Western Maine Coastal Current reduces primary production rates, zooplankton abundance and benthic nutrient fluxes in Massachusetts Bay

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Abstract. Primary production was measured from 1992-2010 in Massachusetts Bay and just outside Boston Harbor for the Massachusetts Water Resources Authority's outfall monitoring program. In 2003, annual primary production decreased by 221-278 g C m^{-2} $year^{-1}$, with decreased rates continuing through 2010. Based on a conceptual model, oceanographic and meteorological variables were analyzed with production rates to determine if concurrent environmental changes were responsible for the reduced primary production in Massachusetts Bay. Results indicated that stronger influx of low salinity water from the western Maine Coastal Current (WMCC) in recent years might be responsible for the decreases. The WMCC appeared to have become fresher from increased river discharge in the western Gulf of Maine. Northeasterly winds in recent years promoted WMCC intrusion into Massachusetts Bay. Correlation between primary production and surface salinities suggested the impact of the WMCC on production rates. We hypothesized that increased stratification resulted in reduced vertical mixing and nutrient concentrations in surface waters for phytoplankton growth. However, no significant correlations were observed between the annual primary production and nutrient concentrations in Massachusetts Bay. Reduced production rates in Massachusetts Bay have been associated with reduced zooplankton abundances, benthic ammonium fluxes and sediment oxygen demand in summer months.

Key words: Boston Harbor, Massachusetts Bay, Merrimack River, North Atlantic Oscillation, primary production, western Maine Coastal Current, wind stress

1. Introduction

Primary production measurements estimate carbon fixation rates by photosynthetic organisms (Behrenfeld and Falkowski, 1997) and are used to project higher trophic level production in coastal and open oceanic environments (Ryther, 1969). While chlorophyll *a* concentration is conventionally used as a proxy for phytoplankton biomass, it is a poor gauge of phytoplankton production (Keller *et al.*, 2001). However, the two measurements are often correlated and together provide insight into nutrient cycling by and standing stock of phytoplankton (Brush *et al.*, 2002). Phytoplankton are the base of many marine food webs and are the dominant food source for zooplankton (Durbin *et al.*, 2003; Oviatt *et al.*, 2007; Turner *et al.*, 2011) as well as benthic infauna through benthic-pelagic coupling (Oviatt *et al.*, 2002; Rudnick and Oviatt, 1986). Deposition of organic matter facilitates benthic microbial activity and the remineralization of dissolved inorganic nutrients in sediments, later to be released into overlying waters to support future primary production (Nixon, 1981).

Given the ecological significance of primary production, production rates were measured as part of the Massachusetts Water Resources Authority (MWRA) outfall monitoring program. Since 1992, long-term monitoring has been conducted to assess the impact of relocating the Boston Harbor sewage outfall approximately 15 km offshore in western Massachusetts Bay (Figure 1; Taylor *et al.*, 2011). Prior to the relocation in 2000, annual production ranged from 214-668 g C m^{-2} $year^{-1}$ in Massachusetts Bay (Figure 2). Primary production rates at the mouth of Boston

Harbor (Site F23) decreased markedly from 2002 to 2003 (~ 241 g C m^{-2} $year^{-1}$) with low production rates persisting through 2010 (Figure 2). The production decrease at F23 was anticipated and attributed in large part to the reduced nutrient loadings from the Harbor outfall removal (Libby *et al*., 2011; Oviatt *et al*., 2007). Contrary to predicted patterns, similar reductions were also documented at Massachusetts Bay sites N04 and N18 (221 and 278 g C m^{-2} $year^{-1}$ decreases, respectively) near the new sewage outfall diffuser (Figure 2). Oviatt *et al*. (2007) found no significant changes in production as a result of the outfall relocation, as reductions in the Nearfield region appear to be unrelated to the effluent from the new outfall (Libby *et al.*, 2011). Yet the decreases in production before and after the 2002-2003 drop in annual production are significant across all sites (Figure 2). Therefore, greater investigation of the oceanic environment was required to determine potential changes dictating the reduced primary production patterns.

A myriad of factors impact primary production rates, including sunlight irradiance, mixed-layer depth and stratification (Gran *et al*., 1931; Sverdrup, 1953), temperature and grazing pressure (Keller *et al.*, 1999; Keller *et al.*, 2001). Typically in temperate latitudes, primary production increases in the winter-spring months with increased irradiance, high nutrient concentrations in surface waters from strong vertical mixing during the winter, and water column stratification to suspend phytoplankton in the euphotic zone. As temperatures increase, stratification strengthens and inhibits vertical mixing of nutrients. Phytoplankton stock then decreases due to nutrient depletion as well as increased grazing pressure. Summer blooms may occur in temperate latitudes, but are highly variable and dependent upon nutrients becoming available either from large mixing events (i.e. persistent and favorable winds) or high runoff. In the fall, production biomass increases again with increased vertical mixing introducing nutrients; however, primary production decreases in early winter with decreased irradiance until the following year's winter-spring bloom (Hunt *et al.*, 2010; Keller *et al.*, 2001; Oviatt *et al.*, 2007).

Massachusetts Bay interacts with the Gulf of Maine via the western Maine coastal current (WMCC), making it imperative to understand the dynamics of the local currents. Northern Gulf of Maine coastal surface waters flow south along the Maine coast via the eastern Maine Coastal Current (EMCC.) When the EMCC bifurcates at Penobscot Bay, water either continues along the coast to what becomes the WMCC, or moves offshore to the center of the Gulf with the EMCC extension (Brooks, 1985; Pettigrew *et al*., 2005.) The WMCC is a buoyant and wind driven current that accumulates plume water from Maine rivers (including the Kennebec, Androscoggin, Penobscot, Merrimack and St. Johns Rivers) as it flows southwestward (Geyer *et al*., 2004; Janzen *et al.,* 2005). Once around Cape Ann, the WMCC either enters northern Massachusetts Bay or moves offshore along the eastern edge of Stellwagen Bank, depending on the wind conditions (Balch *et al.*, 2012; Jiang *et al.*, 2007; Lynch *et al*., 1997).

Wind and precipitation patterns are also influenced by the North Atlantic Oscillation (NAO), the dominant cyclical force responsible for large-scale variations in climate and winds in the Northwest Atlantic (Hurrell, 1995.) The NAO is a measure of the surface pressure difference between the Arctic (Iceland) and the subtropical Atlantic (Azores.) During the positive phase of the NAO, westerly winds are most intense, whereas during the negative phase, north/south winds predominate as Rossby waves develop in the northern hemisphere (Mann and Lazier, 2006). While variable from year to year, there had been a recent NAO phase change from positive (in the last decades of the 20^{th} century) to more negative (over the past decade) (Greene and Monger, 2012). Given this recent phase change, questions arise of how wind and precipitation/river discharge patterns have responded and influenced marine systems in the Northwest Atlantic.

1.1 Conceptual model and hypotheses

In this synthesis, we examined the relationships between climate variables (river discharge and wind speed) and primary production patterns in Massachusetts's coastal waters over a 19-year period to determine the potential driving forces and ecological consequences of reduced primary production. We constructed a conceptual model emphasizing our hypotheses on the physical-biological interactions in Massachusetts Bay (Figure 3). The model is broken into 2 time periods of contrasting conditions influencing primary production rates: 1992-2002 highlighting years of increased production rates (Figure 3a), and 2003-2010 representing the years of decreased production rates (Figure 3b).

We hypothesized that, in comparison to earlier years (1992-2002), a recent (2003-2010) increase in Maine river discharge freshened and strengthened the buoyancy driven component of the WMCC. The WMCC, flowing stronger southwestward, and coupled with weaker westerly winds, resulted in greater penetration of low-salinity waters into Massachusetts Bay (Balch *et al.*, 2012; Geyer *et al.*, 2004). A shift in weaker westerly winds and more meridionally dominated winds would have occurred from the recent phase change in the NAO (Green and Monger, 2012; Weibe *et al.*, 2012), providing favorable conditions for the WMCC to enter Massachusetts Bay. Increased surface freshwater and weaker westerlies would intensify water-column stratification in Massachusetts Bay through greater density differences between surface and bottom waters and reduced turbulent water-column mixing. We hypothesized that strengthened stratification inhibited nutrients in the benthos from entering the euphotic zone, thus decreasing surface nutrients for potential primary production. We also tested the impact of reduced production rates on other biological variables, including zooplankton abundances and benthic metabolism rates. As a result of reduced primary production, we expected that zooplankton abundances (either total or genera specific) and benthic nutrients fluxes would also have reduced in recent years due to decreased food availability and organic matter deposition.

This work examines evidence for interactions between climate and oceanic variability in marine ecosystems and how changes in the base of food webs may have ramifications on other trophic levels and ecosystem processes. Production rates and environmental variables at the opening of Boston Harbor were also analyzed under the conceptual model to determine the role of nutrient reductions in the production decrease at F23 in relation to other potential factors. Testing both Site F23 and the Nearfield Region against the conceptual model allows for comparison of forces responsible for the markedly similar production drops in the two regions.

2. Methods

2.1 Sampling

Oceanographic variables were analyzed from the three MWRA Water Quality-Monitoring Program sites where primary production measurements were made. Two of the stations are located within the designated Nearfield area, a 100-km^2 grid centered on the new outfall diffuser in western Massachusetts Bay (Figure 1). Station N18 (~ 27 m depth) is in close proximity to the outfall diffuser, while N04 (~ 49 m depth) is located in the northeast corner of the Nearfield region. The third station (F23, ~ 24 m depth) is located just outside Boston Harbor, but relatively close to the previous outfall diffuser site (Keller *et al.*, 2001). From 1992-2003, 17 water-column-monitoring surveys were conducted each year at the Nearfield sites; however, sampling frequency was reduced to 12 surveys per year from 2004-2010. Conditions in Boston Harbor (F23) have been measured 6 times per year since 1994 (Hunt *et al.*, 2010).

Technical reports describing field and laboratory methods, results and quality assurance and control procedures by their respective principle investigators are publically available through the MWRA Environmental Quality Department website (http://www.mwra.state.ma.us/harbor/enquad/trlist.html, last accessed 3 March 2013). At each site, hydrographic parameters were measured continuously on downward casts using a conductivity-temperature-depth (CTD) system fastened to a rosette (Hunt *et al.*, 2010.) Measurements taken by the CTD included temperature, salinity, pH, dissolved oxygen, chlorophyll fluorescence and photosynthetically-active irradiance (PAR). PAR measurements were used in calculating extinction coefficients and euphotic depths. On the upward cast, Go-Flo/Niskin bottles attached to the rosette collected water samples at 5 discrete depths: surface (1-2 meters depth), mid-surface, mid-depth (the chlorophyll *a* maximum depth), mid-bottom and within 5 m of the bottom (Hunt *et al.*, 2010). Water samples were used for nutrient, plankton and primary production analyses (Libby *et al.*, 2011.)

Stratification was calculated as the difference between the bottom and surface water densities at each site. Density was calculated based on the temperature and salinity at the given depths. Dissolved inorganic nutrient samples were filtered through 0.4-µm pore-sized membrane filters and frozen until analysis with a colorimetric auto-analyzer (Hunt *et al.*, 2010). Dissolved inorganic nitrogen (DIN) is the sum of nitrate (NO_3), nitrite (NO_2) and ammonium (NH_4), while dissolved inorganic phosphorus and silica are in the forms of phosphate (PO_4) and silicate (SiO_4) respectively. All non-detectable concentrations were assigned the concentration half of the detectable limit of the autoanalyzer.

Primary production measurements have been made in Massachusetts Bay and Boston Harbor since 1992, with minor modifications to productivity measurements and sampling design made in 1995 (Keller *et al.*, 2001; Oviatt *et al.*, 2007). Production rates were not measured at N18 until 1997, thus rates from 1995 and 1996 at N16 (adjacent to N18 in the Nearfield region) were used for analyses at N18. There were no significant differences in production rates at sites N04, N16 and N18 over the study period ($p > 0.05$). For the earlier years (1992-1994), only annual primary production rates were available for analysis from Kelly and Doering (1997), thus these years are not included in the seasonal analyses. Primary production rates were measured with ^{14}C incubations in light boxes to simulate different irradiances over depth, as described in Strickland and Parsons (1972) and Lewis and Smith (1983). Samples were filtered with a 300-µm mesh to remove grazers and stored in dark bottles prior to analysis. Incubations were held at ± 2ºC of the ambient sample temperature for each respective depth and were conducted for one hour. Productivity versus irradiance curves were constructed based on productivity incubation results and fit to either the Platt et al. (1980) or Webb et al. (1974) models, depending on the presence or absence of photoinhibition. Hourly production rates were calculated based on the productivity results from the incubations and light observations at Deer Island (Keller *et al.*, 2001). Daily production rates (mg C m^{-2} d^{-1}) were calculated with trapezoidal integration of production over the five depths and then summing the hourly rates. Daily production rates were then used to interpolate between days of unmeasured data, and the summation of daily production was used to obtain annual production (g C m^{-2} $year^{-1}$) (Keller *et al.*, 2001; Oviatt *et al.*, 2007).

Zooplankton tows were conducted over the top 25 m of the water column with a 0.5-m diameter, 102-µm mesh net. Samples were preserved in 5% formalin at sea and later in 70% ethanol solutions. Zooplankton were reduced to aliquots of at least 250 individuals with a Folsom plankton splitter and identified to the most discernible taxon (Turner *et al.*, 2006; Turner *et al.*, 2011). Zooplankton surveys were not conducted at N04 in 1995 and at N18 from 1992-1996, thus, a Nearfield average of N04, N18 and N16 data was used for analyses.

Sediment cores and water samples for benthic analyses were obtained via SCUBA divers and a 50 x 50-cm box corer for Boston Harbor and Massachusetts Bay respectively (Giblin *et al.*, 1997). Cores were transported and incubated in dark, insulated containers at ± 2ºC of *in situ* station temperature. Water overlying the cores was replaced by filtered water from each specific site to measure the flux of nutrients between the cores and overlying water. Incubation times varied depending on the time required for oxygen concentrations to drop by at least 2 ppm, but always remaining above 3 ppm. Oxygen concentrations were measured with a polargraphic electrode (Orbisphere; 1993-2009) or an optical electrode (Hach LDO; 2010). At 4-5 time points during the incubation, 20-30 ml' of overlying seawater were sampled for nutrients. Subsamples were immediately analyzed for ammonium using phenol-hypochlorite method (Solorzano, 1969) modified for small sample volume or preserved for later analysis of other nutrients (Tucker and Giblin, 2005). Ammonium fluxes and sediment oxygen demand were the only benthic rates analyzed in this study. Due to sampling frequency, analyses were only based on summer rates from 1993-2010. Sampling did not occur in Massachusetts Bay in 1998.

Surface wind speed and direction data were obtained from the NOAA National Data Buoy Center (NDBC) station 44013 (http://www.ndbc.noaa.gov/, last accessed 13 June 2011) adjacent to the Nearfield, and data gaps were filled with observations from the Gulf of Maine Ocean Observing System (GoMOOS) Buoy A located in northern Massachusetts Bay (Figure 1). Wind stress was calculated following Large and Pond (1981), using the wind speed data, an air density constant of 1.22 kg m^{-3} and a calculated drag coefficient. River flow for the Merrimack and Charles River basins were obtained from United States Geological Survey (USGS) monitoring sites (http://waterdata.usgs.gov/ma/nwis/current/?type=flow, last accessed 15 October 2012). Charles River flow was used for analyses of the mouth of Boston Harbor (Site F23) due to its proximity. The Merrimack River was chosen for Nearfield region

(Sites N04 and N18) analyses because it is the closest major river to the Nearfield region that empties into the WMCC. Annual Merrimack River flow patterns were positively correlated to the other major rivers emptying into the Maine coastal currents, such as the St. Johns, Penobscot and Kennebec Rivers (p values < 0.05.)

2.2 Data aggregation

Data were analyzed from the years of 1992-2010. Sampling frequency varied greatly between data sets, thus to remove sampling frequency bias, all variables were averaged by months. These monthly averages were then used to calculate average annual and seasonal values. Seasons were defined as follows based on the exhibited patterns of primary production in Massachusetts Bay: winter-spring (February-April), summer (May-August), and fall (September-November). When examining relations between primary production and other biological variables, production rates at N04 and N18 were averaged to create Nearfield region results because rates were not significantly different ($p > 0.05$).

One-and-two-way ANOVA's were used to determine significant differences between variables at different sites and time periods. The term "production drop" in the following text refers to the decrease in annual primary production rates that occurred between 2002 and 2003. Aggregating years before and after 2002-2003 for ANOVA's was chosen over other break points based on the greater statistical significance in primary production differences than other break points. Additionally, the 2002-2003 break point was chosen over 2000-2001 (when the outfall was relocated) because there were no significant changes in production rates found as a result of the outfall relocation (Oviatt *et al.*, 2007). Linear regressions and

ANCOVA's were also used to determine the correlation and variance between hypothetical independent-dependent relationships at different sites.

3. Results

3.1 Climate impacts

Annual average surface salinities at N04, N18 and F23 ranged from 29.3-33.0, 27.5-31.9 and 29.4-31.3 psu, respectively, and were not significantly different from each other from 1992-2010 ($p > 0.05$). Charles and Merrimack River discharges had similar patterns over the study period and were strongly correlated ($R^2 = 0.69$, $p < 0.0001$), with the average Merrimack River discharge 25 times greater than that of the Charles River. River flow was tested against surface salinities at all sites to determine the influence of river discharge on the sites' surface water salinities. The variables were significantly negatively correlated in both systems; years of higher river discharge corresponded to those of lower surface salinities at all sites (Figure 4). While there was some overlap between periods, years before the production drop were typically characterized by higher surface salinities and low river flows, and vice versa from 2003-2010. All three sites had 1998 conditions that were similar to those of the post-production drop period.

Wind speed and stress over Massachusetts Bay were also tested against surface salinities to understand the impact of wind in transporting surface waters in Massachusetts Bay and vertically mixing the water column. Annual surface salinities at F23 and N04 were correlated with both annual meridional and zonal wind speed and stress components, with stronger correlations between salinities and wind stress (Figure 5). Years of stronger westerly and weaker northerly wind stresses corresponded to those of higher surface salinities. While surface salinities were correlated to meridional wind stress at N18 (Figure 5d), zonal wind stress was not (Figure 5c). There was no distinct division among years, although 1998 was characterized by low surface salinities, weak westerly wind stress and moderate northerly wind stress.

Surface salinities were then compared to stratification indices to ascertain whether changes in surface waters reflected changes in water column stratification at the three sites. Annual stratifications at N04, N18 and F23 ranged from 1.06-1.79, 0.73-1.47 and 0.34-1.51 kg/m^3 respectively. Average annual bottom salinities at N18 in years after the outfall relocation decreased in relation to years prior, but were shy of being statistically significant at an alpha of 0.05 ($F_{1,17} = 4.19$, $p = 0.06$). This pattern was not seen at N04. Stratification at N04 was significantly stronger than that at N18 ($F_{1, 36} = 40.1$, $p < 0.0001$). There were significant, yet slightly different, relationships between the surface salinities and stratification indices among the three sites, with years of fresher surface waters resulting in stronger water column stratifications (Figure 6). This relationship was stronger for the sites closer to their associated river origin (F23: $R^2 = 0.46$, $p = 0.001$; N04: $R^2 = 0.60$, $p = 0.0001$) and significantly weaker at N18 ($R^2 = 0.22$, $p = 0.04$), located near the new outfall diffuser. Annual stratification indices at N04 were also correlated to annual meridional and zonal wind speed and stress (zonal stress: R^2=0.27, p = 0.02; meridional stress: R^2=0.41, p = 0.003), but stratification indices at N18 were not correlated with wind speed and stress.

Stratification indices were tested against nutrients and primary production to discern the impact of water-column stratification on the mixing of nutrients for phytoplankton growth. Annual stratification in the Nearfield region was negatively correlated to annual primary production rates (ANCOVA: $F_{1,35} = 22.24$, $p < 0.0001$) indicating that stronger water-column stratification lead to less primary production, and the relationship differed between N04 and N18 (ANCOVA: $F_{1,35} = 8.88$ $p = 0.0052$). This relationship did not exist between stratification and primary production at F23. Nutrient concentrations in the Nearfield before and after the primary production decrease had a tendency to increase at N18 (perhaps, due to the outfall diffuser) while only nitrate and silicate slightly increased at N04 (Figure 7). The increase in silicate at both sites may suggest more freshwater in the recent years consistent with greater stratification. However, counter to our conceptual model, annual Nearfield surface nutrient concentrations were not significantly correlated to stratification or primary production at either site in the Nearfield region. When comparing nutrient concentrations before and after the production drop, ammonium and phosphate significantly decreased at F23 ($F_{2,51} = 15.12$, $p < 0.0001$). Phosphate significantly increased at N18 ($F_{2,51} = 19.44$, $p < 0.0001$). Ammonium, nitrate, phosphate and silicate were all higher at F23 than the Nearfield sites before the production drop, but after the drop, N18 had higher ammonium concentrations than F23 and N04 (Figure 7). Annual DIN and phosphate concentrations were positively correlated to production rates at F23, with years prior to 2003 indicative of high production and nutrient concentrations, and vice versa for post 2002 (Figure 8). Nutrient concentration profiles at all sites indicated that most nutrient concentrations increased over depth, but only those in surface waters were correlated to the annual primary production rates (concentrations over euphotic zone, water column or in the benthos depths did not correlate, p-value's > 0.05).

3.2 Biological ramifications

Average annual total zooplankton abundances were not correlated to annual primary production; however, summer zooplankton abundances and primary production were positively correlated (Figure 9a). Zooplankton, both the total number as well as the most common genera, were significantly more abundant in the summer than the winter-spring or fall ($F_{2, 54} = 26.19$, $p<0.0001$). *Oithona* spp. was the most abundant genus at F23, N18 and N04, but in greater abundance in the Nearfield region than at the mouth of the Harbor. For extensive zooplankton taxonomic breakdown in the Nearfield region, please refer to Turner *et al*. (2011). Years of increased rates of summer production corresponded to years of higher summer zooplankton abundances (i.e. 1990's and early 2000's), with an opposite trend for the years 2003-2010. Within this relationship, 1998 was most similar to years after 2003 (Figure 9a).

Summer benthic fluxes and metabolism rates were examined with primary production to understand the changes in benthic pelagic coupling over the study period. Summer benthic flux rates of ammonium and sediment oxygen demand differed greatly between directly outside the Harbor and the Nearfield region, with annual averages at F23 over the times series greater by a factor of 10 and 4 respective to each rate. Summer benthic ammonium flux and respiration rates were strongly correlated to summer primary production rates in the Nearfield region (Figure 9b).

Years before 2003 had increased sediment oxygen demand and ammonium fluxes from the sediments, whereas from 2003-2010 these rates decreased.

4. Discussion

4.1 Conceptual model and Western Maine Coastal Current influence

The results of climate and physical interactions were consistent with our conceptual model for the reduced primary production patterns in Massachusetts Bay (Figure 4). Less-saline surface waters in the Nearfield region with increased river discharges (Figure 4) provide evidence for the influence of the Gulf of Maine's coastal current on Massachusetts Bay. Years of increased river discharge likely resulted in strengthening and freshening of the WMCC, which moved into Massachusetts Bay. While emphasis is placed on the WMCC, coastal river plumes from Maine rivers located between the Maine shoreline and the WMCC (Geyer *et al.*, 2004; Keafer *et al.*, 2005) also likely impacted the Nearfield region with the WMCC. Both the WMCC and coastal plumes are buoyant currents heavily comprised of and driven by the Maine coastal rivers. However, as they enter Massachusetts Bay, the coastal plumes are pinched against the shore by the WMCC, thus the coastal plumes' impact is likely restricted to the shore, whereas the WMCC is capable of reaching farther out into the Bay. The apparent division of years based on the surface salinities – stratification relationship (Figure 6) suggests that the lower surface salinities in the Nearfield region in the recent years (2003-2010) strengthened stratification relative to pre production drop years (1992-2002.) Temperatures were tested directly against production as well as indirectly through the same process as salinity to see if both water properties were impacted by the river discharges. While Keller *et al*. (1999) found that temperature impacted winter-spring production rates, non-significant results indicated that, annually, temperature did not impact the annual production rates ($p > 0.05$).

Decreased westerly winds resulted in stronger stratification in the Nearfield as hypothesized (Figure 5). However, the role of wind in advecting fresh surface waters of the WMCC appears to have been stronger than the role of the wind in mixing the water column, evident from stronger correlations of salinities to wind stress in both directions than to wind speed. Wind patterns impact both the volume and direction of intruding WMCC into Massachusetts Bay (Jiang *et al*., 2007). Downwelling-favorable winds from the north/northeast, coupled with increased river discharge, result in a strong narrow jet of the WMCC to enter Massachusetts Bay close to the coast (Geyer *et al*., 2004). Southwest winds create upwelling conditions along the Massachusetts coastline and impedes waters from entering Massachusetts Bay (Anderson *et al.*, 2005; Jiang *et al.*, 2007; MERCINA, 2004). The recent increase in northeasterly wind stresses (reduced westerlies/southwesterlies, Figure 5c-d), coupled with increased river discharge (Figure 4), resulted in WMCC water in northwestern Massachusetts Bay. Jiang *et al.* (2007) estimated the impact of Ekman transport on moving the WMCC into Massachusetts Bay during the spring based on wind stress, Coriolis force and mixed layer depth. They found that Ekman transport during this time period was minimal in comparison to the speed of the WMCC, which complements our conclusion that winds, and likely Ekman transport, aid the transport of the WMCC into Massachusetts Bay, while the baroclinic influence from fresh Maine coastal waters drives the general strength of WMCC and it's impact on Massachusetts Bay.

Correlations suggest meridional and zonal components were both major contributors in transporting the WMCC to F23 and N04, while only meridional winds impacted the surface salinities at N18 (Figure 5). The counter clockwise circulation pattern in Massachusetts Bay is most pronounced along the coasts (Geyer *et al.*, 1992.) Thus, it is not surprising to see the influence of wind transporting waters to the F23 region in the presence of northeasterly winds, especially when the wind and river conditions produce the strong jet flow and downwelling conditions. N18 may be impacted less than N04 and F23 because of outfall plume effects overriding weather forces and it's located in central Massachusetts Bay, more removed from the major counter-clockwise circulation.

4.2 Massachusetts Bay and the year 1998 in perspective

Annual production rates in Massachusetts Bay and at the mouth of Boston Harbor seem to be much higher on average than offshore waters in the Gulf of Maine (270 g C m^{-2} yr^{-1}), Scotian Shelf (96 g C m^{-2} yr^{-1}) and the Grand Banks (200 g C m^{-2} yr^{-1}) (Townsend and Ellis, 2010.) However, in both Massachusetts Bay and the Gulf of Maine, low salinity waters appear to influence the primary production rates and stratification (Thomas *et al.,* 2003; Ji *et al*., 2007; Ji *et al.* 2008.) Similar conditions between 1998 and 2003-2010 provide further evidence that the same oceanographic forces influenced surface salinities and primary production in Massachusetts Bay. Environments from 2003-2010 and in 1998 were characterized by high freshwater discharges and low surface salinities (Figure 4), weaker zonal winds (Figure 5), increased stratification (Figure 6) and decreased primary production rates (Figures 2.) In 1998 and from 2003-2010, increased intrusion of freshwater from rivers transported by the WMCC resulted in less-saline waters within the Nearfield region. Jiang *et al.* (2007) have suggested that intrusion of diluted, low-chlorophyll waters from the WMCC in 1998 caused the winter-spring bloom absence in western Massachusetts Bay. In years with higher salinity waters and chlorophyll concentrations, such as 2000, primary production was higher in Massachusetts Bay (Jiang *et al.*, 2007). It's also apparent that the production patterns Massachusetts Bay are impacted by Gulf of Maine dynamics. The anomalous 1998 primary production patterns seen in Massachusetts Bay were also observed spanning the entire Gulf of Maine via satellite imagery, and Thomas *et al*. (2003) suggests that lower than usual nitrate/nitrite concentrations entering the Gulf of Maine were responsible for the patterns.

4.3 Impact of the NAO

The shift from stronger westerly winds toward northeast winds aligns with the recent phase change of the NAO (Greene and Monger, 2012; Weibe *et al.*, 2012). Northeast winds, which may also be associated with increased precipitation and river runoff from the more negative phase of the NAO, would tend to strengthen the WMCC's impact on Massachusetts Bay. Thus, the NAO may have an impact on the climate and oceanographic conditions of the Gulf of Maine and Massachusetts Bay through local river runoff and directional wind speeds.

While the NAO influences climate patterns such as winter temperatures, precipitation and westerly wind intensities (Turner *et al.*, 2006), it also influences the type of slope water in the Coupled Slope Water System (CSWS) (MERCINA, 2001; Townsend *et al*., 2010.) Regional Slope Water Temperature Indices (RSWTI) for the Gulf of Maine/Western Scotian Shelf (GOM/WSS) were used to infer the dominant mode of the CSWS and the salinity of water masses moving into the Gulf of Maine deep through the Northeast Channel and help determine the potential influence of the CSWS water on waters transported to Massachusetts Bay (C. Greene, pers. comm.; MERCINA, 2001.) Indices were positively correlated to the Winter NAO ($R^2 = 0.41$, $p = 0.006$) and surface salinities at N04 ($R^2 = 0.27$, $p = 0.03$), indicating that years of fresher CSWS waters resulting from the decrease in NAO intensity corresponded to less saline conditions at N04. This relationship was not significant at N18 ($R^2 = 0.22$, $p = 0.06$). While a significant correlation was found between surface salinities at N04 and RSWTI, the stronger correlation between Merrimack River discharge and Nearfield surface salinities implies that river input has a greater influence on the surface water properties than the NAO induced RSWTI. Additionally, because the RSTWI are representative of bottom waters, the deep Gulf of Maine waters reflected by the RSWTI would only impact the surface waters given strong and consistent vertical mixing and limited stratification in the northern reaches of the Gulf of Maine, thus allowing them to be transported through the WMCC and into the Nearfield region.

4.4 Influence of nutrients on the Nearfield region.

From these analyses, nutrient availability at the Nearfield sites did not appear to cause the primary production drop in Massachusetts Bay. Correlations between primary production and stratification (Figure 6) and surface salinities (N04: $R^2 = 0.37$, $p = 0.006$; N18: $R^2 = 0.37$, $p = 0.006$) implied that the influx of the WMCC waters resulted in reduced primary production rates in Massachusetts Bay, but the nutrient concentrations did not change between periods before and after the production drop as a result of oceanographic variability.

The impact of nutrient availability on primary production rates in the Nearfield may not have been discernible from this monitoring effort due to coarse sampling. While measurements taken every three weeks is considered a frequent sampling program, the monitoring most likely did not capture quick response of phytoplankton to nutrient availability, and only represents the aftermath of nutrient luxury uptake. For example, during the Massachusetts Bay spring bloom in 2000, DIN concentrations dropped from 5 to 1.5 μmol^{-1} in 2 weeks (Jiang *et al*., 2007). Additionally, the production seen in Massachusetts Bay may be the result of plankton-nutrient dynamics upstream of the WMCC, representing the bloom conditions in the Gulf of Maine. Ji *et al.* (2008) suggest that nutrient uptake by phytoplankton occurred much earlier in the Gulf of Maine and Scotian shelf as a result of low salinity water. With the recent decrease in surface salinities, perhaps nutrient depletion is occurring earlier and faster than in pre production drop years in Massachusetts Bay, and thus not captured by the sampling.

Balch *et al.* (2012) found similarly an increase river discharge and low salinity surface waters appear to play a critical role in the long-term productivity rates in the Gulf of Maine. They suggested that CDOM and detritus were the causal mechanism in decreased primary productivity through outcompeting phytoplankton for light. While we did not have CDOM measurements, we tested to see if annual euphotic depths and extinction coefficients differed between years before and after the production drop, with the hypothesis being that a decrease in euphotic depth and/or increase in extinction coefficient would be an indication that there was an increase in CDOM and detritus. There were no significant differences between either variable before and after the production drop ($p > 0.05$); thus it appears unlikely that Balch *et al*. (2012)'s theory is applicable to Massachusetts Bay.

4.5 Comparison of systems and sites

The similar relationships between physical forces and surface salinities at F23 and the Nearfield sites indicated that the environment at the mouth of the Harbor was influenced by the same climate variability as the Nearfield. Surface salinities at F23 were not significantly different from the Nearfield region and also were not correlated to surface nutrient concentrations. River discharge influenced salinities in both regions, as the Charles and Merrimack Rivers' discharges had strongly correlated surface salinities in their respective regions (Figure 4). Northeasterly winds corresponded to less-saline waters at the mouth of the Harbor (Figure 5), perhaps resulting from increased WMCC and coastal plume transport along the shore, reaching the periphery of Boston Harbor. Insignificant relationships between production and stratification and surface salinities may be masked by tidal flushing and mixing at the mouth of the Harbor (Kelly, 1997). Similar conditions and responses between the regions during the anomalous year of 1998, as well as strikingly similar annual production rates from 1992-2010 (Figure 2), also suggest that the same climate and oceanographic variability effected primary production in both systems. Thus, it appears that the changes in the physical environment in recent years impacted primary production rate patterns in both Massachusetts Bay and at the mouth of Boston Harbor. .

As previously hypothesized, some variability in annual production rates at F23 was explained by changes in the inorganic nutrients loading to Boston Harbor (Figure 8). The DIN and phosphate relationships with production indicate that conditions in the interior of the Harbor may reach the mouth of the Harbor. Export has been observed to reach the mouth of the Harbor depending on the season, driven primarily by tidal flushing (Kelly, 1997). However, changes in the wastewater management activities, particularly during the intermediate phase (i.e. the merging of the Deer and Nut Island Waste Water Treatment Facilities effluent discharges in the northwest corner of the Harbor, adjacent to the mouth) or in 2000-2001 when the outfall was relocated, do not appear to correspond with changes in production rates (Figure 2; Taylor *et al.,* 2011). While it is unclear whether oceanographic changes or the outfall relocation from Boston Harbor is more responsible for the changes in production at F23, both certainly have certainly influenced the system.

Difference between the two Nearfield sites' stratifications may have resulted from their proximities to the new outfall diffuser. While not statistically significant, the decrease in bottom salinities at N18 after the outfall relocation suggests that the diffuser's freshwater plume may have influenced bottom and surface water density differences, thus responsible for differences in stratification at N04 and N18 (Figure 6). Signell *et al.* (2000) have also showed that the new diffuser is capable of impacting water column properties within 2-3 kilometers of it. Weaker and fewer relationships between N18 surface salinities and wind patterns also suggest that more local forces may be influencing the environment there, like the diffuser. Greater increase in ammonium concentrations at N18 than N04 after the production drop were most likely driven by the outfall relocation, reflecting the site's close proximity to the new anthropogenic source of nutrients (Figure 7.)

When comparing western Gulf of Maine surface nutrient concentrations to those at the Nearfield sites, the sum of nitrate and nitrite concentrations and phosphate at N04 were highly correlated to those along the western Gulf of Maine coast, whereas those at N18 were not correlated (Table 1.) Similar to the differences between N04 and N18 in wind stress-surface salinity relationships, the differences in nutrient relationships between N04 and N18 to western Gulf of Maine also are likely because N04 is more northern and closer to the inflow of the WMCC. Lack of correlation between the silicate concentrations at N04 and western Gulf of Maine may be the result of silicate uptake by phytoplankton as waters are advected to Massachusetts Bay, or differences in plankton silicate uptake rates between the two regions. Relationships between nitrate+nitrite and phosphate concentrations at N04 and the western Gulf of Maine suggest that phytoplankton uptake these nutrients similarly temporally and that the western Gulf of Maine is a significant source of nutrients to the system at N04, as suggested by Jiang *et al.*, 2007.

4.6 Implications on trophic dynamics

As conceived in the conceptual model, the positive correlation between summer primary production and zooplankton abundances suggested that zooplankton have decreased in response to reduced organic matter in Massachusetts Bay (Figure 9a). The trophic significance of seasonal phytoplankton blooms on zooplankton abundances has been observed throughout the northwest Atlantic (Durbin *et al.*, 2003; Turner *et al.*, 2011). In temperate estuaries and coasts, summer zooplankton species abundances increase as temperatures increase and regulate summer phytoplankton standing stock through grazing (Keller *et al.*, 1999; Keller *et al.*, 2001; Turner *et al.*, 2011). In our study, summer zooplankton abundances, which were higher than other seasons, decreased roughly 25% between periods before and after the production drop and were positively correlated to primary production. Changes in small, highly-abundant zooplankton species such as *Oithona similis* likely accounted for the observed zooplankton decrease and masked the abundance patterns of other zooplankton species, like *C. finmarchicus*. Therefore, the relationship between summer primary production and zooplankton abundances likely resulted from reduced organic matter availability (Figure 9a).

Decreased benthic ammonium fluxes and sediment oxygen demand reflected the ecosystem responses to changes in organic matter in Massachusetts Bay (Figure 9b). As hypothesized, recent years of decreased organic matter production and benthic-pelagic coupling led to less remineralization of ammonium and respiration in sediments (Figure 9b). Diminished ammonium remineralization likely acted as a negative feedback, providing less ammonium for primary production in the water column. Rates of ammonium fluxes and sediment oxygen uptake were less in Massachusetts Bay than those observed in the Harbor (Giblin *et al.*, 1997). Differences between the Harbor and Nearfield region were likely a result of the outfall diffuser. The sampling sites used for the Harbor region were adjacent to the old outfall diffuser, thus ammonium concentrations were likely elevated in the Harbor during the 1990's from effluent and not benthic remineralization. Using annual rates, results indicated that from 1992-2010, roughly 20 ± 8% of primary production was mineralized in sediments each year. This percent is just below what Nixon (1981) found for estuaries (23.8%) and slightly greater than the 16% that Seitzinger and Giblin (1996) determined when using a myriad of continental shelf regions throughout the globe.

5. Conclusion

This study identifies Massachusetts Bay as a subsystem of the larger Gulf of Maine, for the physical and biological oceanography of Massachusetts Bay often reflected the oceanographic variability in the northwestern Atlantic. As developed in our conceptual model, recent reduced annual primary production of Massachusetts Bay likely resulted from greater intrusion of Gulf of Maine-derived waters. Traced through changes in salinity, the less-saline waters within the WMCC derived from increased river discharge intrude into Massachusetts Bay as a result of favorable northeasterly winds, highlighting the influence of climate variability on coastal Gulf of Maine and Massachusetts Bay, and the apparent linkage between wind conditions and recent shifts in the NAO phases.

It's unclear from our results what is the direct causal mechanism for reduced primary production in the Nearfield region, because stratification did not inhibit nutrient availability for phytoplankton growth, nor did nutrient concentrations change between before and after the drop in production or correlate to primary production rates. However, this may be due to the inability of the sampling frequency to capture the changes in nutrient concentrations. However, production rates in the Nearfield region were influenced by larger, regional patterns of oceanographic variability and showed no evidence of being affected by the new outfall. The decrease in primary production at the mouth of Boston Harbor appears to be explained by both the oceanographic changes experienced in Massachusetts Bay and the outfall relocation. The ecological consequences of reduced primary production were evident in the Nearfield in the summer months, when zooplankton abundances and benthic flux rates decreased concurrently.

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Figure Legends

Figure 1. Location of stations in the MWRA Outfall Monitoring Program. Hydrographic conditions, primary production rates, nutrient concentrations and zooplankton abundances were measured at F23 (Boston Harbor station) and at Nearfield (black box) stations N04, N18 and N16. NOAA NDBC and GoMOOS Moorings (red squares) are the sites of wind data used. Benthic sediment flux monitoring sites are indicated as black triangles. The new outfall diffuser (white circle) is located in the center of the Nearfield region. Black arrows highlight Merrimack and Charles Rivers and the western Maine Coastal Current flows. Within the locus map, arrows indicate the general circulation of surface (red) and deep (blue)waters into the Gulf of Maine and coastal currents waters movement toward Massachusetts Bay. Depth contours were obtained from the Commonwealth of Massachusetts' Office of Geographic Information.

Figure 2. Primary production patterns in Massachusetts Bay. Annual primary production rates at the Boston Harbor site (F23) and the Nearfield sites (N04 and N18). The dashed line represents the relocation of the outfall diffuser from Boston Harbor to the Nearfield Region in Massachusetts Bay. Annual production rates from 1992-2002 were significantly higher than those from 2003-2010 at N04 ($F_{1,17} = 15.37$, $p = 0.001$), N18 ($F_{1,17} = 28.43$, $p < 0.0001$) and F23 ($F_{1,17} = 17.92$, $p = 0.0006$)

Figure 3. Conceptual model hypothesizing influences on primary production patterns in Massachusetts Bay through (a) weak stratification from 1992-2002 and (b) strong stratification from 2003-2010. Solid lines are used to explain increase

in a physical force, while dashed lines indicate a weakening of the force..

Figure 4. Annual river runoff correlated against surface salinities at each site. (a)Merrimack River discharge was used for N04 (dark grey, solid line) and N18 (grey, dashed line) and (b) Charles River flow for F23 (black). The circles indicate years before the primary production drop (1992-2002) and the squares are years after (2003-2010). The stars are 1998.

Figure 5. Annual average wind stress components against surface salinities in (a, b) the Harbor (F23, black symbols) and (c, d) Nearfield stations N04 (dark grey symbols, solid line) and N18 (grey symbols, dashed line).Greater values for zonal and meridional measurements indicate increased westerly (i.e. from the west) and decreased northerly (i.e. from the north) wind stresses respectively. The circles indicate years before the primary production drop (1992-2002) and the squares are years after (2003-2010). The stars are 1998.

Figure 6. Annual surface salinities correlated with stratification at N04 (dark grey), N18 (grey) and F23 (black). The circles indicate years before the primary production drop (1992-2002) and the squares are years after (2003-2010). The stars are 1998. Lines through datasets represent the linear relationship between the variables. Statistics refer to the ANCOVA results testing the significance of the linear relationships between respective sites salinities and stratifications (Salinity) and how the relationships differ among sites (Sites).

Figure 7. Annual average surface nutrient concentrations at the Harbor site F23

(black) and Nearfield sites N04 (dark grey) and N18 (grey) before and after the production drop (1992-2002 vs. 2003-2010). Bars indicate standard deviations for the specific nutrient of a given site and period.

Figure 8. Annual surface DIN and phosphate concentrations tested against primary production rates at F23. The circles indicate years before the primary production drop (1992-2002) and the squares are years after (2003-2010). The stars are 1998.

Figure 9. Average Nearfield summer primary production rates tested against (a) average summer Nearfield zooplankton abundances and (b) average Nearfield benthic ammonium fluxes (grey) and sediment oxygen demand (white). Data from station N16 were also used in averages for zooplankton abundances to accommodate for missing data at N04 and N18. Production rates and zooplankton abundances did not significantly differ between the 3 Nearfield sites. Sediment rates were averaged from three benthic monitoring sites in the Nearfield region and production rates were averaged from N04 and N18. The circles indicate years before the primary production drop (1996-2002) and the squares are years after (2003-2010). Benthic flux sampling did not occur in 1998.

Table Legends

Table 1. Pearson correlation coefficients for monthly surface nutrient concentrations between the western Gulf of Maine and Nearfield sites N04 and N18. Asterisks indicate degree of significance at greater than 95% confidence, whereas coefficients without asterisks are insignificant at the same confidence level. Data from the western Gulf of Maine (43º28'-44º29'N, 67º41'-70º8'W) were obtained from Gulf of Maine Region Nutrient and Hydrographic Database (http://grampus.umeoce.maine.edu/nutrients/, last accessed 18 July 2013) at depths no deeper than 10 meters.

Tables.

Nearfield Site	NO_3+NO_2	PO_4	SiO_4
N04	0.73**	0.57**	0.28
N18	0.46	0.26	-0.17

** $p < 0.0001$
* $p < 0.01$

Table 1.