Water Column Monitoring of Cape Cod Bay and Stellwagen Bank National Marine Sanctuary 2014-2016

Massachusetts Water Resources Authority

Environmental Quality Department

Report 2017-07

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Water Column Monitoring Results for Cape Cod Bay and Stellwagen Bank National Marine Sanctuary 2014-2016

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Executive Summary

This report documents phytoplankton and zooplankton communities, nutrient and plant pigment chemistry, and right whale observation data in Cape Cod Bay (CCB) during 2014 through 2016. The data presented in the report were collected by the Center for Coastal Studies (CCS), to document conditions in the Bay, and to better understand the linkages between nutrient and plankton conditions in the Bay, and whale usage of the Bay. Data presented include data from the three locations in Cape Cod Bay and Stellwagen National Marine Sanctuary that MWRA is required to monitor, as well as water quality data collected by CCS year round at eight additional stations in CCB, and by CCS's right whale aerial and right whale habitat surveys in CCB conducted from January – May.

The physical environment, water chemistry, plankton communities and whale sightings varied widely between the three years covered by this study. During the course of the three years, the second coldest February on record occurred in the Northeast (2015), and the second warmest winter on record was also experienced (2016). These extremes were reflected in the water temperatures with some of the coldest winter water temperatures recorded in 2015 and some of the warmest recorded in 2016. The strength of stratification also varied among the three years, and this variability influenced both near bottom dissolved oxygen concentrations and near bottom nitrogen concentrations. During all three years, with the exception of 2014 when bottom-water dissolved inorganic nitrogen (DIN) was slightly higher than the long-term average, dissolved inorganic nutrients (nitrogen, phosphorus, and silica) were lower than the long-term averages at both near surface and bottom depths. Redfield ratios indicate the Bay is nitrogen (N) relative to phosphorus (P limited, and that diatom production is likely limited by availability of silicate.

Annual average phytoplankton biomass (measured as chlorophyll *a*), both at near surface and bottom depths, increased between 2014 and 2016. Phytoplankton cell counts, again averaged annually, decreased. During none of the three years did the Bay show large winter/spring diatom blooms. Diatoms were however present during the February and March surveys, with the predominant species different year to year: *Skeletonema costatum* and *Chaetoceros* sp. in 2014, *Thalassiosira* sp. and *Detonula* sp. in 2015, and *Guinardia delicatula* in 2016. Overall the February/March phytoplankton biomass during both 2015 and 2016 were much greater than in 2014.

Zooplankton abundance during this three-year period has been higher than observed during the last six years with 2016 having the highest annual average. These higher abundances are due primarily to non-copepod species (e.g., cladocerans and pteropods). Copepods are of particular interest in Cape Cod Bay because they provide a winter food resource for right whales. Over the last three years zooplankton abundance in oblique samples taken around feeding right whales has been slightly higher than the long-term average of approximately 8,000 organisms/m^3. These samples were typically dominated by calanoid copepods including *Centropages* spp., *Pseudocalanus* spp. and *Calanus finmarchicus*.

The number and spatial distribution of right whales in Cape Cod Bay varied greatly during this three-year period. The number of individual right whales observed in Cape Cod Bay in 2014 was the second highest since these surveys started in 1998, and in 2015, the lowest since 2006. The whales deviated from their standard use of the eastern side of Cape Cod Bay, seen during 2014, shifting west in 2015 and becoming evenly distributed during 2016. Zooplankton abundance can explain some but not all of this variability.

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1. INTRODUCTION

As part of the environmental monitoring program implemented by MWRA in Massachusetts and Cape Cod Bays in support of MWRA's outfall in Massachusetts Bay, the Center for Coastal Studies has continued the ambient water column monitoring required at three locations by adding these three stations to CCS's ongoing Cape Cod Bay monitoring program. Two of the stations are located in Cape Cod Bay (CCB) and one in Stellwagen Bank National Marine Sanctuary (SBNMS).

CCB and SBNMS are both ecologically diverse and highly productive areas. They encompass essential habitats for commercially valuable species of finfish and shellfish as well as many species of endangered birds and mammals. Both these areas serve as feeding grounds for the critically endangered North Atlantic right whale. Several other species of whales including humpback, fin, and minke migrate to these waters each year to feed.

The environmental monitoring work conducted by CCS in collaboration with MWRA provides the data necessary to track the health of these waters. Water quality data, such as those collected as part of this project, are needed to safeguard these areas, and for tracking changes in them that may affect the whales and fisheries of the systems.

This report summarizes the finding of the monitoring work conducted by CCS from 2014-2016. The results of the monitoring of the three MWRA stations are presented in the context of some of the other work CCS does in this region, including the concurrent, year round water quality monitoring surveys at eight additional stations in CCB and the right whale aerial and right whale habitat surveys in Cape Cod Bay conducted from January – May.

2. METHODS

Over the past three years, CCS has monitored MWRA's three stations in CCB and SBNMS (Figure 1, Table 1) as part of their on-going program to monitor for possible outfall impacts on areas downstream of the outfall. The three sites have been sampled nine times per year (Table 2). Water quality monitoring at these stations included measurements of surface photosynthetically active radiation (PAR); water column measurements of temperature, salinity, dissolved oxygen, fluorescence, PAR; near surface and near bottom nutrient concentrations (dissolved and total nitrogen and phosphorous, silicate); near surface and near bottom phytoplankton biomass (chlorophyll *a* and phaeophytin), and phytoplankton and zooplankton (identification and enumeration).

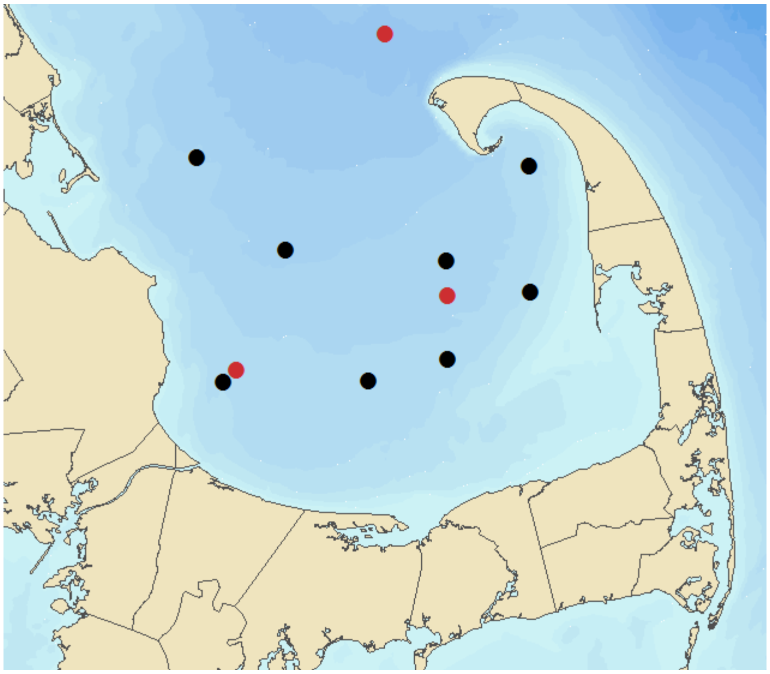

Figure 1. Sampling locations in CCB and SBNMS. CCS stations are in black; MWRA stations are in red

Table 1. Locations of MWRA and CCS stations

Station	Latitude	Longitude
	MWRA	
F01	41.8508	-70.4533
F02	41.9082	-70.2283
F03	42.1167	-70.2900
	CCS	
5N	42.0093	-70.1387
6M	41.9352	-70.2287
5S	41.9100	-70.1398
6S	41.8572	-70.2283
7S	41.8408	-70.3135
9S	41.8415	-70.4677
9N	42.0202	-70.4937
8M	41.9457	-70.4002

Table 2. Sampling dates of surveys, 2014-2016

2014			2015			2016		
Survey	Targeted	Actual	Survey	Targeted	Actual	Survey	Targeted	Actual
WN141	2/4/14	2/4/14	WN151	2/3/15	2/8/15	WN161	2/9/16	2/10/16
WN142	3/18/14	3/18/14	WN152	3/17/15	3/20/15	WN162	3/22/16	3/23/16
WN143	4/8/14	4/7/14	WN153	4/7/15	4/12/15	WN163	4/12/16	4/18/16
WN144	5/13/14	5/9/14	WN154	5/12/15	5/9/15	WN164	5/17/16	5/19/16
WN145	6/17/14	6/14/14	WN155	6/16/15	6/24/15	WN165	6/21/16	6/22/16
WN146	7/22/14	7/22/14	WN156	7/21/15	7/21/15	WN166	7/26/16	7/26/16
WN147	8/19/14	8/19/14	WN157	8/18/15	8/18/15	WN167	8/23/16	8/23/16
WN148	9/2/14	9/2/14	WN158	9/1/15	9/10/15	WN168	9/6/16	9/26/16
WN149	10/21/14	10/30/14	WN159	10/20/15	10/21/15	WN169	10/25/16	11/1/16

A complete description of methods is provided in the PCCS/MWRA CWQAPP (Costa *et al*. 2014). During each survey, hydrographic data were collected from all three stations, and samples were collected for analysis for dissolved inorganic nutrients (nitrate/nitrite, ortho-phosphate, ammonia), total nitrogen, total phosphorous, and chlorophyll from near surface (1-2 m from surface) and near bottom (3-5 m from bottom). Near surface water was also collected for phytoplankton analysis, and a zooplankton sample was collected with an oblique net tow (Table 3). All samples were processed according to SOPs included in the PCCS/MWRA CWQAPP.

Table 3. Routine measurements conducted at the three stations

Type of measurement	Depth	Parameter
Hydro profile	From near surface (approximately 0.5-1.5 m) to near-bottom (3-5 m from bottom). Profiling at 0.5 m intervals	Surface PAR Temperature Salinity Dissolved oxygen Depth of sensor Chlorophyll fluorescence PAR
Water chemistry	Two depths: Near- surface Near- bottom	Nitrate + nitrite Ammonia Ortho-phosphate Silicate Total nitrogen Total phosphorus Extracted chlorophyll
Phytoplankton Zooplankton	Near-surface Oblique net tow	Enumeration + Identification Enumeration + Identification

3. RESULTS AND DISCUSSION

3.3 Hydrographic Data

During the three individual years (2014, 2015, and 2016) the hydrographic conditions at the three locations were distinctive. Differences in weather patterns between years were responsible in part for the differences. During 2015, the Northeast experienced its second coldest February on record, with Boston having record snowfall. The following year, 2016, was the extreme opposite with Boston experiencing its second warmest winter on record. The summer of 2016 was also unusally warm with much of the Northeast experiencing one of the warmest Augusts on record (www.ncdc.noaa.gov). Average annual surface and near bottom temperatures showed a progressive increase from 2014 to 2016 (Figure 2). During 2016 both the annual average surface and near-bottom values were the warmest of the three years.

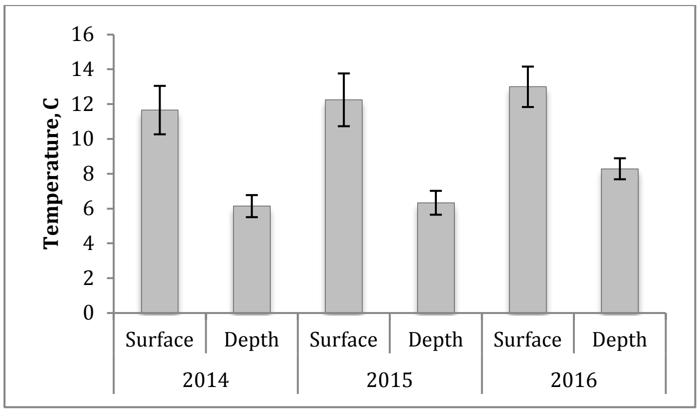

Figure 2. Average annual water temperature recorded in the surface and near bottom waters from 2014-2016

The higher water temperatures in 2016 were most notable during the winter (Feb-Mar) and spring months (Apr-May) (**Figure 3**).

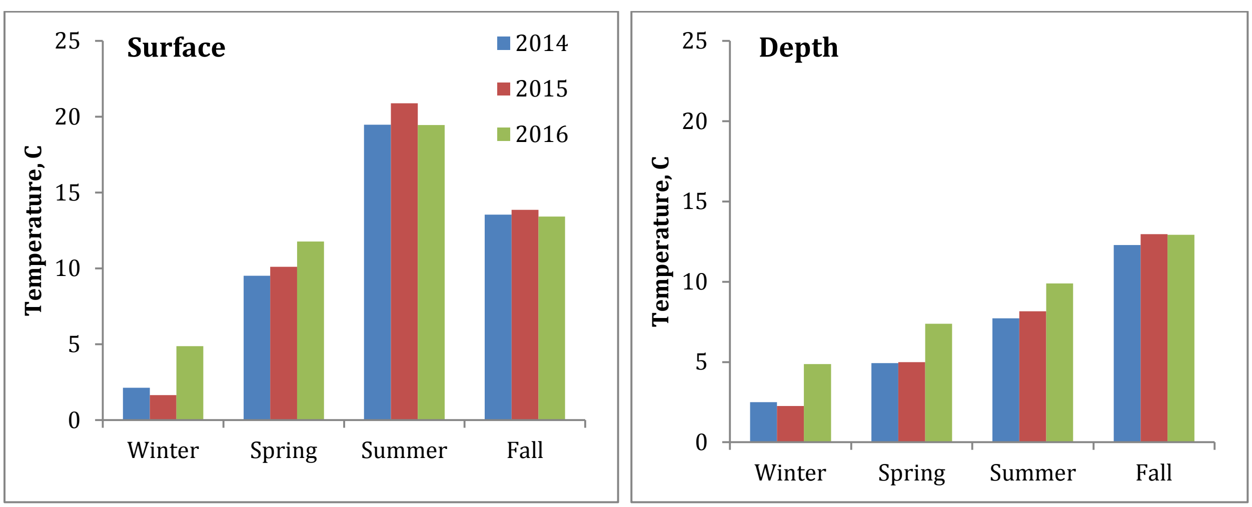

Figure 3. Average water temperatures by season recorded in the surface and near bottom waters from 2014-2016

Despite abnormally dry conditions during 2016, and because of lowered salinities at depth during the winter months during 2016, average salinity at depth during 2016 was lower than during the previous two years (Figure 4).

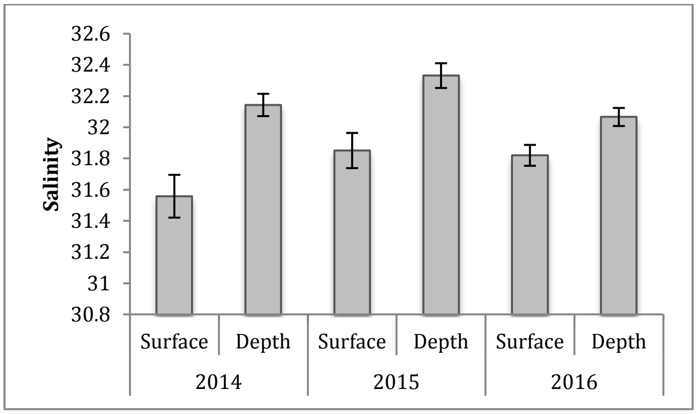

Figure 4. Average annual salinities recorded in the surface and near bottom waters from 2014-2016

During all three years stratification was greatest between days 170 to 250 (Figure 5). The water column was not as strongly stratified during summer 2016 compared to the previous two years. At all three stations the surface waters during summer 2016 were slightly more dense and the bottom waters slightly less dense than the previous two years.

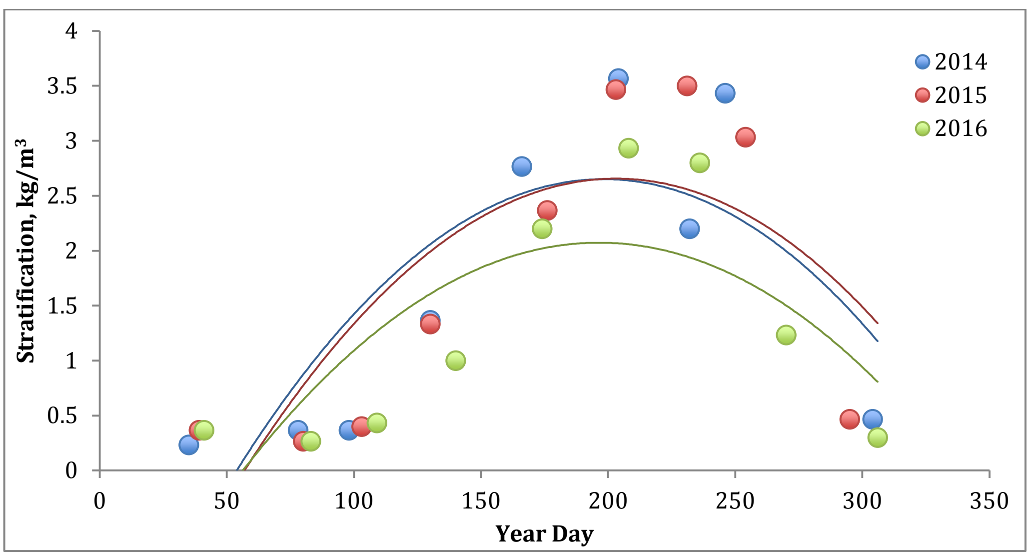

Figure 5. Average stratification strength (bottom density - surface density) for each survey from 2014-2016

During 2014 and 2015, the years stratification was strongest, dissolved oxygen levels in the near bottom waters were lower than in 2016 (Figure 6). Dissolved oxygen concentrations in the bottom waters of the Bay have been shown to be determined by the strength and duration of stratification (Jiang *et al.* 2007).

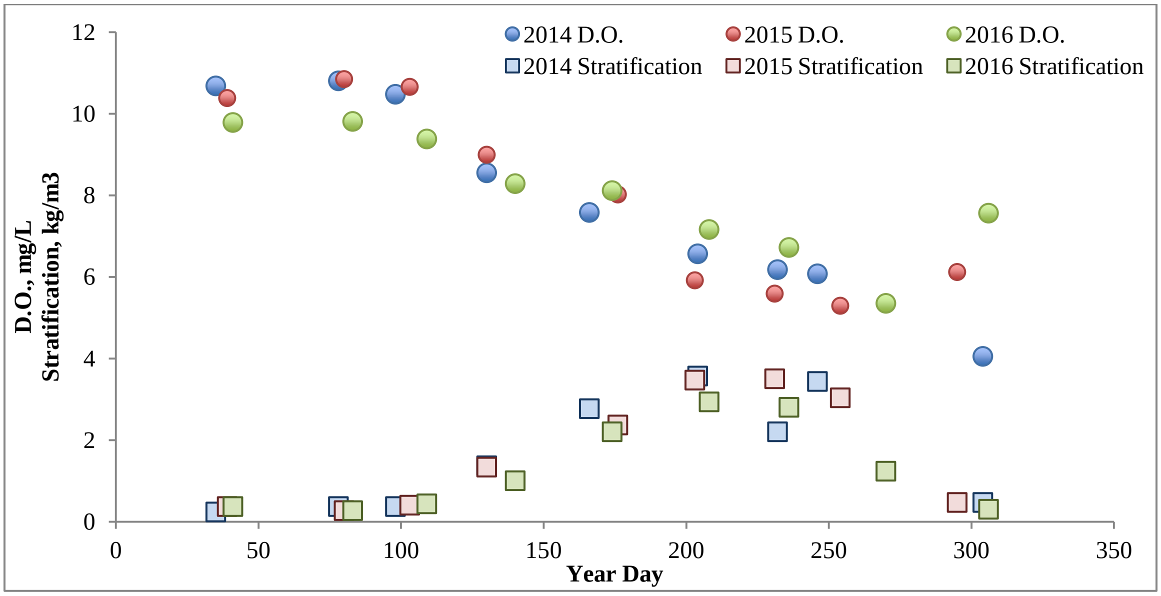

Figure 6. Comparison of stratification strength and near bottom dissolved oxygen levels, 2014-2016, averaged for the three stations

3.3 Water Chemistry

3.3.1 Nutrient Concentrations

Annual averaged dissolved inorganic nitrogen (DIN) at the three stations combined, declined between 2014 and 2016 (Figure 7). The declines were most pronounced at depth where concentrations during all three years were higher than at the surface.

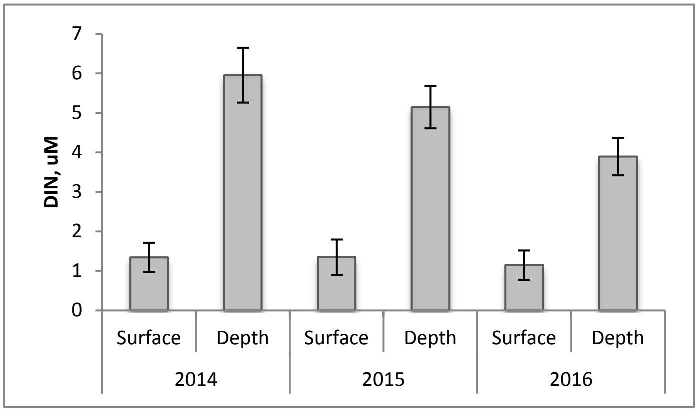

Figure 7. Average annual dissolved inorganic nitrogen (DIN) concentrations measured in the surface and near bottom waters from 2014-2016.

It is not clear why the DIN concentrations especially at depth in 2016 were lower than in the other two years, but one contributing factor might have been the weaker stratification during this year. Nutrient concentrations, especially at depth, in Cape Cod Bay are influenced by a number of factors including stratification strength and duration, the strength of the Gulf of Maine coastal current, and residence time of the Bay (Jiang *et al*. 2007, Gardner *et al*. 1996). Comparison of the interannual and seasonal variation of the Gulf of Maine coastal current would add valuable insight to these observed patterns, but is beyond the scope of this report.

During 2014-2016, neither ortho-phosphate nor silicate concentrations showed the decreasing pattern observed with dissolved inorganic nitrogen (Figure 8).

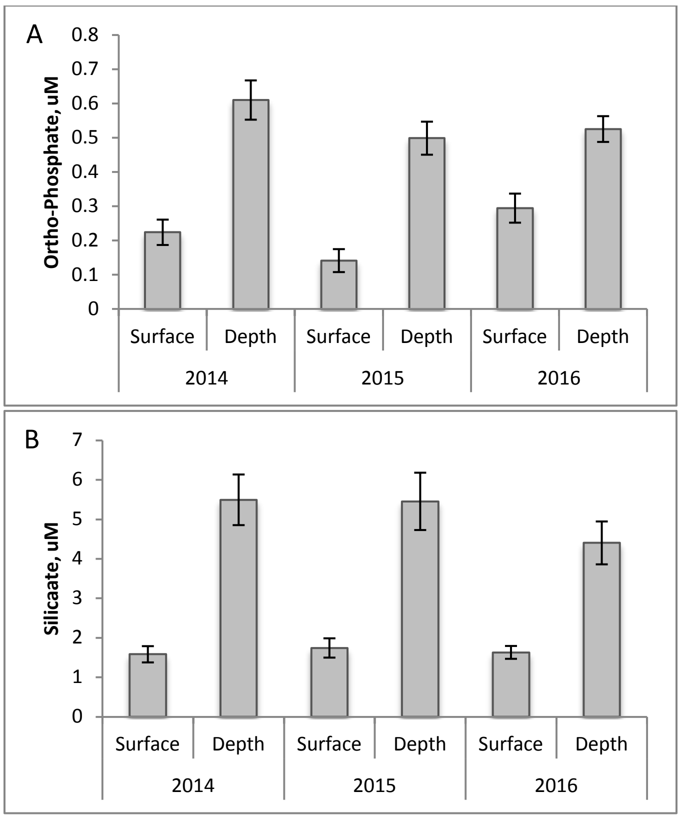

Figure 8. (A) Ortho-phosphate and (B) silicate concentrations measured in surface and near bottom waters from 2014-2016

The MWRA has been monitoring these three stations since the 1994 (F01 and F02 since 1992). The long-term average DIN concentrations over this period were 2.19 μM and 5.61 μM for surface and bottom respectively. The 2014-2016 surface averages fell well below the average of 2.19 μM for the full period, continuing a declining trend observed since 2010 (Figure 9). The near bottom DIN concentrations were slightly above the longterm average (5.61 μM) in 2014. In 2015 and 2016, DIN concentrations were below average, with 2016 having the lowest recorded value since 1994.

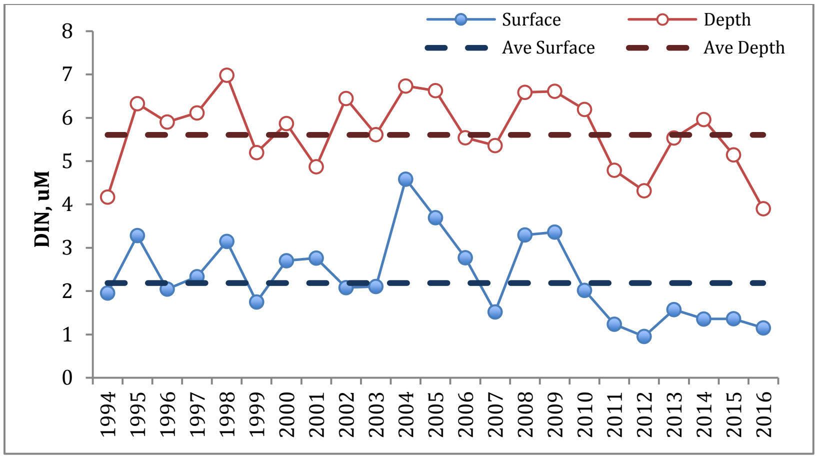

Figure 9. Average annual DIN concentrations in surface and near bottom waters at F01, F02 and F29 from 1994-2016. Long-term averages are indicated with the dashed line.

The 2014-2016 surface and bottom ortho-phosphate concentrations values fell below their long-term averages of 0.385 µM and 0.709 µM for the 1994 -2016 period. (Figure 10). Similarly, for silicate concentrations, the 2014-2016 surface and bottom values fell below the long-term averages of 2.77 µM and 6.59 µM for surface and bottom respectively (Figure 11).

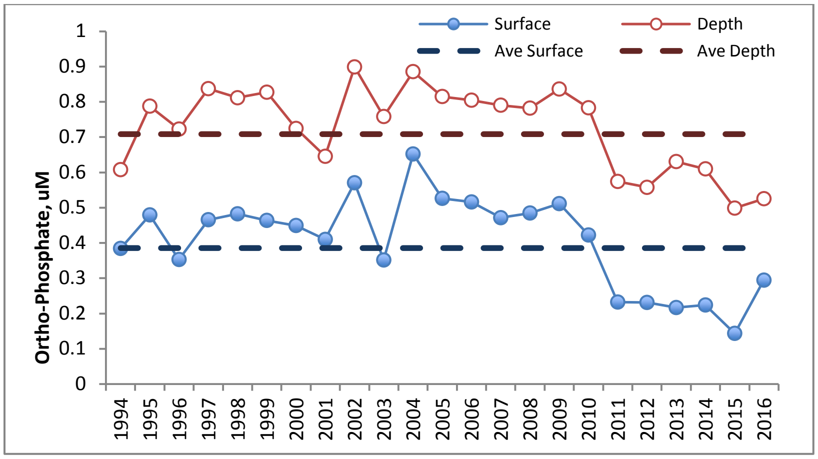

Figure 10. Average annual ortho-phosphate concentrations in surface and near bottom waters at the three MWRA stations from 1994-2016. Long-term averages are indicated with the dashed line.

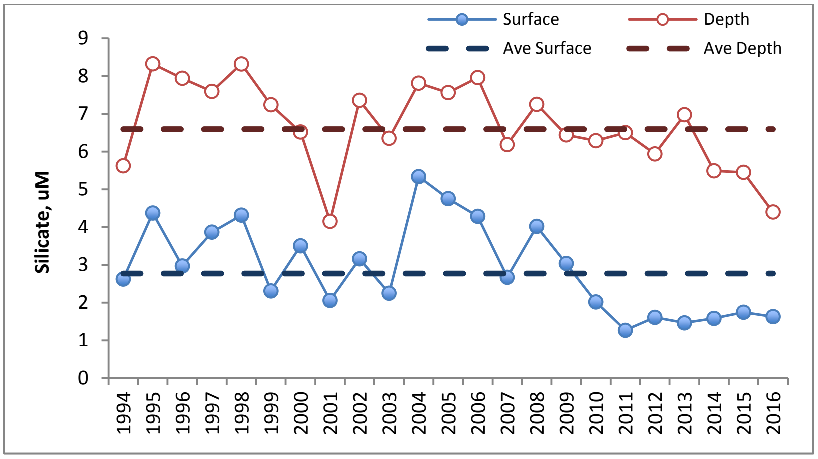

Figure 11. Average annual silicate concentrations in surface and near bottom waters at the three MWRA stations from 1994-2016. Long-term averages are indicated with the dashed line.

3.3.2 Nutrient Concentration Ratios

The ratio of dissolved inorganic nitrogen to phosphorus to silicate (DIN:DIP:DISi) provides information about which nutrient is limiting production. This ratio, known as the Redfield ratio, is 16:1:1.07. For 2014-2016, the average DIN:DIP was less than 16:1 in both the surface and near bottom waters, indicating that the Bay is N relative to P limited and therefore especially sensitive to increased N inputs (Figure 12).

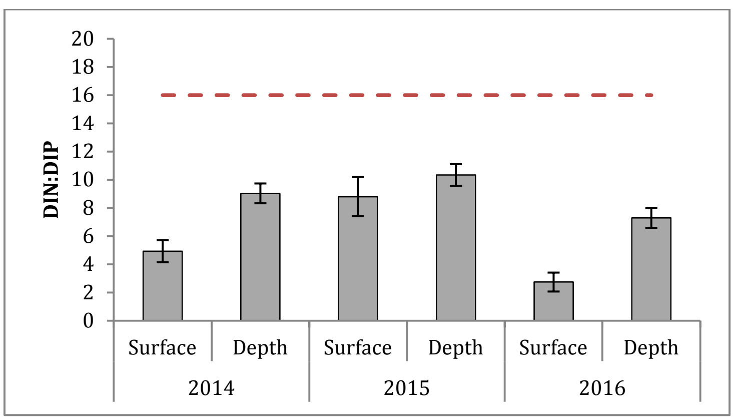

Figure 12. Average ratio of DIN to DIP for surface and near bottom waters from 2014-2016. The dashed red line indicates the Redfield Ratio.

Since monitoring of these three stations began in 1994 the average annual ratio of DIN to DIP has always been below the Redfield Ratio of 16:1 for both surface and bottom waters (Figure 13).

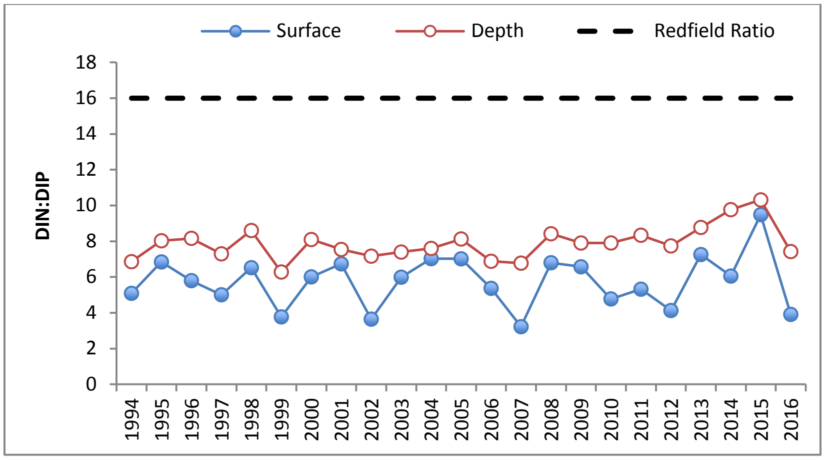

Figure 13. Average annual ratio of DIN:DIP at the three MWRA stations since 1994. The dashed line indicates the Redfield Ratio.

The ratio of DIN:DISi is particularly important for diatoms since they require silicate to form their external shell. If this ratio falls below 1.07, diatom productivity is limited. For 2014-2016, the average ratio of DIN:DISi was limiting to diatom production in the surface waters during all years and at depth during all years except 2014 (Figure 14).

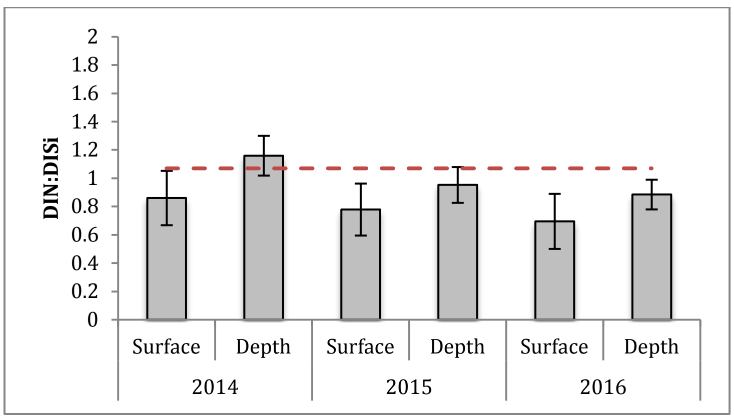

Figure 14. Average ratio of DIN to DISi for surface and near bottom waters from 2014-2016. The dashed red line indicates the Redfield Ratio.

The longer time series of average annual DIN to DISi ratios shows that with only three exceptions in the surface waters (2001, 2009, and 2013) and two exceptions at depth (2001 and 2014), silicate was limiting.

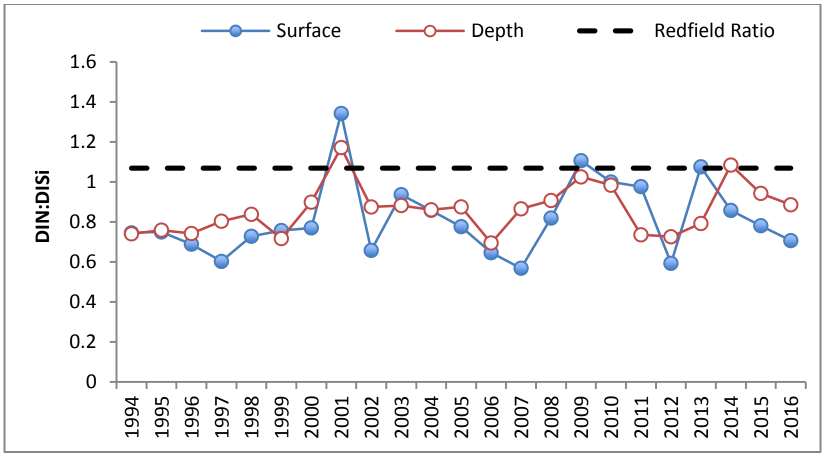

Figure 15. Average annual ratio of DIN:DISi at the three MWRA stations since 1994. The dashed line indicates the Redfield Ratio.

3.3.3 Phytoplankton Biomass (Chlorophyll a)

Chlorophyll *a* (chl-*a*) concentrations averaged for the three locations, increased between 2014 and 2016 (Figure 16). Both at surface and near-bottom depths, 2016 chl-*a* concentrations were the highest of the three years.

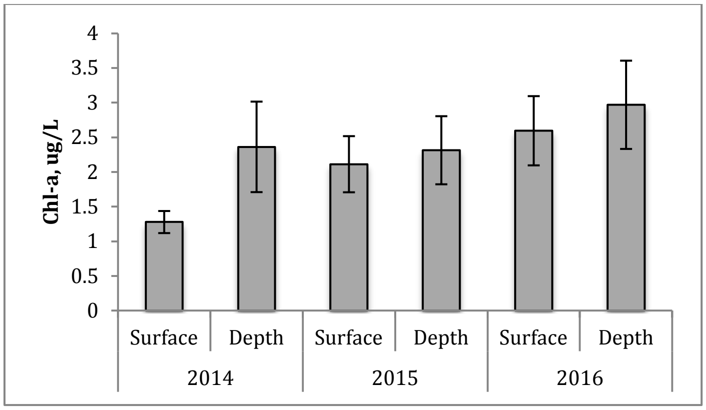

Figure 16. Average annual concentrations of chlorophyll a measured in the surface and near bottom waters from 2014-2016

Figure 17 shows average surface chl-*a* concentrations for the three stations combined during each survey. As can be seen from this plot, an increase in the size or duration of the winter-spring bloom may have been one of the changes that contributed to the chl-*a* increase between 2014 and 2016.

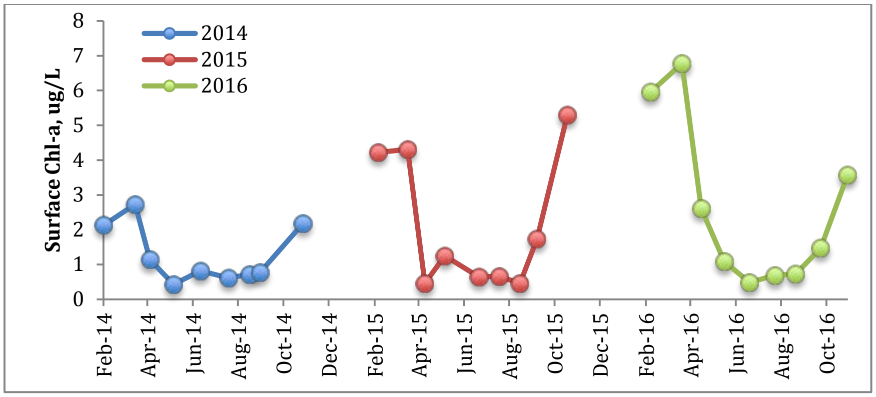

Figure 17. Average surface chl-a concentrations measured during each survey from 2014-2016

Figure 18 shows the combined chl-*a* data for the three MWRA locations, and the CCS's eight additional monitoring stations. Concentrations at most locations are greater during winters than summers, but the concentrations during winters differ between years (compare winter 2014 with that of 2014/15 and 2016). There are also different patterns among locations, suggesting that the seasonal patterns in different parts of the Bay might differ. This confirms the observations of Gardner *et al*. (1996) that there is extreme variability throughout Cape Cod Bay over relatively short distances, especially with respect to phytoplankton biomass.

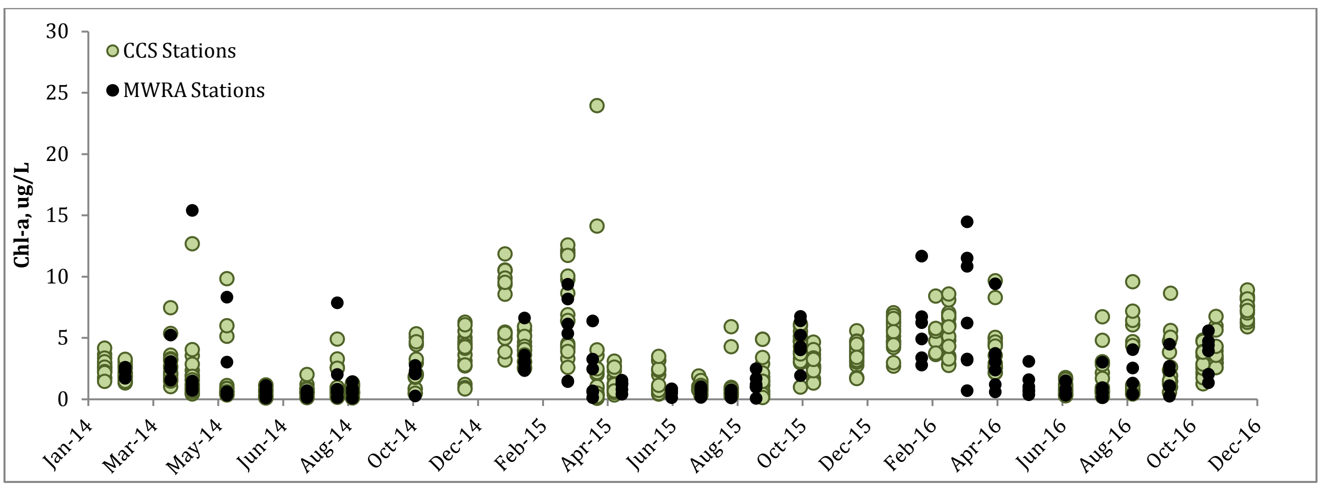

Figure 18. Concentrations of chl-*a* measured at MWRA and CCS stations in Cape Cod Bay, 2014-2016

3.3 Phytoplankton and Zooplankton

3.3.1 Phytoplankton

For the two CCB stations and one SBNMS station combined, phytoplankton abundances declined from 2014 through 2016 (Figure 19).

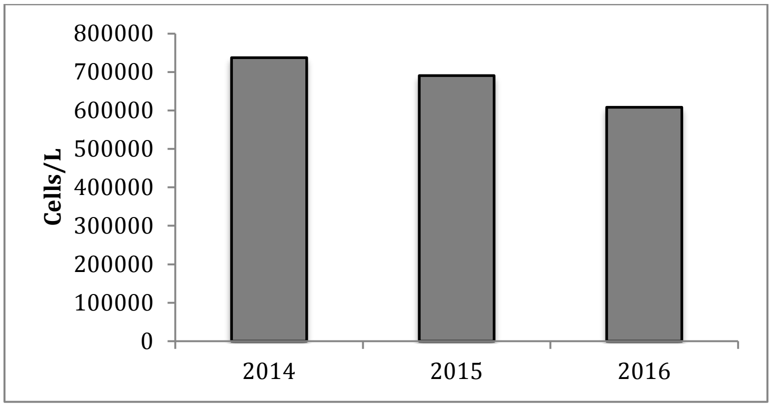

Figure 19. Average annual phytoplankton abundance, 2014-2016

A moderate *Phaeocystis* bloom in March of 2014 elevated the annual abundance during that year (Figure 20). During the subsequent years the *Phaeocystis* blooms were negligible and were observed a month later (April).

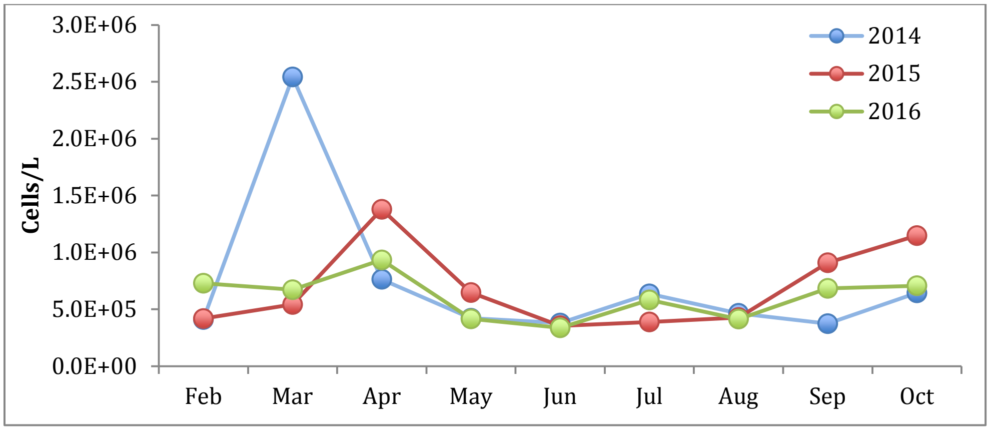

Figure 20. Average phytoplankton abundances during each survey, 2014-2016

In Cape Cod Bay, the winter/spring bloom typically occurs during February or March and is usually driven by an increase in diatoms in response to increasing light intensities and water temperatures. During this February-March period, during each of the years from 2014 to 2016, despite the lack of a pronounced winter/spring bloom, centric diatoms were prevalent (second in abundance to microflagellates). However, the diatom species that predominated during the bloom period was different each year (Table 4).

Table 4. Dominant species of centric diatoms during the winter/spring bloom period

Month	Station	Species	Number of Cells	Percent of Total Cells
		2014		
Feb	F02	*Skeletonema costatum*	218514	35
Mar	F01	*Chaetoceros* sp.	336462	32
Mar	F01	*Chaetoceros* sp.	362769	34
		2015		
Feb	F01	*Thalassiosira* sp.	55180	13
Feb	F02	*Thalassiosira* sp.	120928	22
Mar	F01	*Thalassiosira* sp.	88429	18
Mar	F02	*Detonula confervacea*	218669	23
Mar	F02	*Thalassiosira* sp.	175399	19
		2016		
Feb	F02	*Guinardia delicatula*	230057	21
Mar	F02	*Guinardia delicatula*	436578	51

3.3.2 Zooplankton

Annual average total zooplankton abundances in CCB and SBNMS have increased since 2011 and 2012, with 2016 exceeding previous years (Figure 21). A smaller mesh size was used to sample Massachusetts Bay zooplankton, but abundances of zooplankton and the dominant copepod taxa in Massachusetts Bay have also been showing an increasing trend since 2005 (Libby *et al*. 2016).

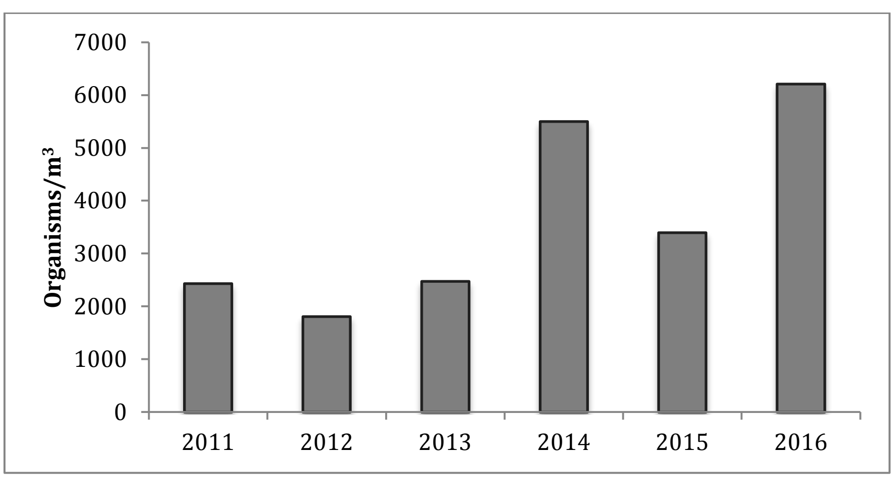

Figure 21. Average annual zooplankton abundance, 2011-2016

This high annual average abundance observed in 2016 was due to a peak in May of the pteropod, *Limacina retroversa* and in September, of the cladoceran, *Penilia avirostris* (Figure 22). Zooplankton abundance documented during the remaining seven 2016 surveys fell below that of 2014 during the winter and spring (Feb, Mar and Jun) and below both years during the summer and fall (Jul, Aug and Oct).

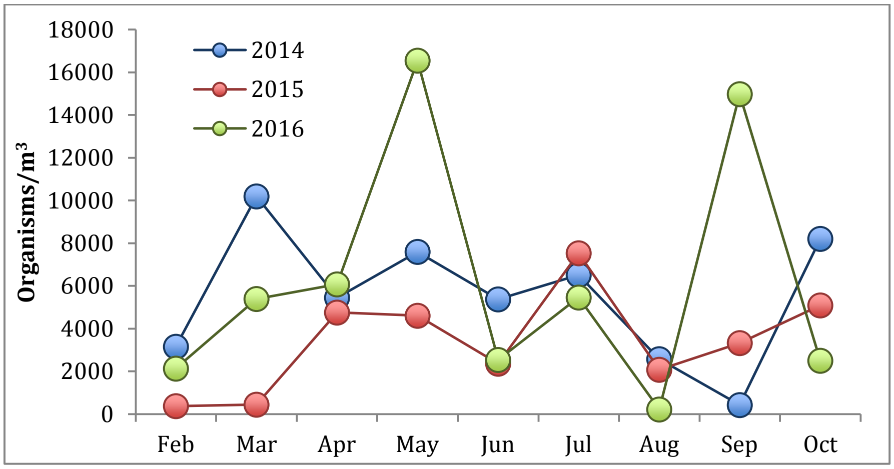

Figure 22. Average zooplankton abundance during each survey for the 2016 season

In Cape Cod Bay, the winter and spring months are of particular interest. During this time, the Bay is the only known feeding ground for the critically endangered North Atlantic right whale. CCS conducts weekly boat-based surveys to document the zooplankton resource and aerial surveys to locate, document and identify the whales. Since 2007, with the exception of two years (2008 and 2012), zooplankton abundances in oblique samples taken around feeding right whales have been close to or higher than the long-term average of approximately 8,000 organisms/m^3 (Figure 23). Samples have typically been dominated by calanoid copepods including *Centropages* spp., *Pseudocalanus* spp., and *Calanus finmarchicus*.

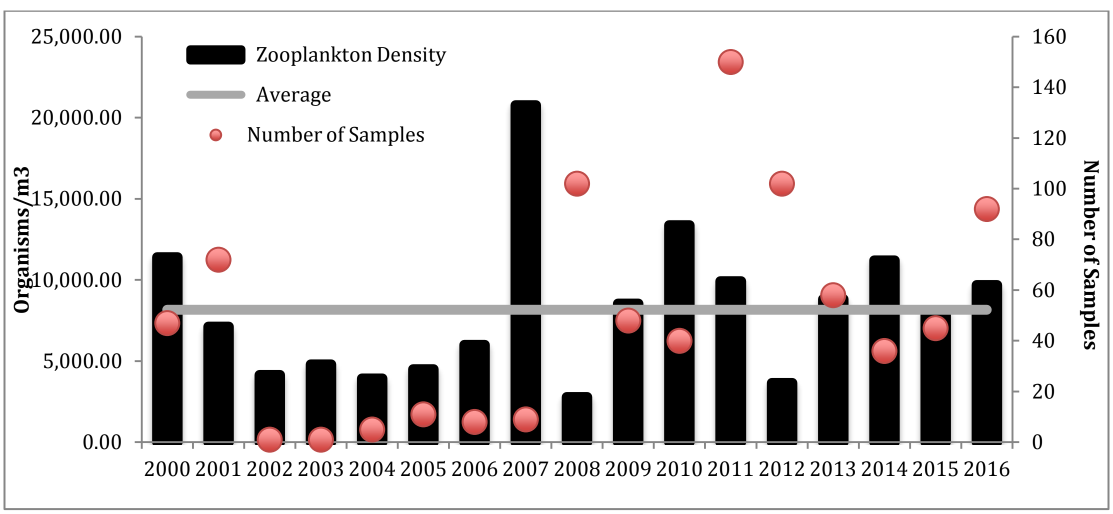

Figure 23. Average zooplankton density and number of samples taken during the season right whales occupy Cape Cod Bay (Jan-May). The gray line indicates the long-term average zooplankton density (2000-2016).

3.3.2.1 Right Whales and Zooplankton

Right whale use of the bay is also highly variable from year to year. Since 2007, there has been an increase both in individuals identified and in the sightings per unit effort (Figure 24). The 2014 season had the second highest number of individuals identified since the aerial surveys started in 1998. 2015 had the lowest number identified since 2006. During the two years zooplankton counts were especially low (2008 and 2012), the whale numbers and numbers per unit effort, were not especially low.

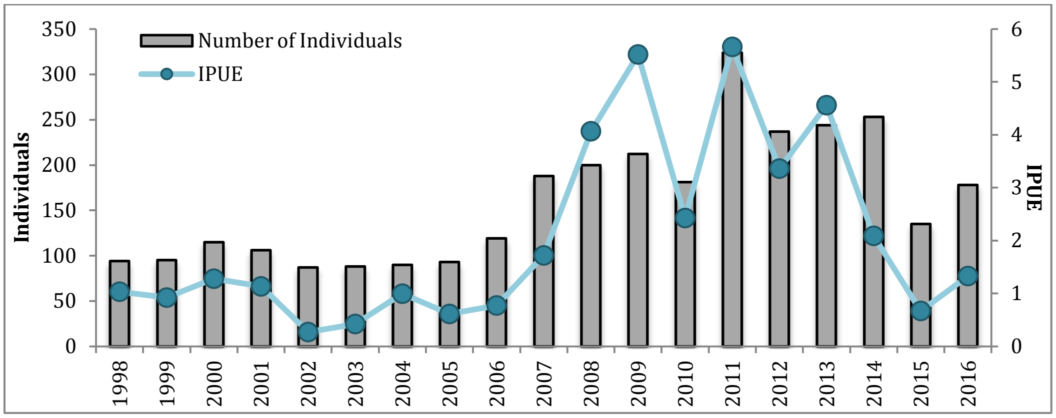

Figure 24. The number of right whales identified in Cape Cod Bay each year. The blue line indicates the number of individuals per unit effort (IPUE) sighted during the aerial surveys

The distribution of whales within Cape Cod Bay has shifted during this three-year period (Figure 25). The 2014 distribution represents the more typical pattern of sightings observed over the years with whales concentrated more to the east of the Bay. During both 2015 and 2016, when the numbers were lower than in 2014, the whale were spread more evenly across the Bay.

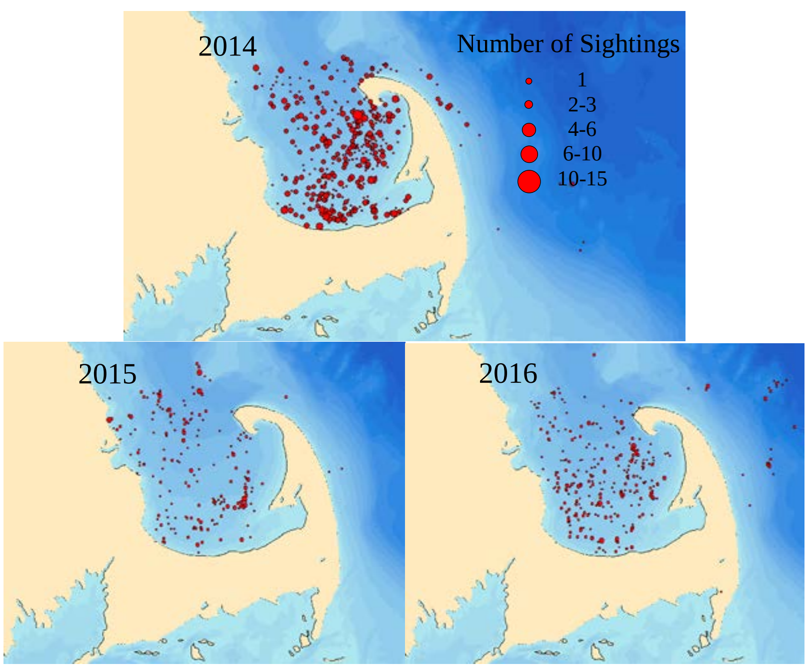

Figure 25. Distribution of right whale sightings each year, 2014-2016. CCS Image, NOAA Permit 14603 and 14603-1

Several studies have suggested relationships between whale distributions and zooplankton abundance (e.g. Baumgartner *et al*. 2003, Beardsley *et al*. 1996, Mayo & Marx 1990, Murison & Gaskin 1989, Wishner *et al.* 1988). A simple overlay of the spatial distribution of the zooplankton abundance and right whale sightings each year somewhat supports these findings. Figure 26 shows this relationship for the month of April, typically the peak month of right whale sightings in the Bay. In areas of the Bay where right whale sightings were most numerous, zooplankton densities too were elevated. While there is undoubtedly a relationship between zooplankton and right whales, there are likely additional factors of the physical environment that impact right whale distribution. That along with the logistical challenges of sampling an extremely patchy resource makes this relationship hard to define.

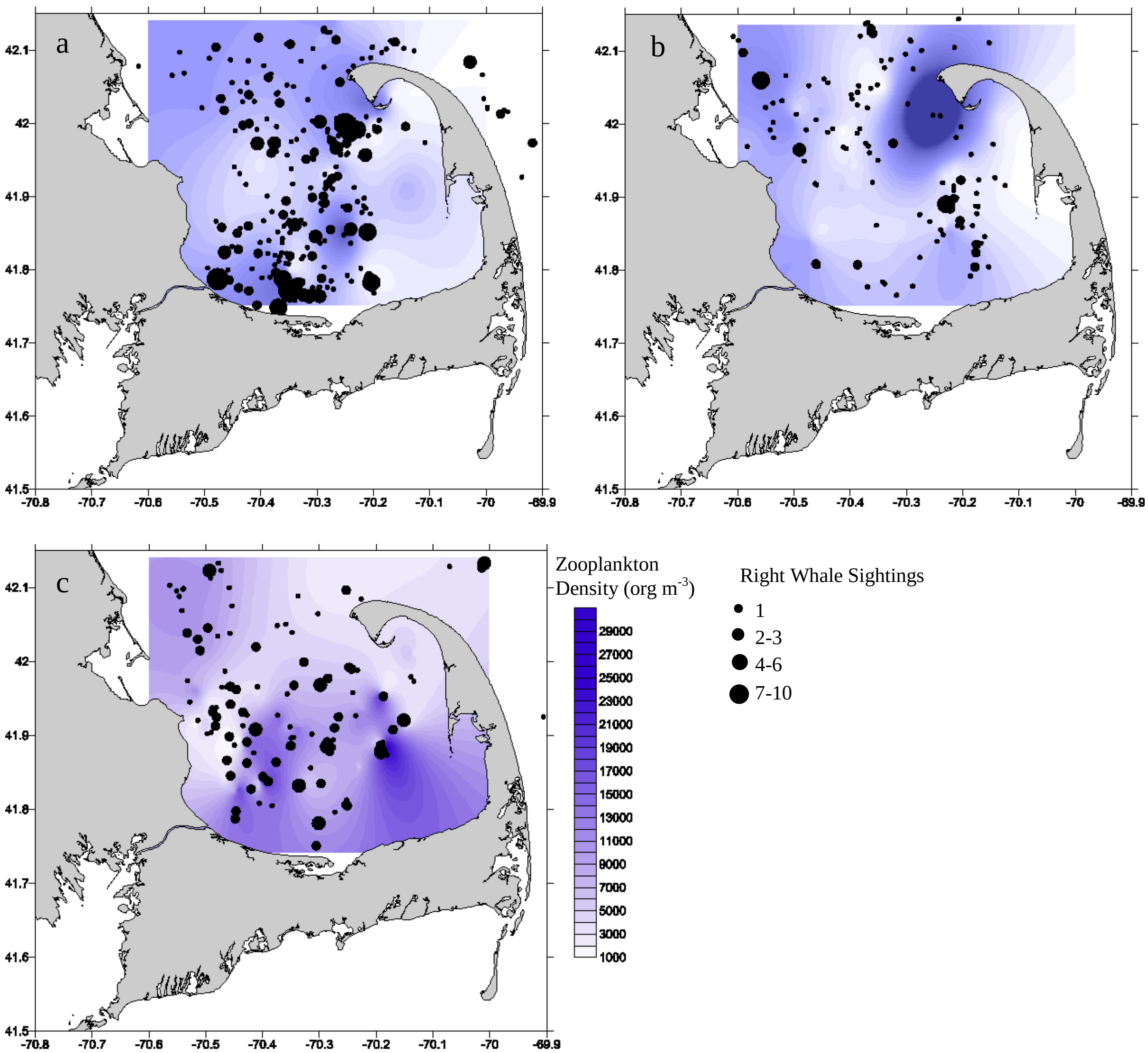

Figure 26. Distribution of right whale sightings (indicated with black dots) and zooplankton density (purple contours plots) for the month of April in a) 2014, b) 2015, and c) 2016.

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