The ecological effects of climate change on the Narragansett Bay estuary

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Abstract: Narragansett Bay is an estuary within the United States Northeastern Continental Shelf Large Marine Ecosystem (LME). Because of its transitional location between two temperature driven biogeographical provinces, it provides a useful case study on the impacts of climate change. Narragansett Bay has undergone changes in productivity coincident with increasing temperature. The Bay's productivity cycle was traditionally dominated by a winter/spring bloom, which has been reduced or absent since the 1970's. Localized episodic summer blooms are now the dominant annual feature with the annual chlorophyll maximum observed within 1 month of the summer solstice. The Lower Bay has also shown a long-term decrease in productivity. These changes in productivity may be related to long-term climate driven changes in cloud cover and irradiance, and temperature driven changes to grazing patterns. The long-term decline in productivity is not evident in the upper portions of Narragansett Bay where summer hypoxic events have become common in due to increased stratification from rainfall events, increased temperature and organic matter loading from phytoplankton blooms supported by anthropogenic nutrient sources. This suggests that the Providence River and Lower Bay have responded differently to the same changes in climate. To mitigate eutrophication and hypoxia in Upper Narragansett Bay, the State of Rhode Island has implemented mandatory nitrogen reduction by wastewater treatment plants. The first upgraded treatment plants went online in 2006. It is unclear how this nitrogen reduction strategy will interact with the already observed climate driven changes to Narragansett Bay's productivity and phenology or how the effects may vary along the estuarine gradient.

Introduction

Narragansett Bay (Figure 1) is an estuary in the state of Rhode Island within the United States Northeastern Continental Shelf Large Marine Ecosystem (LME). Because of its transitional location between two temperature driven biogeographical provinces, it provides a useful case study on the impacts of climate change.

Annual average air temperatures in this region have risen by 0.94° C between 1905 and 2006 (Pilson 2008). This is slightly higher than the global average temperature increase of 0.74 °C reported during the same period by the Intergovernmental Panel on Climate Change (IPCC 2007). There was a cool period in the 1960s, with the coolest year being 1961 so that the increase from 1961 to 2006 was 1.14°C (Pilson 2008). The period of more rapid warming since the 1960s is coincident with a shift in the winter (Dec-March) North Atlantic Oscillation index (NAO) from a negative phase to a positive phase. This is an important consideration because most of the oceanographic data in this region is concentrated in the period of more rapid warming where the NAO phase-shift occurred.

Narragansett Bay has undergone changes in productivity coincident with increasing temperature. The Bay's productivity cycle was traditionally dominated by a winter-spring bloom (Pratt 1965), which has been reduced or absent since the 1970's (Oviatt et al. 2002). This change significantly alters the seasonal delivery of organic matter to feed the ecosystem and could potentially impact the life cycles of fish, zooplankton and benthic fauna. Related to the reduction of the winter-spring bloom, several studies have reported a decrease in annual chlorophyll and an increase in water clarity in the lower to mid-Bay (Li and Smayda 1998, Fulweiler et al. 2007, Nixon et al. 2009).

There have also been shifts in the zooplankton. Warmer winter temperatures have led to more effective overwintering by the ctenophore *Mnemiopsis leidyi* (Sullivan et al. 2001). In the past *M. leidyi* populations did not peak until August, but now the peak is in early June (Sullivan et al. 2001). The seasonal shift in ctenophore abundance has impacted other species. For example, the copepod *Arcatia tonsa* on which *M. leidyi* is a predator has greatly declined since the seasonal shift in ctenophores was observed (Costello et al. 2006).

As with planktonic organisms, fish and benthic invertebrate populations have undergone changes. There has been a decrease in the ratio of demersal to pelagic fish (Oviatt et al 2003, Collie 2008). There has also been a decrease in colder water species such as the winter flounder (*Psuedoplueronectes americanus*) (Oviatt et al. 2003, Collie et al. 2008) and an increase in warmer water species such as scup (*Stenotomus chrysops*) (Collie et al. 2008). Concurrent with changes in the fish populations, there has been an increase in overall invertebrate abundance (Oviatt et al. 2003, Collie et al. 2008).

An issue more tangible to the general public than shifting plankton dynamics or species composition has been summer hypoxic events. In Narragansett Bay hypoxic conditions have occasionally produced highly visible fish kills such as in late August of 2003 (Bergondo et al. 2005, Deacutis et al. 2006, Melrose et al. 2007). Warmer temperatures promote hypoxia through reduced oxygen solubility and increased respiration rates. Climate can also affect the risk of hypoxic events by changing primary productivity, freshwater flow, and stratification.

Changes in Narragansett Bay due to climate variability are superimposed on variability due to pollution, fisheries, invasive species and other possible stressors. Wastewater discharge from sewage is of particular concern in Narragansett Bay, which has a densely populated watershed (Nixon et al. 1995, Bergondo et al. 2005, Nixon et al. 2005, Deacutis et al. 2006, Fulweiler et al 2007, Melrose et al. 2007, Nixon et al. 2009). To address eutrophication and hypoxia concerns, the State of Rhode Island is currently undertaking a major effort to reduce nitrogen discharges by wastewater treatment plants. The first upgraded plants became operational in 2006.

In this paper, we examine regional changes in water temperature, wind, cloud cover and precipitation and their potential impact on primary production in Narragansett Bay. We will also examine changes in chlorophyll, water temperature and surface salinity over the last decade and possible links to climate change.

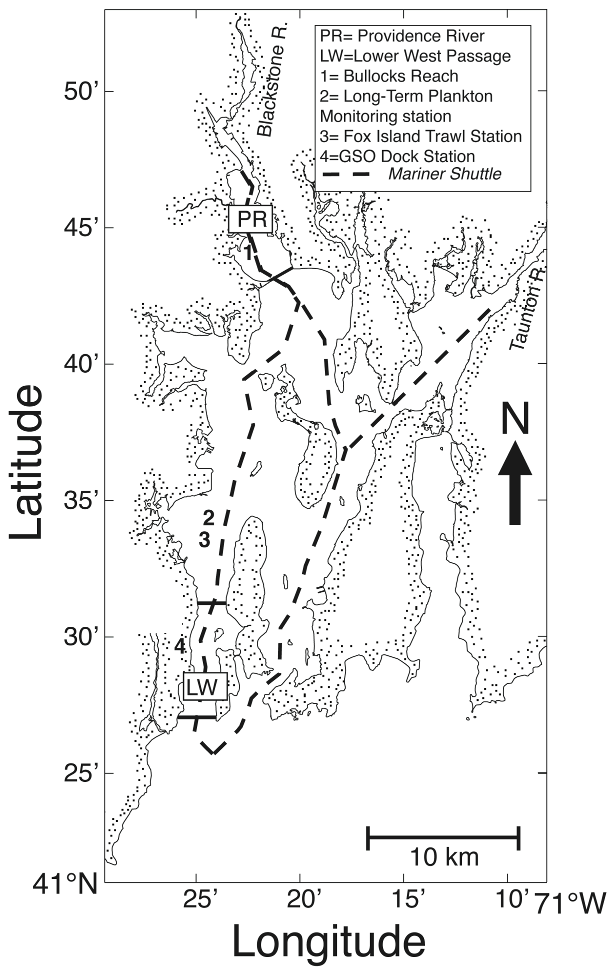

Figure 1. Narragansett Bay, RI island. Dotted lines represent the *Mariner Shuttle* Transect coverage in the the East and west Passage of Narragansett Bay. The regions of the Bay used for grouping the *Mariner Shuttle* Data when calculating regional means and anomalies are denoted by the heavy solid lines.

Methods

Between March of 1998 and January of 2009, a time series of monthly surveys was performed in Narragansett Bay using a custom Chelsea Technologies NuShuttle towed sampling platform known as the *Mariner Shuttle*. It was towed during daylight hours at 8 to 9 kts on a circuit of Narragansett Bay (Fig. 1) that included the East Passage, West Passage, Mount Hope Bay and the Providence River.

The *Mariner Shuttle* is able to sample through the water column by undulating between preset depths using a movable wing. The *Mariner Shuttle* was flown between the surface and 5 to 20 m depending on the depth of the water column. The instrument was programmed to climb at an average rate of 10 meters per minute except when the maximum depth was 5 m, in which case a rate of 5 meters per minute was used.

An Aquapak CTD/Fluorometer was part of the *Mariner Shuttle*'s sensor suite and was used to measure temperature, salinity and *in vivo* chlorophyll fluorescence. *In vivo* chlorophyll fluorescence was calibrated with samples extracted in 90% buffered acetone and measured with a Turner Designs Model 10 laboratory fluorometer prior to 2004 and a Model 10 AU fluorometer after 2004. Calibration samples were collected from 1 m depth at stations in the upper and lower Bay. The exact location and number of stations per cruise varied depending on conditions, but typically 2 or 3 calibration stations were performed. A regression of all calibration data taken during the survey has an r^2 of 0.75 indicating that a generalized calibration relationship accounts for 75% of the variability between *in vivo* fluorescence and actual chlorophyll concentrations. The mean ratio of extracted chlorophyll to *in vivo* fluorescence was used to calibrate the *in situ* measurements.

Total precipitation, monthly average wind speed, and total annual cloudy days were obtained from the NOAA National Climate Data Center (www.ncdc.noaa.gov). Monthly surface data were collected in Providence, RI (NCDC station 94707) and then later at T.F. Green Airport (NCDC station 14765). Over a century of data collection, the location of the station changed several times. This did not have a large impact on precipitation and cloud cover data. For wind, there are several periods where the data were unusable due to changes in the exposure of the anemometer. Only data from 1925-1927 and 1954-2008 where the anemometer was unobstructed for the entire year were used.

Bay water temperature data from several surveys conducted at the University of Rhode Island Graduate School of Oceanography (GSO) were combined. Surveys included were: The GSO Fish Trawl Fox Island Station (Figure 1) 1959-2008, data accessed at http://www.gso.uri.edu/fishtrawl/; The Narragansett Bay Long-Term Plankton Monitoring Program station (Figure 1) 1959-1996 data accessed at www.narrbay.org; 1999-2008 data accessed at www.gso.uri.edu/phytoplankton; The GSO Dock Survey (Figure 1) 1978-1983 and 2001-2007 data accessed at www.gso.uri.edu/merl/data.

Daily averaged summer chlorophyll and salinity data were analyzed from two stations within the Narragansett Bay Fixed Station Monitoring Network (NBFSMN 2005, 2006, 2008). One station was located in the Providence River at the Bullocks Reach buoy (Figure 1) and in the Lower West Passage at the Graduate School of Oceanography (GSO) Dock (Figure 1). Data at the NBFSMN buoys were collected every 15 minutes from 0.5 to 1 meter below the surface and 0.5 meters above the bottom. At the GSO dock, the water column was too shallow to warrant a bottom sensor. To facilitate comparison with the GSO dock, only data from the surface at Bullocks Reach was used in the analysis. Using only surface data, it was impossible to calculate stratification so surface salinity was used as proxy. Surface salinity was deemed a better proxy for stratification than surface temperature because it typically accounts for largest fraction of the surface to bottom density difference in Narragansett Bay. Daily average data were used for the months June, July, and August for the years 2001-2003, 2005-2006, and 2008 as these were the years on record that did not have gaps greater than 10 days in the months analyzed.

A historical comparison of vertically integrated annual productivity in the Providence River and the Lower West Passage of Narragansett Bay was made by examining data from a recent survey (2006-2008) and two previous surveys: 1971-1973 (Oviatt et al. 1981) and 1997-1998 (Oviatt et al. 2002). The 1971-1973 survey used oxygen incubations (Oviatt et al. 1981), the 1997-1998 used a ^{14}C incubation method (Oviatt et al. 2002) and the 2006-2008 study used a different variation of the ^{14}C incubation method (Hyde et al. 2008). Data used from the 1971-1973 surveys were an average of all Providence River stations and the GSO Dock station. Data used from the 1997-1998 surveys were an average of two stations in the Providence River area close to the present location of the Bullocks Reach buoy and the GSO Dock in the Lower West Passage. The 2006-2008 survey is part of the National Oceanic and Atmospheric Administration (NOAA) Coastal Hypoxia Research Program (CHRP) study in Narragansett Bay. Sampling stations were Bullocks Reach and the GSO Dock (Figure 1).

Results

Narragansett Bay's annual average water temperature has increased over the past 50 years (Figure 2) following the trend in warming air temperatures over the same period. The increase was 1.26° C, which is slightly more than the 1.14° C increase in air temperature reported by Pilson (2008) over roughly the same period.

As temperature has increased, cloudiness (Figure 2) has also increased ($r^2 = 0.63$, $p < 0.0001$) by 61 days per year from 1925 to 1996. An increase in cloudiness and the associated decrease in irradiance have been proposed as one possible explanation for the shift in the phytoplankton productivity in Narragansett Bay (Nixon et al. 2009). The increased cloudiness coincides with an increase ($r^2 = 0.23$ $p < 0.0001$) in precipitation (Figure 2) by 31.7 cm per year between 1905 and 2008.

Wind speed has decreased (Figure 2) by approximately 5.8 km/hr from 1925 to 2008 ($r^2 = 0.81$ $p < 0.0001$).

The Providence River does not exhibit a clear trend in productivity over time (Figure 3). In the 2007-2008 study productivity was 429 g C m^{-2} yr^{-1}, identical to the value in 1971-1973 with periods of high (1997-1998) and low (2006-2007) productivity over the intervening period. The GSO Dock in the lower West Passage of Narragansett Bay has in contrast shown a decreasing trend in productivity over the same period.

There is a relationship ($r^2 = 0.32$ $p < 0.0001$) between surface salinity and chlorophyll during the summer months in Lower West Passage of Narragansett Bay. This relationship is not apparent in the Providence River ($r^2 = 0.03$ $p = 0.007$).

The average seasonal cycle over 11 years (March 1998-December 2008) measured by the Narragansett Bay *Mariner Shuttle* study in the Providence River (Figure 5), indicates that surface salinity is highly variable, but usually reaches the lowest values in June when variability is highest. Surface salinity usually decreases in the warmer and dryer summer months where evaporation and reduced precipitation act in synergy. The Lower West Passage (Figure 6) has less variability in surface salinity and reaches the lowest surface salinity values earlier in the spring during the month of April.

Peak temperatures typically occur in August, while the coldest month is usually February in all regions of the Bay (Figures 5, 6).

Chlorophyll is highest in the summer months (Figures 5, 6) and reaches the maximum within 1 month of the summer solstice when light is most abundant. In the Providence River, highest concentrations typically occur in July (Figure 5). Chlorophyll reaches its peak in June in the Lower West Passage (Figure 6). Minimum values occur in either November or December, though the difference between these months is minimal. The concentration at the summer peak, the seasonal range of concentrations, and variability in the monthly mean chlorophyll all decrease along a north-south gradient down Narragansett Bay. A large winter-spring bloom is not evident in the mean pattern for any of the regions; though individual years contributing the mean did have localized winter-spring blooms focused in the northern half of the estuary.

Monthly anomalies were calculated for all months of the *Mariner Shuttle* study between 1998 and 2008. Surface salinity was generally above mean values from 1999-2003 in all regions and below from 2004-2008 (Figures 7, 8). This multi-year pattern is more consistent in the Lower Bay than in the Providence River where month-to-month variability is more pronounced.

There is no clear trend in the water temperature anomalies between 1998 and 2008 in any of the regions (Figures 7, 8). Instead there appears to be an alternation of warm and cold periods often within the same year. Given that the 1959-2008 water temperature increase (Figure 2) was only 1.264° C or 0.026° C per year, the temperature change between 1998 and 2008 would not be expected to be noticeable with limited temporal resolution (monthly samples) of the monthly *Mariner Shuttle* studies.

The chlorophyll in the Lower West Passage (Figure 8) has more negative anomalies during the period of high salinity between 1999 and 2003. This is consistent with the relationship noted in Figure 4 showing a correlation between reduced surface salinity and increased chlorophyll in the Lower Bay. In addition, positive chlorophyll anomalies occur during winter periods with positive temperature anomalies (for example the winter of 2000 and 2008 in all regions shown in Figures 7, 8) as well as negative anomalies (For Example February of 2003 and January 2004 in Figure 7).

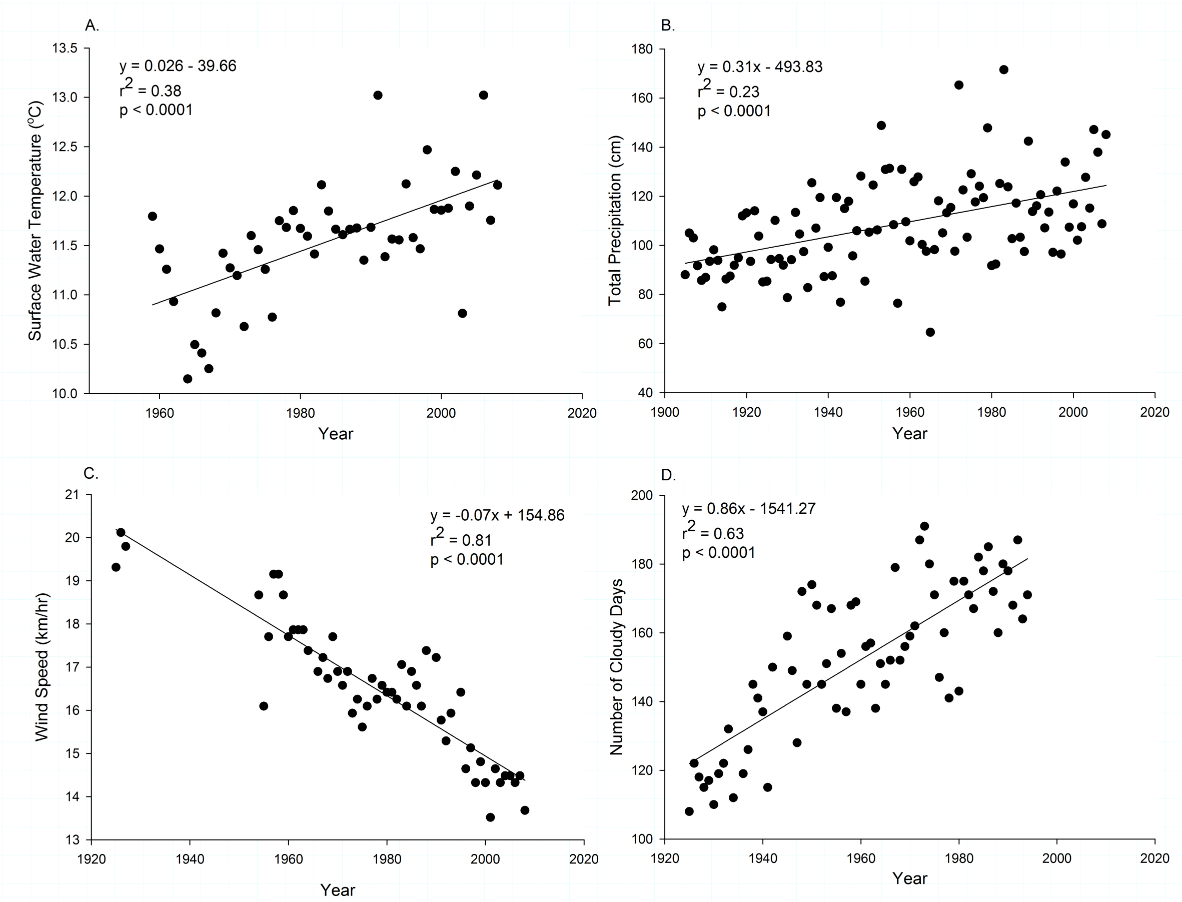

Figure 2.
A. Narragansett Bay Annual Average Water Temperature from 1959-2008. Annual average water temperature has increased significantly over the past 50 years (simple linear regression $r^2 = 0.38$ p <0.0001). Data collect from within the Bay through various surveys at the URI Graduate School of Oceanography. GSO Fish Trawl Fox Island Station (41 34.5N, 71 24.3W) 1959-2008, data accessed at http://www.gso.uri.edu/fishtrawl/. Narragansett Bay Long-Term Plankton Monitoring Program (Figure 1) 1959-1996 data accesed at www.narrbay.org; 1999-2008 data accessed at www.gso.uri.edu/phytoplankton. GSO Dock Survey (Figure 1) 1978-1983 and 2001-2007 data accessed from MERL database.
B. Total Annual Precipitation from 1905-2008. There has been a significant increase in total annual precipitation over the last century (simple linear regression $r^2 = 0.23$ $p < 0.0001$). Data collected in Providence and T.F. Green airport (see Table 1 for years) and accessed through NCDC www.ncdc.noaa.gov.
C. Annual Average Wind Speed Through Time. There has been a significant decrease in annual average wind speed over the past 8 years (simple linear regression $r^2 = 0.81$ $p < 0.0001$). Data collected in Providence and T.F. Green airport (see Table 1 for years) and accessed through NCDC www.ncdc.noaa.gov. Data is a subset of the overall dataset to take into account variation of station location years used include: 1925-1927 and 1954-2008 (with gaps in 1965, 1989, and 1994).
D. Total Number of Cloudy Days in Each Year from 1925-1934, 1936-1942, 1945-1996. There has been a significant increase in cloudy days over the past 80 years (simple linear regression $r^2 = 0.63$, $p < 0.0001$). Data collected in Providence and T.F. Green airport and accessed through NCDC www.ncdc.noaa.gov.

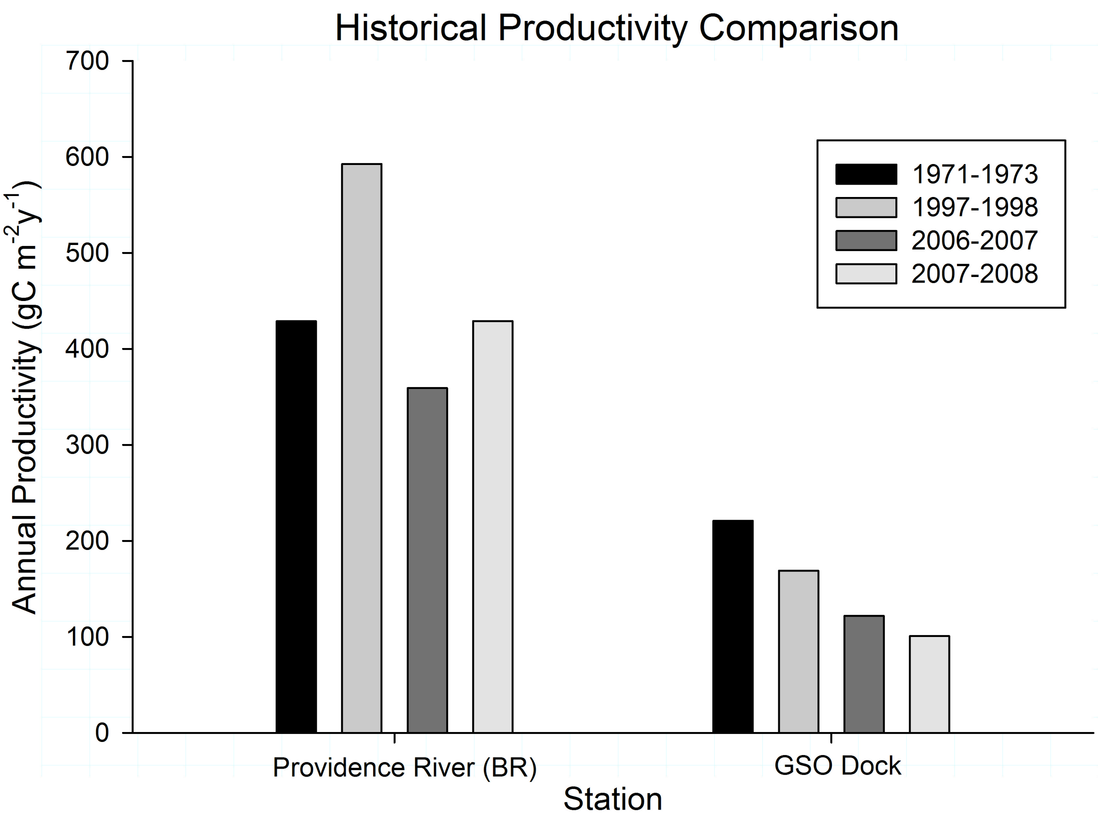

Figure 3. A historical comparison of total annual aerial productivity in the Providence River and the Lower West Passage of Narragansett Bay was made by examining, data from a recent survey, 2006-2008, (Smith unpublished data) and two previous surveys, 1971-1973 (Oviatt et al. 1981) and 1997-1998 (Oviatt et al. 2002). Data from 2006-2008 are at Bullocks Reach (Figure 1) and GSO Dock (Figure 1). Further detail of stations from previous surveys can be found in Oviatt et al (1981 & 2002).

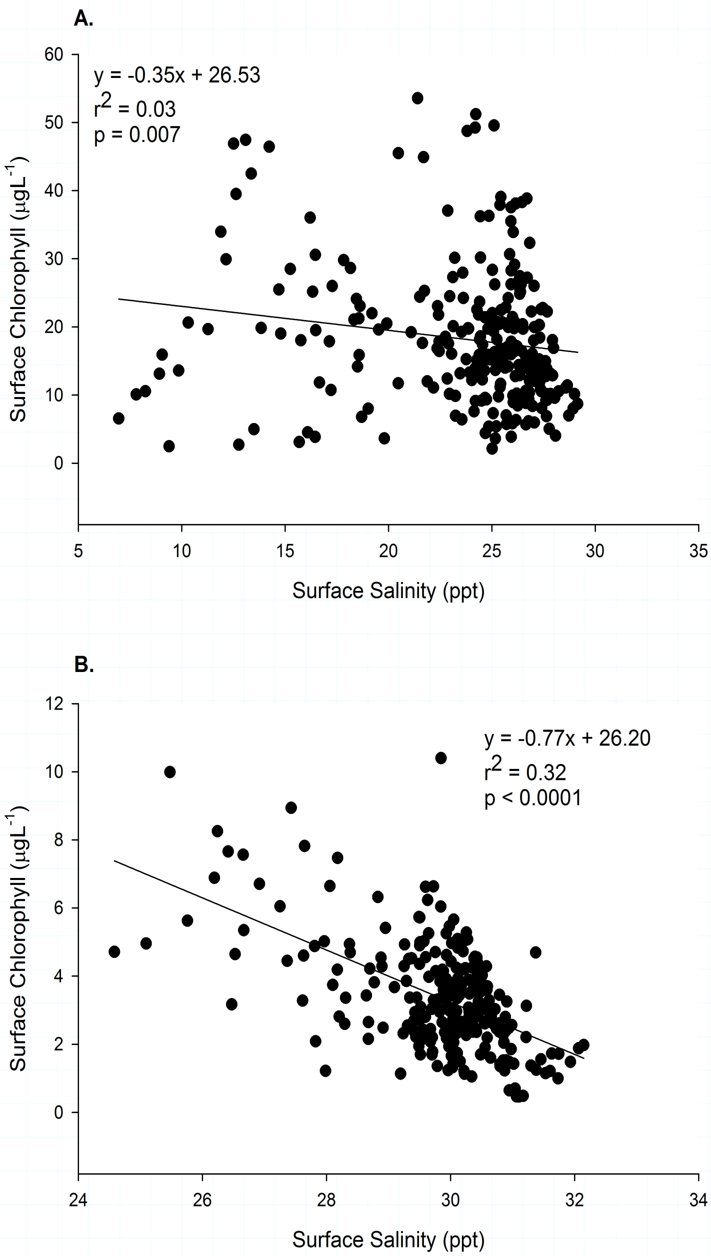

Figure 4. Summer Surface Salinity and Surface Chlorophyll. A) Providence River showed a poor relationship between surface salinity and precipitation (simple linear regression $r^2 = 0.03$ $p = 0.007$). B. Lower West Passage showed a significant relationship between surface salinity and precipitation (simple linear regression $r^2 = 0.32$ $p < 0.0001$). Data points used are from June, July, and August for 2001-2003, 2005-2006, and 2008. Data accessed from www.narrbay.org.

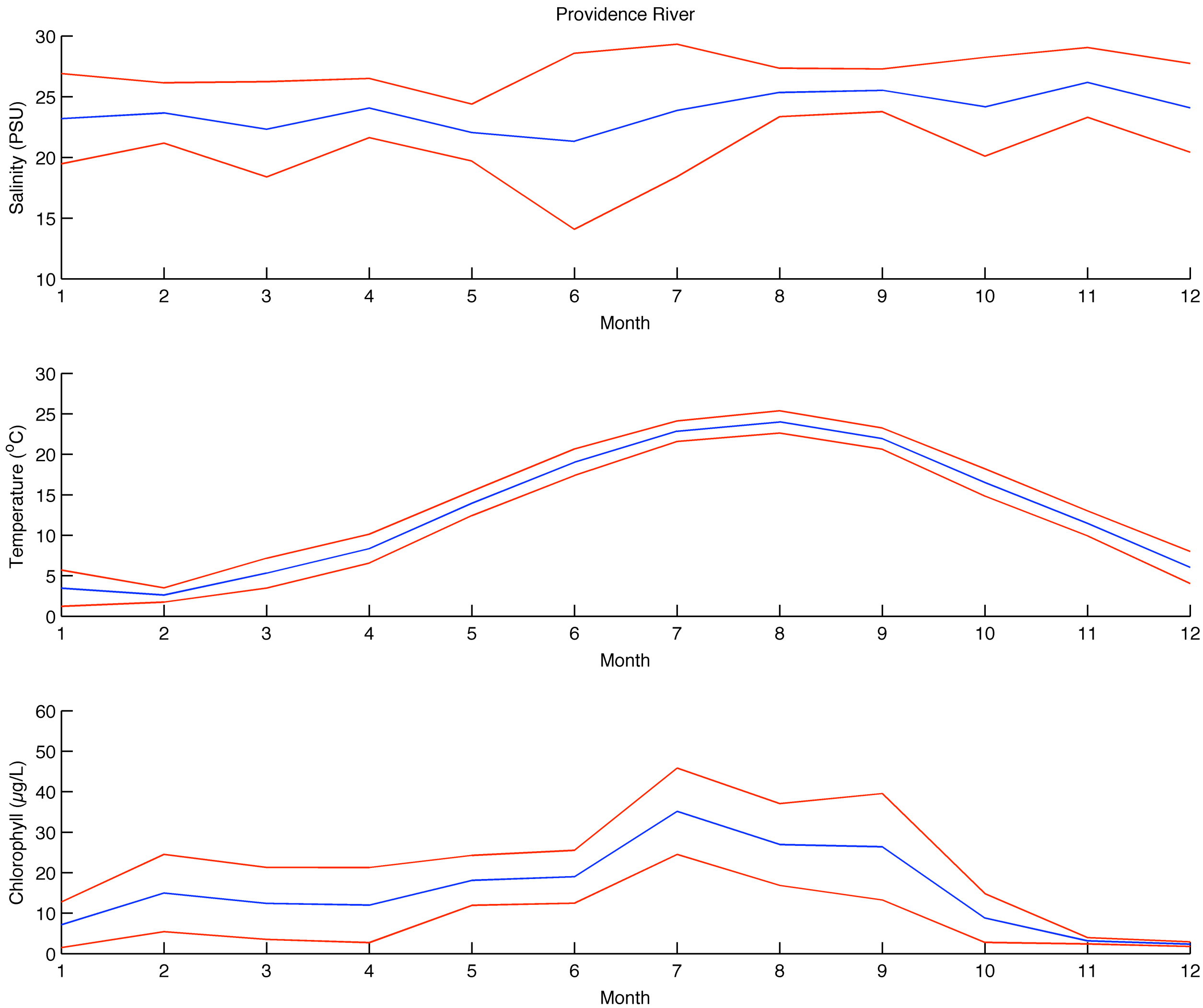

Figure 5. The 1998 to 2008 mean +/- 1 standard deviation of surface salinity, surface chlorophyll and chlorophyll concentration at the chlorophyll maximum layer for each month in the the Providence River (Figure 1)

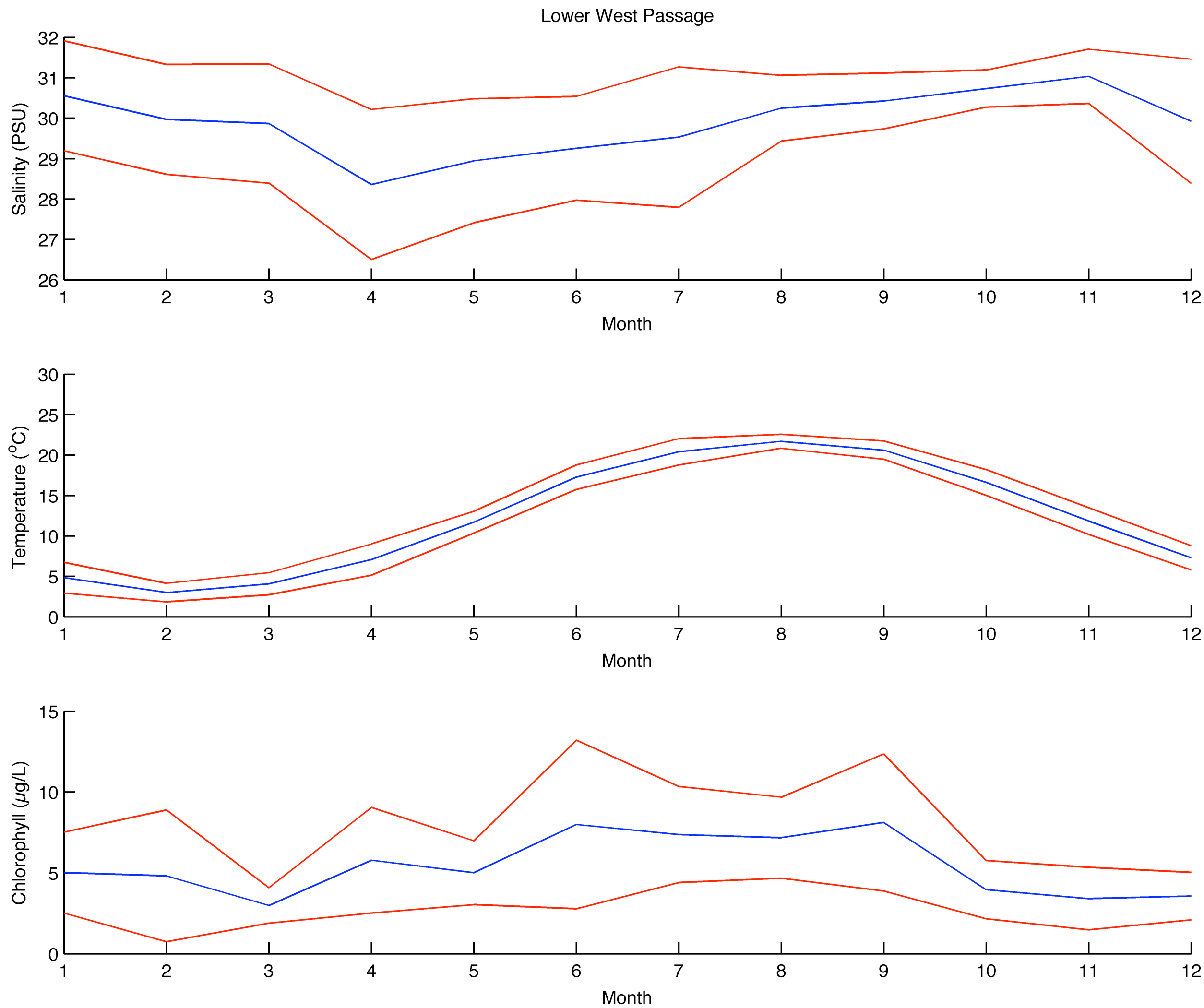

Figure 6. The 1998 to 2008 mean +/- 1 standard deviation of surface salinity, surface chlorophyll and chlorophyll concentration at the chlorophyll maximum layer for each month in the the Lower West Passage (Figure 1).

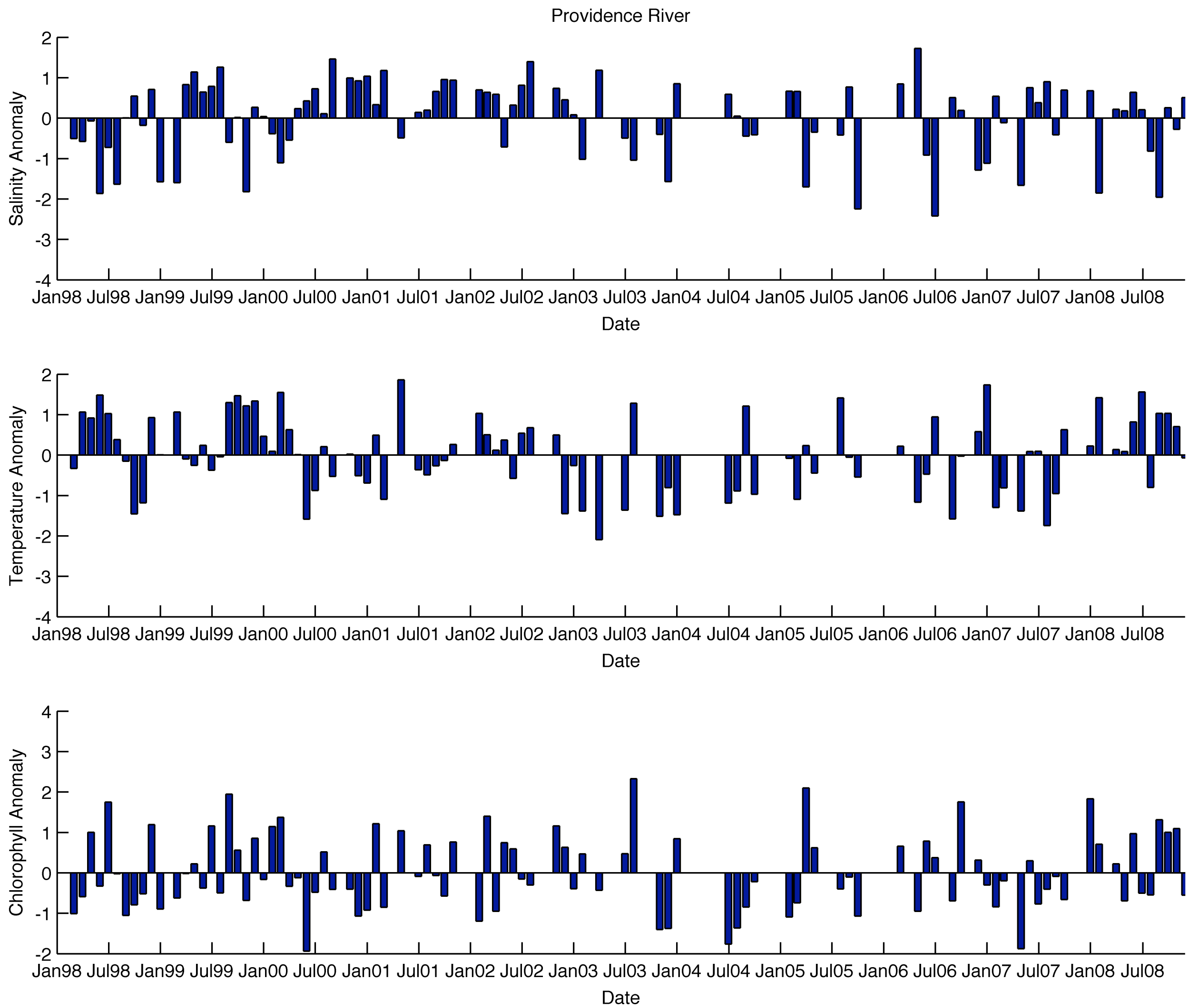

Figure 7. The 1998 to 2008 monthly anomalies for surface salinity, surface chlorophyll and chlorophyll concentration at the chlorophyll maximum layer for each month in the the Providence River (Figure 1). The anomalies are calculated as the difference between the regional mean for that year minus the mulityear mean (Figure 9), divided by the standard deviation of the muliyear mean. A value greater than +1 or less than -1 indicates the anomaly is larger than 1 standard deviation. Months with no bars inidcate holes in the coverage.

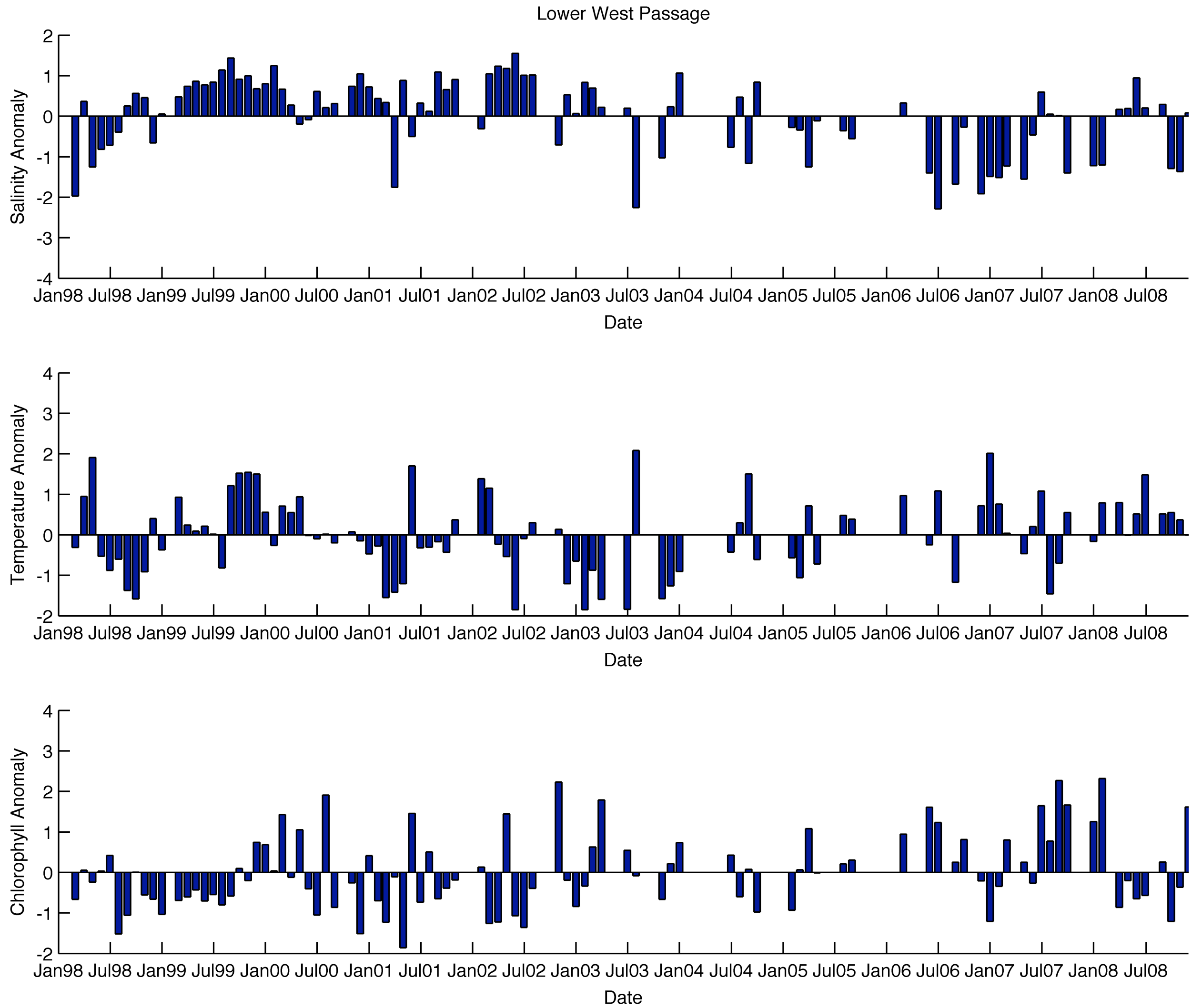

Figure 8. The 1998 to 2008 monthly anomalies for surface salinity, surface chlorophyll and chlorophyll concentration at the chlorophyll maximum layer for each month in the the Lower West Passage (Figure 1). The anomalies are calculated as the difference between the regional mean for that year minus the mulityear mean (Figure 11), divided by the standard deviation of the muliyear mean. A value greater than +1 or less than -1 indicates the anomaly is larger than 1 standard deviation. Months with no bars inidcate holes in the coverage.

Discussion

Changing climate means more than changing temperature. It also brings with it changes in wind, rainfall, and cloud cover resulting in complex and difficult to predict effects on marine ecosystems.

The complex interaction of variables is exemplified by the changes in productivity that have been reported in Narragansett Bay and the difficulty that researchers have had in identifying the cause. One aspect of the changes in productivity is a decline in annual productivity and chlorophyll in the mid-Bay (Li and Smayda 1998, Fulweiler et al. 2007, Nixon et al. 2009). Another aspect is a reduction in the winter-spring bloom (Li and Smayda 1998, Keller et al. 1999, Oviatt et al 2002). These two changes are related since the winter-spring bloom contributed a significant fraction of the annual total biomass and productivity (Pratt 1965, Li and Smayda 1998, Oviatt et al. 2002). These observations are supported by our own analysis showing a decrease in productivity in the Lower Bay (Figure 3) and a lack of a winter-spring bloom throughout most of the *Mariner Shuttle* survey (Figures 5 and 6). Though notably, the Providence River does not seem to follow the same pattern (Figure 3) with no clear long-term change in productivity.

The cause of the decline in the winter-spring bloom has not been definitively established. Most of the proposed hypotheses suggest climate variability as the underlying cause. One possibility is that an increase in grazing rates of zooplankton due to increased winter water temperatures has suppressed the winter-spring bloom. This effect was demonstrated in mesocosm experiments (Keller et al. 1999). Another hypothesis is that increased cloud cover during the winter-spring period has reduced the winter-spring bloom through light limitation (Nixon et al. 2009). This has also been proposed as a cause of reduced chlorophyll in the mid-Bay (Fulweiler et al. 2007, Li and Smayda 1998, Nixon et al. 2009). It is important to recognize that these mechanisms are not mutually exclusive and that a combination of any of them could be responsible for changes in the annual productivity cycle within the Bay.

The climate data presented in Figure 2 support the notion that increasing temperature or increasing cloud cover might both be related to changing productivity cycles in Narragansett Bay. However, there was not a clear relationship between temperature anomalies and chlorophyll during the winter-spring bloom period (Figure 7, 8) as one might expect if temperature control of grazing were the sole factor that had caused the decline of the winter-spring bloom.

The lack of a winter-spring bloom in most of the *Mariner Shuttle* data also supports the idea that the overall annual decline in productivity in the Lower West Passage can in part be explained by a reduction of the winter-spring bloom. A notable exception is that while there was not a clear winter-spring bloom in the Providence River (Figure 5), productivity did not decline (Figure 3) as it did in the Lower Bay. Overall chlorophyll in the Providence River is much higher than in the Lower Bay (Figures 5 and 6) as is total productivity. It may be that in the Providence River the seasonal distribution of productivity has shifted but the total productivity is largely unchanged. Such a shift in phenology would be an important concern since it would alter when organic matter is delivered to feed the ecosystem and this would impact the lifecycles of higher trophic levels. If a greater fraction of productivity is occurring in the summer months in the

Upper Bay and Providence, this could also increase the occurrence of the hypoxic events in that region.

Another regional contrast in the Bay is the difference in the relationship between surface salinity and chlorophyll in the Lower West Passage compared to the Providence River. The relationship between chlorophyll and surface salinity (Figure 4) in the Lower Bay during the summer can be in part explained by an increase in stratification and water column stability leading to enhanced retention of phytoplankton in the euphotic zone. Another factor is that the source of most of the low salinity water is at the head of the estuary where the major river and wastewater nutrient sources are concentrated (Nixon et al. 1995). The weak chlorophyll-salinity relationship in the Providence River is likely due to the fact that this region is always more strongly stratified than the Lower West Passage. Once stratification crosses a threshold where it is sufficient to retain phytoplankton near surface, further increasing stratification would then have less benefit to phytoplankton, and at some point a high enough fresh water flux would dilute the plankton through higher flushing rates. Thus, in the Providence River, other factors such as light availability or grazing might be expected to have more relative importance in controlling phytoplankton biomass than changes in surface salinity enhancing the retention of phytoplankton cells.

The relationship seen in Figure 4 for the Lower West Passage between decreased salinity and increased chlorophyll coupled with the long-term increase in precipitation (Figure 2) might lead one to expect that productivity at this location would have increased but instead a decrease (Figure 3) was observed. Increasing precipitation should also act synergistically to enhance stratification with the observed decrease in wind-speed over the same period (Figure 2). Thus, another factor or factors must be acting in opposition to the increase in stratification to explain the decline in productivity in the Lower Bay. One possible explanation is that increased cloudiness (Figure 2) has reduced the light available for photosynthesis (Nixon et al. 2009). Other explanations such as climate driven enhancement of grazing rates (Keller et al. 1999) may also be at work. The Providence River, which is more stratified, has a shallower euphotic zone, and greater nutrient inputs, exhibited no clear decline and appears to be responding differently to the same climatic stressors. These examples illustrate that the effects of climate change on primary productivity are difficult to predict using single variables or simple relationships and that a complex interaction of several parameters must be considered. It also illustrates that different climatic parameters will have different degrees of influence in varying environments (i.e. the Providence River vs. the Lower Bay).

Examination of the differences in the annual cycle of salinity between the Providence River and Lower West Passage shed some light on why the two regions respond differently to climatic stressors. The earlier minima in salinity in the Lower West Passage (Figure 6) relative to the Providence River (Figure 5) cannot be due to increased freshwater flow alone because the largest sources of freshwater enter in the north of the estuary (Figure 1). If freshwater flow was the only factor, the period of lowest salinity in the lower bay could never precede the Providence River. Since the surface salinity is a function of both freshwater input and mixing of low salinity surface water entering at the head of the estuary with the higher salinity bottom water entering from the mouth of the estuary, the most likely explanation is that there was reduced mixing in April relative to later in the spring when the peak occurred in the Providence River. This is supported by an increase in the surface salinity difference down Bay between these two periods. When salinity in the Lower West Passage was at its lowest in April, the salinity was 4.29 psu greater than the Providence River during that same month. In June the difference was 7.92 psu between the two regions. A similar north to south pattern in salinity is also seen in the East Passage with the *Mariner Shuttle* dataset, with the peak in the lower East Passage being coincident with the one in the Lower West Passage.

There was greater month-to-month variability in surface salinity anomalies in the Providence River (Figure 7) compared to the Lower West Passage where clear wet and dry periods were apparent. This can be understood from the fact that the Providence River is close to the source of the freshwater input, shallower, and lower in area and volume than the southern portion of the Bay. This allows the Providence River to be more easily perturbed by individual rainfall events, while the Lower Bay surface salinity is more indicative of overall wet or dry periods. This is also why the standard deviation is larger for salinity in the Providence River (Figure 5) than in the Lower West Passage (Figure 6).

The differences in the seasonal salinity cycle with its implications to mixing and stratification and possible effects on plankton distribution may help explain some of the differences between long-term trends in annual phytoplankton productivity and phenology in the Providence River vs. the Lower West Passage. It also helps explain why average chlorophyll (Figure 5) in the Providence River also has such a high standard deviation.

Changes in salinity, temperature, cloud cover and winter-spring bloom patterns in Narragansett Bay between the 1960 and the 2008 may be related to a phase shift in the winter (Dec-March) NAO index from the negative to the positive phase over the same period. A positive NAO index is typically associated with warmer, wetter winters in Narragansett Bay. This does not mean that changes to the NAO are an alternative explanation to long-term climate change, but rather that a shift in the winter NAO may be a mechanism through which climate change is affecting the region.

Summer hypoxic events have become common in upper portions of Narragansett Bay and are likely related to increased stratification from increased summer rainfall events (Figure 2), increased temperature (Figure 2) and summer organic matter loading from phytoplankton blooms supported by anthropogenic nutrient sources. Warmer temperatures are known to promote hypoxia through reduced oxygen solubility and increased respiration rates so hypoxia is likely to increase in frequency and severity if warming trends continue. Susceptibility to hypoxia would be mitigated if the excess production of organic material due to eutrophication were reduced in the higher risk portions of the Bay. The State of Rhode Island now requires wastewater treatment plants to include nitrogen reduction technologies. The first plant upgrades to meet this requirement went online in 2006 with further plant upgrades underway. Nitrogen reduction is intended to mitigate eutrophication in the Upper Bay and reduce the risk of hypoxic events. This may help offset increased hypoxia risks due to climate, and could act in synergy with climate induced changes to productivity in the Lower Bay.

Conclusions

Our data supports the finding that the winter-spring bloom in Narragansett Bay is now reduced compared to historical patterns (Pratt 1965). This may be explained by changing climate patterns, including increased cloud cover and reduced available light. Our analysis also supports a decline in productivity in the Lower Bay similar to findings by others (Li and Smayda, Fulweiler et al. 2007, Nixon et al. 2009), but we find that the Providence River did not exhibit the same decline. This shows that productivity in the less saline, more stratified, more nutrient enriched and generally shallower Providence River responded differently to same climatic stressors experienced by the Lower Bay. Climate driven decreases in productivity previously reported in the lower and mid Bay cannot be applied to all regions of Narragansett Bay. With no decrease in productivity, increasing temperatures and precipitation might also increase the risk of hypoxia and it appears that nutrient reductions in the Providence River are imperative to mitigate hypoxia. It is unclear how these reductions will affect the Lower Bay where a reduction in productivity has already been observed.

Acknowledgements

We wish to the thank Capt. Tom Puckett, Capt. Rick Mello, Capt. Ken Benson, Jack Jossi and Heather Stoffel for their assistance.

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