^{-1} . *Phaeocystis* abundance in 2011 was also reduced relative to the long-term annual mean level. While there was a reduced winter-spring diatom bloom in 2011, elevated summer 2011 centric diatom abundance compensated for this winter-spring decline such that total 2011 centric diatom abundance was not significantly different than long-term mean levels. The abundance of

Skeletonema spp. was high in 2011 with mean abundance (158,000 cells L⁻¹) that was approximately three-time the long-term mean level of about 50,000 cells L⁻¹. The summer character of the 2011 phytoplankton cycle is further illustrated by the increase in the phototrophic ciliate *Myrionecta rubra*, which had a 2011 abundance that was about double the long-term mean level (Table 2-2).

Table 2-2. Comparison of 2011 phytoplankton abundance (cells L⁻¹) to long-term observations for major GROUPS and species. Differences between values were assessed using the Mann-Whitney non-parametric statistical hypothesis test – p values of ≤0.05 are significant.

Group	1992-2010	2011	p value	Change?
CENTRIC DIATOM	319,159	268,936	0.3217	
<i>Chaetoceros</i>	50,268	8,929	0.0005	decline
<i>Dactyliosolen fragilissimus</i>	49,381	45,710	0.8596	
<i>Skeletonema costatum</i> species complex	52,018	157,612	0.0001	increase
<i>Thalassiosira</i>	41,346	10,129	0.0627	
PENNATE DIATOM	51,430	23,109	0.1411	
<i>Pseudonitzschia</i>	11,098	8,732	0.5731	
DINOFLAGELLATES	55,051	46,118	0.0883	
<i>Ceratium</i>	1,584	554	0.0826	
CRYPTOPHYTES	128,363	100,859	0.0031	decline
MICROFLAGELLATES	718,960	504,200	0.0001	decline
<i>Myrionecta rubra</i>	81	193	0.0104	increase
<i>Phaeocystis pouchetii</i>	267,697	87,082	0.0453	decline
TOTAL				
PHYTOPLANKTON	1,554,006	1,037,788	0.0001	decline

Shifts within the phytoplankton community assemblage associated with long-term, regional trends have been noted previously (Hunt *et al.* 2010). Diatom and *Phaeocystis* abundance fluctuate inversely over multiple years. In 1992-2003, dinoflagellates went through periods of decreasing and increasing abundance sometimes dominated by rarer, but larger species (e.g. *Ceratium* spp.) and sometimes by more plentiful, smaller species (e.g. *Heterocapsa rotundatum*, *H. 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 2011 zooplankton abundance and community structure were generally comparable to historical patterns for harbor and coastal stations, but were above historical levels in spring for the nearfield and offshore stations, especially for April-June at station F22 (Appendix D slide 10). Total zooplankton abundance in 2011 was higher than most long-term (1992-2010) levels at nearfield station N18 in the spring (April-June), primarily due to higher abundances of copepods (total adults + copepodites) (Figure 2-21). *Calanus finmarchicus* peaked in April and *Acartia* in May at levels nearly double long-term numbers for those months, and contributed about 20% of total zooplankton abundance during those surveys (Figure 2-21). *Oithona* was also elevated in May. A second peak in zooplankton abundance in September was apparently spurred by increases in nutrient loadings caused by Hurricane Irene. The levels of total zooplankton and copepods in September 2011 were close to the historical September maximum.

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.* 2009). Total zooplankton and copepod abundances have rebounded slightly over the last few years (Libby *et al.* 2011b) and continue to follow that trend in 2011 (Appendix D slide 11).

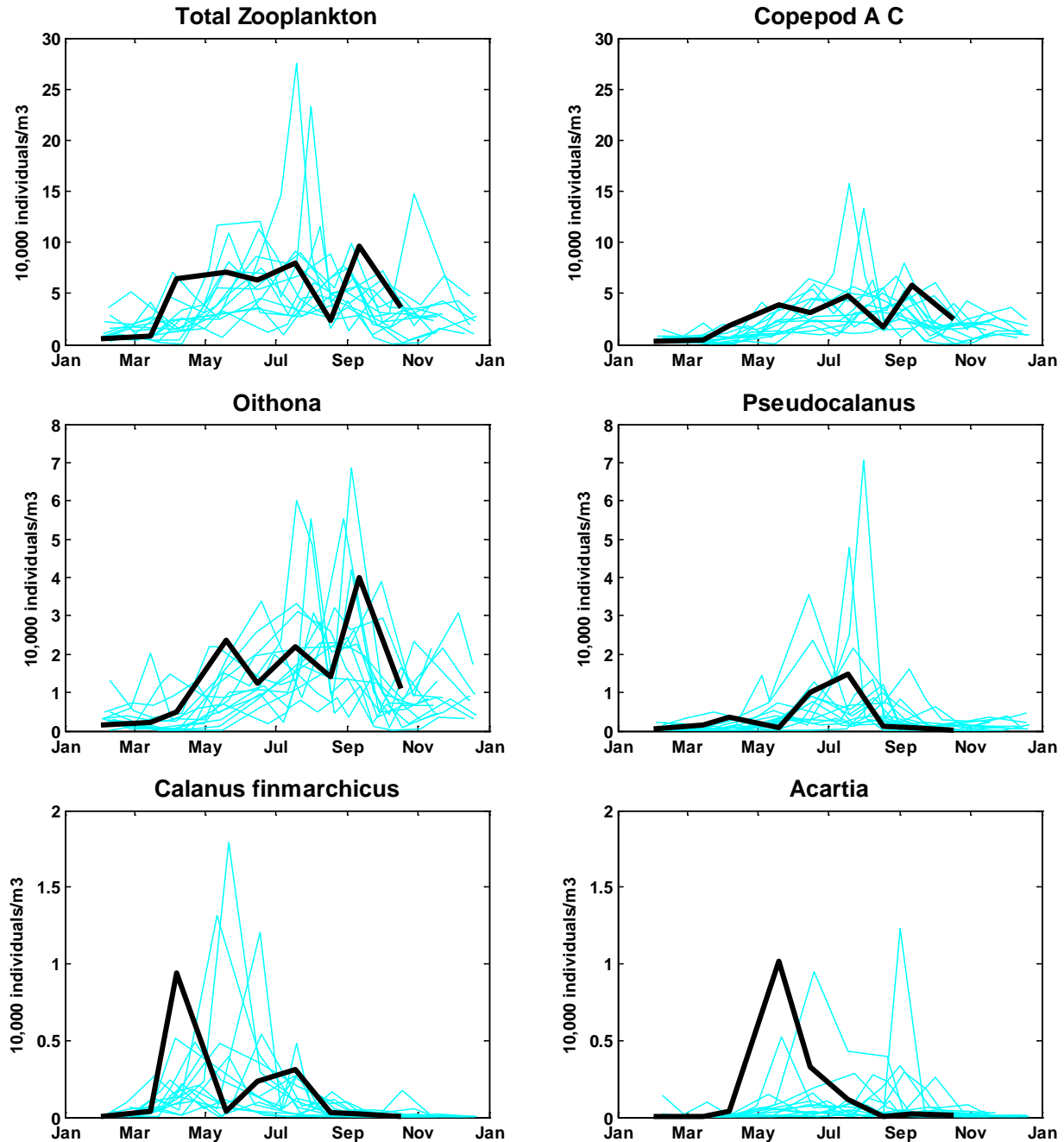


Figure 2-21. Abundance (10,000 individuals m⁻³) of total zooplankton, copepods, *Oithona*, *Pseudocalanus*, *Calanus finmarchicus*, and *Acartia* near the outfall site (station N18) for 2011 (black line) compared to the previous 19 years of observations (1992-2010; light blue). Note change in scale for each row of plots.

3 SUMMARY

2011 was the first year of sampling following MWRA's second revision of its effluent outfall ambient monitoring plan. Fourteen stations in Massachusetts and Cape Cod Bays were sampled nine times. The changes implemented in 2011 do not appear to have affected our ability to observe the typical seasonal trends seen for a wide variety of parameters nor appreciably decrease our capability to understand potential impacts to the Massachusetts Bay ecosystem. Differences in the timing of blooms and changes in conditions were apparent within and between the two bays. The revised monitoring plan delineated inshore to offshore gradients across Massachusetts Bay for temperature, salinity, DO, chlorophyll, and various nutrients. The phytoplankton blooms and zooplankton species showed clear inshore to offshore differences—even though the typical seasonal sequence of water quality events was also observed as it has been over the entire 1992-2011 monitoring program.

2011 was wet throughout, with river discharges well above the 50th percentile nearly all year, compared to 1992-2010. Although overall discharge was elevated, no single major discharge events were measured for the Merrimack and Charles Rivers. Two meteorological conditions mark 2011- strong northeaster storms in May and Hurricane Irene in late August. Each of these events impacted conditions in the bay. The May northeaster storms likely transported *Alexandrium* cells into Massachusetts Bay, beginning its red tide event. Then strongly downwelling NE winds changed to strongly upwelling SW winds in late May and early June, which likely mitigated the severity of the 2011 *Alexandrium* bloom as waters became fully mixed and pushed offshore. Hurricane Irene arrived in New England between the August and September surveys which occurred about 10 days before and after the hurricane. There were clear changes in water quality parameters between these surveys and satellite imagery shows large regional changes such as cooler surface waters and higher chlorophyll levels after this major event. Although the upper water column was not mixed into the deeper bottom waters from the storm-associated winds, the change in chlorophyll and the phytoplankton bloom of *Skeletonema* observed in September suggests a large influx of nutrients, likely from a combination of increased riverine runoff and near-surface mixing from below the pycnocline as a result of this storm. The relatively calm weather in September and October enabled the water column to remain stratified into late October as indicated by the NERACOOS A01 buoy DO data. The continuous record from this buoy shows that that bottom water DO continued to decline until a strong storm in late October.

Consistent with the past twenty years of monitoring, nutrient concentrations were at a maximum in February and March in Massachusetts Bay. Nutrients were about 50% lower in Cape Cod Bay, likely due to earlier blooms of diatoms and microflagellates in its shallow waters. A large decrease in dissolved inorganic nutrients in April was coupled with a modest *Phaeocystis* bloom in Massachusetts Bay, the 12th year in a row that *Phaeocystis* has bloomed there. The bloom did not exceed MWRA's Contingency Plan threshold. However, the May bloom of *Alexandrium fundyense* exceeded the 100 cell L⁻¹ threshold. The 2011 red tide peaked early and PSP toxicity shellfishing closures were in place by May 25 from Cape Ann to Duxbury Bay. Fortunately, meteorological conditions were not conducive for supporting a major, extended bloom in Massachusetts Bay and the event had ended by June 16.

The 2011 summer (June-August) nutrient levels remained depleted in the surface waters, and relatively low at depth. The centric diatom *Dactyliosolen fragilissimus* bloomed at shallower, inshore stations for the third year in a row. 'Purple water' was reported to MWRA by the US Coast Guard on August 1, 2011. In response MWRA samples collected off Nahant August 2 found that the coloration was due to the phototrophic aloricate ciliate *Myrionecta rubra*. Abundances of cryptomonads and *M. rubra* were elevated in Massachusetts Bay in June 2011 (2 to 3 times the long term means). While not a concern for human health or seafood safety, these organisms are part of a complex biological interaction that involves potentially toxic dinoflagellates--*Dinophysis* spp. *M. rubra* is an obligate phototroph that 'steals' plastids from a cryptomonad host (Johnson *et al.* 2007). *Dinophysis* in turn takes the cryptomonad plastids from *M. rubra* (Wisecaver and Hackett 2010). However, in the summer of 2011 an increase in abundance of toxic

Dinophysis spp. was not observed in Massachusetts Bay. Researchers at WHOI and others are studying this complex interaction and monitoring the occurrence of each component, especially *Dinophysis fortii*, in Massachusetts Bay.

The lack of strong storms in the fall led to prolonged stratification of the water column across most of Massachusetts Bay, likely promoting elevated abundances of the dinoflagellate *Prorocentrum micans* and microflagellates in October, and the continued decline of bottom water DO through October. DO minima during the last survey were well above the State water quality standard of 6 mg L⁻¹. NERACOOS Buoy A01 measurements showed bottom water DO dipping below 6 mg L⁻¹ in late October.

Observed changes in the nutrient regimes since the outfall went on-line remain consistent with model predictions (Signell *et al.* 1996, Libby *et al.* 2009). Ammonium dramatically decreased in Boston Harbor and nearby coastal waters and has remained low through 2011. The initial increase in nearfield annual mean NH₄ (~1 μM) was much smaller than the decrease in the harbor (~8 μM) due to dilution and transport at the bay outfall (Libby *et al.* 2011b). The increase in nitrogen loading to the nearfield area has been observed as NH₄ concentrations above background levels of 1-2 μM (up to >10 μM). The NH₄ signature of the effluent plume continues to be detected within 10-20 km of the outfall (see **Figure 2-6** and **Figure 2-9** for example). No significant changes in primary production, phytoplankton biomass, or secondary producers such as zooplankton have been detected (Libby *et al.* 2009). In contrast, significant decreases in other nutrients, chlorophyll, and POC, and an increase in bottom water dissolved oxygen are coincident with the dramatic decrease in NH₄ in Boston Harbor (Taylor 2006).

The phytoplankton community assemblage in the nearfield and most of Massachusetts Bay has varied over the twenty years of monitoring, reflecting large-scale regional trends in phytoplankton bloom dynamics. For example, diatom and *Phaeocystis* abundance fluctuated in an inverse pattern over multiple years. Dinoflagellate abundance has varied: some years fewer, larger species (e.g. *Ceratium* spp.) dominate, and some years there are more plentiful, smaller species (e.g. *Heterocapsa rotundatum*, *H. triquetra*, *Gymnodinium* spp., *Prorocentrum micans*).

The zooplankton community assemblage in the bays is consistently 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 also irregular pulses of various meroplankters such as bivalve and gastropod veligers, barnacle nauplii, and polychaete larvae (Libby *et al.* 2007). Seasonal patterns in zooplankton abundance from 1992-2011 generally correlate with temperature, low in winter, rising through spring to maximum in summer, declining in the fall. The most apparent change over the twenty-year monitoring period was the 2001-2006 decrease in zooplankton abundance, but overall abundance of zooplankton appears to be increasing throughout the bays. There is no plausible outfall-related link or causality associated with these shifts in phytoplankton or zooplankton as they occur over large spatial scales; such broad patterns appear instead to be related to regional ecosystem dynamics in the Gulf of Maine.

Nitrogen levels in Massachusetts Bay (including the nearfield) vary considerably over space and time and are governed by regional factors including different loadings to the system, changes in seasonal biological patterns, and circulation shifts related to larger-scale processes such as meteorological events. The observed increase in NH₄ concentrations in the nearfield, relative to the baseline, of about one micromolar was predicted by plume dilution models and hydrodynamically coupled water quality models. The increase in NH₄ has not caused any detectable adverse effects either near or distant from the relocated MWRA discharge. In contrast, the corresponding decrease in nutrient loading to Boston Harbor has resulted in significant improvements in water quality (Taylor 2006).

Finally, the monitoring plan design implemented in 2011 is able to adequately describe the seasonal and spatial trends observed for a wide variety of parameters, retaining our capability to understand potential outfall- driven impacts to the Massachusetts Bay ecosystem.

4 REFERENCES

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Appendices

Appendix A

Physical Characterization

Summary of Physical Processes Influencing Massachusetts Bay, 2011

Rocky Geyer, WHOI

Overview

The notable conditions in 2011 were 1) wetter than normal conditions through the year, although without major discharge peaks; 2) strong Northeaster storms in May, which advected in low salinity water; 3) persistent upwelling in late May and June, resulting in cold surface temperatures and weak stratification in early June, and 4) Hurricane Irene, which briefly caused mixing of the near-surface waters but no persistent influence.

Forcing variables

Air temperature (slide 3) followed the normal seasonal pattern, with anomalously warm conditions in November and December.

River flow (slide 5) was high for both the Merrimack and Charles throughout the year. The Charles set a record for the July-September period because of the contribution of Hurricane Irene. No large discharge peaks occurred through the year (also note slide 6). The annual average of both the Charles and Merrimack was anomalously high (slide 7), continuing the wet trend that started in 2005.

Winds showed strong downwelling in May, moderate upwelling in July, and strong upwelling in August (slide 8). The August upwelling anomaly was mainly due to Hurricane Irene. Persistent upwelling (winds toward north) in late May (May 25-June 3; slide 11) actually produced a significant temperature and stratification anomaly, which is discussed below.

Water properties

Surface water temperature (slide 10) showed a cooling event in the end of May and beginning of June. This was the result of the upwelling-favorable winds in late May (slide 11). Note that both bottom and surface water cooled during the event, and that the bottom water cooled earlier than the surface. This is consistent with advection of cold water up from the deep waters of the bay and the subsequent offshore advection of a surface front.

The upwelling during July and August did not seem to have a significant impact on water temperature, except for Hurricane Irene (slide 12).

Salinity was significantly lower than average through the year, consistent with the large amount of freshwater input (slide 15). A big drop in salinity occurred in mid-May. This occurred not because of a major discharge event but rather because of back-to-back Northeasterlies (slide 17), which advected the low salinity water from the Western Maine Coastal Current into the bay. The low salinity water coming from the Gulf of Maine was evident at the 20-m salinity sensor on the GOMOOS A buoy (slide 16). The large drop in the green trace (GOMOOS A 20-m) at 2011.4 corresponds to around May 15, 2011, when the low-salinity event was observed in the near-field.

Stratification showed a very strong negative anomaly in early June (slide 18). This occurred at the same time as the strong upwelling event observed in the surface temperature (slide 10). This is the condition that Csanady (1977) refers to as “full upwelling”, in which the near-bottom water gets all the way to the surface, weakening or eliminating stratification in the near-shore region (inshore of the upwelling front).

Dissolved oxygen did not show any unusual behavior (slide 19). The dissolved oxygen regression model (slide 20) showed that the temperature effect was negative (relatively warm near-bottom waters during the early fall) but the salinity effect was positive (relatively low-salinity water), resulting in only a slight negative anomaly.

The timeseries data from the GOMOOS A buoy were calibrated against the MWRA station F22 and F27 (station F27 not sampled in 2011) data to provide a reasonably reliable representation of the continuous variation of DO at the mouth of the bay (slide 21). Interestingly, the DO appeared to dip at the end of 2011, perhaps even below 6 mg/l for the first time since the GOMOOS buoy has been deployed. The regression between temperature and DO (slide 22) demonstrates that temperature is the dominant factor resulting in low DO, although it is not the only factor. Another potential factor is the persistence of onshore currents (slide 23), which appear to cause DO to drop as well. The summer and fall of 2011 had unusually strong and persistent onshore flow, which may partially explain the low DO in the fall of 2011.

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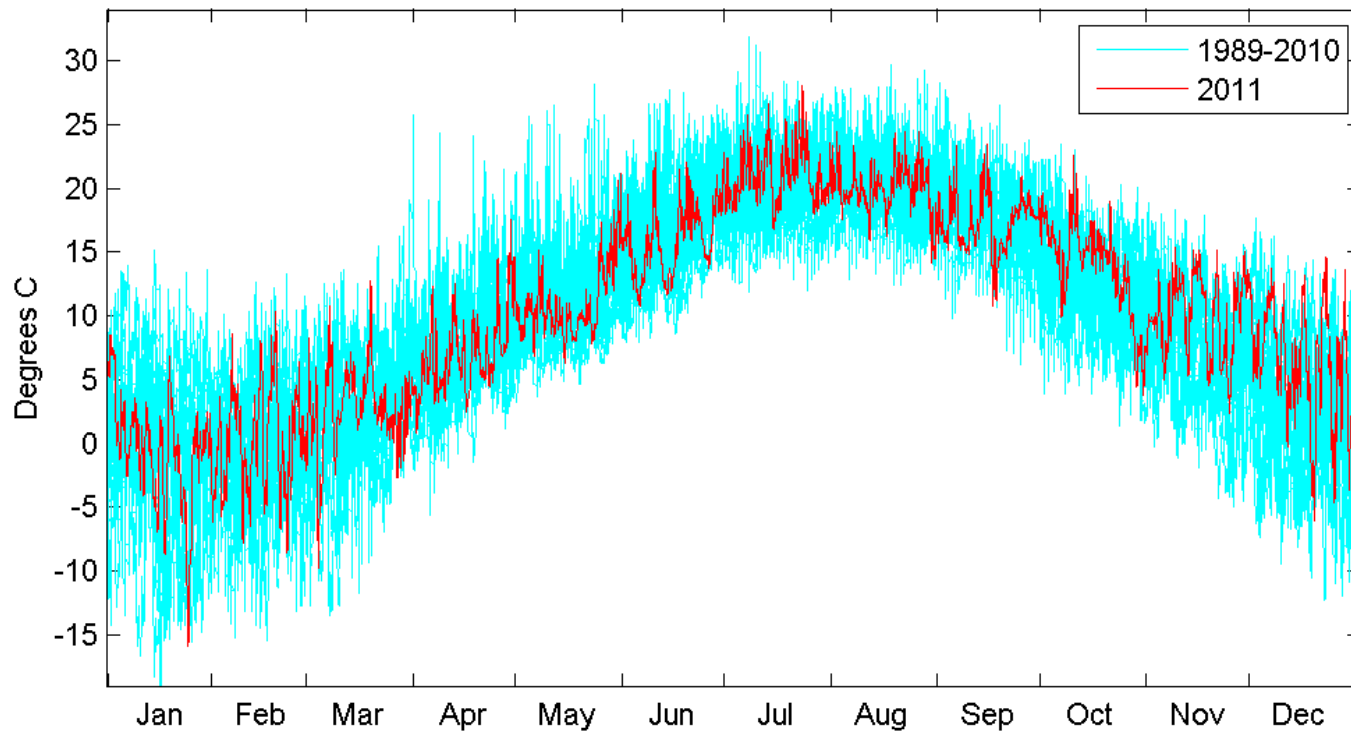
Massachusetts Bay Physics 2011

Rocky Geyer

Woods Hole Oceanographic Institution

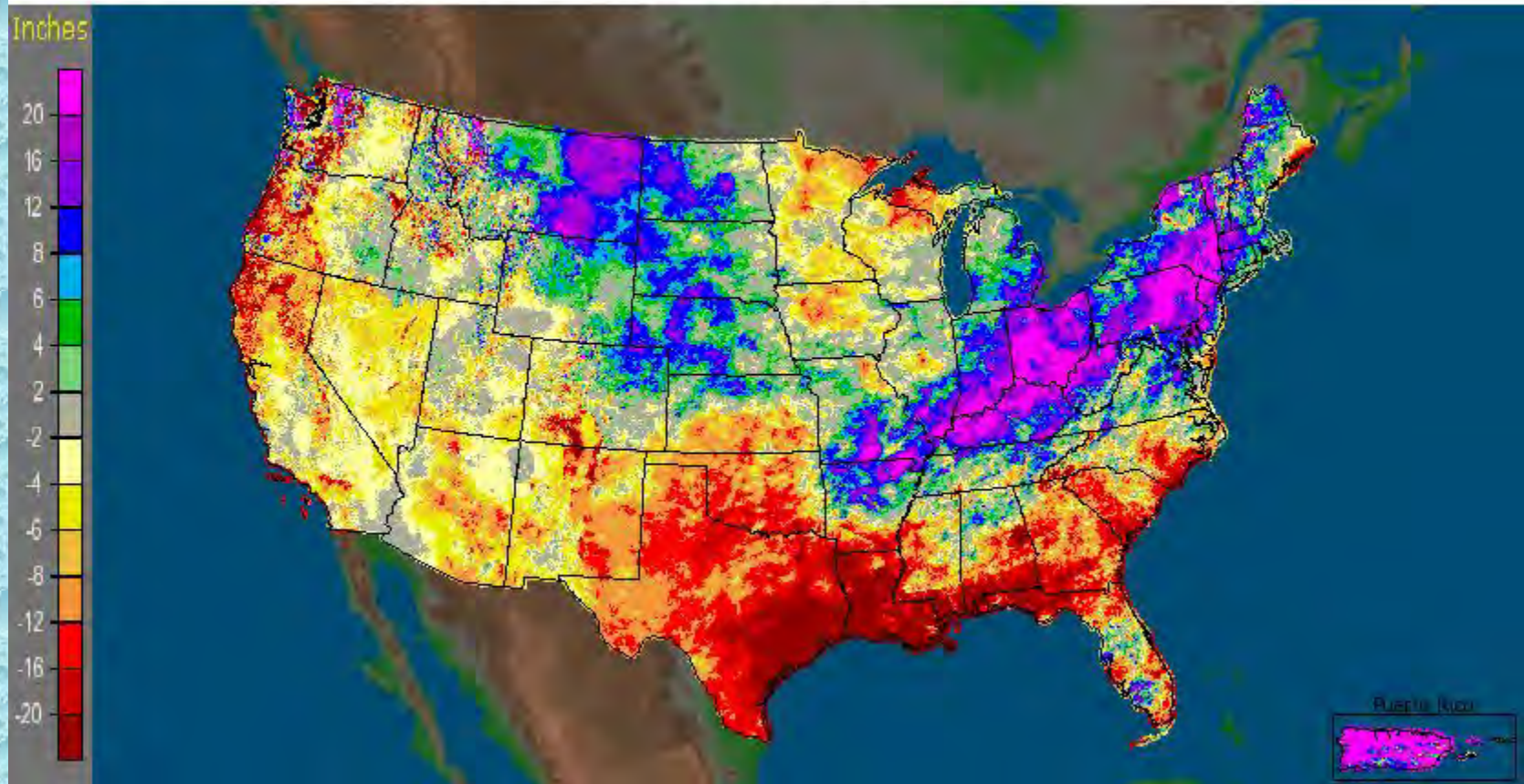
forcing conditions

Air Temperature, Boston Buoy

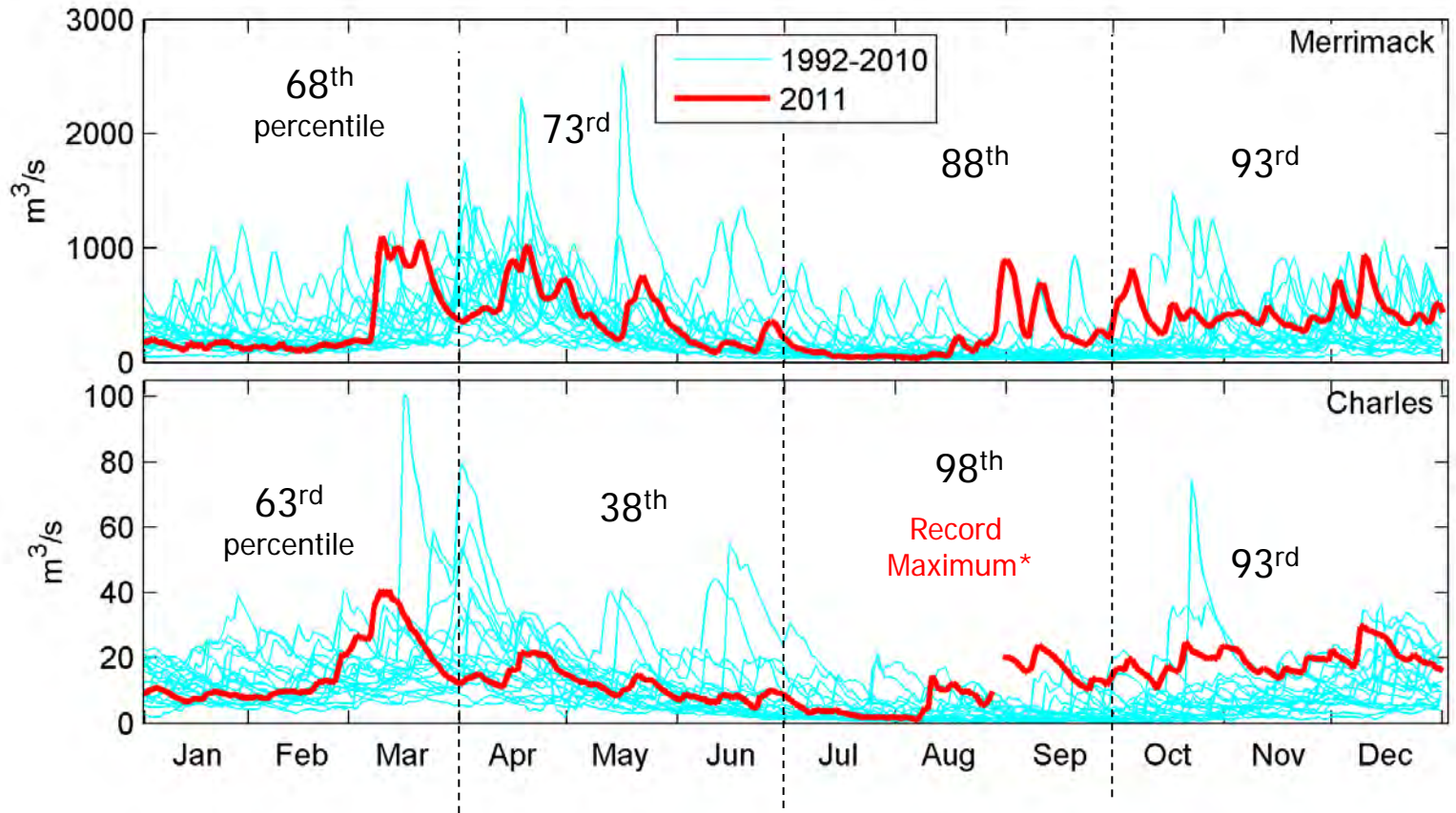


2011: A wet year in the Northeast

CONUS + Puerto Rico: Full Year 2011 Departure from Normal Precipitation
Valid at 1/1/2012 1200 UTC- Created 1/3/12 21:33 UTC

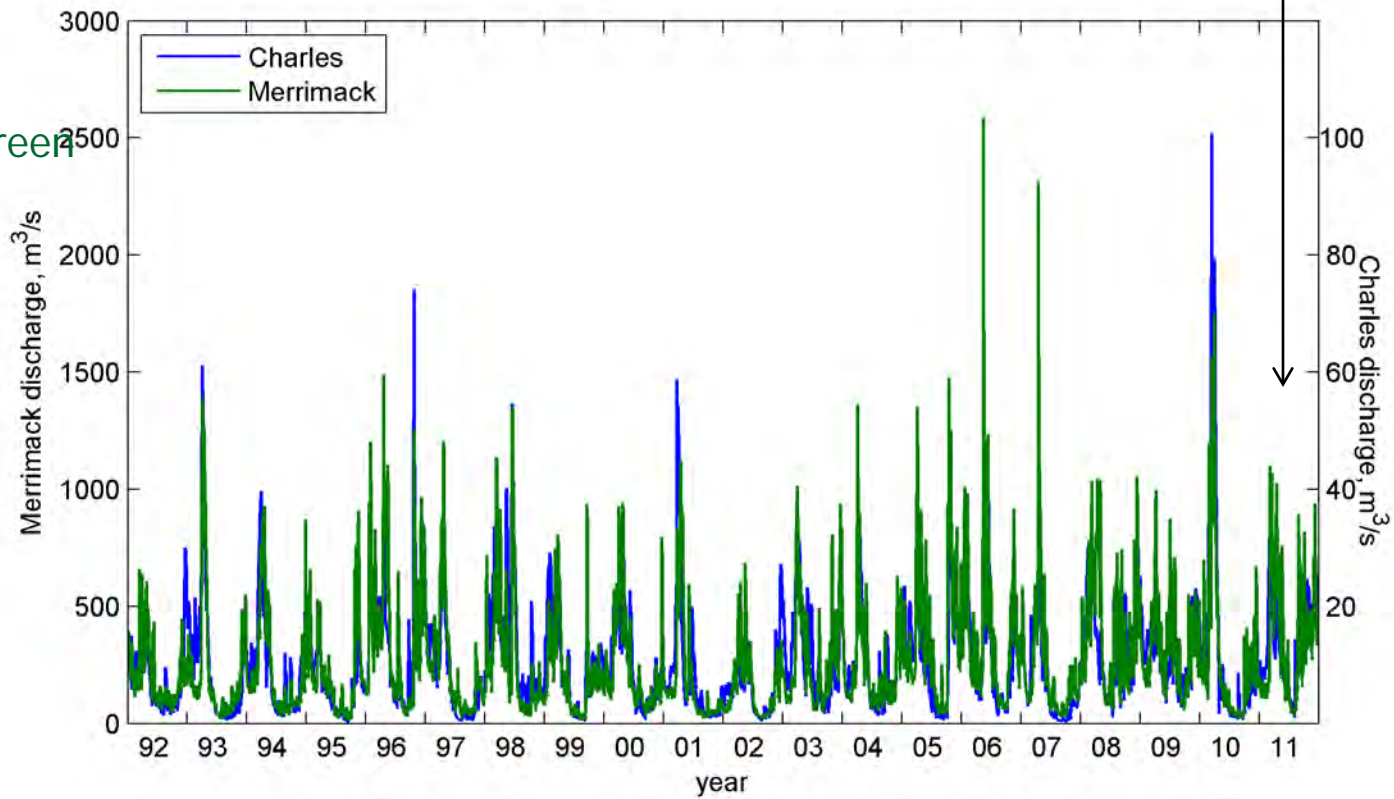


River Discharge, 2011



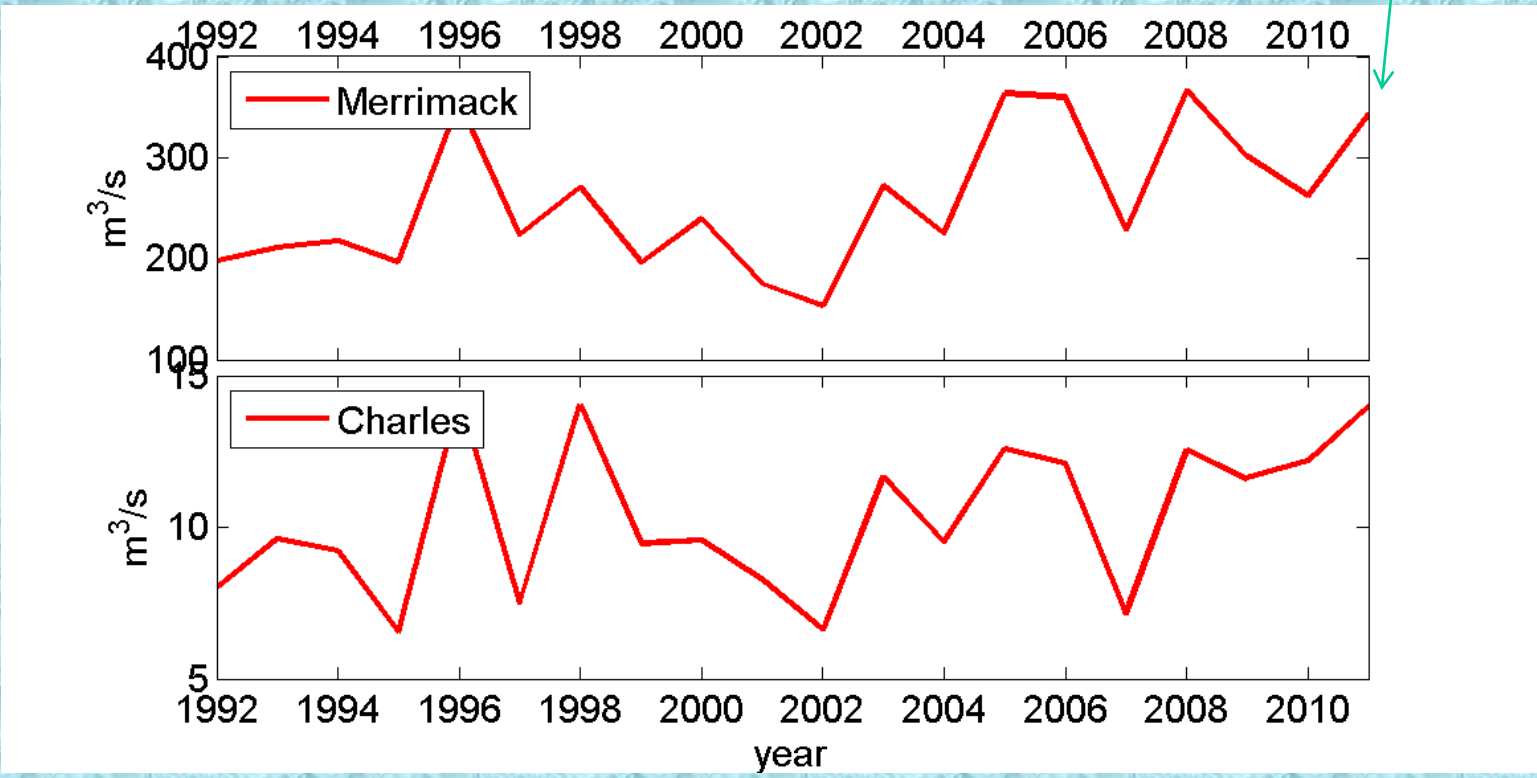
* 1992 - 2011

green

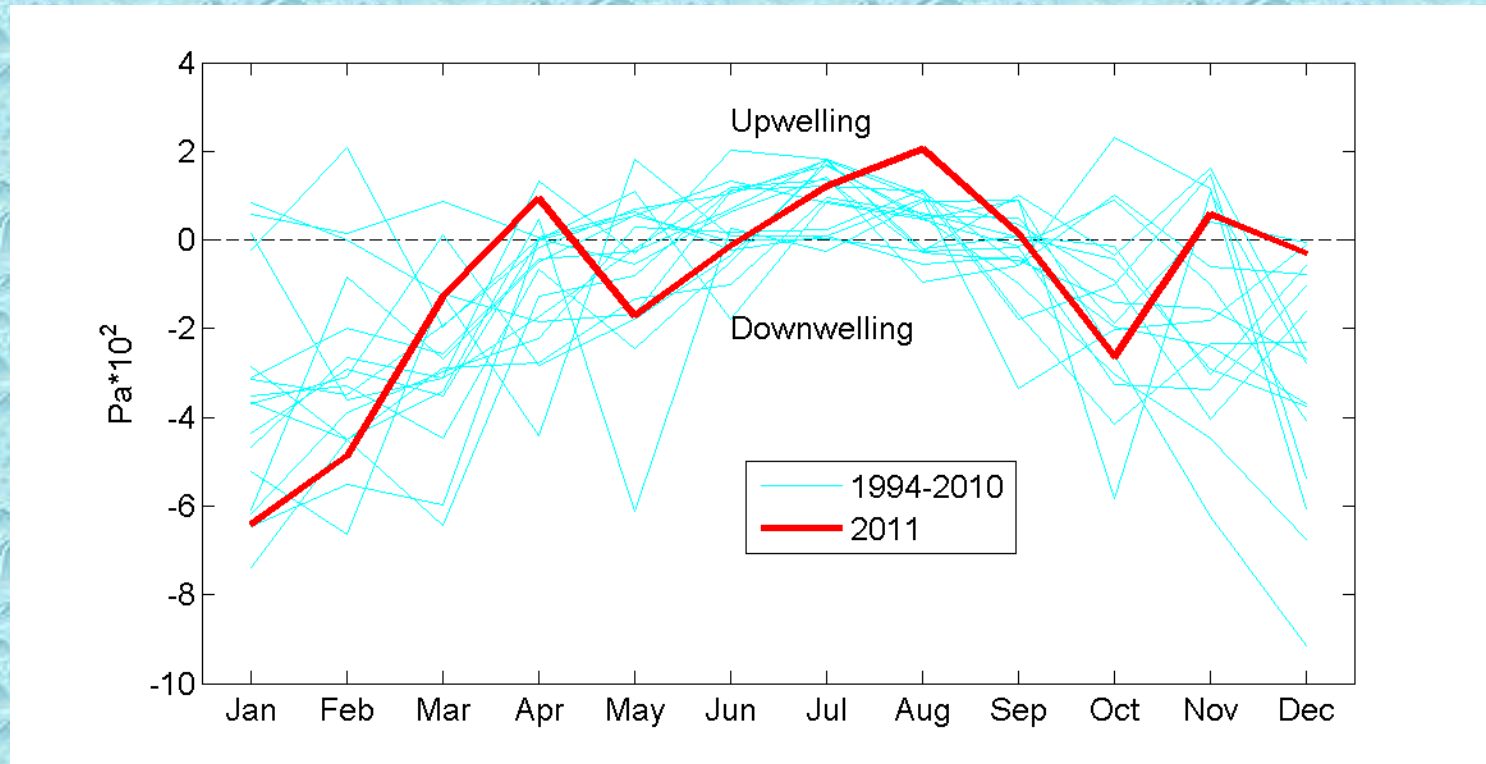


No really big peaks, even with Irene

But the annual average was wet

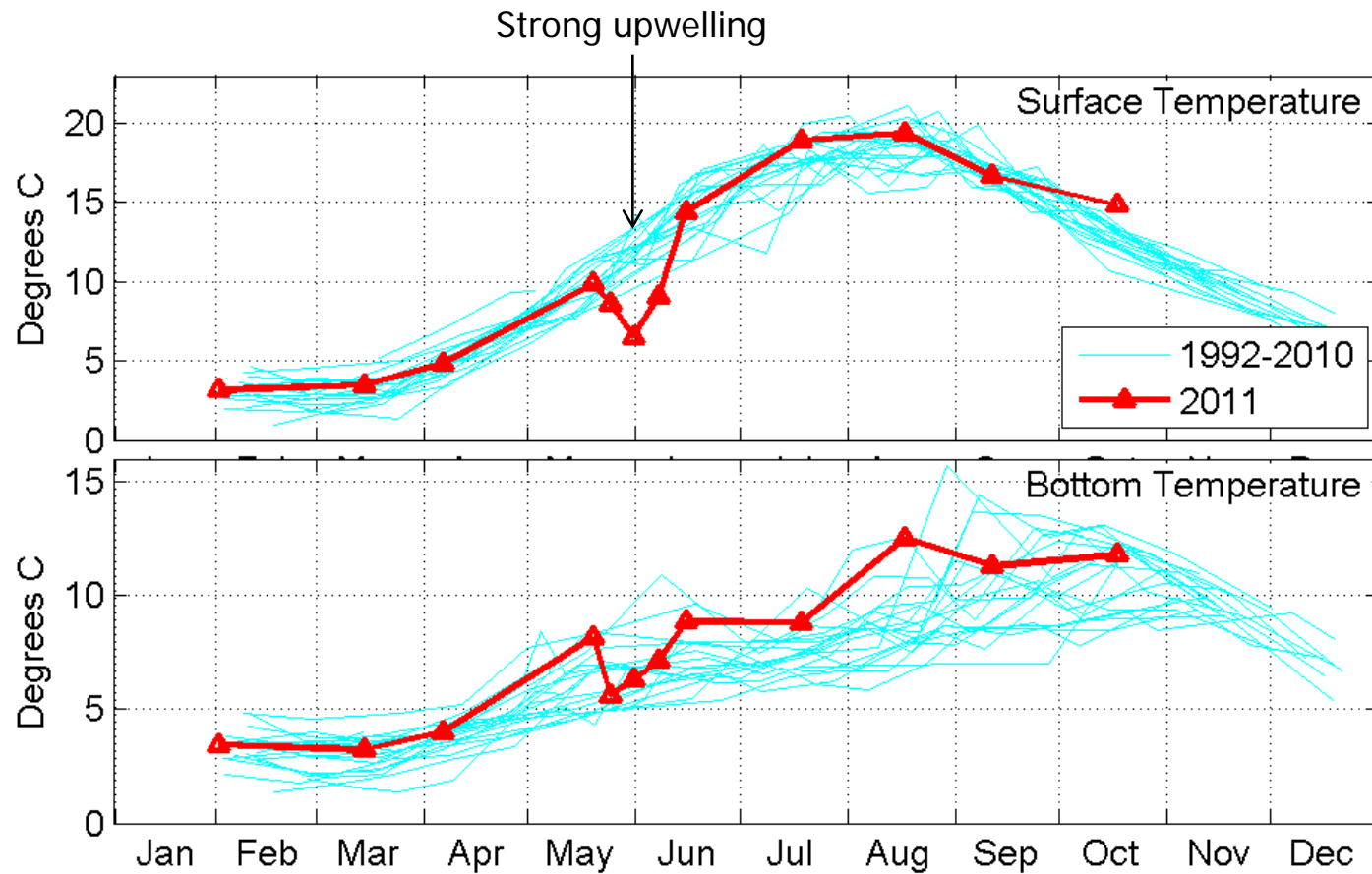


Upwelling index, 2011

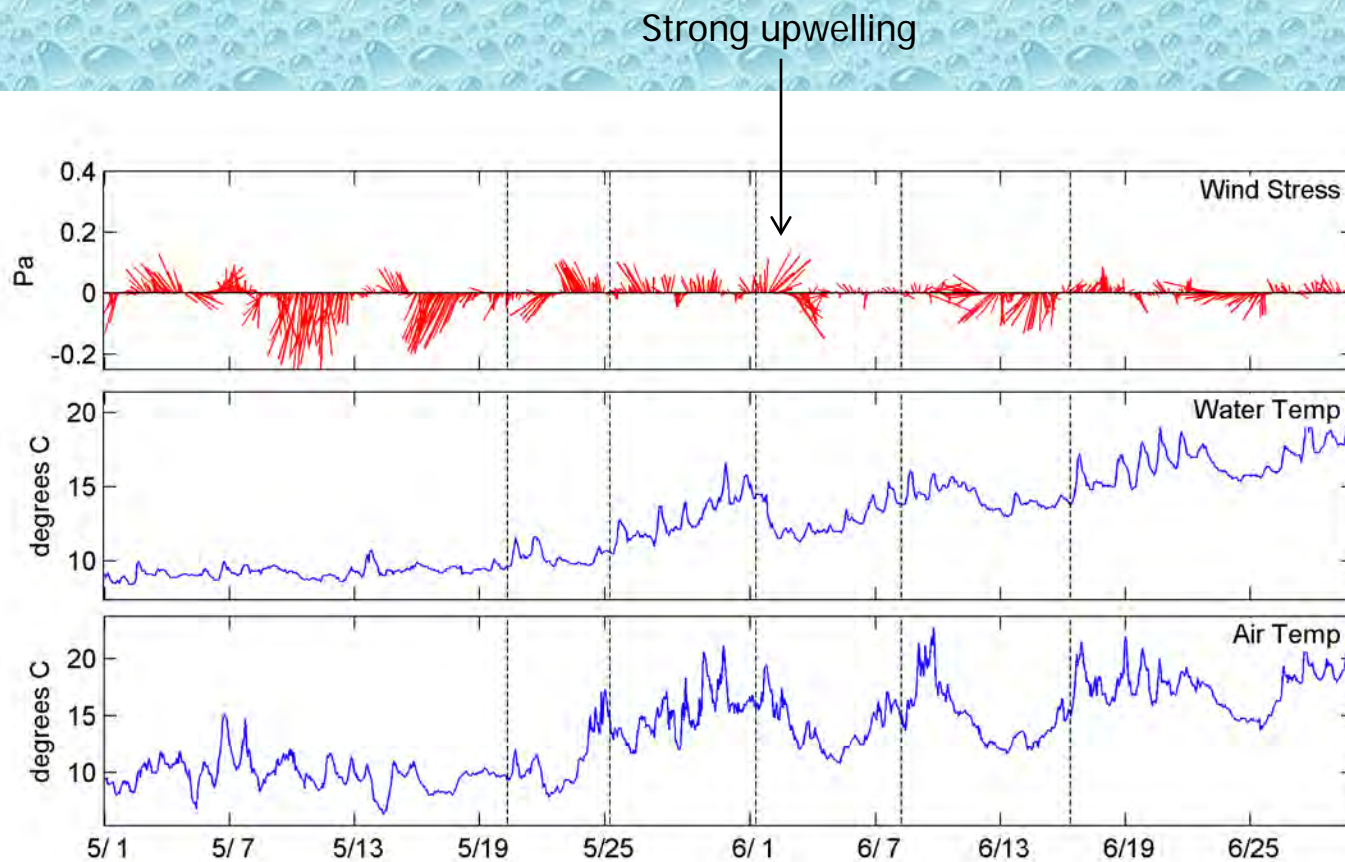


water properties

water temperature

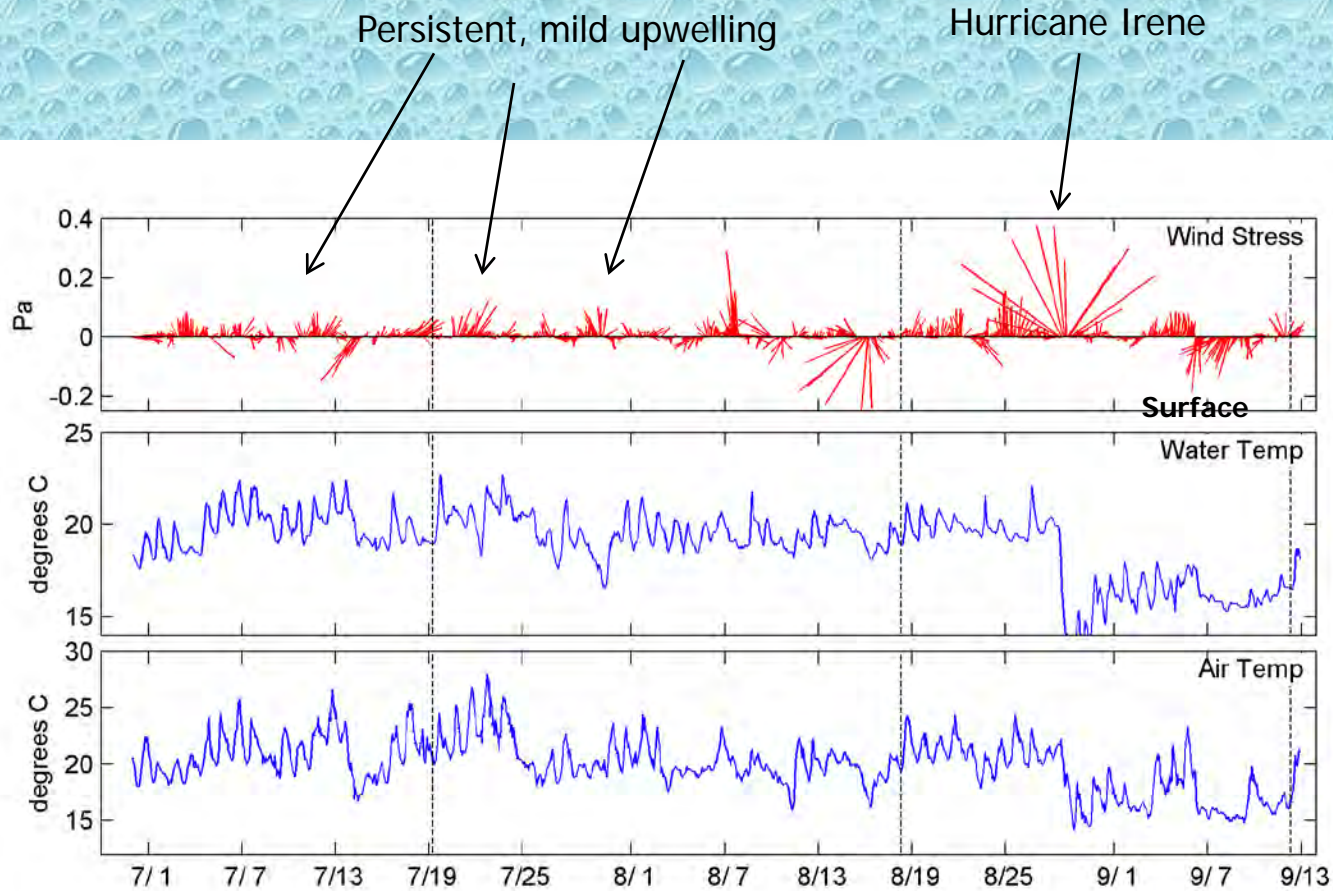


Late spring winds and water temperature



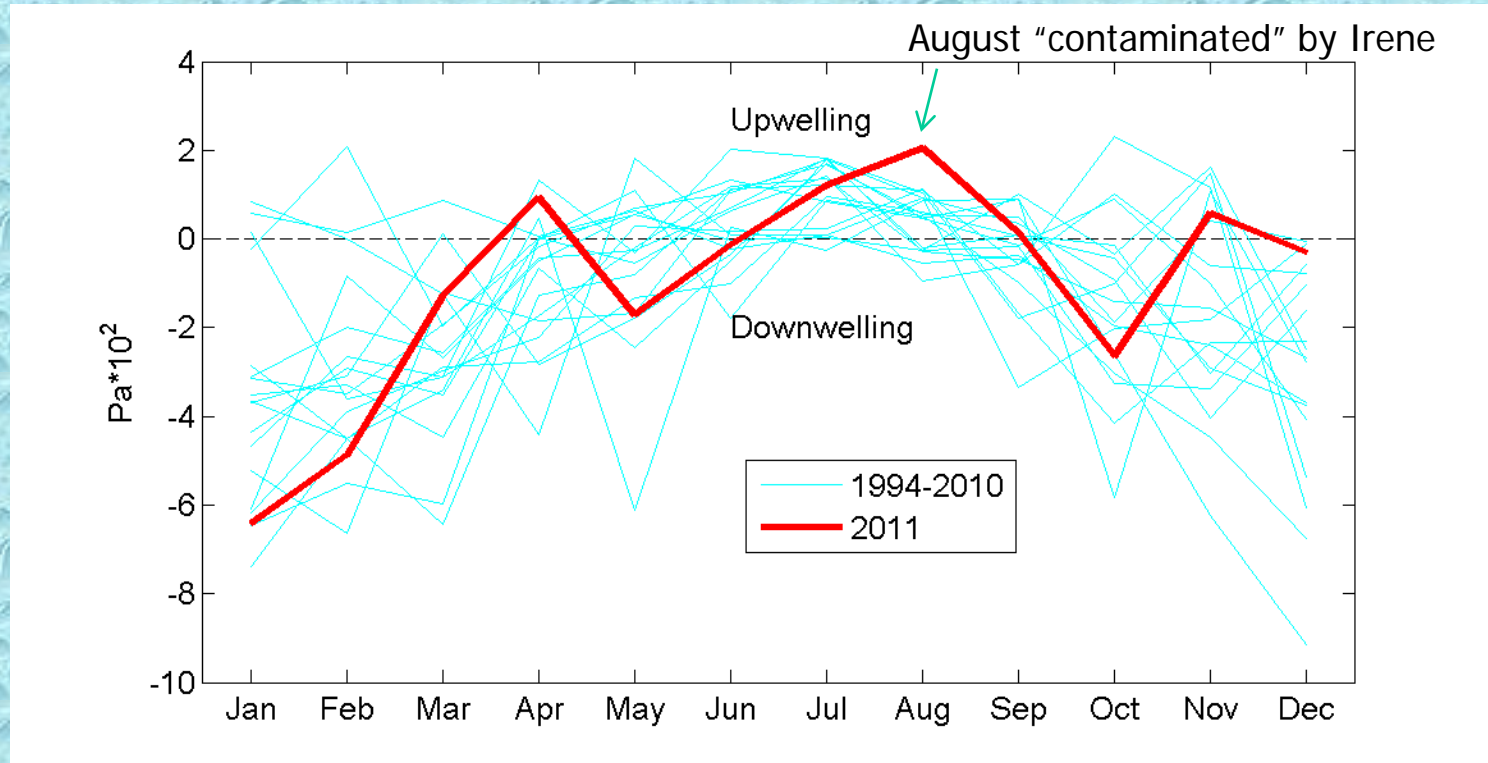
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summer winds and water temperature

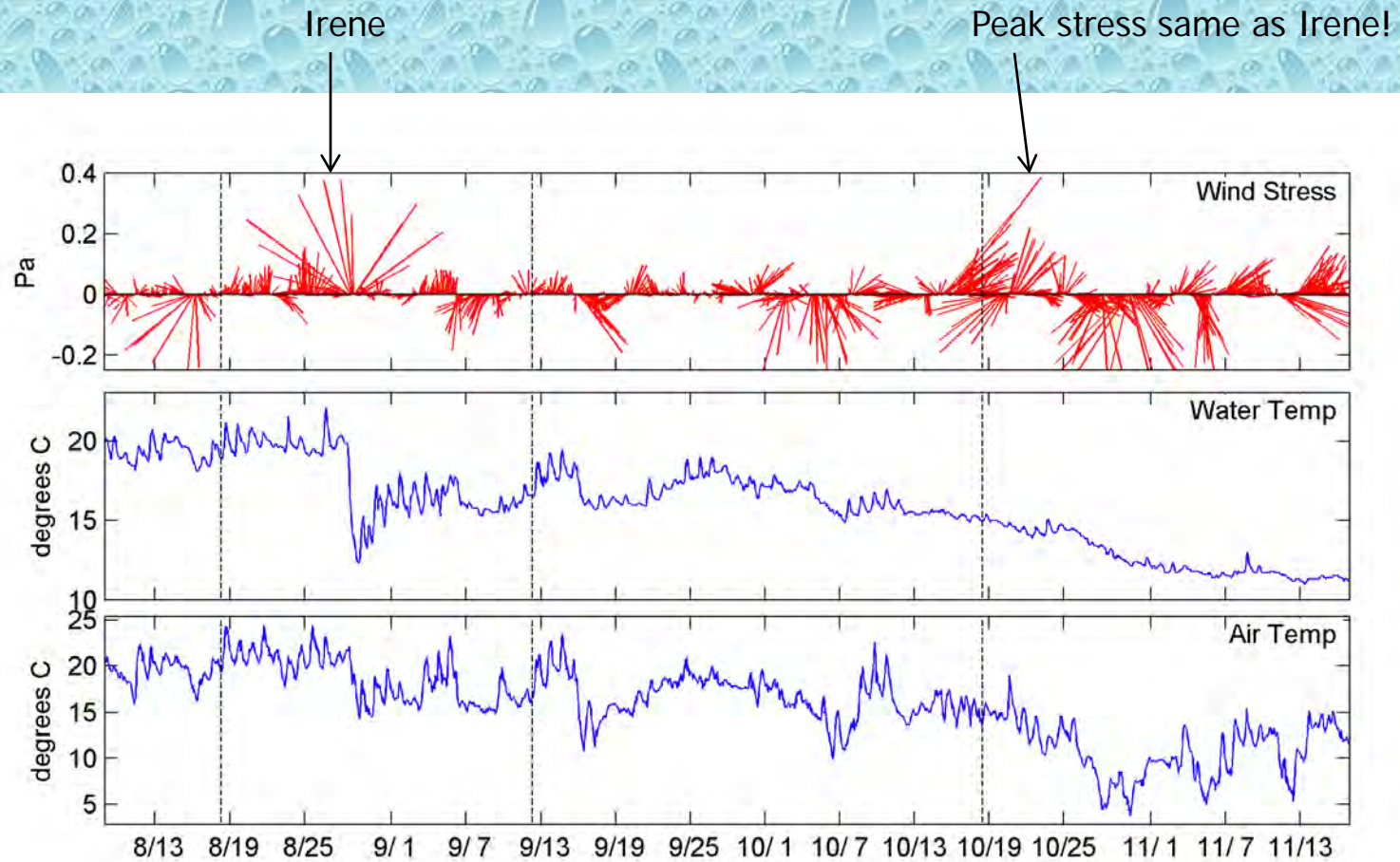


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Upwelling index, 2011

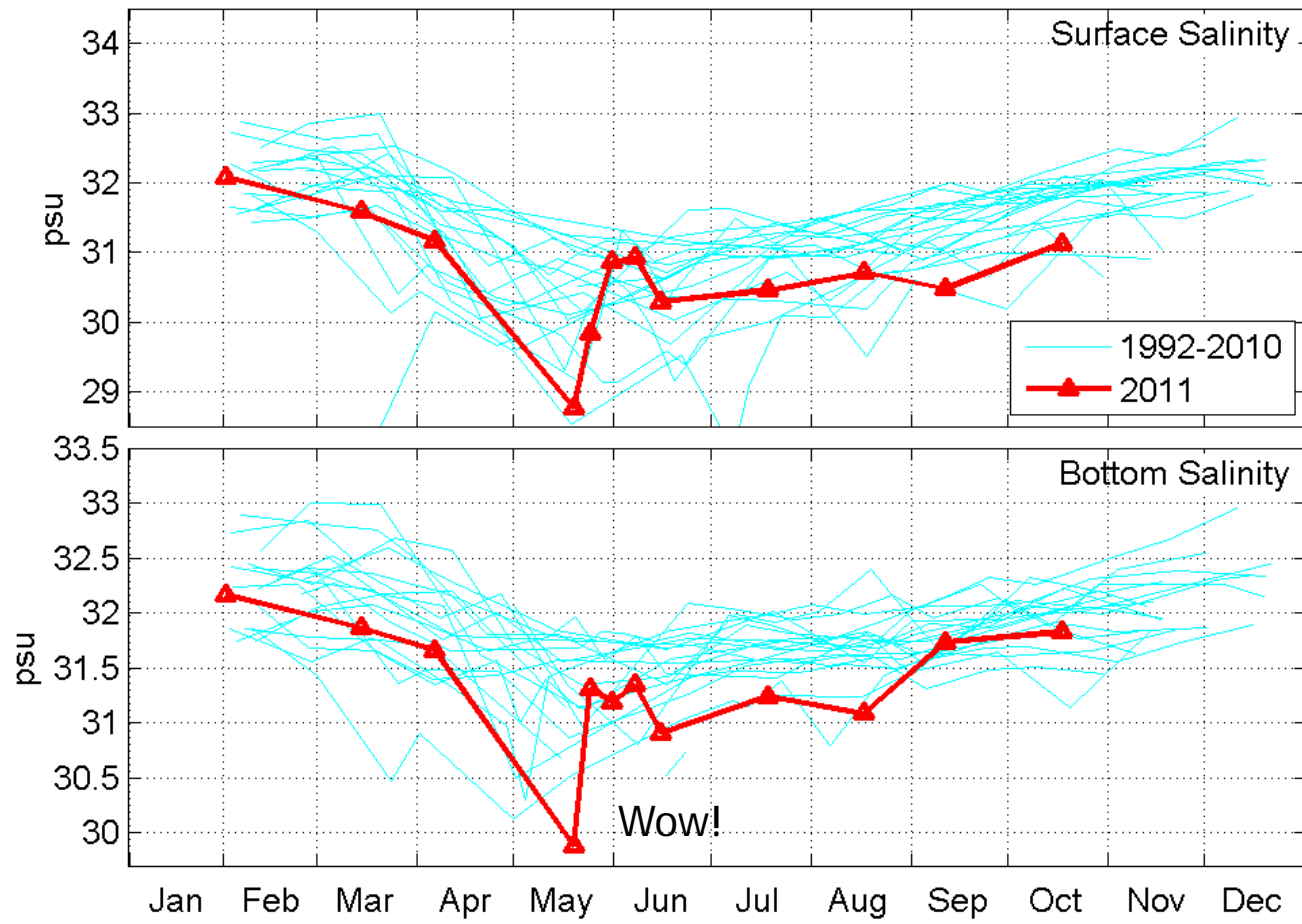


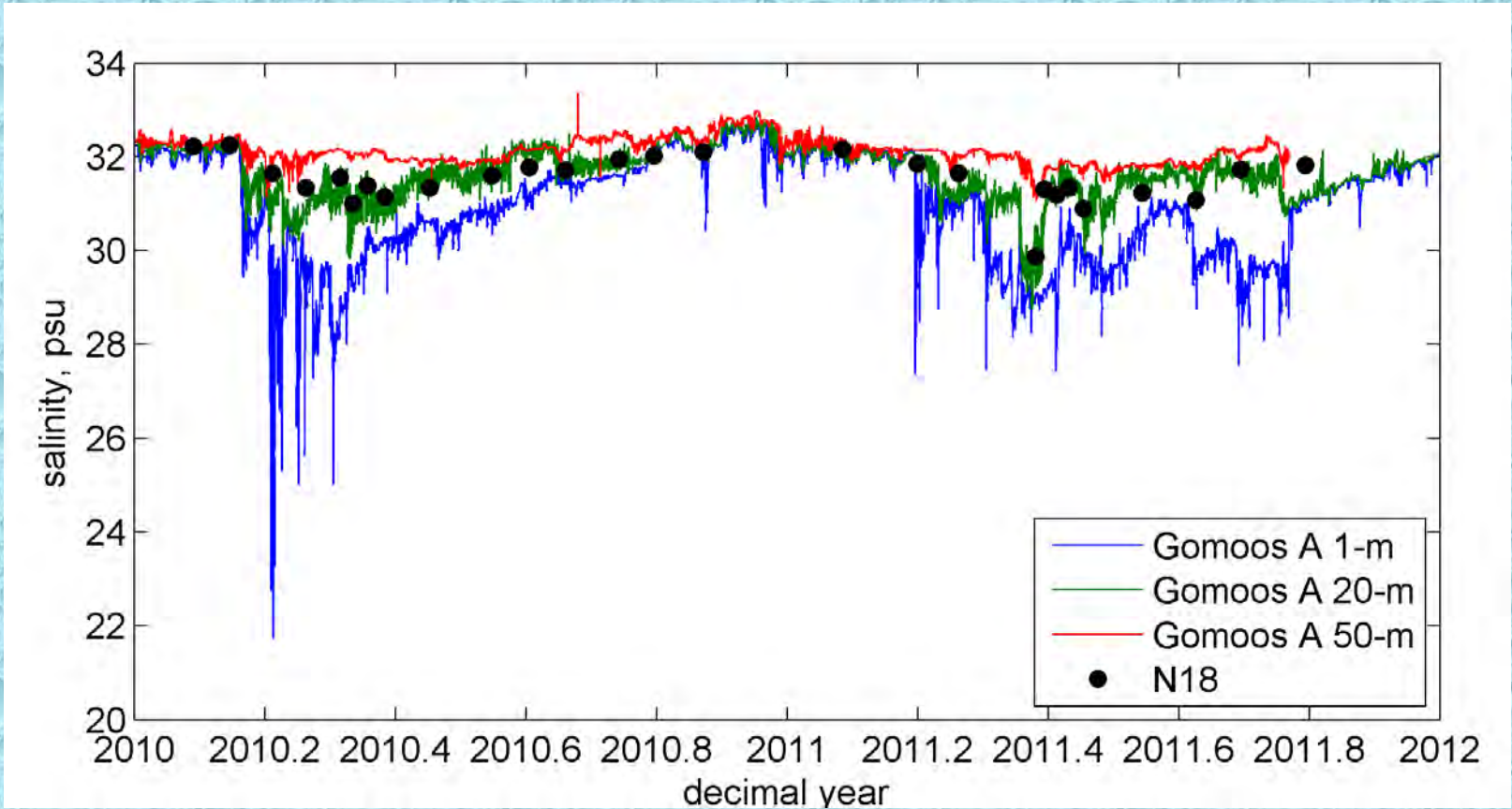
fall winds and water temperature



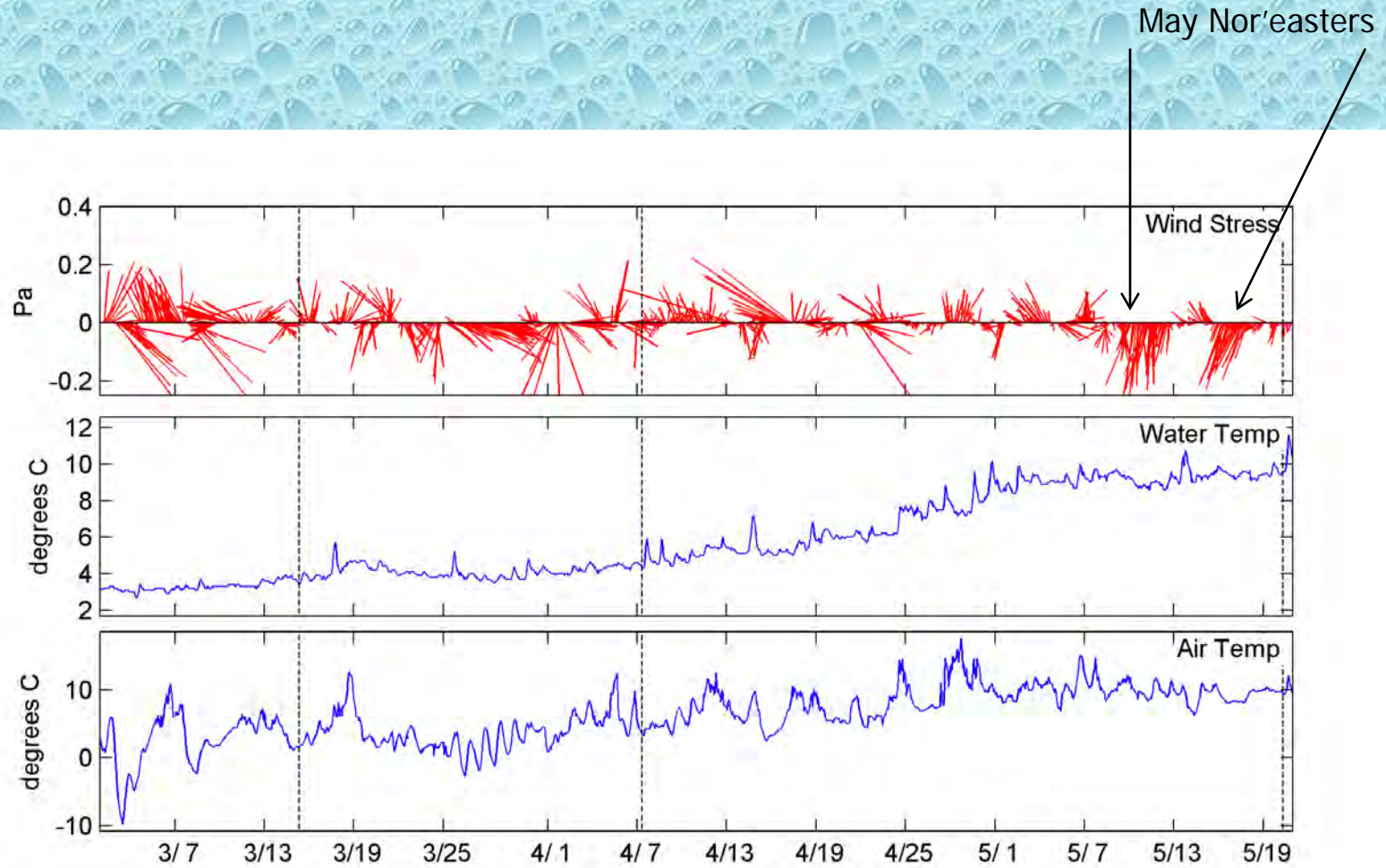
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salinity

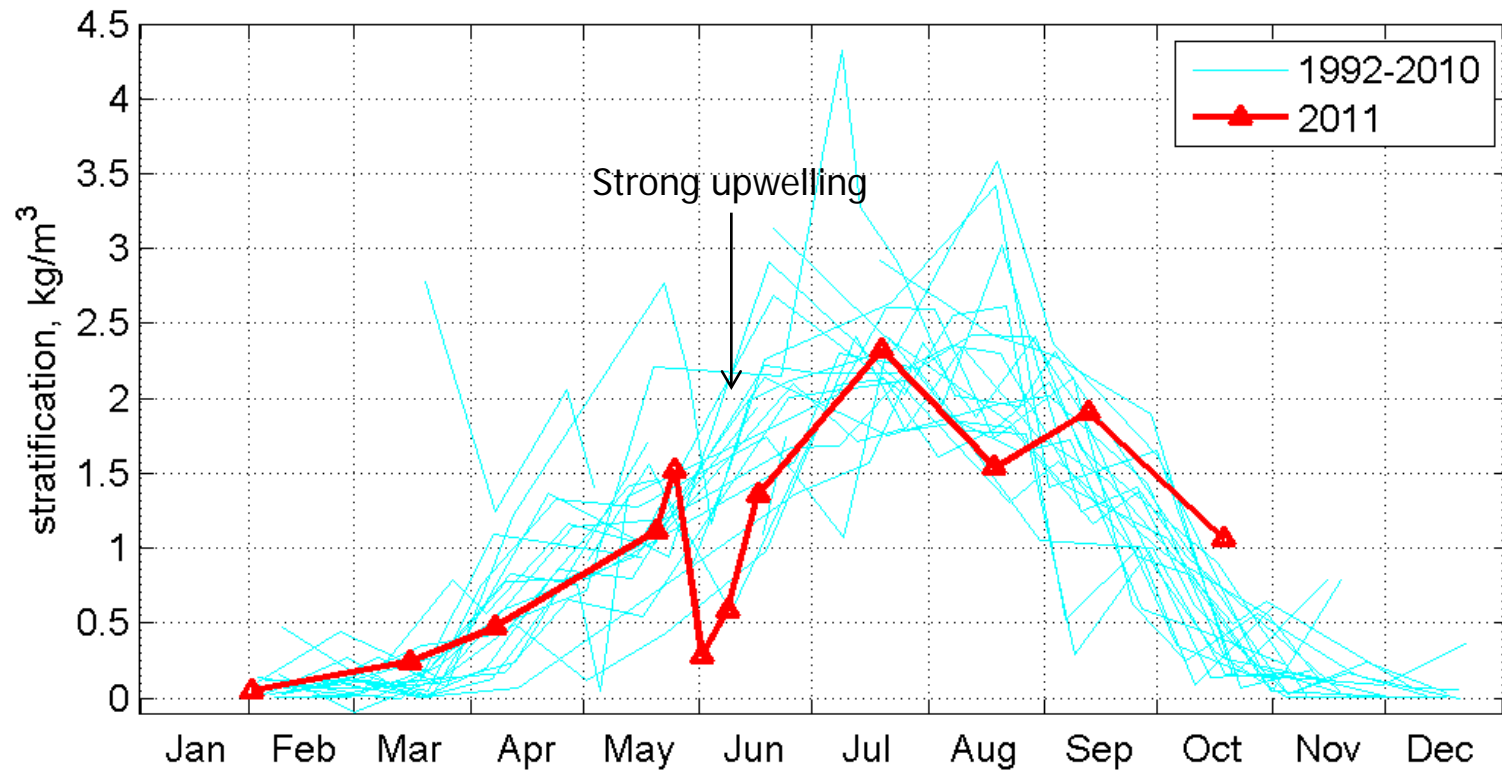




spring winds and water temperature

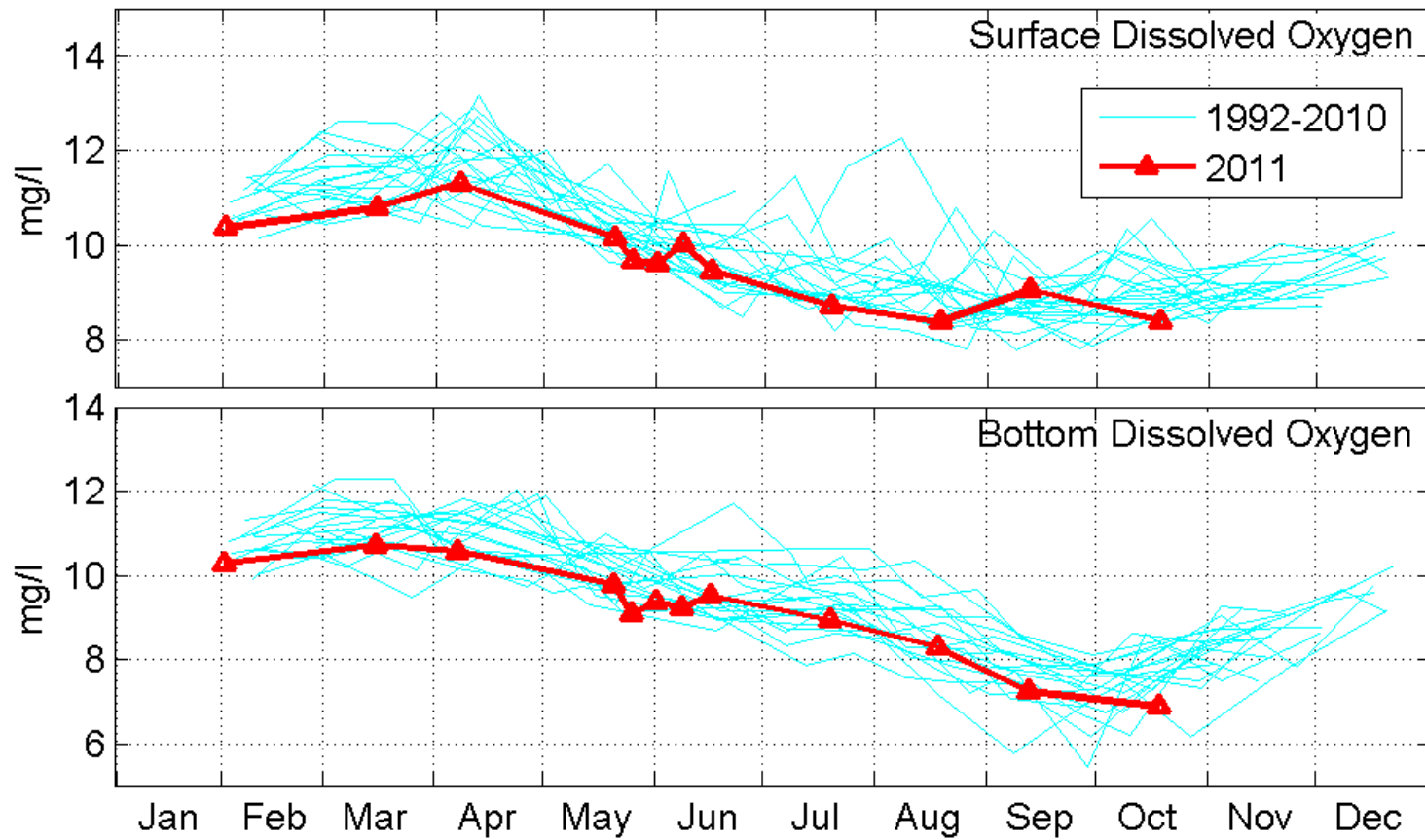


stratification

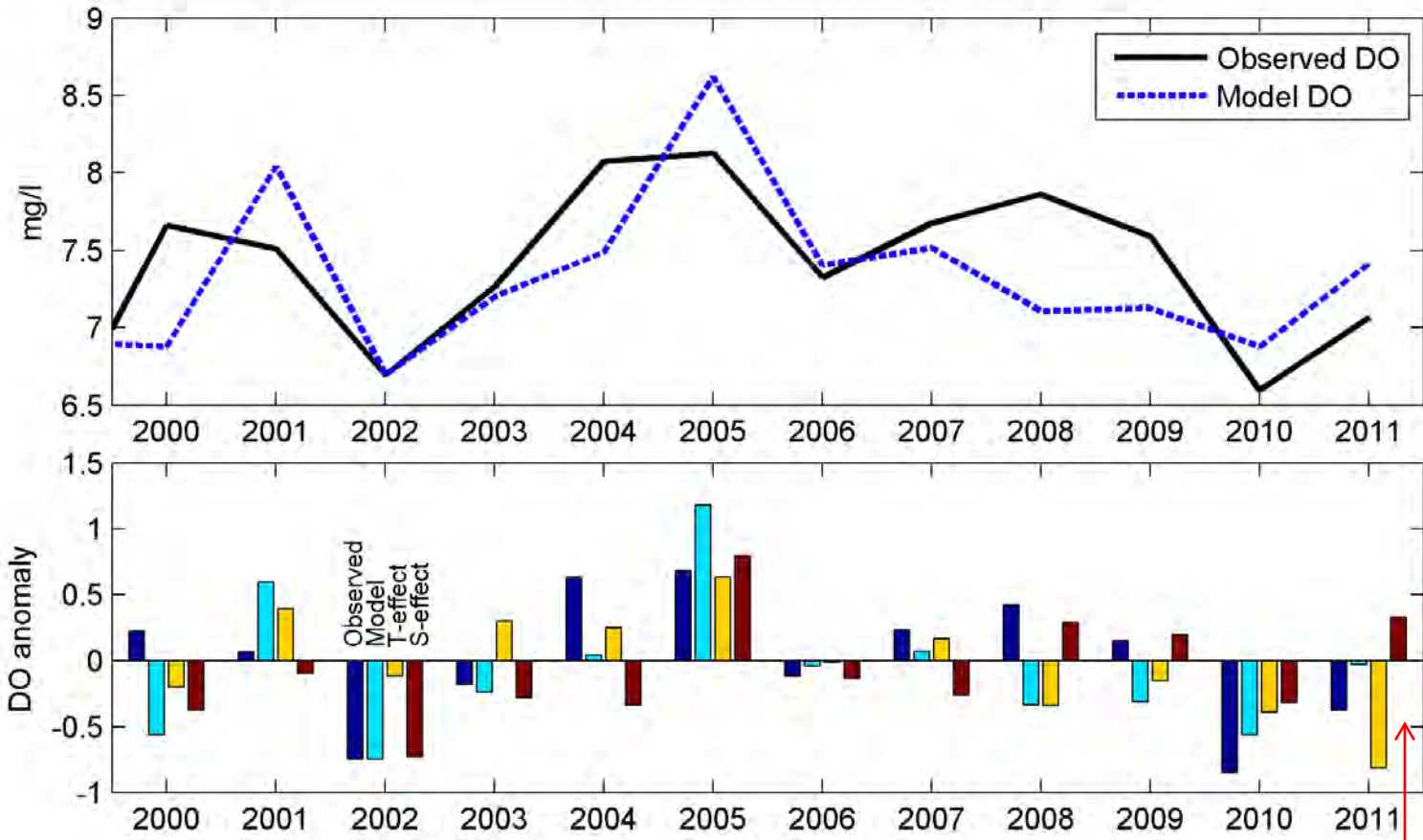


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dissolved oxygen

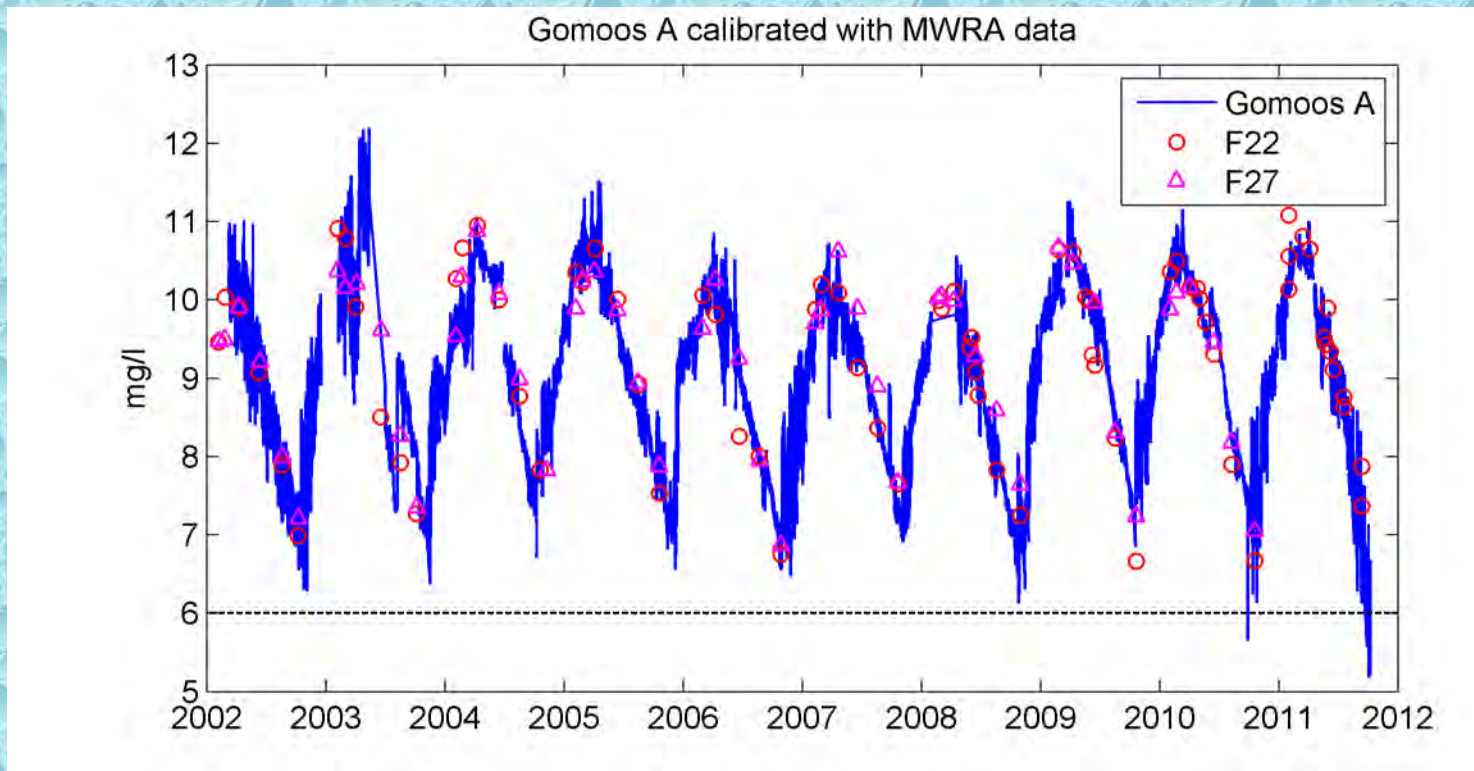


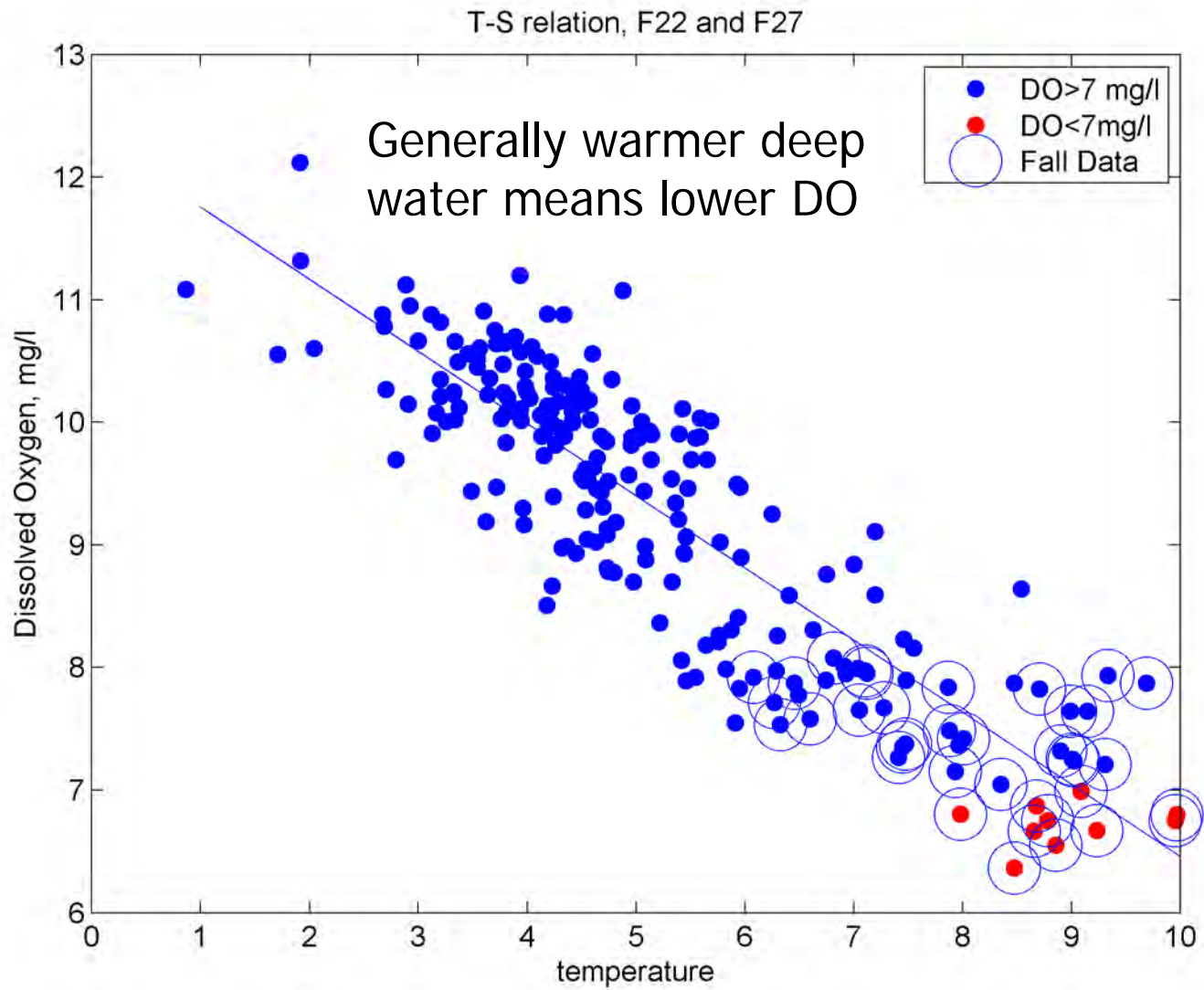
DO model predicts moderately low near-bottom DO for 2011



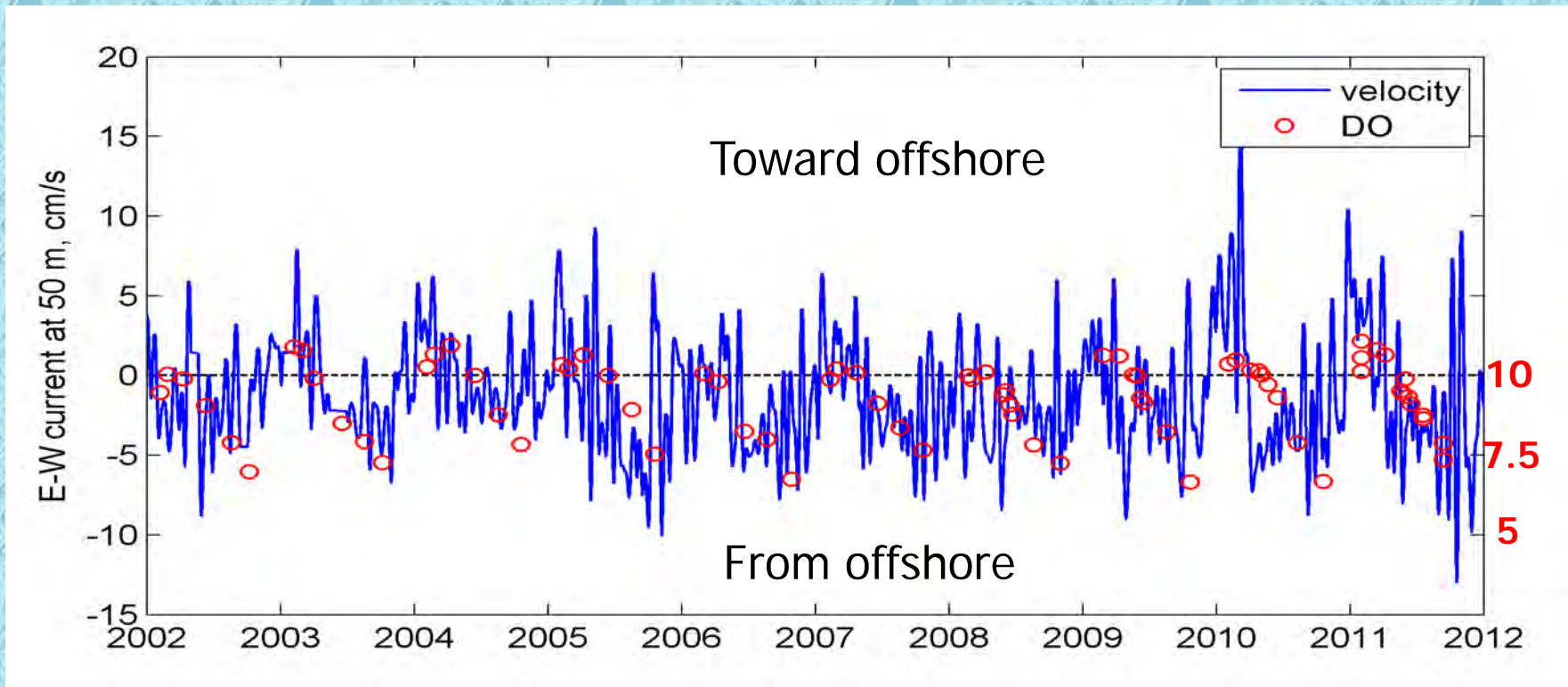
temperature effect negative,
salinity effect positive

GOMOOS A DO calibrated against MWRA data





GOMOOS A East-West current at 50 m— Does it influence DO?



summary

- Wet year overall
- Strong nor'easters in May– advected low-salinity water in
- Strong upwelling in June
- Hurricane Irene– not much effect
- Maybe low DO at GOMOOS A at end of October

Appendix B

Water Quality

2011 Water Column Summary

Scott Libby, Battelle

Overview

For 2011, the MWRA Harbor and Outfall Monitoring (HOM) program was revised to conduct nine monthly surveys from February to October with sampling at 11 stations in Massachusetts Bay (slide 3). The reduction in the total number of stations provided the opportunity to conduct the surveys during a single day and thus collect a relatively synoptic set of water column results. An additional three historic HOM stations were sampled contemporaneously by Provincetown Center for Coastal Studies in Cape Cod Bay and are included in these analyses. As has been observed over the course of the HOM program, the 2011 data follow a seasonal sequence of water quality events in Massachusetts Bay. 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 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 has been evident every year of this 20 year dataset (1992-2001). The major features and differences in 2011 are discussed below.

2011 Water Quality Results

Nutrient concentrations were relatively high in Massachusetts Bay in February and March 2011 (slides 5 and 6). Nitrate+nitrite (NO_3+NO_2) and phosphate (PO_4) levels in Cape Cod Bay were about half those in Massachusetts Bay in February and surface nutrients in Cape Cod Bay were nearly depleted by March. The levels of nutrients were consistent with the elevated chlorophyll concentrations (slides 13 and 14) associated with the winter/spring centric diatom bloom and elevated microflagellate abundances observed in Cape Cod Bay during the first two surveys. In March, the effluent plume (as delineated by elevated ammonium (NH_4) concentrations) was evident in the nearfield surface waters (slide 7).

From March to April, there was a very sharp decrease in nutrients throughout Massachusetts Bay. Surface NO_3 concentrations were depleted at all but harbor station F23, while silicate (SiO_4) levels decreased, but remained elevated relative to NO_3 (slides 5 and 6). In fact, NO_3 concentrations were low throughout the upper 30 m of the water column (slide 12). These decreases in nutrients (absolute and relative concentrations) were coincident with increases in chlorophyll and particulate organic carbon (slide 13) associated with an April *Phaeocystis* bloom. The relative decrease in NO_3 vs. SiO_4 is also consistent with a *Phaeocystis* bloom as this phytoplankton species does not utilize SiO_4 like diatoms. Surface chlorophyll levels in during the April survey were not very high – peaking at $2.7 \mu\text{g L}^{-1}$ in the nearfield (slide 14), but MODIS imagery from late March suggest the bloom may have peaked (at least in chlorophyll concentrations) in mid to late March (slide 15). Elevated *in situ* fluorescence levels were observed near the pycnocline in April and the *in situ* fluorescence signal was a bit noisy (slide

16), which is indicative of large particulates, such as *Phaeocystis* colonies, passing through the fluorometer.

From April to May, chlorophyll and POC concentrations continued to increase in Massachusetts Bay especially in the surface waters (slides 13, 14, and 16). This was coincident with an increase in centric diatoms and smaller dinoflagellates. Surface nutrient concentrations increased slightly over this time period (slides 5 and 6) likely due to freshwater inputs during April and May storms. The increased riverine nutrient input also likely supported the May increase in centric diatoms (primarily *Skeletonema* and *Thalassiosira* spp.) and small dinoflagellates. The May dinoflagellate community included a moderate bloom of *Alexandrium fundyense* with abundances peaking during the May 20th survey at ~2,500 cells L⁻¹ at station N07 in the nearfield (slide 27). The levels were above the 100 cells L⁻¹ trigger for *Alexandrium* rapid response surveys (ARRS) and a series of three weekly ARRSs were conducted from May 25th to June 8th. *Alexandrium* abundances remained elevated in the nearfield during each of these surveys, but by June 16th the bloom was over and only a few *Alexandrium* cells were observed (slides 27 and 28). This moderate bloom did lead to an exceedance of the MWRA Contingency Plan Threshold for *Alexandrium* (slide 24 – only exceedance for 2011) and a PSP toxicity closure of shellfishing beds from Duxbury north to Cape Ann in western Massachusetts Bay (slide 26).

By the June 20th survey, along with the decrease in *Alexandrium*, there was a decrease in nutrients, chlorophyll and POC throughout Massachusetts Bay. The water column had become stratified and nutrients (including those associated with the effluent plume) were confined below the pycnocline (slides 9 and 12). The elevated NH₄ concentrations at nearfield stations N18 and N21 persisted from June through September as seasonal stratification confined the plume to the bottom waters (slides 5, 9, and 10). As shown for station N18, this has been a consistent pattern in the nearfield since diversion of the outfall September 2000 (slide 7 – all elevated summer levels are 2001-2011). In July, surface water nitrogen levels were depleted throughout Massachusetts Bay including the Boston Harbor station F23 (slide 5). This decrease was coincident with annual peak chlorophyll and POC levels at the harbor station and increasing levels in coastal waters (slides 13, 14, and 17). These increases were due to a summer bloom of the centric diatom *Dactyliosolen fragilissimus* at the shallower, inshore stations (see Borkman summary for details).

By August, the chlorophyll and POC concentrations in the harbor and coastal waters had decreased from the July peaks, but remained elevated at the harbor station F23 (slides 13 and 17) due to a near shore increase in *Skeletonema*. The abundance of *Skeletonema* increased throughout Massachusetts Bay in September (see Borkman summary). There was no clear evidence of this bloom in the chlorophyll data except for some elevated subsurface *in situ* fluorescence readings at each station (slide 17), but there was a fall peak in POC concentrations during the September survey (slide 13). In September surface water nutrients remained low in Massachusetts Bay, though there was an increase in surface water concentrations in Boston Harbor. Surface nutrients had remained low from June through September 2011 in the bay and there had been a steady increase in nutrient concentrations in the bottom waters (slides 2, 4 and 12) under the stratified conditions as offshore bottom waters were entrained and organic material was remineralized over the course of the summer. By October, surface water nutrient concentrations had increased at most stations, although nitrogen levels were still depleted at the more offshore stations in Massachusetts Bay (slides 5, 6, and 12). This was concomitant with elevated chlorophyll levels and, for the second year in a row, an increase in large dinoflagellates – specifically *Prorocentrum micans*.

Bottom water dissolved oxygen (DO) concentrations generally declined from March/April to October (slide 18). There was a slight increase at the harbor and coastal stations from August to

September, but minima were observed throughout the survey area during the October survey indicating that the water column had not overturned by the last survey of 2011. Bottom water minima, however, were moderate in comparison to past years with nearfield and Stellwagen basin minima of 6.78 and 7.21 mg L⁻¹, respectively. These DO levels (and their respective percent saturation values) were well above the contingency Plan threshold values (slide 19) as were the 2011 seasonal and annual chlorophyll levels. Hence, there were no threshold exceedances for these water quality parameters in 2011.

As mentioned previously, there was a moderate *Phaeocystis* bloom in the bay in 2011 with abundances reaching millions of cells per liter in April. However, the bloom was short lived and the winter/spring mean *Phaeocystis* abundance (338,000 cells L⁻¹) was well below the threshold value (slide 24). Although *Pseudo-nitzschia* was present at somewhat higher abundances in April 2011, these were not the toxic species included in the *Pseudo-nitzschia* threshold grouping rather they were the nontoxic species *Pseudo-nitzschia delicatissima*. The potentially toxic, threshold *Pseudo-nitzschia* species were again very low abundances during each season, as has been the case during the post-diversion period (slide 24). As discussed above, *Alexandrium* abundances reached moderately high levels with a maximum in the nearfield of 2,454 cells L⁻¹, well above the 100 cells L⁻¹ threshold (slide 26). The 2011 *Alexandrium* bloom lasted about a month and led to shellfishing closures along the western Massachusetts Bay coastline from Cape Ann south to Duxbury.

Historical Comparisons

Overall, the 2011 data were consistent with the trends and patterns observed during both the baseline (1992-2000) and post-diversion (2001-present) time periods. Trends in nutrients at station N18, just south of the bay outfall, are indicative of those that have been observed for NO₃ and SiO₄ since 1992 and for NH₄ and PO₄ since September 2000 when the outfall came on line and elevated concentrations of these nutrients were became noticeable in the nearfield.

Comparisons of biomass (as measured by chlorophyll and POC) and total nitrogen in 2011 vs. historic levels shows that biomass levels are low across the range of representative stations (slides 21 and 22) and that even total nitrogen levels are on the lower end of the range of values in comparison to 1992-2010 results (slide 23). Although the trend of elevated NH₄ is represented in the 2011 total nitrogen plot for nearfield station N18, the total nitrogen values are still quite low compared to historic values.

In comparison to baseline conditions, the changes in the nutrient regimes are quite clear and consistent with model predictions. NH₄ has dramatically decreased in Boston Harbor (>80%) and nearby coastal waters while initially increasing to a lesser degree (~1 μM) in the nearfield (Libby *et al.* 2011). Since 2003 there has been an overall decrease in annual mean NH₄ 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 NH₄ 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 NH₄ 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, but this appears to be related to regional processes governing the consistent annual blooms of *Phaeocystis* in March-April since 2000 (Libby *et al.* 2011).

As predicted, there has been an increase in NH₄ in the nearfield relative to the baseline and also relative to the regional background concentrations. The signature levels of NH₄ in the effluent

plume are generally confined to an area within 10-20 km of the outfall (slides 8, 9, and 10). 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).

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

2011 Water Column Results

MWRA Annual Technical Meeting May 1, 2012

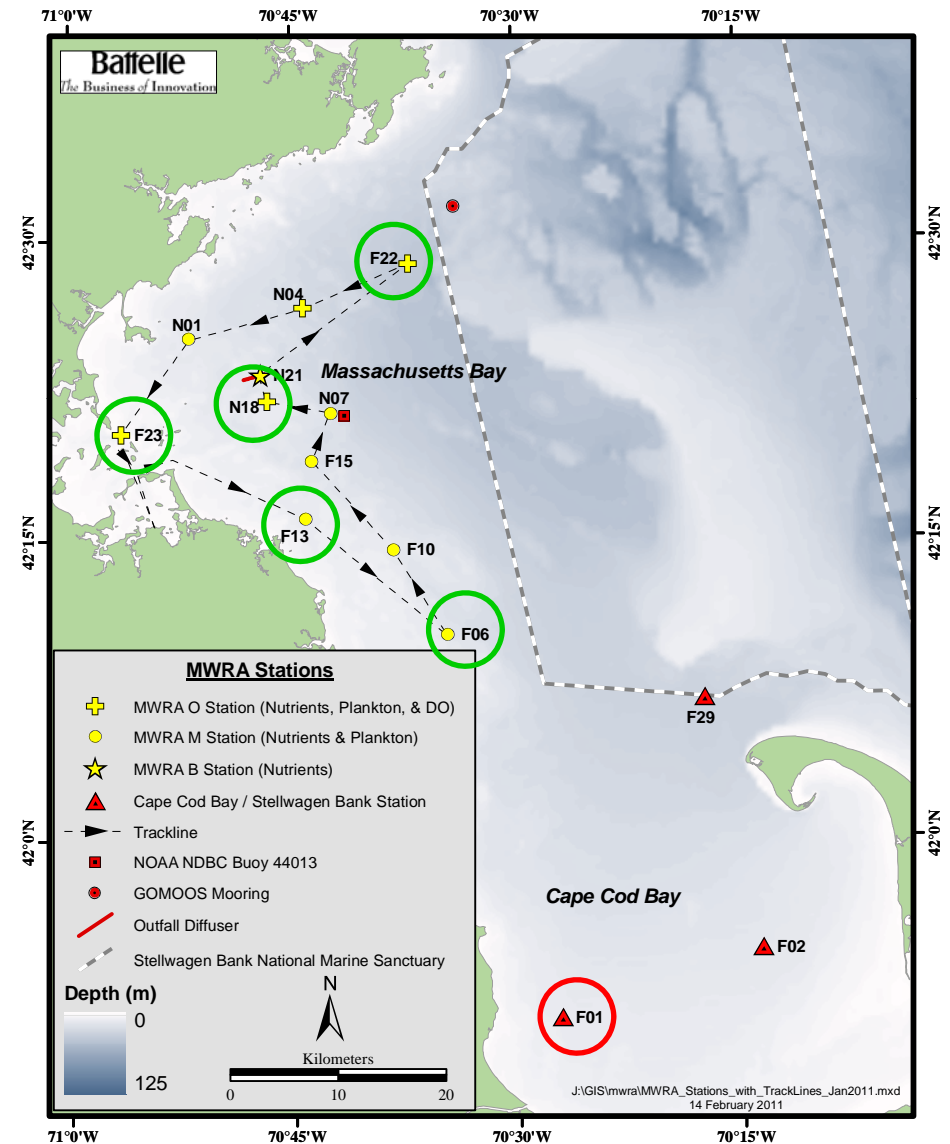
Scott Libby
Battelle

Presentation Overview

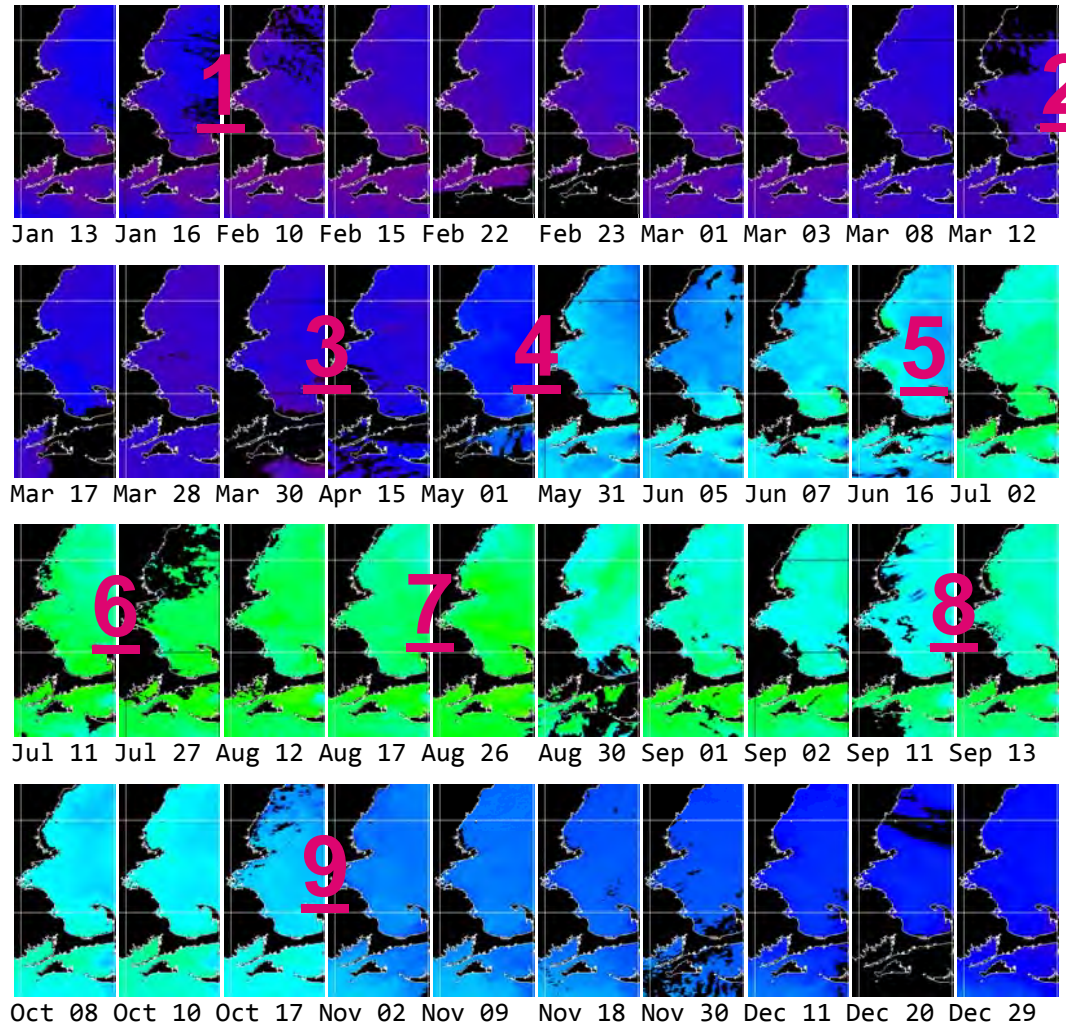
- 2011 nutrient, chlorophyll, and DO results
- “Typical” seasonal trends generally observed in 2011
- 2011 in perspective of 1992-2010 monitoring results
- Contingency Plan threshold results for 2011
 - No chlorophyll or dissolved oxygen exceedances
 - *Phaeocystis* bloom - moderate bloom, but no exceedance
 - *Alexandrium* bloom - moderate bloom exceeded threshold (100 cell/l)

2011 WQ Monitoring Program

- **9 Surveys**
- **11 Stations (+3 in CCB)**
- **Suite of oceanographic parameters measured at each station**
 - *In situ* hydrographic parameters
 - Nutrients
 - Dissolved oxygen
 - Chlorophyll & particulate organics
 - Phytoplankton & zooplankton community structure (not @ N21)
- **Additional data from –**
 - Other components of the MWRA HOM program (PCCS)
 - GoMOOS & NOAA buoys
 - MODIS satellite imagery



MODIS Sea Surface Temperature

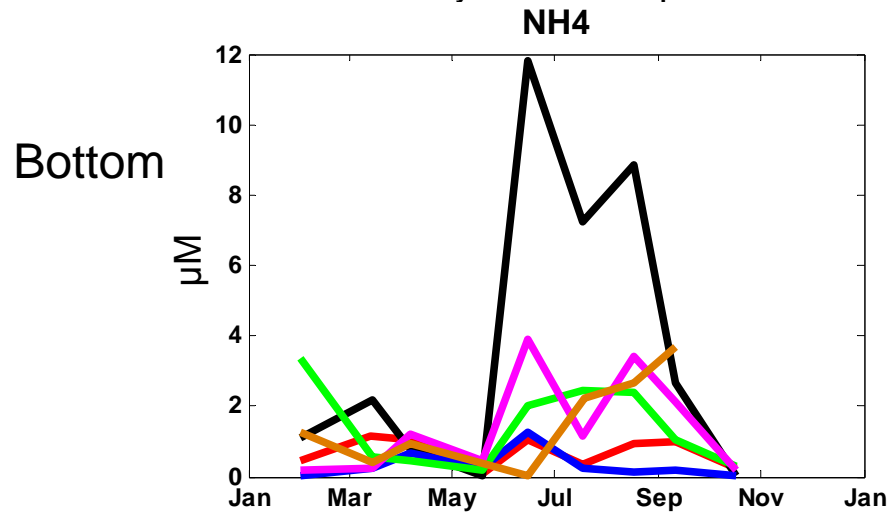
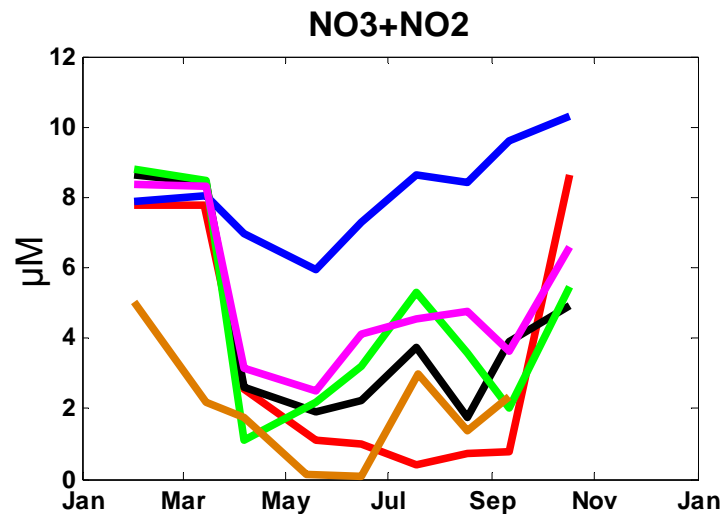
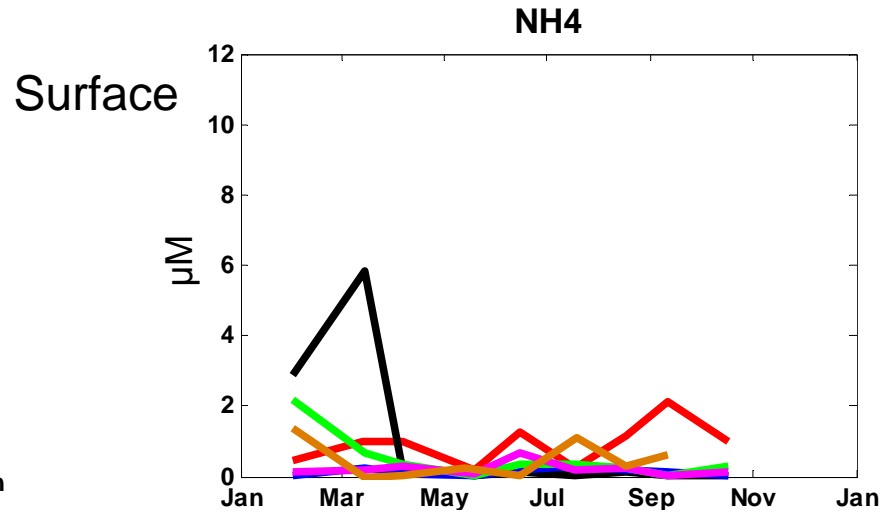
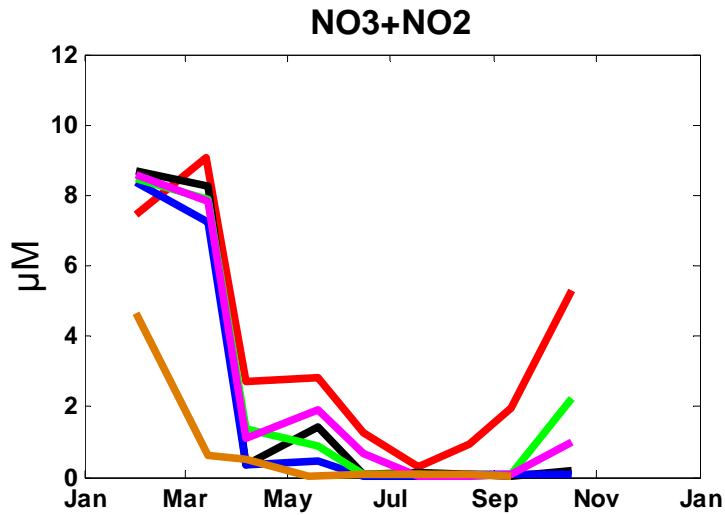


Sea Surface Temperature ($^{\circ}\text{C}$)



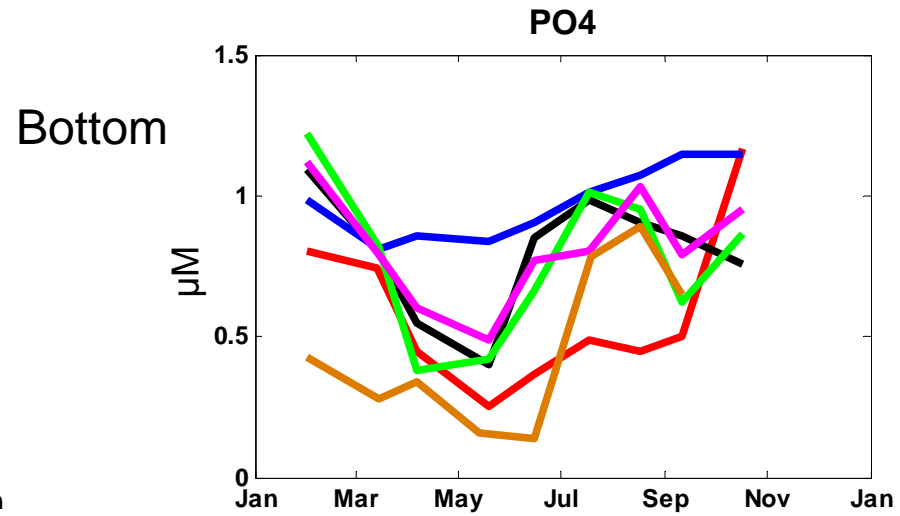
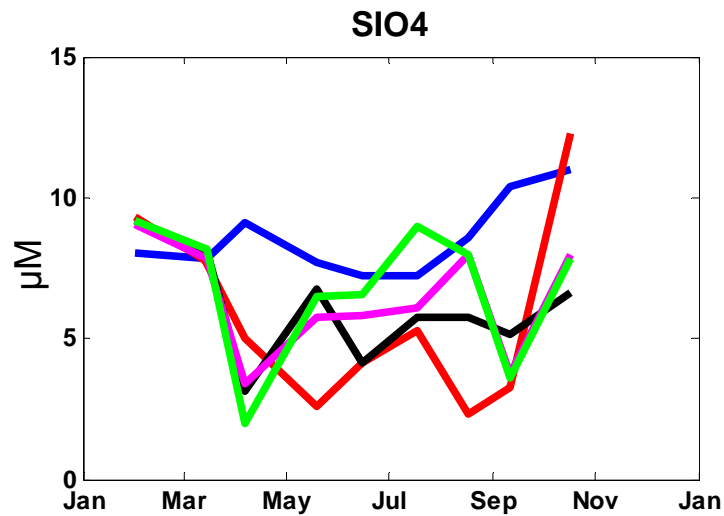
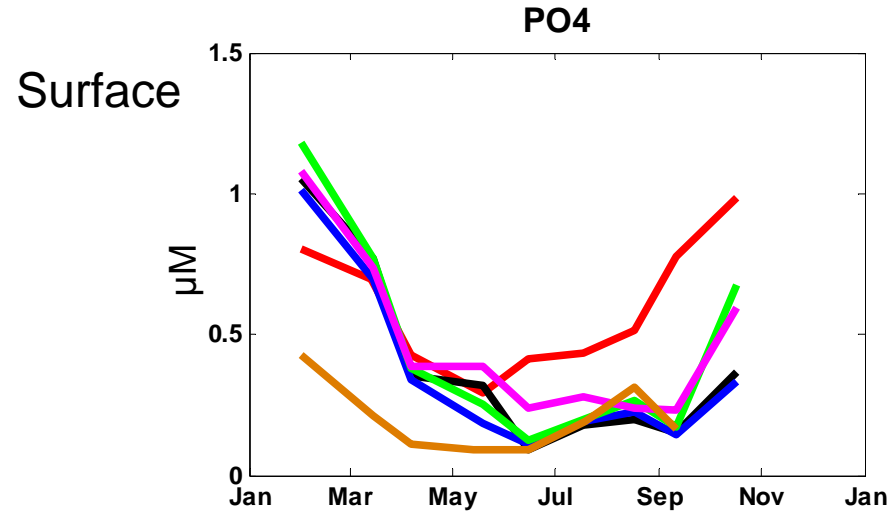
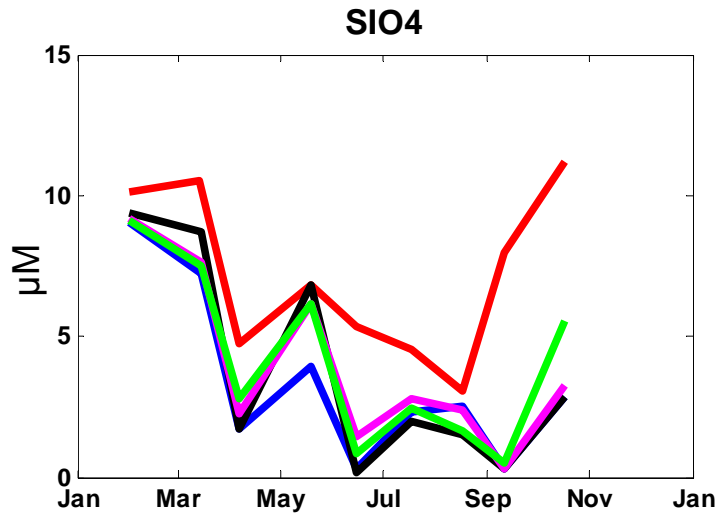
Collage provided by M. Mickelson

2011 Nutrients - $\text{NO}_3 + \text{NO}_2$ & NH_4



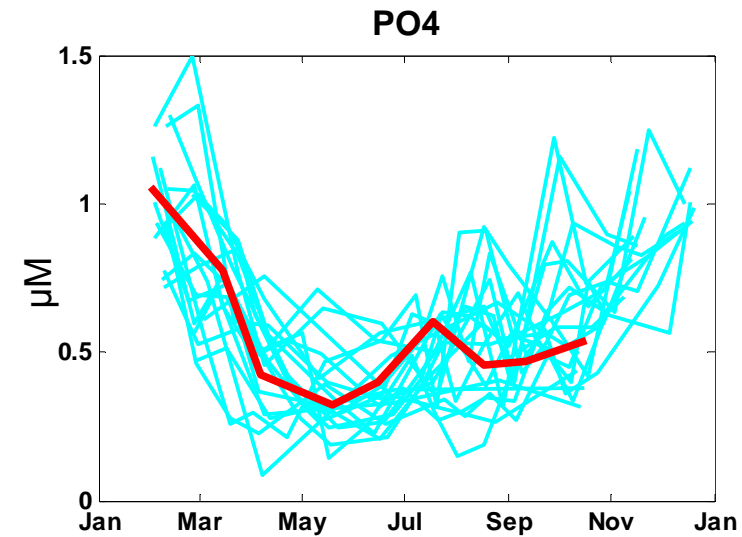
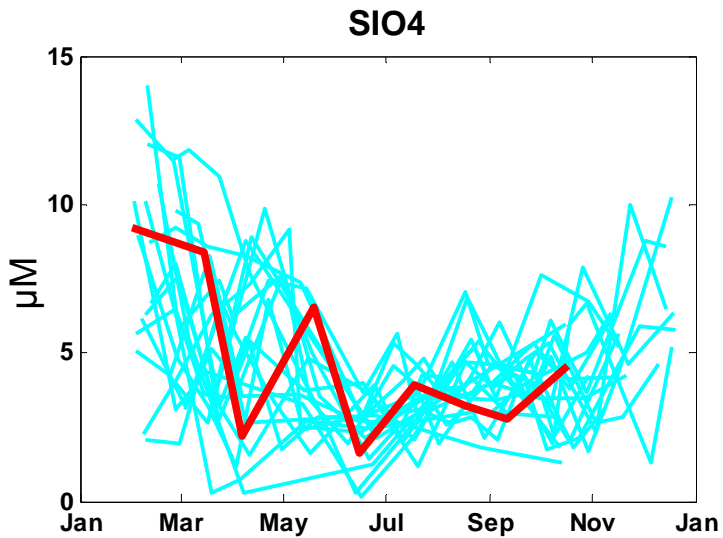
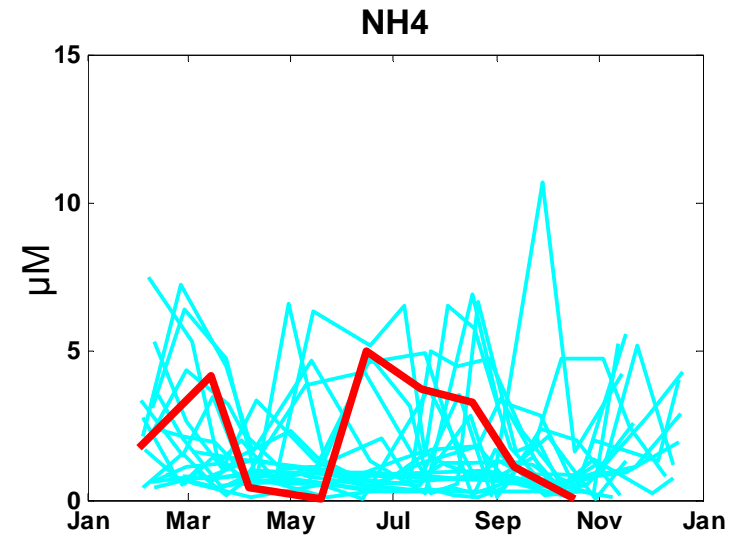
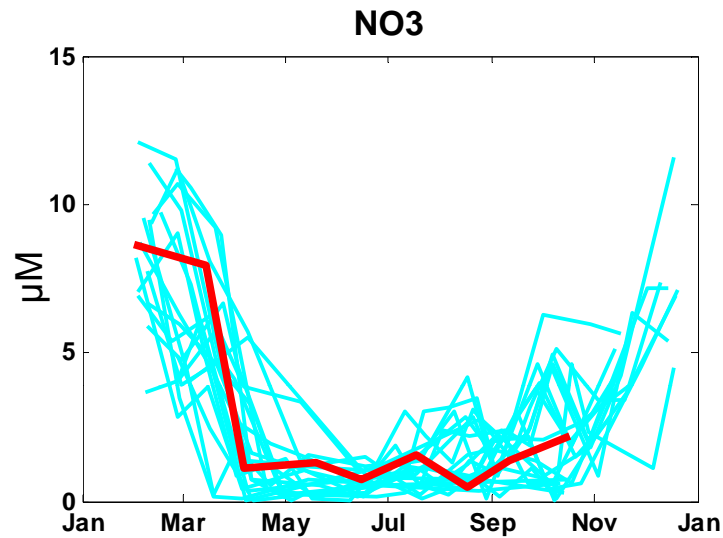
— **F23**
 — **N18**
 — **F22**
 — **F13**
 — **F06**
 — **F01**

2011 Nutrients - SiO₄ & PO₄

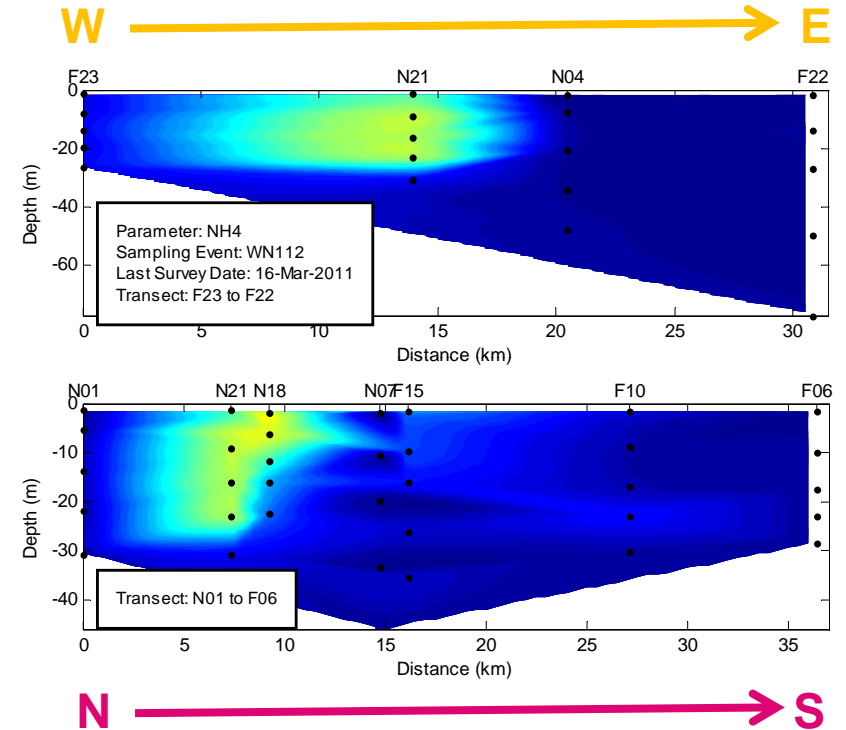
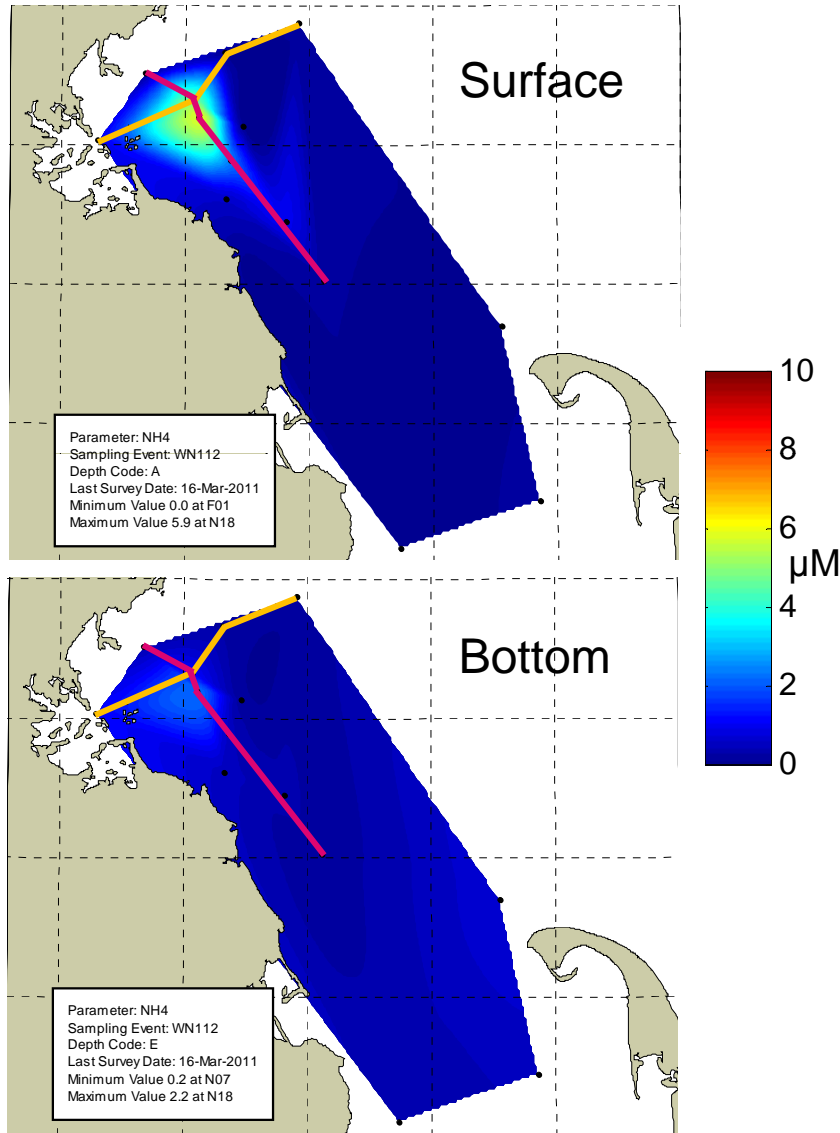


— **F23**
 — **N18**
 — **F22**
 — **F13**
 — **F06**
 — **F01**

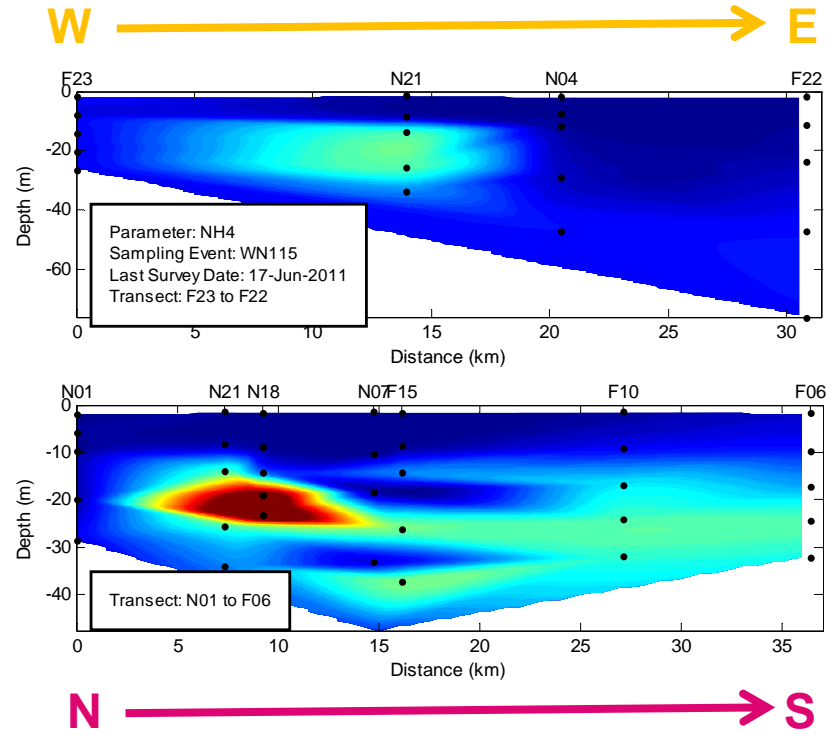
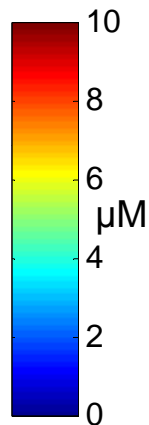
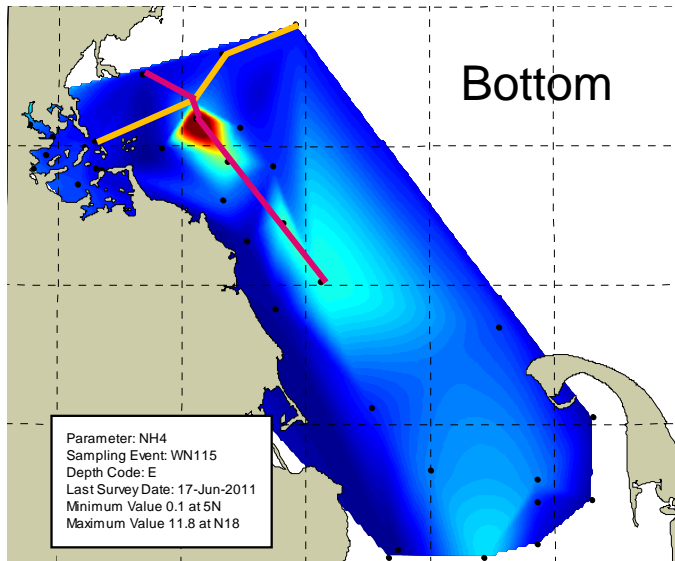
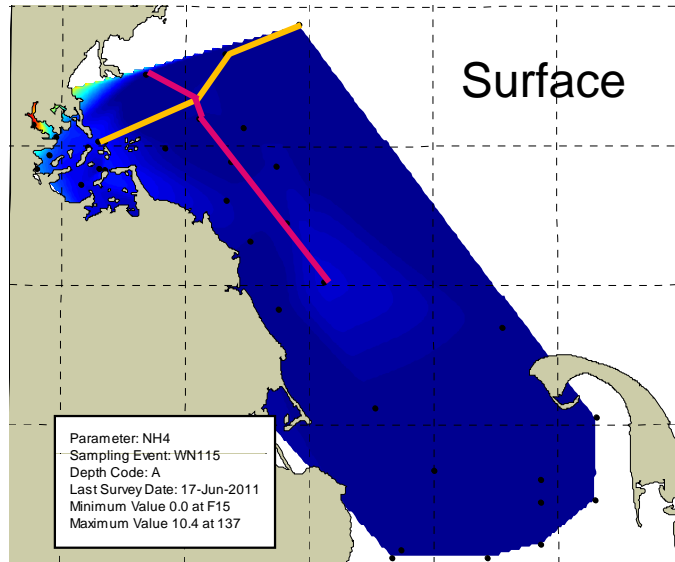
Nearfield – N18 Averages



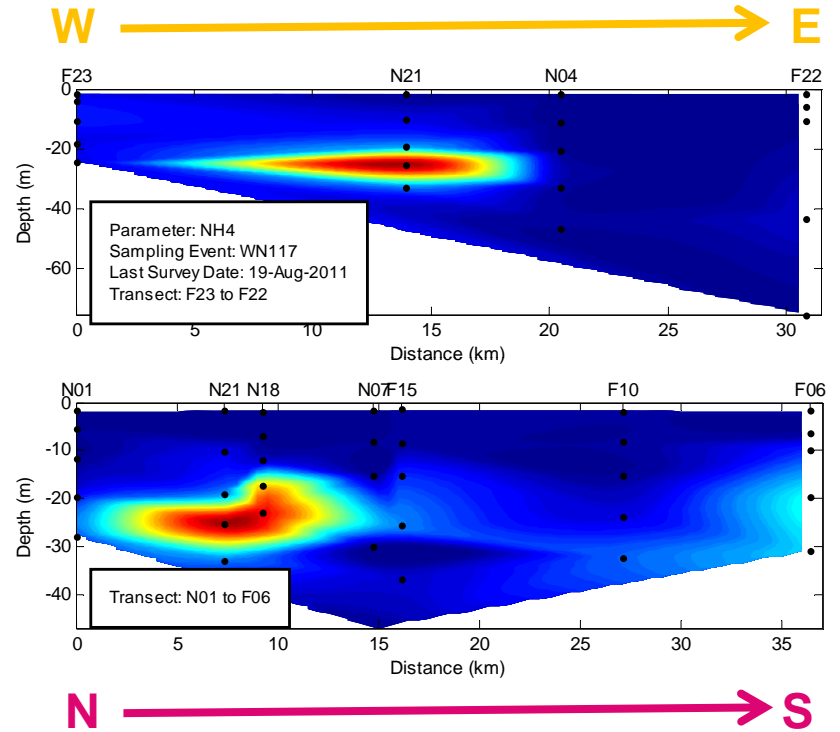
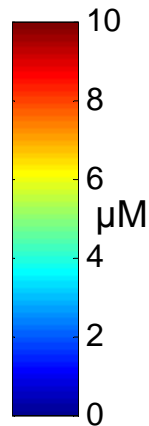
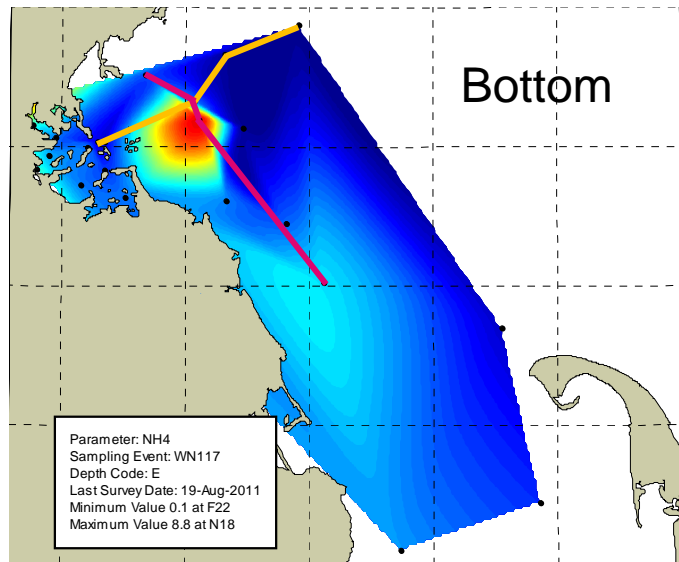
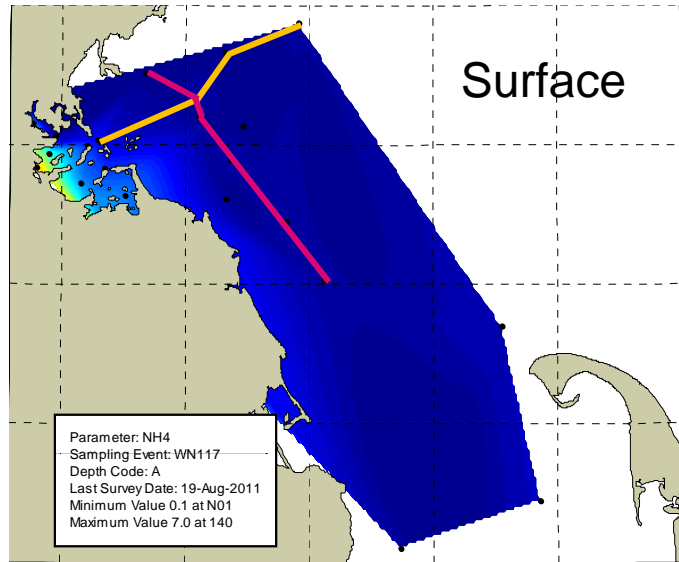
March 2011 - NH₄



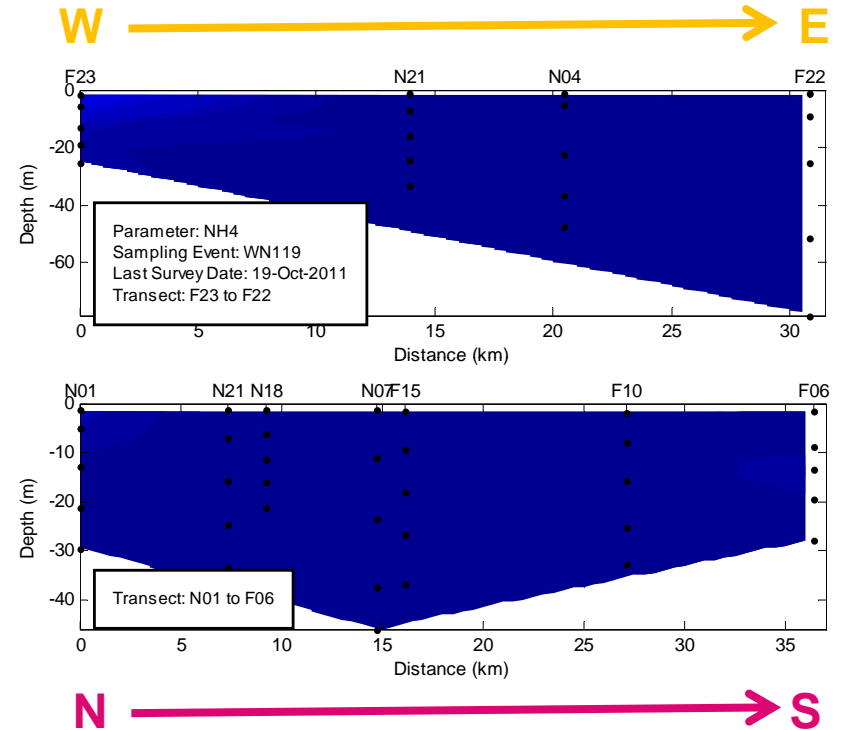
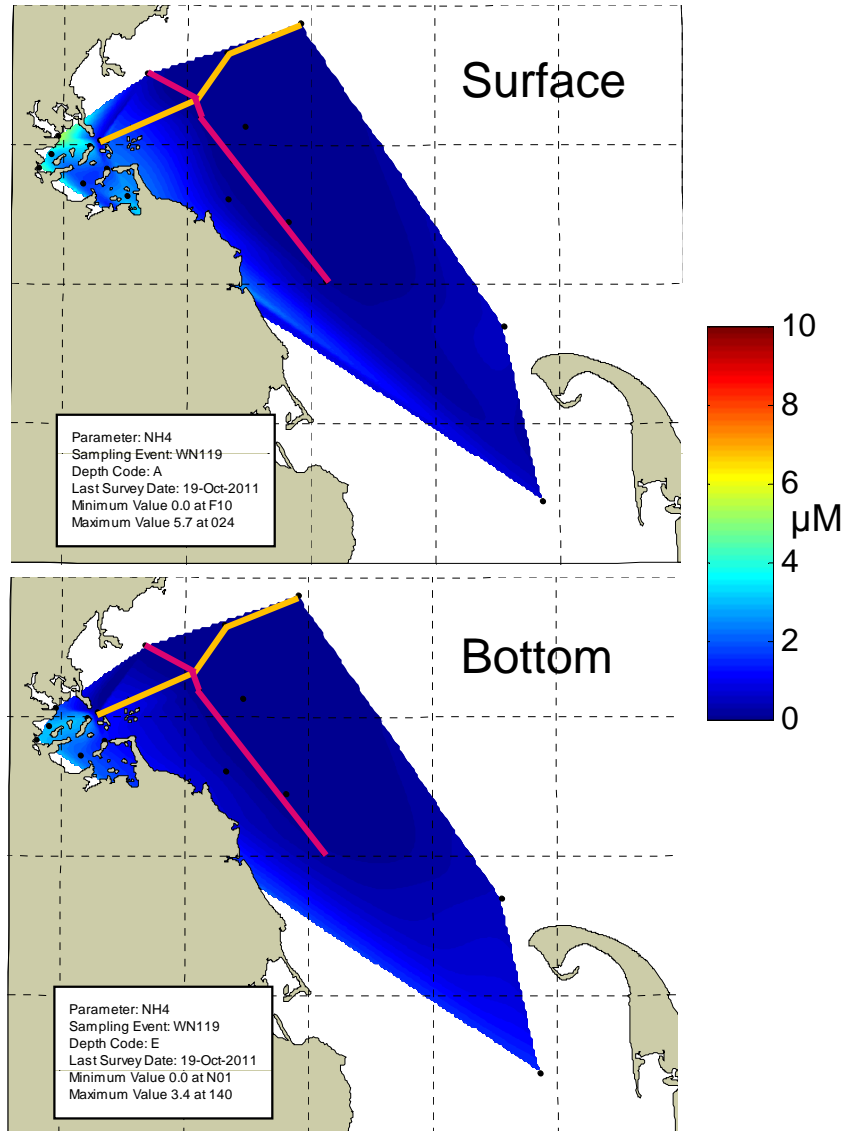
June 2011 - NH₄



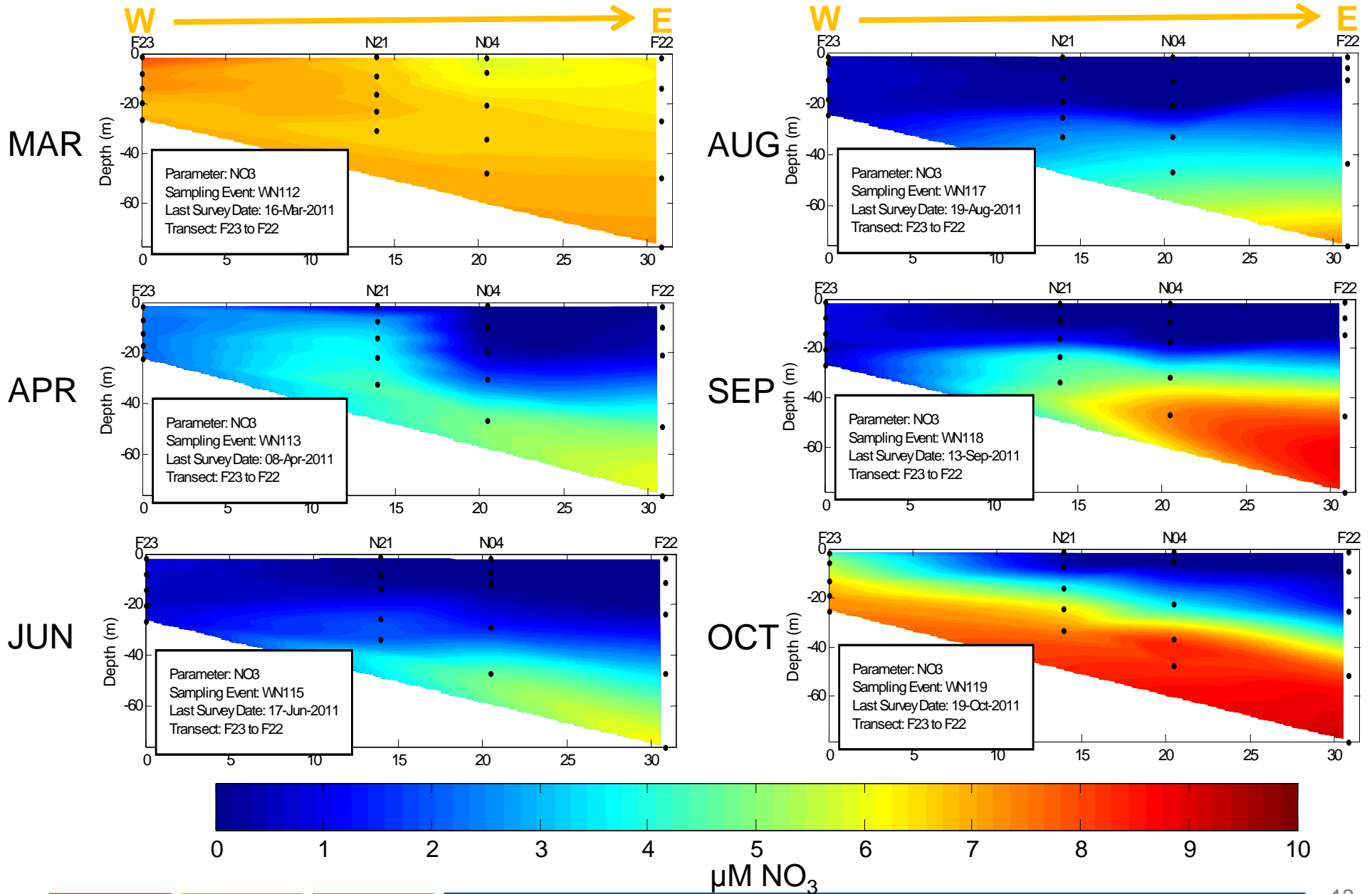
August 2011 - NH₄



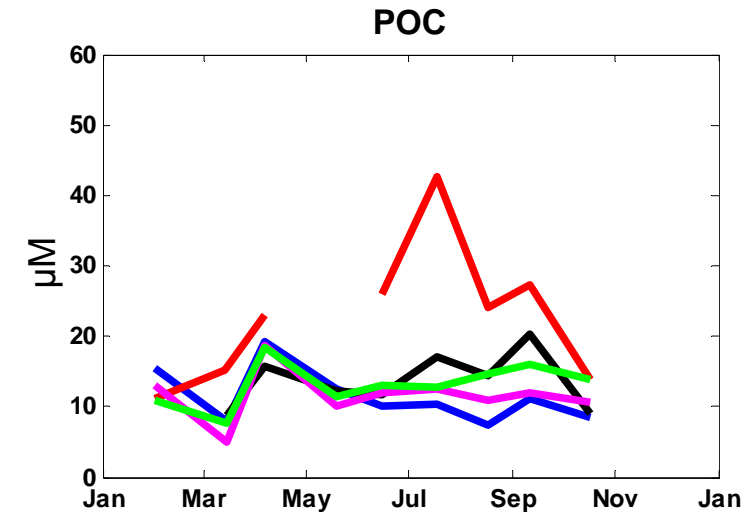
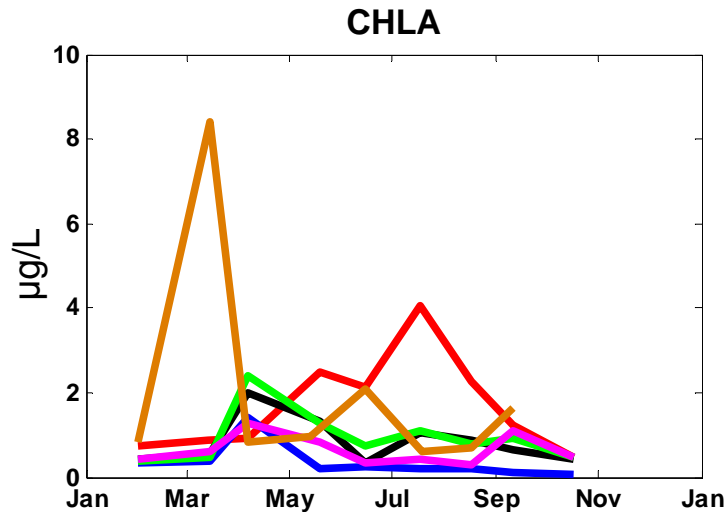
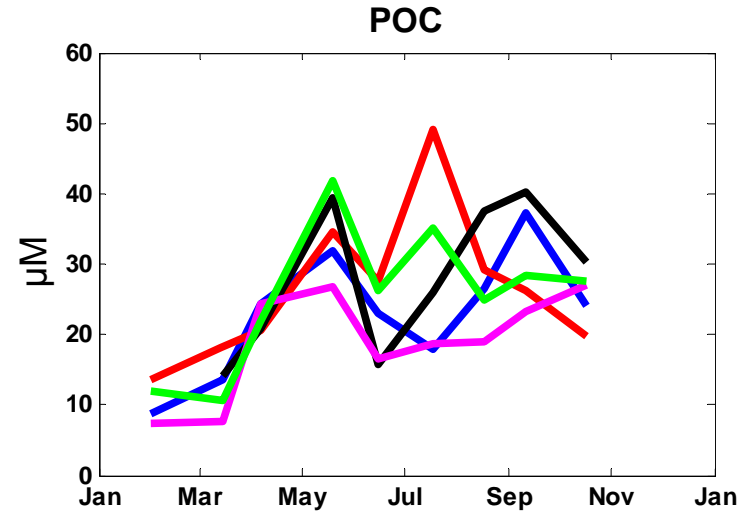
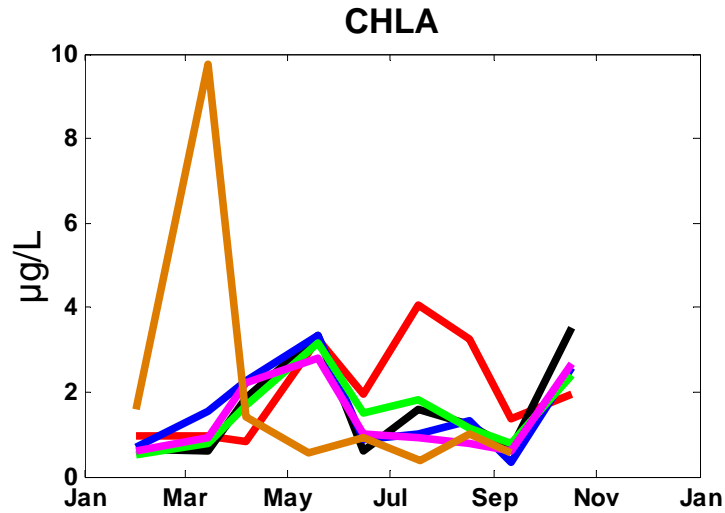
October 2011 - NH₄



2011 NO₃ – W to E transect

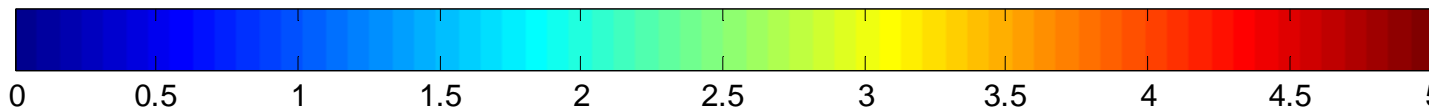
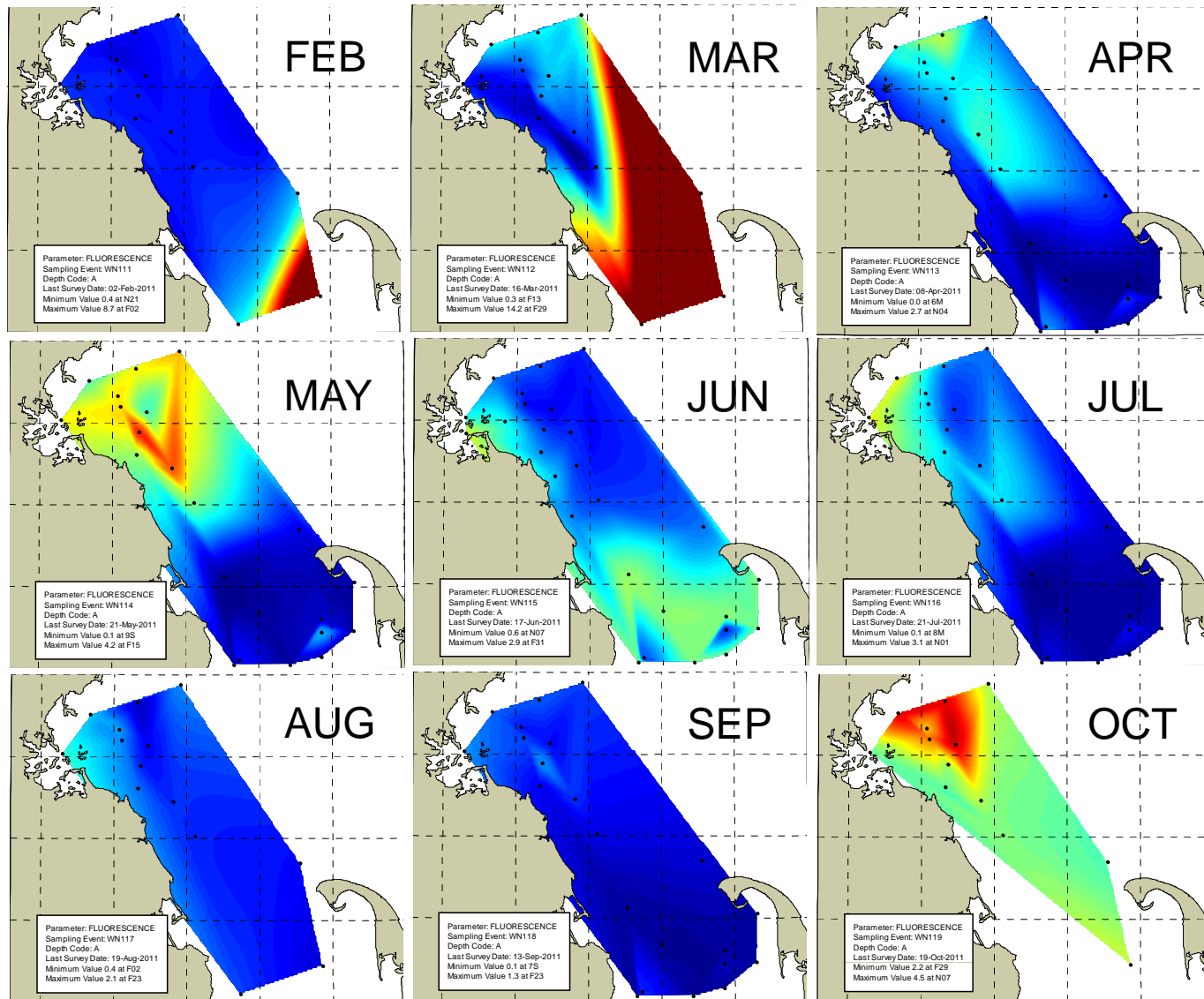


2011 ChlorophyllII & POC

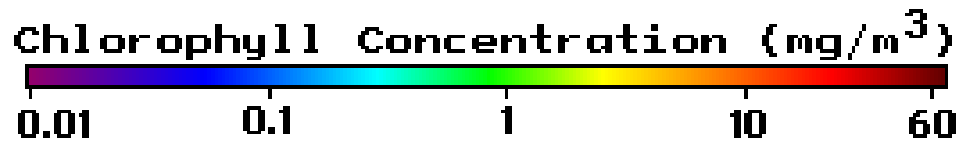
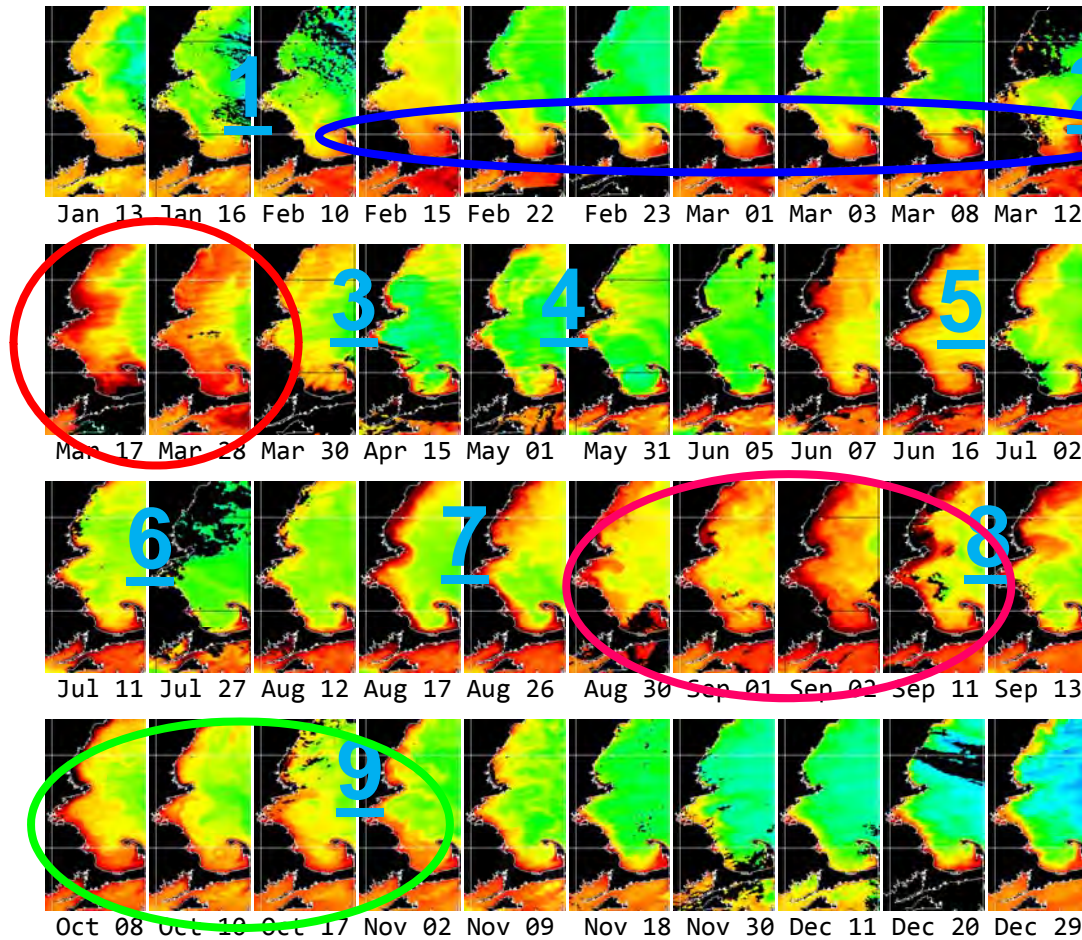


— **F23**
 — **N18**
 — **F22**
 — **F13**
 — **F06**
 — **F01**

Surface Chla Fluorescence ($\mu\text{g/L}$)



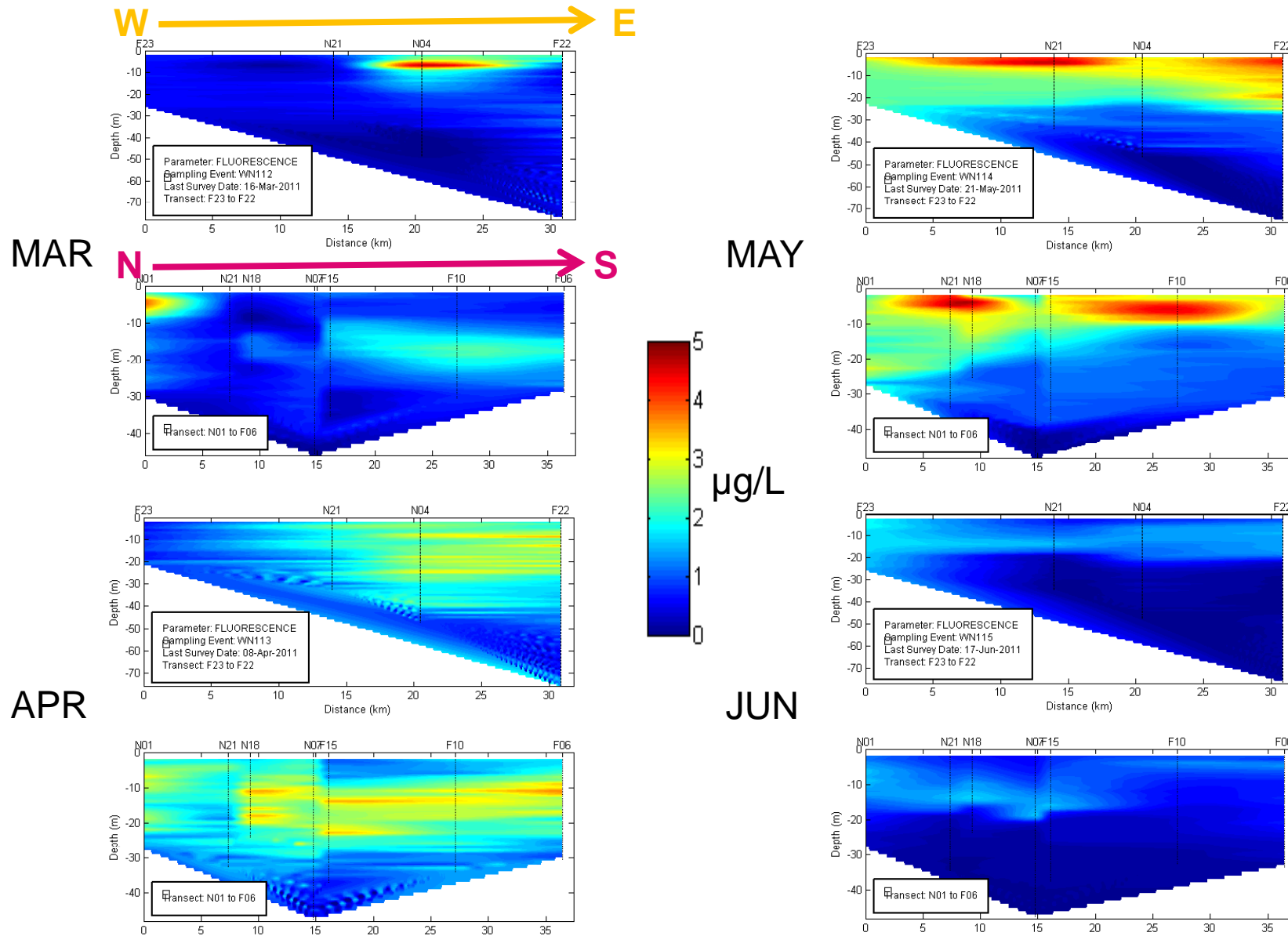
MODIS Chla Fluorescence



Collage provided by M. Mickelson

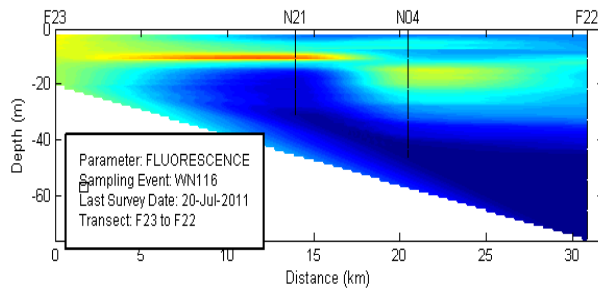
- February bloom in CCB
- Regional Phaeocystis Bloom
- Late Summer diatom bloom (*Skeletonema* dominated)
- October dinoflagellate bloom (*Prorocentrum micans*)

2011 Chla fluorescence

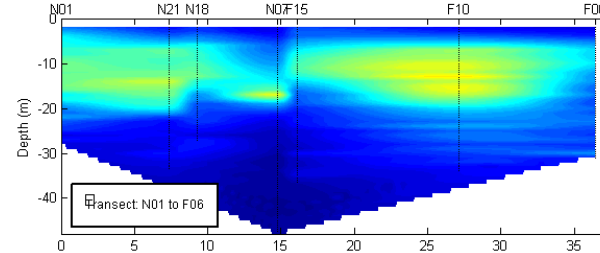
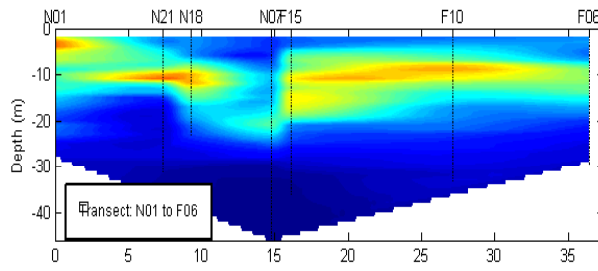
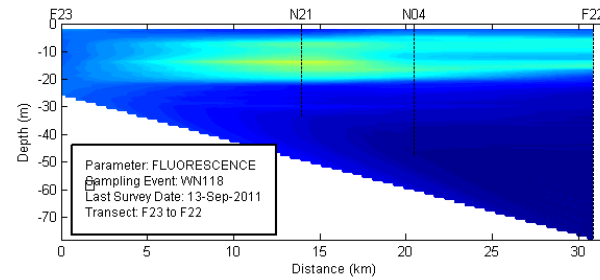


2011 Chla fluorescence

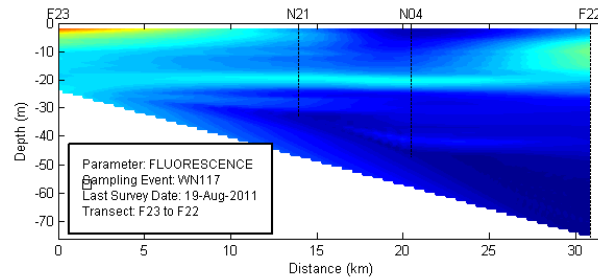
JUL



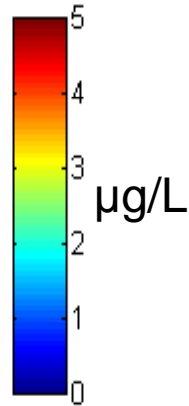
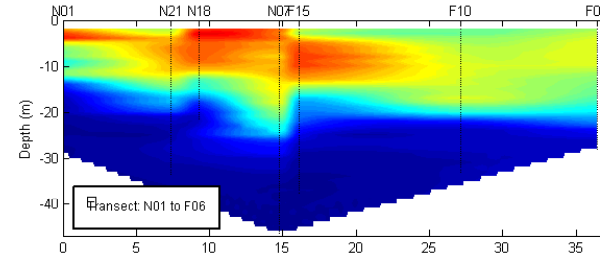
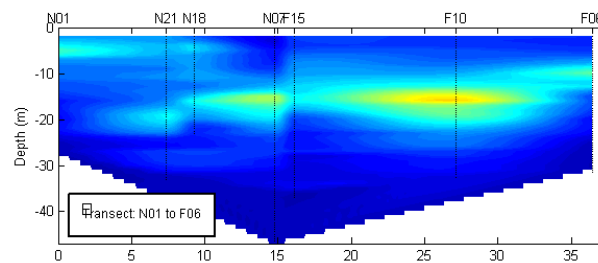
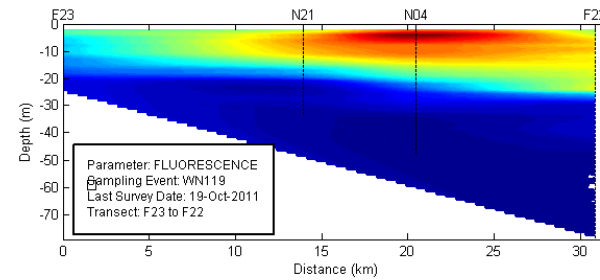
SEP



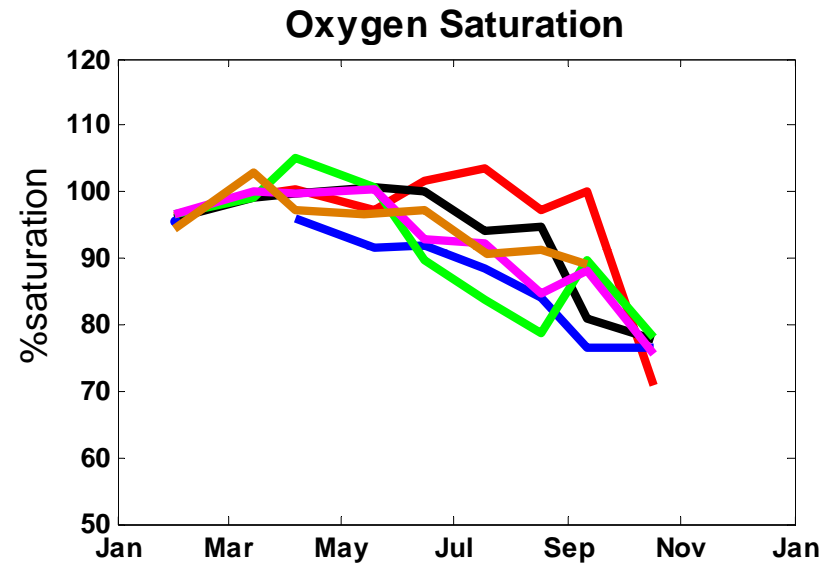
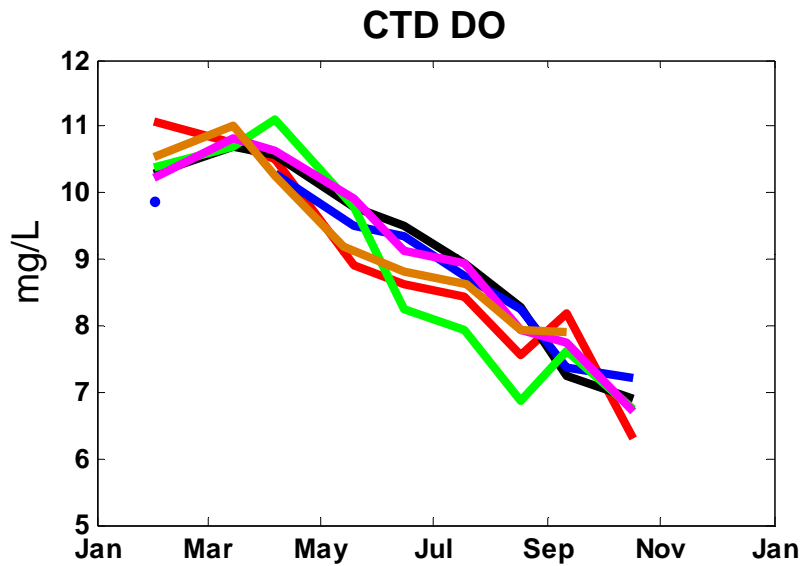
AUG



OCT



2011 – Bottom Water DO



— **F23**
 — **N18**
 — **F22**
 — **F13**
 — **F06**
 — **F01**

Threshold Values for DO and Chlorophyll

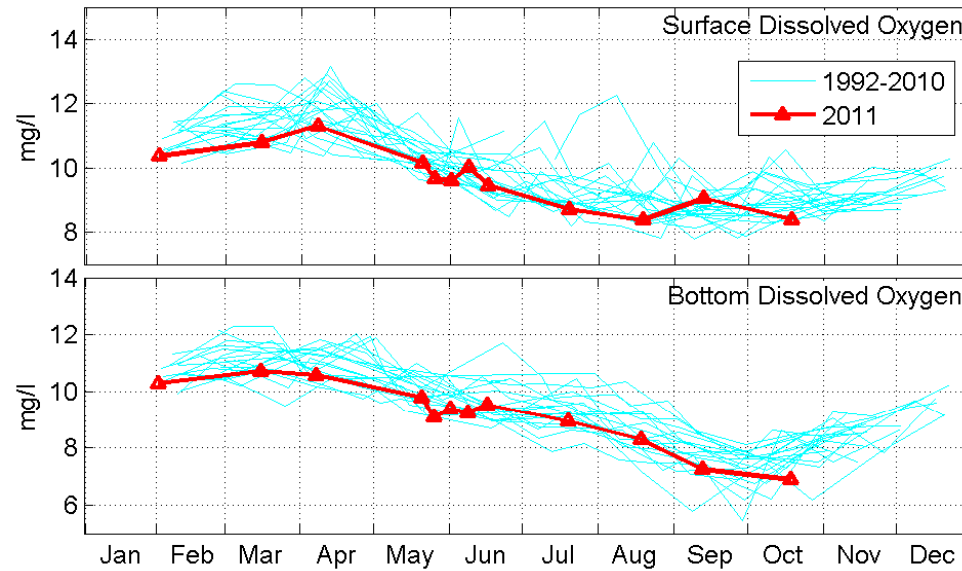
Parameter	Time Period	Caution Level	Warning Level	Background	2011
Bottom Water DO concentration	Survey Mean in June-October	< 6.5 mg/l (unless background lower)	< 6.0 mg/l (unless background lower)	Nearfield 6.05 mg/l Stellwagen 6.23 mg/l	6.78 mg/l 7.21 mg/l
Bottom Water DO %saturation	Survey Mean in June-October	< 80% (unless background lower)	< 75% (unless background lower)	Nearfield - 65.3% Stellwagen - 67.2%	74.4% 76.5%
Bottom Water DO depletion rate	June to October	0.037 mg/l/d	0.049 mg/l/d		0.021 mg/l/d
Chlorophyll	Annual	108 mg/m ²	144 mg/m ²	--	49 mg/m ²
	Winter/spring	199 mg/m ²	--	--	44 mg/m ²
	Summer	89 mg/m ²	--	--	48 mg/m ²
	Autumn	239 mg/m ²	--	--	56 mg/m ²

No DO or Chlorophyll threshold exceedances in 2011

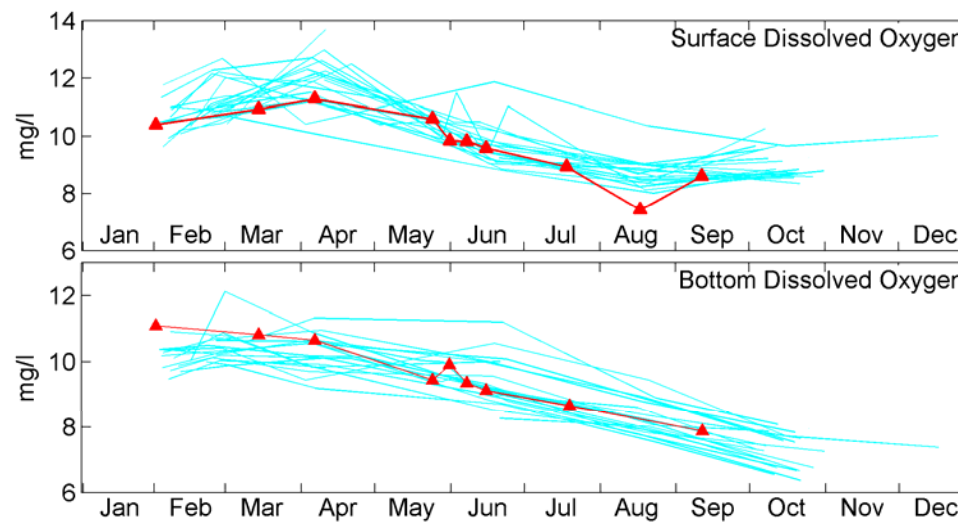
Low chlorophyll levels and relatively high DO concentrations

Bottom DO Nearfield & Stellwagen

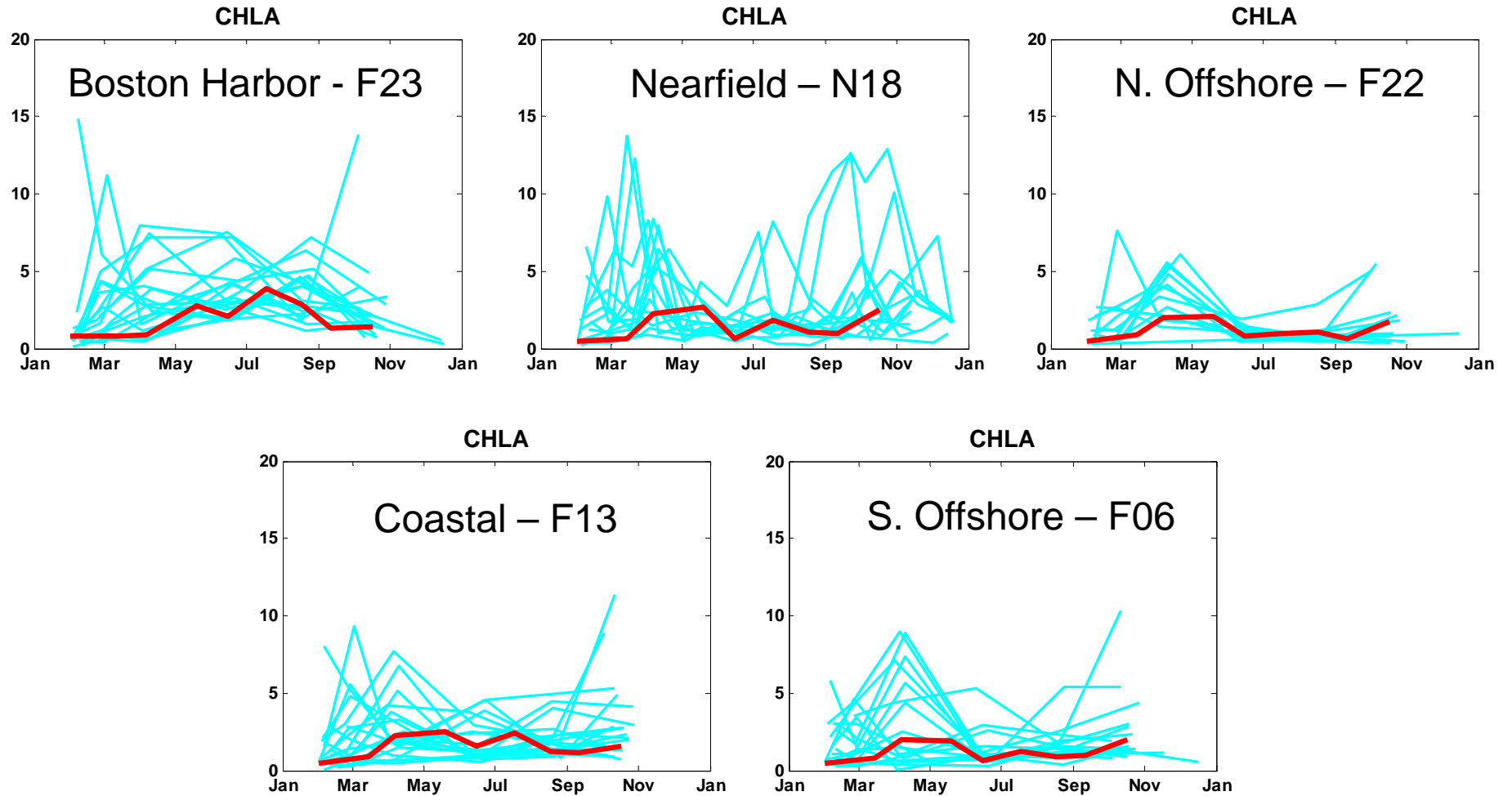
Nearfield
N18



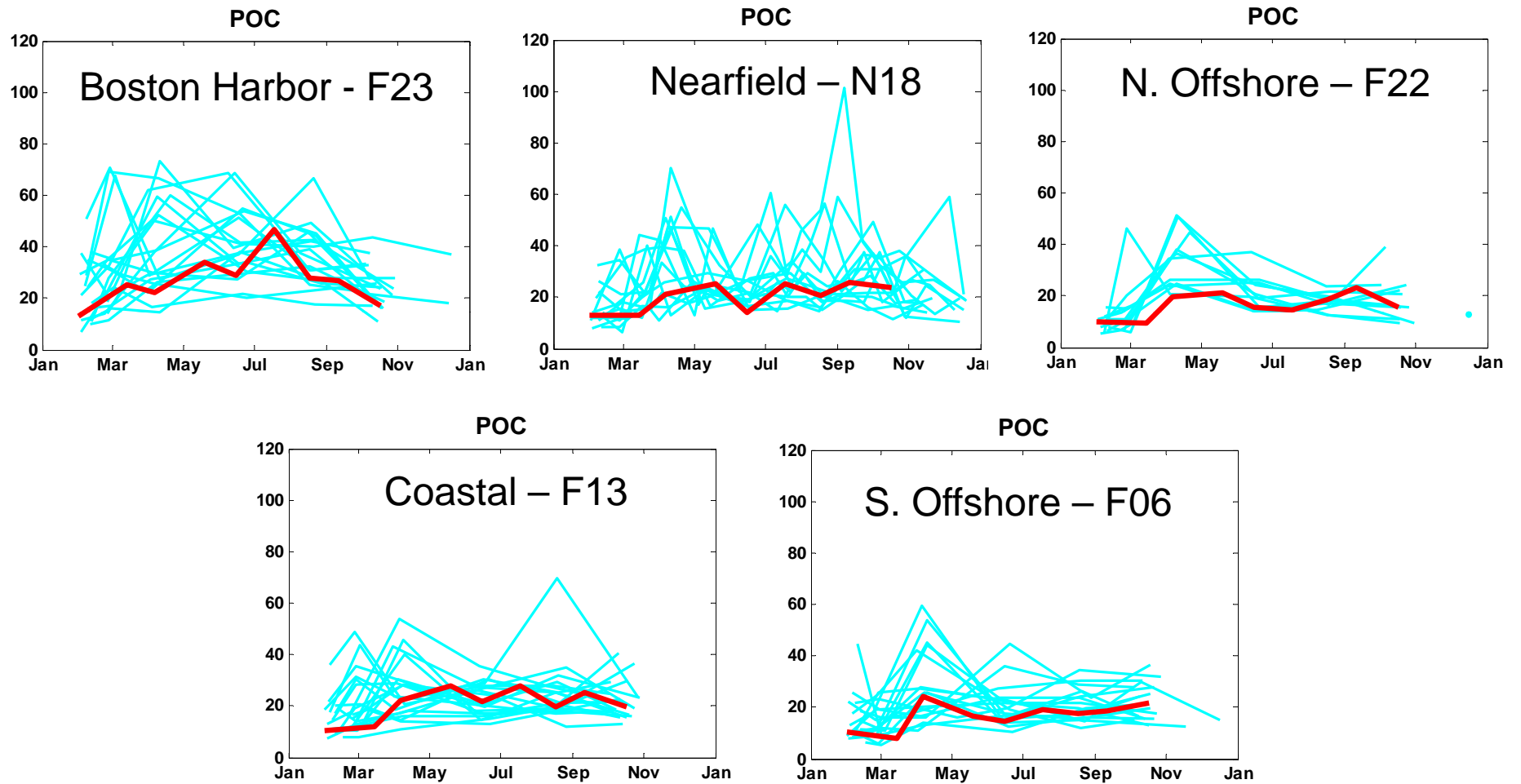
Stellwagen
F22



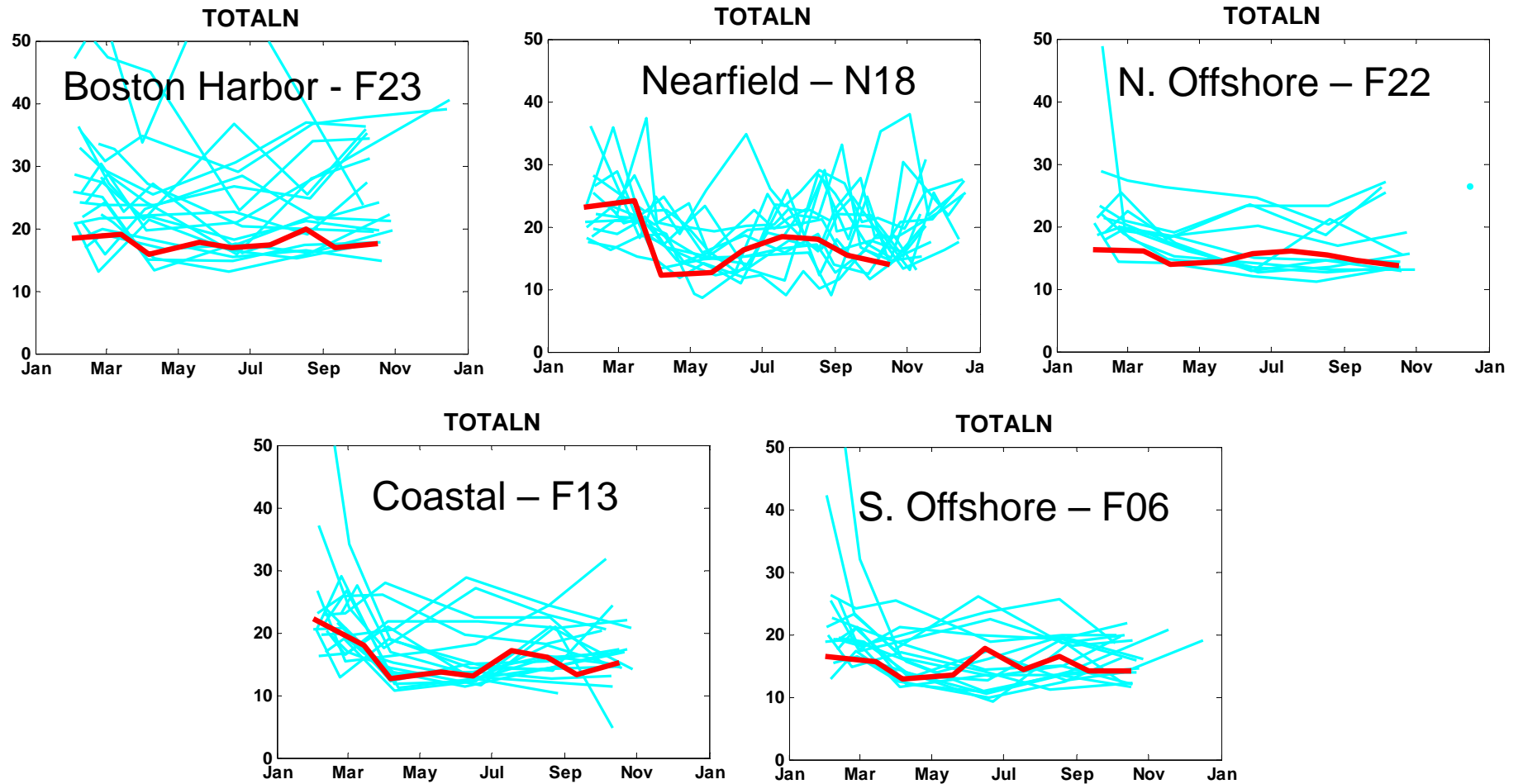
Long term ChlorophyllII ($\mu\text{g/l}$)



Long term POC (μM)



Long term Total N (μM)

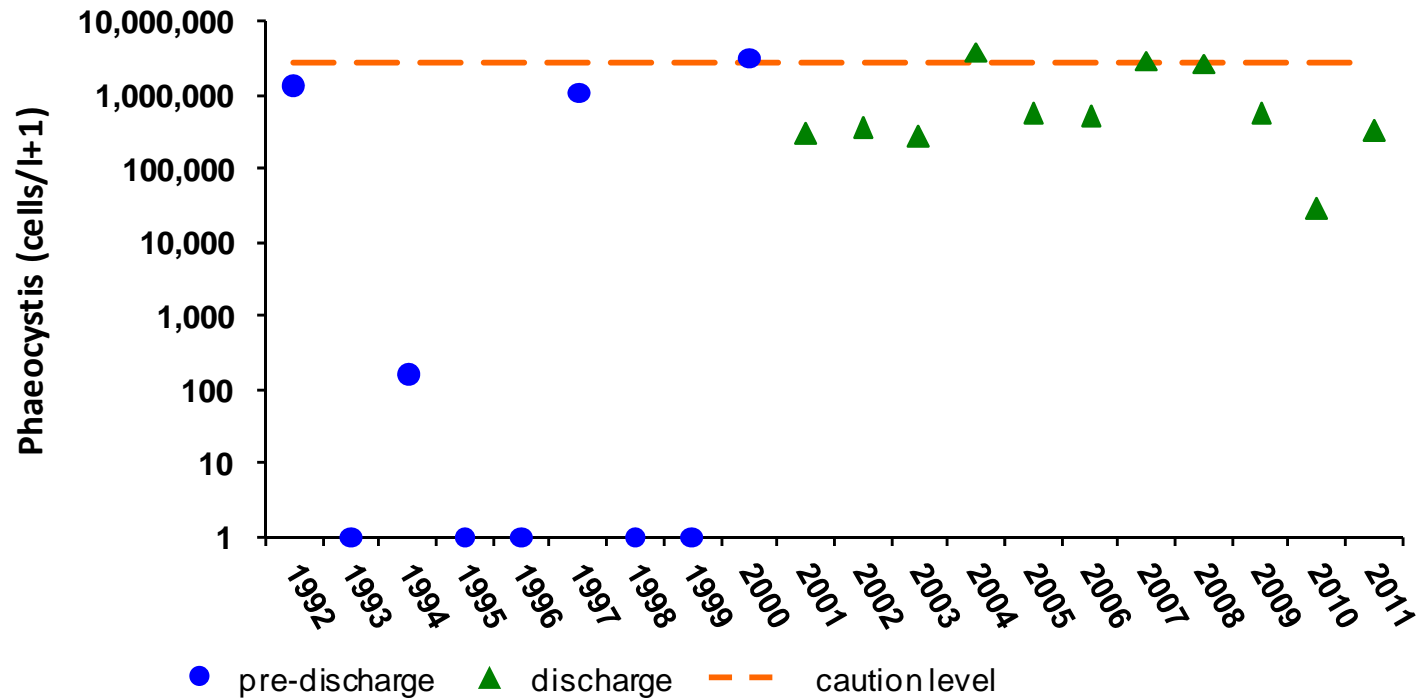


Threshold Values for Nuisance Species

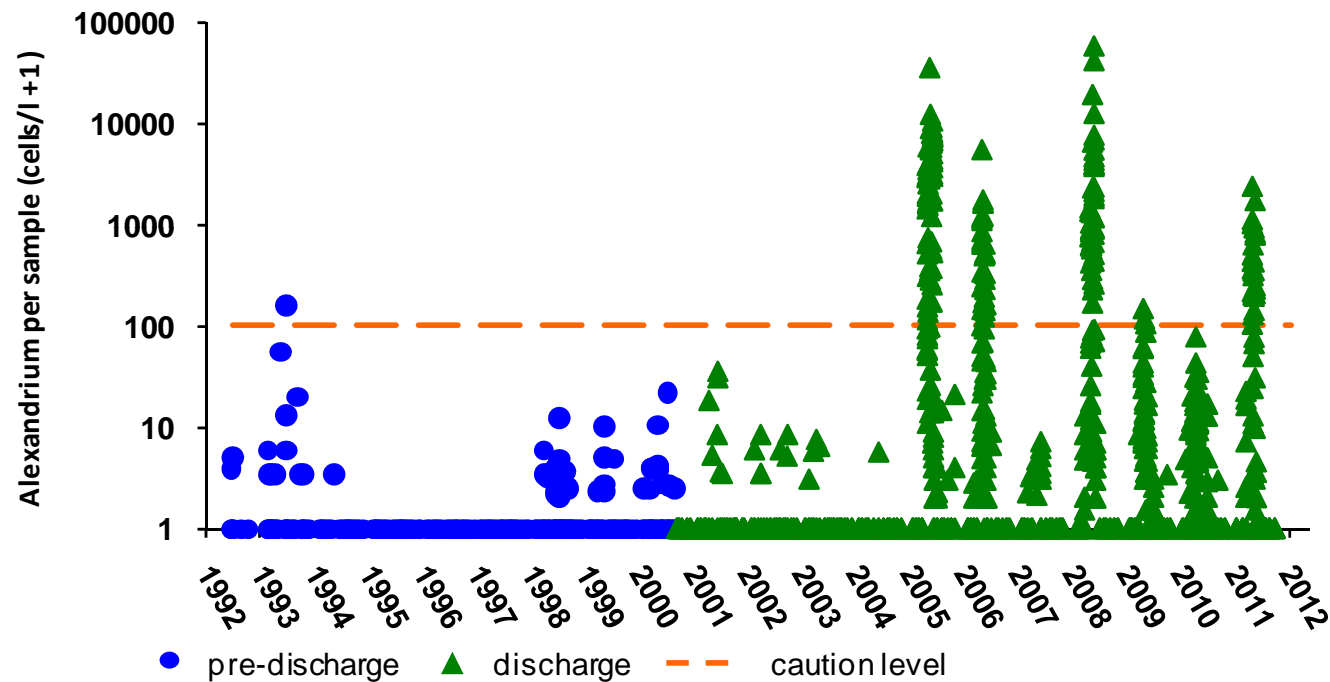
Parameter	Time Period	Caution Level	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
<i>Phaeocystis pouchetii</i> (cells L ⁻¹)	Winter/spring	2,860,000	303,000	366,000	272,000	3,940,000	571,000	526,000	2,960,000	2,720,000	552,000	28,100	338,000
	Summer	357	absent	absent	2,420	164,000	517	16,800	absent	absent	absent	absent	absent
	Autumn	2,960	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent	absent
<i>Pseudo-nitzschia</i> (cells L ⁻¹)	Winter/spring	17,900	8510	1230	149	15.5	202	absent	69	absent	absent	664	absent
	Summer	43,100	163	234	83.5	380	3320	absent	absent	540	absent	53.7	660
	Autumn	27,500	3930	3090	833	1190	80.4	absent	absent	309	71.7	522	1240
<i>Alexandrium</i>	Any nearfield sample	100	35	8	7	5	36,831	5,668	7.2	60,430	151	79	2,454

Alexandrium threshold exceedance in 2011

Phaeocystis winter/spring mean 92-10



Nearfield *Alexandrium* Abundance



Moderate bloom for 2011 in Massachusetts Bay (as forecast)

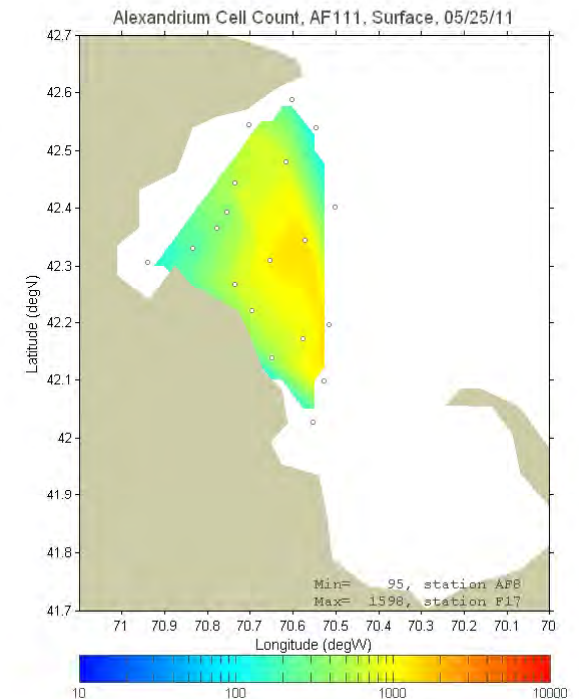
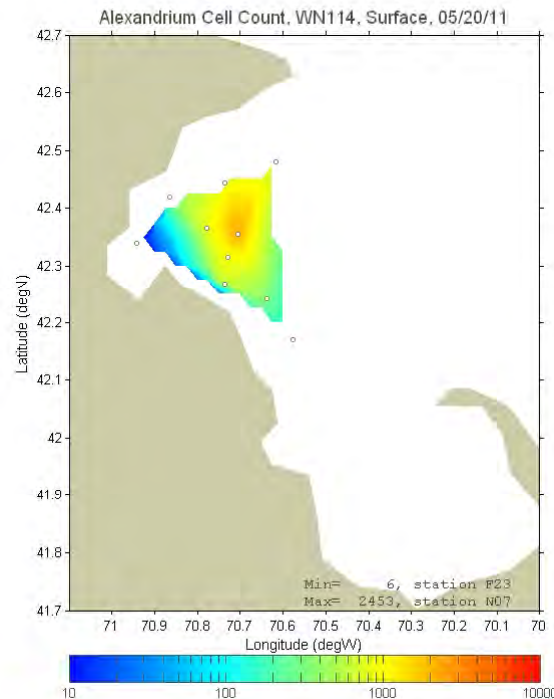
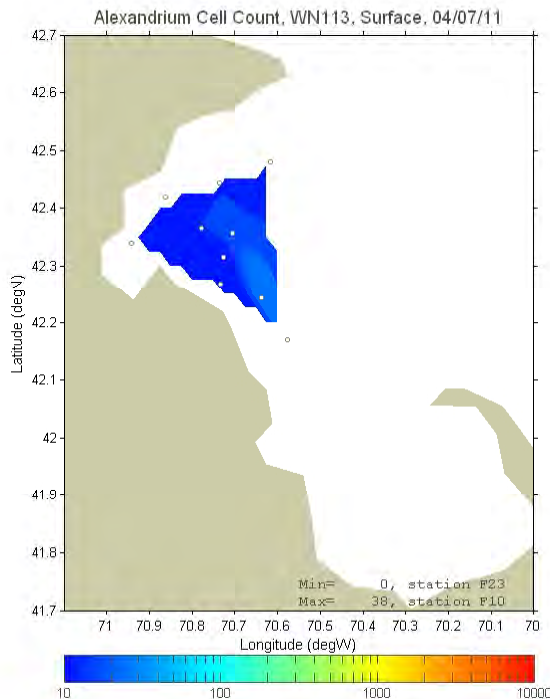
Shellfishing closures throughout Massachusetts Bay

2011 *Alexandrium* "Bloom" in the Bay

April 4

May 20

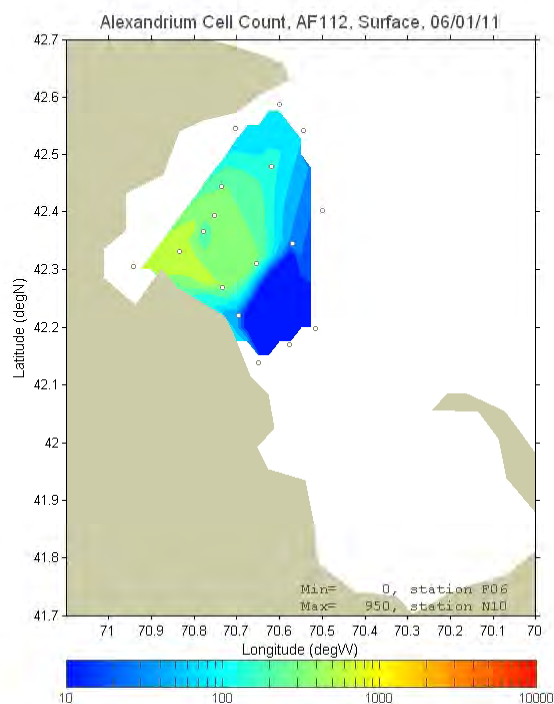
May 25



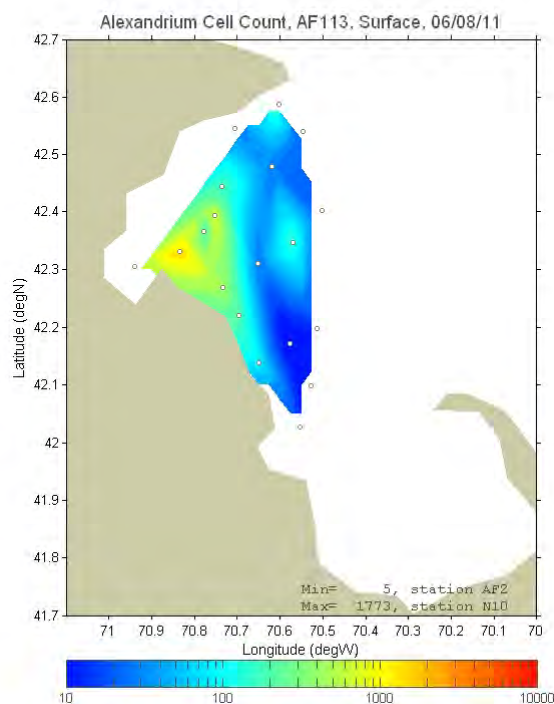
- Early presence of *Alexandrium* in MB in April – low abundance
- Nearfield peak abundance May 20 at N07 – 2,453 cells/l
- Relatively high abundances present through late May

2011 *Alexandrium* "Bloom" in the Bay

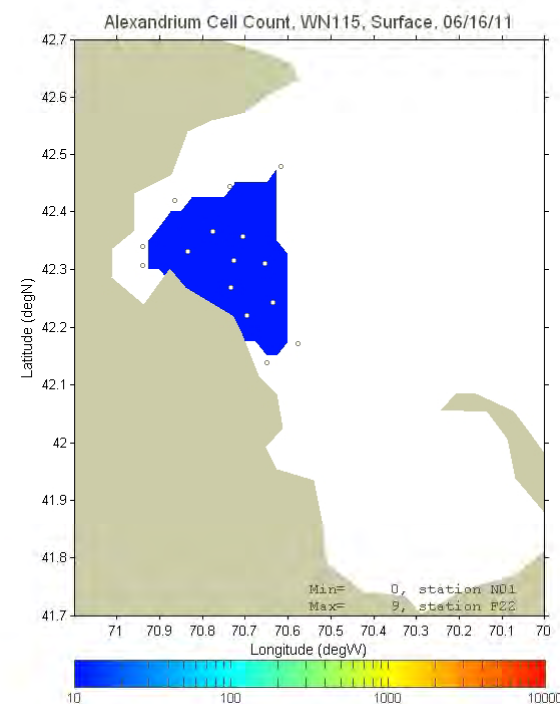
June 1



June 8

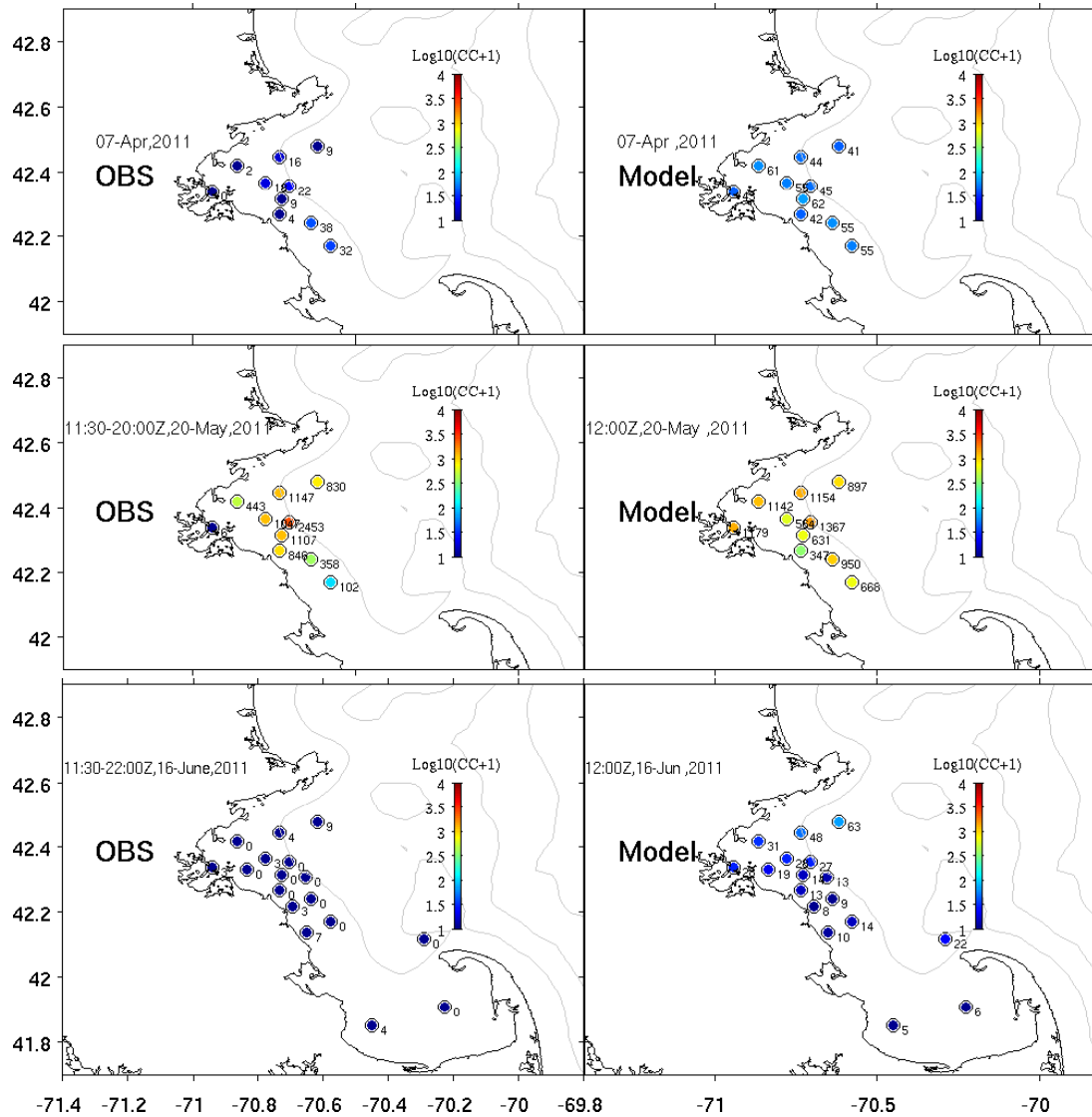


June 16



- Elevated counts (500-1800 cells L⁻¹) in nearfield and coastal waters in early June
- Bloom was over by mid-June
- Overall a Moderate *Alexandrium* event in Massachusetts Bay
 - Abundances in the 1000s cells L⁻¹
 - PSP toxicity closures from Cape Ann south to Plymouth

2011 Observations vs. Model



- Good overall concurrence between data and model
- Captured initial, peak and end of the bloom
- Some variability, but essentially captured the temporal and spatial trends in the observed data

Summary

- Nutrients
 - Lower nutrients in CCB in February and March (NO_3 and PO_4) compared to MB stations (early winter/spring bloom of centric diatoms and microflagellates)
 - Surface NO_3 and NH_4 depleted from March to April surveys in MB, sharp decrease in SiO_4 too, but still present in April and increased by May (mixed diatom/*Phaeocystis* bloom in late March and April)
 - Surface nutrients remained low during summer with increasing concentrations and variability into the fall
 - Bottom nutrients increased in summer and into the fall
 - NH_4 plume clearly observed in the surface waters during well mixed conditions and elevated subsurface concentrations were seen in the nearfield and vicinity during stratified conditions – in October no evidence of plume in NH_4 measurements
 - Except for the elevated NH_4 levels in the effluent plume (which have been consistently high since diversion to the bay outfall September 2000) – nutrient levels in 2011 were similar to those observed in 1992-2010 in Massachusetts Bay.

Summary

- Chlorophyll
 - High chlorophyll in CBB in February and March (annual maxima) with early winter/spring bloom of *Chaetoceros* and microflagellates
 - Sharp decrease in chlorophyll levels in CCB in April and remained low for rest of 2011
 - Steady increase in chlorophyll (and POC) from February to May at MB stations coincident with April *Phaeocystis* bloom and May increase in *Skeletonema* & *Thalassiosira*
 - MB stations had peak chlorophyll and POC concentrations in both spring and fall 2001 with comparable levels achieved each season with lower levels during the summer.
 - Boston Harbor station peak chlorophyll and POC levels were observed in July and August coincided with peak phytoplankton abundance during a nearshore centric diatom bloom (dominated by *Dactyliosolen fragilissima*)
 - Increase in nearfield chlorophyll in late September during a fall diatom bloom
 - There was a late summer/fall increase in chlorophyll and POC in MB with POC levels peaking in September (bloom of centric diatom *Skeletonema*) and surface chlorophyll levels increasing in October once the water column had become mixed
 - The elevated October chlorophyll levels in MB were also coincident with a bloom of the large dinoflagellate *Prorocentrum micans*

Summary

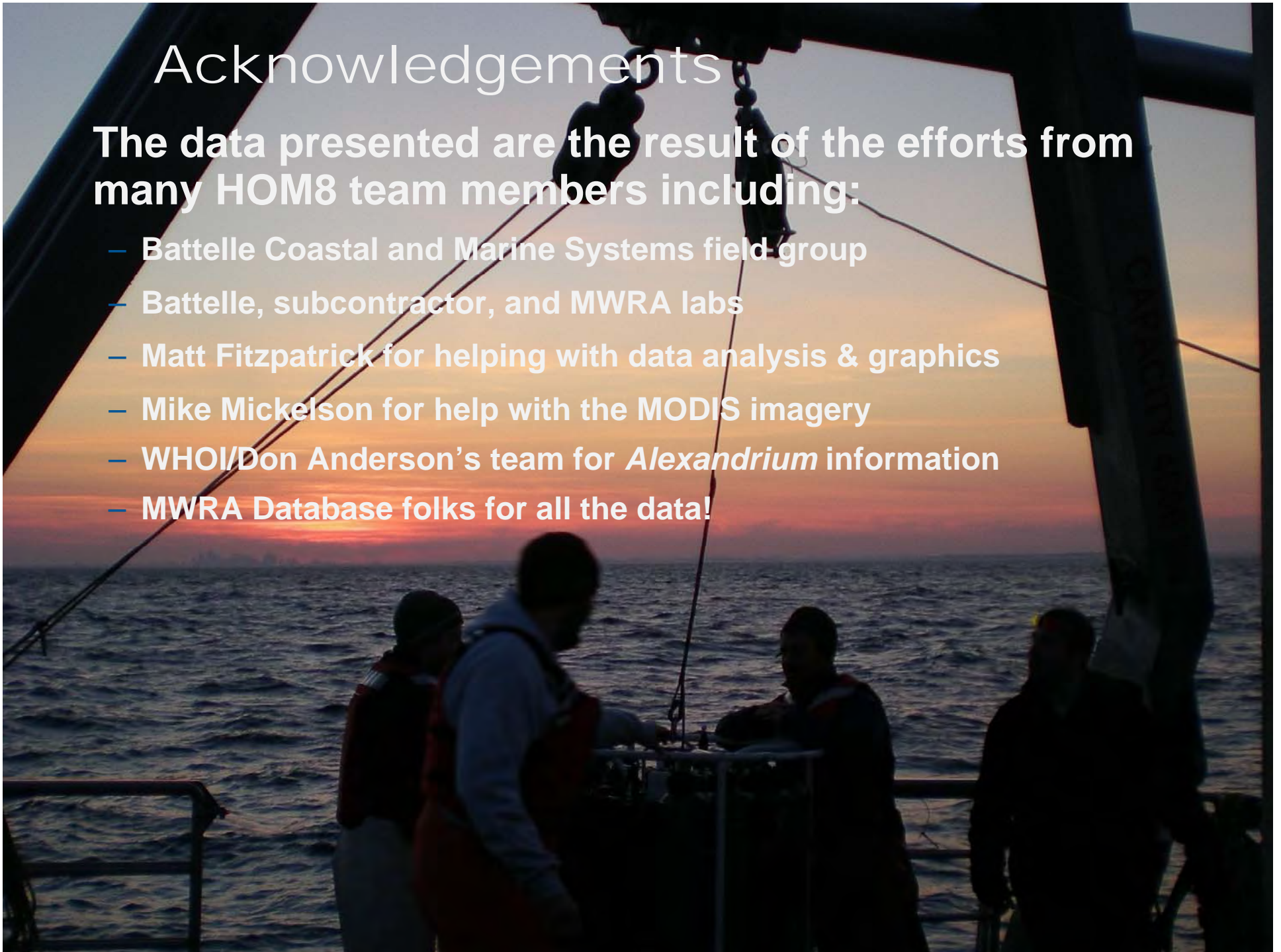
- Dissolved Oxygen
 - Bottom water 2011 levels and rate of decrease comparable to historic results at the nearfield and Stellwagen Basin stations
 - There has been no apparent change in bottom water DO over the 1992-2011 period (interannual variability driven by regional processes)

- Contingency Plan Thresholds (*Alexandrium* exceedance only)
 - Spring and fall phytoplankton blooms were minor in comparison to past blooms and chlorophyll levels were relatively low resulting in low seasonal and annual chlorophyll threshold values
 - DO concentrations were well above threshold levels and percent saturation were above baseline background levels in in both nearfield and Stellwagen Bank bottom waters
 - *Phaeocystis* present in the bays in February-April, but at moderate abundances
 - *Pseudo-nitzschia* abundance continues 10+ year trend of low abundances
 - A moderate *Alexandrium* bloom was observed in MB in 2011
 - Abundances peaked at 2,500 cell/L in the nearfield in late May.
 - Shellfishing closures extended across western MB from Cape Ann to Duxbury Bay.
 - Continues trend of larger blooms and higher PSP toxicity in MB since the 2005 red tide event

Acknowledgements

The data presented are the result of the efforts from many HOM8 team members including:

- Battelle Coastal and Marine Systems field group
- Battelle, subcontractor, and MWRA labs
- Matt Fitzpatrick for helping with data analysis & graphics
- Mike Mickelson for help with the MODIS imagery
- WHOI/Don Anderson's team for *Alexandrium* information
- MWRA Database folks for all the data!



Appendix C

Phytoplankton

2011 MWRA Phytoplankton Monitoring Summary

David Borkman, URI

Phytoplankton monitoring was conducted as part of the 2011 MWRA comprehensive water column monitoring program. All phytoplankton analyses were conducted according to procedures described in Libby *et al.* (2011). 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) phytoplankton samples. Phytoplankton samples were collected from ten Massachusetts Bay stations at two depths (near-surface and chlorophyll maximum depths) during nine monthly surveys from February to October 2011. This was the first year of the revised monitoring program in which all ten stations were sampled for phytoplankton during a single day, synoptic survey. 2011 was the 20th consecutive year of MWRA phytoplankton monitoring (1992-2011).

2011 Phytoplankton Annual Cycles

The 2011 phytoplankton annual cycle was characterized by relatively reduced winter-spring phytoplankton abundance (with exception of a modest April *Phaeocystis pouchetii* bloom) and elevated summer phytoplankton abundance. As such, the 2011 phytoplankton annual cycle had an annual peak in summer or autumn at most stations (slide 7). Only the nearfield stations had total phytoplankton annual cycles characterized with annual maxima in relative peaks in the late spring (April; slide 7). This peak was due to a modest *Phaeocystis pouchetii* bloom. 2011 total phytoplankton abundance was moderate to low compared to levels observed in previous years (slide 7) and the key 2011 phytoplankton events were a reduced or absent winter-spring diatom bloom, a modest April *Phaeocystis pouchetii* bloom, a series of summer centric diatom blooms and modest dinoflagellate blooms in spring and autumn.

Microflagellate abundance during 2011 was at the low end of the range observed during 1992-2011 (slide 8). Microflagellates had maximum annual values in summer or autumn of 2011 with peaks at individual stations in June (coastal station F13), August (southern offshore station F06) and October 2011 (nearfield and northern offshore stations). A late autumn annual peak in microflagellate abundance was also observed in 2010 at nearfield and northern stations. This late autumn peak in microflagellates appears to be a new, emerging pattern that may be related to warmer water late into the autumn and a possible delay in the onset of winter un-stratified conditions in the water column.

The 2011 centric diatom annual cycle had a summer character. Annual maximum centric diatom abundance was observed in the summer or autumn at all stations monitored (slide 9). Centric diatom abundance was at the lowest end of the range of observed abundance, with values of $<100,000$ cells L^{-1} , at most stations during February through April of 2011. During February and March centric diatom abundance was slightly elevated in Cape Cod Bay relative to the rest of the region due to the presence of *Chaetoceros* spp. and *Thalassiosira* spp. From May through September a series of several centric diatom species blooms elevated centric diatom abundance to levels of 1×10^6 to 2×10^6 cells L^{-1} at harbor and coastal stations (slide 9). This series of summer diatom blooms began with *Skeletonema* spp. and *Thalassiosira* spp. reaching 1×10^6 cells L^{-1} in May 2011 in the coastal region. In June diatom abundance was elevated in Cape Cod Bay relative to other regions. In July a bloom of *Dactyliosolen fragilissimus*, peaking at 1.25×10^6 cells L^{-1} in the harbor and coastal regions (slide 10) followed by a bloom (reaching ca. 1.9×10^6 cells L^{-1}) of *Skeletonema* spp. during August and September of 2011 (slide 11). During October centric diatom abundance was relatively low with a maximum of about 250,000 cells L^{-1} .

Pennate diatom abundance remained relatively low in 2011, continuing the trends of low pennate diatom abundance observed over the past several years. Two notable peaks in pennate diatom abundance were noted in 2011 (slide 12). In April, pennate diatom abundance increased to 120,000 cells L⁻¹ mainly due to the elevated abundance of *Pseudo-nitzschia* spp. which reached a maximum of 114,000 cells L⁻¹. Many of these *Pseudo-nitzschia* spp. cells were associated with, observed on or embedded in, *Phaeocystis pouchetii* colonies. In September 2011, a second peak in pennate diatom abundance was observed (slide 12) due to increased abundance of the planktonic pennate diatom *Asterionellopsis glacialis* which achieved abundances of up to 202,000 cells L⁻¹.

Dinoflagellate abundance during 2011 was in the low to moderate range when compared to previous observations (slide 14). Dinoflagellate abundance ranged from tens of thousands of cells per liter in February through April, increased to levels reaching up to 375,000 cells L⁻¹ in May, levels of 10,000 to 100,000 cells L⁻¹ during June through September followed by a relative peak of up to 150,000 cells L⁻¹ in October. The summer dinoflagellate flora, dominated by large *Ceratium* spp., was relatively sparse in 2011 continuing a post-2000 pattern of reduced *Ceratium* abundance. Two relative peaks in 2011 dinoflagellate annual abundance pattern, observed in May (maximum of 375,000 cells L⁻¹) and in October (maximum of 152,000 cells L⁻¹), were due to two different taxonomic and size-classes of dinoflagellates. The May 2011 peak was from elevated abundance of small dinoflagellates such as *Heterocapsa triquetra*, *Heterocapsa rotundata*, *Gymnodinium* spp. and *Prorocentrum minimum*. The October peak in dinoflagellate abundance was largely due to an increase in *Prorocentrum micans*, especially in the northern offshore and nearfield stations (slide 14). The late autumn increase in dinoflagellates led by *Prorocentrum micans*, especially evident in the northern offshore region, has now been observed for the past two years. This increase may be related to warmer water temperature late in the season (see slide 10 of Physical Processes presentation) and a concomitant delay in seasonal water column de-stratification.

Cryptomonad abundance was near long-term mean levels at most stations during 2011 (slide 16). Cryptomonad abundance peaked at most stations during the summer months (May to August) at levels of 1-2 × 10⁵ cells L⁻¹. An exception to this pattern was the northern offshore station F22 which had peak cryptomonad abundance late in the season (September and October). A late autumn peak in abundance of most phytoplankton groups characterized the northern offshore station in 2011.

There was an exceptional observation of elevated cryptomonad abundance in the summer of 2011. An abundance estimate of ca. 65,000 cryptomonads L⁻¹ was made at station F06 (southern offshore region) in July 2011 (slide 16). This is three-times the long-term mean level and approximately double the highest July observations made during 1992-2010 in that region. In the summer of 2011, there were reports of 'red water' in Massachusetts Bay. Samples collected by MWRA showed that this red water was due to elevated abundance of the phototrophic aloricate ciliate *Myrionecta rubra*. *Myrionecta rubra* abundance was elevated in the MWRA monitoring area in June 2011, with *Myrionecta* abundance of up to 3,300 cells L⁻¹ (slide 18). June 2011 *Myrionecta* abundance was about twice the long-term mean level and the highest level that has been observed in the harbor and northern offshore stations (slide 18). While elevated cryptomonad and *Myrionecta rubra* abundance are not a concern for human health or seafood safety, they are of interest in that they are part of a complex biological interaction that involves potentially toxic dinoflagellates. *Myrionecta rubra* is an obligate phototroph that 'steals' plastids from a cryptomonad host (Johnson *et al.*, 2007). The kleptoplasty does not end there however. *Dinophysis* spp. (dinoflagellates), including potentially toxic species are also kleptoplastic, containing cryptomonad plastids. However, *Dinophysis* does not take plastids directly from the cryptomonad, instead relying on *Myrionecta* as an intermediate and taking the cryptomonad plastids from *Myrionecta rubra* (Wisecaver & Hackett, 2010). In the summer of 2011, the first two components of this serial kleptoplastic sequence, elevated cryptomonad and *Myrionecta rubra* abundance, were observed.

However the third and potentially harmful component of this sequence, an increase in abundance of toxic *Dinophysis* spp. was not observed.

The 2011 phytoplankton annual cycles are summarized by the following highlights:

- Microflagellate reduced relative to long-term levels.
 - Elevated in March (Cape Cod Bay) and July (southern offshore), October (nearfield).
 - Late season (October) increased microflagellate abundance observed past two years. Emergent pattern? Related to warming?
- *Phaeocystis*
 - A moderate “*Phaeocystis* year”; blooms in 15 of 20 years
 - *Phaeocystis* blooms ($>10^6$ L⁻¹) observed over the past 12 years running
 - April 2011 observed in all regions except Cape Cod Bay
- Diatoms
 - Winter-spring bloom reduced or absent in 2011
 - Summer (*Skeletonema*, *Dactyliosolen fragilissimus*) at harbor & coastal stations
 - *Asterionellopsis glacialis* in September 2011
- Dinoflagellates
 - Small cells (*Gymnodinium*, *Heterocapsa*) in May 2011
 - Transition to larger forms (*Ceratium*) June - August 2011, but relatively low *Ceratium* abundance in 2011
 - *Prorocentrum micans* bloom in October 2011 (max of 26,000 cells L⁻¹); 2nd year in a row of autumn *P. micans* bloom.
 - Increased dinoflagellate abundance in autumn appears to be emerging pattern. Related to warming?

2011 Phytoplankton Regional Patterns

Phytoplankton abundance and species composition were usually similar at all stations sampled on each monthly survey with several noteworthy exceptions summarized below:

Total Phytoplankton (slide 2)

- Elevated abundance in Cape Cod Bay in March
- Elevated abundance in Massachusetts Bay in April (*Phaeocystis*)
- Elevated abundance in harbor and coastal regions during summer (centric diatom blooms)

Microflagellate

- Elevated in Cape Cod Bay during March 2011.

Centric Diatoms

- Elevated in Cape Cod Bay in February-March and June
- Elevated in harbor, nearfield and coastal regions July - August
- Elevated in north region in September

Dinoflagellates

- Reduced abundance in Cape Cod Bay in March
- Elevated abundance in northern region in September & October

Cryptomonads

- Elevated abundance at station F06 (offshore) in July 2011

2011 Potentially Harmful Phytoplankton:

2011 featured a moderate *Phaeocystis pouchetii* bloom in April 2011 and a moderate *Alexandrium fundyense* (Paralytic Shellfish Poisoning) bloom in April-June of 2011. *Pseudo-nitzschia* spp. (Amnesiac Shellfish Poisoning) abundance remained relatively low in 2011. Summary of 2011 harmful phytoplankton events are below:

- Modest *Phaeocystis* bloom in April 2011
 - maximum of 2.11×10^6 cells L⁻¹ in late April 2011
- 2011 *Alexandrium* (2,931 cells L⁻¹ maximum)
 - April - June bloom, peak in late May 2011
- 2011 *Pseudo-nitzschia*
 - 2011 abundance up vs. 2010, but still reduced relative to long-term levels.
 - 2011 peak = 127,691 cells L⁻¹, station N18 in April 2011 (many cells associated with *Phaeocystis* colonies).

2011 Phytoplankton Abundance Relative to Prior Years

The 2011 abundance of main phytoplankton groups was compared to long-term (1992-2010) levels using a Mann-Whitney test (slide 21). Total phytoplankton abundance in 2011 (mean of 1.04×10^6 cells L⁻¹) was reduced relative to levels observed in the previous 19 years of monitoring (mean of $1. \times 10^6$ cells L⁻¹; $p = 0.0001$). This can largely be related to declines in microflagellates which had a mean 2011 level of 500,000 cells L⁻¹ compared to a 1992-2010 mean level of 720,000 cells L⁻¹ (slide 21). *Phaeocystis* abundance in 2011 was also reduced relative to the long-term mean level. While there was a reduced winter-spring diatom bloom in 2011, elevated summer 2011 centric diatom abundance compensated for this winter-spring decline such that 2011 centric diatom abundance was not significantly different than long-term mean levels. 2011 was a *Skeletonema* spp. year, with mean 2011 abundance (158,000 cells L⁻¹) that was approximately three-time the long-term mean level of about 50,000 cells L⁻¹ (slide 21). The summer character of the 2011 phytoplankton cycle is further illustrated by the 2011 increase in the phototrophic ciliate *Myrionecta rubra*, which had a 2011 abundance that was about double the long-term mean level (slide 21).

References

Johnson, Oldach, Delwiche and Stoecker, 2007. *Nature* **445**: 426-428.

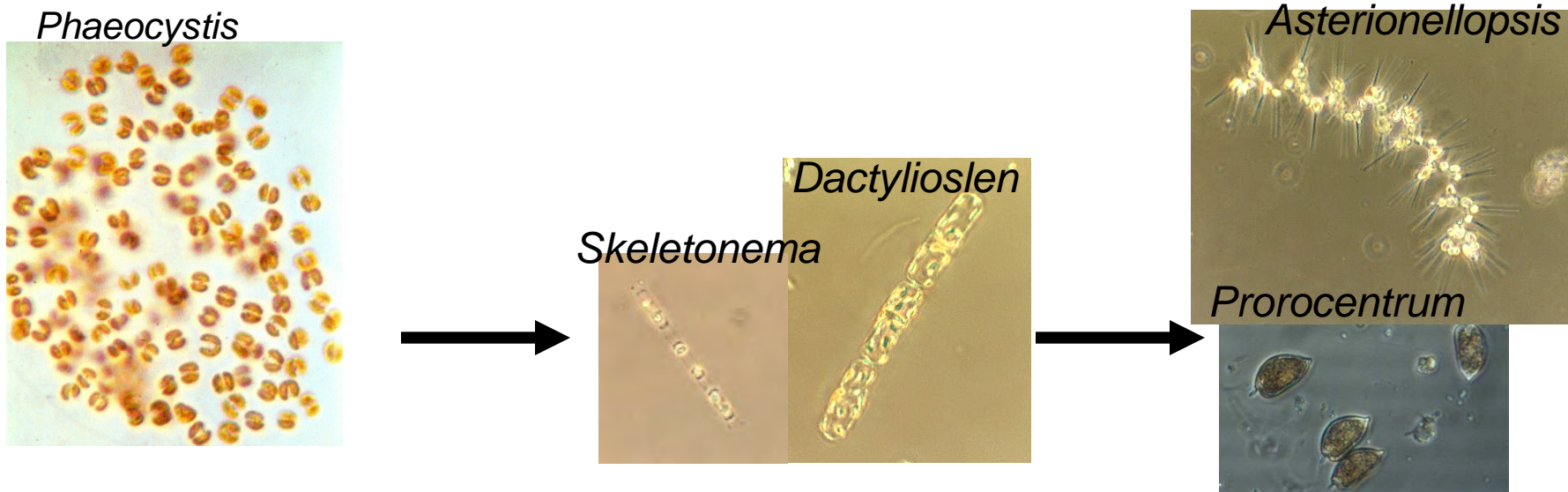
Wisecaver, JH and Hackett, JD. 2010. Transcriptome analysis reveals nuclear-encoded proteins for the maintenance of temporary plastids in the dinoflagellate *Dinophysis acuminata*. *BMC Genomics* 11: 366.

2011 Phytoplankton Summary

David Borkman

URI Graduate School of Oceanography

- Phytoplankton regional distribution patterns
- Annual cycles: 2011 vs. prior years
- Abundance: 2011 relative to prior years



Total Phytoplankton 2011

Regional Patterns

March

-Microflagellates &
Chaetoceros CCBay

April

-*Phaeocystis* to north

Summer

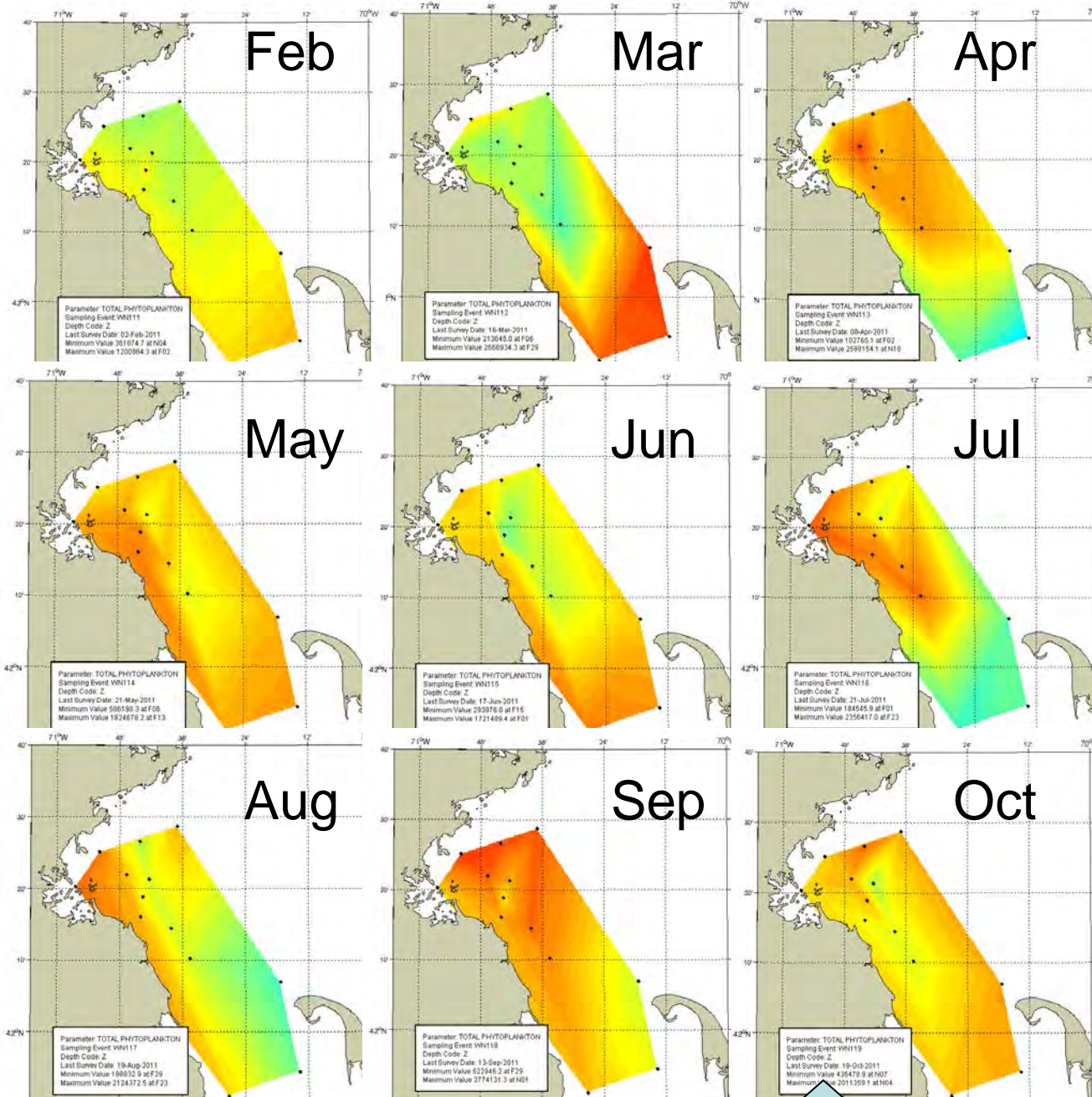
- Coastal diatom increase
(*Dactyliosolen fragilissimus*)

September

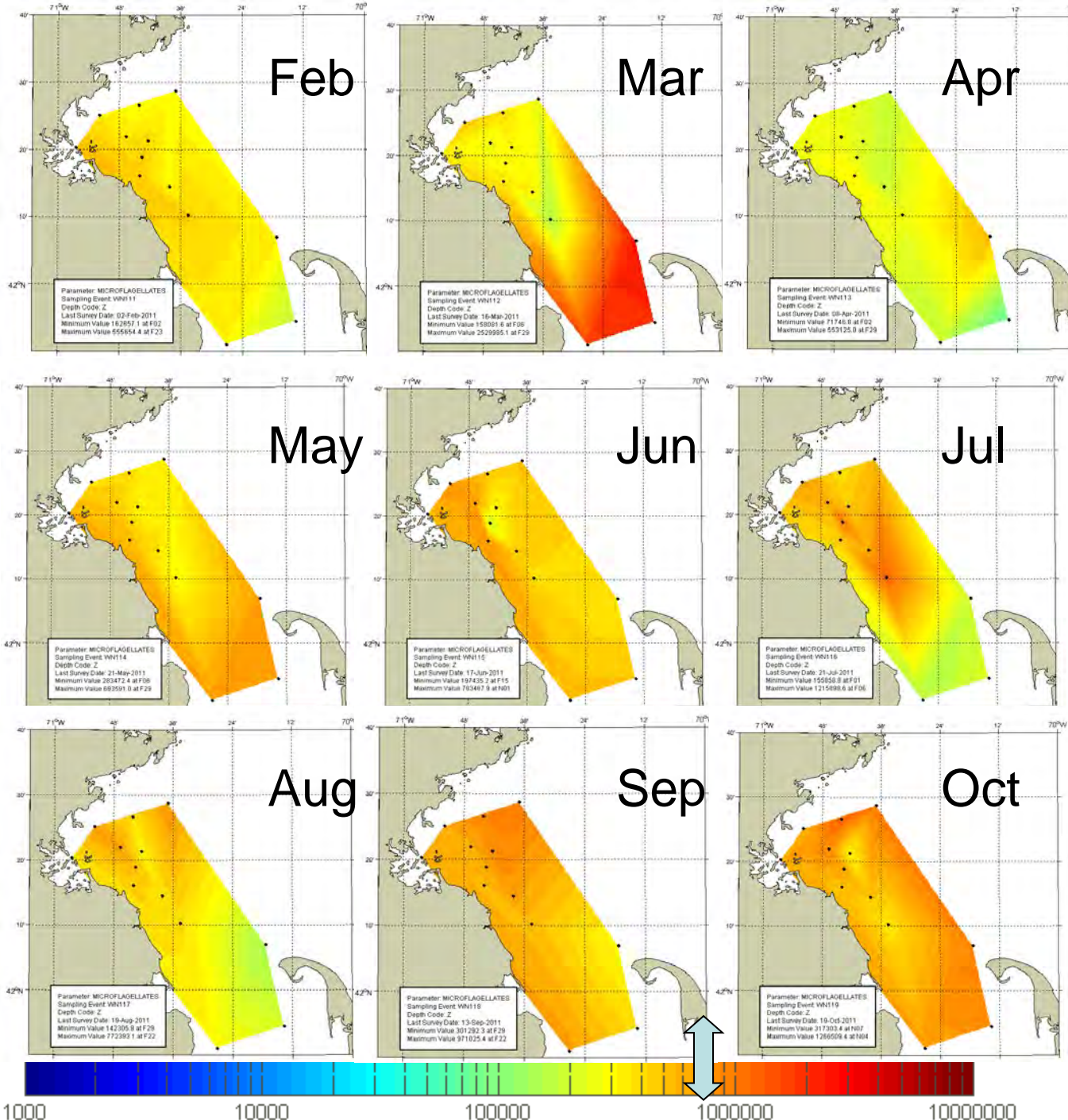
- *Skeletonema* to north

October

- *Prorocentrum micans* to
north



Microflagellates 2011



- Mainly regionally uniform

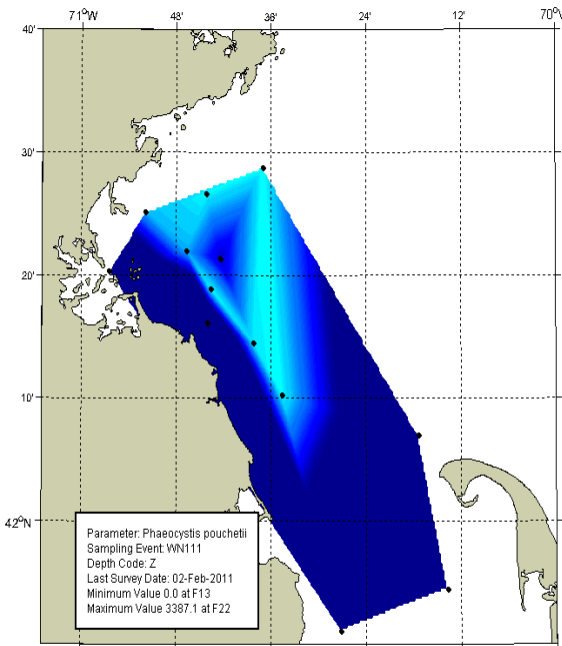
-CCBay in March

- elevated coastal abundance (May & June)

-Elevated northern area Sept & October

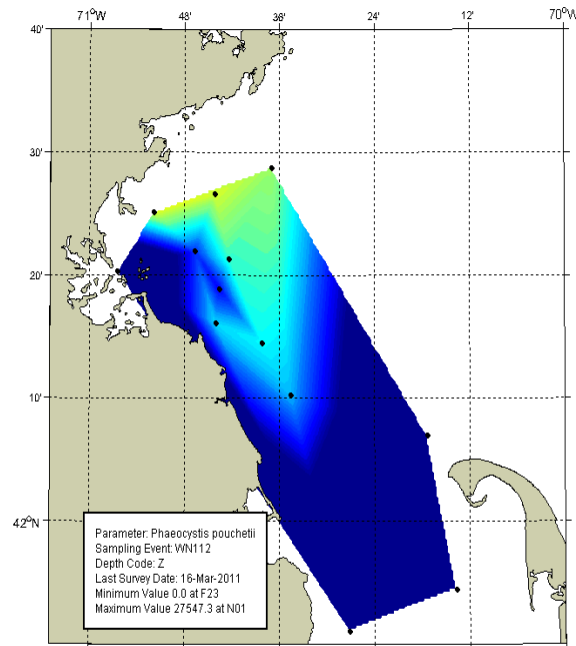
Cells L⁻¹

Phaeocystis pouchetii 2011



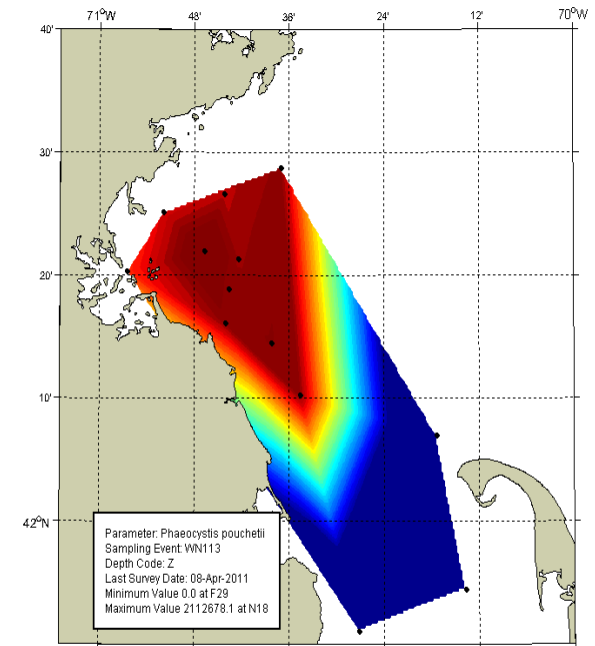
February

Max = 3,387 cells L⁻¹



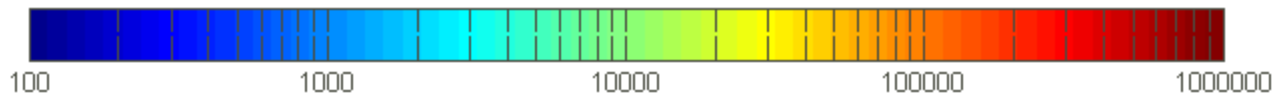
March

Max = 27,547 cells L⁻¹



April

Max = 2.11 X 10⁶ cell L⁻¹



Centric Diatoms 2011

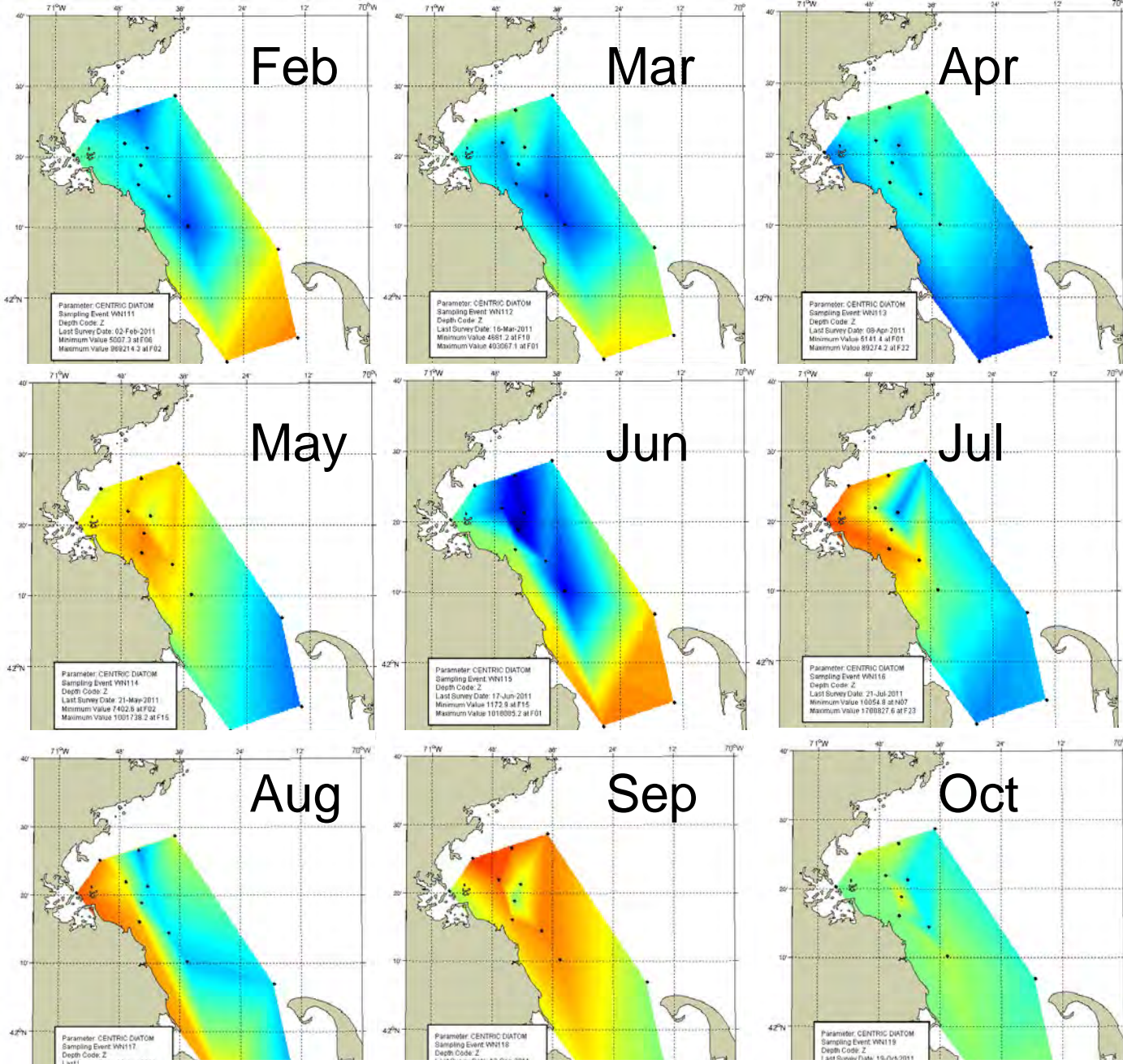
-Summer - early
autumn dominated
annual cycle

-Winter:
Thalassiosira,
Chaetoceros,
Skeletonema

-May: *Skeletonema* &
Thalassiosira spp.

-Summer:
Dactyliosolen
fragilissima (July),
Skeletonema spp.
(August)

- Autumn:
Skeletonema to north



Cells L⁻¹

Dinoflagellates 2011

May

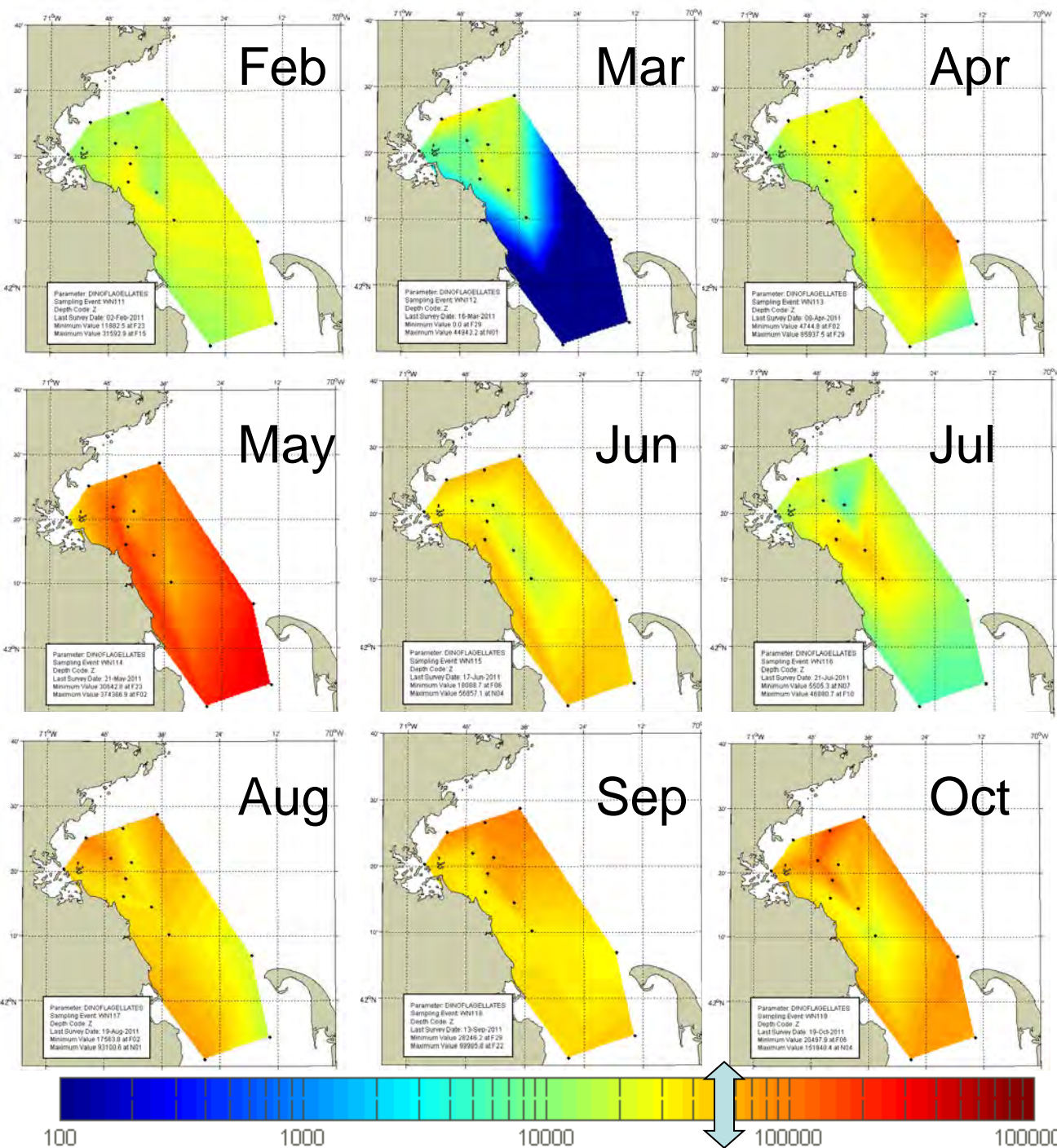
Small dinoflagellates
Gymnodinium spp.
Heterocapsa triquetra
Heterocapsa rotundata
Prorocentrum minimum

Summer

Large dinoflagellates
Ceratium spp.

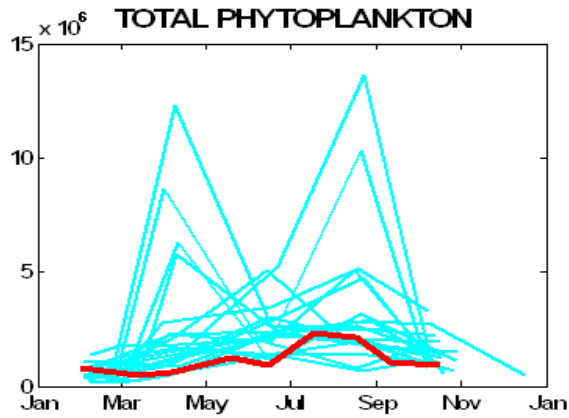
October

Prorocentrum micans
(to 26,000 L⁻¹)
2nd year in a row
New pattern?

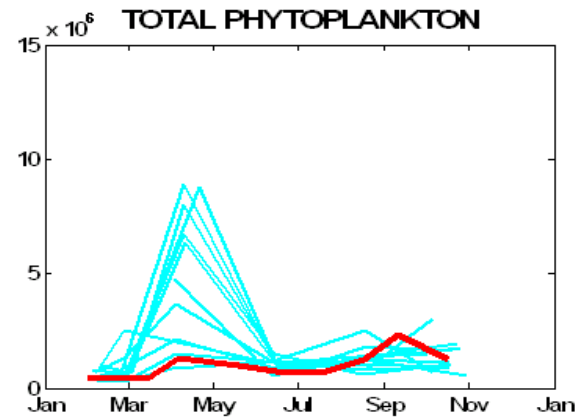


2011 Total Phytoplankton Annual Cycle

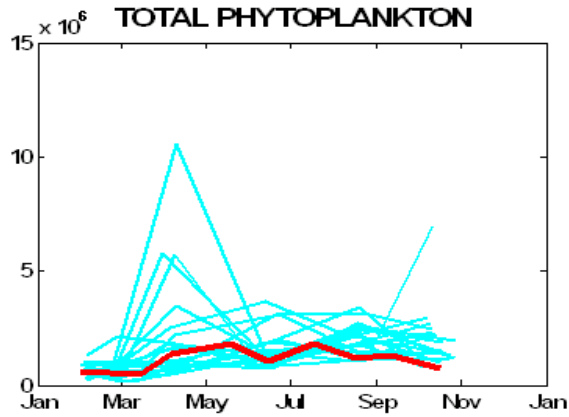
Harbor
(F23)



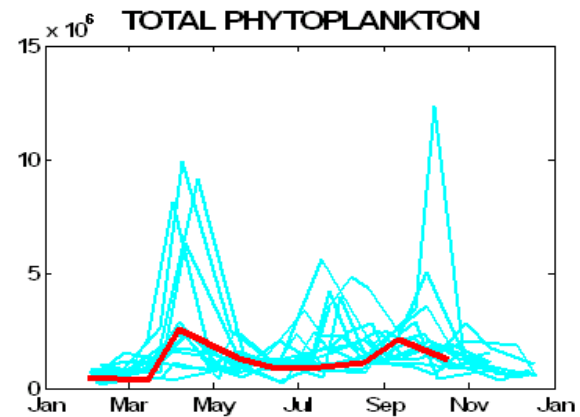
Northern
Offshore
(F22)



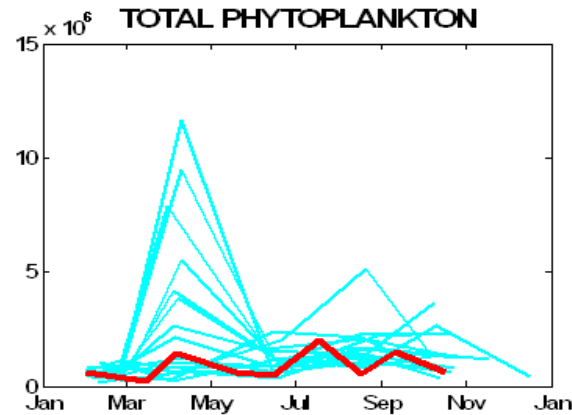
Coastal
(F13)



Nearfield
(N18)



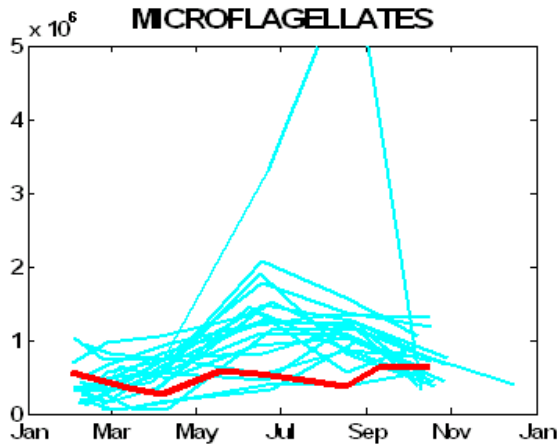
Southern Offshore
(F06)



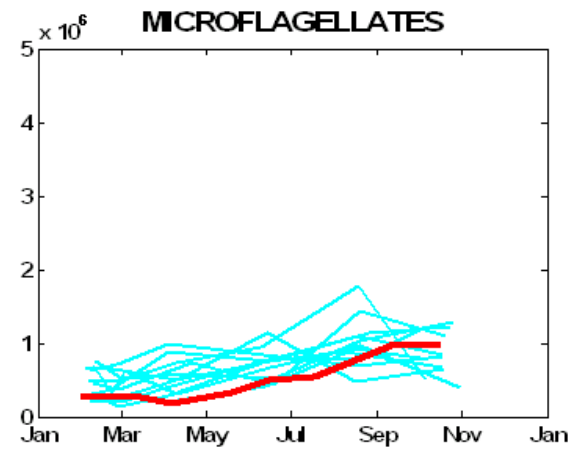
2011 total phytoplankton
relatively low to moderate
abundance

2011 Microflagellate Annual Cycle

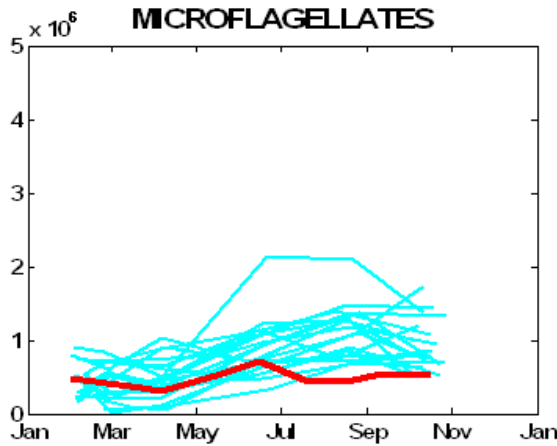
Harbor
(F23)



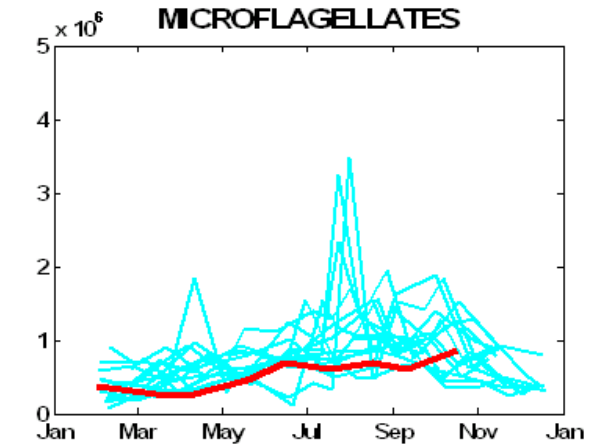
Northern
Offshore
(F22)



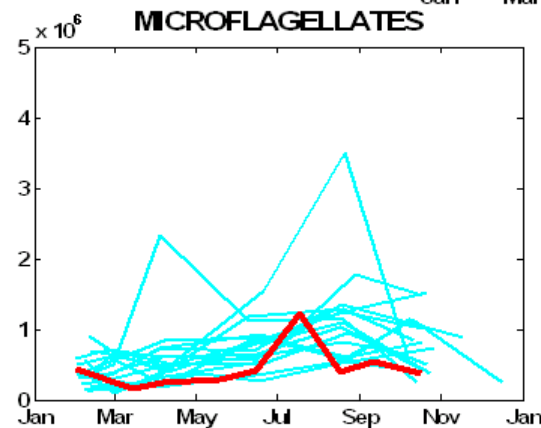
Coastal
(F13)



Nearfield
(N18)



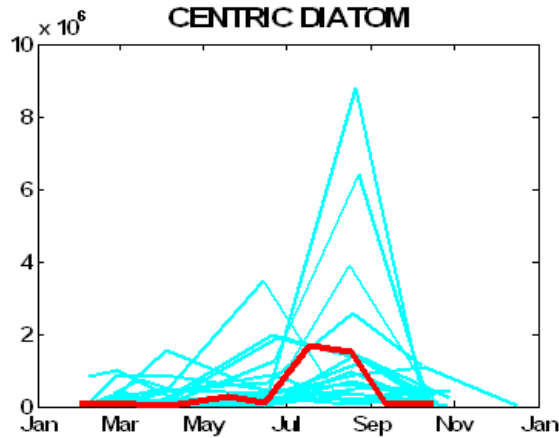
Southern
Offshore
(F06)



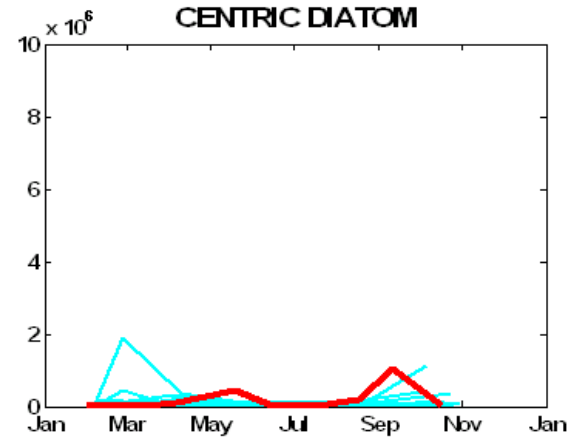
2011 microflagellates
relatively low (W-S,
autumn) to moderate
abundance

2011 Centric Diatom Annual Cycle

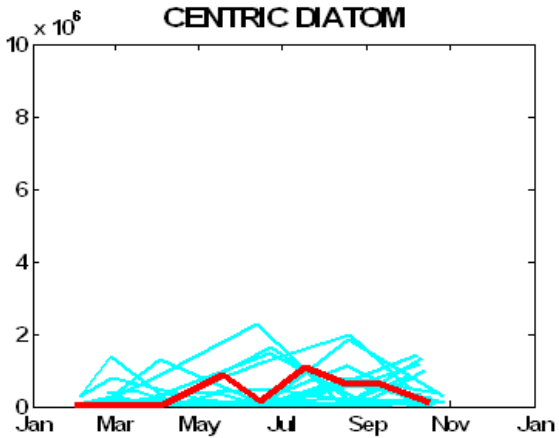
Harbor
(F23)



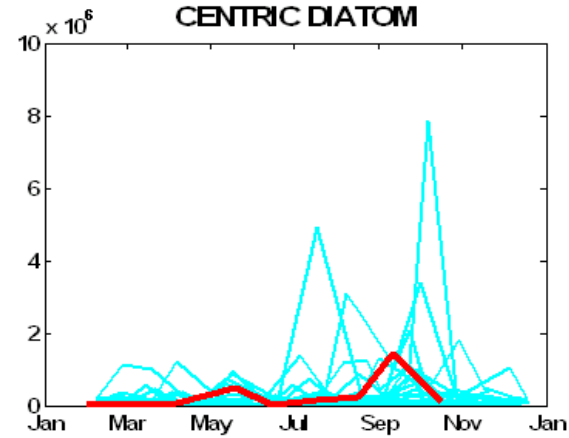
Northern
Offshore
(F22)



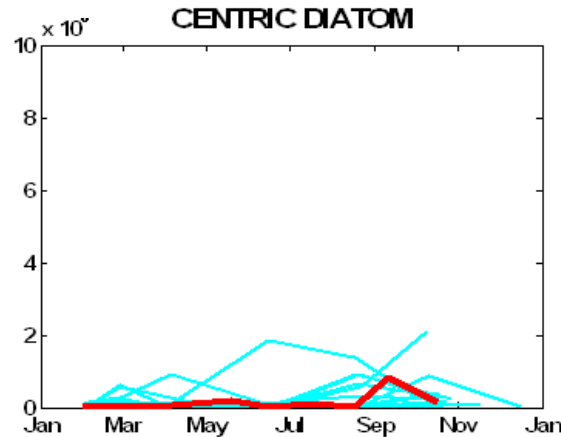
Coastal
(F13)



Nearfield
(N18)

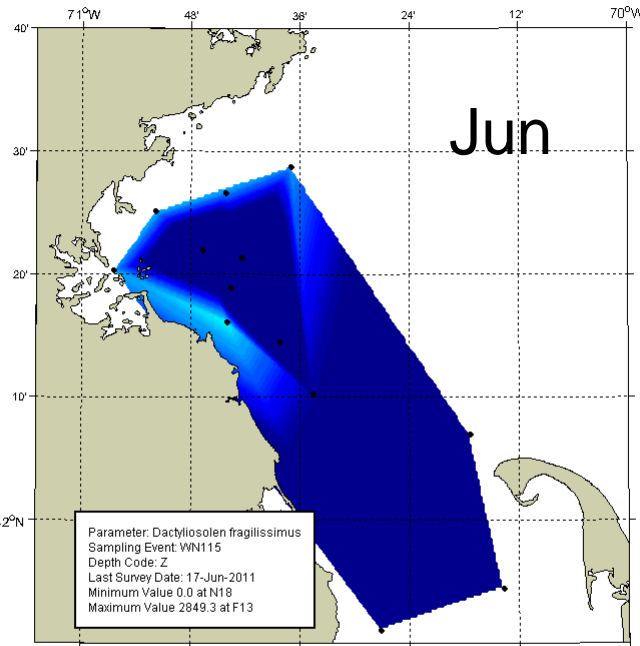


Southern Offshore
(F06)

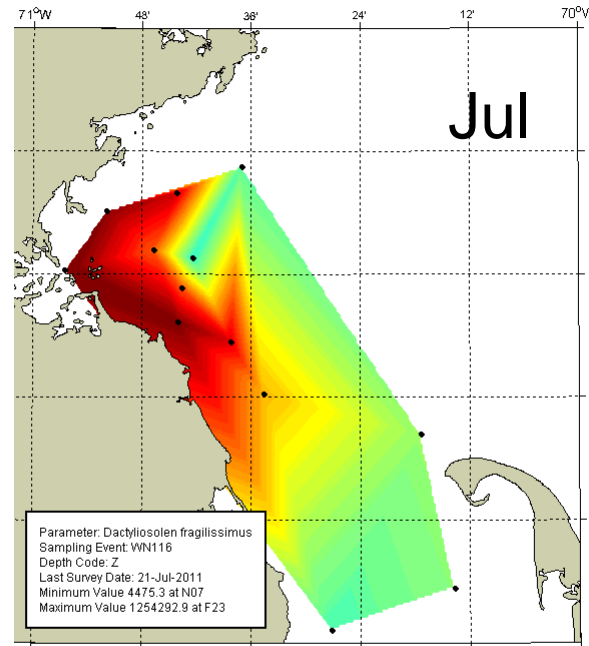


2011 centric diatoms:
relatively low (W-S) to
moderate abundance in
summer-autumn

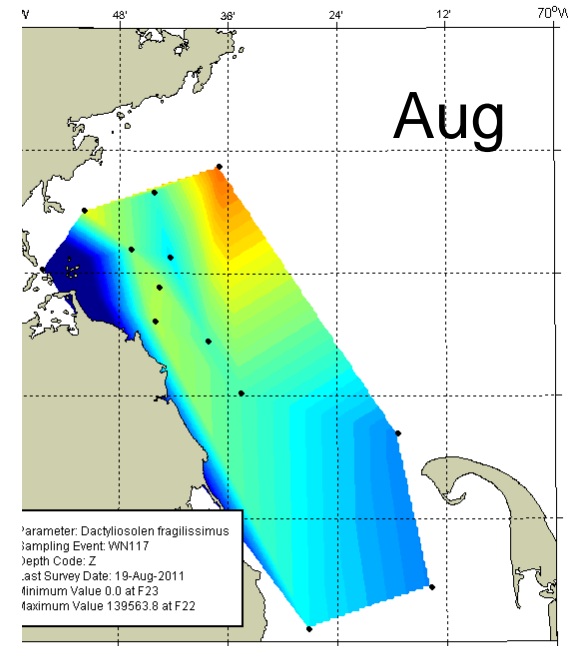
July *Dactyliosolen fragilissimus* bloom (to ca. 1.2×10^6 cell L⁻¹)



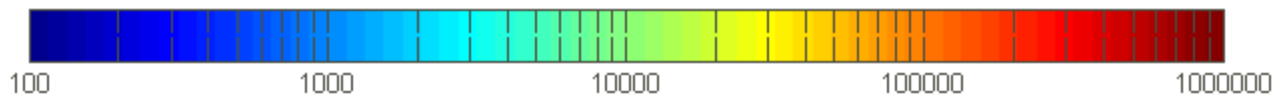
Max = 2,849 cells L⁻¹



Max = 1.25×10^6 cells L⁻¹



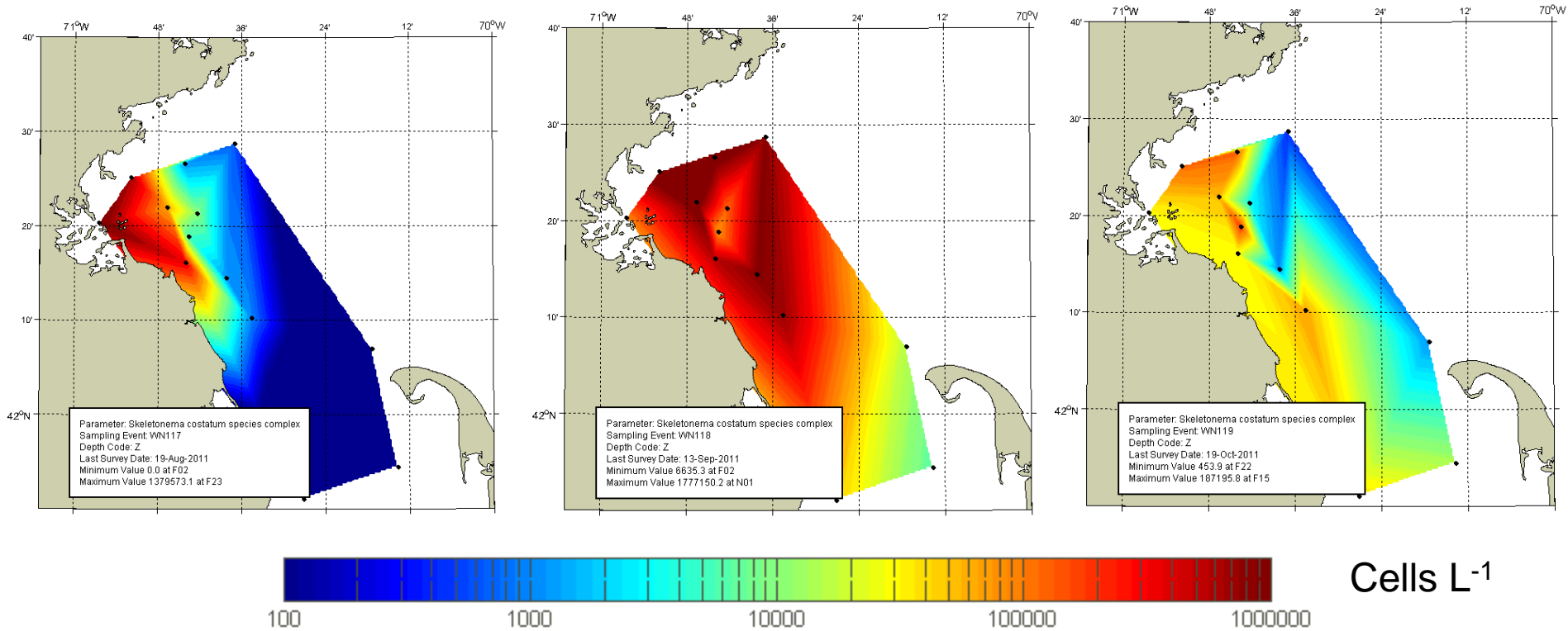
Max = 1.39×10^5 cell L⁻¹



Cells L⁻¹

10

Late summer *Skeletonema* spp. bloom



August

Max = 1.88×10^6 cells L⁻¹

September

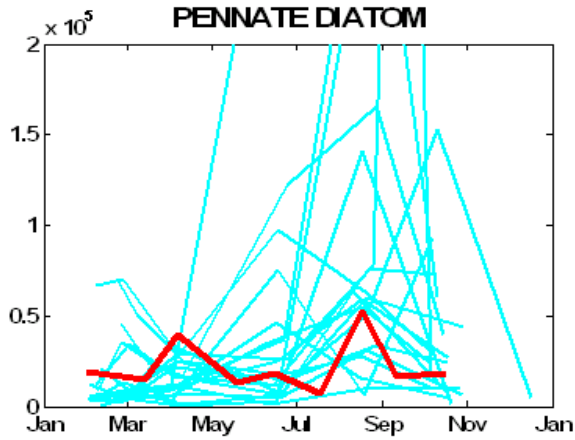
Max = 1.78×10^6 cells L⁻¹

October

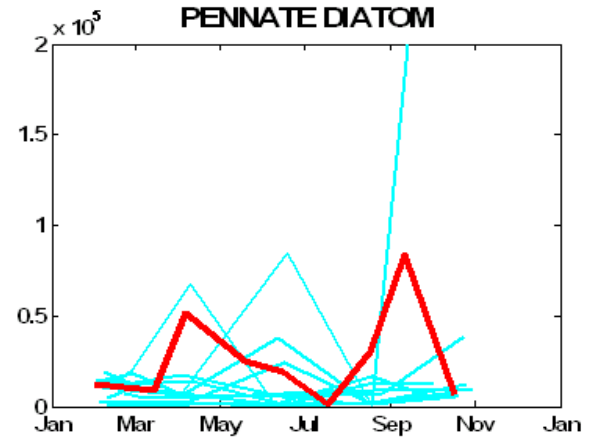
Max = 1.87×10^5 cell L⁻¹

2011 Pennate Diatom Annual Cycle

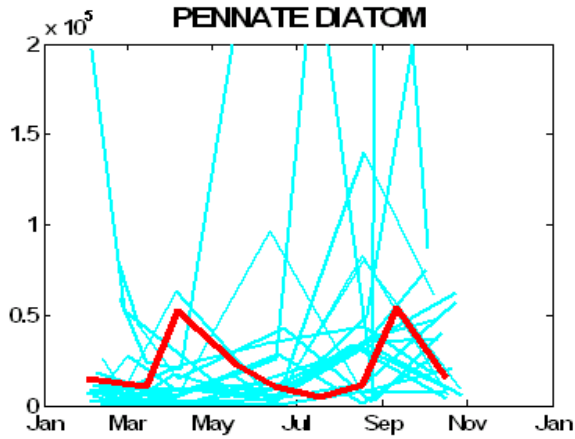
Harbor
(F23)



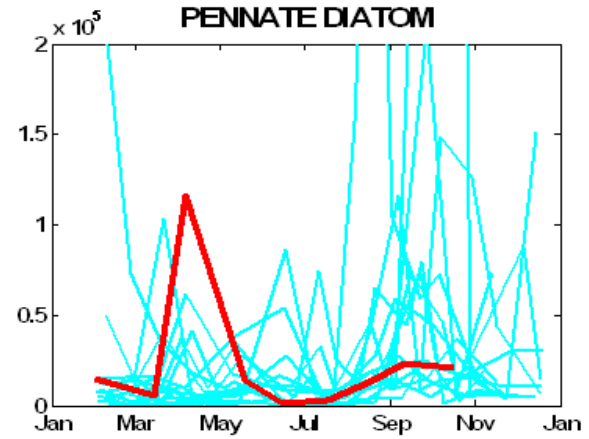
Northern
Offshore
(F22)



Coastal
(F13)

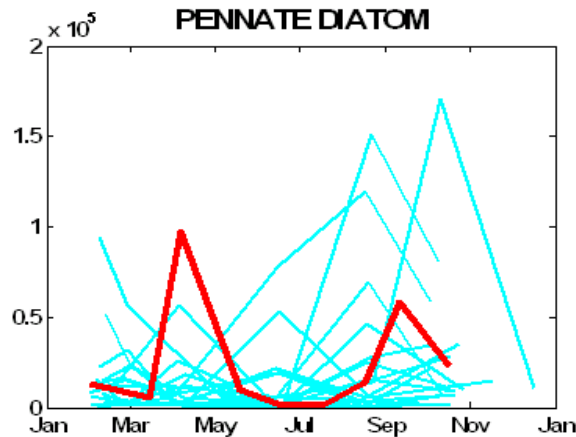


Nearfield
(N18)

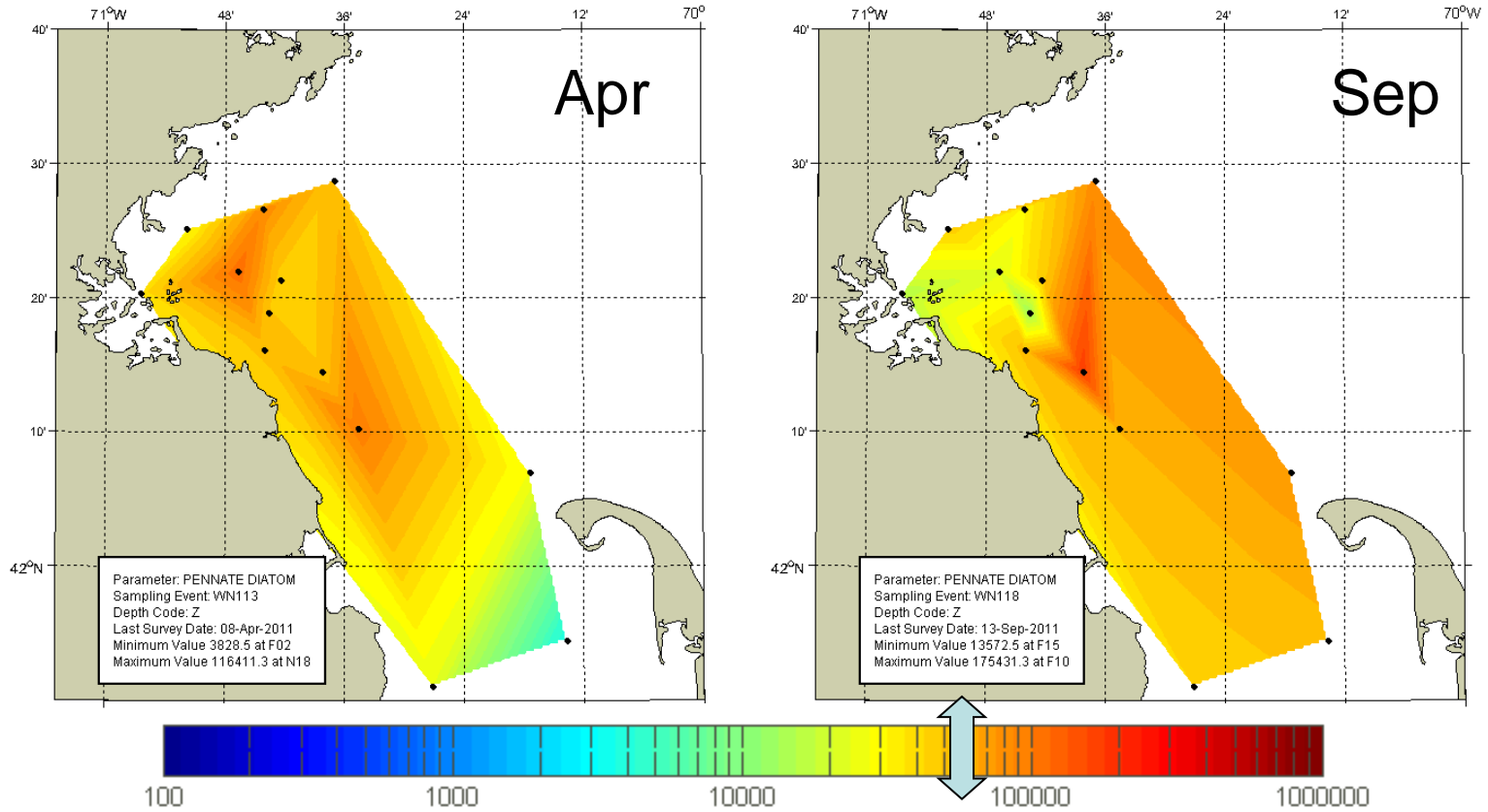


2011 pennate diatoms:
W-S and Autumn pulses

Southern Offshore
(F06)



Pennate Diatoms

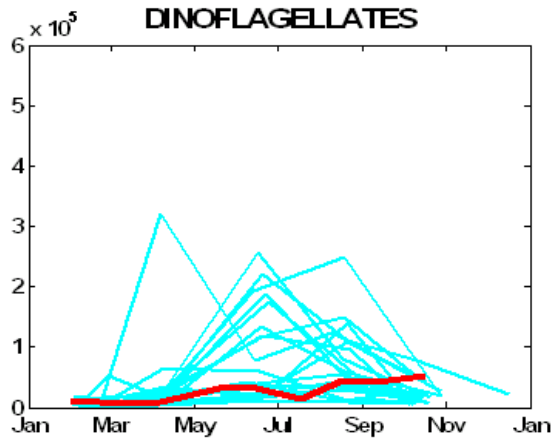


Pennate Diatoms

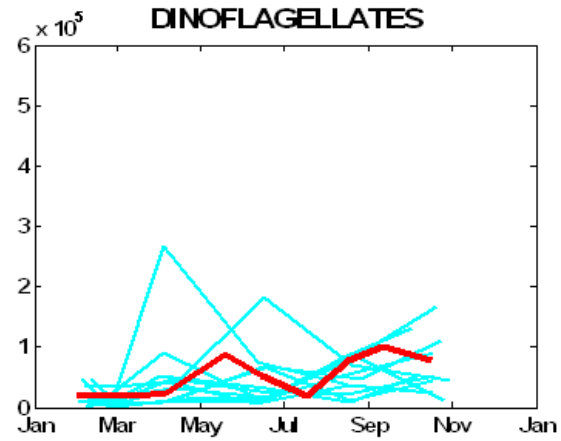
- April: *Pseudo-nitzschia* spp. (114,000 L⁻¹ maximum)
- September: *Asterionellopsis glacialis* (202,000 L⁻¹ maximum)

2011 Dinoflagellate Annual Cycle

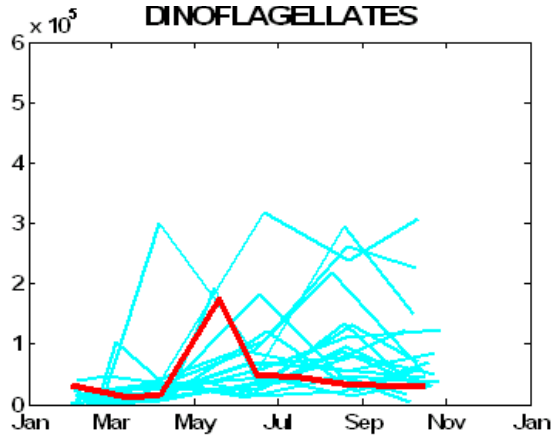
Harbor
(F23)



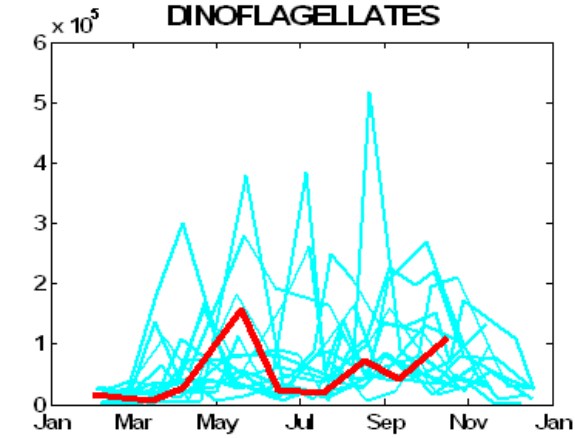
Northern
Offshore
(F22)



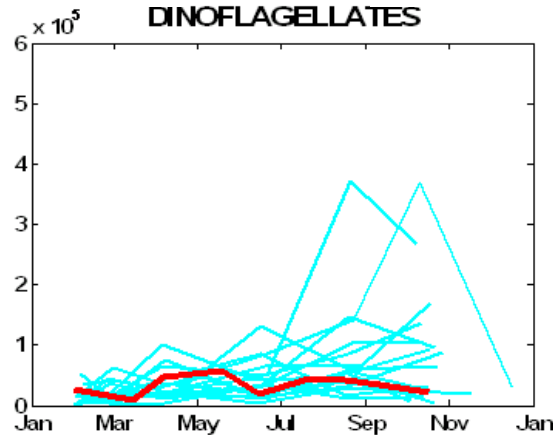
Coastal
(F13)



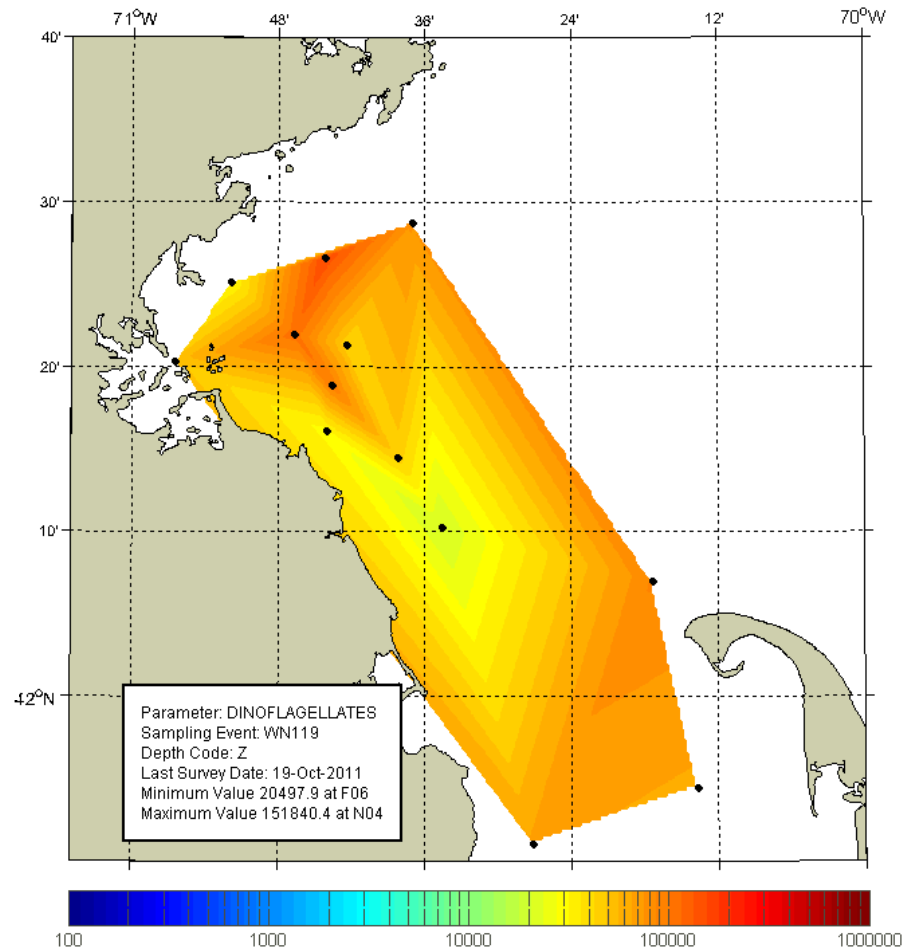
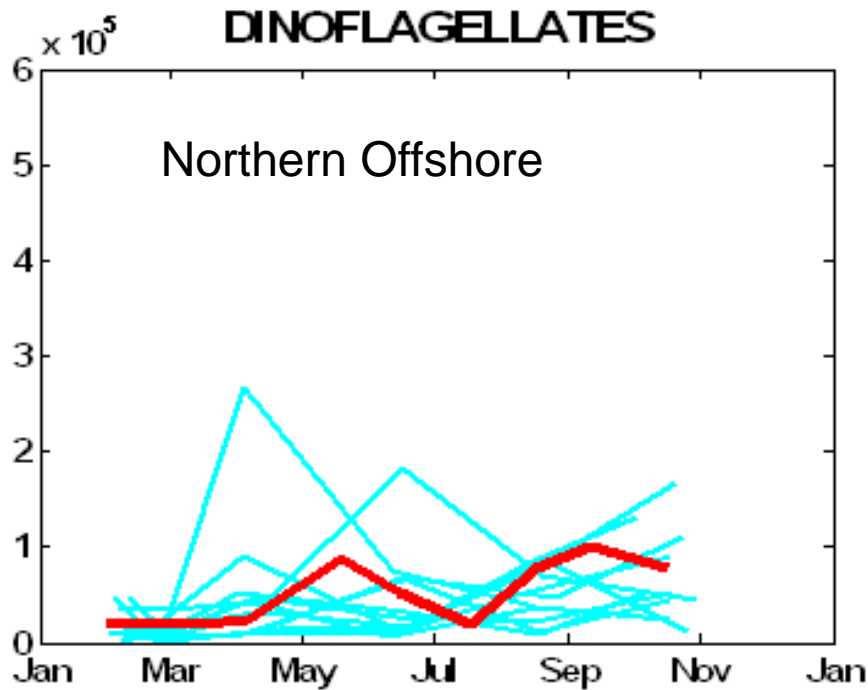
Nearfield
(N18)



Southern Offshore
(F06)



2011 dinoflagellates:
Spring: small forms
Autumn: *Prorocentrum*

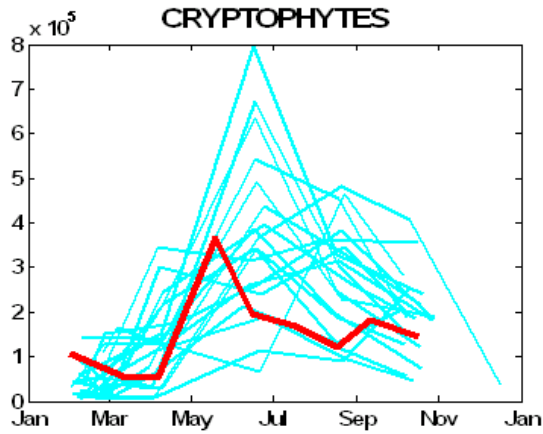


Relatively high Autumn dinoflagellate abundance

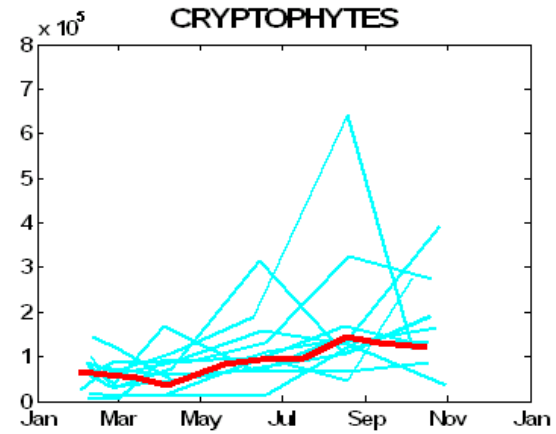
- *Prorocentrum micans* (to 26,000 L⁻¹)
- 2nd year in a row.
- New pattern?

2011 Cryptophyte Annual Cycle

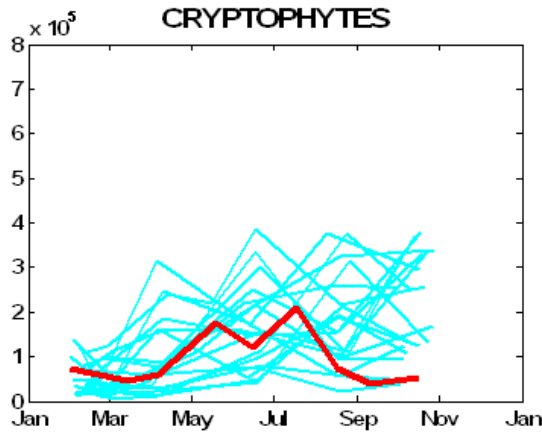
Harbor
(F23)



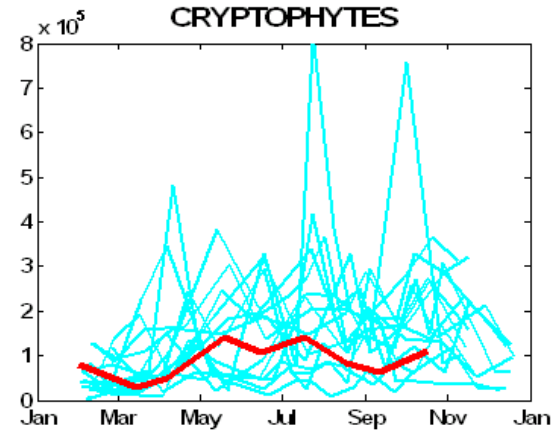
Northern
Offshore
(F22)



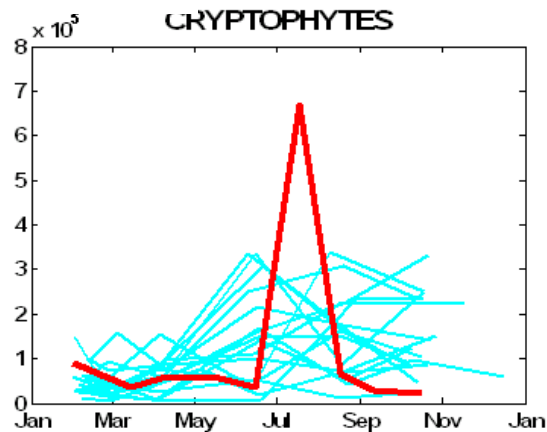
Coastal
(F13)

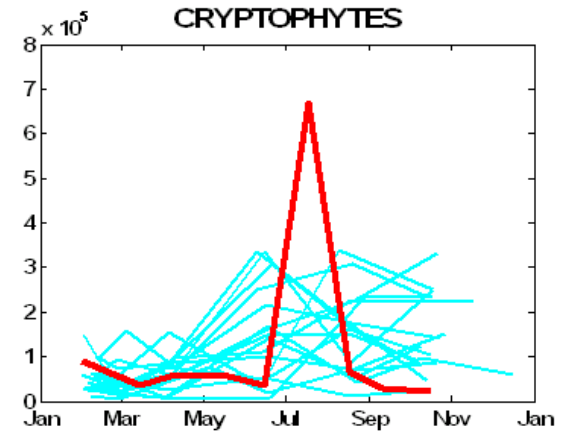
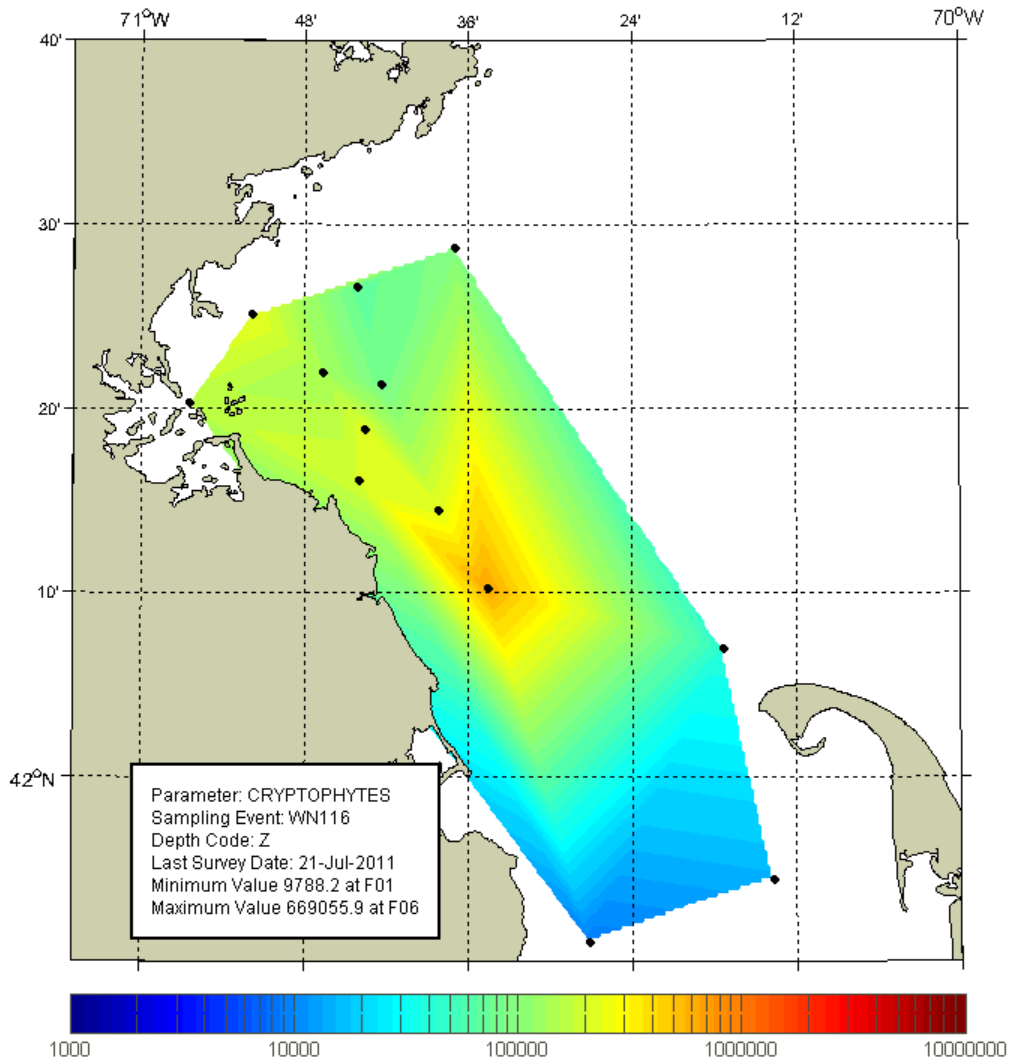


Nearfield
(N18)



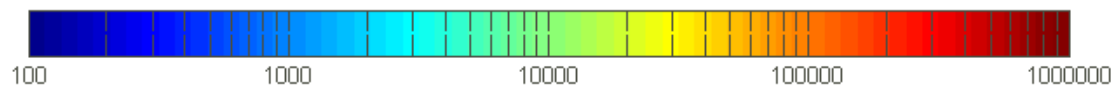
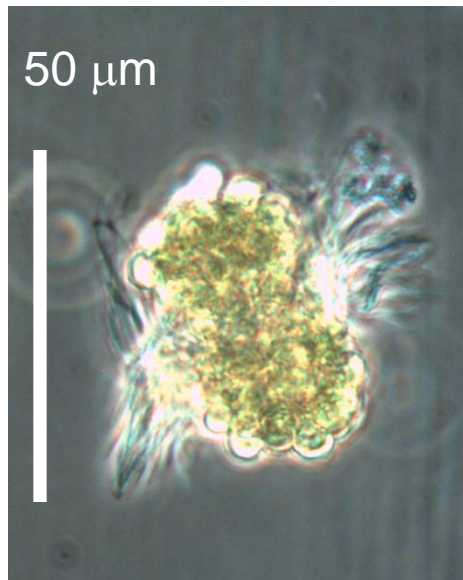
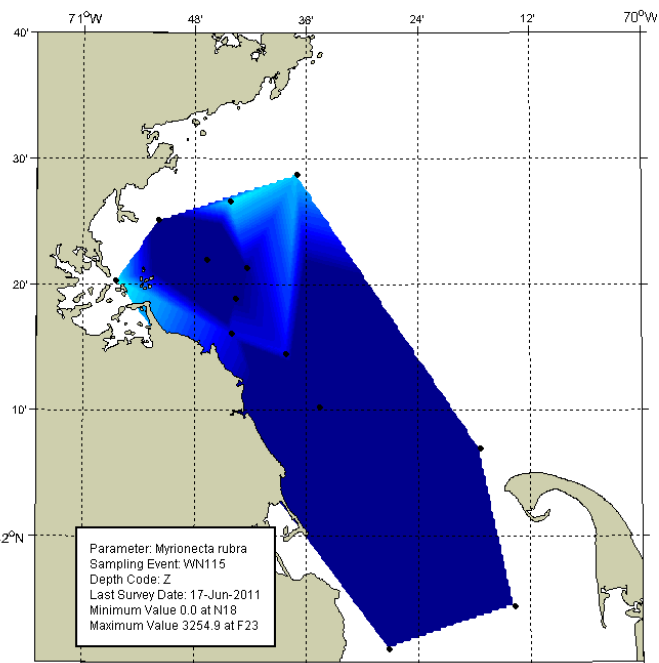
Southern
Offshore
(F06)





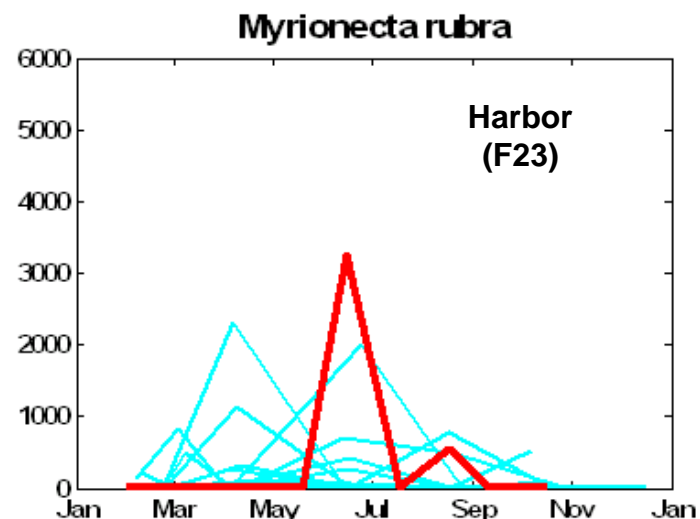
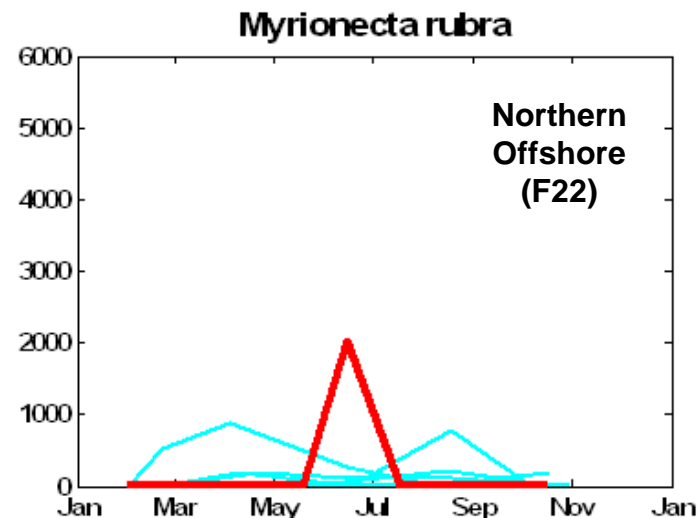
July 2011

Cryptophytes elevated relative to LT mean in southern offshore area (F06)



Myrionecta rubra

- Summer 2011 patchy, water-discoloring blooms in Ma Bay
- Abundance levels (ca. 3,300 per liter) were ~3X mean F22 levels in June
- Peaks of 4,000 L⁻¹ to 5,000 L⁻¹ in patch samples in late July - August



Columbia River, Astoria Bridge
Center Coastal Margin Observation & Prediction (CMOP)



New York Harbor
Summer 2010



Chile

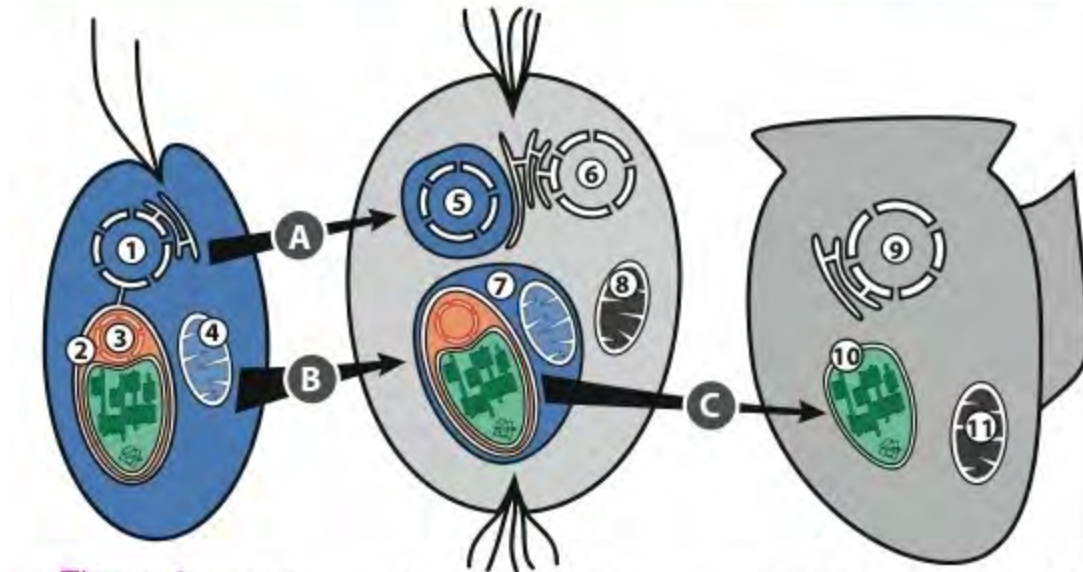
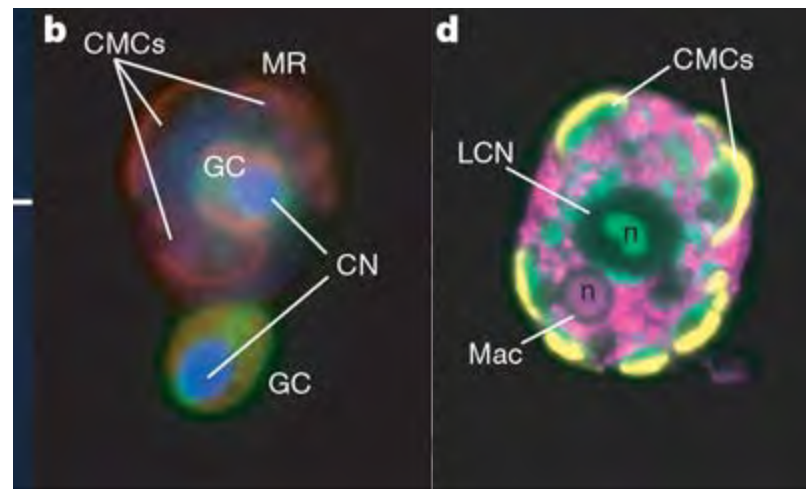
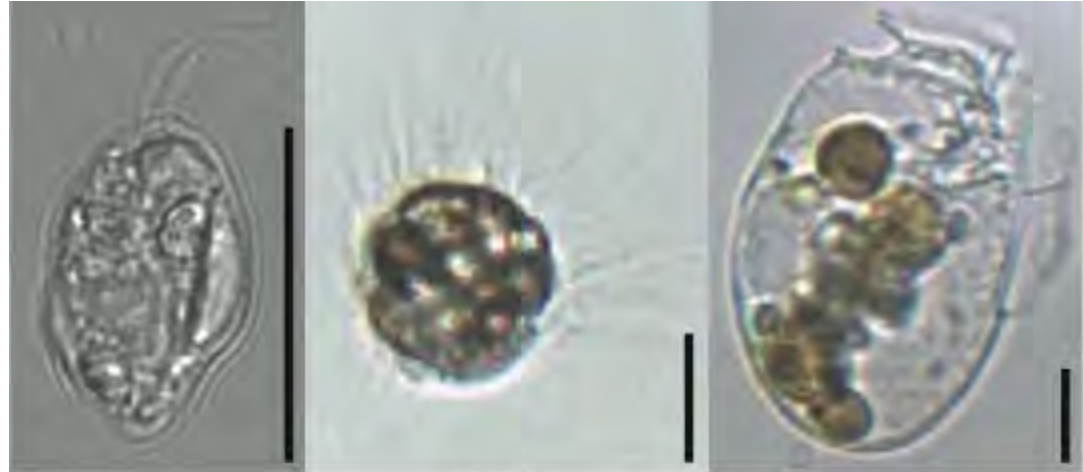


Figure 1
Geminigera cryophila *Myrionecta rubra* *Dinophysis acuminata*
 Wisecaver & Hackett 2010 BMC Genomics

Johnson, Oldach, Delwiche & Stoecker, 2007. (*Nature* **445**, 426-428.)

- Summer 2011 Cryptomonad & *Myrionecta* increase consistent with serial kleptoplasty.
- Did not see *Dinophysis* increase.

Comparison of 2011 abundance compared to long-term observations:

<u>Group</u>	<u>1992-2010</u>	<u>2011</u>	<u>p value</u>	<u>Change?</u>
CENTRIC DIATOM	319,159	268,936	0.3217	
Chaetoceros	50,268	8,929	0.0005	decline
Dactyliosolen fragilissimus	49,381	45,710	0.8596	
Skeletonema costatum species complex	52,018	157,612	0.0001	increase
Thalassiosira	41,346	10,129	0.0627	
PENNATE DIATOM	51,430	23,109	0.1411	
Pseudonitzschia	11,098	8,732	0.5731	
DINOFLAGELLATES	55,051	46,118	0.0883	
Ceratium	1,584	554	0.0826	
CRYPTOPHYTES	128,363	100,859	0.0031	decline
MICROFLAGELLATES	718,960	504,200	0.0001	decline
Myrionecta rubra	81	193	0.0104	increase
Phaeocystis pouchetii	267,697	87,082	0.0453	decline
TOTAL PHYTOPLANKTON	1,554,006	1,037,788	0.0001	decline

Relatively low in 2011:

Chaetoceros, Cryptophytes, Microflagellates, *Phaeocystis*, Total Phytoplankton

Relatively abundant in 2011:

Skeletonema, *Myrionecta*

2011 Phytoplankton Summary

- 2011 relatively low phytoplankton abundance
- Reduce Winter-Spring diatoms
- *Phaeocystis* present (April), but reduced abundance
- Summer diatom blooms (*Dactyliosolen*, *Skeletonema*)
- Increased Cryptophyte abundance (July, southern offshore) and *Myrionecta rubra* abundance
- Autumn *Prorocentrum micans* (northern offshore)

Appendix D

Zooplankton

2011 MWRA Zooplankton Monitoring Summary

Jefferson Turner, UMD

Overview

Zooplankton abundance and community composition was monitored during 2011 as part of the MWRA's comprehensive outfall monitoring program. The zooplankton community was assessed *via* vertical oblique net hauls (102 μm -mesh). In 2011, the first year of the revised monitoring program, zooplankton samples were collected at ten stations across Massachusetts Bay during nine monthly surveys from February to October 2011.

The MWRA time series has consistently shown that zooplankton abundance is numerically dominated by copepod nauplii, and copepodites and adults of small copepod taxa such as *O. similis*, *Pseudocalanus* spp., and in Boston Harbor, *Acartia* spp.. Larger copepod taxa such as *Calanus finmarchicus* which dominate abundance in some other zooplankton time series in temperate waters have been shown to be a relatively minor component of zooplankton abundance in the MWRA time series. There are also sporadic ephemeral pulses of meroplanktonic larvae of benthic animals such as barnacle nauplii, gastropod and bivalve veligers, and larval polychaete worms. A consistent seasonal pattern during all years of the time series has been low zooplankton abundance in the winter, increasing through the spring to maximum levels of abundance during mid- to late-summer and early-fall periods, declining through the late fall and early winter.

Zooplankton monitoring for the MWRA program has produced a unique long-term dataset for seasonal fluctuations of marine zooplankton in a highly seasonal environment. Due to the use of 102 μm -mesh nets, this time-series differs from most others in that the most abundant taxa recorded are copepod nauplii and tiny copepods of the species *Oithona similis*. These small zooplankters have been severely undersampled or missed by most other zooplankton time-series which used nets with meshes of 200 μm or greater. Also, unlike most other long-term zooplankton time series, all samples in the MWRA time series since 1998 have been analyzed by the same experienced analyst, thereby avoiding discrepancies due to different taxonomic decisions by different analysts. Thus, comparisons between the MWRA time series and other zooplankton time series in the Gulf of Maine/Georges Bank area (Pershing *et al.* 2005, Kane 2007, Mountain & Kane 2010) are complicated by the fact that other such time series used nets with meshes that missed the most abundant zooplankton (Turner *et al.* 2011).

2011 Zooplankton Annual Cycle

In terms of zooplankton community composition and seasonal patterns, 2011 was a typical year. Total zooplankton abundance was dominated by copepod nauplii and *Oithona similis* copepodites and adults. Total zooplankton abundance increased from the winter through the spring to peak in the summer, and declined in the fall (slide 4). There was more temporal variability in abundance than spatial variability in abundance. *Calanus finmarchicus* (slide 5) and barnacle nauplii peaked in the spring, whereas *Oithona similis*, *Acartia* spp. (slide 6), *Pseudocalanus* spp. and other zooplankton peaked in summer. *Calanus finmarchicus* was most abundant offshore, whereas *Acartia* spp. was most abundant inshore. *Oithona similis* was ubiquitously abundant everywhere. Total zooplankton abundance (comprised primarily by copepods (adults + copepodites), copepod nauplii and *Oithona*) all had similar seasonal increases through winter and spring into summer with declines in the fall (slides 4 and 7). Abundance of *Calanus* and barnacle nauplii tended to peak earlier in the spring, with much lower abundances than for total zooplankton (slides 5 and 8). Abundance of *Acartia* and *Pseudocalanus* and other zooplankton tended to

peak only in the summer (slides 6 and 9). There were similarities between stations F22, F23, N18, F06, and F13 (slide 7) for seasonal trends and abundances of total zooplankton, copepods (which dominate total zooplankton), and *Oithona* (which dominates copepods). There were also similarities between these stations and spring peaks for barnacle nauplii and *Calanus* (slide 8). However, *Calanus* had lower abundance nearshore. There were similarities between these stations for abundances and patterns of summer peaks for barnacle nauplii and *Pseudocalanus*, with *Acartia* having maximum abundance in summer in Boston Harbor (slide 9). 2011 was comparable to most historic levels of abundance and seasonal patterns for harbor and coastal stations, but was above historical levels in spring for the nearfield and offshore stations, especially for April-June at station F22 (slide 10). Total zooplankton abundance in 2011 was higher than most long-term (1992-2010) levels in offshore waters (stations N18, F06, and especially F22) in the spring (slide 10). Nearfield abundances of copepods (total adults + copepodites) were low in winter and spring of 2011, but very high in April-June, and about average for much of the rest of the year, with a spike in September (slide 12). Copepod nauplii, *Oithona* and *Pseudocalanus* had similar patterns, but at lower levels of abundance. Nearfield abundances of *Acartia* and *Calanus* were very high in May and April 2011, respectively, but barnacle nauplii and other zooplankton were in average abundance (slide 13).

Summary

The overwhelming numerical dominance of *Oithona similis* in the MWRA time series raises issues in terms of our understanding of planktonic food webs in coastal waters. The classical paradigm of feeding interactions in lower trophic levels of pelagic food webs has been that of copepods and other zooplankters grazing upon phytoplankton, and in turn being eaten by larger consumers such as larval fish. This paradigm is complicated by the fact that *Oithona similis* is primarily a microzooplankton predator, feeding mainly upon protozoans such as ciliates and heterotrophic dinoflagellates, rather than grazing upon phytoplankton (Nakamura & Turner 1997; Lonsdale *et al.* 2000; Castellani *et al.* 2005). Thus, the overwhelming numerical dominance of *Oithona similis* in Massachusetts Bay (Turner *et al.* 2011), as well as globally (Gallienne & Robins 2001), in waters as diverse as the Antarctic (Lonsdale *et al.* 2000) and the northeastern North Atlantic (Castellani *et al.* 2005), fundamentally challenges the classical paradigm of how pelagic marine food webs function. Linkages from the most abundant phytoplankton (namely “microflagellates”) to the zooplankton appear to be primarily through protozoans, and not directly through copepods in most areas of the sea. These protozoans are then consumed by copepods such as *Oithona similis* (Turner 2004), which in turn are consumed by fish larvae (Lough & Mountain 1996).

Overall, 2011 was a fairly typical year in terms of zooplankton community composition, abundance, seasonality, and distributional patterns. It will be extremely interesting to compare 2011 and all preceding years to data from 2012, which thus far has been an extremely atypical year with warmer temperatures, earlier *Phaeocystis* blooms, and other differences from most previous years.

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2011 Zooplankton Results



MWRA Harbor Outfall Monitoring Program

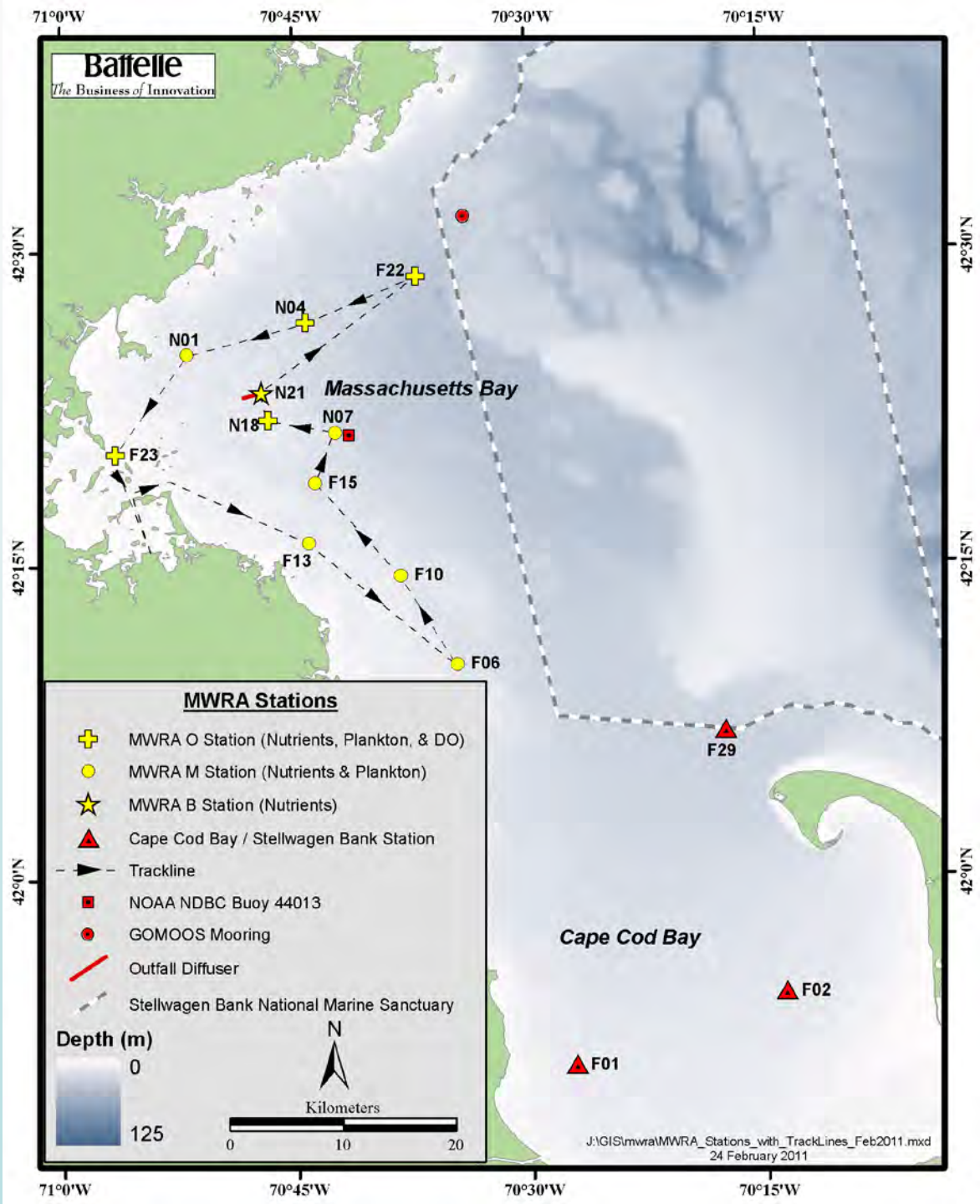
Jefferson T. Turner
School for Marine Science & Technology
University of Massachusetts Dartmouth

Battelle Annual Science Meeting
Duxbury, Massachusetts
May 1, 2012



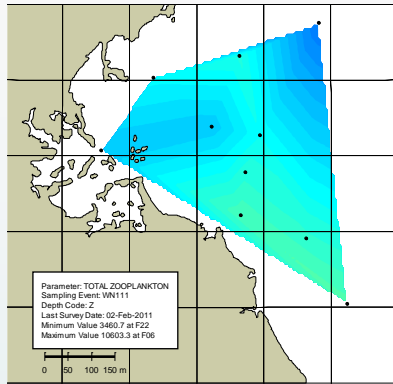
2011 Zooplankton - Overview

- 2011 was a typical year in terms of patterns and composition.
- Abundance was dominated by copepod nauplii and *Oithona similis* copepodites and adults.
- Abundance increased from the winter through the spring to peak in the summer, and declined in the fall.
- There was more temporal variability in abundance than spatial variability in abundance.
- *Calanus finmarchicus* and barnacle nauplii peaked in the spring.
- *Oithona similis*, *Acartia* spp., *Pseudocalanus* spp. and other zooplankton peaked in summer.
- *Calanus finmarchicus* was most abundant offshore, whereas *Acartia* spp. were most abundant inshore.
- *Oithona similis* was ubiquitously abundant everywhere.

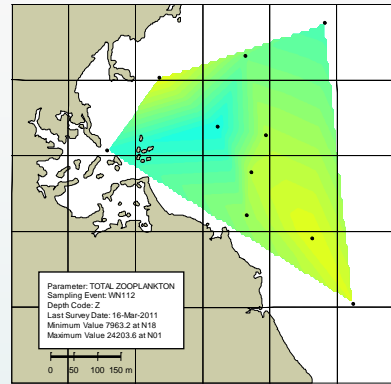


2011 Total Zooplankton

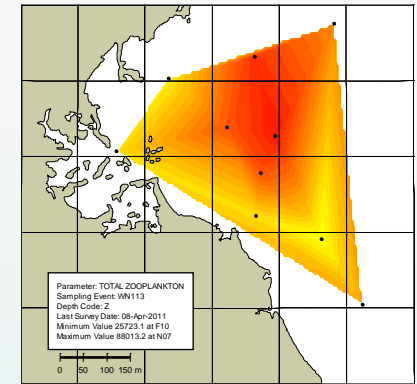
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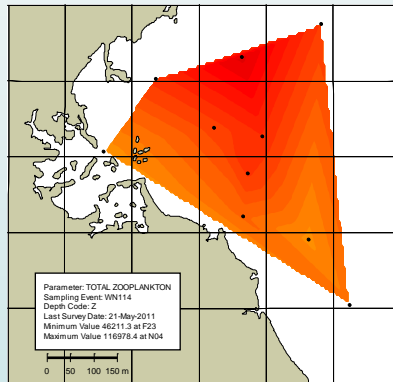
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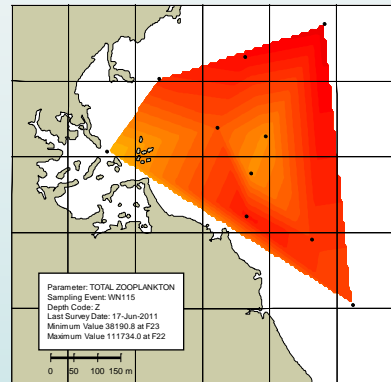
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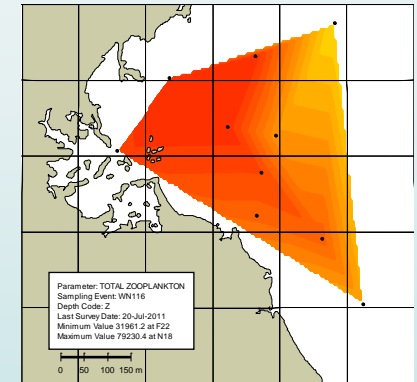
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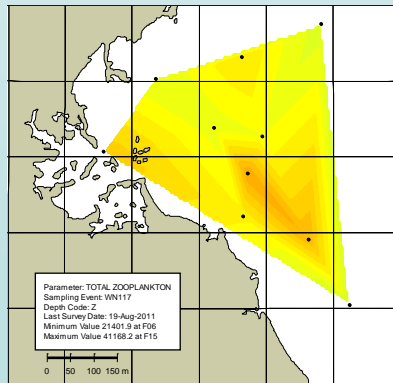
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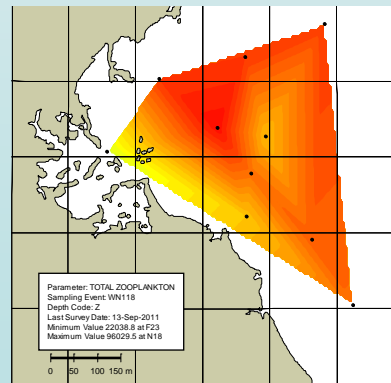
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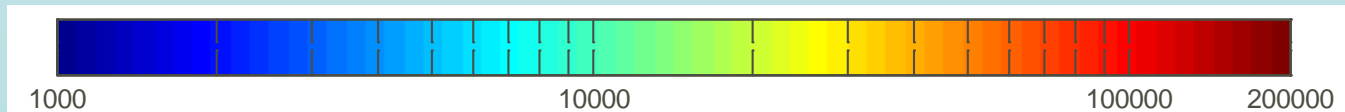
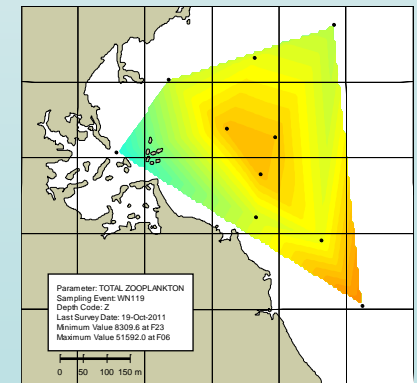
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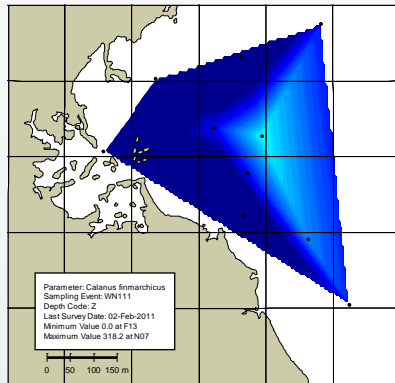


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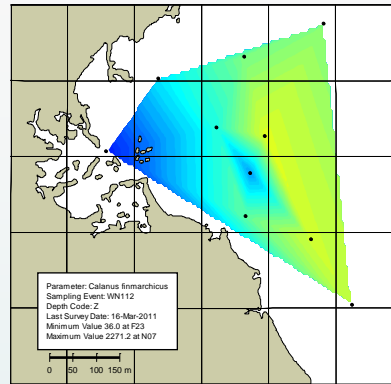


2011 Calanus finmarchicus

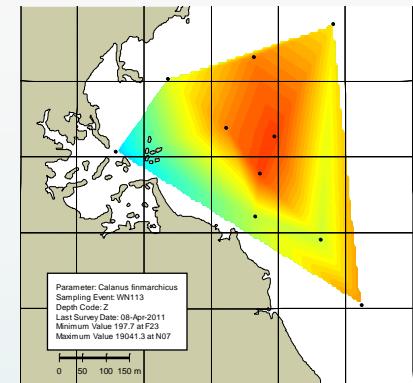
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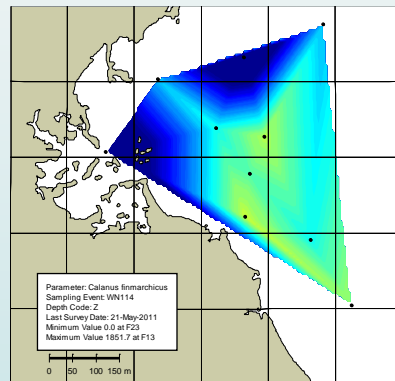
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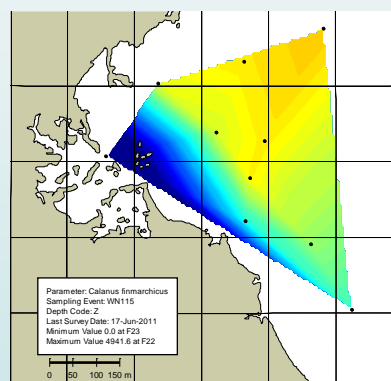
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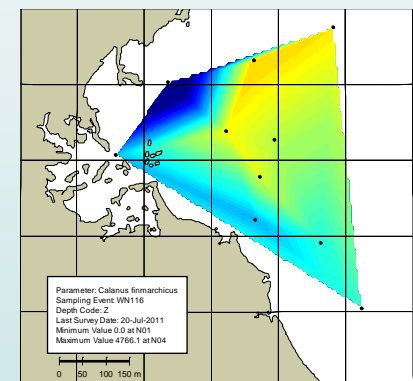
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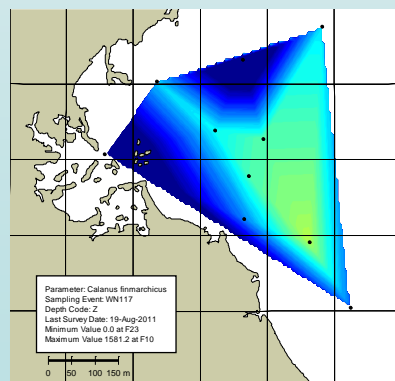
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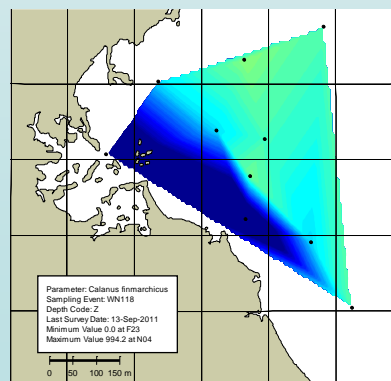
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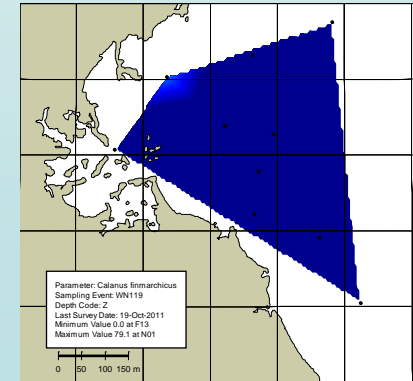
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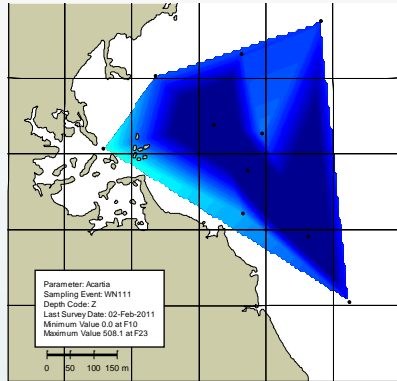
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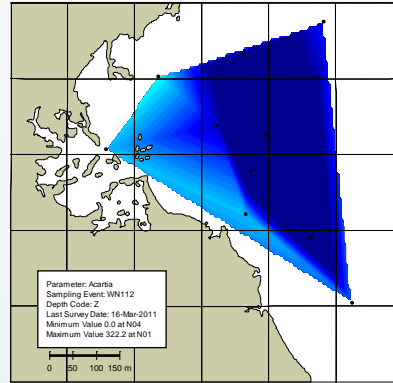
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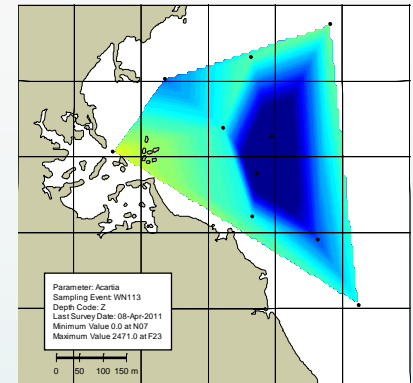
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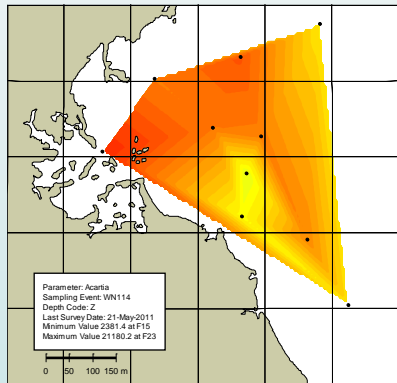
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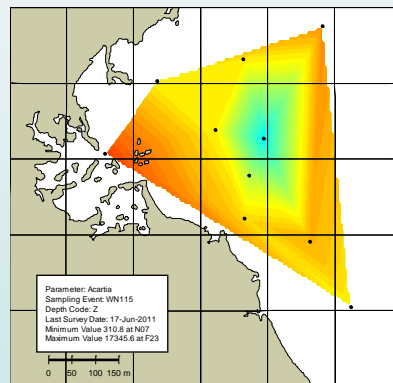
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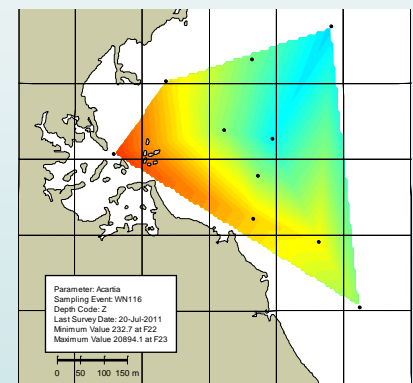
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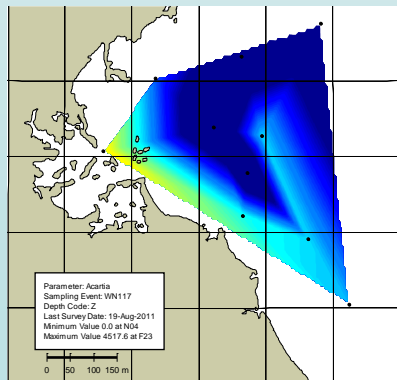
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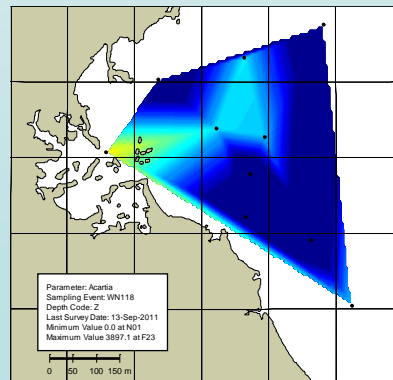
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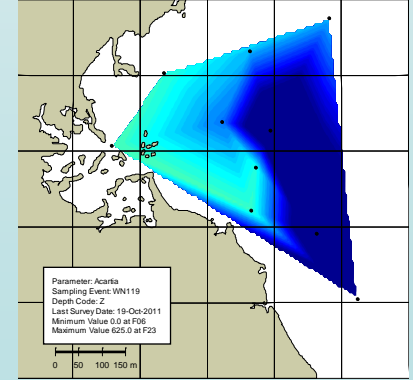
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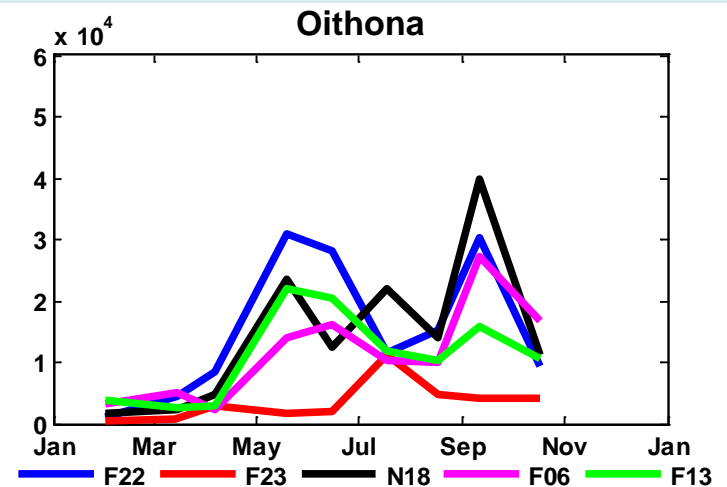
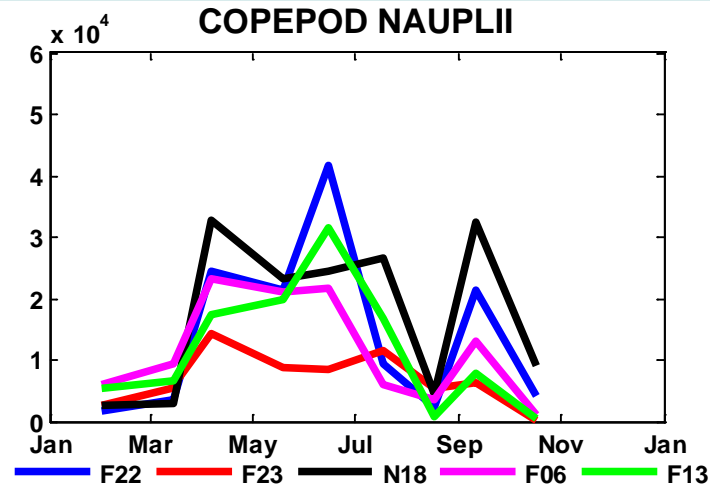
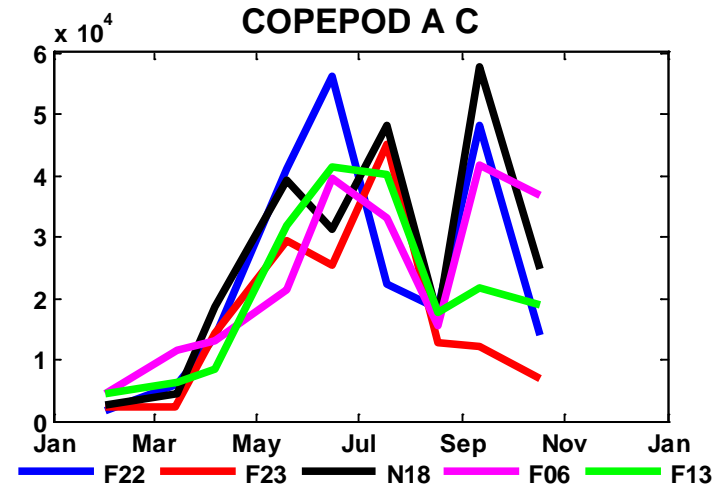
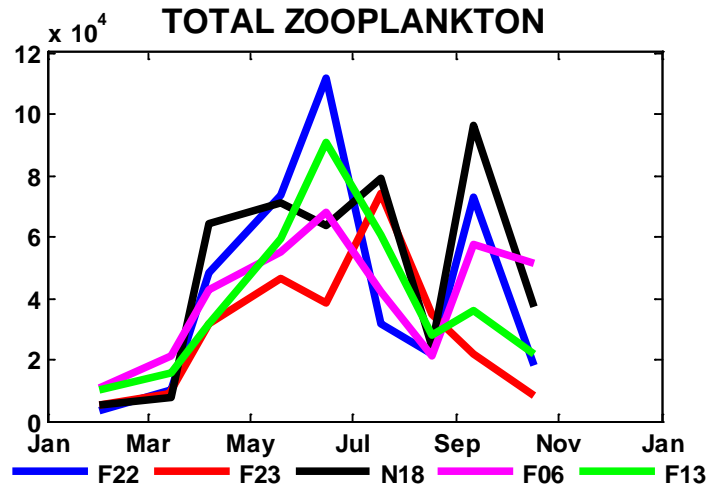
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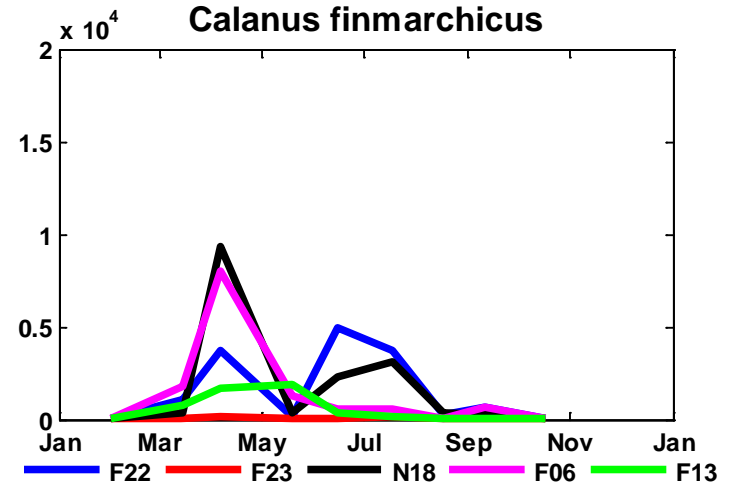
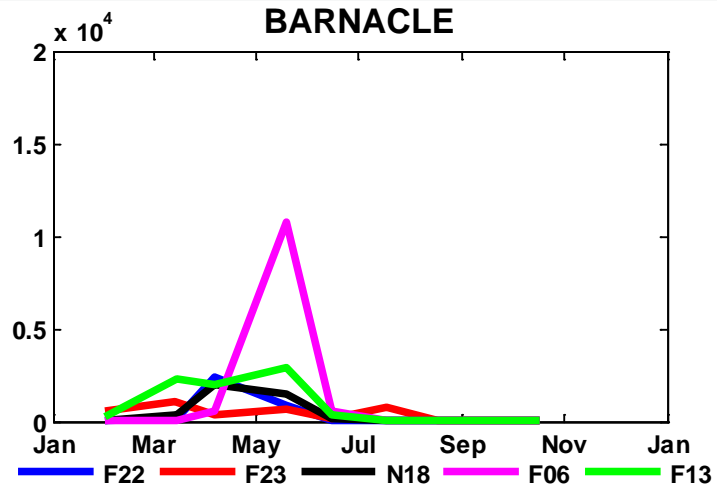
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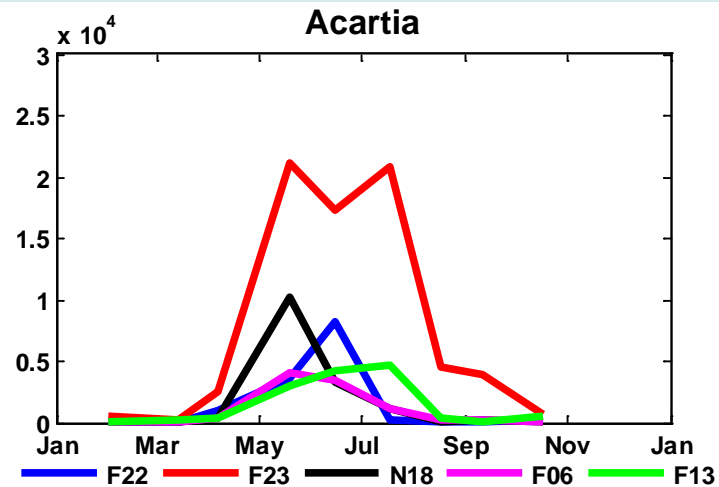
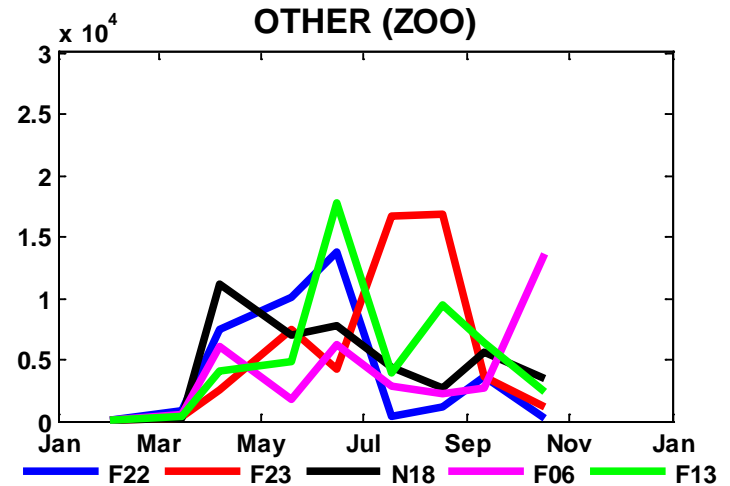
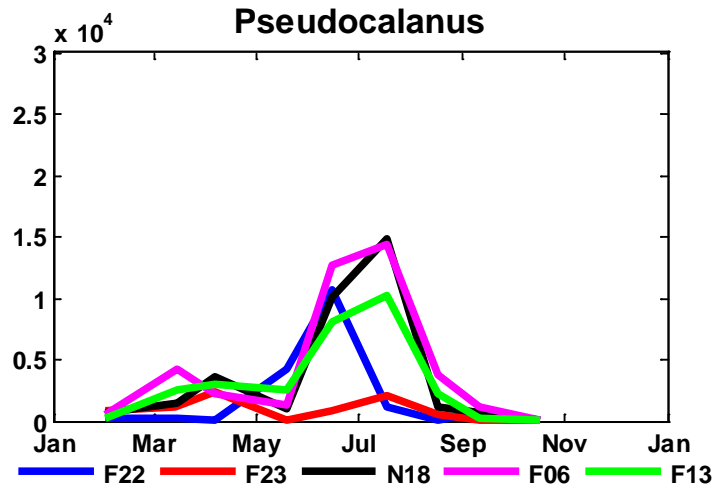
2011 Zooplankton



2011 Zooplankton

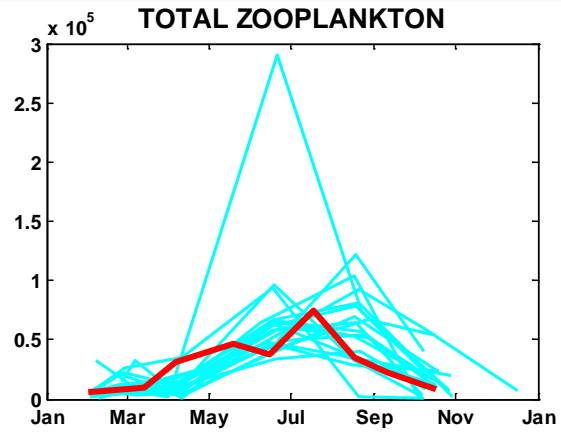


2011 Zooplankton

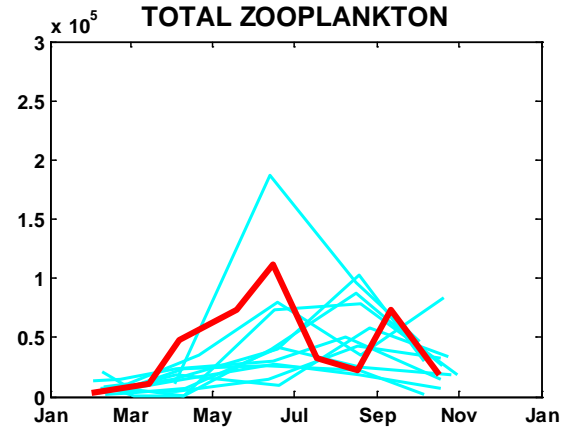


Total Zooplankton 2011 Annual cycle

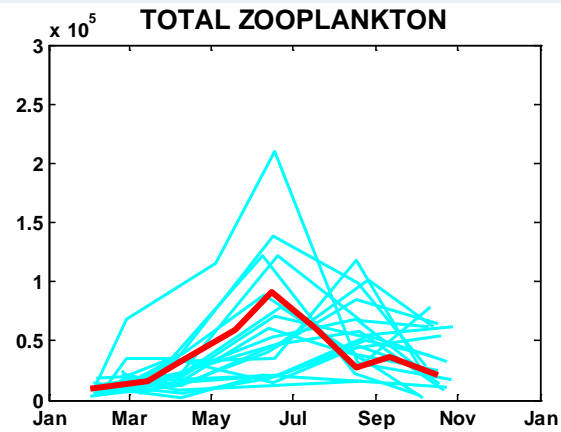
Harbor
(F23)



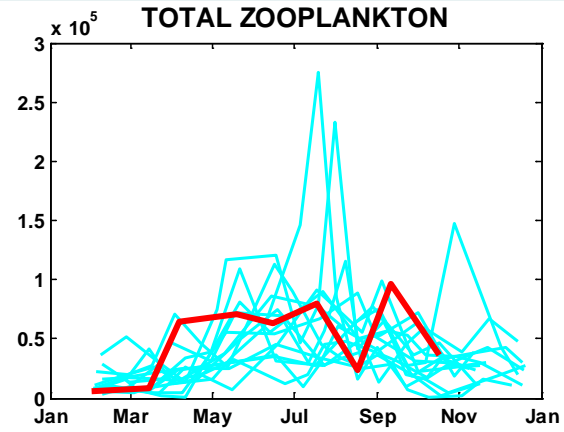
Northern
Offshore
(F22)



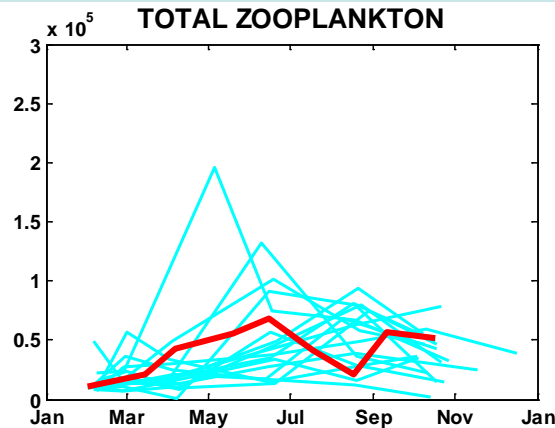
Coastal
(F13)



Nearfield
(N18)

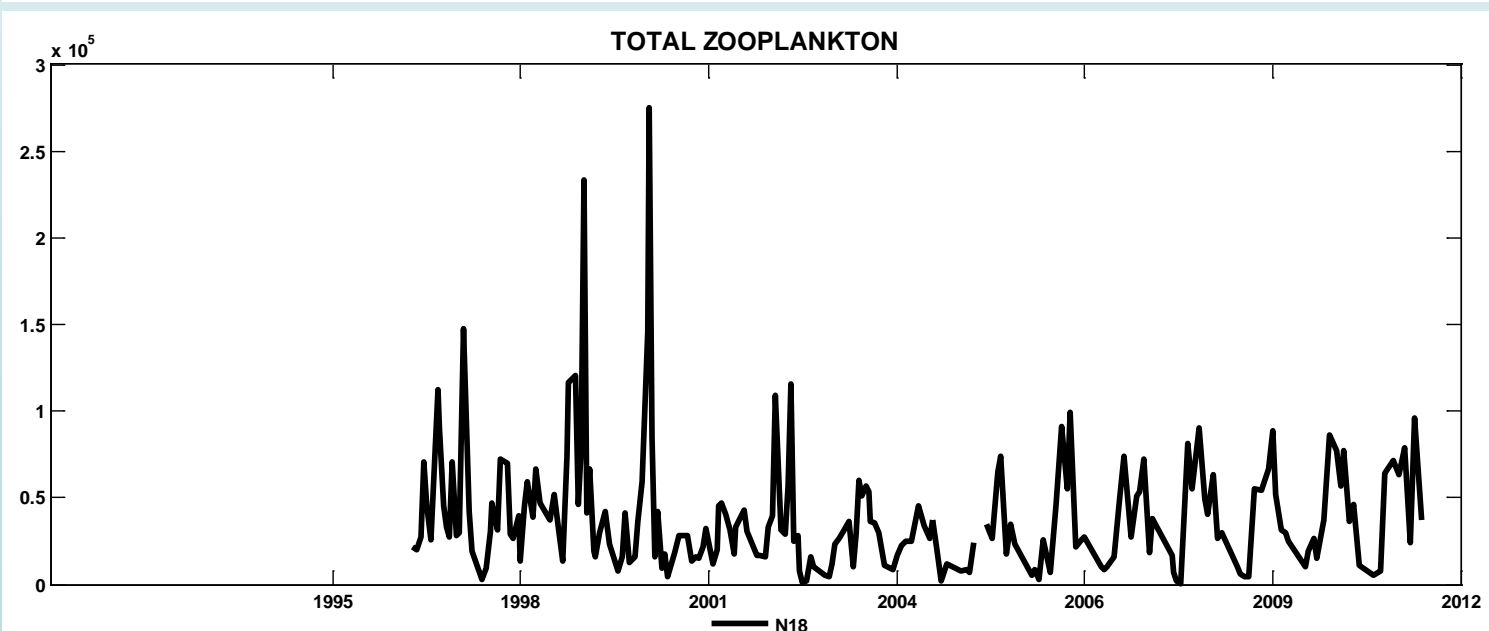
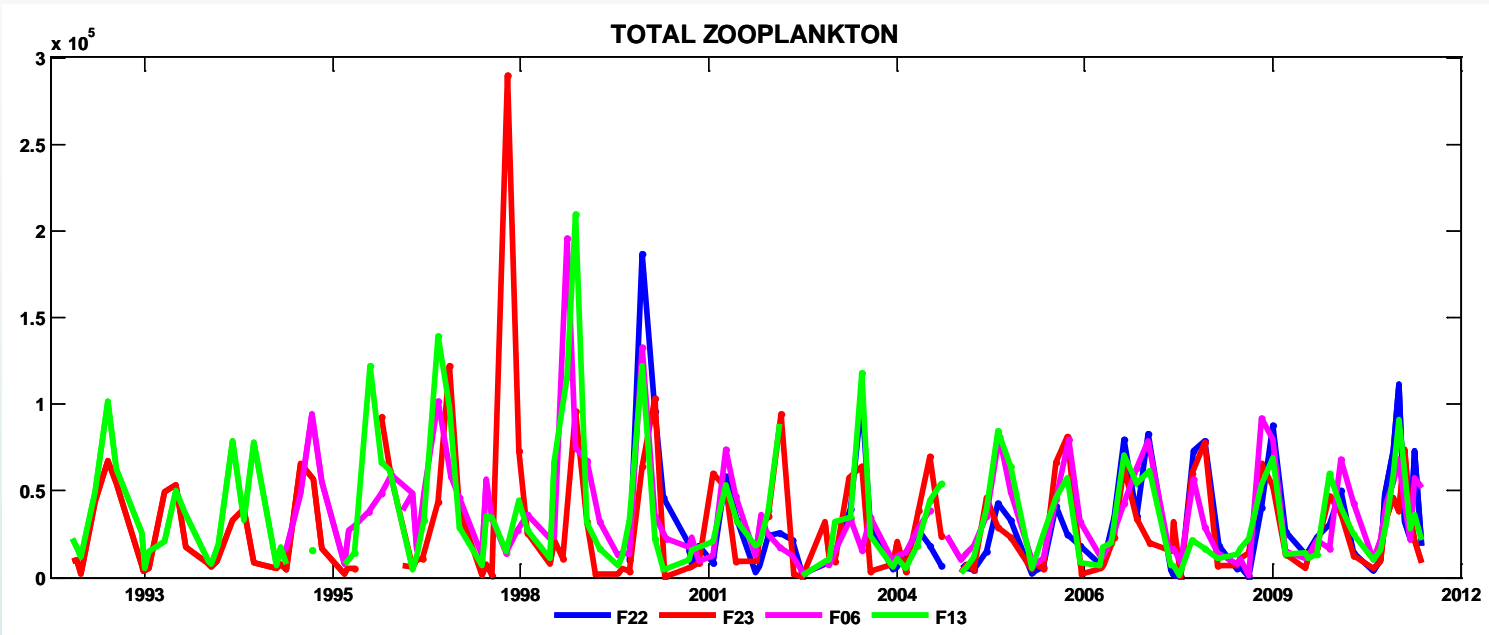


Southern Offshore
(F06)

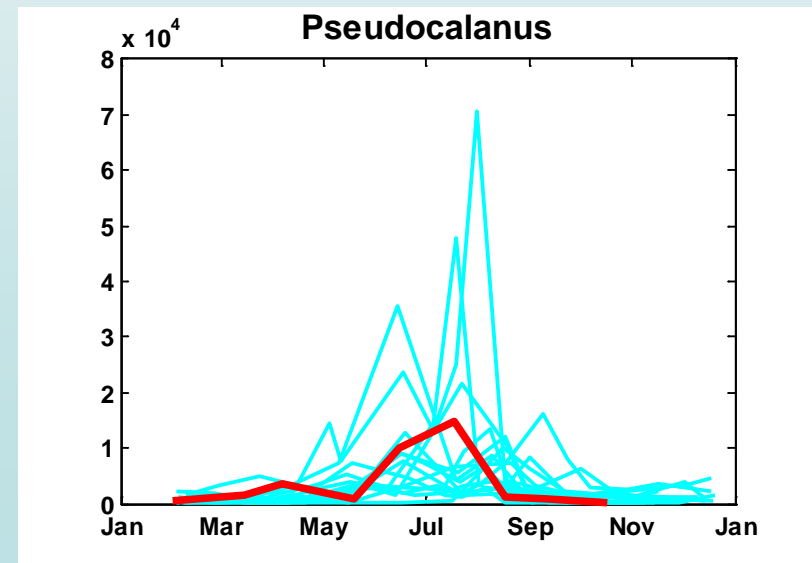
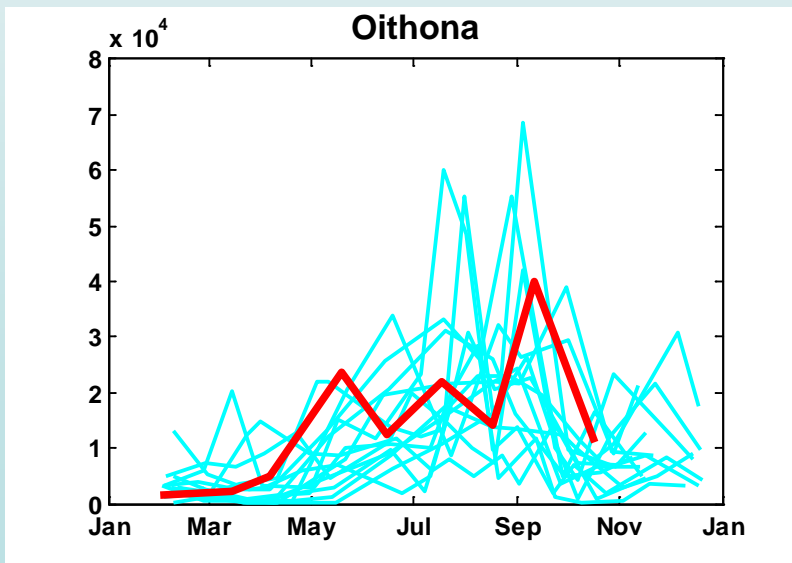
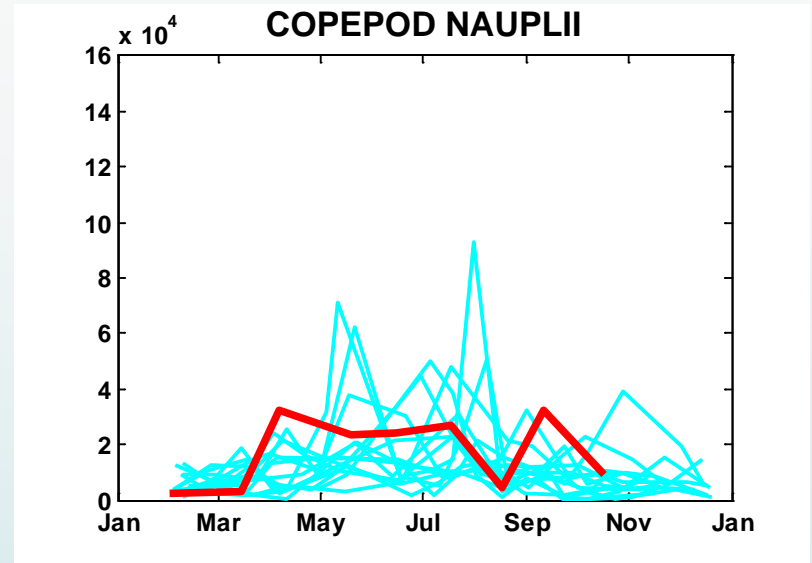
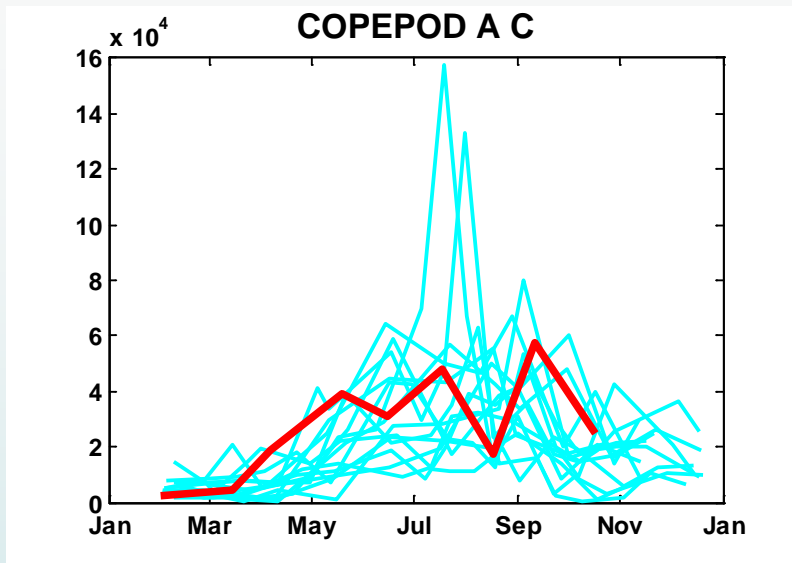


Total zooplankton long-term pattern, 1992-2011

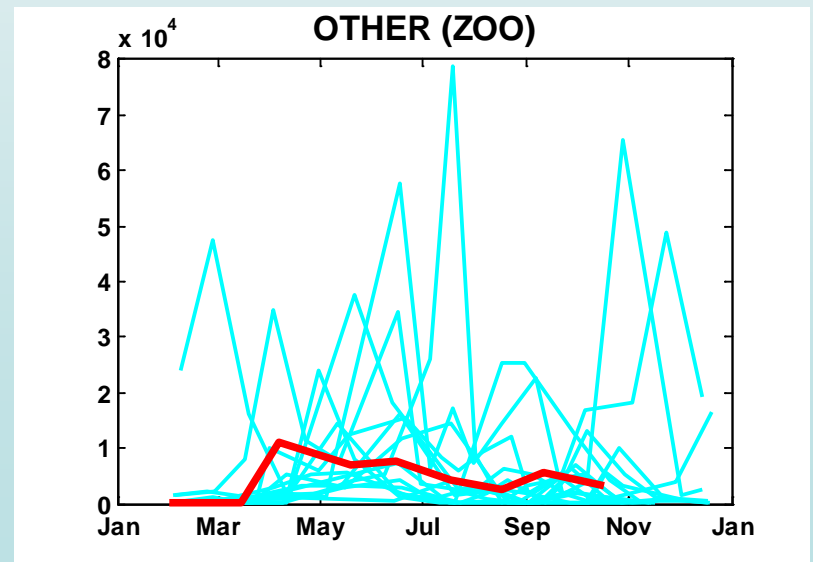
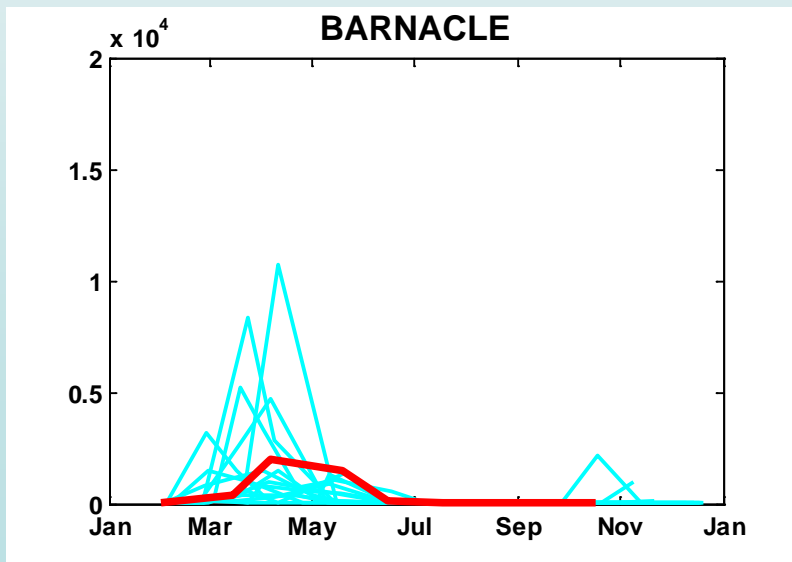
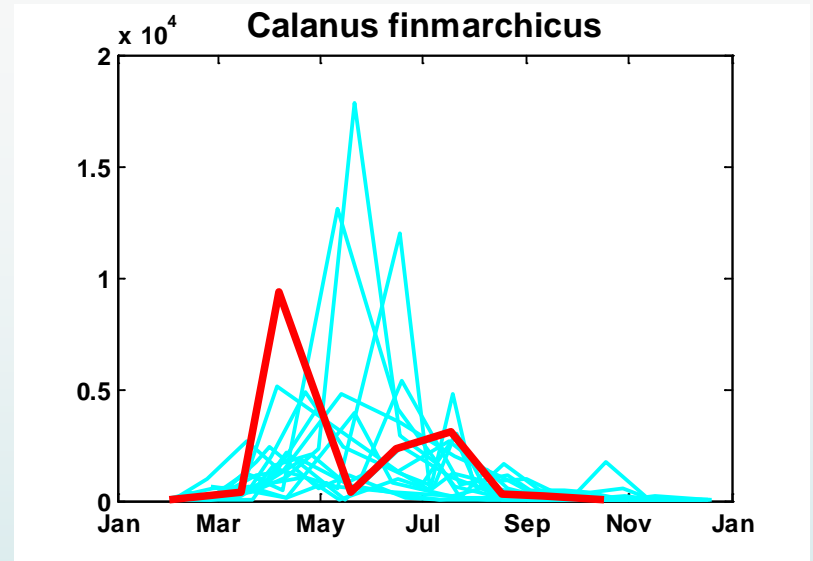
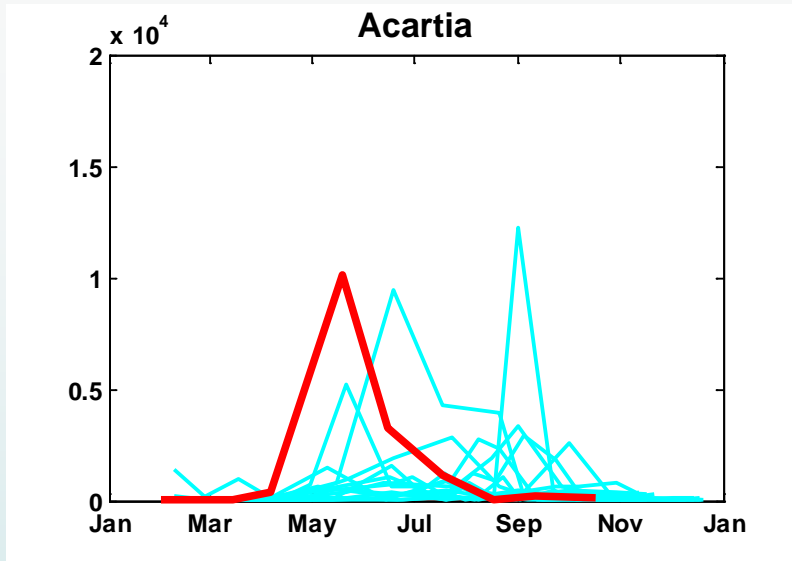
Farfield stations top and nearfield stations bottom



Nearfield Zooplankton



Nearfield Zooplankton



2011 Zooplankton Summary

- 2011 was generally a typical year in terms of patterns and composition.
- Total zooplankton abundance was dominated by copepod nauplii and *Oithona similis* copepodites and adults.
- Abundance increased from the winter through the spring to peak in the summer, and declined in the fall.
- There was more temporal variability in abundance than spatial variability in abundance.
- *Calanus finmarchicus* and barnacle nauplii peaked in the spring.
- *Oithona similis*, *Acartia* spp., *Pseudocalanus* spp. and other zooplankton peaked in summer.
- *Calanus finmarchicus* was most abundant offshore, whereas *Acartia* spp. were most abundant inshore.

Appendix E

Cape Cod Bay Monitoring

In 2011, the Provincetown Center for Coastal Studies (PCCS) completed 16 surveys to conduct water column monitoring in Cape Cod Bay and the southwestern corner of Stellwagen Bank (Table 1). Nine of these surveys focused on monitoring 3 of MWRA’s farfield stations. When time and weather permitted, 8 additional PCCS stations were monitored in Cape Cod Bay during these surveys. Otherwise, the 8 PCCS stations were monitored as closely as possible to the targeted MWRA survey date. Coincident monitoring of all 11 stations occurred during the surveys in April, May, June, July, and September. Only PCCS stations were monitored in January, November and December.

Table 1. Surveys conducted by PCCS during 2011

Date	MWRA Survey	Stations
1/6/11		CCB
2/2/11	WN111	MWRA
2/7/11		CCB
3/15/11	WN112	MWRA
3/23/11		CCB
4/7/11	WN113	CCB/MWRA
5/14/11	WN114	CCB/MWRA
6/16/11	WN115	CCB/MWRA
7/20/11	WN116	CCB/MWRA
8/18/11	WN117	MWRA
8/31/11		CCB
9/12/11	WN118	CCB/MWRA
10/18/11	WN119	MWRA
10/23/11		CCB
11/26/11		CCB
12/30/11		CCB

This report presents the data collected at the 3 MWRA stations (F01, F02, F29) in 2011 and puts these data in the context of the monitoring work done throughout the rest of Cape Cod Bay by PCCS (Figure 1).

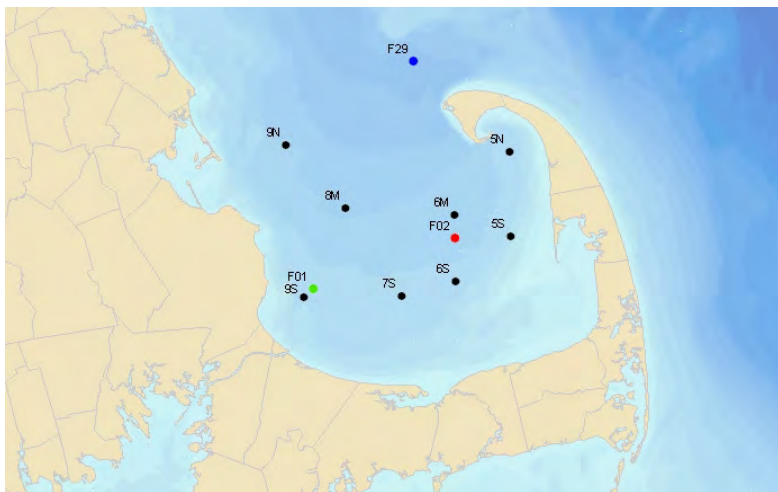


Figure 1. Locations of stations sampled in Cape Cod Bay and Stellwagen Bank. The colors of the symbols correspond to the data from these stations in the following figures.

Hydrography: Hydrographic data collected during 2011 (Figure 2) followed similar patterns as observed in previous years. Surface water temperatures were coldest in February. All stations were well-mixed through the spring. A thermocline began to form in June, strengthening over the course of the summer. In October, cooling temperatures and wind events began to break down the water column stratification. Typical seasonal changes in salinity were observed with lower surface salinities during the spring. Density, being driven by changes in temperature and salinity, reflected these seasonal changes. Dissolved oxygen concentrations remained greater than 8 mg/L in the surface waters for all stations throughout the year. Bottom waters of F02 and a few of the PCCS stations had notably lower levels of dissolved oxygen from June through September when stratification of the water column was strongest.

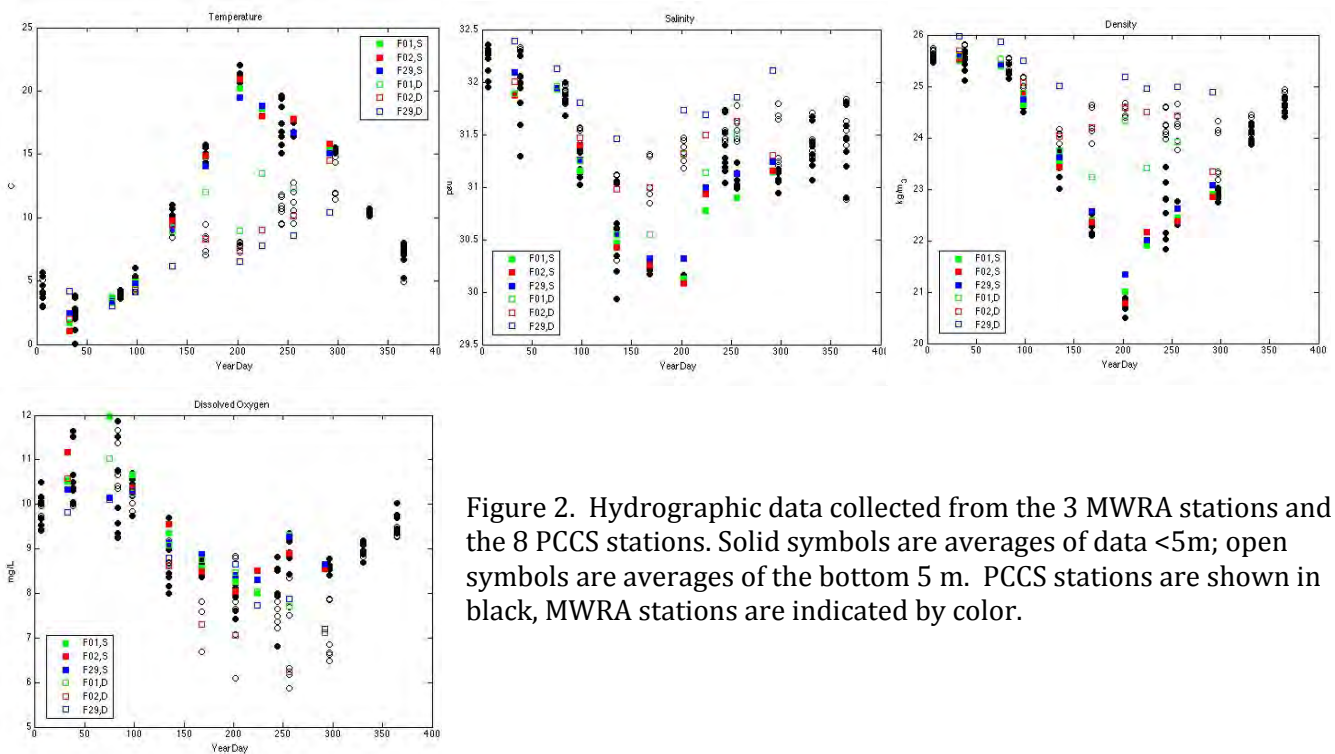


Figure 2. Hydrographic data collected from the 3 MWRA stations and the 8 PCCS stations. Solid symbols are averages of data <5m; open symbols are averages of the bottom 5 m. PCCS stations are shown in black, MWRA stations are indicated by color.

Water Chemistry: As with hydrography, water chemistry followed patterns typical of this area. Dissolved nutrients were highest in the surface waters when the water column was well mixed (Figure 3). This precipitated the seasonal blooms in phytoplankton (winter/spring and fall) as evidenced by the peaks in chlorophyll levels (Figure 4). Bottom waters tended to show an increase in dissolved nutrients when the water column was strongly stratified (Figure 3).

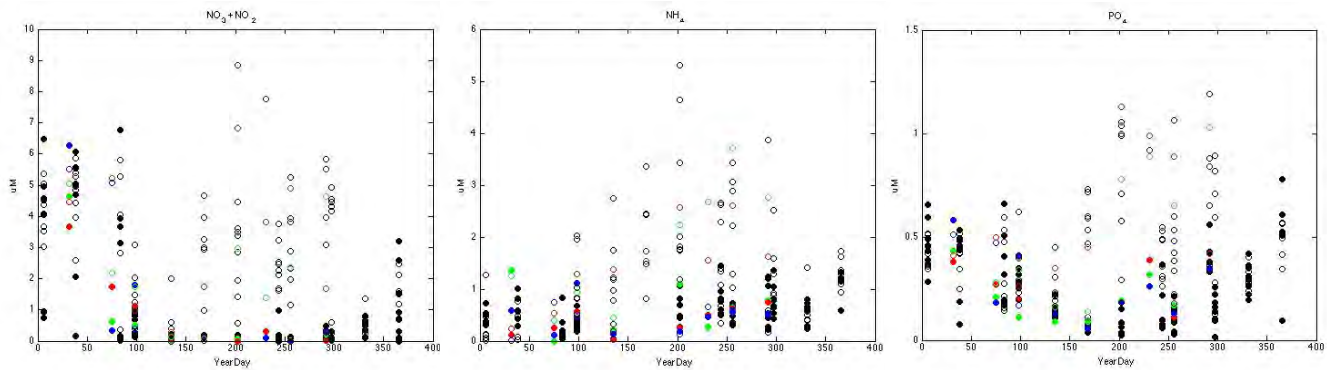


Figure 3. Dissolved nutrient concentrations. Symbols follow the same color scheme as Figure 2.

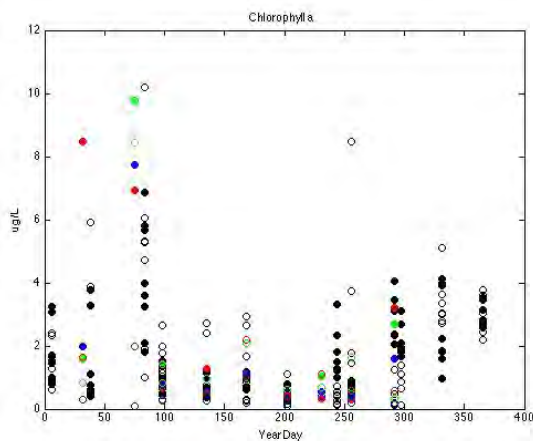


Figure 4. Chlorophyll concentrations. Symbols follow the same color scheme as Figures 2 and 3.

Plankton: The phytoplankton assemblage was typically dominated by microflagellates. During February, March and June diatoms (*Skeletonema* spp., *Chaetoceros* spp., and *Leptocylindrus* spp., respectively) were prevalent. In May, chrysophyte and dinoflagellate abundances peaked (Figure 5).

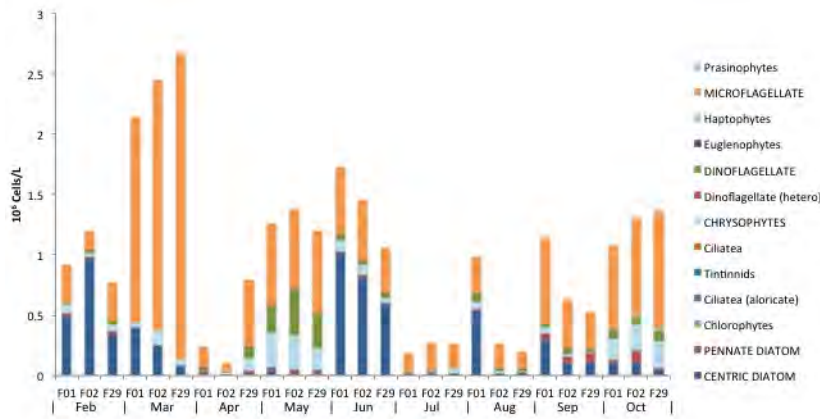


Figure 5. Phytoplankton abundance and composition observed at the 3 MWRA stations.

Zooplankton was dominated by *Centropages* spp. during the winter, *Pseudocalanus* spp. and *Calanus finmarchicus* during the spring, and Cladocera and *Temora longicornis* during the summer. *Centropages* spp. and radiolarians were predominant in the fall (Figure 6).

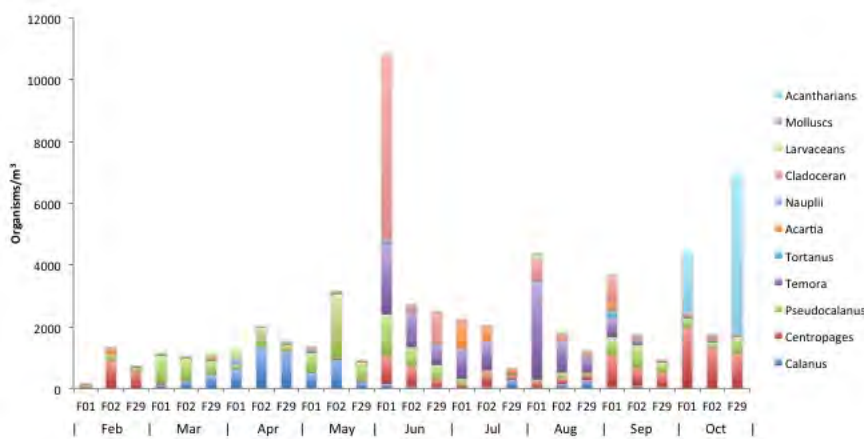


Figure 6. Zooplankton abundance and composition observed at the 3 MWRA stations.

During the winter and spring, much of the sampling effort for zooplankton in Cape Cod Bay is focused around right whales. During 2011, both zooplankton and whale abundances were high, with peak abundances occurring slightly later in the season than observed in previous years.

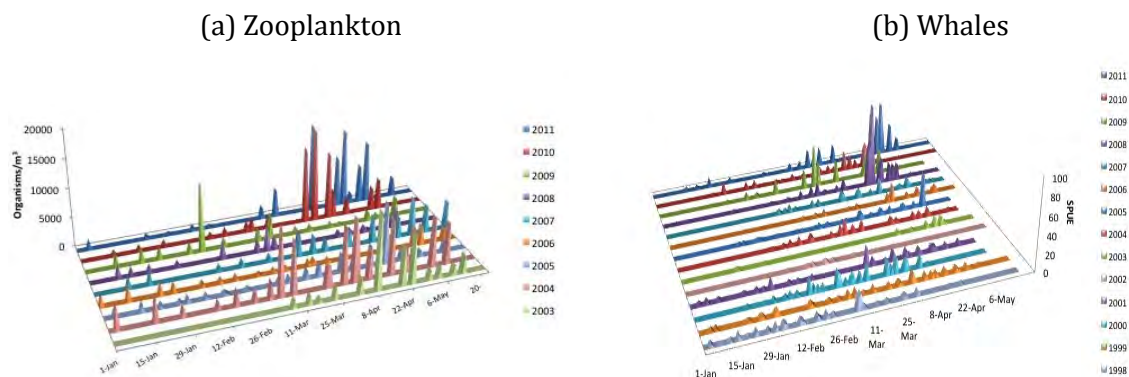
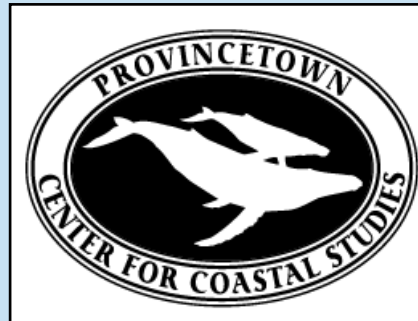
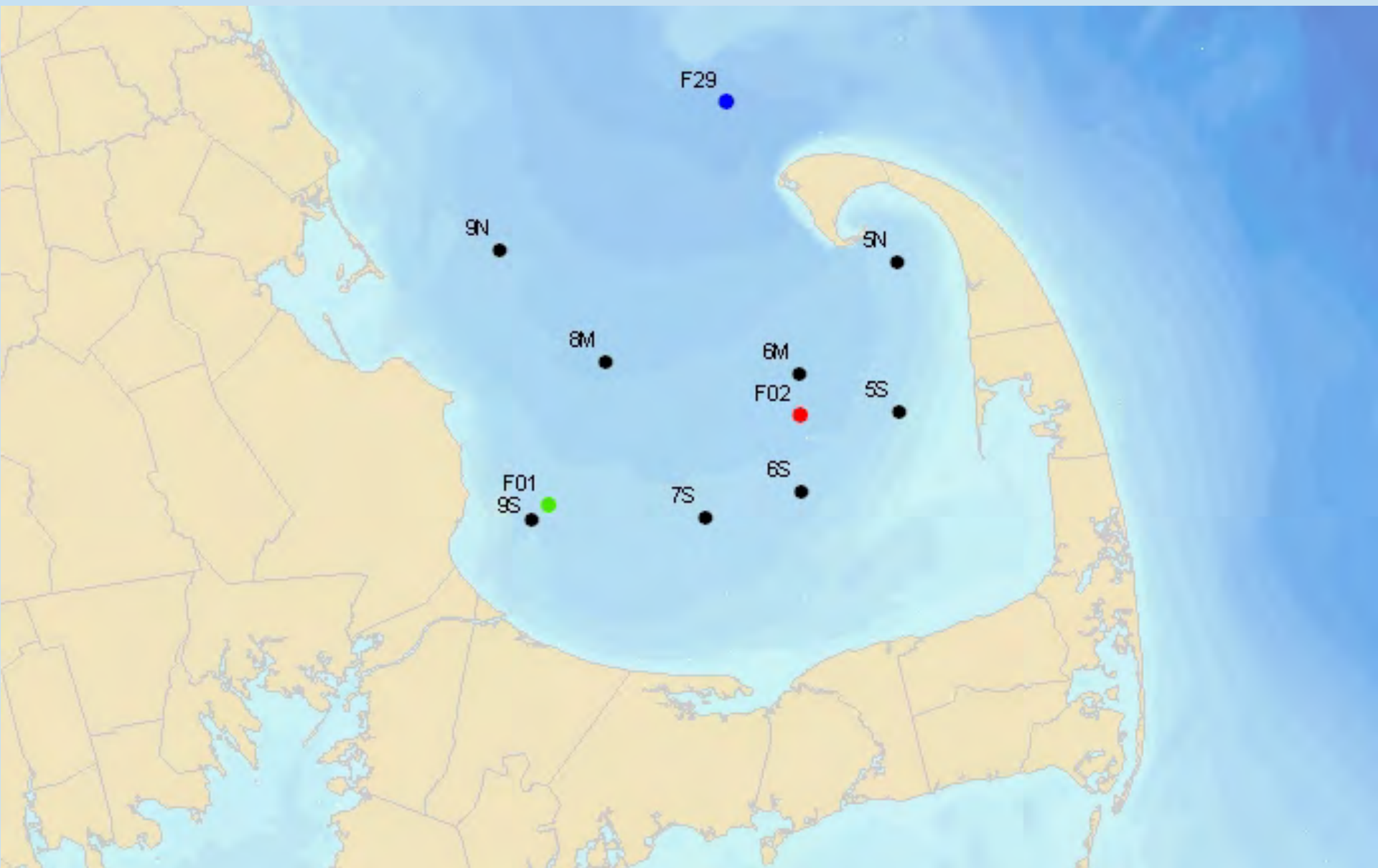


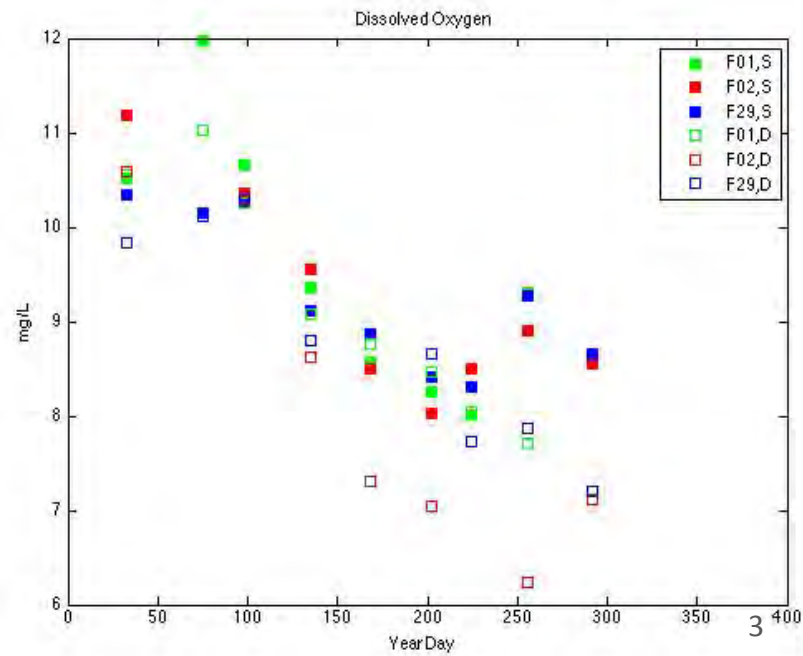
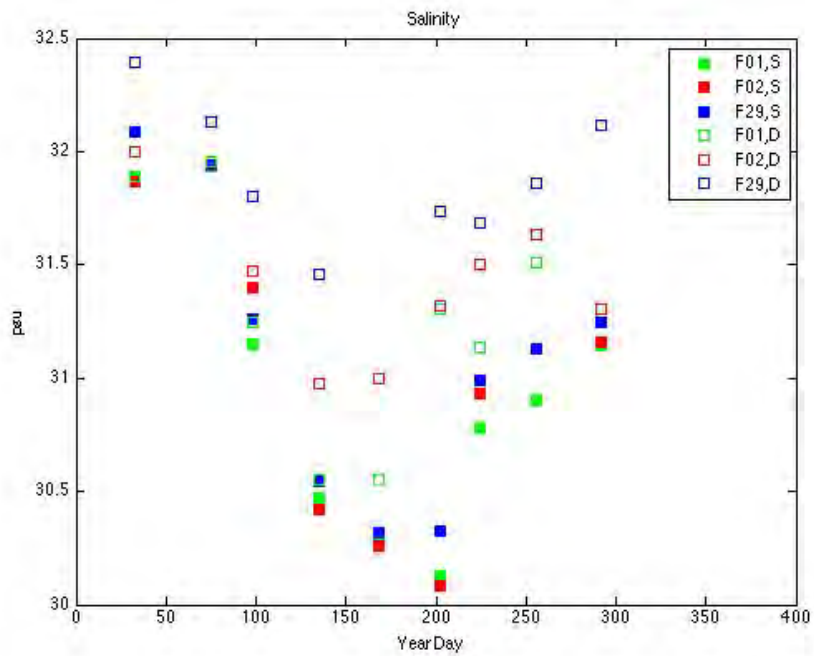
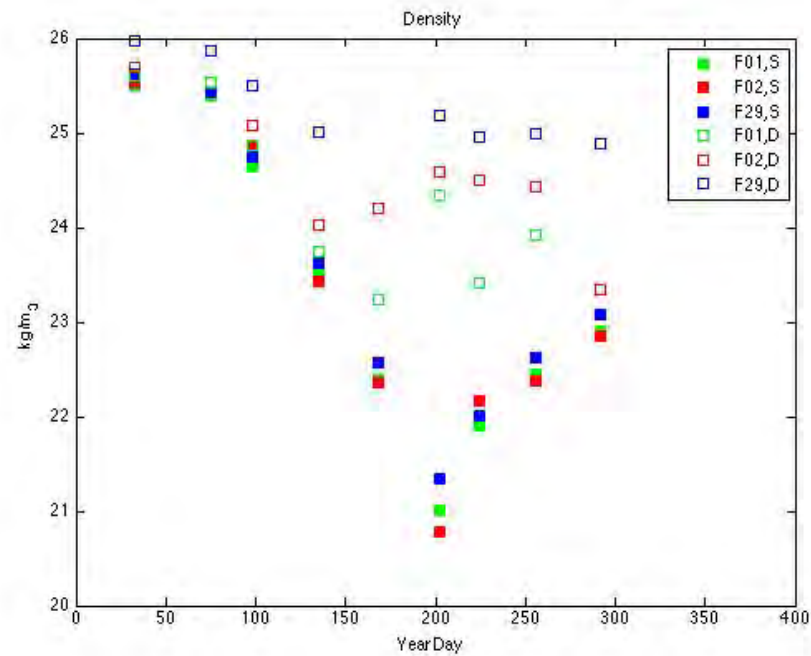
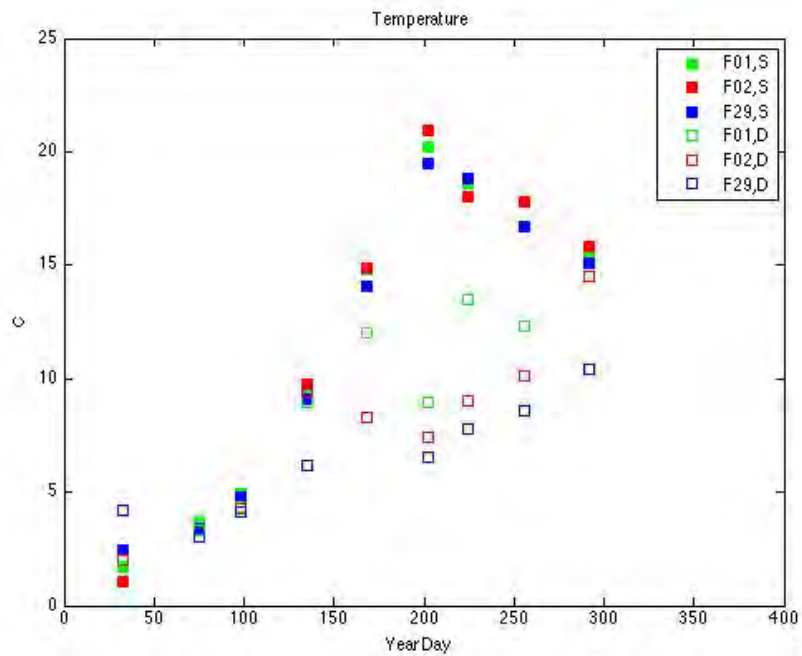
Figure 7. Monthly abundances of (a) zooplankton and (b) whales by year.

Cape Cod Bay Monitoring 2011

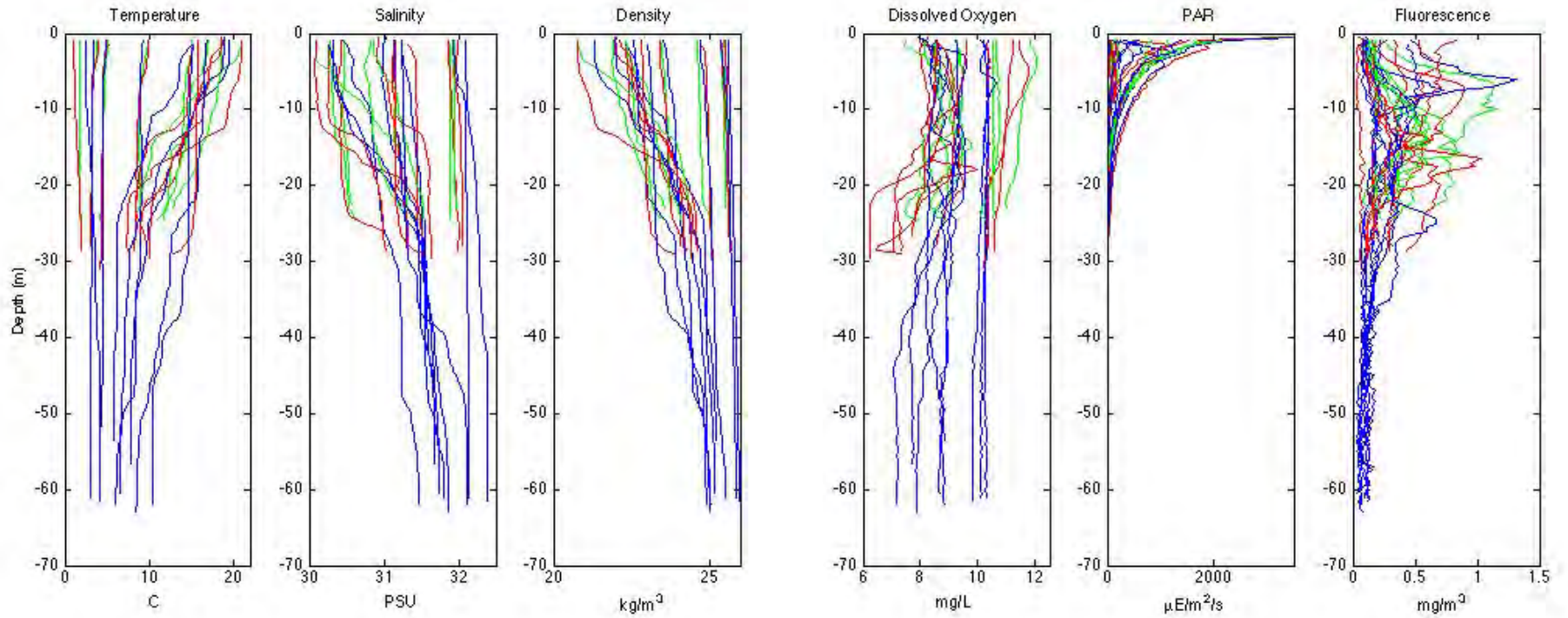
Provincetown Center for Coastal Studies

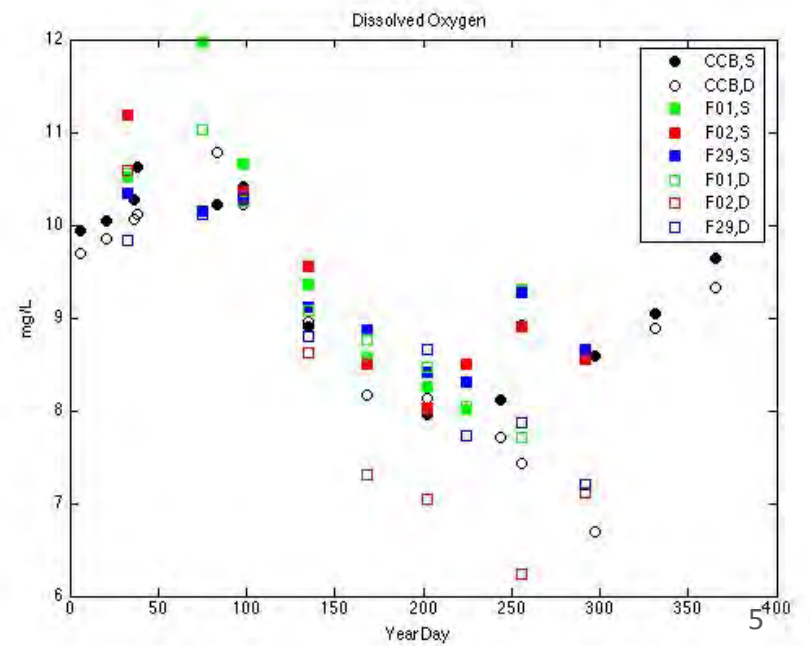
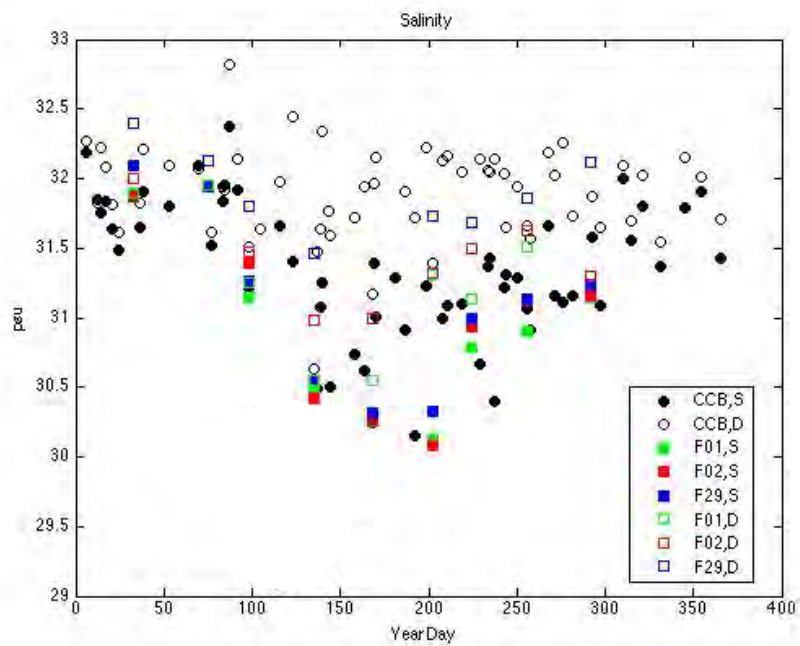
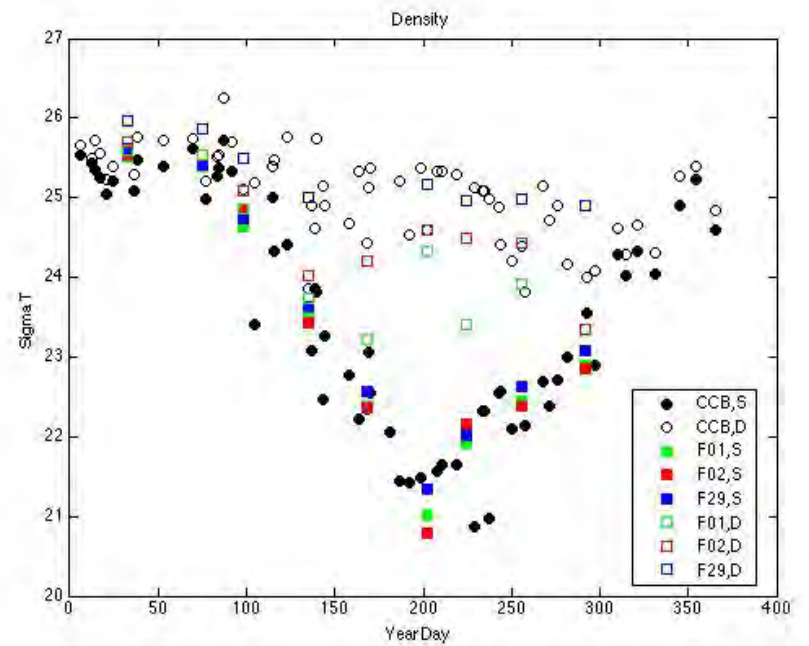
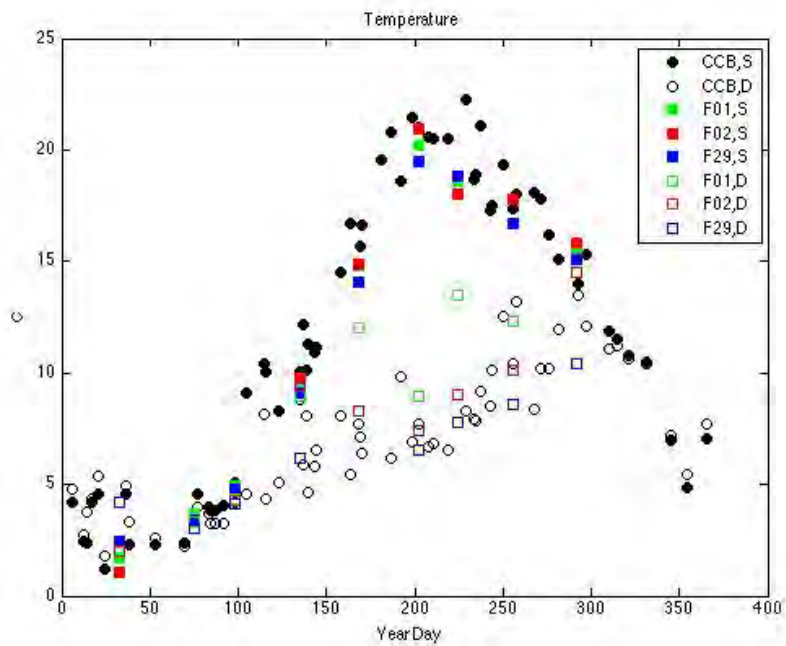




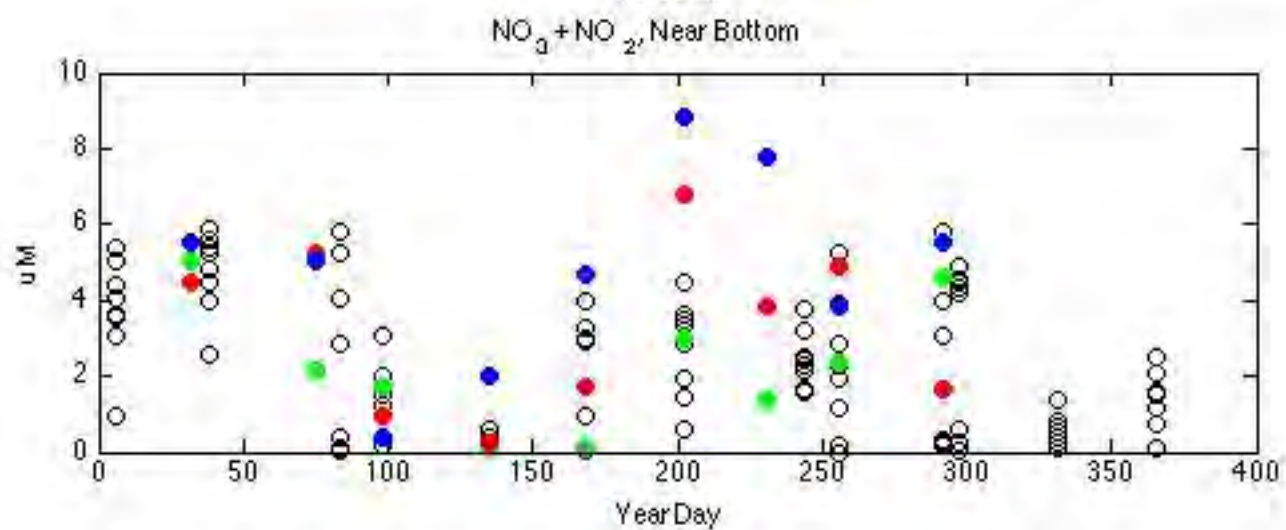
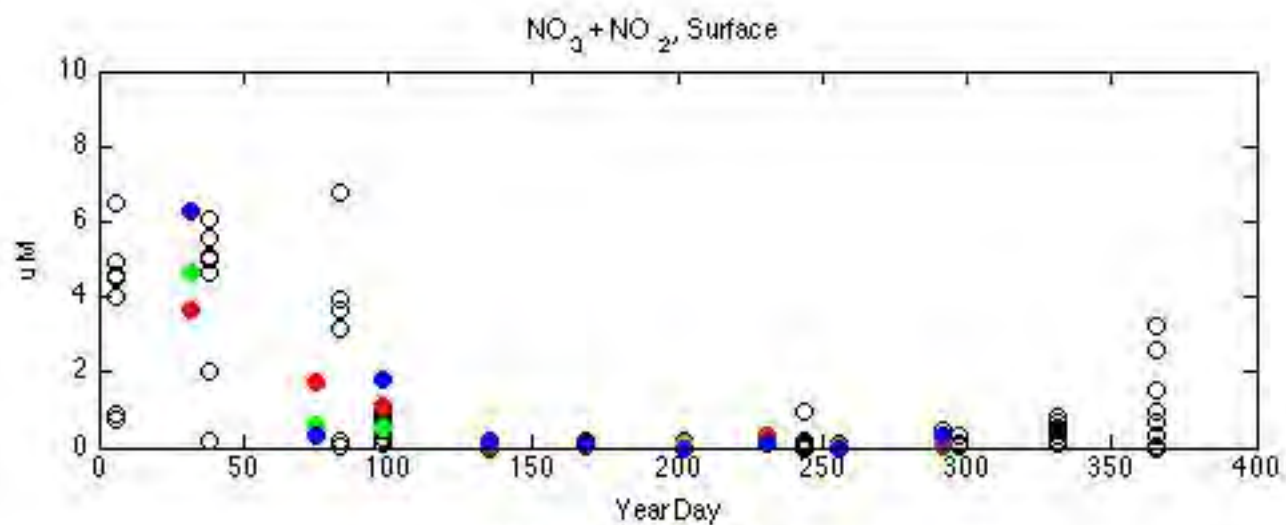


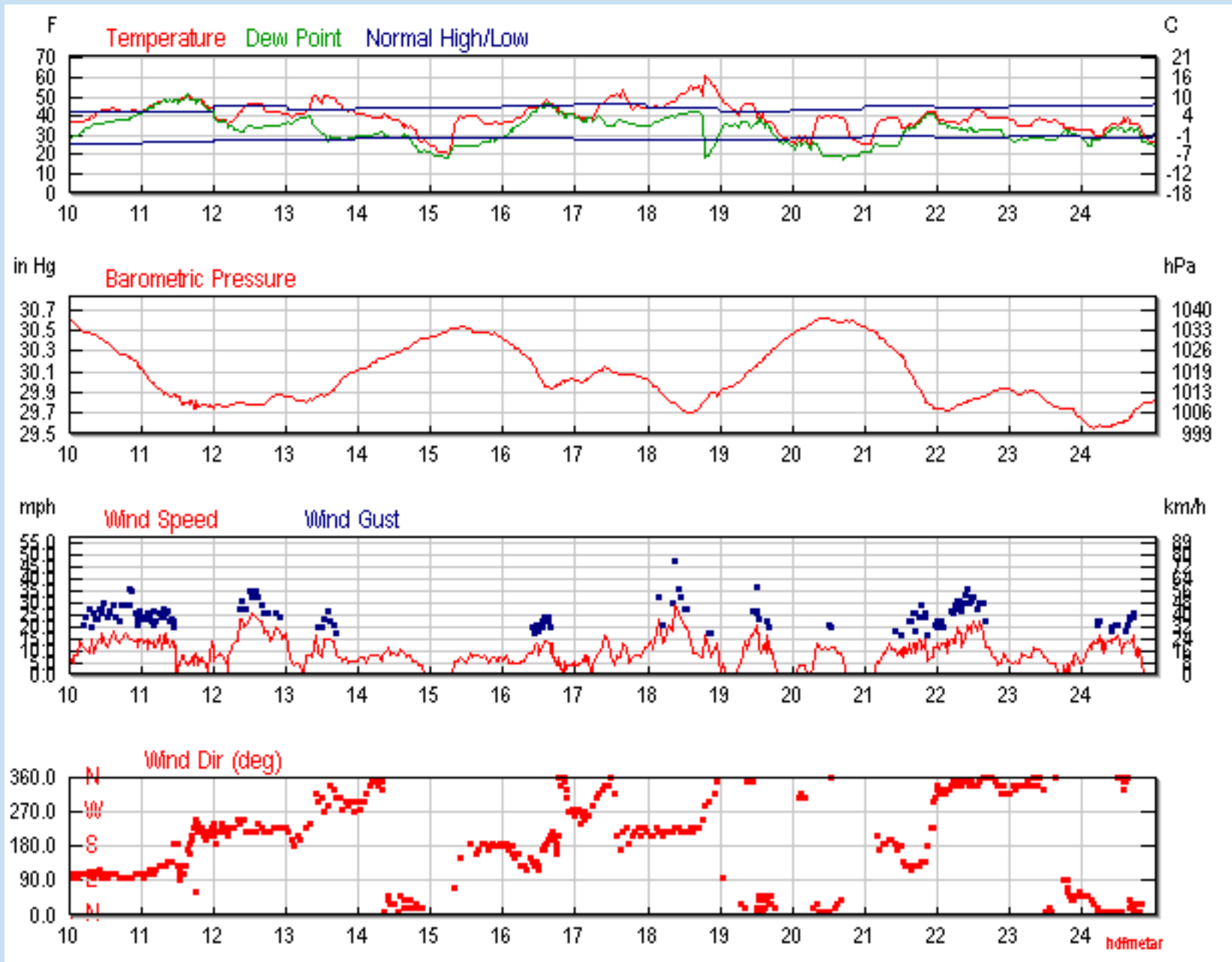
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- F02
- F29



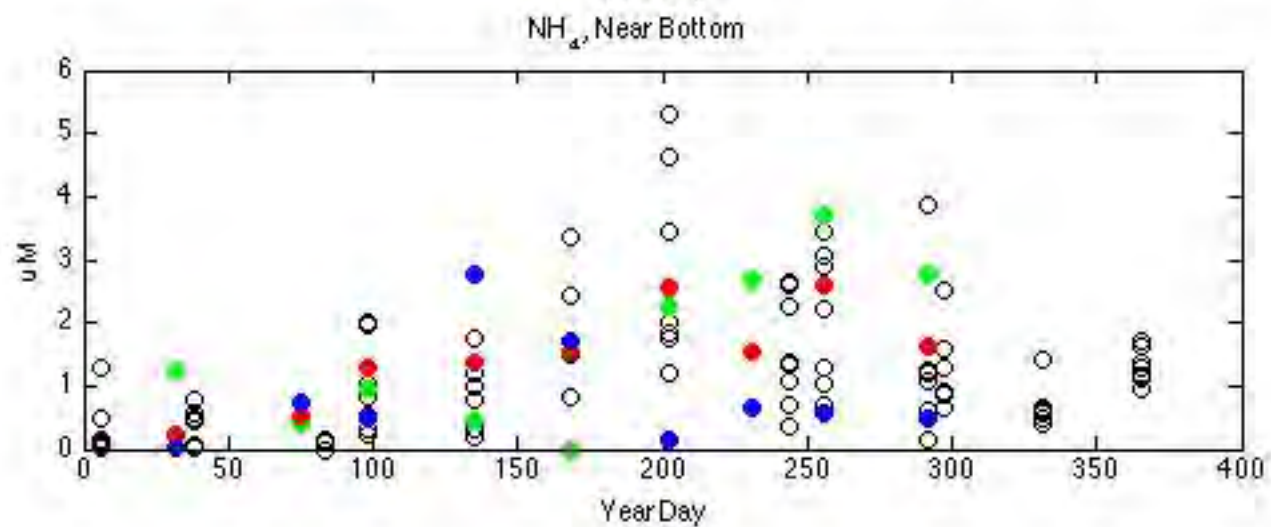
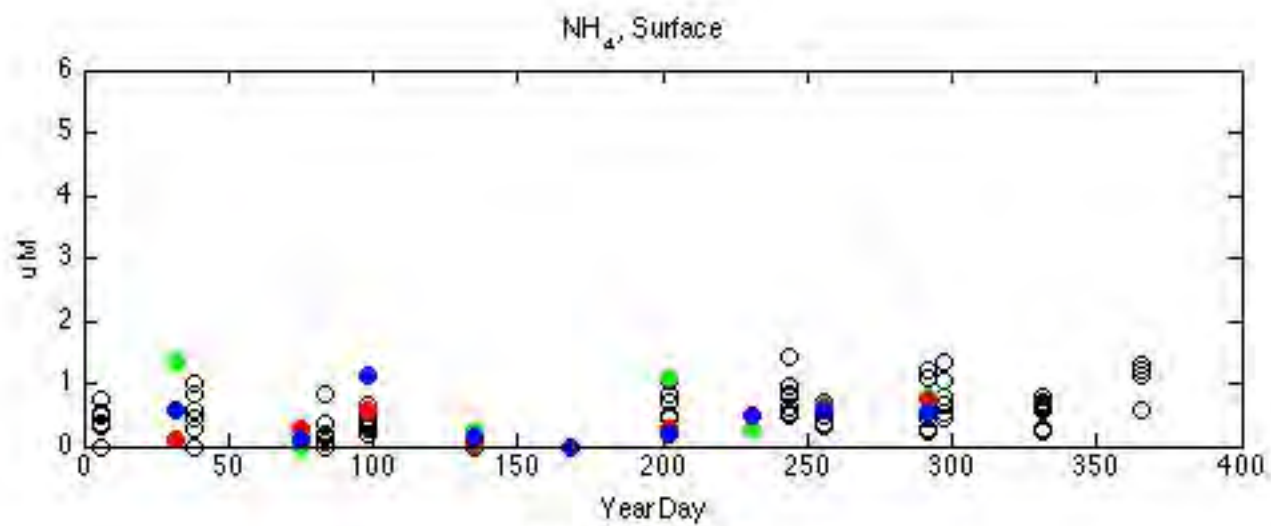


- CCB
- F01
- F02
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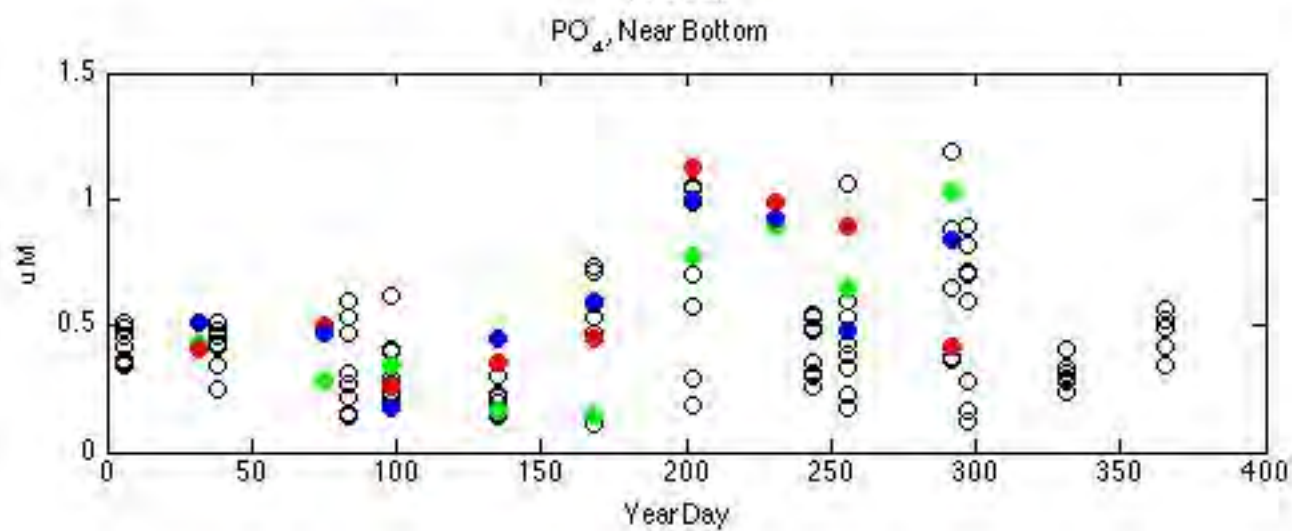
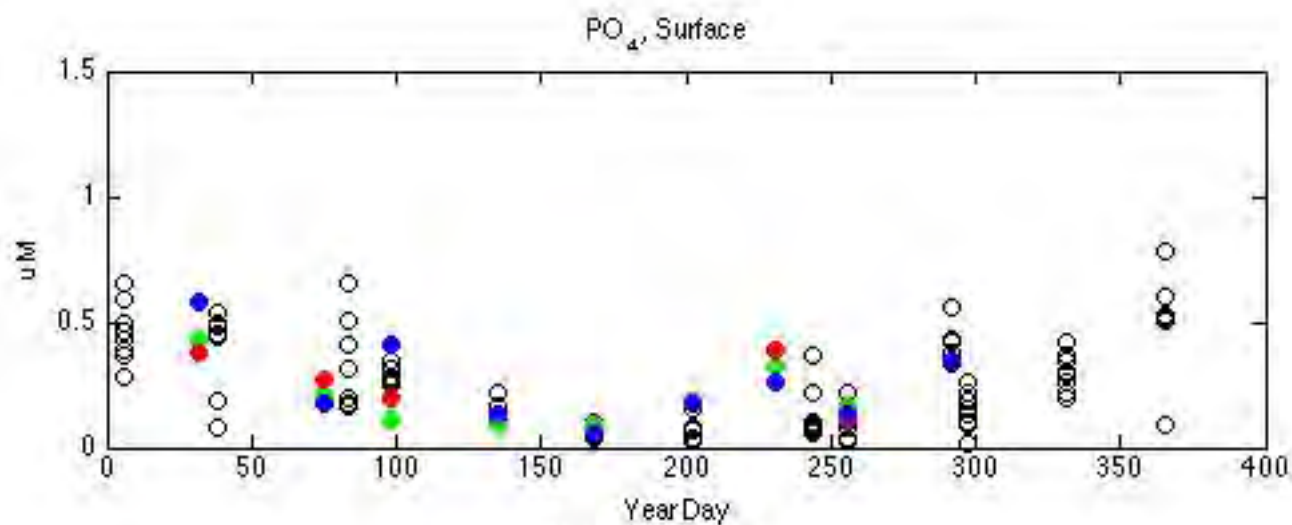




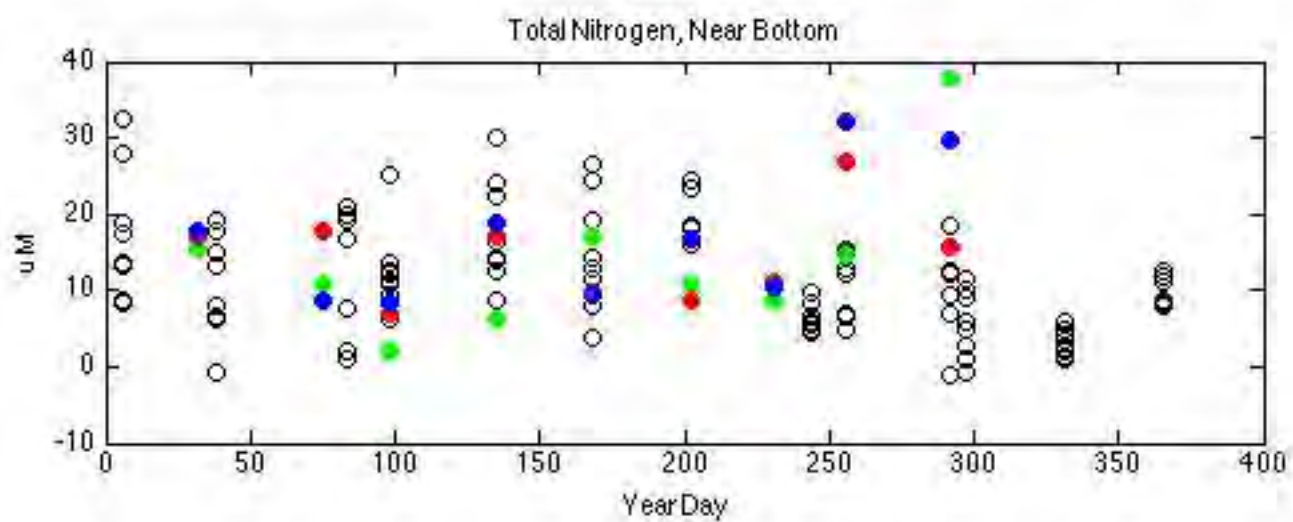
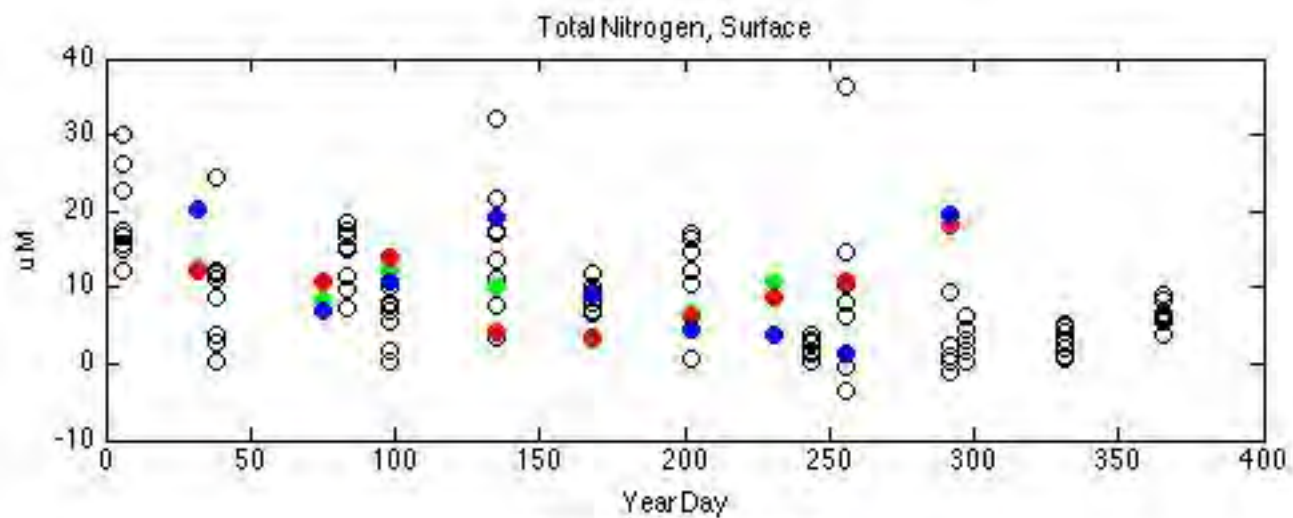
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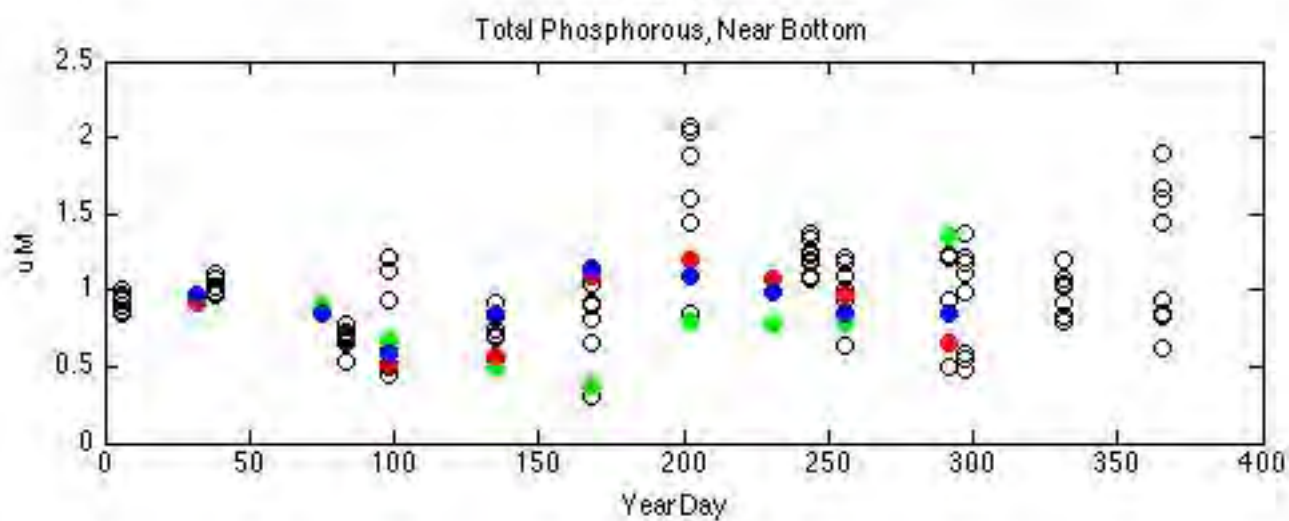
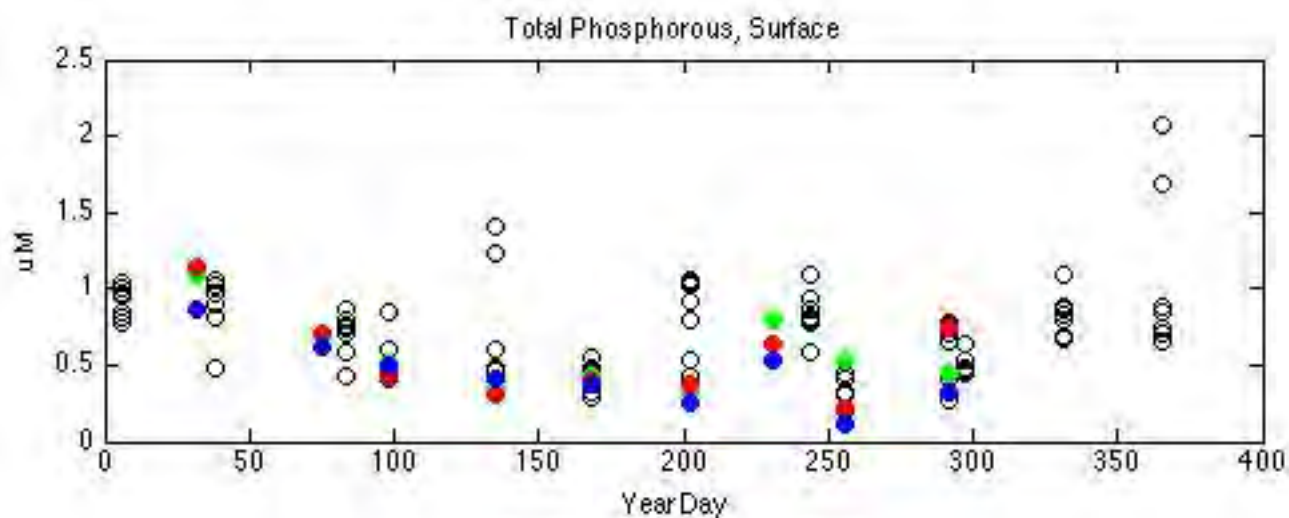
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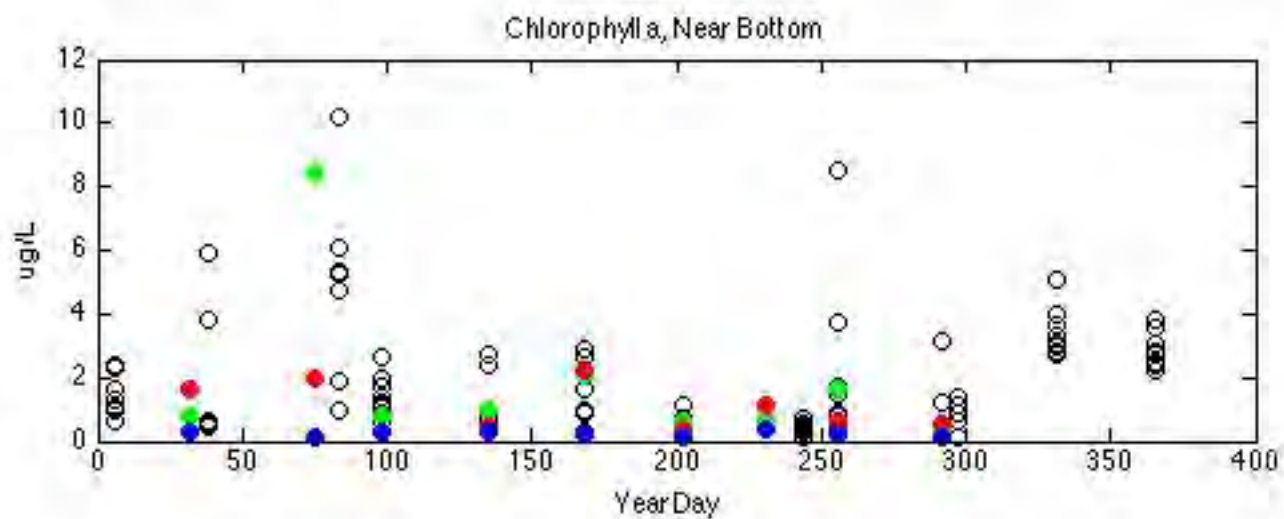
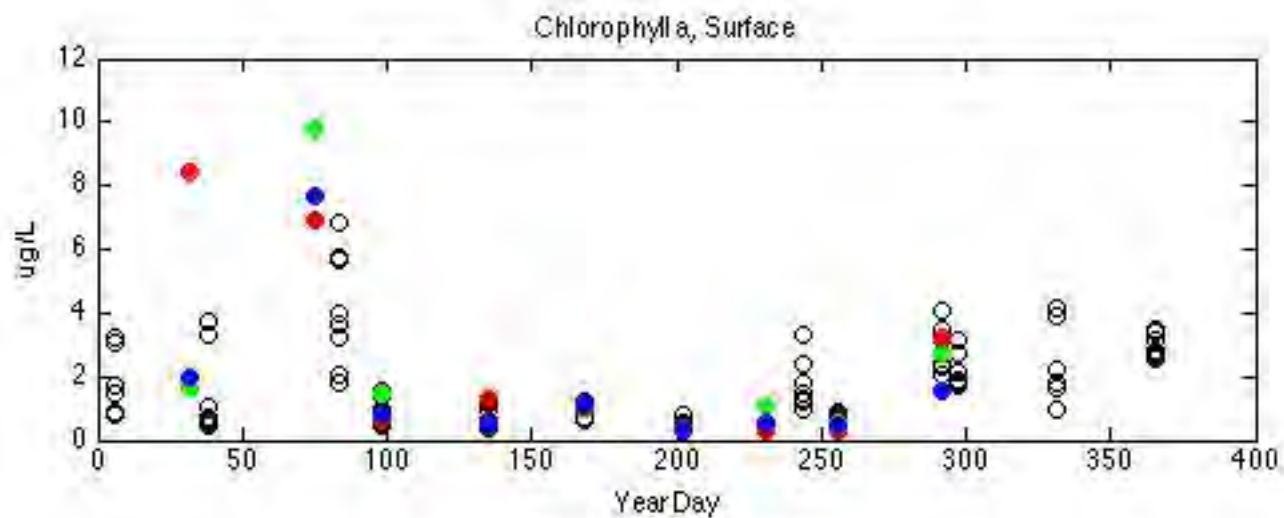
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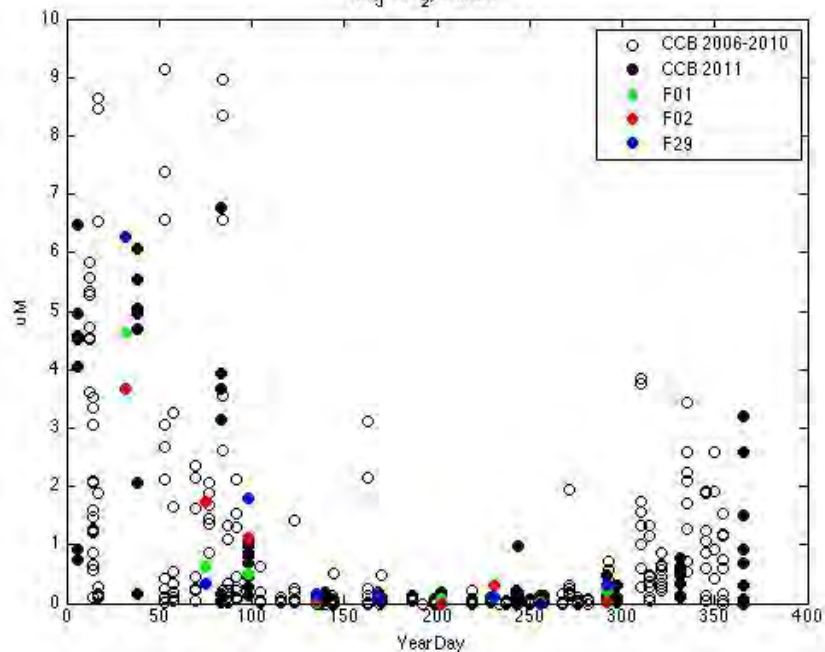
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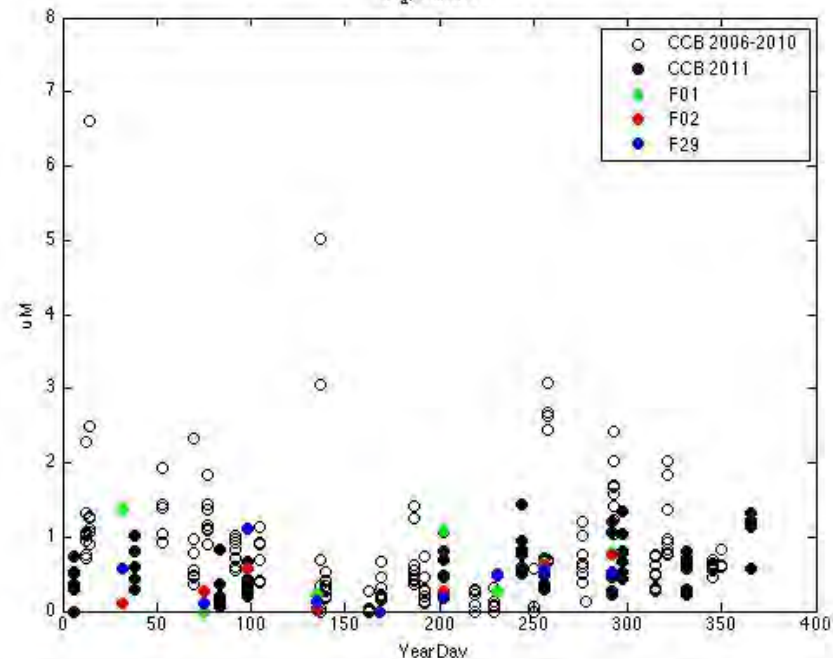
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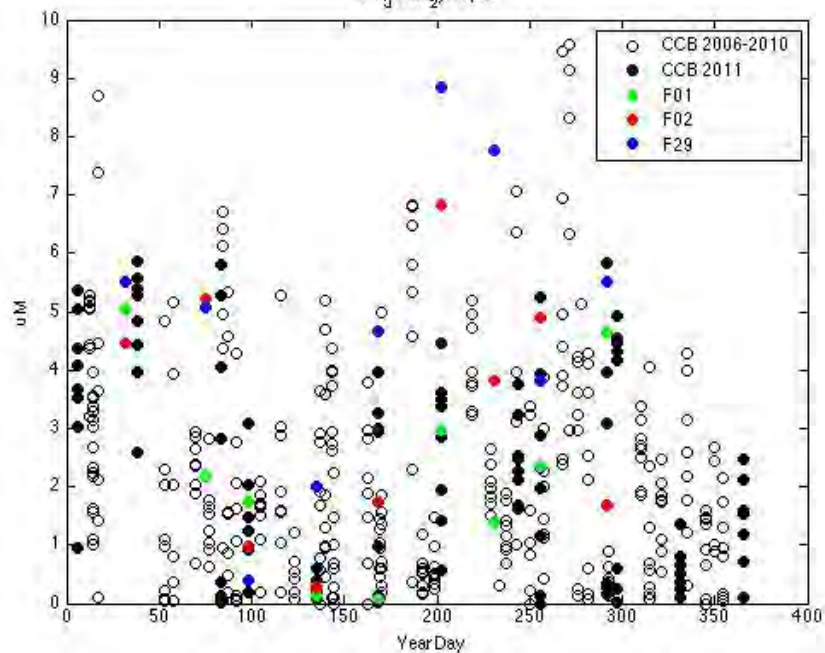
NO₃+NO₂, Surface



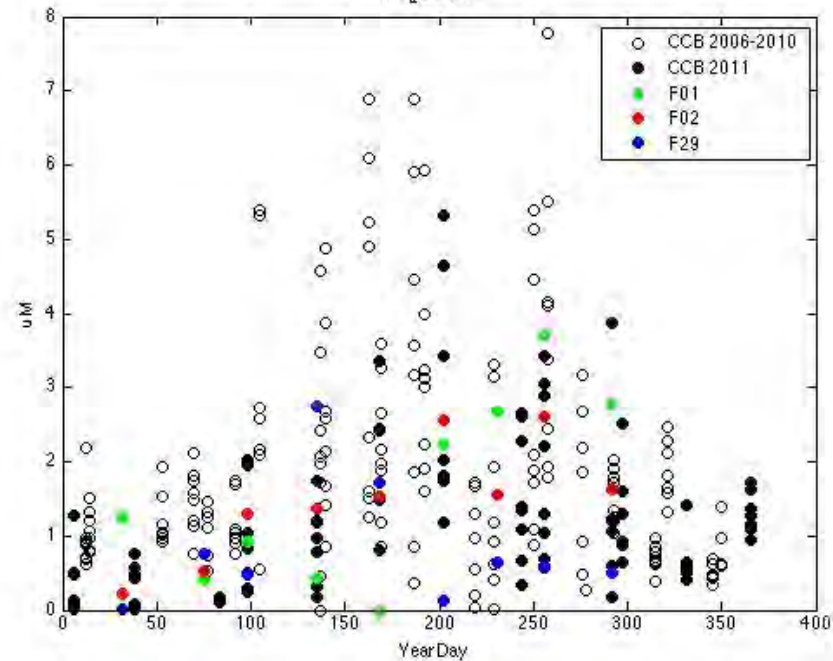
NH₄, Surface

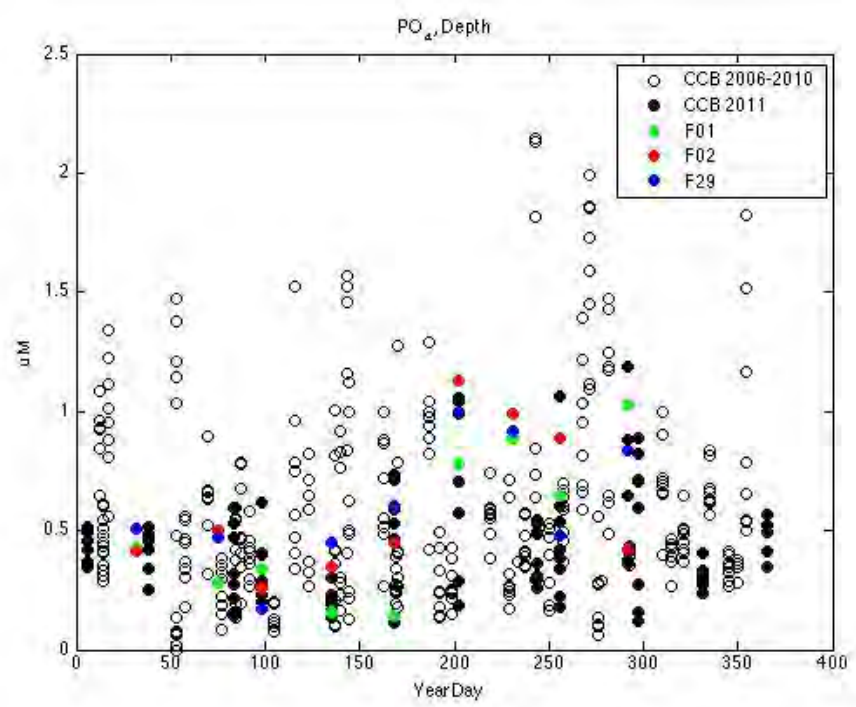
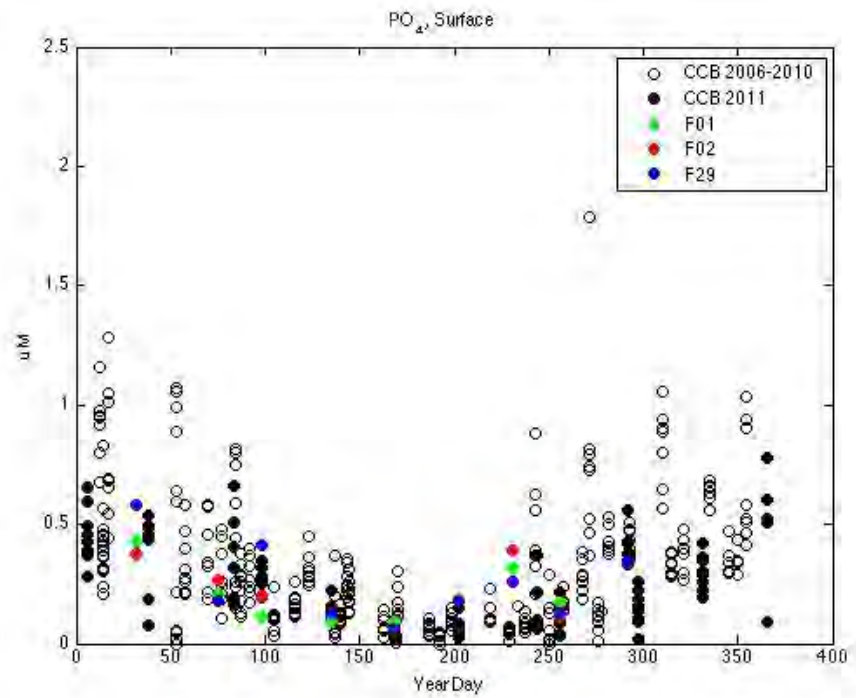


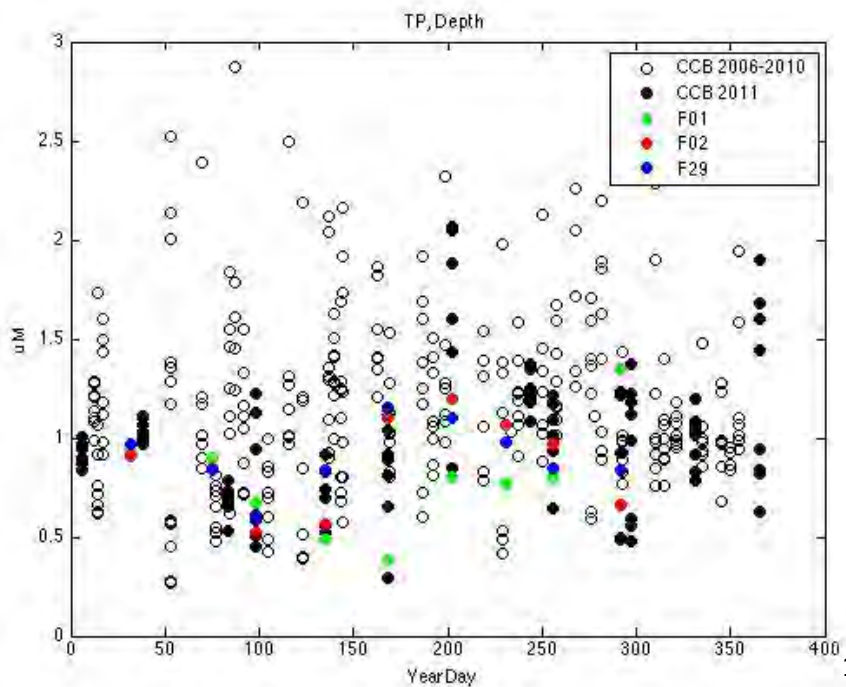
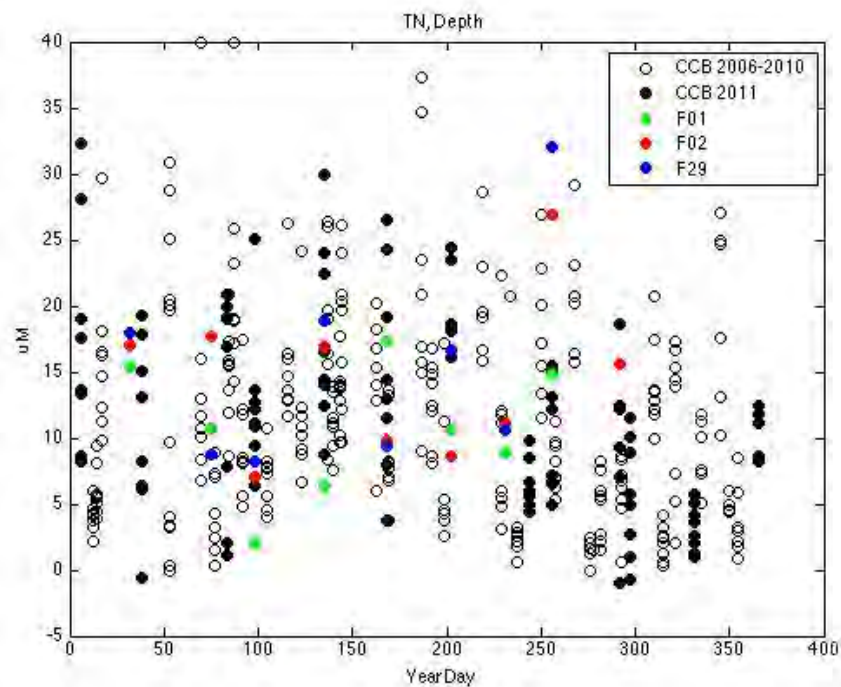
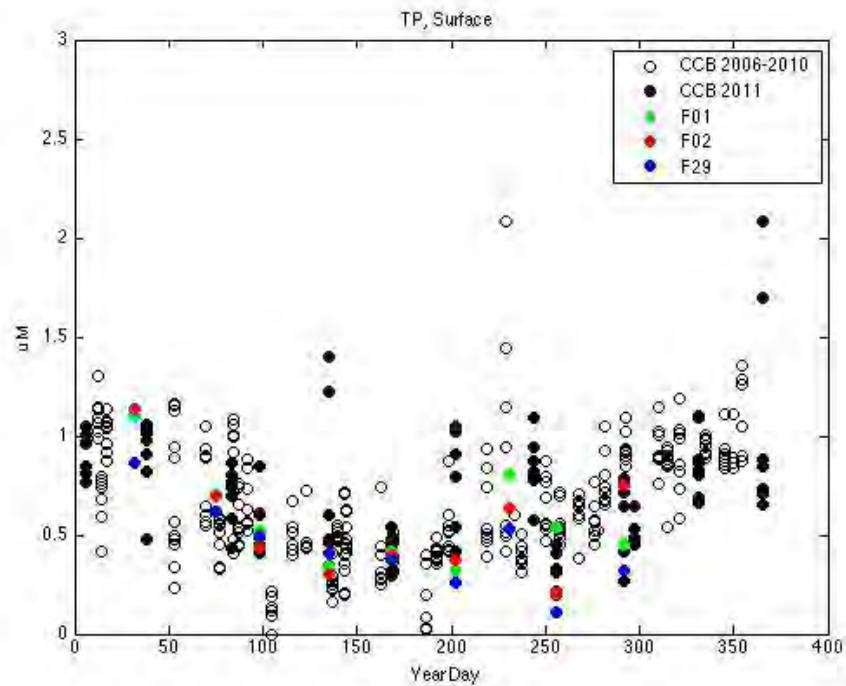
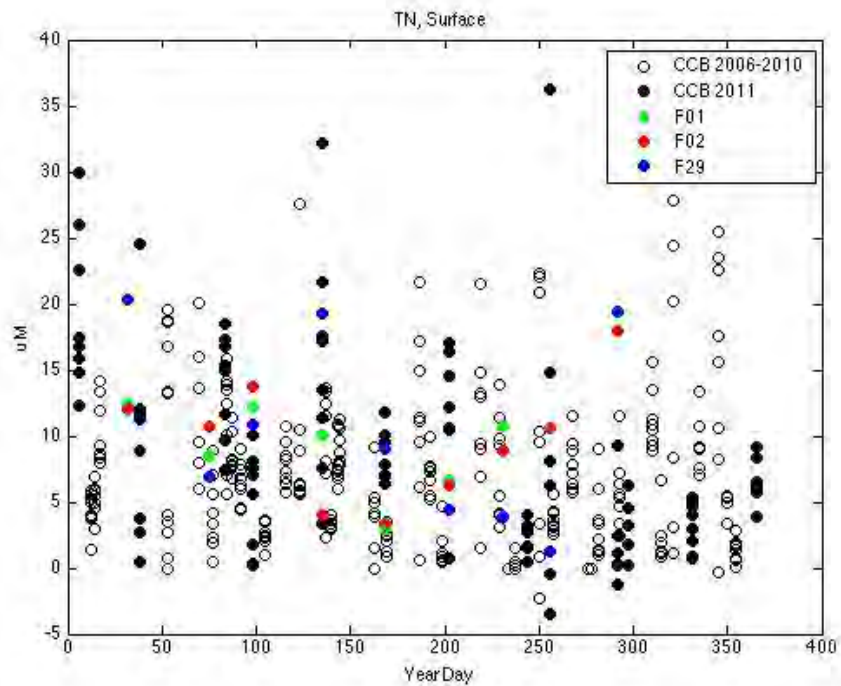
NO₃+NO₂, Depth

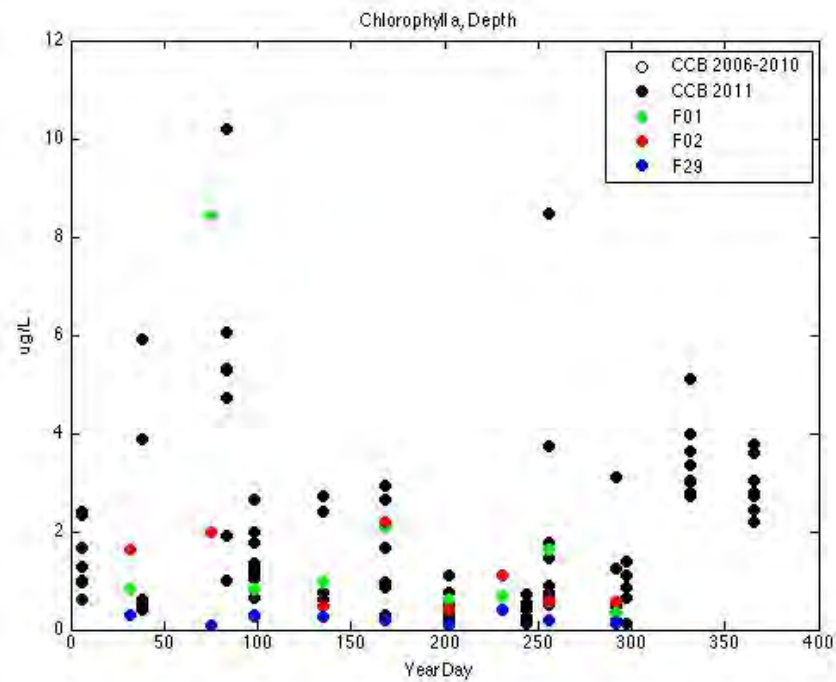
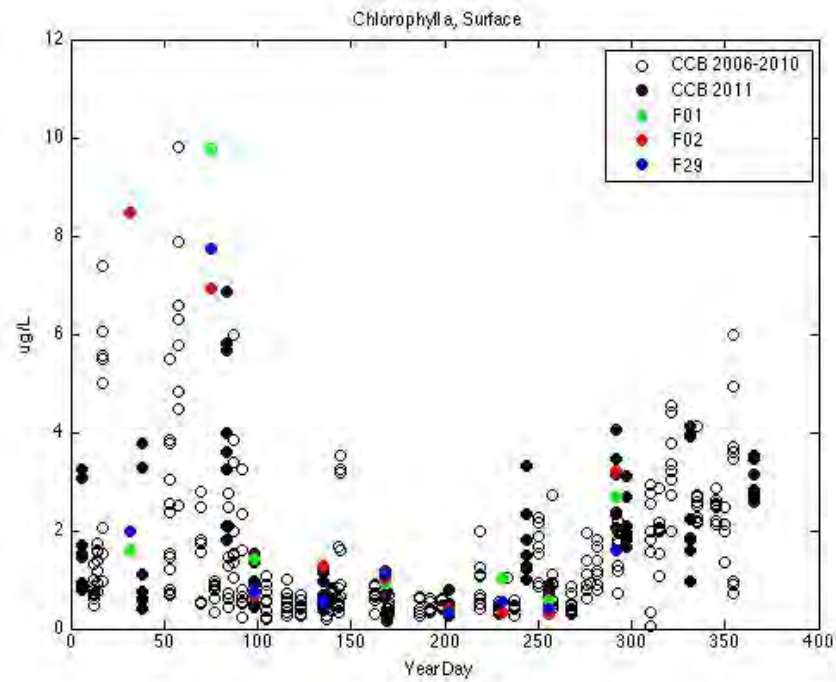


NH₄, Depth

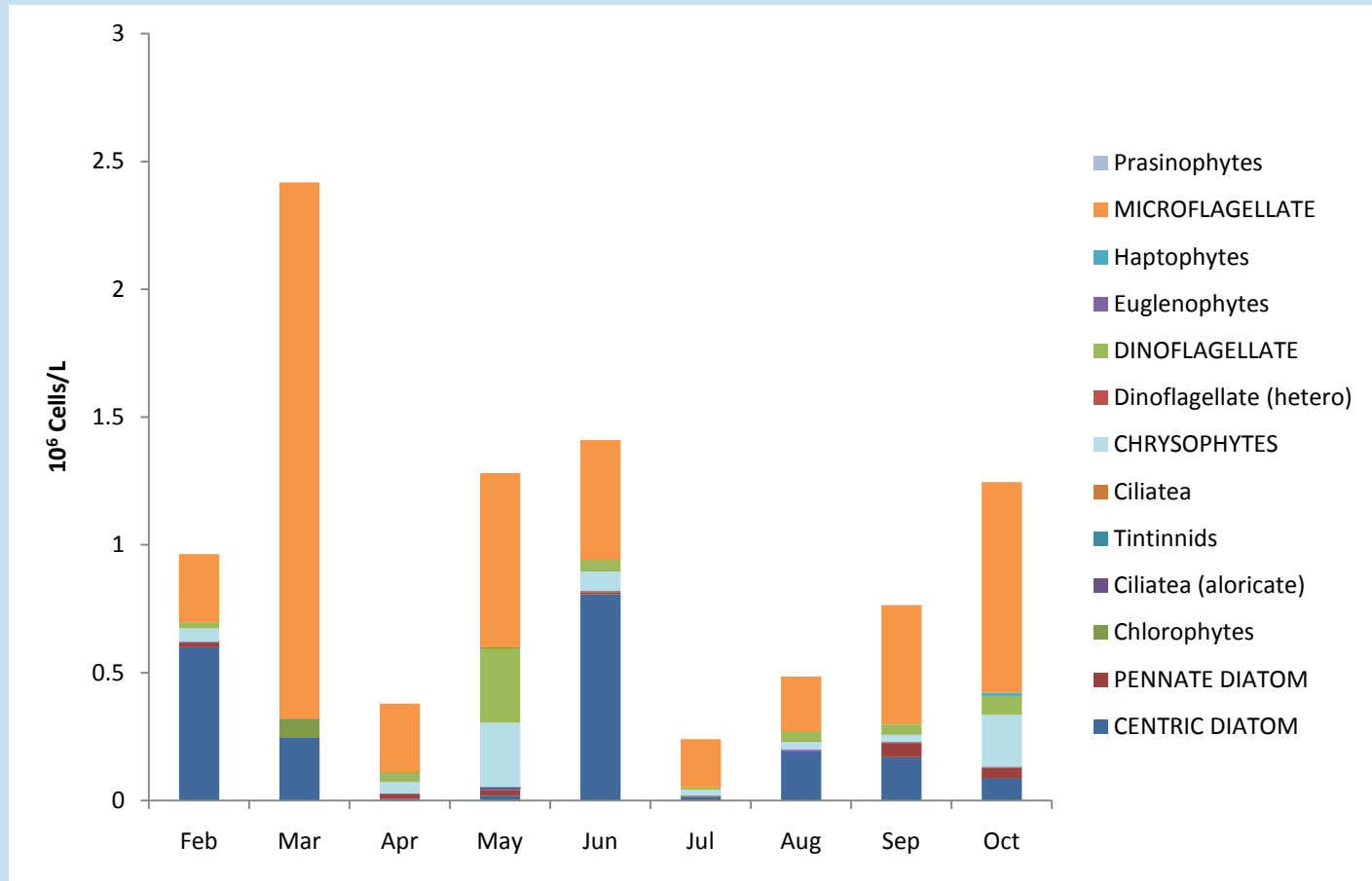








Phytoplankton



February: *Skeletonema costatum* species complex

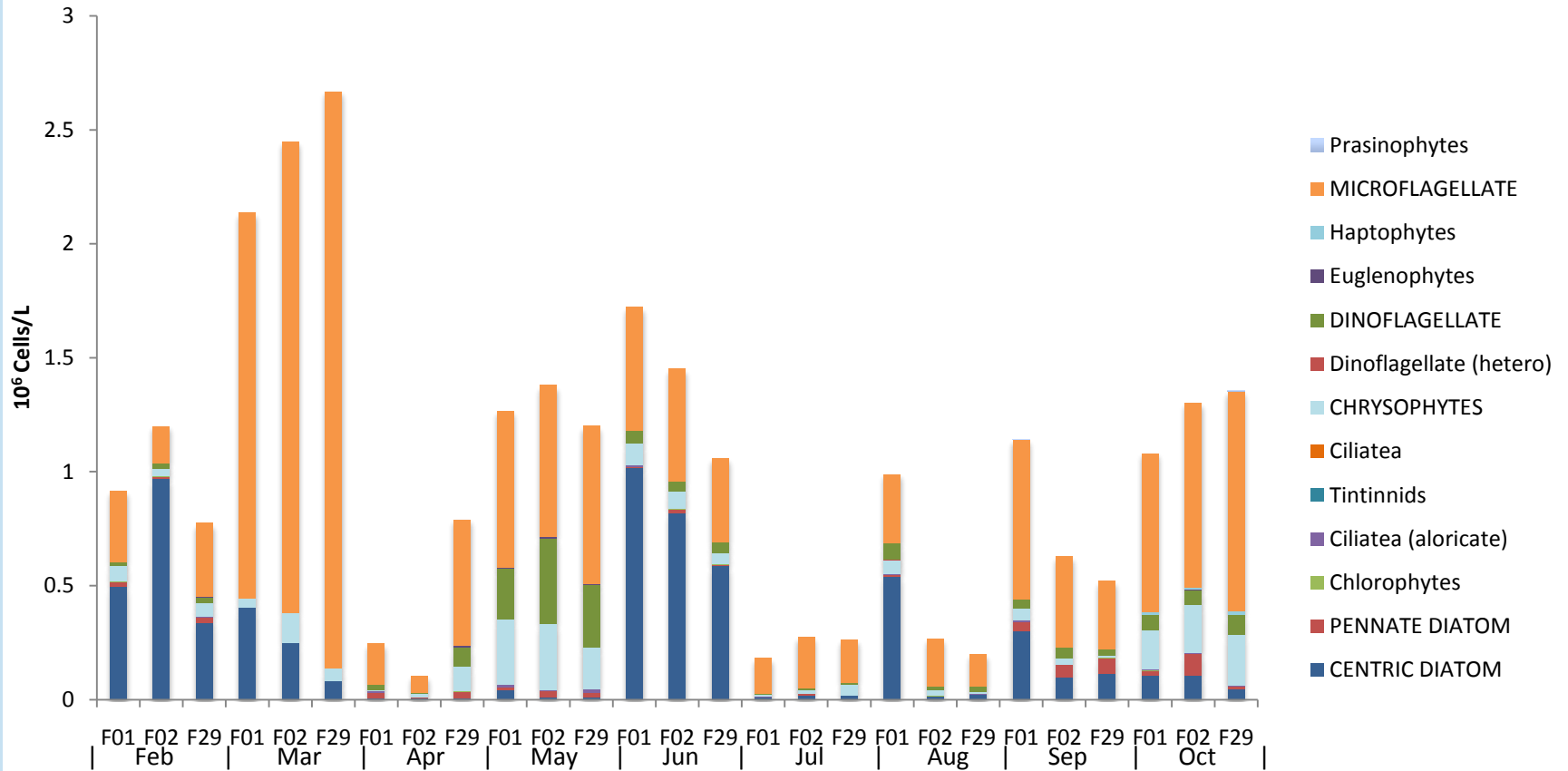
March: *Chaetoceros* spp.

May: *Cryptomonas* sp. (<10 microns) and *Prorocentrum minimum*

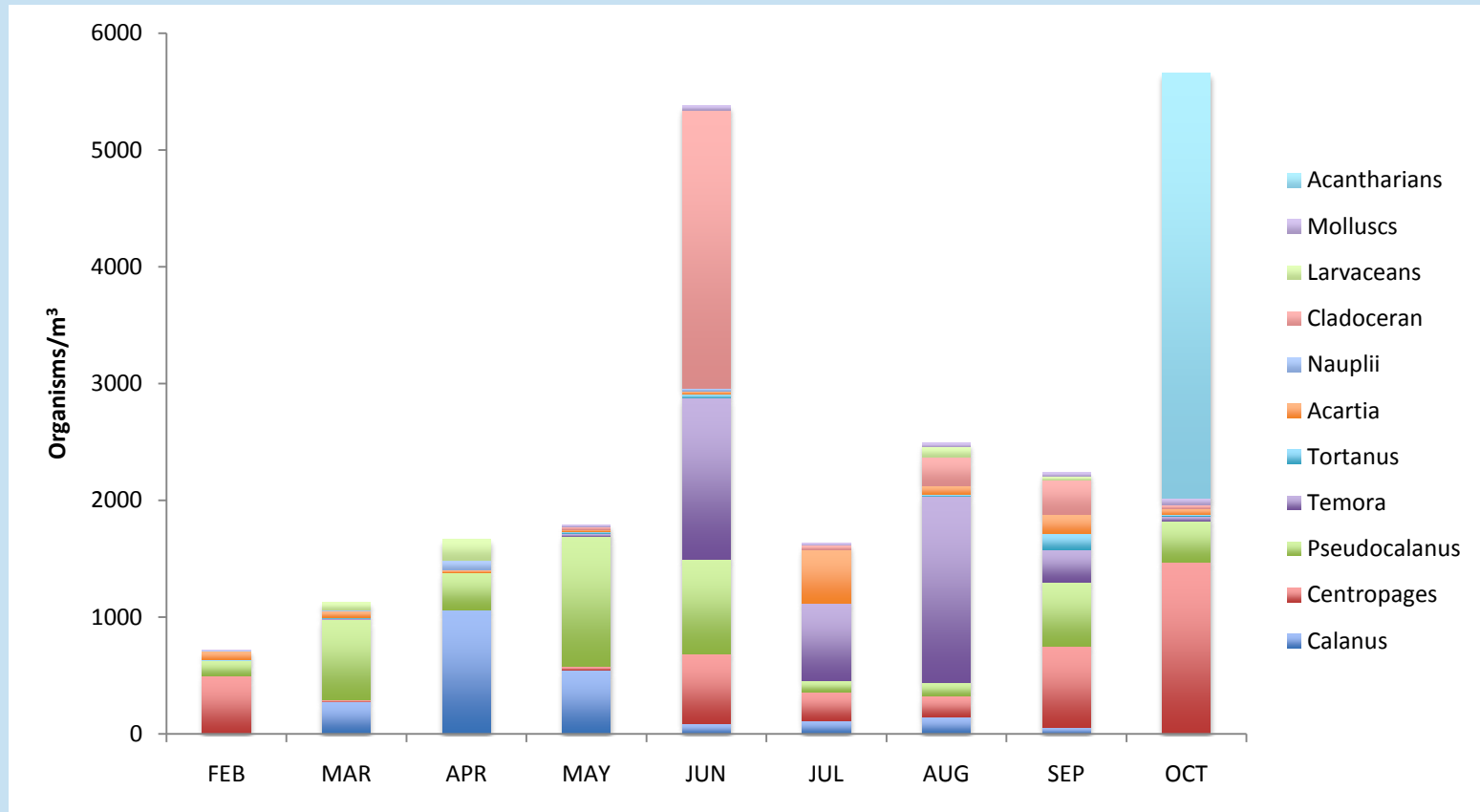
June: *Leptocylindrus minimus*

All Months: Unidentified micro-phytoflagellate (<10 microns)

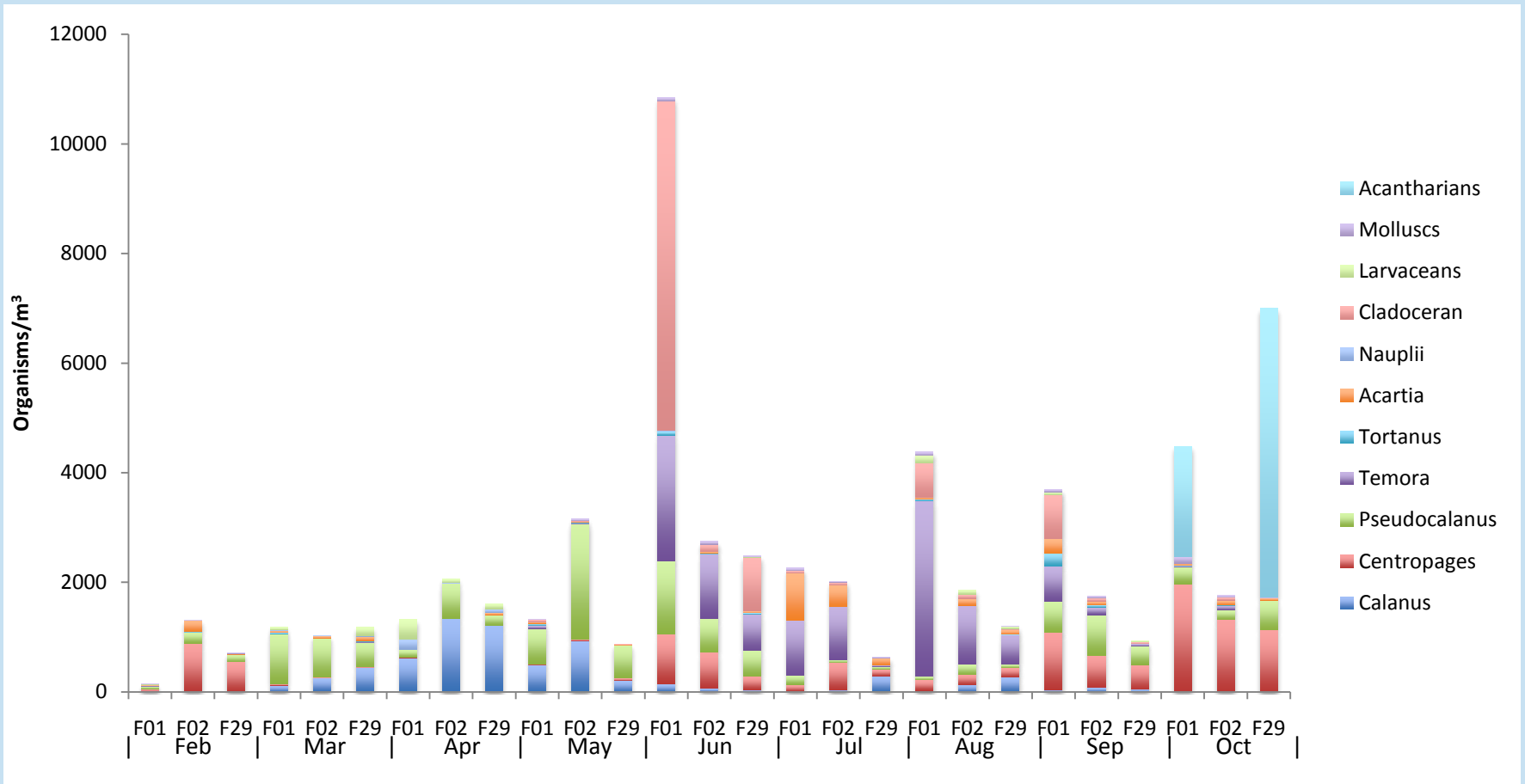
Phytoplankton



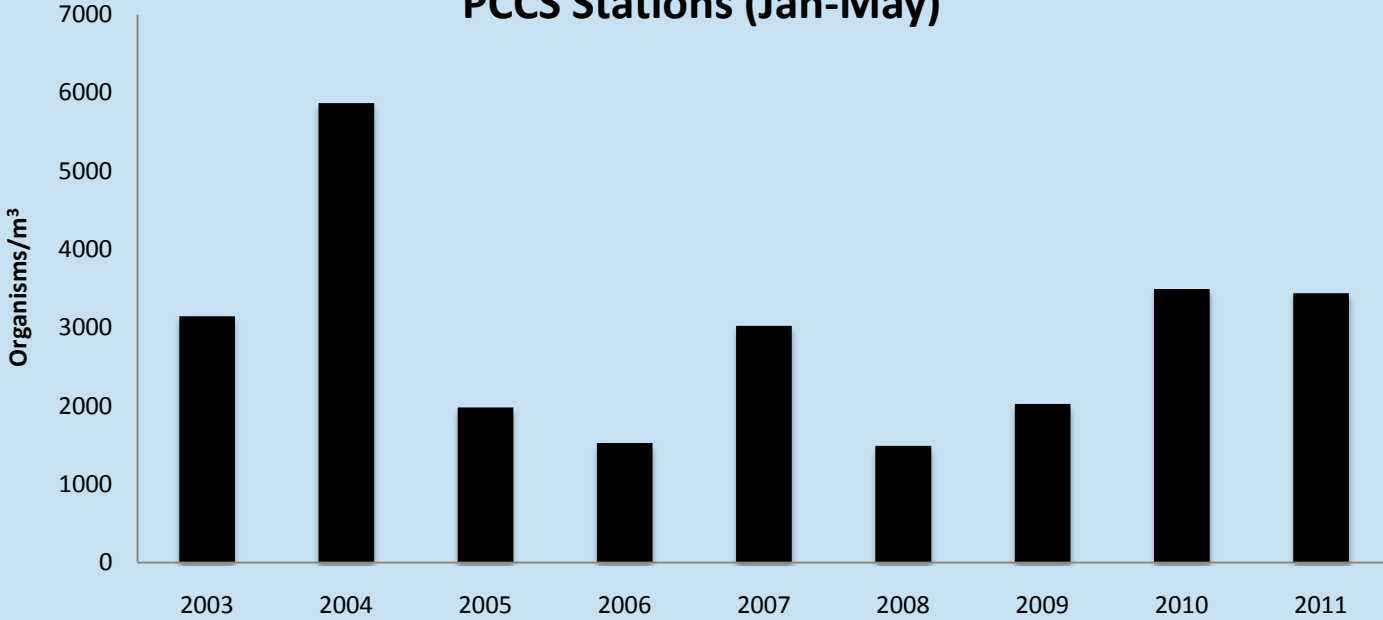
Zooplankton



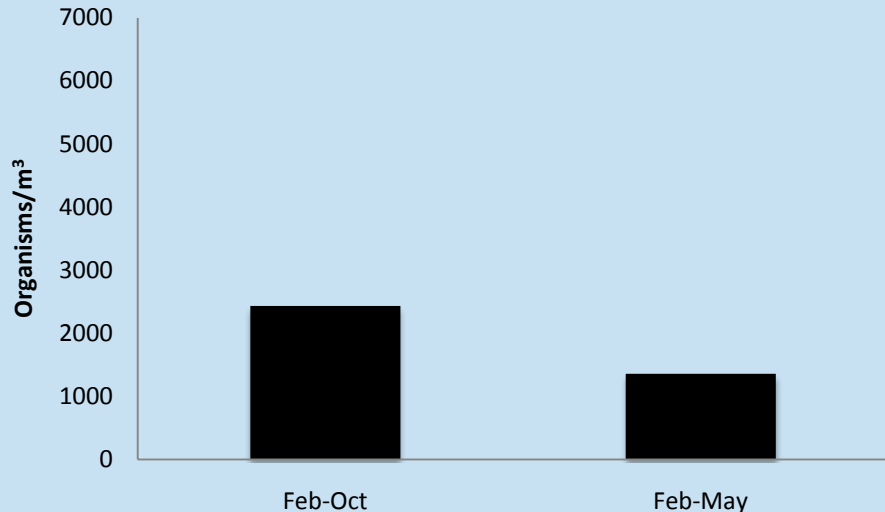
Zooplankton



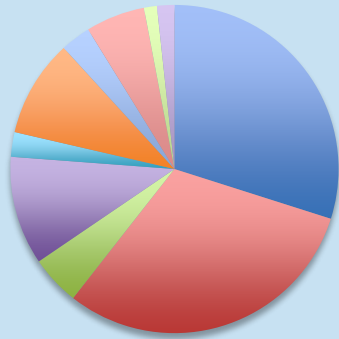
Total Zooplankton PCCS Stations (Jan-May)



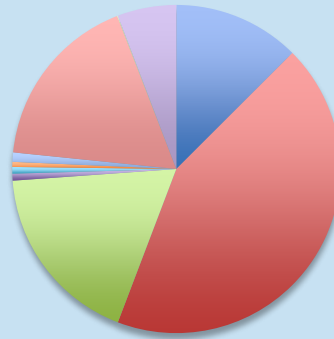
Total Zooplankton MWRA Stations



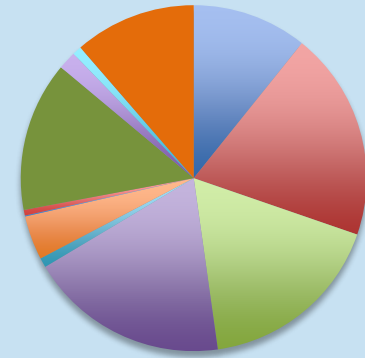
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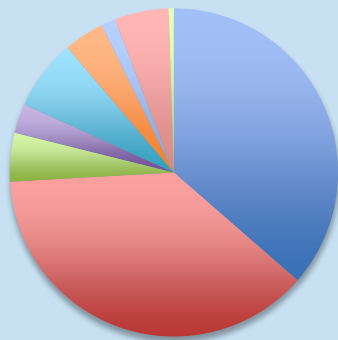
2009



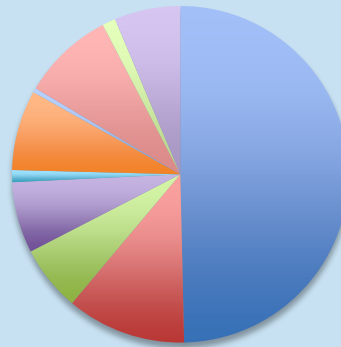
**2011: MWRA
Feb-Oct**



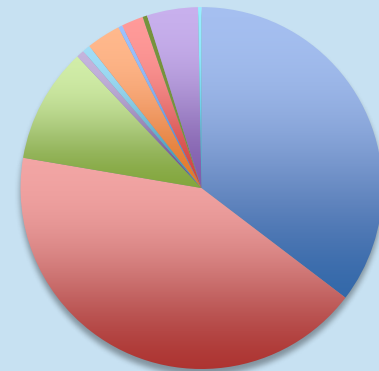
2007



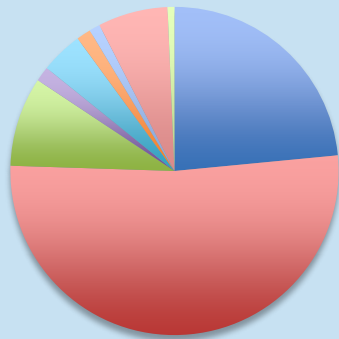
2010



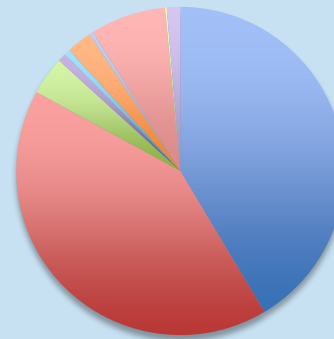
**2011: MWRA
Feb-May**



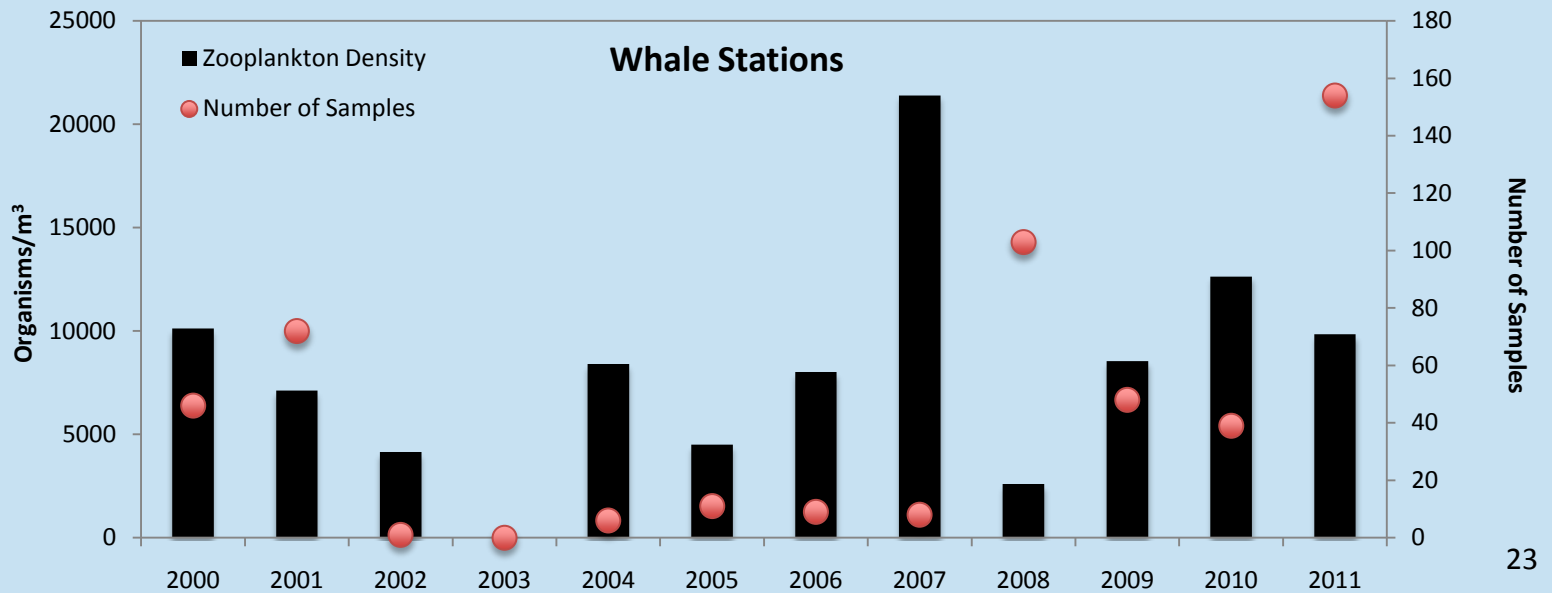
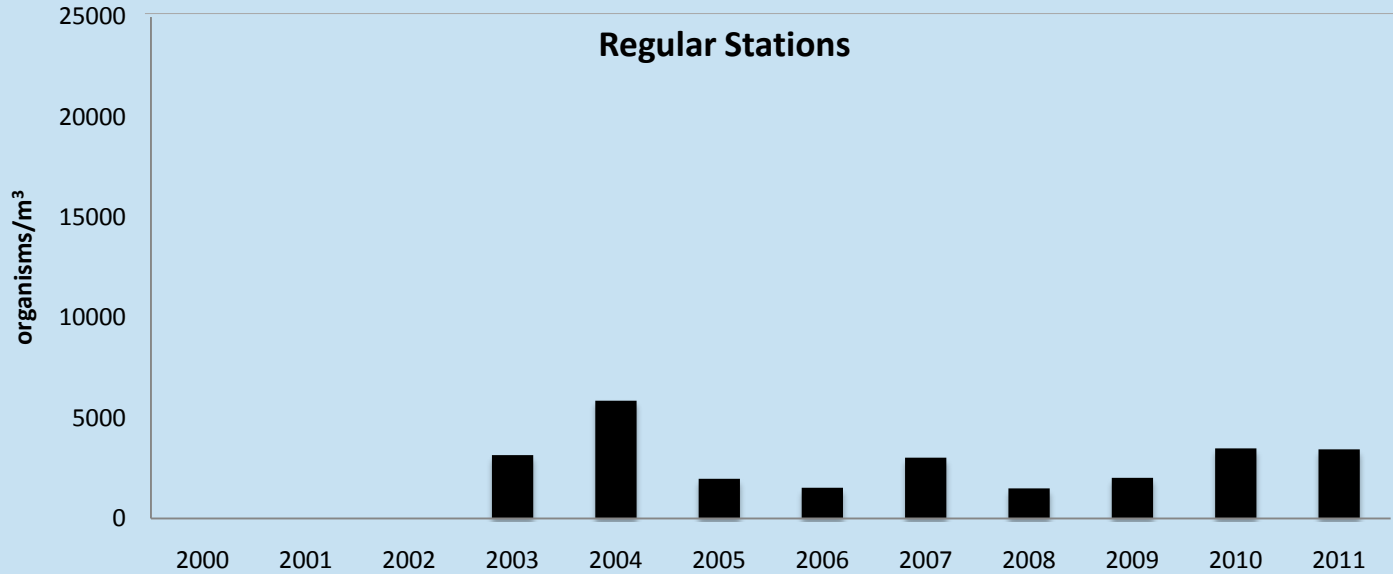
2008



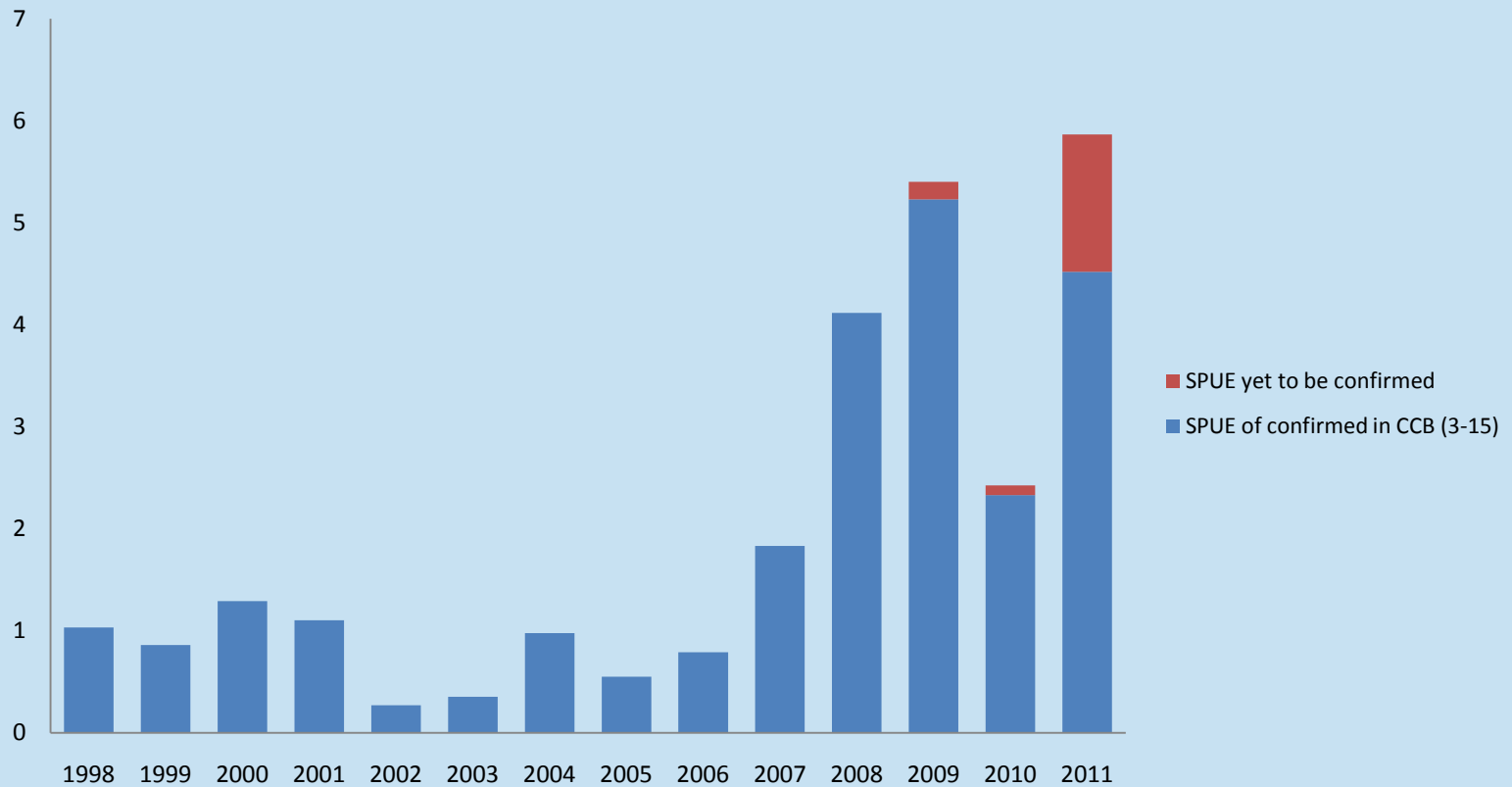
2011



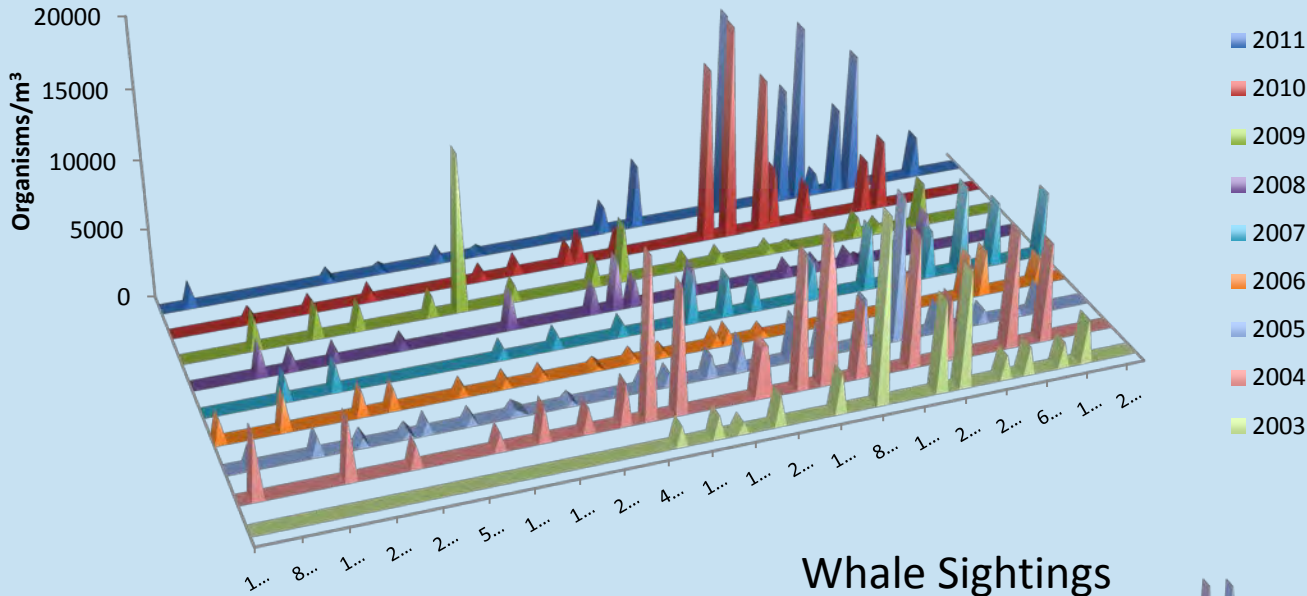
Total Zooplankton



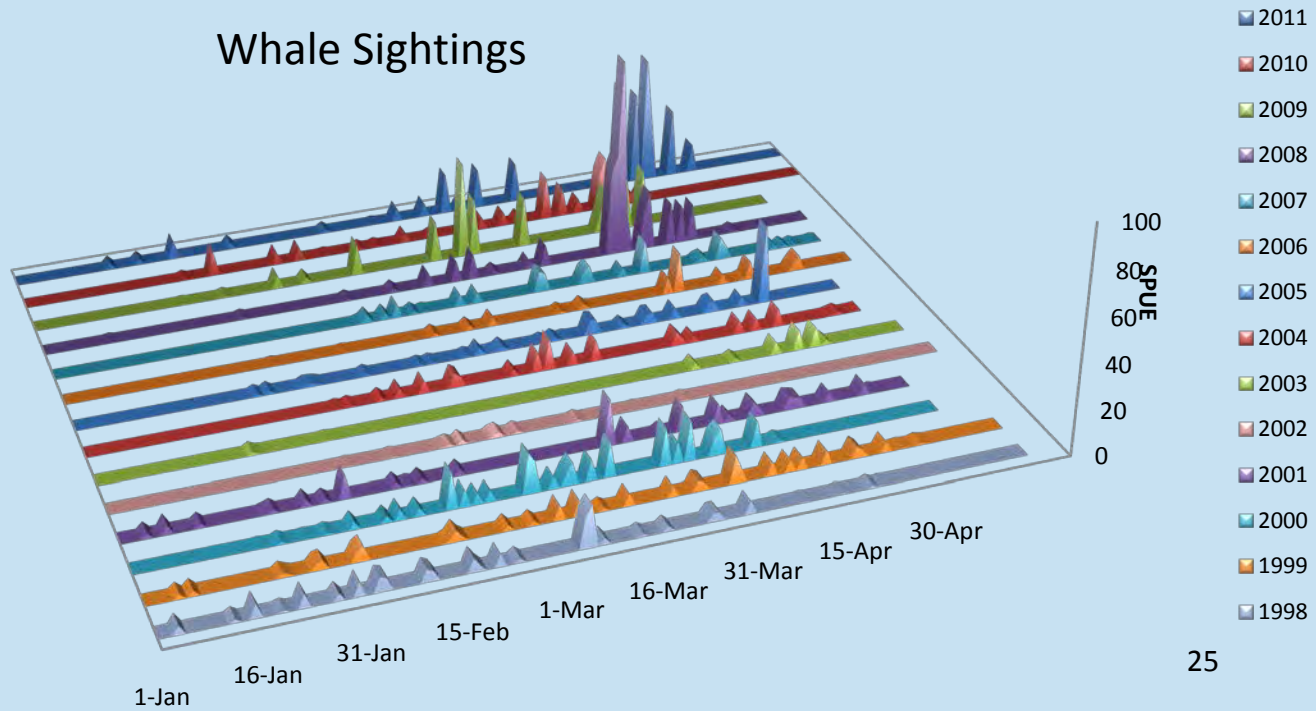
SPUE of right whales in CCB: 1998 - 2011



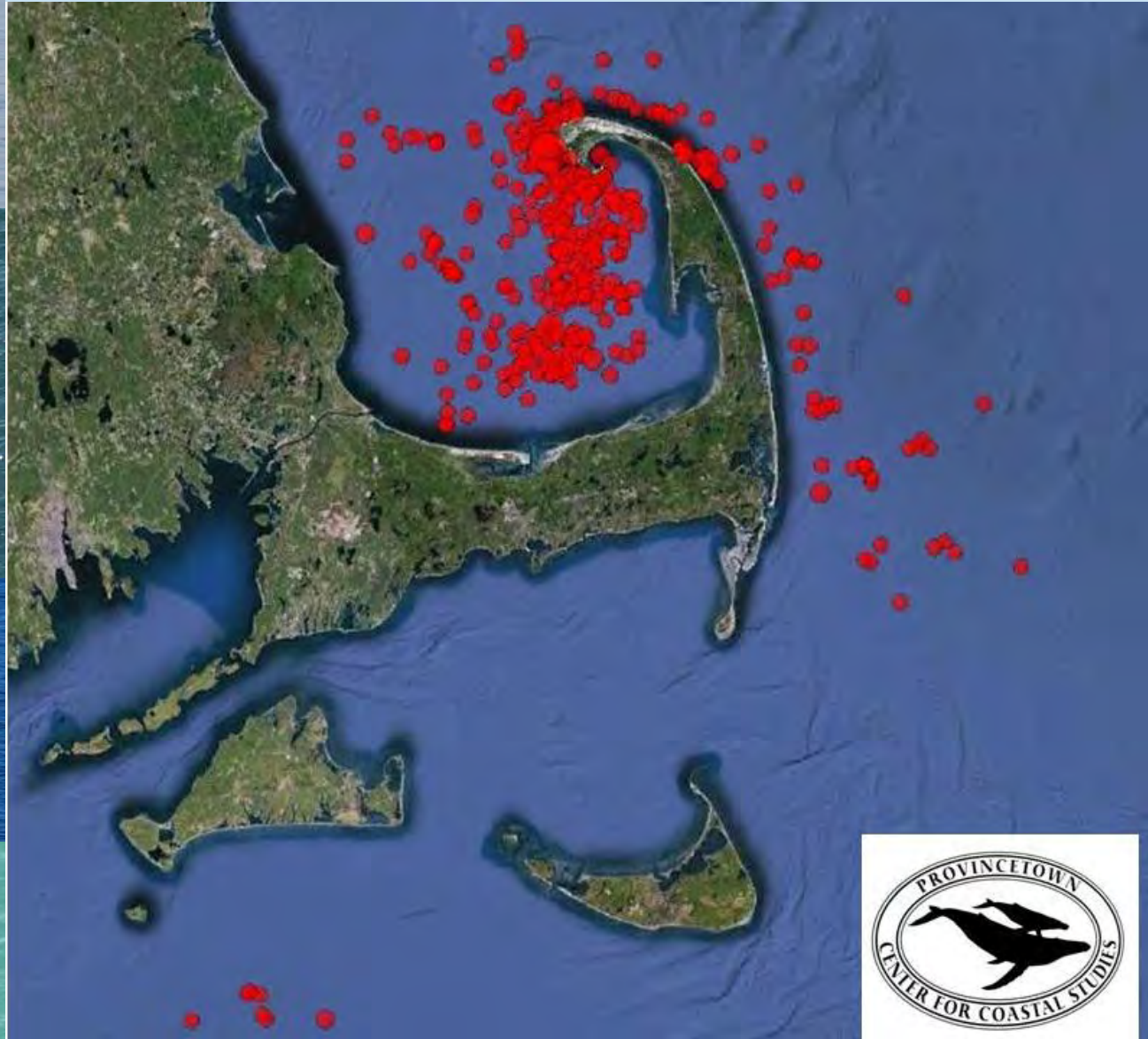
Zooplankton Densities



Whale Sightings



2011 Right Whale Sightings



Thank you...

Cape Cod Bay Monitoring
Marc Costa
Jenny Burkhardt

Right Whale Habitat
Stormy Mayo
Beth Larson
Christy Hudak

Right Whale Aerial Survey
Cyndy Tynan
Laura Gangle

Phytoplankton
David Borkman

Appendix F

Bay Eutrophication Model

The 2011 Water Quality Assessment in Massachusetts Bay using the Bay Eutrophication Model (MB-FVCOM/UG-RCA)

Changsheng Chen¹, Liuzhi Zhao¹ and R. C. Beardsley²

¹School for Marine Science and Technology
University of Massachusetts-Dartmouth

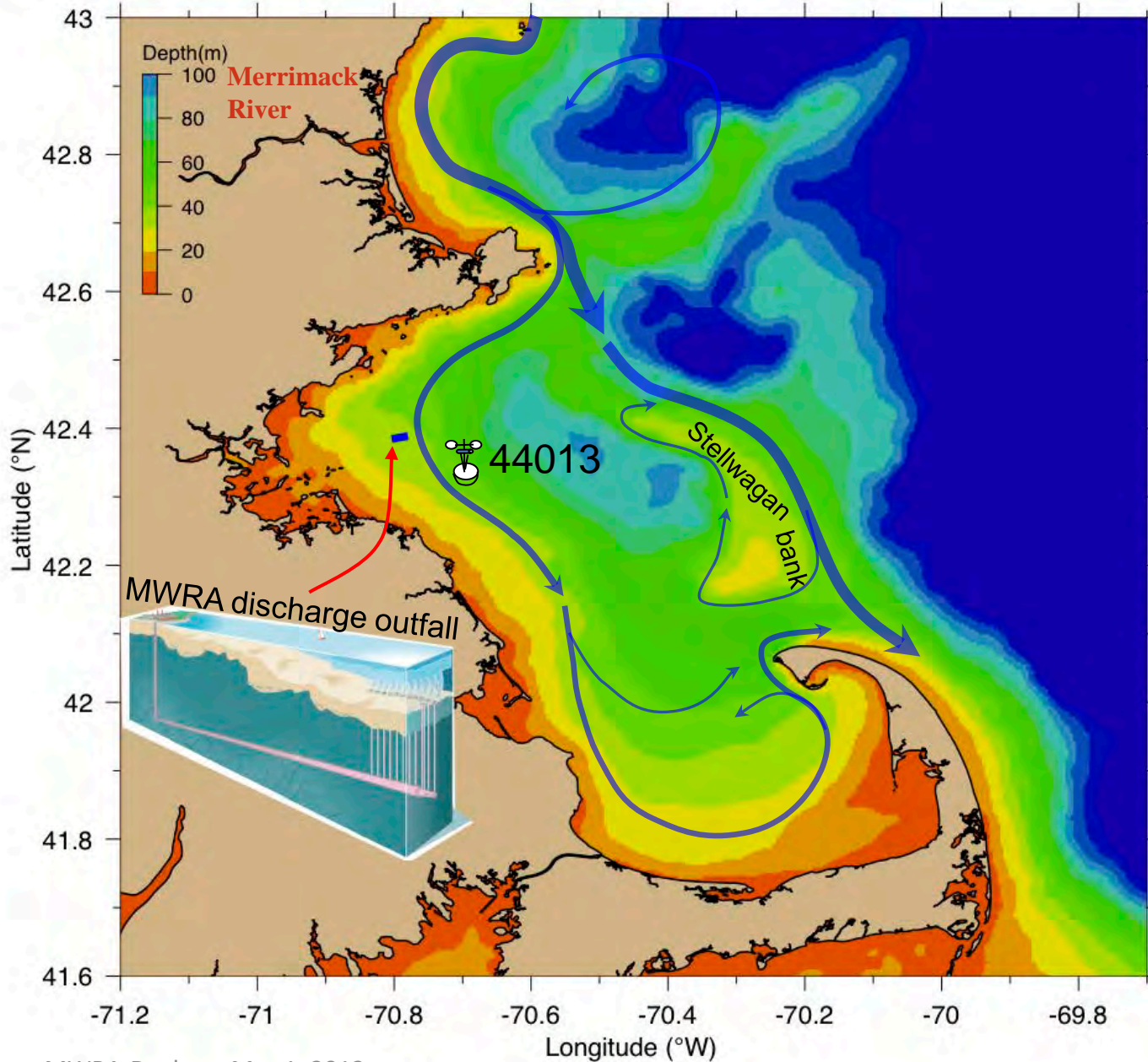
²Department of Physical Oceanography
Woods Hole Oceanographic Institution

Email: c1chen@umassd.edu, lzhao@umassd.edu

OUTLINE

1. Objectives and Required Tasks;
2. Physical Background and Model simulation (MB-FVCOM);
3. Water Quality simulation (UG-RCA);
4. MWRA outfall projection.

Massachusetts (Mass) Bay



Physical Processes:

- Tides
- Winds
- Heat flux
- Precipitation via Evaporation
- River discharges
- Groundwater

Winter:

Well-mixed

Summer:

Stratified

Contract Tasks

1. Simulation of current, temperature and salinity for the calendar year 2011 using MB-FVCOM
1. Simulation of water quality variables for the calendar year 2011 using UG-RCA, including inorganic nutrients, phytoplankton, chlorophyll and organic substances.
1. Assessment of dispersal of the MWRA outfall effluent, both in the horizontal and vertical.
2. Projection analysis on the possible influence of the MWRA outfall on water quality and ecosystem function in MB.

The MWRA Massachusetts Bay Water Quality Model System

Regional FVCOM domain: up to 2.5 km

Driven by five tidal constituents at GOM open boundary (M_2 , S_2 , N_2 , K_1 and O_1);

33 rivers;

WRF-assimilated meteorological forcing (wind, net heat flux/solar irradiance, and precipitation minus evaporation).

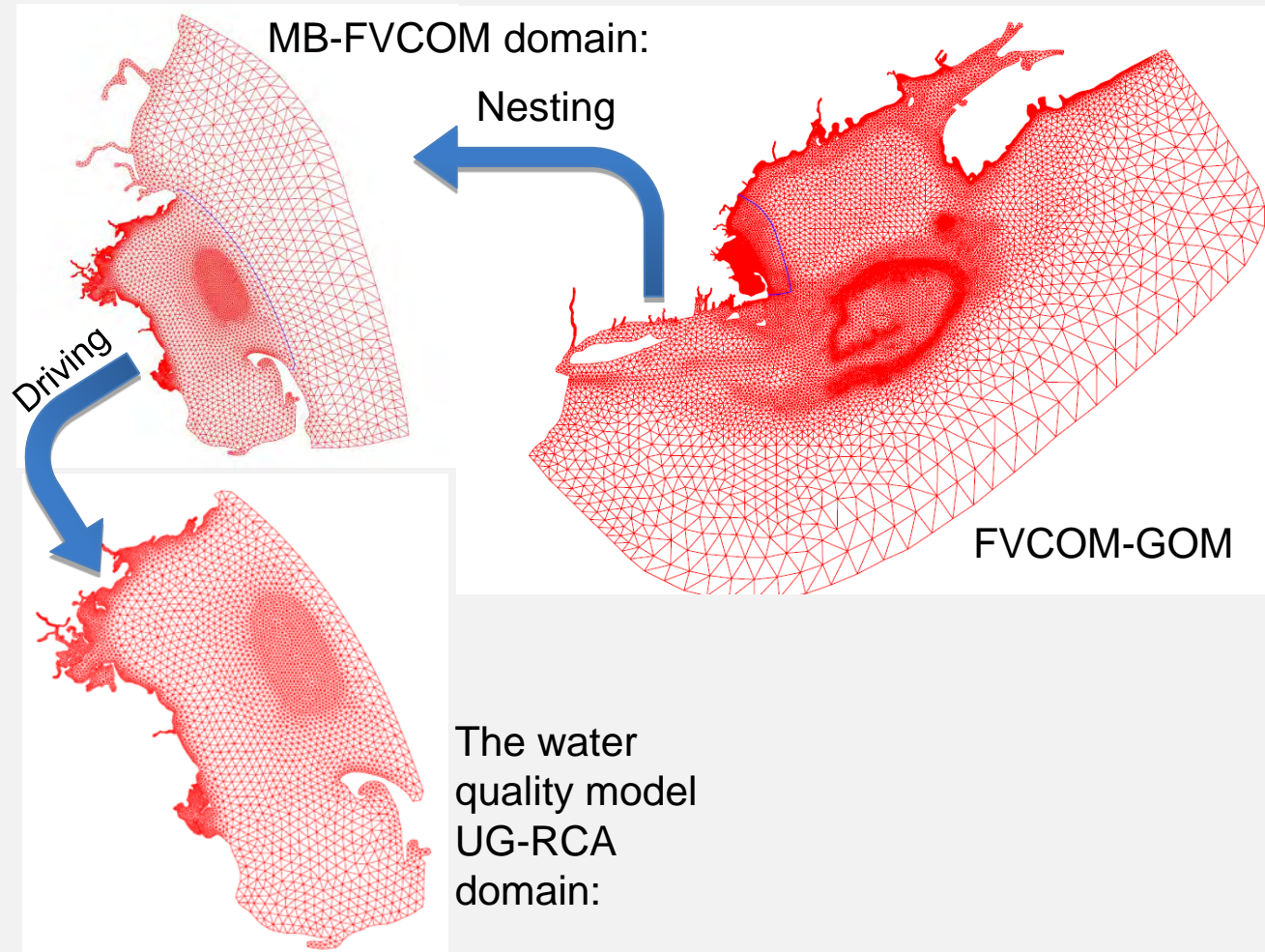
Data assimilation of all available T, S data

MB FVCOM domain: 0.5-1 km

Driven by

Regional FVCOM fields at the nested boundary and the same meteorological and river discharges (13 rivers).

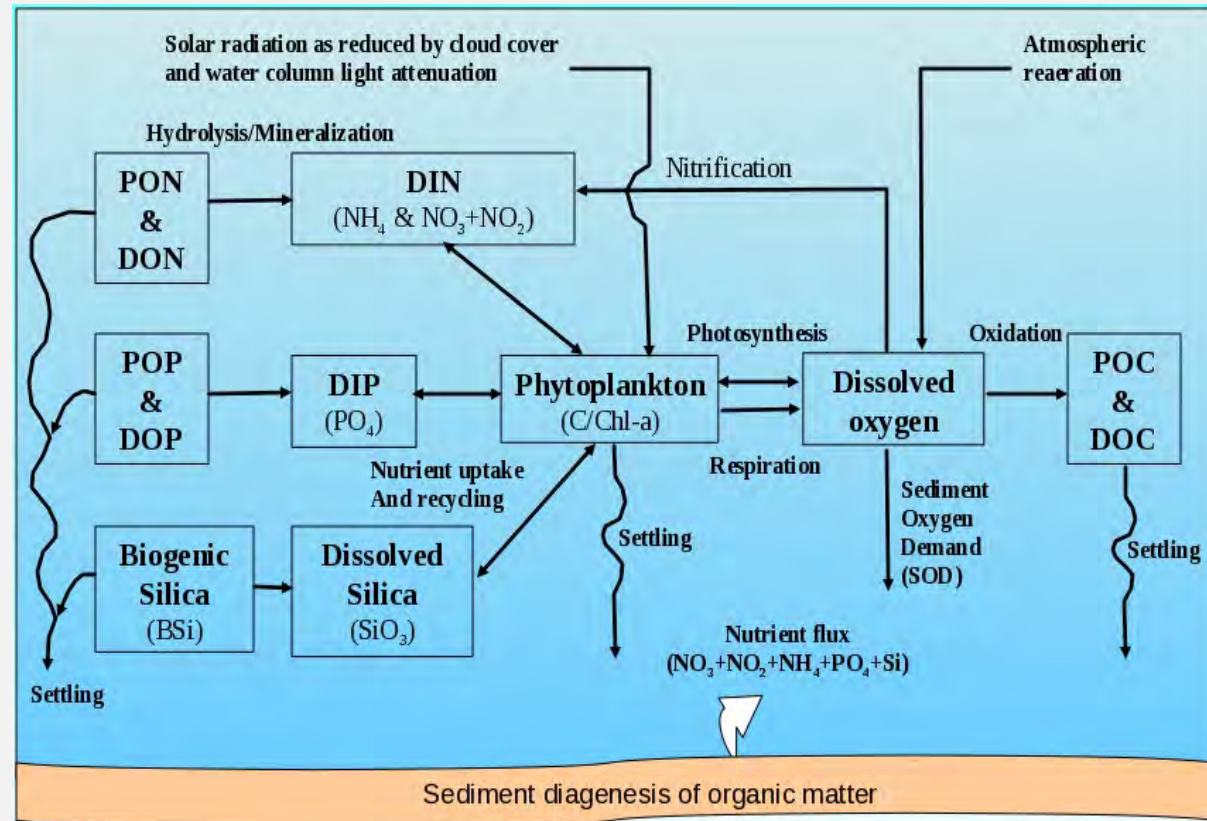
Total vertical layers: 30.



UG-RCA Simulation

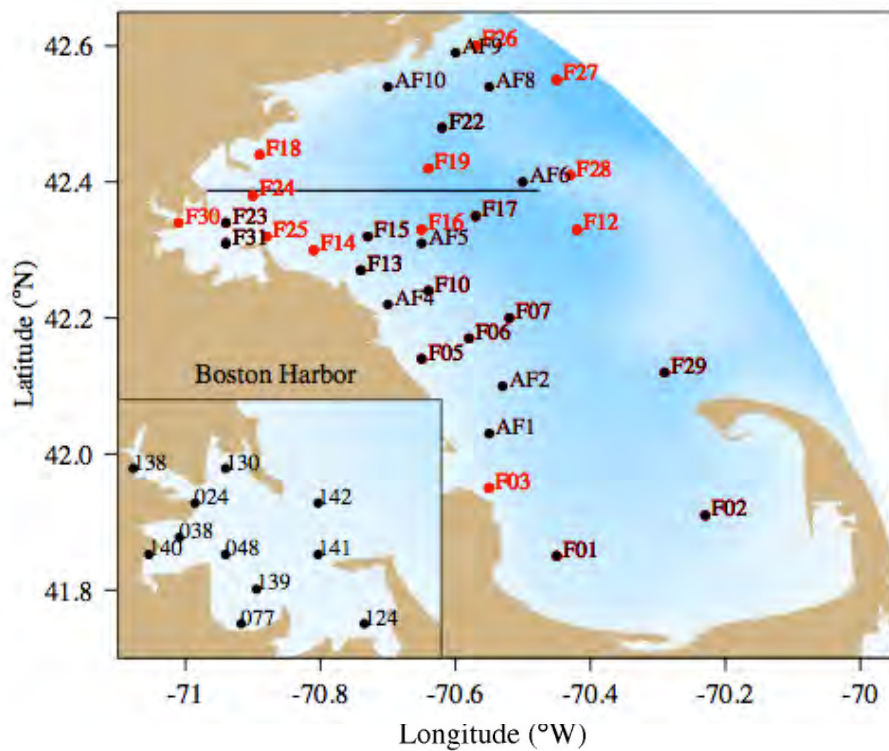
- Driven by hourly FVCOM physical fields
- WRF-calculated solar radiation for photosynthesis
- winds for DO reareation
- point source loadings
- non-point source loadings
- rive discharges (3 rivers)
- atmospheric loading
- boundary conditions extrapolated based bio-monthly MWRA observations

UG-RCA

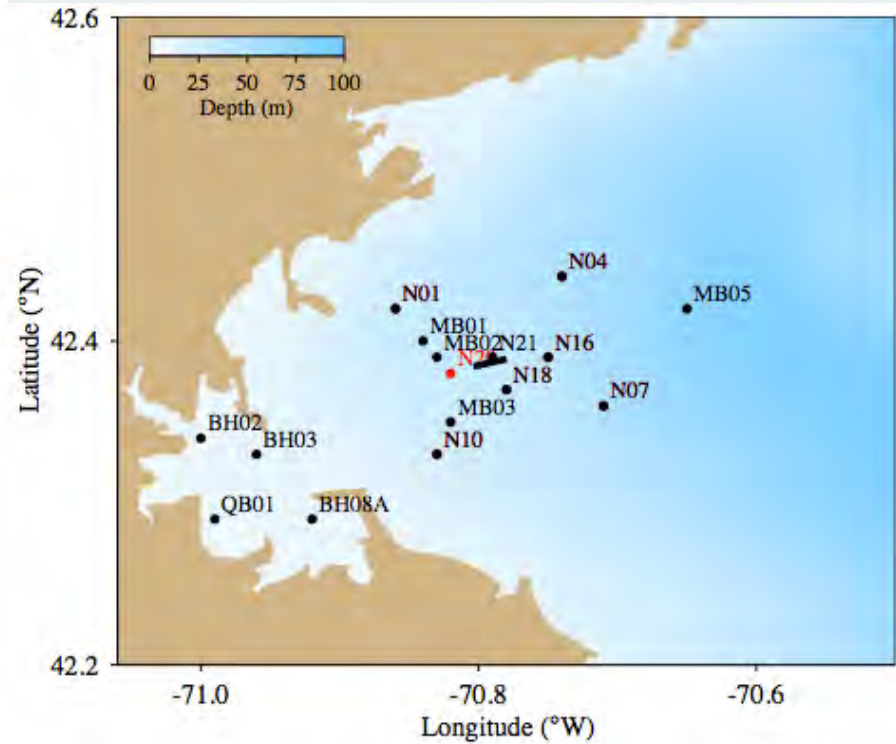


MWRA field observation stations

Far-field stations



Near-field stations



Note: 11 Sampling stations were removed for bio-monthly surveys (see stations marked by “red”).

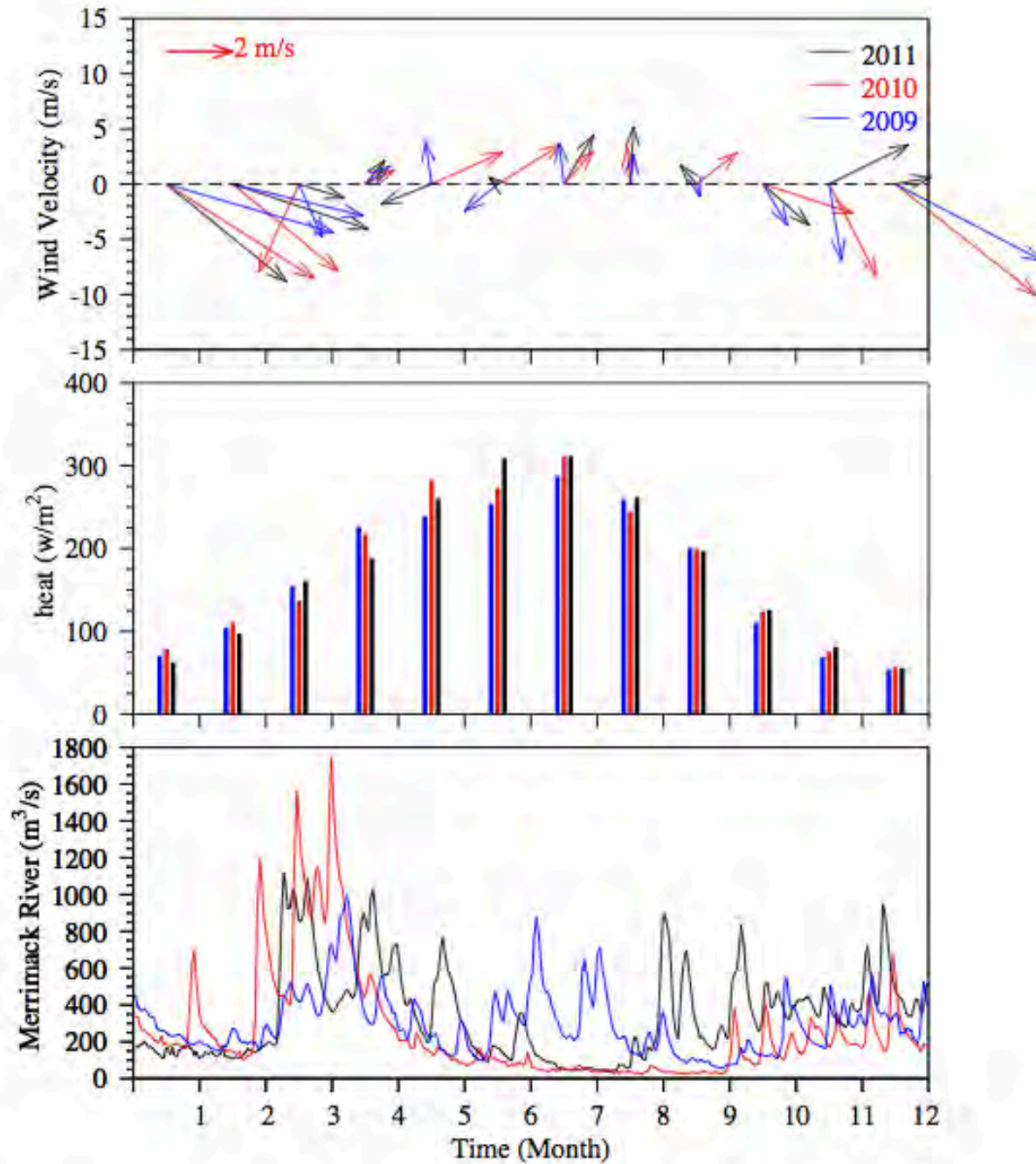
Note: One station was removed for monthly surveys

At 44013
In MB

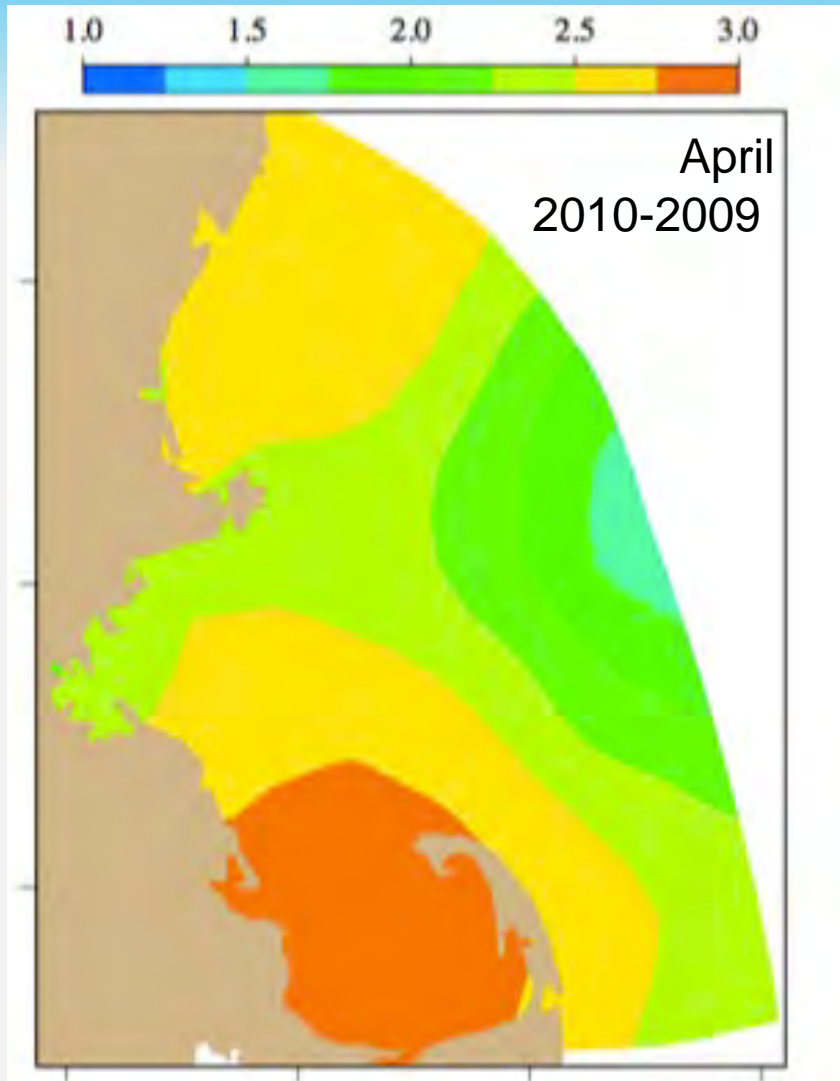
Monthly
averaged
wind

Surface
net flux

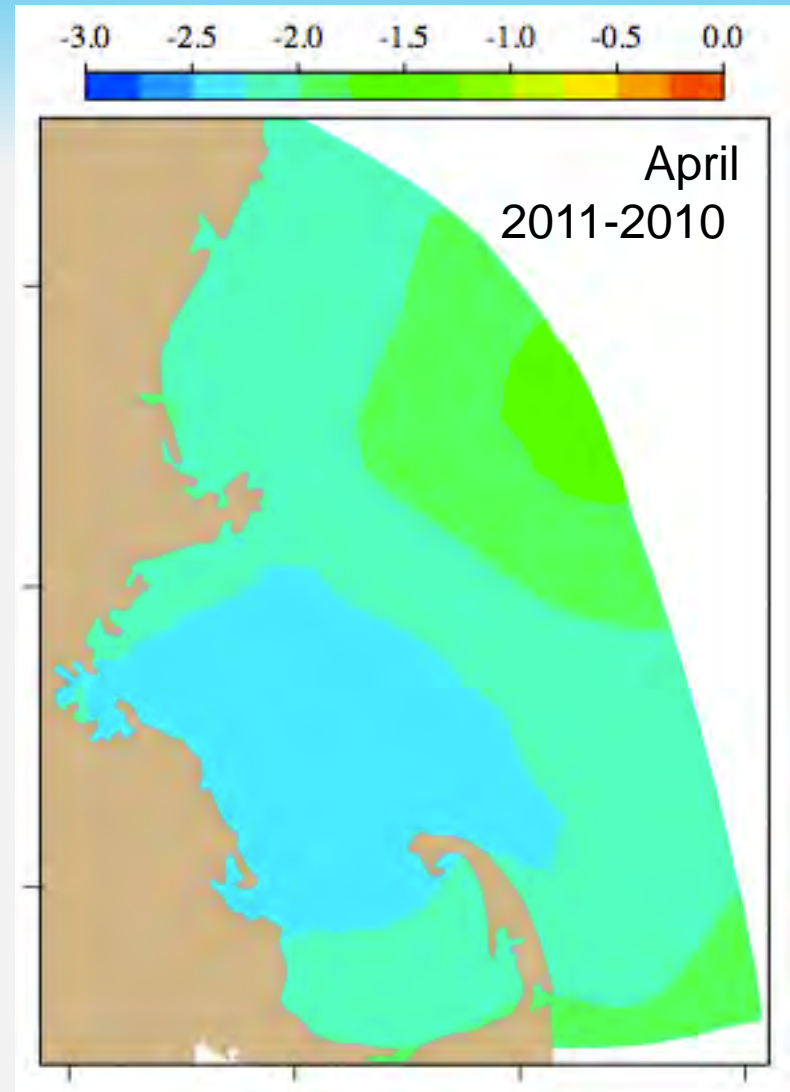
River
discharges



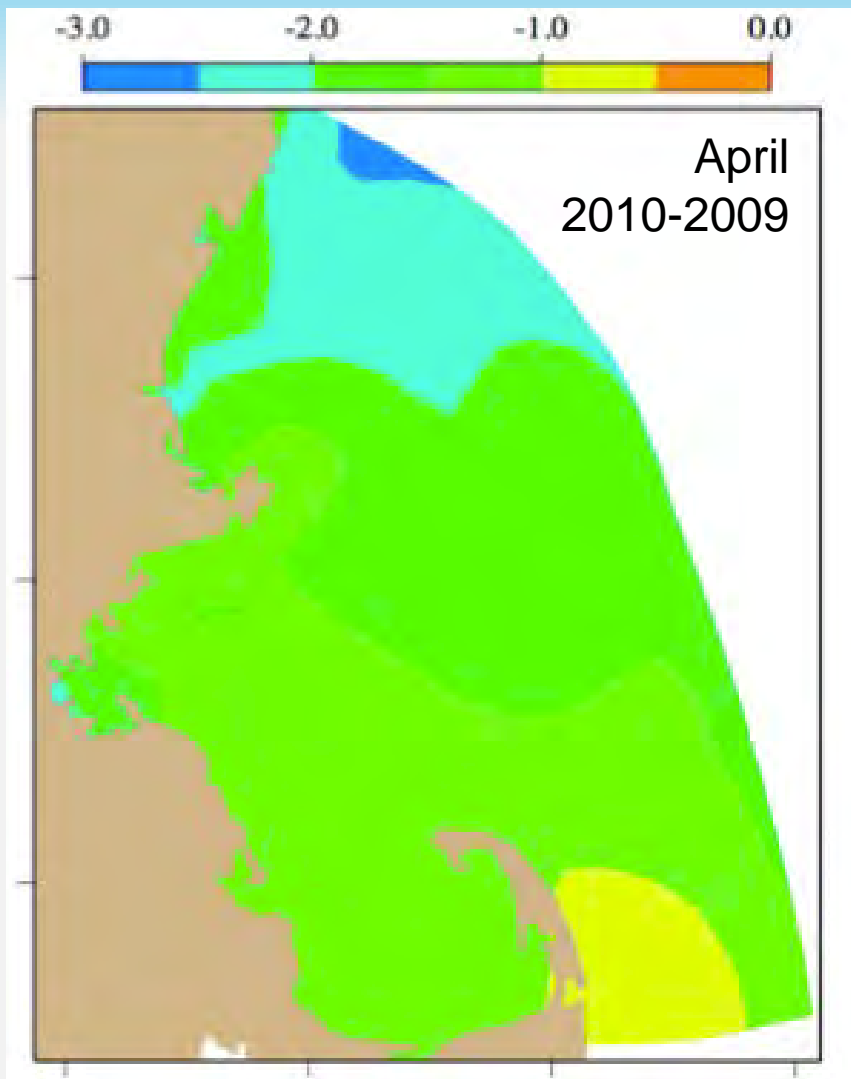
Difference between April 2010 and 2009 averaged surface temperatures



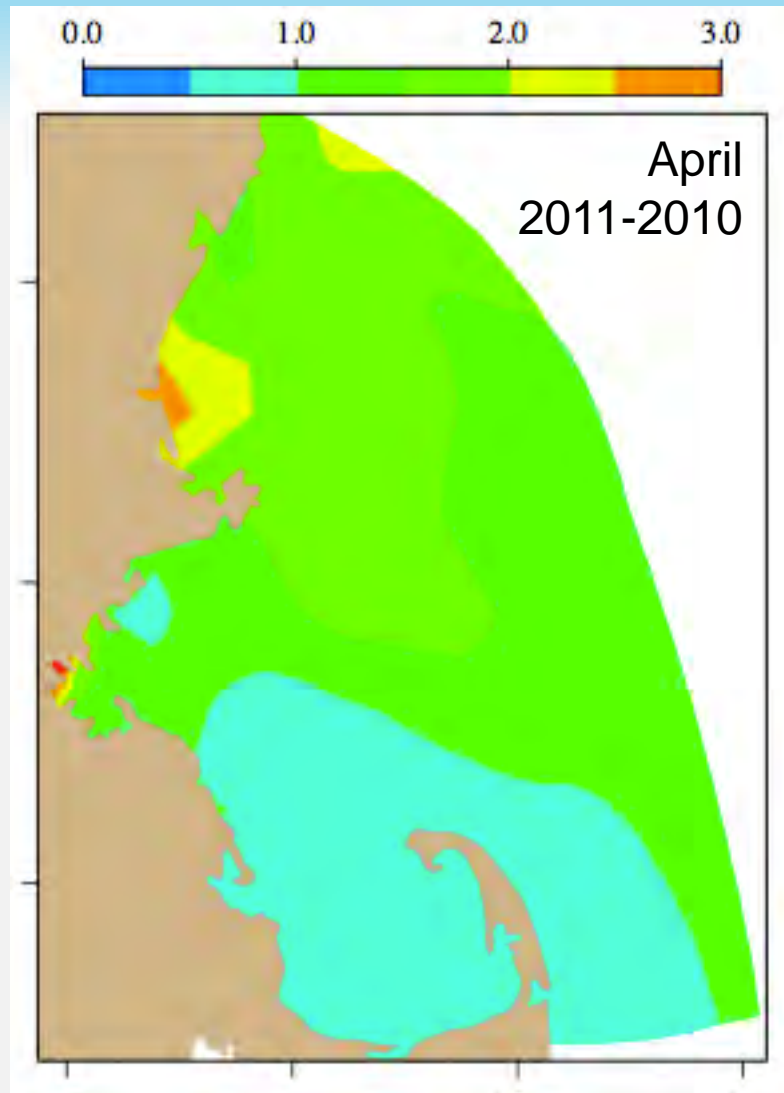
Difference between April 2011 and 2010 averaged surface temperatures



Difference between April 2010 and 2009 averaged surface salinities

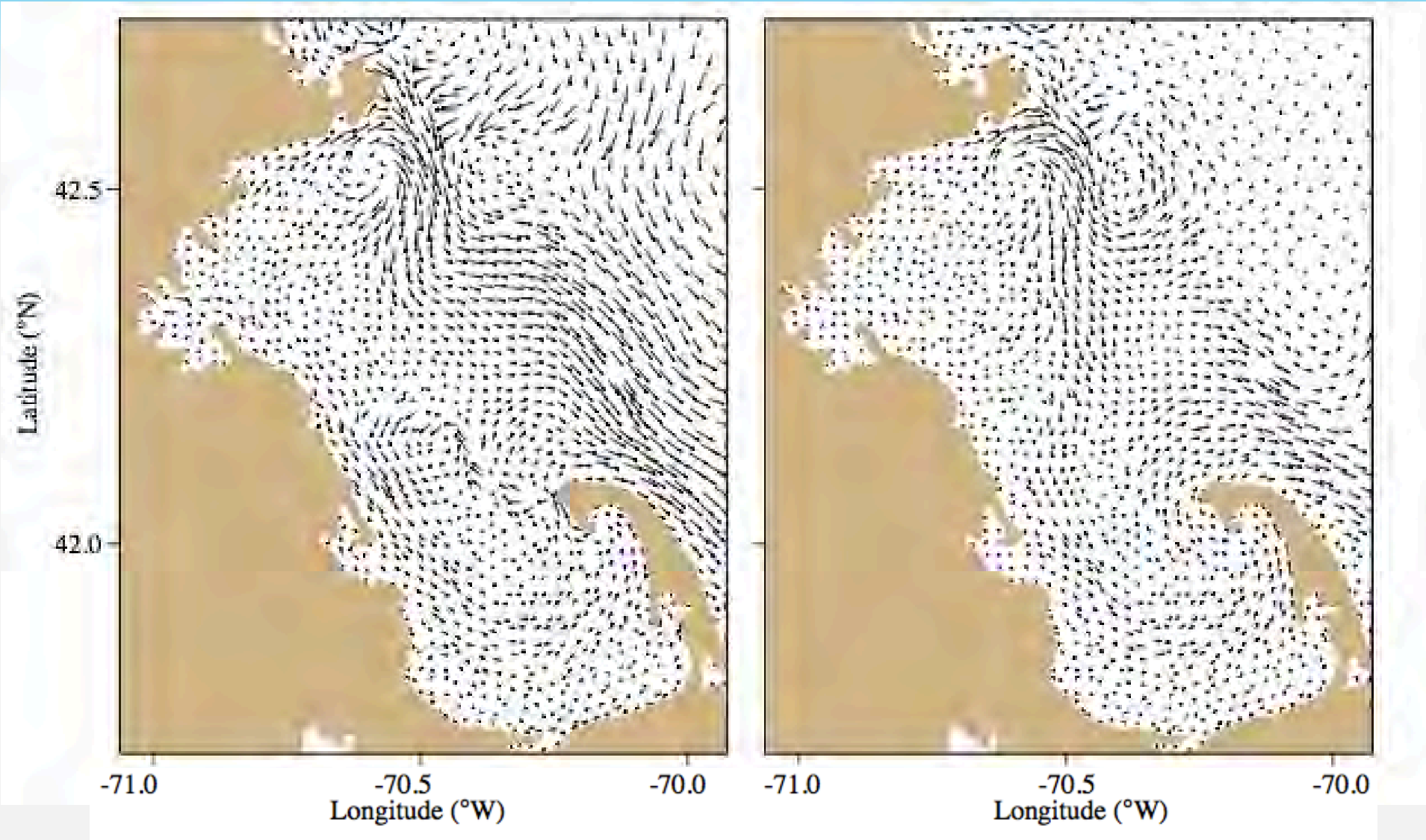


Difference between April 2011 and 2010 averaged surface salinities



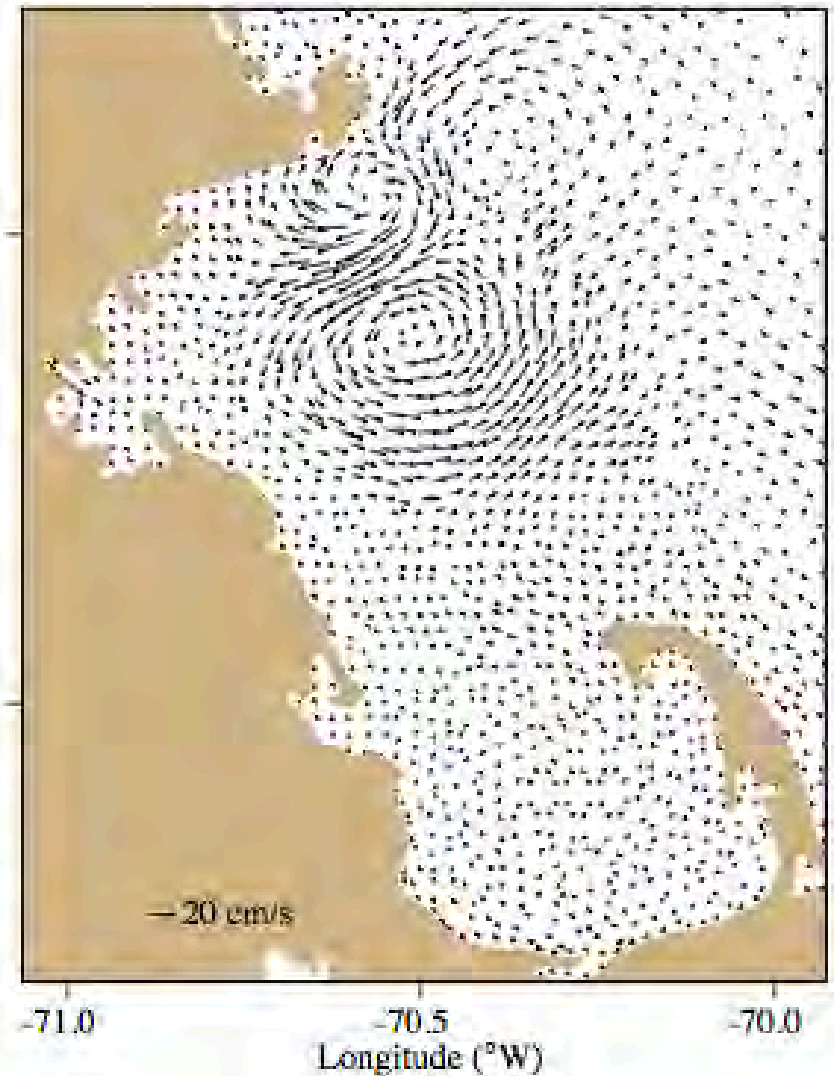
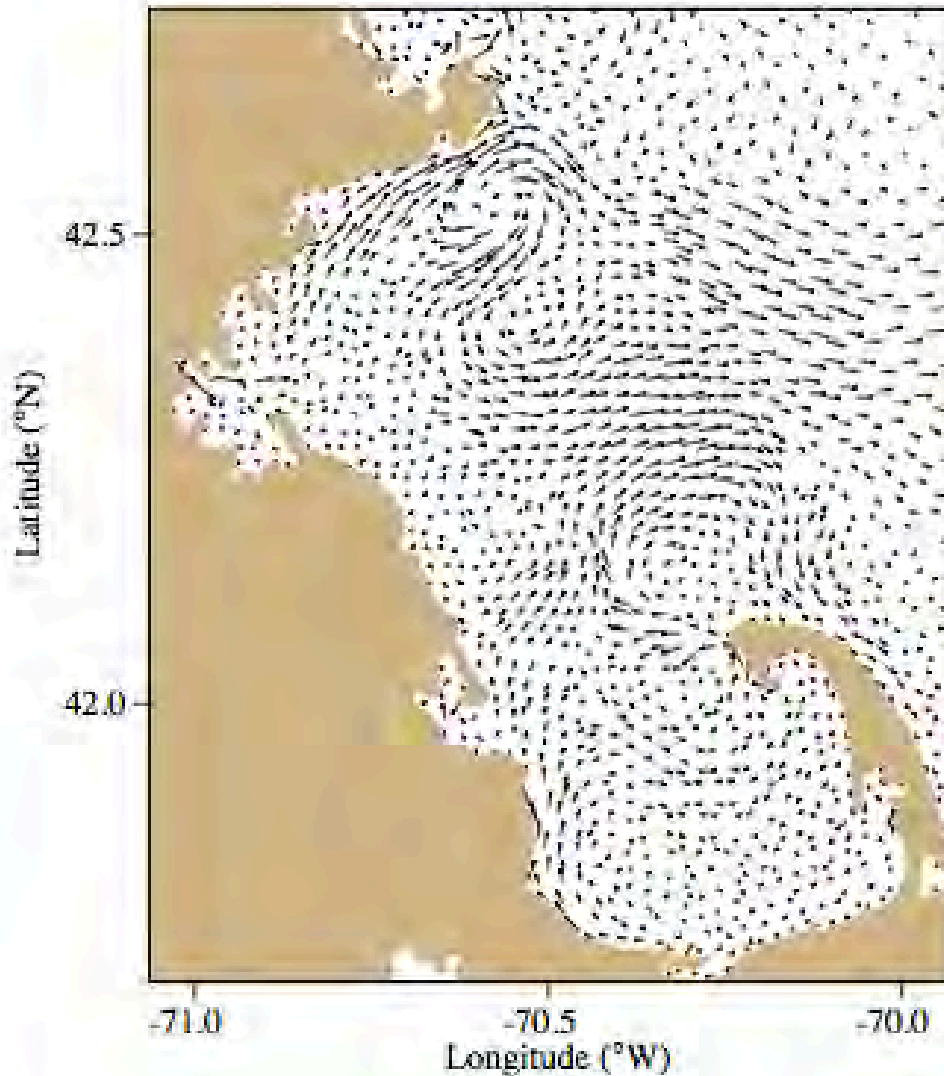
April 2011 averaged surface currents

Difference between April 2011 and 2010 averaged surface currents



September 2011 averaged surface currents

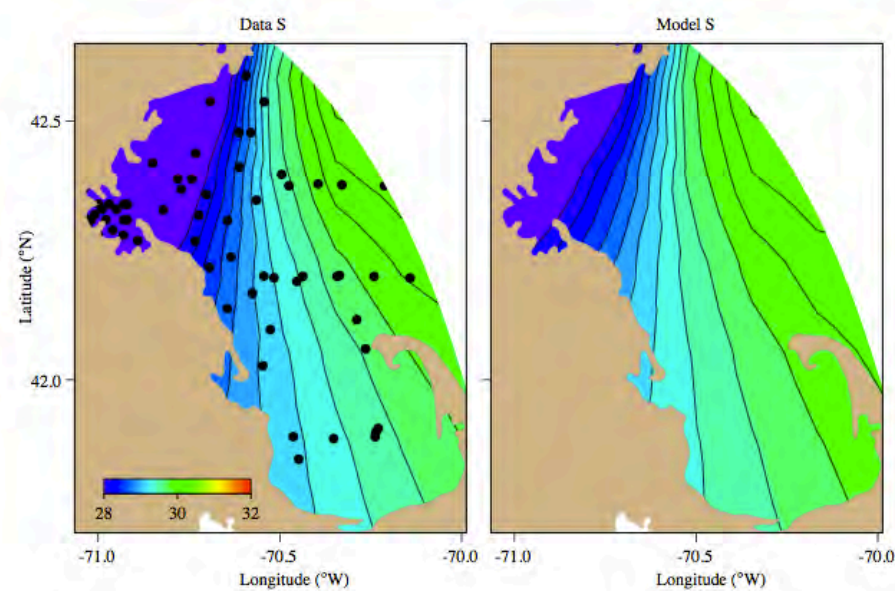
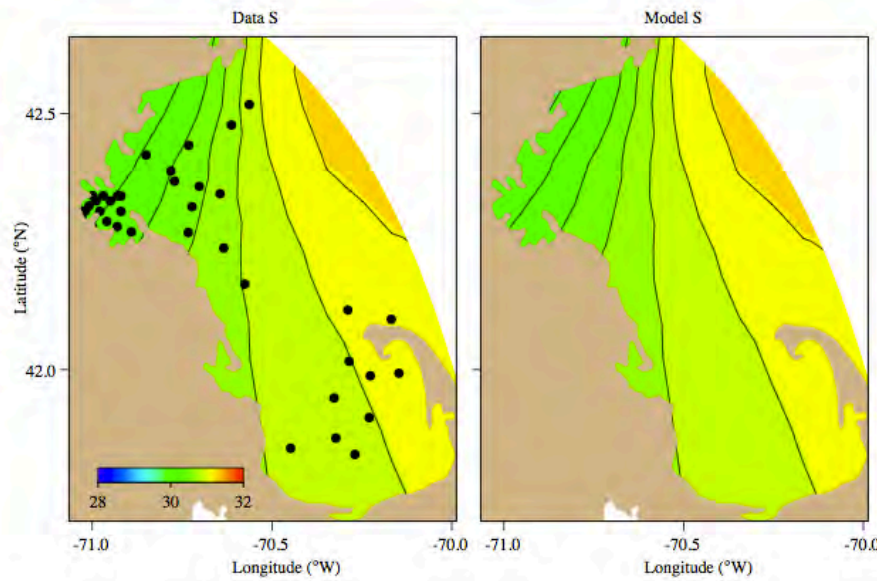
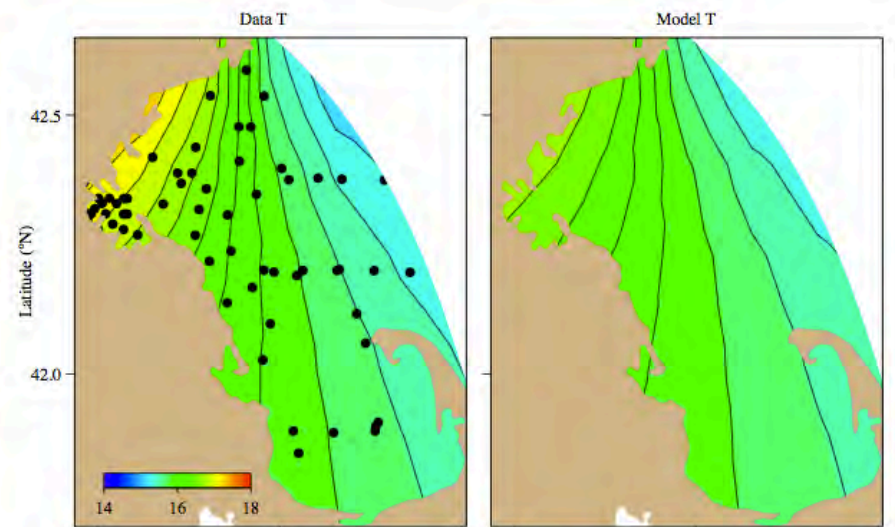
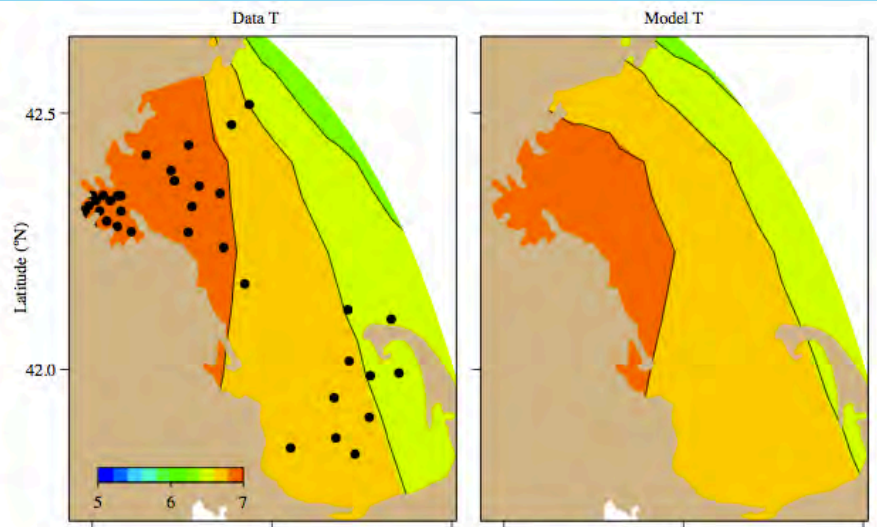
Difference between September 2011 and 2010 averaged surface currents



Comparison between computed and observed surface temperatures and salinities

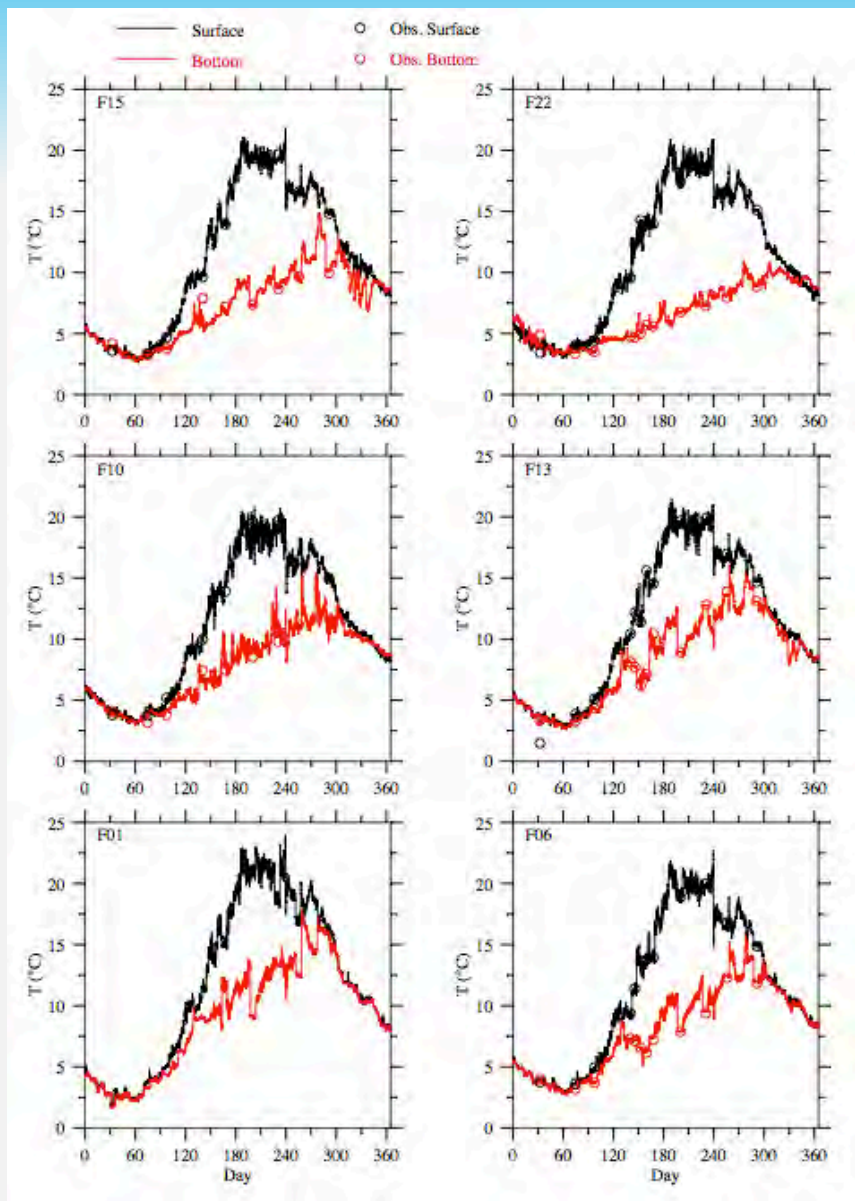
April, 2011

June, 2011

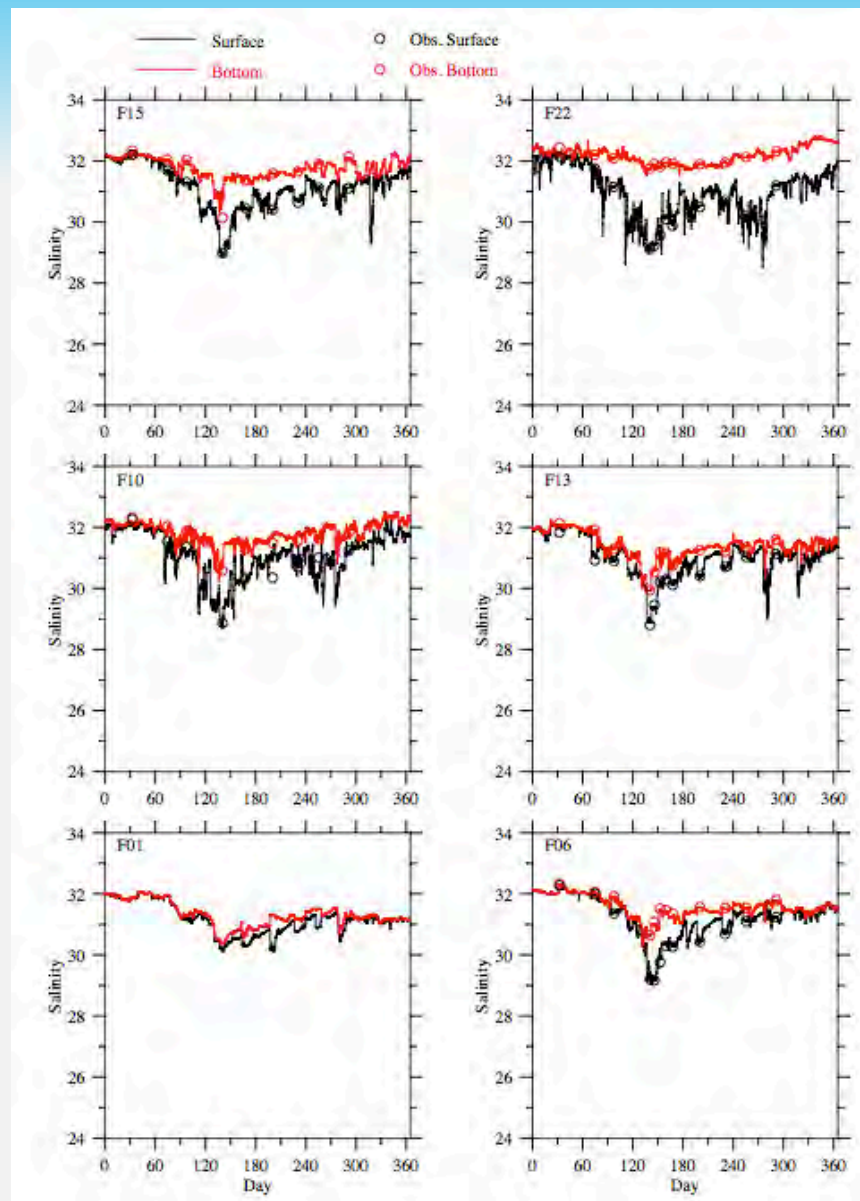


Assimilated surface temperature and salinity via T/S profiles

Temperature



Salinity



Water Quality Simulation

Question 1:

Did the 2011 nutrient condition significantly differ from previous years?

Answer: Yes.

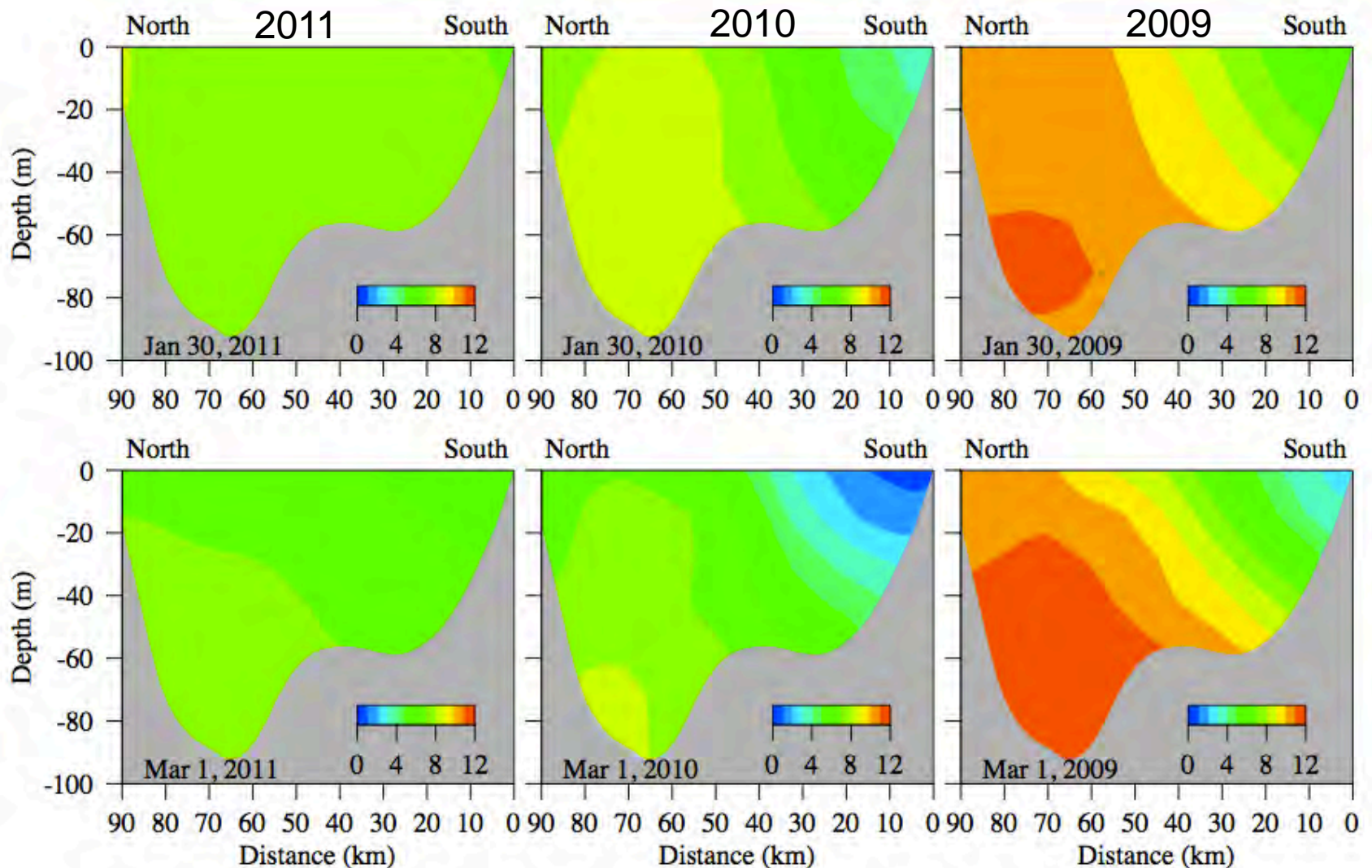
Question 2:

If “yes” for question 1, could the water quality condition significantly differ from previous years?

Answer: No

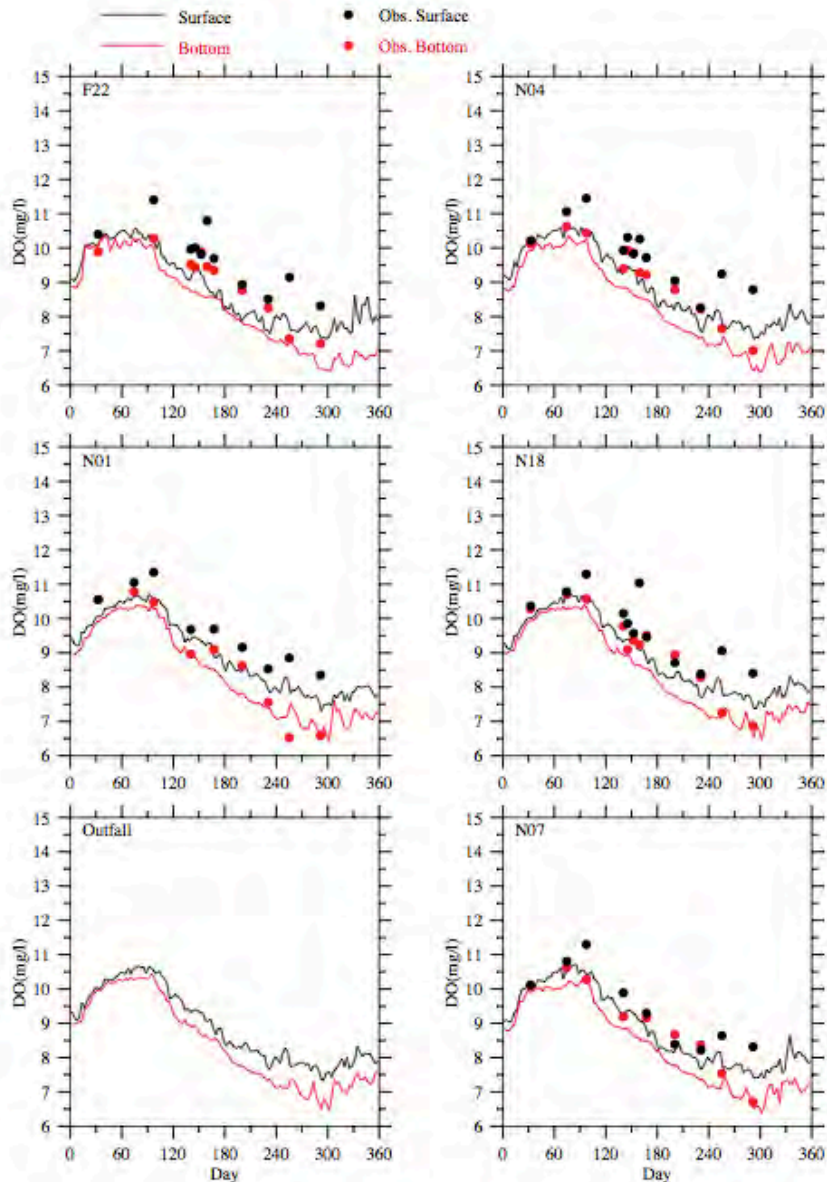
Boundary condition of NO₃ (μM)

(OA mapping results based on MWRA observations)

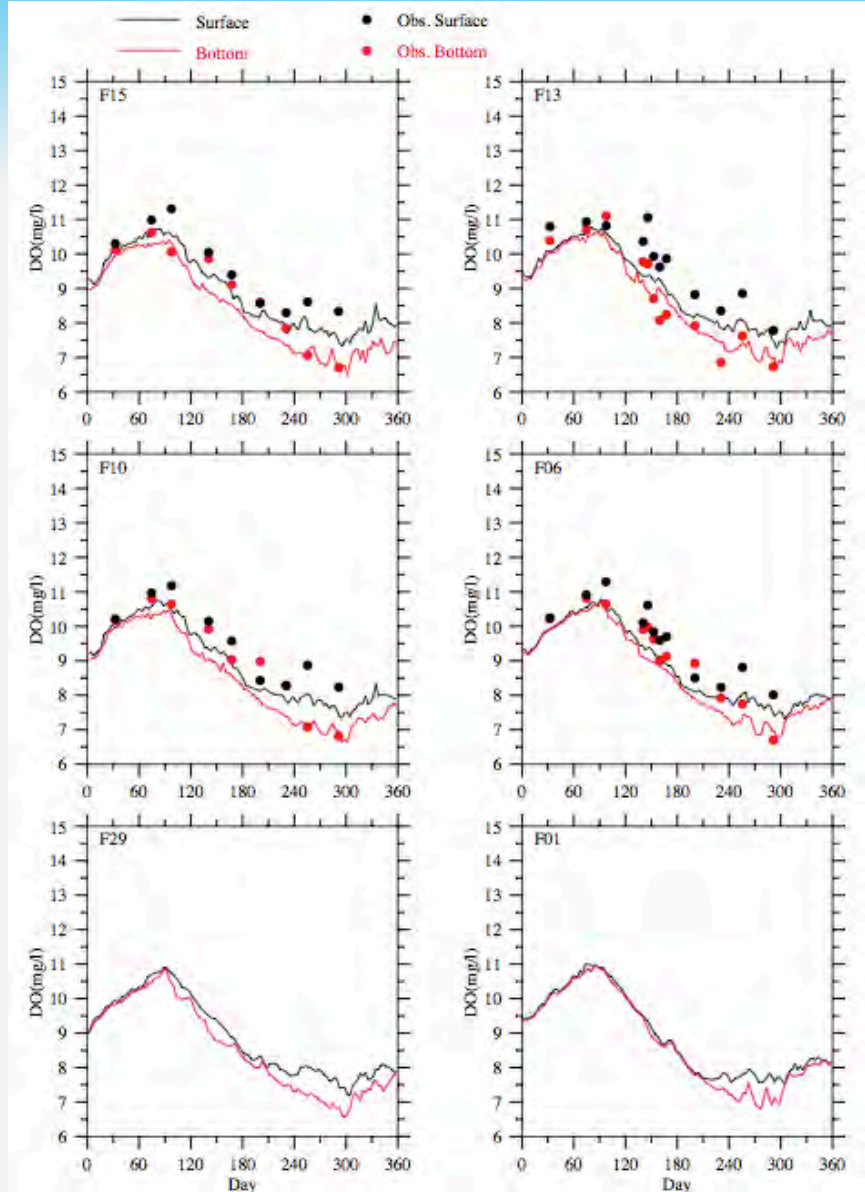


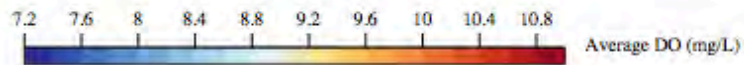
Simulated surface (black) and bottom (red) DO

Near-field stations (except F22)

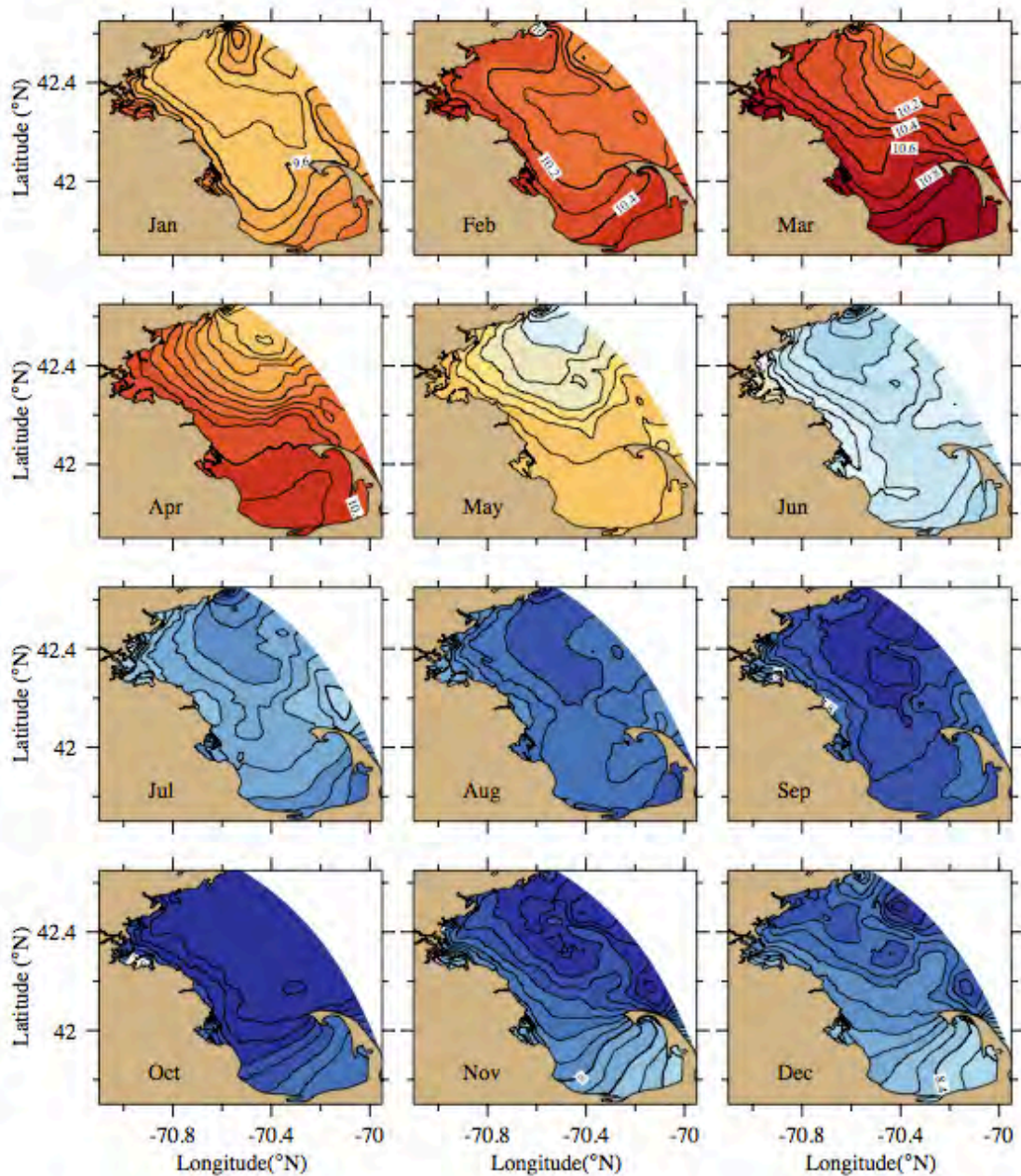


Far-field stations



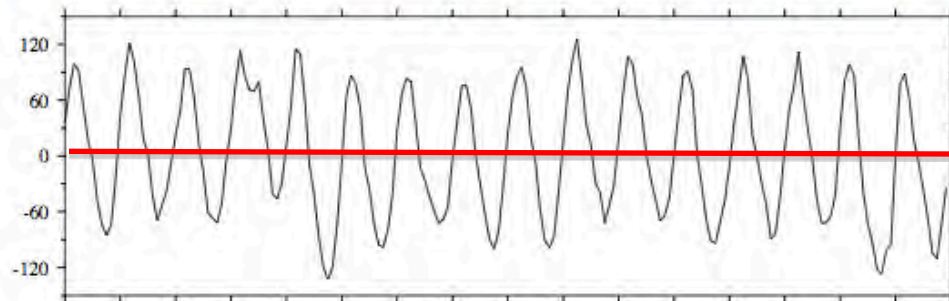
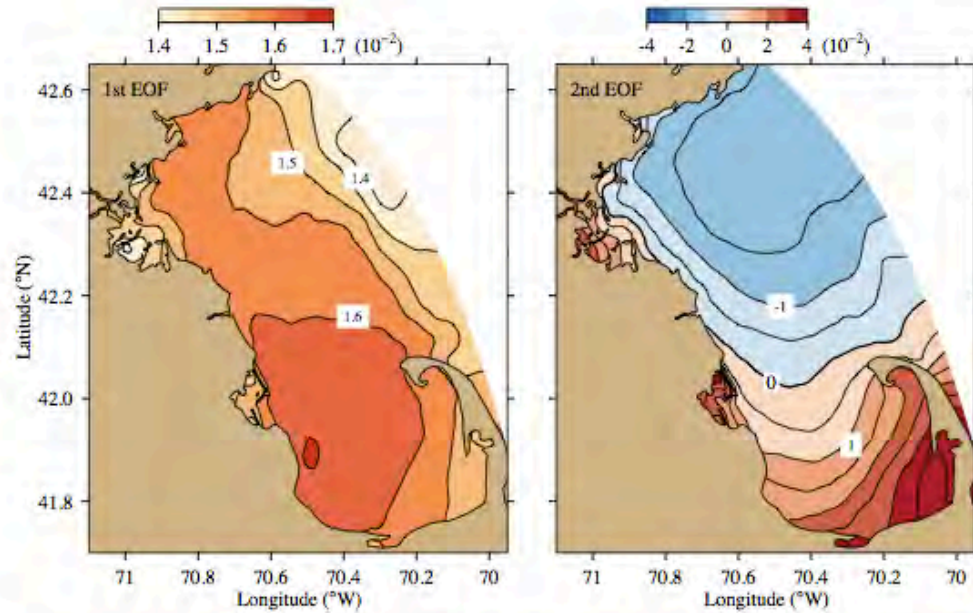


Distributions of the monthly averaged DO concentration in 2011

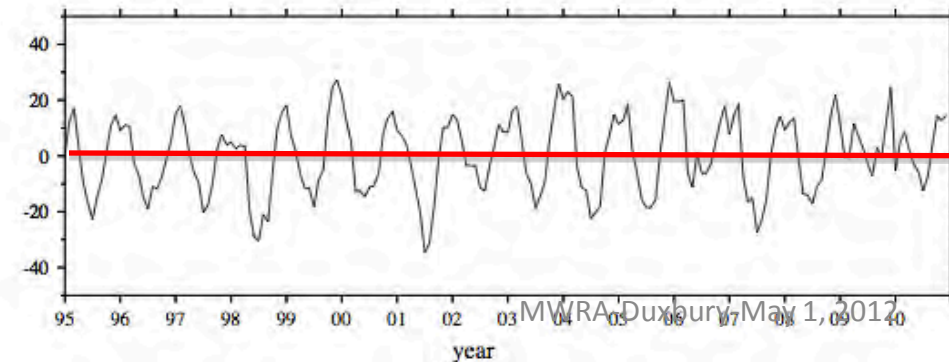


First EOF mode

Second EOF mode

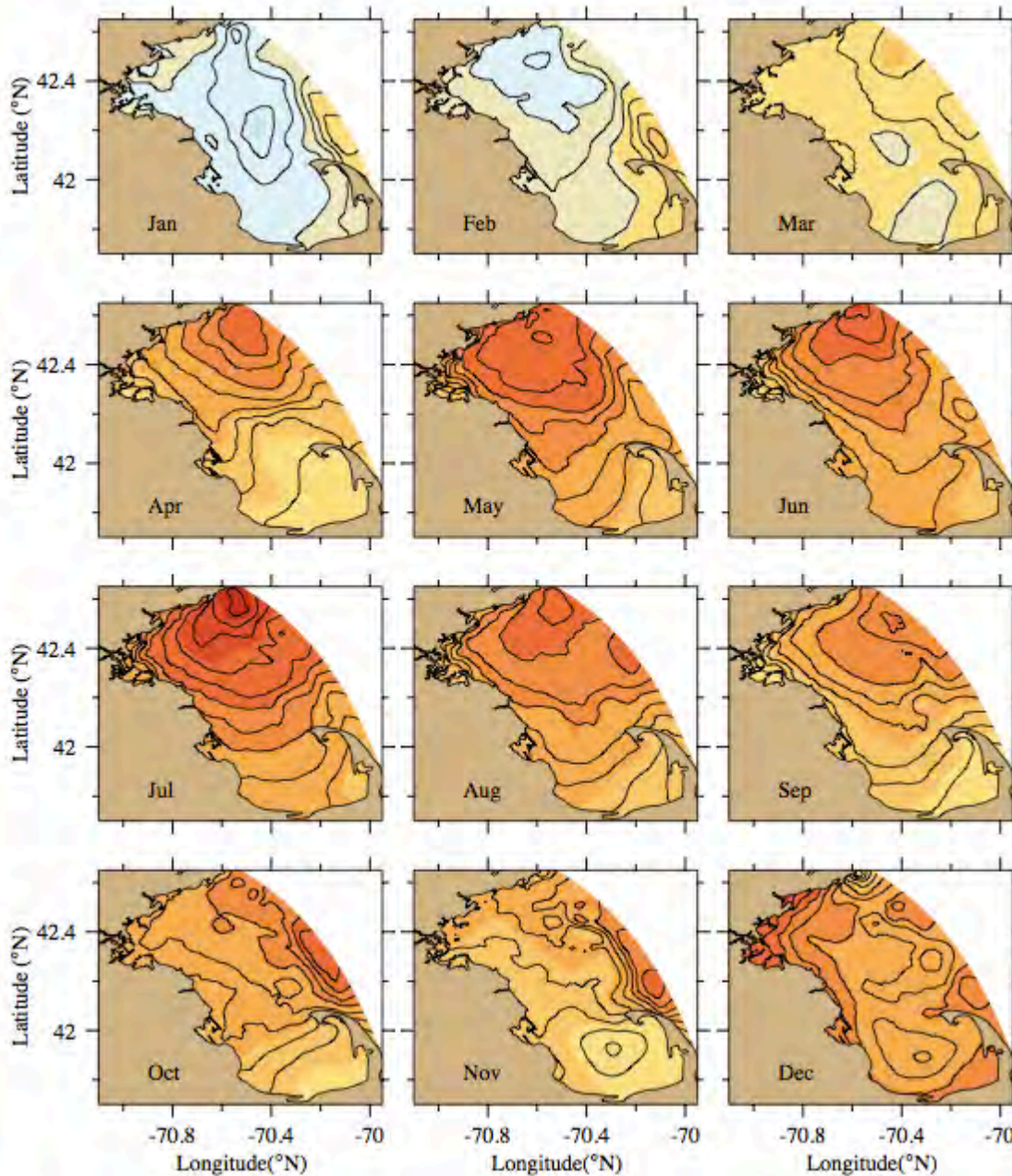
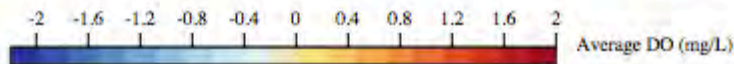


First EOF mode



Second EOF mode

1. The first EOF mode represents a seasonal variation, which remains uncharged in the past 16 years;
1. The second EOF mode represents a spatial variation, which revise in summer via in winter.



$$DO_{2011} - DO_{\text{climatological}}$$

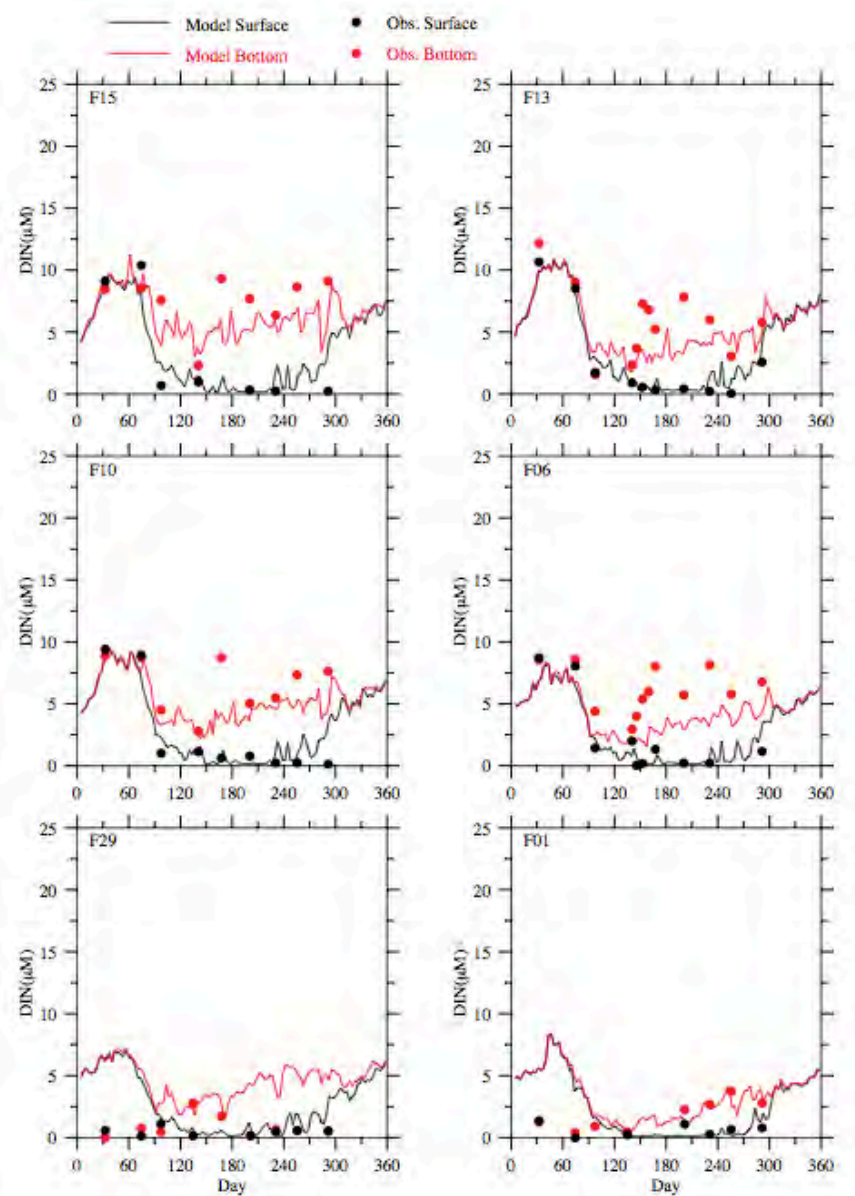
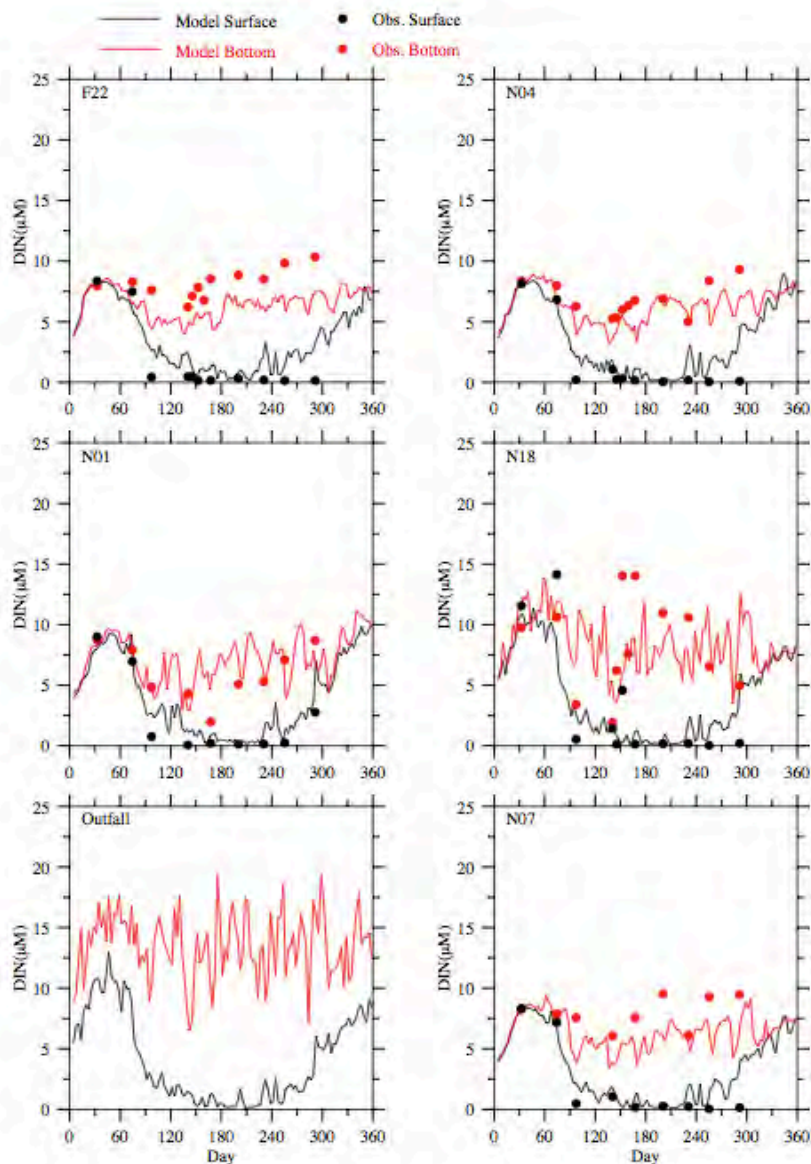
DO_{2011} : The 2011 monthly averaged DO concentration.

$DO_{\text{climatological}}$: The climatologic-monthly averaged DO concentration.

Simulated surface (black) and bottom (red) DIN

Near-field stations (except F22)

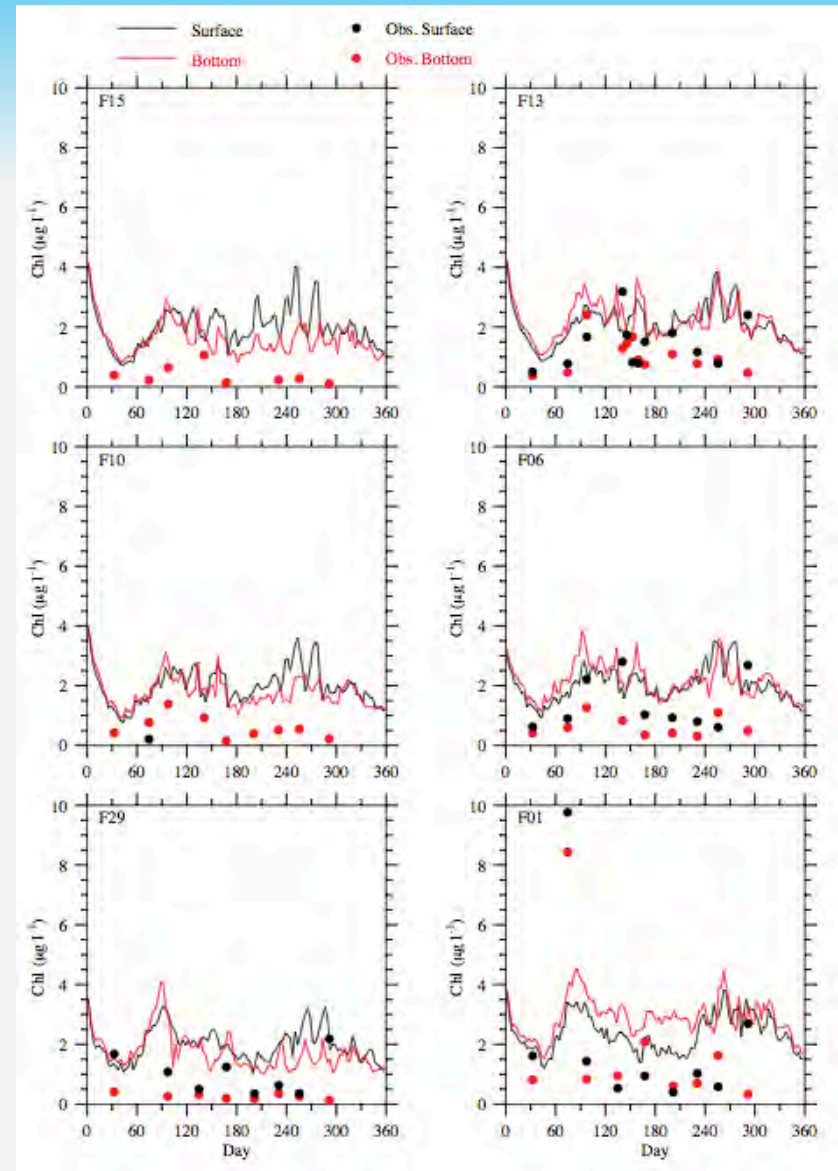
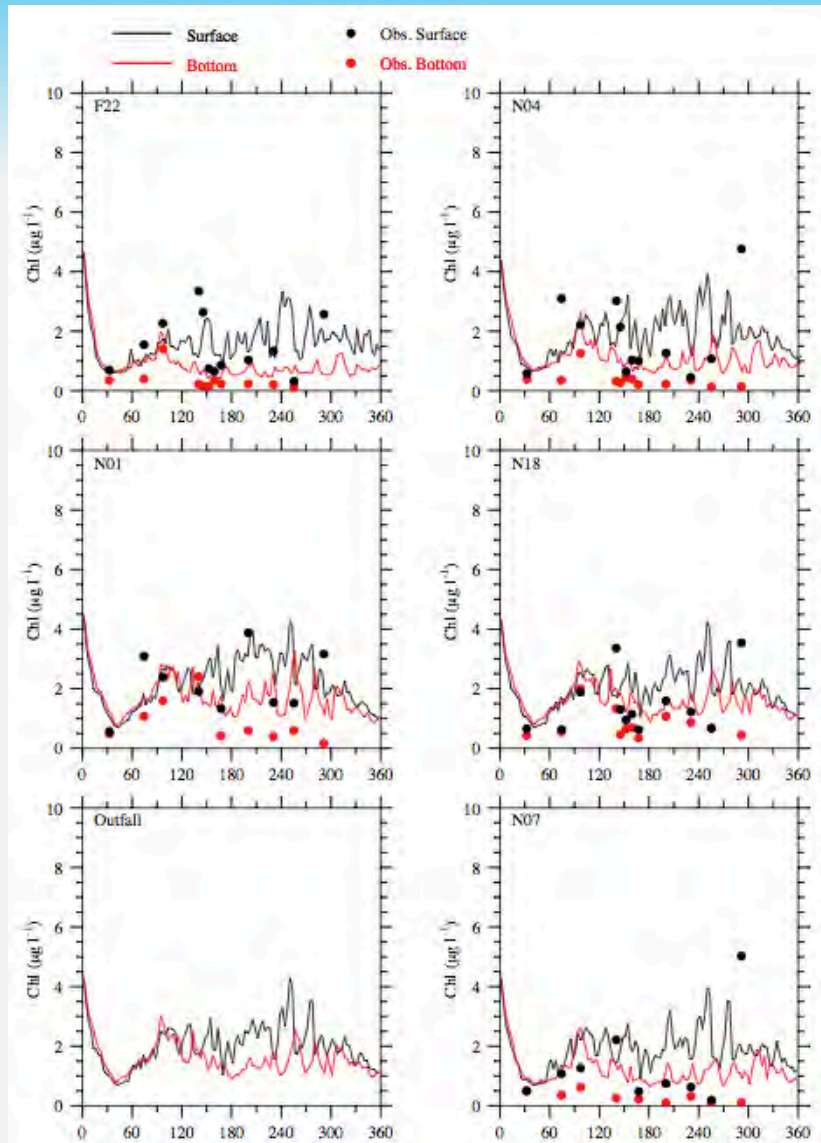
Far-field stations



Simulated surface (black) and bottom (red) chlorophyll

Near-field stations (except F22)

Far-field stations



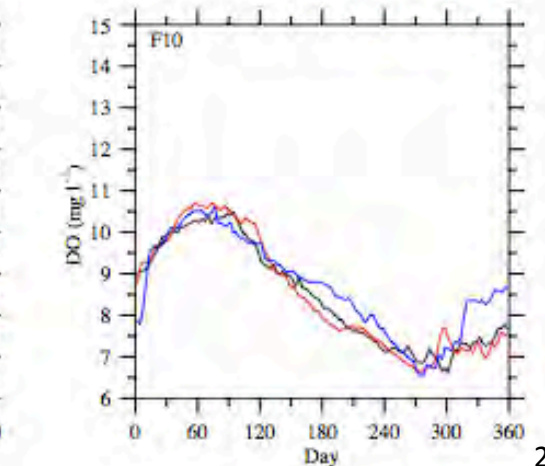
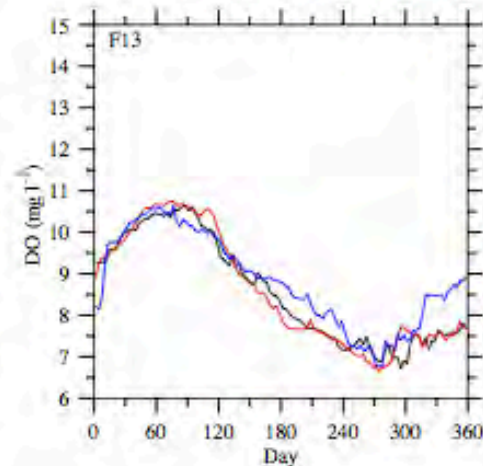
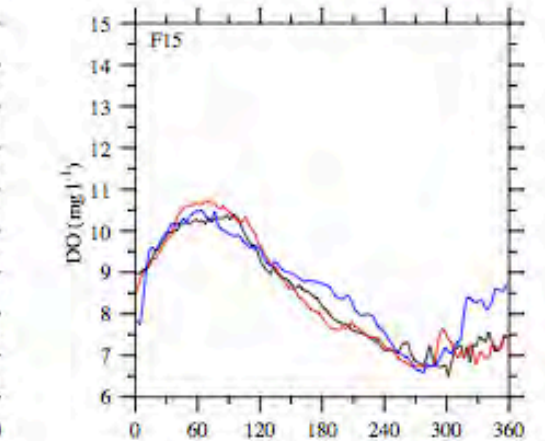
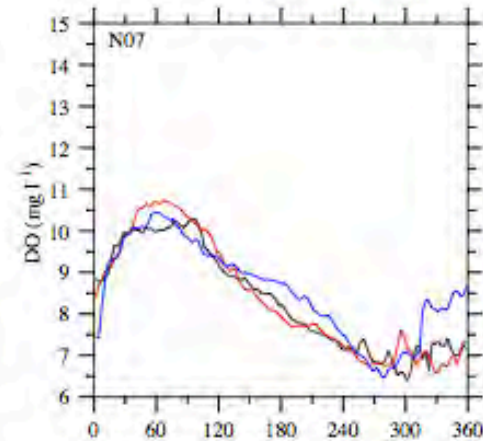
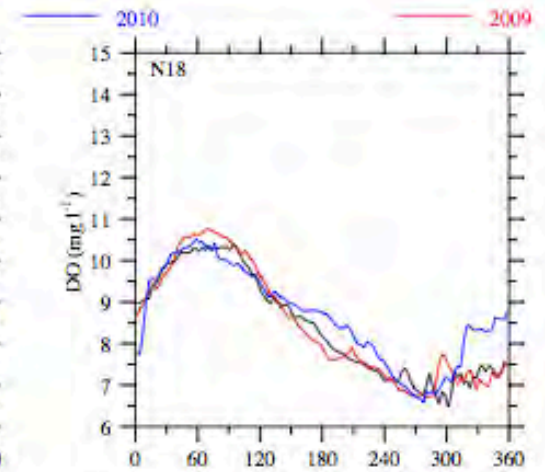
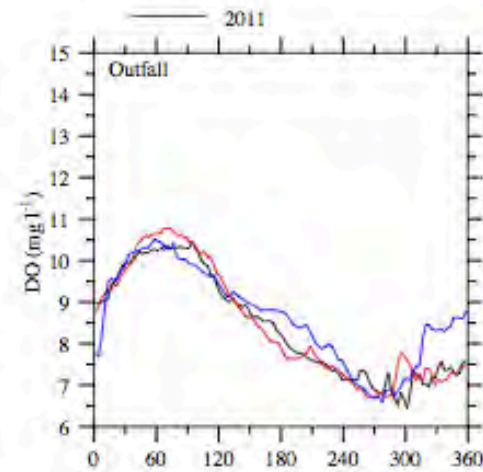
Multi-year comparison of DO in the bottom layer

Black: 2011.

Blue: 2010.

Red: 2009.

Stations: Outfall, N18, N07, F15, F13, F10)



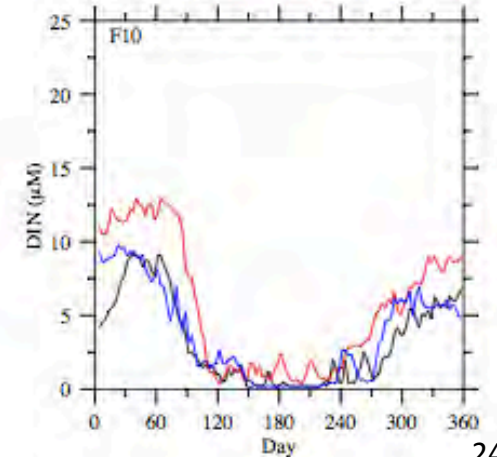
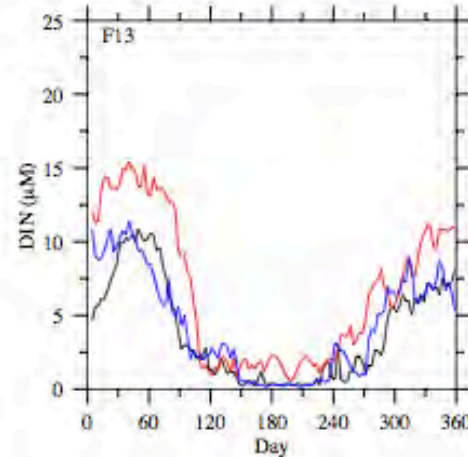
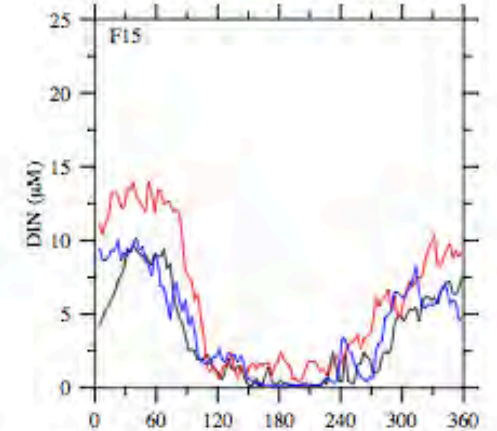
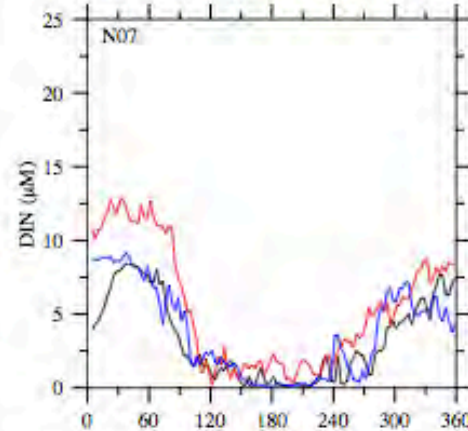
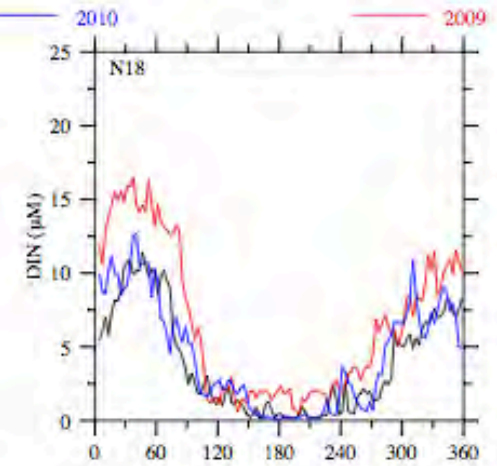
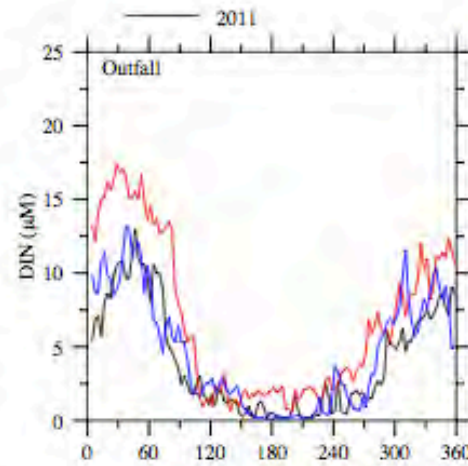
Multi-year comparison of DIN in the surface layer

Black: 2011.

Blue: 2010.

Red: 2009.

Stations: Outfall, N18, N07, F15, F13, F10)



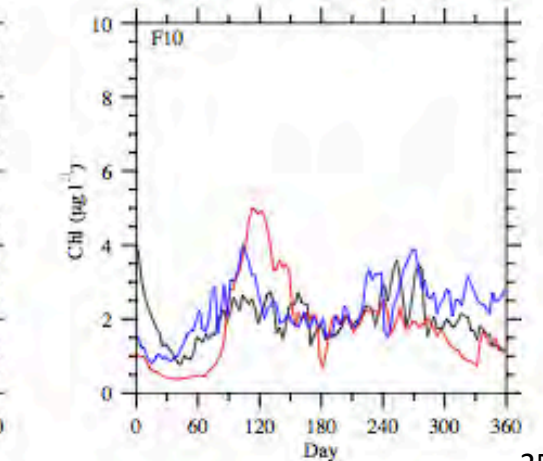
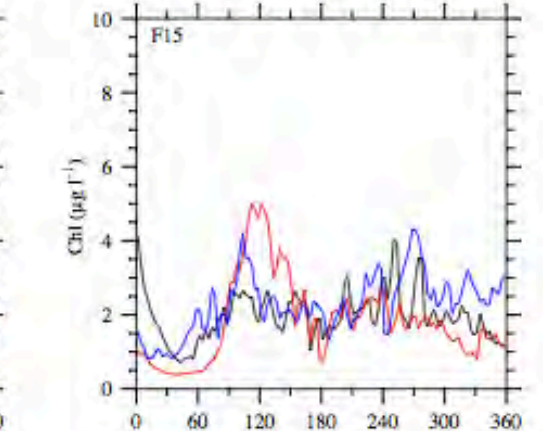
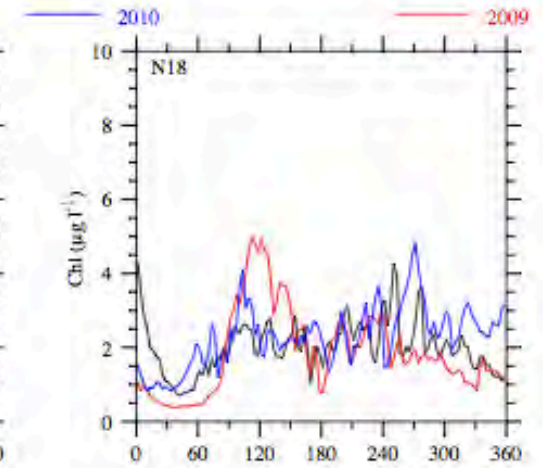
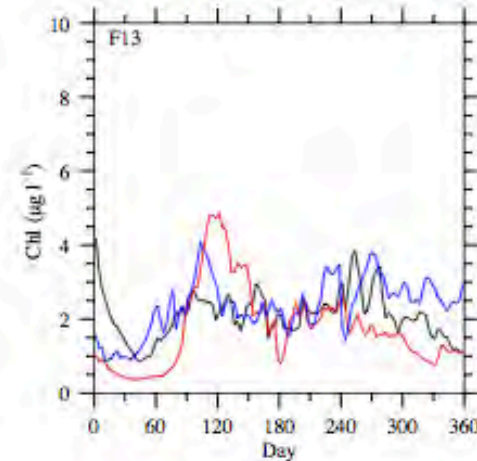
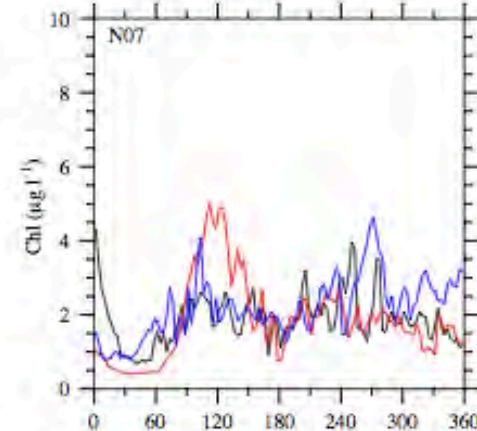
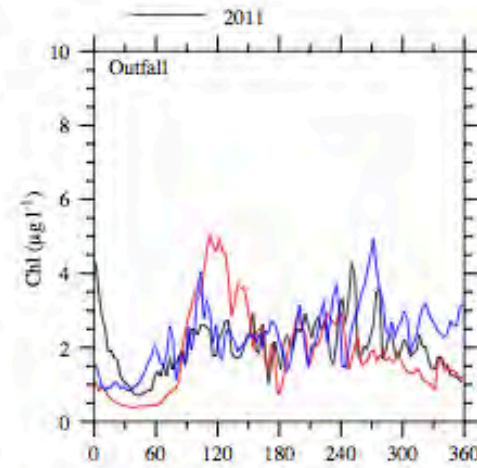
Multi-year comparison of chlorophyll in the surface layer

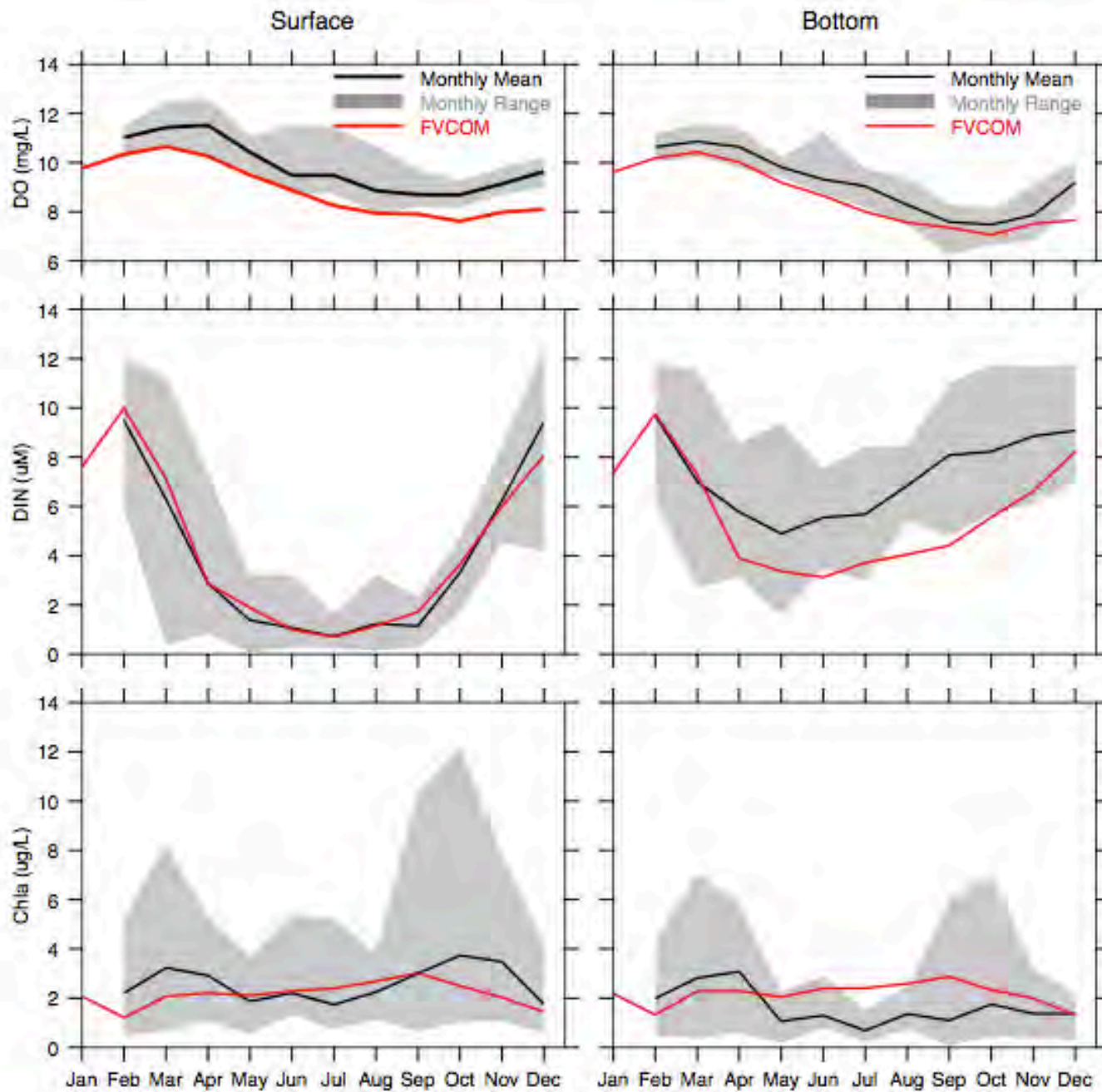
Black: 2011.

Blue: 2010.

Red: 2009.

Stations: Outfall, N18, N07, F15, F13, F10)





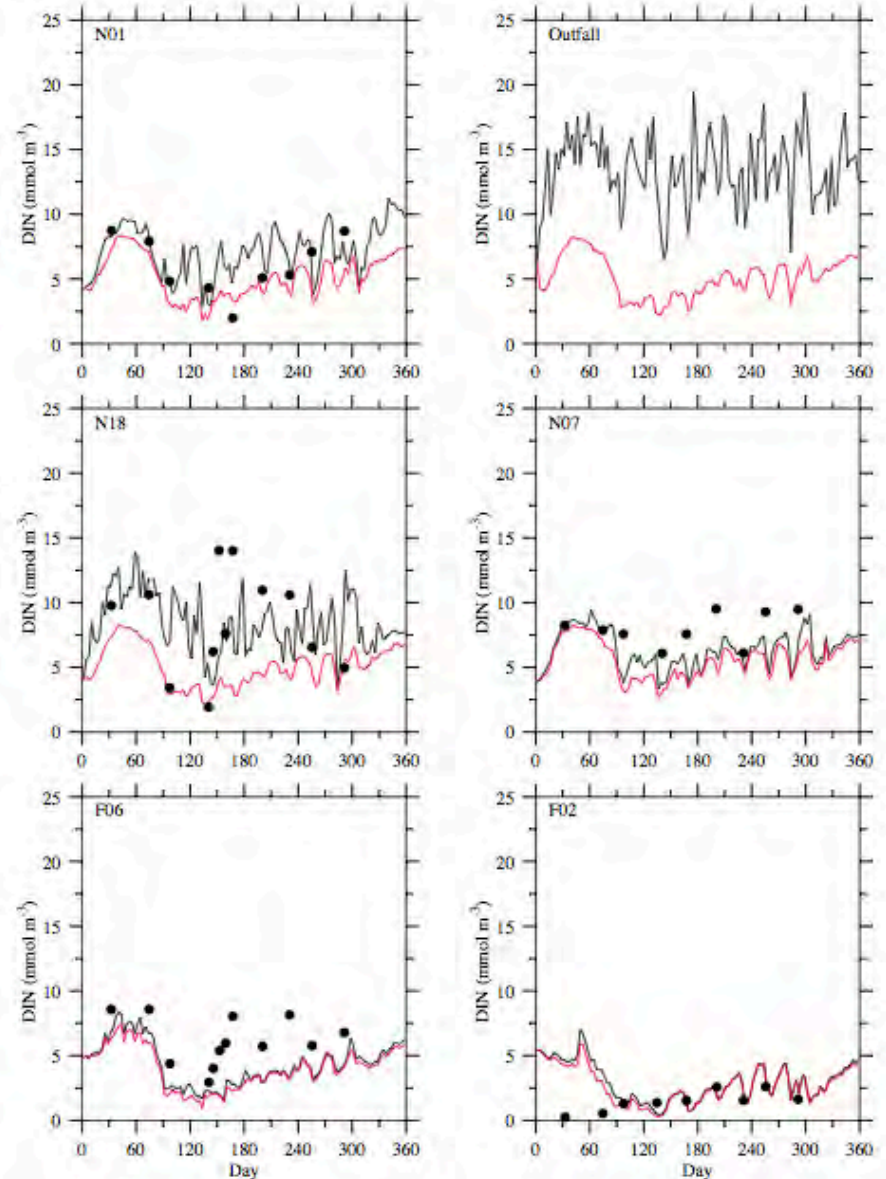
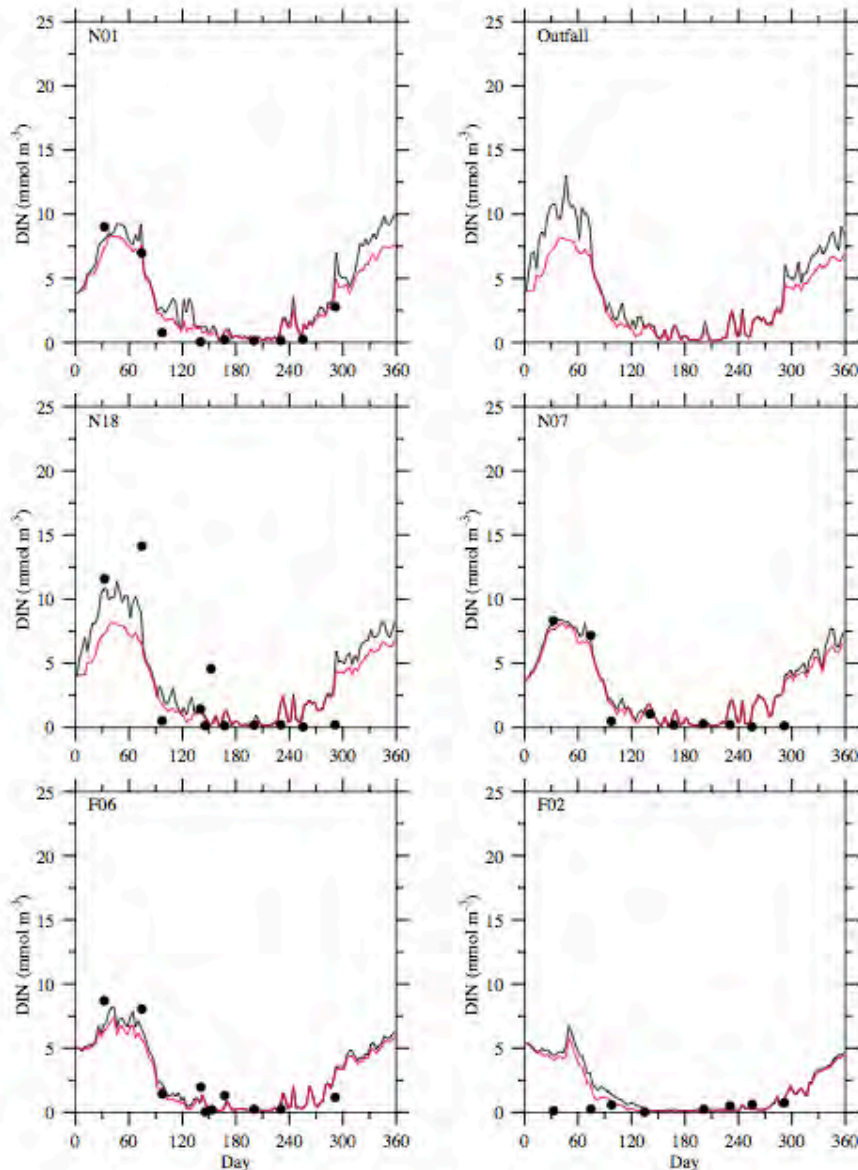
MWRA outfall projection

- The projection was done by the comparison between two runs with and without the MWRA outfall loadings under the same forcing conditions;
- Comparison was made for DO, DIN and chlorophyll levels;
- The outfall effluent plume is exemplified by using NH_4 , which is one of the most abundant effluent of inorganic nutrients.
- Effluent horizontal dispersal and vertical scale are evaluated by the difference of NH_4 concentration between the two runs.

DIN projection (black: with outfall; red: without outfall)

Surface waters

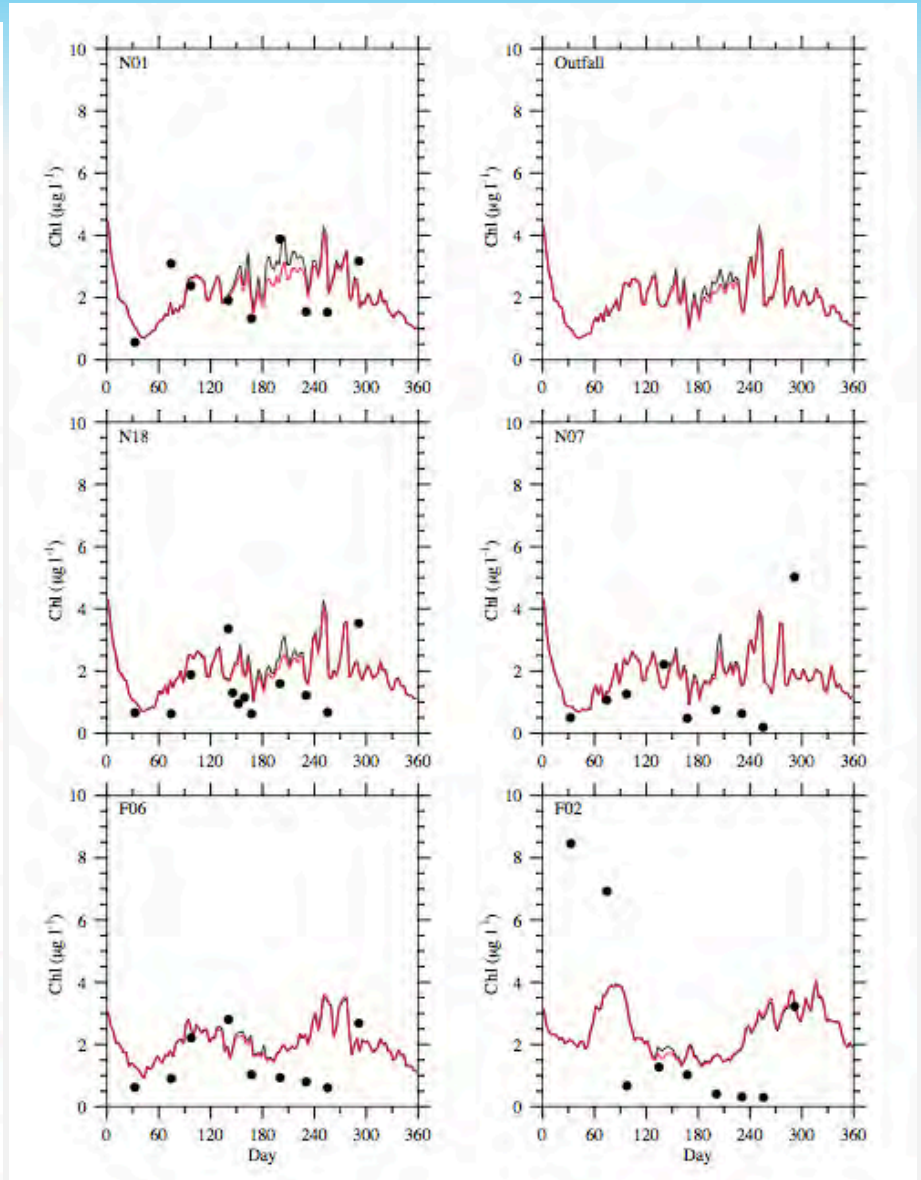
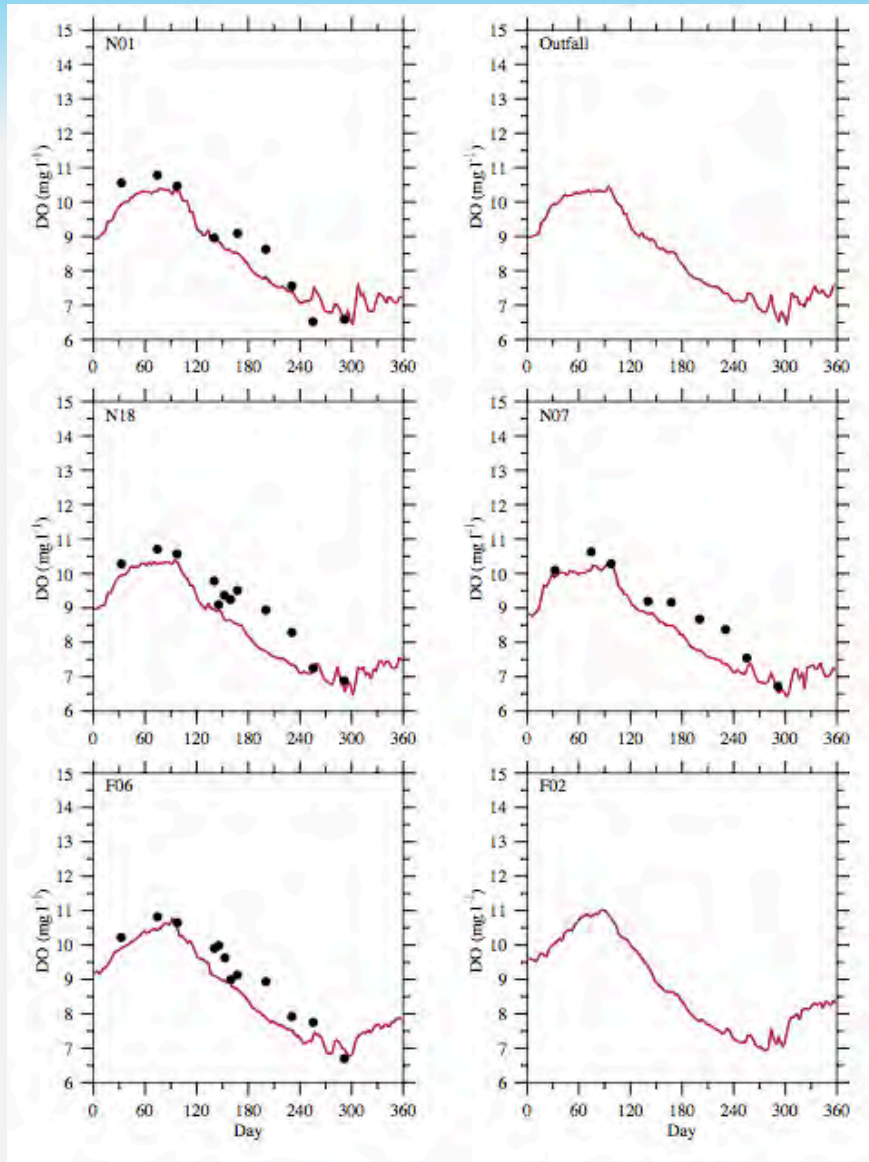
Bottom layer



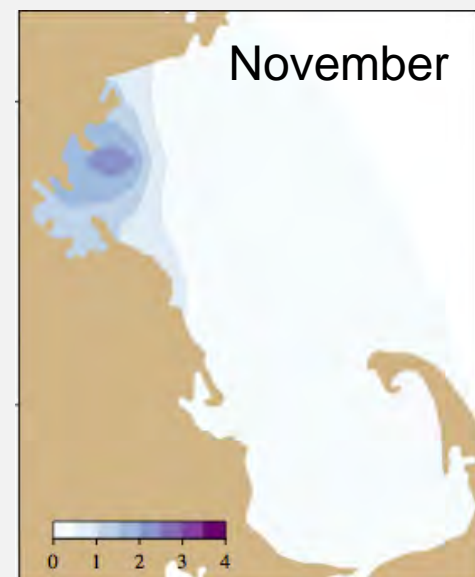
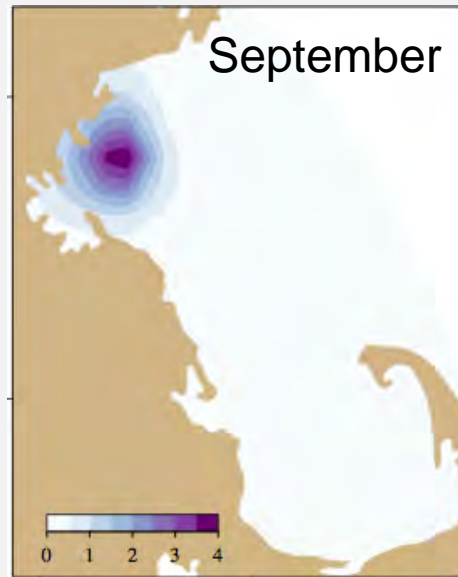
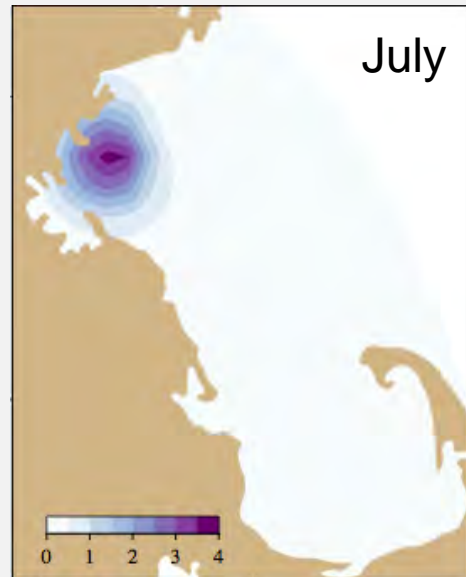
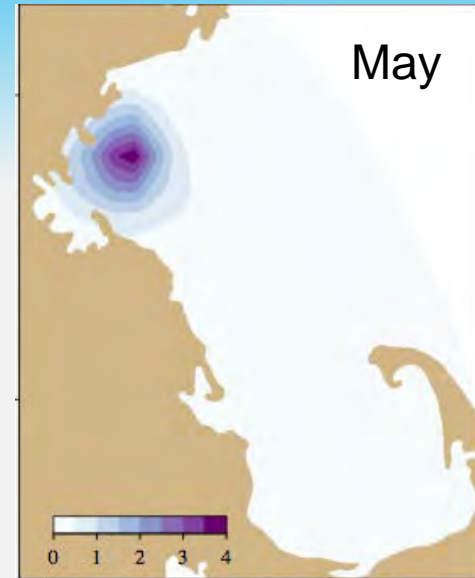
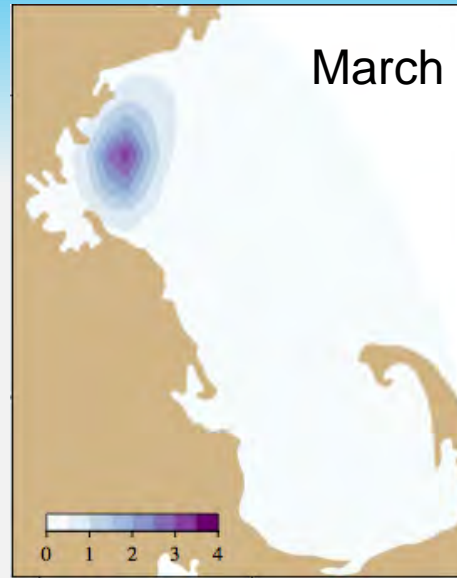
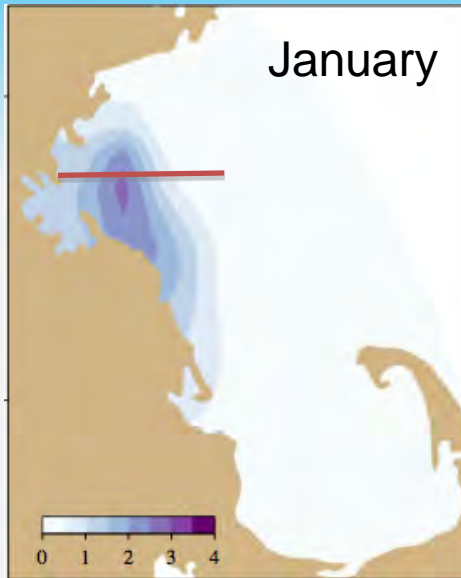
Do and chlorophyll projection (black: with outfall; red: without outfall)

Bottom DO

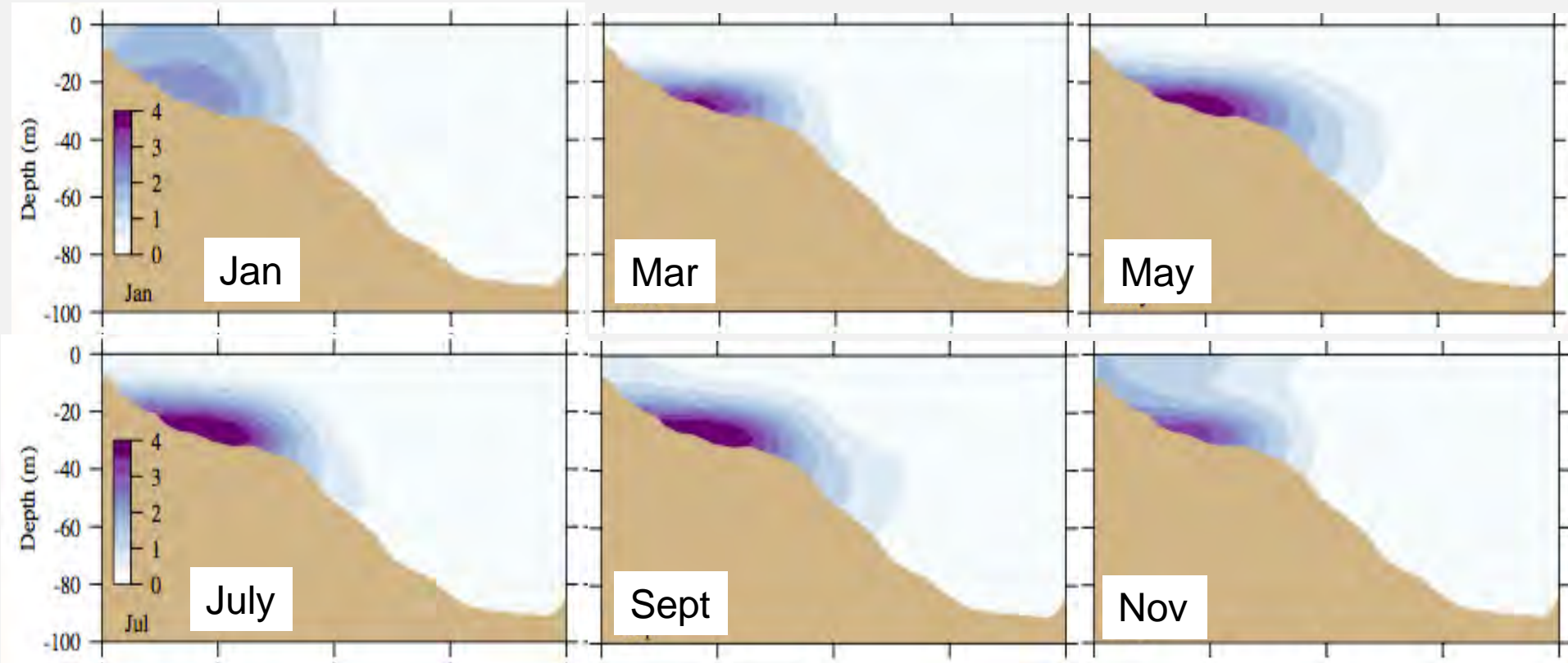
Surface chlorophyll



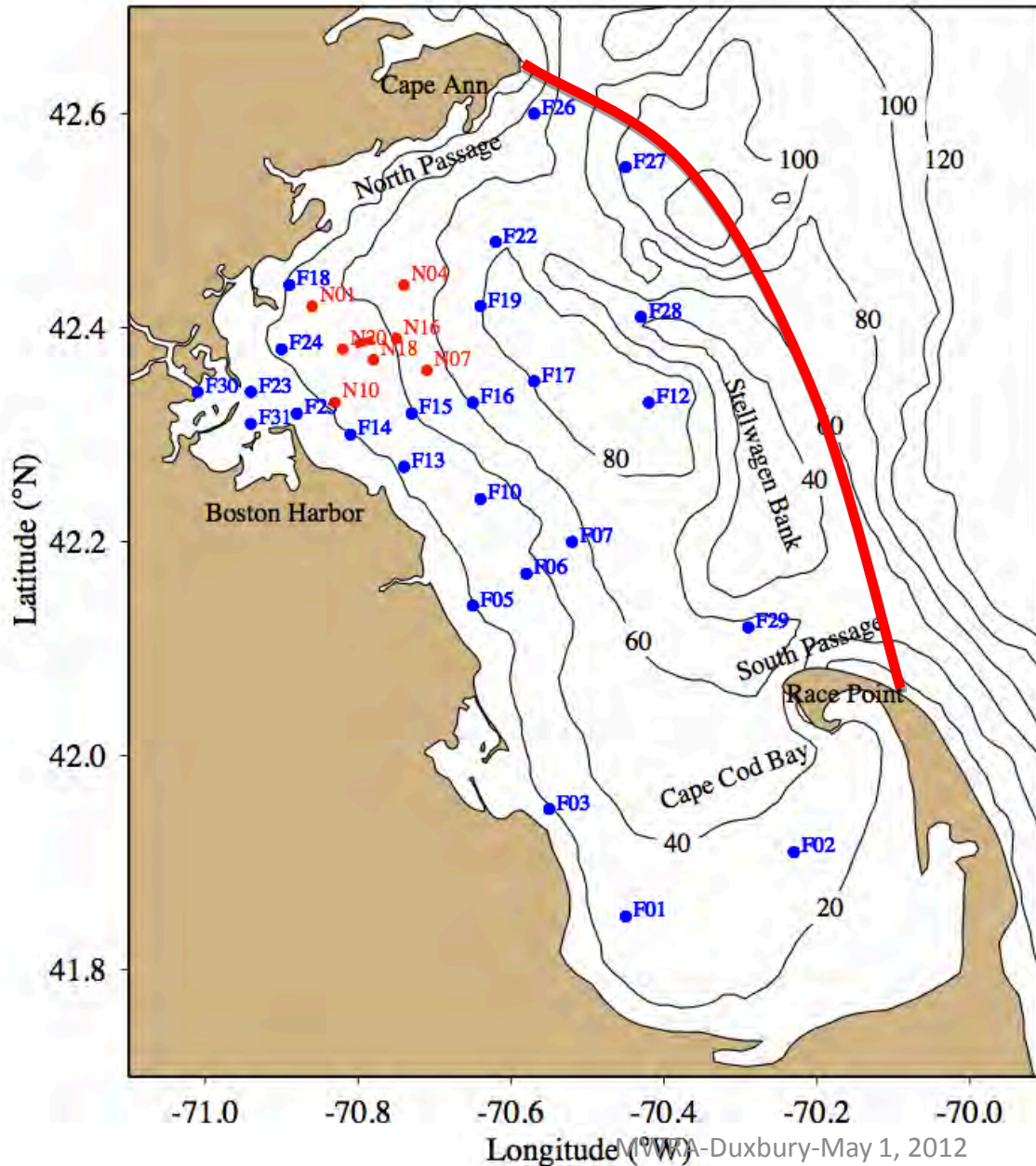
2011 Outfall plume at the last day of every two months
(NH₄ difference in μM)



2011 outfall plume vertical scale at the last day of every two months
(NH₄ difference in μM)



Observing System Simulation Experiments (EnKF)



- In UG-RCA: the open boundary conditions were determined by interpolated values from the measurement sites near the boundary;

Questions:

1. How are the simulation results sensitive to the boundary condition?
2. Could the DO field restore back to the true state after perturbation?

Observing System Simulation Experiments (EnKF)

1. Initial perturbation experiments:

First run the model to see if DO field could restore back to the true state;

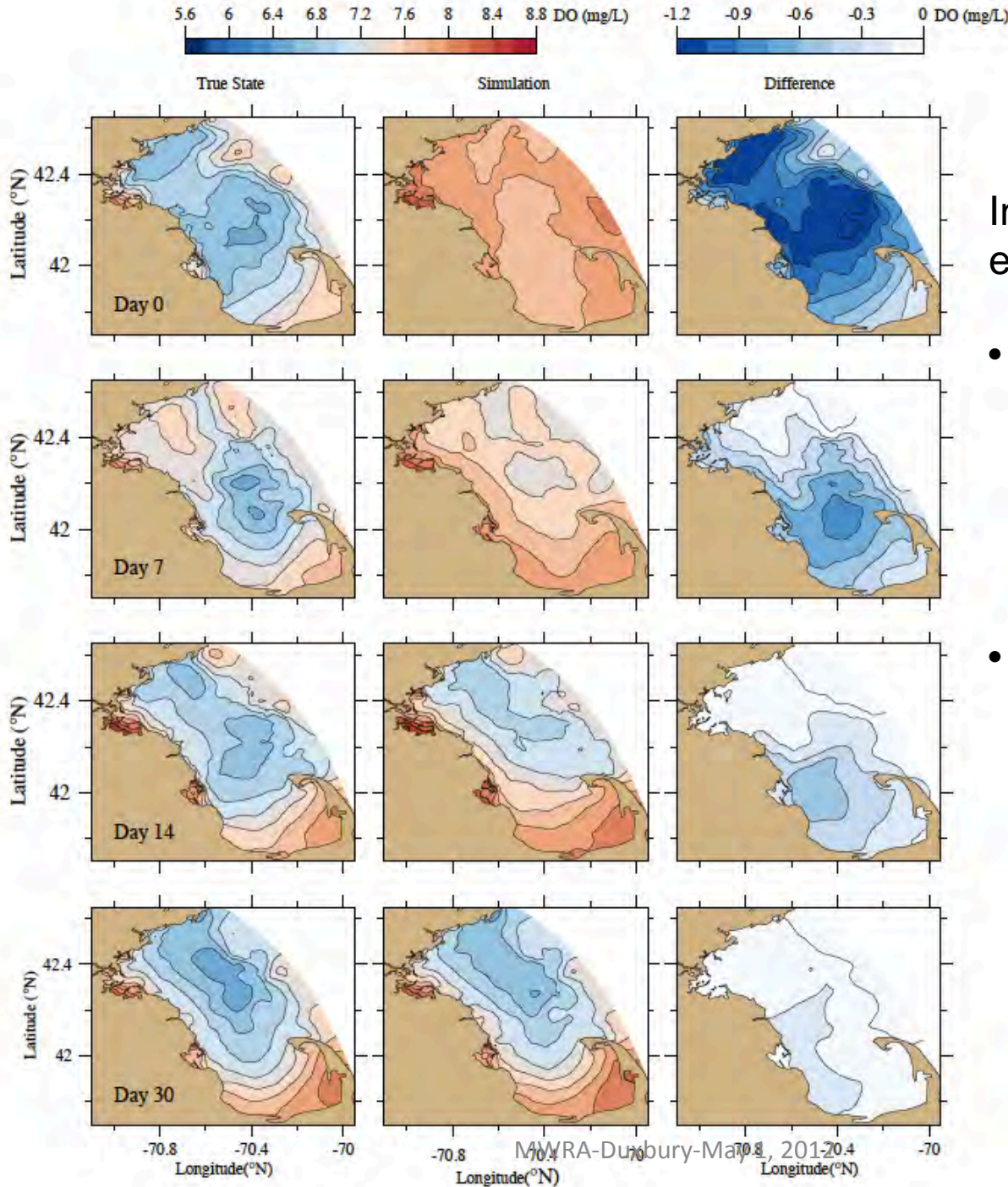
Then placing a monitoring site within Mass Bay and see if EnKF could restore the DO field back to the true state.

2. Boundary perturbation experiments:

First run the model with inaccurate open boundary condition specified by the 16-year (1995-2010) averaged values to examine how the errors from the boundary propagate into the interior.

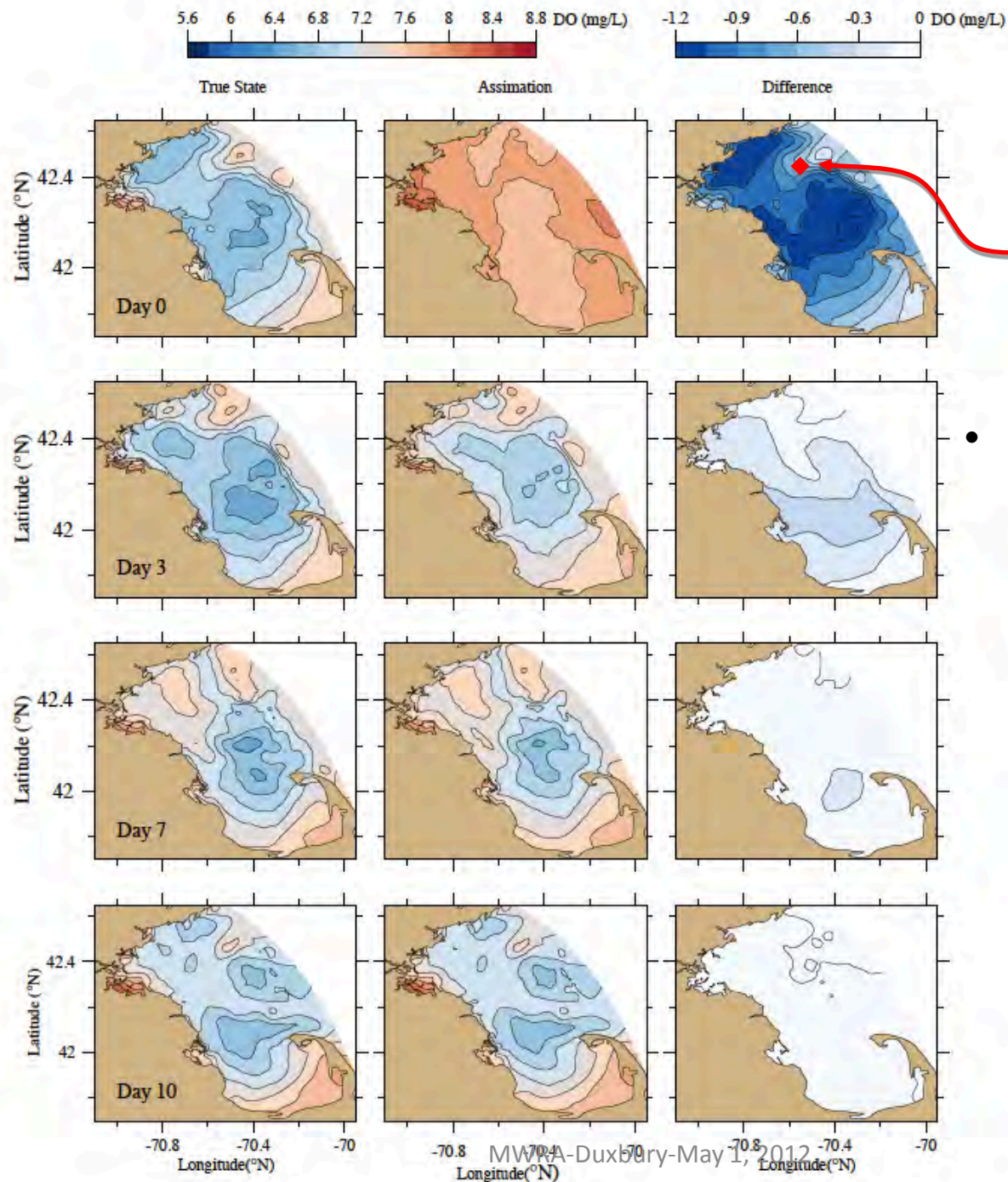
Then placing a monitoring site on the key point where the major error propagate to see if EnKF could restore the DO field back to the true state.

All experiments were made for October 1999.



Initial perturbation experiments:

- Under correct boundary forcing, the DO field is able to restore back to a true state over a time scale of ~one month.
- The restoration is faster in the northern region than in the southern region. It suggests that the northern boundary condition is a control factor to this system.

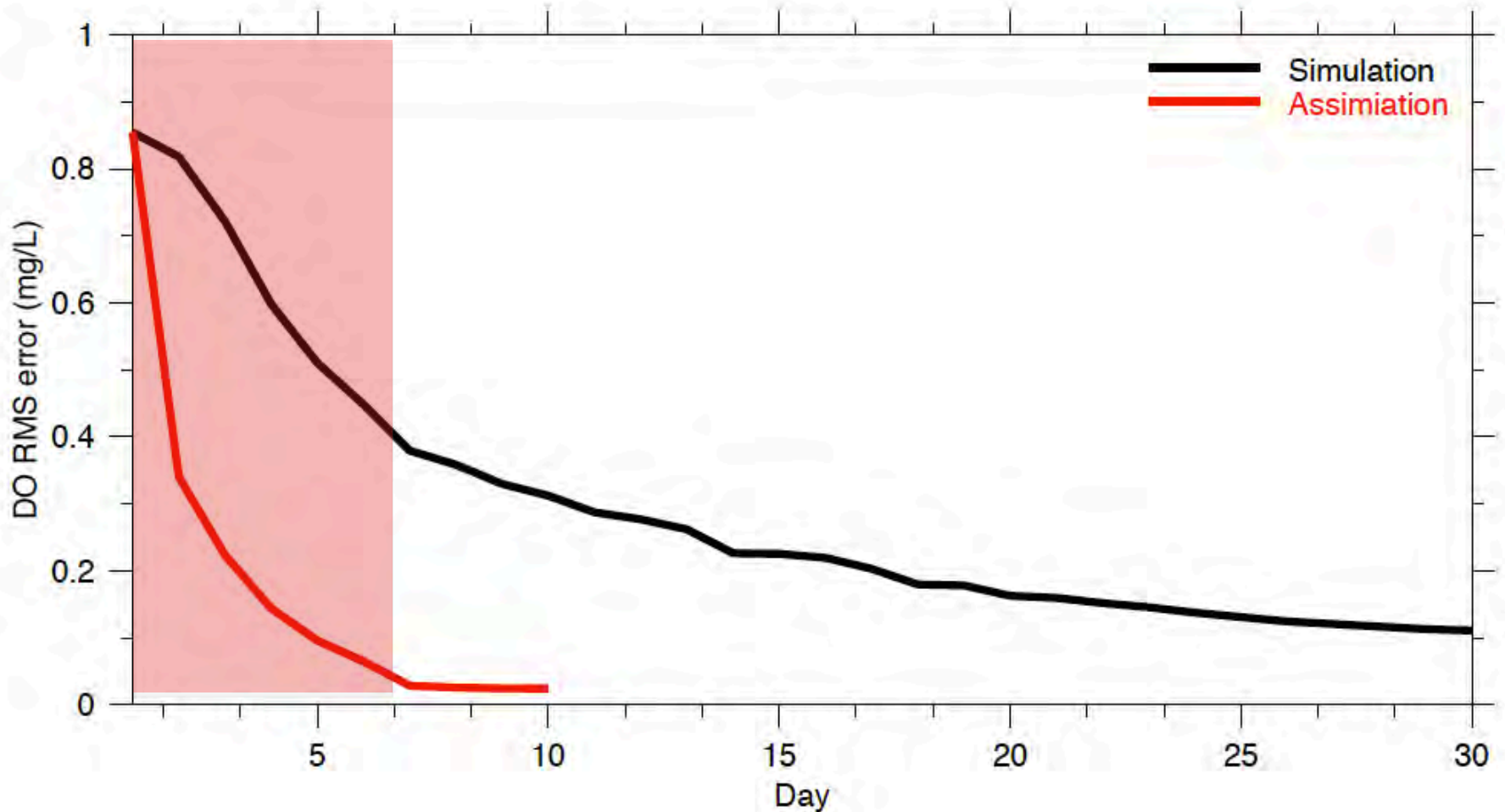


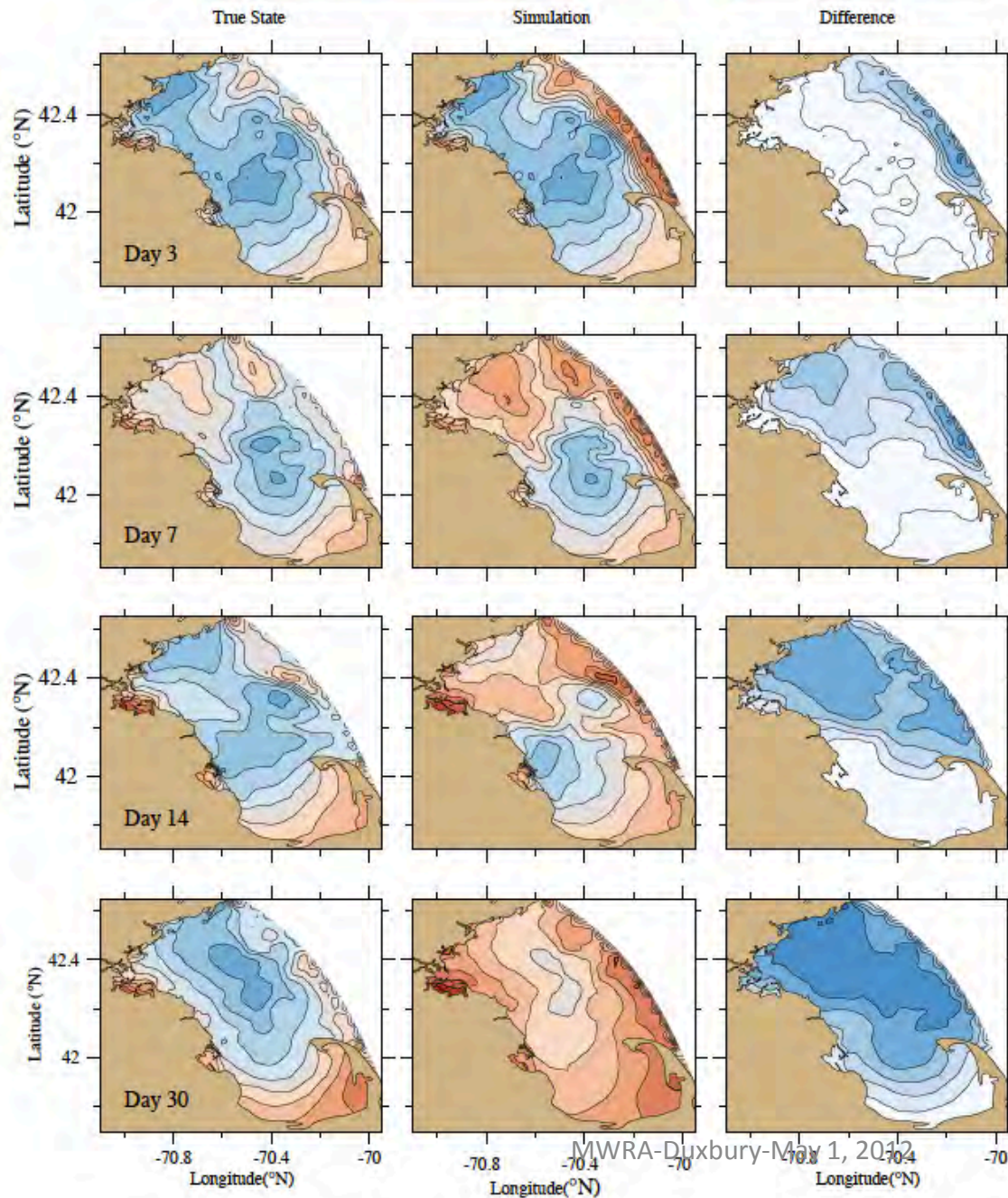
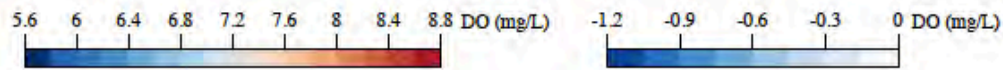
EnKF experiments

Monitoring site

- Placing a monitoring site for DO near the northern boundary and using EnKF to assimilate the measurement value into the model, the error can decrease rapidly and the DO field can restore back to the true state over a time scale of a week.

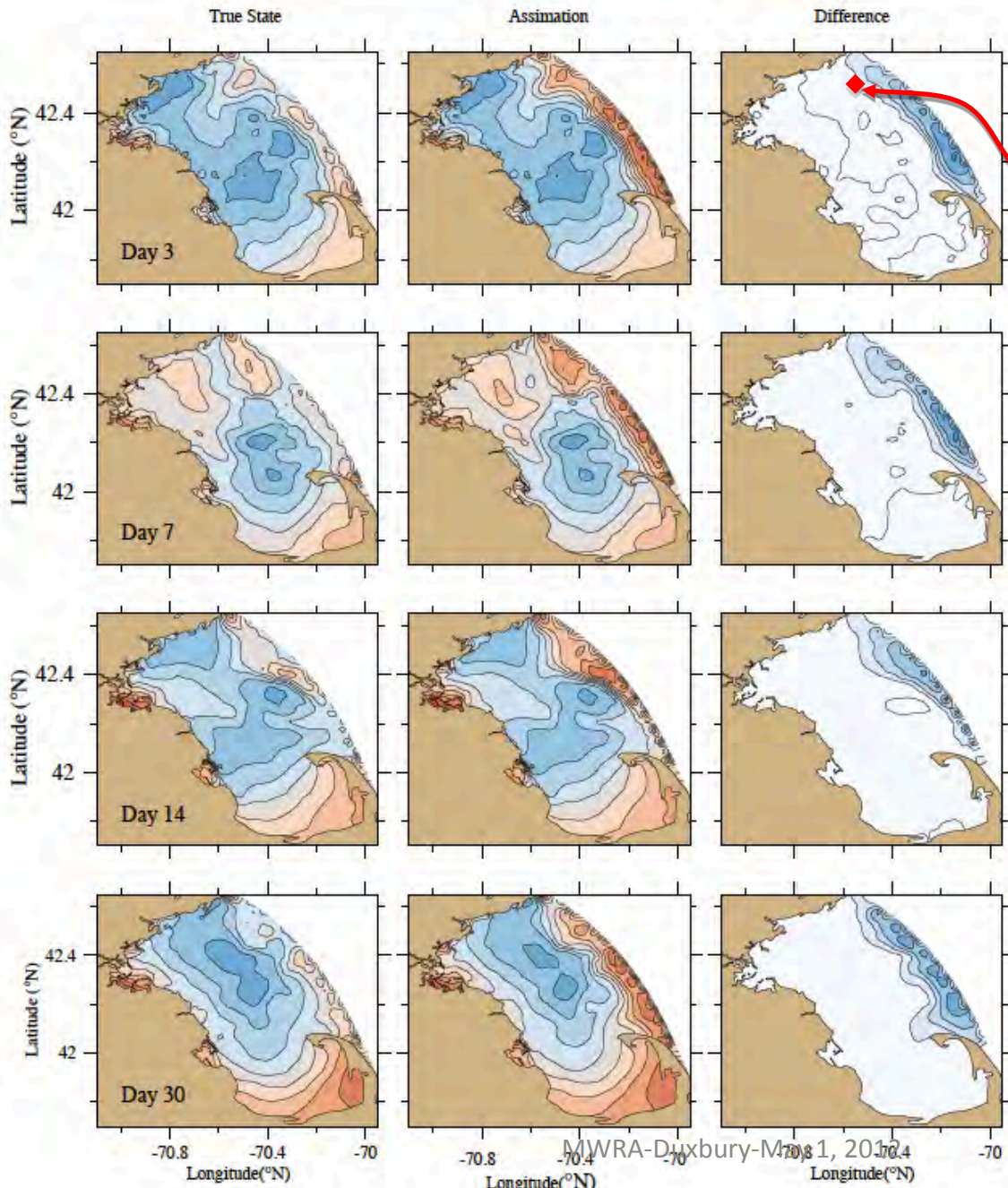
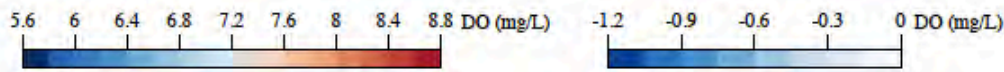
Change of the errors in the cases without (black) and with (red) assimilation





Boundary perturbation experiments:

- The boundary errors propagate into Mass Bay from the northern boundary and then spread over the entire bay over a time scale of ~one month. Without assimilation, the DO field fails to restore back to the true state.

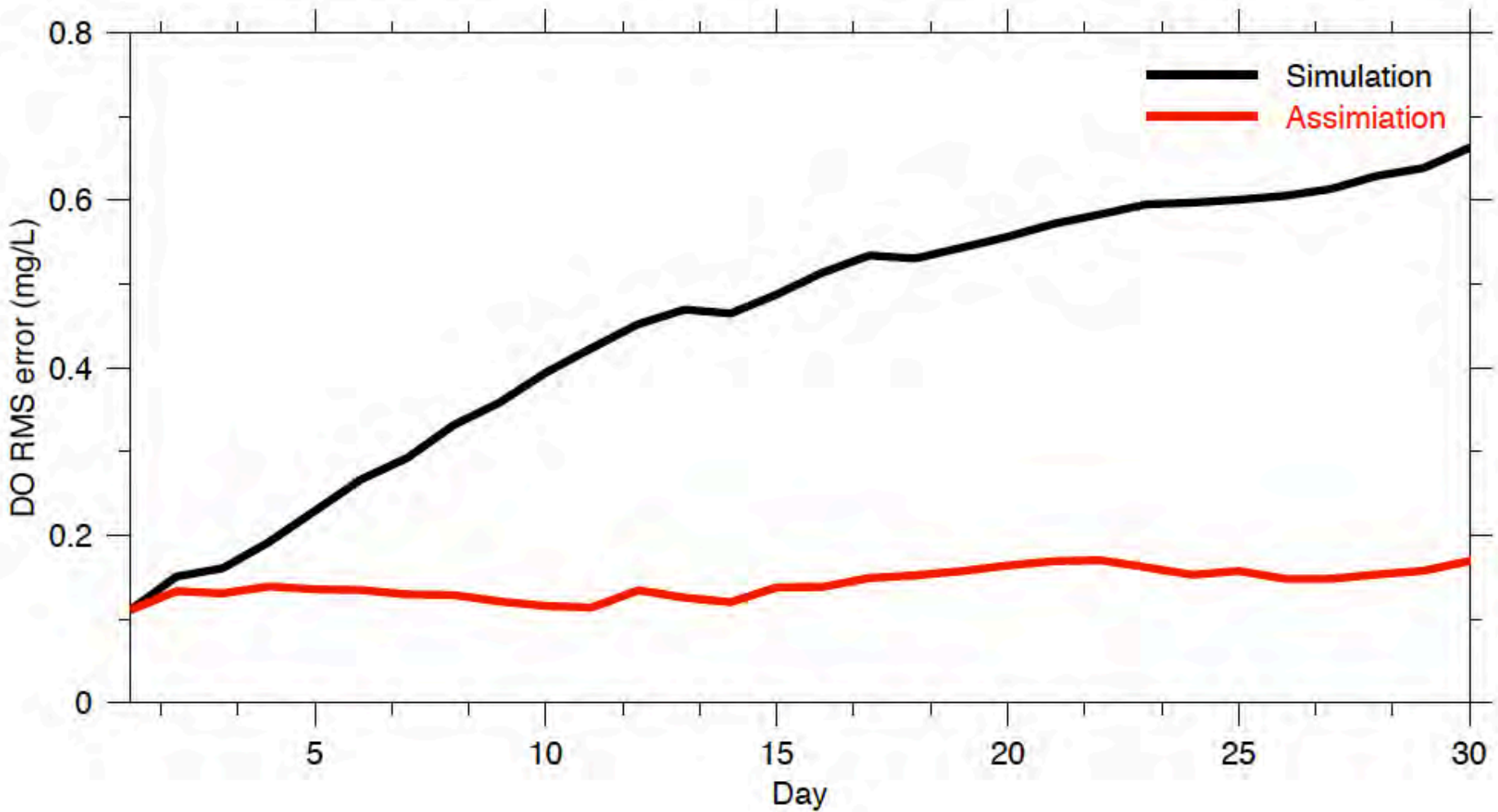


EnKF experiments

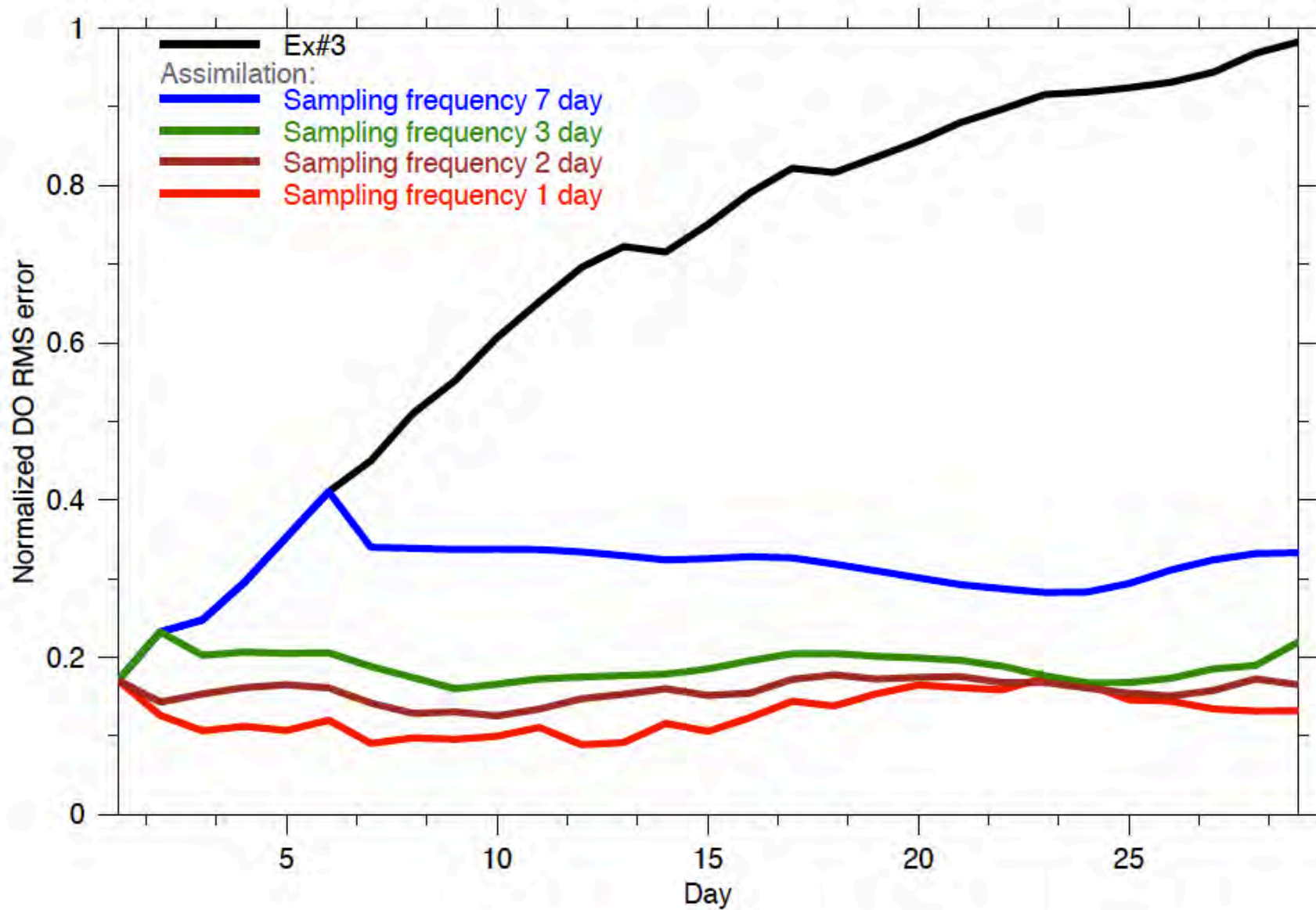
Monitoring site

- Placing a monitoring site for DO near the northern boundary and using EnKF to assimilate the measurement value into the model, the error can be controlled, with no propagating into the interior. In this case, the DO field in the interior can restore back to the true state rapidly.

Change of the errors in the cases without (black) and with (red) assimilation



Remaining errors shown in the assimilation case is almost in the boundary zone.



Conclusions

- The 2011 water quality condition (DO) remains similar to previous years.
- The model results suggest that there was no a significant spring phytoplankton bloom in 2011.
- Having a sampling station near the northern boundary could significantly improve the accuracy and reliability of DO simulation in Mass Bay.

Recommendations

An effort should be made to re-examine the parameterization for the DO simulation at the surface, since UG-RCA seems to underestimate the near-surface DO concentration.



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