HYPOXIC CONDITIONS IN NARRAGANSETT BAY DURING THE SUMMER OF 2001

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ABSTRACT:

How hypoxic is Narragansett Bay? To address this question, I examined data from multi-institutional water quality monitoring surveys conducted in mid July, August, and September, 2001. Each survey is a snapshot (sampled in less than 7 hours) with the water column at over 60 locations throughout Narragansett Bay. Data collected continuously throughout the summer from the surface and bottom at 3 locations provided temporal context for the snapshot surveys. Narragansett Bay is a partially to well-mixed estuary and thus hypoxia is expected to be minimal. However, we found that hypoxic conditions were extensive and persistent in Upper Narragansett Bay during the summer of 2001. The hypoxic waters formed in shallow water near the head of the estuary and were subsequently advected into adjacent regions of the bay along surfaces of constant density. The isopycnal distribution of dissolved oxygen implies that the dominant source of hypoxic water was bottom decomposition and respiration due to high levels of organic matter and nutrient loading on the shallow flats near the head of the estuary. We observed that a high bottom oxygen demand and stratification of the upper 3 meters of the water column were both crucial for the development of hypoxia.
1. INTRODUCTION:

Hypoxia is a subject of increasing concern in coastal ecosystems. As human populations in coastal regions continue to grow, anthropogenic inputs of nutrients and organic matter alter the metabolism coastal environments. One frequently consequence of nutrient loading and eutrophication is oxygen depletion of subsurface waters. Major ecological problems including mass mortality of marine organisms and decline in fisheries production have been associated with hypoxia in many parts of the world (Baden et al. 1990a,b; Diaz & Rosenberg, 1995; Lu and Wu, 2000). While hypoxic environments have existed through geological time, the severity, frequency, duration, and spatial coverage of hypoxic conditions has been increasing at an alarming rate due to human activities (Diaz & Rosenberg 1995). In some coastal waters anthropogenic impacts act to enhance natural oxygen depletion during summer months, while in others current hypoxic conditions are believed to be a historically unprecedented phenomenon (Rosenberg et al. 1991; Pihl et al. 1992; Hoback & Barnhart, 1996; Richardson & Jørgensen 1996). Anthropogenically induced hypoxia has been documented as a serious environmental threat in many coastal waters and estuaries including the Gulf of Mexico, Chesapeake Bay, and Long Island Sound (NRC, 2000). Based upon the physical characteristics of Narragansett Bay, oxygen depletion in subsurface waters is expected to be minimal, however, the magnitude of anthropogenic nutrient inputs to the system has undoubtedly greatly altered the Bay’s metabolism (Nixon et al. 1995) and thus increased the potential for hypoxia. Recently observed fish kills have sparked concerns that hypoxia may be a significant problem in Narragansett Bay during the summer months. The concern has motivated a variety of water quality monitoring efforts within the Bay including those upon which this study is based. The main source of data for this study is the result of a series of spatial surveys conducted during the summer of 2001.
1.1. Narragansett Bay:

Narragansett Bay (Fig. 1.1) is a large coastal embayment and estuary complex located in southern New England (USA). The water area of Narragansett Bay\(^1\) is approximately 328 km\(^2\) with an average depth of 8.6 m (Chinman & Nixon 1985). The Bay receives runoff from a predominantly urban watershed encompassing 4,674 km\(^2\) only 40% of which lies within Rhode Island and the remaining 60% in Massachusetts (NEP, 2002). This watershed is home to over 2 million people making it one of the most densely populated estuarine watersheds in the nation (NBEP, 2002). Narragansett Bay is generally classified as a partially to well-mixed estuary with relatively low freshwater inputs (average 105 m\(^3\)/s) most of which enters over dams (Pilson, 1985a; Ries, 1990). The low overall freshwater inputs contribute to high salinities and well mixed to weakly stratified conditions observed throughout most of the bay (Nixon \textit{et al.} 1995). However, an estimated 40% of freshwater inputs to Narragansett Bay enter through the Providence River (Asselin & Spaulding, 1993) contributing to stronger stratification in the Providence River as compared to the rest of the bay.

1.2. Hypoxia and Eutrophication:

The development of hypoxia in estuarine systems is often a consequence of anthropogenic eutrophication. The simplest definition of eutrophication is “An increase in the rate of supply of organic matter to an ecosystem” (Nixon 1995). Organic matter in the system can increase either from increased carbon fixation by primary producers within the system (autochthonous carbon) or an input of organic matter from outside the system (allochthonous carbon). In Narragansett Bay primary production is the major source of organic carbon, making up approximately 4/5 of the total organic carbon input to the bay (Nixon \textit{et al.} 1995). Eutrophication is accompanied by an increased demand for oxygen within the water column due to respiration by the large biomass of organisms supported in the nutrient loaded system and respiration of bacteria that consume organic

\(^{1}\) Narragansett Bay proper (East and West Passages from the mouth to Conimicut Point including side bays and harbors), the Providence and Seekonk River estuary, and Mount Hope Bay and the Taunton River estuary. The Sakonnet River was excluded due to restricted hydraulic connection with the rest of the bay.
Figure 1.1: Narragansett Bay, RI
matter during the process of decomposition. If this increased biochemical oxygen demand (BOD) is not offset by an increased oxygen supply through photosynthesis or mixing processes, hypoxia results (Richardson & Jørgensen 1996; NRC, 2000).

1.3. Nutrient Inputs:

The limiting nutrient in marine and estuarine systems is typically nitrogen thus nitrogen inputs to Narragansett Bay are likely responsible for the high levels primary productivity occurring within system. Detailed reconstructions of the historical nutrient inputs to Narragansett Bay over the past 250 years indicate that Narragansett Bay currently receives a startling five times more dissolved inorganic nitrogen (DIN) and twice as much dissolved inorganic phosphorus (DIP) as it did under prehistoric conditions (Nixon 1997).

In Narragansett Bay, land drainage and upstream sewage and fertilizer are the major sources of nitrogen to the system with rivers being the main pathway by which this nitrogen enters the system (Nixon et al. 1995). Nitrogen fluxes are strongly correlated with river flow and the variation in the amount of nitrogen entering the bay from land drainage between wet and dry years indicates that non-point sources\(^2\) of this nutrient are significant (Nixon et al. 1995).

A more recent study examining the relative importance of different nutrient sources to Narragansett Bay separated out the influence of all Waste Water Treatment Facilities (WWTFs) in Rhode Island, both those that discharge to rivers and directly to the bay. The results of this study indicate that WWTF effluent contributes and estimated 66% of the total nitrogen entering the Upper Bay\(^3\) with an additional 30% contributed by non-point sources through freshwater inputs (Liberti, 2000).

\(^2\) In Nixon et al., 1995 only WWTFs discharging directly into Narragansett Bay were included as point-sources of nitrogen and all upstream WWTF discharge was considered a non-point source.

\(^3\) In Liberti, 2000 the Upper Bay is defined as the region north of Prudence Island.
1.4. Development of Hypoxia:

Although the high oxygen demand associated with eutrophication increases the potential for hypoxia within a system, stratification of the water column directly controls the development of hypoxic conditions by restricting the supply of oxygen to bottom waters. There are three sources of oxygen to the water column: photosynthesis, diffusion from the atmosphere, and advection of oxygen rich water from surrounding regions. Of these sources, the two most important are photosynthesis and diffusion both of which are closely linked to the surface (Richardson & Jørgensen, 1996). Thus, the regions in which hypoxia is most likely to develop are those where surface and bottom waters are separated from one another by a steep density gradient, or pycnocline, that prevents down-mixing of oxygen rich surface waters. The density of water is determined by its temperature and salinity characteristics (cold, salty waters are the most dense) with salinity dominating in estuarine systems. In stratified estuarine systems the mixed layer above the pycnocline exhibits relatively homogeneous physical characteristics due to mixing driven by surface winds. The characteristics of the mixed layer are largely determined by the salinity, temperature, and oxygen inputs it receives through direct contact with the atmosphere. In contrast, salinity, temperature, and oxygen characteristics of water below the pycnocline are relatively conservative, changing mainly through processes occurring within the water (respiration), and mixing with surrounding waters.

Relatively small freshwater inputs to Narragansett Bay mean that it has a high average salinity (27-31 ‰ in the bay proper) and stratification of the water column in most of the bay is usually minimal (Nixon et al. 1995). However, the high salinity also means that there is a large difference in density between riverine inputs and the rest of the water column. Strong pulses of fresh water input following precipitation events may consequently tend to spread out over the surface of the estuary forming a transient lens of low salinity water with an associated strong, shallow pycnocline. These transient stratification events in combination with the effects of anthropogenic eutrophication

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4 Density is a non-linear function of temperature and salinity that can be calculated using a lengthy formula (Pond & Picard, 1991)
could set the stage for the development of hypoxic conditions in Narragansett Bay during the summer months when temperature differences between surface and bottom water reinforce salinity related stratification.

1.5. Biological consequences of Hypoxia:

Hypoxia can have a wide range of negative impacts on the biological community. Severe hypoxia is associated with fish kills and mass mortality of benthic invertebrates (Baden et al. 1990a,b; Diaz & Rosenberg, 1995; Diaz, 1998; Lu and Wu, 2000; Wu, 2002). Even moderate hypoxia can reduce growth rates of marine organisms, cause shifts in the benthic and pelagic community structure, and alter predator-prey interactions (Diaz and Rosenberg, 1995; Breitburg et al., 1997; NRC, 2000; Thursby et al., 2000).

Hypoxia plays a major role in structuring coastal communities because species differ in their sensitivity to oxygen depletion (NRC, 2000). Finfish and pelagic species exhibit the lowest tolerance for hypoxic conditions with larvae of all taxa being the most sensitive life stage (Thursby et al., 2000; Miller et al., 2002). Possibly due to their low tolerance for hypoxia, reduction of fish biomass has been generally observed in hypoxic areas (Dyer et al., 1983; Rosenberg & Loo, 1988; Pihl et al., 1991; Baden et al., 1990a,b).

Species diversity and richness are reduced as the novel disturbance regime caused by hypoxia eliminates sensitive species and encourages the proliferation of a few tolerant species. Where hypoxia is a recurrent problem, benthic and pelagic communities tend to shift from domination by large, long-lived species to domination by more tolerant or opportunistic, short-lived species (Pearson & Rosenberg, 1978; NRC, 2000). These shifts occur at all trophic levels as suspension feeders are replaced by deposit feeders, macrobenthos replaced by meiobenthos and metazoans, and the phytoplankton community becomes dominated by microflagellates and nanoplanckton (Josefson & Widbom, 1988; Diaz & Rosenberg, 1995; Levin 2001). Hypoxia not only effects community structure but also the tropodynamics of marine ecosystems as the relative importance of specific trophic pathways is altered (Wu, 1982; Breitburg et al., 1994).
Given the evidence from this multitude of studies on the impacts of hypoxia, the importance of oxygen for maintaining healthy coastal communities and fisheries is clear. The EPA considers hypoxia to be “a major concern” in estuarine waters along the Atlantic coast (Thursby et al., 2000). Currently, an estimated 25% of coastal waters between Cape Cod and Cape Hatteras are exposed to some degree to low oxygen conditions\(^5\) (Strobel et al., 1995) and there is good reason to believe that the problem hypoxia will only continue to spread unless actions are taken to reduce nutrient inputs and other human impacts to coastal waters (Wu, 2002).

1.6. Definition of hypoxia:

There is currently no universally agreed upon definition of hypoxia. A water mass is considered to be hypoxic when the dissolved oxygen concentration falls below a critical level. Many studies have used 2 mg/L (\(\approx 27\%\) air saturation)\(^6\) as the cut off for designating conditions as hypoxic because of severe declines in the diversity and abundance of species observed in systems that fall below this level (Pihl et al., 1991, 1992; Schaffner et al., 1992; NRC, 2000). Other studies, however, have revealed that 2 mg/L might not be the universal threshold. In Long Island sound the threshold level for finfish and squid was shown to be 3 mg/L (40% saturation) (Howell & Simpson, 1994). A single, definition of hypoxia universally applicable to estuarine systems may not be appropriate if dissolved oxygen criteria are designed to minimize the negative impacts of hypoxia on the organisms living in the system.

In an attempt to define biologically significant water quality criteria for dissolved oxygen, the U.S. Environmental Protection Agency conducted a series of laboratory experiments with selected coastal and estuarine species from the cold temperate waters of the Atlantic coast (Thursby et al., 2000; Miller et al., 2002). The study was focused on sensitive species in order to describe the upper portion of the lethal range and resulted in two significant dissolved oxygen criteria recommendations: (1) DO in coastal waters

\(^5\) “Low oxygen conditions” are defined here as concentrations below 5 mg/L (\(\approx 67\%\) air saturation) which is roughly the maximum oxygen concentration shown to have negative effects on marine organisms.
\(^6\) The conversion from mg/L to % saturation used throughout this paper is specific to the range of temperature and salinity observed in Narragansett Bay during the summer of 2001 (see section 2.3)
should never fall below 2.3 mg/L (≈31% air saturation) to ensure survival of most coastal species and (2) DO should never fall below 4.8 mg/L (64% air saturation) to ensure normal growth of most coastal species (Thursby et al., 2000). The DO criteria were developed from lethality data using the same formula that the EPA uses to establish limits for toxic pollutants. The criteria developed from these experiments are applicable to estuaries and coastal waters from Cape Cod to Cape Hatteras.

For the purpose of this paper, I have chosen to adopt the 3 mg/L (40% sat) threshold determined by Howell & Simpson (1994) for Long Island Sound. There are several reasons for this choice: (1) Long Island Sound is close the Narragansett Bay and thus probably shares many species, (2) this threshold is close to the EPA recommended criteria to ensure survival of coastal species, and (3) there is evidence that estuarine communities experience hypoxia-induced stress even at oxygen concentrations greater than 3 mg/L (Breitburg et al., 1997; Miller et al., 2002). A full list of the definitions and terms used in this study are outlined in table 1.6.1 (developed with guidance from Chris Deacutis, RI DEM).

Table 1.6.1:

<table>
<thead>
<tr>
<th>Definition</th>
<th>DO (mg/L)</th>
<th>DO (% sat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-hypoxic</td>
<td>3-4</td>
<td>40-53</td>
</tr>
<tr>
<td>Hypoxic</td>
<td>&lt;3</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Severely hypoxic</td>
<td>&lt;1</td>
<td>&lt;13</td>
</tr>
<tr>
<td>Anoxic</td>
<td>&lt;0.1</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

1.7. Assumptions and Preliminary Hypotheses:

The timing of the snapshot surveys was intended to capture the worst-case hypoxia scenario for Narragansett Bay because even short and infrequent hypoxia events can have drastic consequences for the biological community. Three assumptions guided the choice of data collection dates/times. First, surveys were conducted during the summer months because warming of the water column (from the surface) reinforces salinity-dominated stratification, decreases the solubility of oxygen in the water, and
increases respiration rates and oxygen demand (NRC, 2000). Second, surveys were conducted during neap tides (minimal tidal amplitude) to reduce tidal mixing that could weaken stratification. Third, the surveys were conducted at night because the absence of photosynthetic activity removes one important oxygen source to the water but the oxygen demand created by respiration is not diminished.

Beyond the predictable physical conditions used to choose survey dates, a variety of factors may influence the development of hypoxia in Narragansett Bay. Given four key pieces of information: (1) nutrient inputs increase the oxygen demand in bottom water, (2) nutrient inputs to the bay are linked to freshwater flux, (3) stratification is a necessary condition for the development of hypoxia, and (4) stratification in an estuary is linked to freshwater flux, I was able to make several predictions about when and where the lowest DO levels would be found within the snapshot dataset collected from Narragansett Bay. I hypothesized that the lowest DO would be observed near the head of the estuary several days after a precipitation event that caused an increase in river flow. High fresh water inputs from the rivers should increase stratification near the head of the estuary as well as delivering a pulse of nutrients to the Bay that could induce a phytoplankton bloom. Several days after the nutrient and freshwater input, decomposition of organic matter from the phytoplankton bloom will raise oxygen demand while stratification remains relatively strong and these conditions will lead to oxygen depletion in waters below the pycnocline.

1.8. Research Questions:

1. Does the data available from the summer of 2001 support my preliminary assumptions and hypotheses?
2. How extensive and persistent was hypoxia during the summer of 2001?
3. What is the source of hypoxic water to Narragansett Bay: in situ formation or advection from coastal waters or riverine tributaries?
4. If hypoxia is forming within the bay, can particular regions of the bay be identified as sources of hypoxic water?
5. What insights can spatial patterns of DO throughout the Bay provide about the movement/dynamics of hypoxic waters?
2. DATA AND METHODS:

2.1. Survey Data:

The water quality monitoring surveys from which I obtained the majority of my data were a multi-institutional\(^7\) volunteer effort organized by Chris Deacutis from the Narragansett Bay Estuary Program. Surveys were conducted by 6-8 boats between midnight and 7:00 am on July 13\(^{th}\), August 15\(^{th}\) and September 13\(^{th}\) 2001. Over 80 stations within Narragansett Bay were monitored on each survey date (see fig. 2.1.1 for station locations\(^8\)). YSI probes were used to take measurements of temperature, salinity, and dissolved oxygen and depth at approximately 1.5-meter depth intervals from surface to bottom for each station. From the temperature and salinity data, I was then able to calculate density assuming pressure equal to zero (Unesco, 1981). Consistent with most estuarine and coastal research sigma-T (\(\delta_t\))\(^9\) units for density are used in this study.

2.2. Uncertainty, Corrections, and Filtering of Survey Data:

During the snapshot surveys, each boat group participated in at least one dip-in (sampling of a common bucket) with one or more boat groups so that the measurements of temperature, salinity, and DO made in the same water by the different instruments could be compared. A summary of the dip in data is included in tables 2.2.1-2.2.3.

In addition to the dip-ins, several stations were monitored by two boat groups (at different times) during each survey. This additional data allowed more in-depth comparison of instrument performance and qualitative assessment of changes due to the time of the tidal cycle.

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\(^7\) Participants from the following institutions volunteered boats, equipment, and time during the summer of 2001: Rhode Island Department of Environmental Management (RIDEM), Roger Williams University (RWU), University of Rhode Island (URI), Massachusetts Coastal Zone Management (CZM), Brown University (BRN), and Save the Bay (STB)

\(^8\) All survey stations located in Mount Hope Bay are omitted from this map (data was not used for this study due to instrument error).

\(^9\) Sigma-T units are defined as the difference in g/L between the density of the water in question and the density of fresh water at 5 °C (=1000 g/L).
Figure 2.1.1: Map of Narragansett Bay
Includes important landmarks, the regions of the bay referred to in this study, the names and locations of all survey stations used, and the locations of the transects described in this study.
Table 2.2.1: July Dip-ins
DO, salinity, and temperature data from all dip-ins with the mean and standard deviation calculated for each station. Starred values indicate sufficient instrument error to warrant exclusion of the data or application of a correction factor where possible.

<table>
<thead>
<tr>
<th>Dip-in Site</th>
<th>Boat Group</th>
<th>DO (% sat)</th>
<th>Salinity (%)</th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Hope Bay</td>
<td>CZM</td>
<td>122.6</td>
<td>25.90</td>
<td>22.05</td>
</tr>
<tr>
<td></td>
<td>RWU II</td>
<td>93.5</td>
<td>28.87</td>
<td>22.17</td>
</tr>
<tr>
<td>Statistics</td>
<td>Mean</td>
<td>108.1</td>
<td>27.34</td>
<td>22.11</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>20.6*</td>
<td>2.10*</td>
<td>0.09</td>
</tr>
<tr>
<td>Prudence Island</td>
<td>URI</td>
<td>90.1</td>
<td>27.30*</td>
<td>20.35</td>
</tr>
<tr>
<td></td>
<td>RWU I</td>
<td>92.9</td>
<td>28.22</td>
<td>20.30</td>
</tr>
<tr>
<td></td>
<td>DEM I</td>
<td>92.8</td>
<td>28.01</td>
<td>20.35</td>
</tr>
<tr>
<td>Statistics</td>
<td>Mean</td>
<td>91.9</td>
<td>27.84</td>
<td>20.33</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>1.6</td>
<td>0.48*</td>
<td>0.03</td>
</tr>
<tr>
<td>Upper Bay</td>
<td>BRN</td>
<td>118.2</td>
<td>24.30</td>
<td>20.91</td>
</tr>
<tr>
<td></td>
<td>DEM I</td>
<td>117.3</td>
<td>23.80</td>
<td>20.88</td>
</tr>
<tr>
<td>Statistics</td>
<td>Mean</td>
<td>117.8</td>
<td>24.05</td>
<td>20.89</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.6</td>
<td>0.35</td>
<td>0.02</td>
</tr>
<tr>
<td>Providence River</td>
<td>BRN</td>
<td>96.3</td>
<td>20.43</td>
<td>20.27</td>
</tr>
<tr>
<td></td>
<td>STB</td>
<td>85.0</td>
<td>20.45</td>
<td>20.36</td>
</tr>
<tr>
<td>Statistics</td>
<td>Mean</td>
<td>90.7</td>
<td>20.44</td>
<td>20.32</td>
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<td></td>
<td>Std. Dev.</td>
<td>8.0</td>
<td>0.01</td>
<td>0.06</td>
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</table>

Table 2.2.2: August Dip-ins
DO, salinity, and temperature data from all dip-ins with the mean and standard deviation calculated for each station. Starred values indicate sufficient instrument error to warrant exclusion of the data or application of a correction factor where possible.

<table>
<thead>
<tr>
<th>Dip-in Site</th>
<th>Boat Group</th>
<th>DO (% sat)</th>
<th>Salinity (%)</th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Hope Bay</td>
<td>CZM</td>
<td>84.8</td>
<td>27.99</td>
<td>23.12</td>
</tr>
<tr>
<td></td>
<td>RWU I</td>
<td>85.9</td>
<td>28.14</td>
<td>23.12</td>
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<td>Statistics</td>
<td>Mean</td>
<td>85.4</td>
<td>28.07</td>
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<td></td>
<td>Std. Dev.</td>
<td>0.8</td>
<td>0.11</td>
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<tr>
<td>Prudence Island</td>
<td>URI</td>
<td>97.0</td>
<td>27.50*</td>
<td>21.19</td>
</tr>
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<td></td>
<td>DEM I</td>
<td>96.4</td>
<td>29.04</td>
<td>21.23</td>
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<td></td>
<td>DEM II</td>
<td>97.6</td>
<td>29.16</td>
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<tr>
<td>Statistics</td>
<td>Mean</td>
<td>97.0</td>
<td>28.56</td>
<td>21.21</td>
</tr>
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<td></td>
<td>Std. Dev.</td>
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<td>0.93*</td>
<td>0.02</td>
</tr>
<tr>
<td>Upper Bay</td>
<td>BRN</td>
<td>90.5</td>
<td>25.12</td>
<td>22.15</td>
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<tr>
<td></td>
<td>STB</td>
<td>89.5</td>
<td>25.58</td>
<td>22.07</td>
</tr>
<tr>
<td></td>
<td>DEM I</td>
<td>89.6</td>
<td>25.68</td>
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<tr>
<td>Statistics</td>
<td>Mean</td>
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<td>Std. Dev.</td>
<td>0.6</td>
<td>0.30</td>
<td>0.05</td>
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Table 2.2.3: September Dip-ins
DO, salinity, and temperature data from all dip-ins with the mean and standard deviation calculated for each station. Starred values indicate sufficient instrument error to warrant exclusion of the data or application of a correction factor where possible.

<table>
<thead>
<tr>
<th>Dip-in Site</th>
<th>Boat Group</th>
<th>DO (% sat)</th>
<th>Salinity (‰)</th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Hope Bay</td>
<td>CZM</td>
<td>100.5</td>
<td>28.71</td>
<td>22.57</td>
</tr>
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<td></td>
<td>RWU I</td>
<td>98.6</td>
<td>29.97*</td>
<td>22.75</td>
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<td></td>
<td>RWU II</td>
<td>99.7</td>
<td>28.71</td>
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<td>DEM I</td>
<td>105.5</td>
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<td>Mean</td>
<td>101.1</td>
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<td>Std. Dev.</td>
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<td>Prudence Island</td>
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<td>28.82*</td>
<td>20.95</td>
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<td>DEM I</td>
<td>95.2</td>
<td>30.20</td>
<td>20.95</td>
</tr>
<tr>
<td></td>
<td>DEM II</td>
<td>93.5</td>
<td>30.48</td>
<td>20.99</td>
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<td>Statistics</td>
<td>Mean</td>
<td>94.8</td>
<td>29.83</td>
<td>20.96</td>
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<td>Std. Dev.</td>
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<td>0.89*</td>
<td>0.02</td>
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<tr>
<td>Upper Bay</td>
<td>BRN</td>
<td>107.7</td>
<td>28.51</td>
<td>21.53</td>
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<td>21.59</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.8</td>
<td>0.15</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Figure 2.2.1: Data Corrections
Comparison of salinity measurements made by URI and DEM I at the Prudence Island dip-in and two overlapping survey stations (GRB07 & GRB09) for each survey date. The best-fit linear regression lines (with equations and R-values) are shown in red on each plot. The green dashed line on each plot indicates the 1:1 relationship expected without instrument error.
Analysis of the data obtained from the dip-ins and overlapping station indicated significant error in two segments of the data.

1. In Greenwich Bay, the instrument used by URI consistently measured low salinity with respect to the other instruments. Data from the dip-ins and two overlapping stations monitored by both URI and DEM I in all three surveys allowed me to fully characterize this offset through a representative range of salinity and formulate a correction factor with a high degree of confidence. A separate correction factor for each survey date was obtained by running a linear regression (Fig. 2.2.1) between measurements made by URI and DEM I during the dip-ins and at similar depths in the overlapping stations. This correction was then applied to all data collected by URI.

2. In Mount Hope Bay, one of the instruments used by RWU (RWU II in July and RWU I in Sep.) consistently measured high salinity with respect to the other instruments. Unfortunately, in July, neither RWU II or the other boat group (CZM) that participated in the shared dip-in, monitored an overlapping station or dip-in with any other boat group making characterization of the instrument error impossible. For the sake of simplicity, I consequently chose to exclude the data collected from Mount Hope Bay in all subsequent analyses.

Aside from the instrument errors addressed above, the precision of measurements made by all instruments appears high. For most dip-ins, the standard deviation of DO, salinity, and temperature measurements was within the error range defined in the instrument manual (± 2% sat, ± 0.3‰ and ± 0.15 °C respectively).

2.3. Comparison of Dissolved Oxygen Units:

Two common units for measurement of dissolved oxygen levels are mg/L and % saturation. Mg/L is a measurement of the absolute concentration of DO in the water, while % saturation is a measurement of DO relative to the solubility of oxygen, which is influenced by both temperature and salinity. Because the mg/L unit is not dependent on the temperature and salinity characteristics of the water in which it is measured, it
Figure 2.3.1:
In this plot, all recorded DO values (in both mg/L and % sat) from the July, Aug, and Sep. surveys are plotted against one another to determine the relationship between the two units. The resulting linear regression line (with equation and R-value) is plotted in red.

![Correlation between DO units]

Table 2.3.1: Conversion between DO units
The conversion factor used in this table is taken from the linear regression equation in Fig. 2.3.1

<table>
<thead>
<tr>
<th>From % sat to mg/L</th>
<th>From mg/L to % sat</th>
</tr>
</thead>
<tbody>
<tr>
<td>% sat</td>
<td>mg/L</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
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<tr>
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<td>10.5</td>
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<tr>
<td>150</td>
<td>11.25</td>
</tr>
</tbody>
</table>
remains meaningful for comparisons between coastal systems and thus is often preferred for biological applications. For oceanographic studies, on the other hand, % saturation units are preferred precisely because of the relationship to salinity and temperature. I have chosen to use % saturation units both because this is a study of the physical conditions and dynamics of hypoxia and because the YSI instruments we used directly measure % saturation\textsuperscript{10} and then calculate mg/L values based upon simultaneous measurements of temperature and salinity thus increasing the potential for measurement error. Both units were recorded during the surveys, so I plotted the relationship between the two and found that within, the narrow range of temperature and salinity observed in Narragansett Bay, % saturation and mg/L show a strong linear correlation (Fig. 2.3.1) enabling easy conversion from between units (Table 2.3.1).

2.4. Data analysis:

2.4.1. T-S diagrams:

T-S diagrams (temperature vs. salinity) were made using the Surfer program for all data from each survey (Figs. 3.1.1-3.1.3). Density ($\delta$) is indicated on the plots by labeled gray contour lines. DO (% sat) is indicated through the color of the data points using a similar color scale to other analyses in this study\textsuperscript{11}. T-S diagrams are often used to trace oceanic deep waters. In these cases temperature and salinity are strictly conservative because no inputs to the system occur other than mixing of different water masses with different characteristics. In a shallow estuarine system like Narragansett Bay, temperature and salinity cannot be expect to be conservative due to external inputs to the mixed layer which change temperature and salinity in situ. However, the T-S diagrams exhibit consistent organization and structure and provide important information about the relationships between temperature, salinity, density, and DO.

\textsuperscript{10} Dissolved oxygen measurements are made with a patented YSI Rapid Pulse system that measures the current associated with the reduction of oxygen (to hydroxide), which then diffuses through a Teflon membrane. The current produced by this reduction process is proportional to the partial pressure (% saturation) of oxygen in the water.

\textsuperscript{11} Orange and red indicate hypoxic conditions (<40% sat). Yellow indicates near hypoxia (40-50% sat).
In addition to compiling all data from each survey on one T-S diagram, T-S diagrams were plotted individually (Figs. 3.1.1-3.1.3) for each of the 5 regions of the bay (defined in Fig. 2.1.1) to examine the spatial patterns of water properties.

2.4.2. Transects:

Seven transects through representative regions of the bay provide a cross-sectional view of salinity, temperature, and DO distribution in the water column (Fig. 3.2.1.1-3.2.3.4). The transects were constructed by connecting stations in relatively straight lines through representative portions of the bay (see Fig. 2.1.1). The Surfer program was then used to interpolate from the scattered data points by kriging so that contoured patterns could be mapped.

2.4.3. Aerial View Maps:

Aerial view maps (Figs. 3.3.1-3.3.3) of the DO distribution on isopycnal surfaces within Narragansett Bay were created using ArcMap (a GIS program). The intention of these maps is to illustrate the spatial patterns of advection of hypoxic waters from their sources into adjacent regions of the bay. Both the transects and T-S diagrams indicate a mid-water (mid-density) oxygen minimum zone in the bay. The density of water in this oxygen minimum zone remains relatively constant between adjacent stations and shows a general pattern of increasing density as you progress seaward. From this information, and station-specific depth profiles, appropriate density surfaces were chosen to track the mid-water oxygen minimum zone throughout the bay. Linear interpolation between data points within each station was used to obtain depth, temperature, salinity, and DO values for the specific density surface. Contours of DO distribution on the density surface were drawn in the ArcMap program using the “inverse distance weighting” option for interpolation between stations. Interpolation was controlled to include no more than 3 neighboring data points within a small ellipse (semi-major axis = 9000, semi-minor axis = 5000) oriented so that its major axis was roughly aligned along the length of the Providence River (155° rotation).
2.5. Buoy Data:

The time series data collected as part of a long-term monitoring effort by Dana Kester from URI GSO provides temporal context for the snapshot surveys. I used data from one of the 5 moorings (“Bullock’s Reach”) that Dana Kester maintains in strategic locations throughout the bay (see Fig. 2.1.1. for the mooring location) Each mooring includes one near-surface and one near-bottom YSI probe that recorded temperature, salinity, DO, and depth at 15 minute intervals through the duration of the summer. The YSIs were swapped for recently calibrated and serviced instruments on a biweekly basis to maintain accuracy of the measurements.

2.6. River flow data:

Daily average river flow data (from gauging stations) was obtained from the USGS website. Only data for the Blackstone and Pawtuxet rivers was available for the period of study. Original data was in ft³/s, which I converted to m³/s for the sake of unit consistency.

2.7. Atmospheric temperature data:

Atmospheric temperature data for Providence from the summer of 2001 was obtained from a NWS/NOAA website. Average daily temperature (the simple arithmetic mean of the maximum and minimum temperature recorded for the day) was used after conversion from °F to °C for the sake of consistency.

2.8. Tide data:

Tide predictions (both tidal height and timing) from the Harbor Master Pro program for Nayatt Point, RI (located at the southern end of the Providence River) were used for the entire bay in the place of measured data.
3. RESULTS:

The data was examined in four separate formats, (1) T-S diagrams were created for each survey date to examine the relationship between temperature, salinity, density, and dissolved oxygen in a non site-specific way, (2) transects were constructed through 3 main regions of the bay for each survey date for resolution of vertical and horizontal patterns of temperature, salinity, density, and dissolved oxygen, (3) the data from the three snapshot surveys was examined in the context of data collected continuously from a buoy moored in the Providence River during July, August, and September 2001, and (4) the spatial distribution of dissolved oxygen for the entire bay was mapped onto relevant density surfaces to provide an aerial view of hypoxia in Narragansett Bay during the summer of 2001.

3.1. T-S Diagrams:

It is important to remember that for estuaries, unlike the deep ocean (a more common application of T-S diagrams) T-S diagrams are not strictly conservative because estuarine waters are not isolated from sources/sinks of temperature and salinity. Solar radiation, direct contact with the atmosphere, evaporation, and precipitation at the surface of the bay all act to change the characteristics of water masses in the bay in situ and alter system from a strictly conservative mixing of two input waters.

3.1.1. Mixing lines:

The T-S diagrams for all parts of the bay in all surveys (Figs. 3.1.1-3.1.3) indicate a primary relationship between temperature and salinity. This roughly linear relationship can be interpreted as a “mixing line” between high salinity oceanic waters and low salinity waters in the Upper Bay and tributaries. Low salinity waters in Narragansett Bay were warmer than high salinity oceanic inputs during the summer of 2001 as indicated by the negative slope of the mixing line. The T-S diagrams do not show the full range from freshwater (salinity = 0 ‰) to coastal water (salinity ≈ 35 ‰). In fact, the linear
relationship between temperature and salinity only becomes apparent at relatively high salinities (>28‰ for all three months). The scatter of low salinity points from the mixing line indicates that low salinity water remains isolated from mixing processes within the main body of the estuary. A surface layer of low salinity water, isolated from deeper water by a strong density gradient, may be an important feature in some regions of Narragansett Bay. A closer look at the T-S diagrams shows that the low salinity surface water is relatively uniform in temperature (due to direct contact with the atmosphere) but encompasses a wide range of salinities.

3.1.2. Relationship between DO and density:

A relationship between DO and density is apparent in the T-S diagrams from all three summer surveys. The distribution of DO (shown in color, Figs. 3.1.1-3.1.3) exhibits a consistent pattern with hypoxic and near-hypoxic waters concentrated at an intermediate density along the mixing line. The lowest salinity surface waters are generally saturated with respect to oxygen, while high salinity coastal waters can be characterized by DO between 50 and 80% saturation. Intermediate density water only exists in the estuary where riverine and oceanic waters mix so this is an indication that hypoxic waters are forming in the bay, not entering it from either oceanic or terrestrial sources.

3.1.3. Patterns between regions of the bay:

The individual T-S diagrams for each region of the bay (Figs. 3.1.1-3.1.3) highlight the spatial heterogeneity of the system. Consistent patterns emerge that illustrate how the importance of a surface layer of low salinity water varies throughout the bay and how this may be related to hypoxia. The scatter of low salinity points divergent from the mixing line is most pronounced near the head of the estuary (Providence River, and Upper Bay) where freshwater inputs are concentrated. Closer to the mouth of the estuary, (East and West Passages) nearly all data points fall neatly onto the mixing line indicating that in these areas the water column is relatively well mixed.
Coincident with the lowest salinities in the bay, the Providence River also has the most extensive hypoxic region in all 3 surveys; nearly all of the intermediate density measurements made in the Providence River show DO values below 50% saturation. Greenwich Bay, which is shallow and receives little freshwater input, contains the warmest waters in the bay as well as an extensive hypoxic region. Stratification in Greenwich Bay may be temperature related and not dependent on low salinity surface water.

3.1.4. Patterns between months:

Comparison of the T-S diagrams from each monthly survey provides insights into how the physical condition of the estuarine system changed from month to month during the summer of 2001 and how the physical conditions may relate to the extent of the observed hypoxia.

The T-S diagrams from August (Fig. 3.1.2) show the widest range of salinity for the entire bay due to low salinity surface waters. Coincident with low surface salinities, the August survey also shows the greatest number of hypoxic and near hypoxic DO measurements made in the upper bay region.

The T-S diagrams from September (Fig. 3.1.3) exhibit the narrowest range of salinities for the entire bay due to the absence of very low salinity surface water. The September survey also indicates the fewest hypoxic or near hypoxic measurements from the upper bay and west passage, and Greenwich bay.

Water temperature patterns between months also show up in the T-S diagrams. Data from July (Fig. 3.1.1) contains the lowest bottom temperatures (as low as 16 °C) and most surface temperatures are range from 20-22 °C. In August (Fig. 3.1.2) the whole bay was markedly warmer with bottom temperatures not below 17.5 °C and most surface temperatures between 22-24 °C. In September, the temperature range between surface and bottom water is reduced due to cooling of the surface waters, which are mostly between 21-23 °C.
Figure 3.1.1: July T-S diagrams
Graphs of temperature (°C) vs. salinity (%) with density contours (δt) in gray. DO (% sat) is indicated with colored symbols for all data points. Graphs include all data from the July survey 2001 (a) combined in a single plot, and (b-f) separated into regions.
Figure 3.1.2: August T-S diagrams
Graphs of temperature (°C) vs. salinity (‰) with density contours ($\delta_t$) in gray. DO (% sat) is indicated with colored symbols for all data points. Graphs include all data from the August survey 2001 (a) combined in a single plot, and (b-f) separated into regions.
Figure 3.1.3: September T-S diagrams
Graphs of temperature (°C) vs. salinity (‰) with density contours (δt) in gray. DO (% sat) is indicated with colored symbols for all data points. Graphs include all data from the September survey 2001 (a) combined in a single plot, and (b-f) separated into regions.
3.2. Transects:

Two dimensional transects constructed through three major regions of the bay resolve the vertical and spatial patterns of temperature, salinity, and dissolved oxygen during the three surveys and provide more detailed information on the immediate conditions that coincide with the observed hypoxic events.

3.2.1. July Survey:

Shipping Channel:

In July the difference between temperature, salinity and DO patterns observed in the Providence River versus those in the Upper Bay and East Passage is significant enough to deserve separate description.

Providence River:

The Providence River section exhibits strong vertical stratification with a well-defined pycnocline located in the upper 2 meters of the water column (Fig 3.2.1.1.b). This stratification appears to be driven by salinity with a distinct lens of low salinity water at the surface overlying more saline water. Temperature decreases gradually and relatively uniformly from surface to bottom without a defined thermocline depth (Fig 3.2.1.1.a). The Providence River contains a large hypoxic and near hypoxic zone which extends from just below the pycnocline to the bottom (Fig. 3.2.1.1.c). The oxygen minimum zone is located at 3-5 m depth. Maximum oxygen depression occurs at 3-5m depth just south of Field’s Point with the lowest recorded DO concentrations at less than 20% saturation.

In the Providence River, the dredged shipping channel (10-15 m depth) is surrounded on both sides by much shallower waters (2-5 m depth). Transects constructed over these sub-tidal flats on either side of the shipping channel (Fig. 3.2.1.2) indicate that the salinity and temperature patterns observed in the shipping channel extend over the flats resulting in strong stratification even in waters less than 5 m deep. DO decreases sharply with depth below the pycnocline, reaching minimum DO concentrations near the
sediment/water-column interface (Fig. 3.2.1.2.c&d). In the Field’s point transect, DO measurements fall below 10% saturation at the bottom. The Bullock’s Cove transect shows a less severe and extensive hypoxic zone with the lowest measurements between 20 and 30% sat. In both shallow transects the hypoxic water near the sediment surface appears continuous with the hypoxic water in the adjacent portion of the shipping channel having similar temperature, salinity, and DO characteristics.

**Upper Bay and East Passage:**

The Upper Bay and East Passage portions of the shipping channel transect (Fig 3.2.1.1) show temperature, salinity, and DO patterns distinct from those seen in the Providence River. South of Conimicut Point, density stratification is reduced with a deeper (5-10 m) and less clearly defined pycnocline due to the absence of a distinct surface lens of low salinity water (Fig. 3.2.1.1.b). The thermocline is more clearly defined (Fig 3.2.1.1.a) and its depth appears to correspond closely to the depth of the pycnocline. Hypoxia is does not occur in the southern regions of the shipping channel transect (Fig 3.2.1.1.c) possibly due to the advection of well-oxygenated coastal water up the channel from the mouth of the estuary.

**Greenwich Bay:**

The Greenwich bay transect (Fig. 3.2.1.3) has three sections: 2 shallow regions extending from the northernmost and southernmost tips of the bay to the center (Apponaug and Greenwich coves respectively), and a transect extending from west to east through the deepest parts of the bay. The temperature of surface waters in Greenwich Bay average 1-2 °C warmer than the surface water in the Providence River (Fig. 3.2.1.3.a). Stratification in Greenwich Bay appears moderate in contrast to the low salinity surface lens and associated pycnocline apparent in the Providence River (Fig. 3.2.1.3.b). However, DO concentrations decrease sharply with depth in the shallow parts of the bay (Fig. 3.2.1.3.c) indicating that stratification is sufficient to isolate bottom waters from the surface source of oxygen. Minimum DO concentrations were recorded near the sediment surface with values below 10% saturation in both coves. The deeper region of Greenwich Bay shows a stronger pycnocline than the shallow regions. DO
Figure 3.2.1.1: July Shipping Channel Transect
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
**Figure 3.2.1.2:** July Providence River Shallow Transects
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
Figure 3.2.1.3: July Greenwich Bay Transects
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
Figure 3.2.1.4: July West Passage Transect
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
concentrations decrease sharply below the pycnocline and then remain relatively constant to the bottom. Hypoxia in the deeper parts of the bay is less intense than the shallow regions but DO values still fall below 30% saturation.

**West Passage:**

The West Passage transect (Fig. 3.2.1.4) shares one station with the shipping channel transect at its northernmost end (UPB10) and one station with the Greenwich Bay transect just south of Warwick point (UPB01). Stratification is strongest at the northernmost end of the transect (in the Upper Bay) with the pycnocline gradually becoming deeper and less clearly defined as you move seaward (Fig. 3.2.1.4.b). Surface temperatures in West Passage are comparable to surface temperatures in the southern part of the shipping channel transect but bottom waters are warmer as a result of shallower waters and less coastal water influx (Fig 3.2.1.4.a). An interesting bathymetric feature in the West Passage is a deep hole (depth ≈ 20 m) just south of Warwick Pt where Greenwich bay feeds into the passage. Temperature, salinity, and density surfaces roughly follow the bathymetry through this hole.

In the West Passage, (Fig. 3.2.1.4.c) a large near-hypoxic zone made up exclusively of water with density between 20 and 22 δt is located in “the hole” with a smaller mid-depth hypoxic area (DO = 30-40% saturation) at its center. The region of maximum DO depression in West Passage is continuous with the hypoxic waters seen in the overlapping Greenwich bay station (Fig 3.2.1.3.c). The absence of strong DO gradients or a well-defined pycnocline in West Passage suggest that the hypoxic water found there did not form in situ but advected from adjacent regions of the Bay.

**3.2.2. August Survey:**

**Shipping Channel:**

The temperature, salinity, and DO patterns in the shipping channel transect from August (Fig. 3.2.2.1) are similar to the patterns described for the July survey (Fig. 3.2.1.1). One major difference is that stratification of the upper 2 m of the water column in the Providence River is even stronger than in July and the surface lens of low-salinity
water driving this stratification extends approximately 5 km further down the bay through the Upper Bay (Fig. 3.2.2.1.b). As in July, south of the low salinity surface lens, the pycnocline is deeper and less clearly defined. The temperature of the entire water column (Fig. 3.2.2.1.a) has warmed 1-2 °C from July but the same pattern of a warmer and deeper mixed layer in the southern part of the transect persists with the thermocline closely linked to the pycnocline in this region.

The seaward extension of the low-salinity lens in comparison with the July survey appears to have important consequences for the DO patterns. As in July (Fig. 3.2.1.1.c), almost all of the water underlying the strong pycnocline in August (Fig. 3.2.2.1.c) is hypoxic or near-hypoxic. DO concentrations decrease sharply below the pycnocline with a DO minimum zone at 3-5 m depth. Below the DO minimum zone, oxygen levels gradually increase to the bottom but remain below 50% saturation in most cases. The region of maximum DO depression is once again located in the upper part of the Providence River but this time it extends all the way from the hurricane barrier to about 1 km south of Field’s Point with values below 20% saturation. The extension of the freshwater lens an additional 5 km into the upper bay is coincident with an extension of the hypoxic zone 5 km further down the transect relative to the July survey.

In the August, the patterns of temperature and salinity described for the shipping channel transect once again extend over the subtidal flats shown in the shallow water transects from the Providence River (Fig. 3.2.2.2) resulting in strong stratification of the water column even in waters less than 5 m deep. Below the shallow pycnocline DO falls off sharply with minimum DO values at the sediment surface (Fig. 3.2.2.2.c&f). Hypoxia at the sediment surface is much more severe in the Field’s Point transect than the Bullock’s cove transect. In both transects, the hypoxic water at the sediment surface is continuous with the DO minimum zone seen in the adjacent part of the shipping channel.

Greenwich Bay:

Patterns observed from the Greenwich Bay transect in August (Fig. 3.2.2.3) are almost identical to July (Fig. 3.2.1.3) except that the entire water column is 2-3 °C warmer and density stratification due to salinity is slightly stronger (Fig. 3.2.2.3.b). Both of the shallow transects indicate DO concentrations decreasing sharply with depth below
Figure 3.2.2.1: August Shipping Channel Transect
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L
Figure 3.2.2.2: August Providence River Shallow Transects
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L
Figure 3.2.2.3: August Greenwich Bay Transects
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
Figure 3.2.2.4: August West Passage Transect
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
the pycnocline and minimum values (<10% sat.) at the sediment surface (Fig.3.2.2.3.c) but the extent of the hypoxic zone in Greenwich Cove is markedly reduced from July. In the deeper portions of Greenwich Bay, surface waters are supersaturated with respect to oxygen but DO concentrations fall off sharply just below the pycnocline and then remain relatively constant down to the bottom.

**West Passage:**

The patterns in the west passage transect in August (Fig. 3.2.2.4) are very similar to July (Fig. 3.2.1.4) except that the entire water column here has warmed 1-2 °C (Fig 3.2.2.4.a). In August (Fig 3.2.2.4.c), a hypoxic zone is once again located in “the hole” south of Warwick Point and continuous with the hypoxic zone in Greenwich Bay (Fig. 3.2.2.3.c) with minimum DO values <30% sat.

**3.2.3. September Survey:**

The September survey provides valuable information about the development of hypoxia in Narragansett Bay because the salinity, temperature, and DO patterns observed are in sharp contrast to the July and August surveys.

**Shipping Channel:**

Data from the September survey (Fig. 3.2.3.1) shows high surface salinities in the Providence River relative to both July and August. In the absence of a surface lens of low-salinity water (Fig. 3.2.3.1.b) the pycnocline is both deeper (3-5 m at the hurricane barrier and 5-10 m just north of Popasquash point) and less clearly defined than it was in July (Fig. 3.2.1.1) or August (Fig. 3.2.2.1). Surface temperatures (Fig. 3.2.3.1.a) are generally 1-2 °C warmer in the Providence River than they were in August (Fig. 3.2.2.1) suggesting that freshwater inputs may act locally to cool the surface water shortly after precipitation events. In September the vertical extent of warm surface water closely mirrors the depth of the pycnocline. The surface mixed layer south of Conimicut Point extends slightly deeper but exhibits similar temperature and salinity characteristics to the August survey.
During the September survey an extensive hypoxic zone was present in the Providence River (Fig. 3.2.3.1.c). DO concentrations fall sharply just below the pycnocline with an oxygen minimum zone at 5-7 m and then gradually increase to the bottom. The maximum DO depression occurs between the hurricane barrier and Field’s point with values below 10% saturation.

The changes in dissolved oxygen patterns attendant upon the deeper pycnocline are visible in the shallow transects on either side of the shipping channel (Fig. 3.2.3.2). The Field’s Pt transect exhibits stratification of the water column in September but in contrast to the July and August surveys the pycnocline is only about ½ m above the sediment surface (Fig. 3.2.3.2.b). DO concentrations fall sharply below the pycnocline with a DO minimum zone at the sediment surface, but due to the depth of the pycnocline there is only a thin layer of hypoxic water overlying the sediment surface (Fig. 3.2.3.2.c). The Bullock’s reach transect does not show significant stratification over the shallow subtidal flats and there is consequently, no hypoxic region at the sediment surface (Figs. 3.2.3.2.e&f).

**Greenwich Bay:**

The September survey (Fig. 3.2.3.3) shows a deeper mixed layer than July and August and the water column overlying the shallow parts of Greenwich bay is only weakly stratified due to almost uniform salinity and temperature throughout Greenwich Bay. In the absence of stratification DO concentrations did not fall below 40% saturation in any part of Greenwich Bay (Fig. 3.2.3.3.c).

**West Passage:**

The West Passage transect (Fig. 3.2.3.4) demonstrates the same deepening of the mixed layer and weakening of the stratification relative to the August survey as observed in all other regions of the bay during September. Figure 3.2.3.4.c indicates a small near-hypoxic region in the northern part of the transect (Upper Bay) which is continuous with the hypoxic zone observed in the Shipping Channel transect (Fig. 3.2.3.1). Hypoxia is absent from the deep area south of Warwick Pt.
Figure 3.2.3.1: September Shipping Channel Transect
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
Figure 3.2.3.2: September Providence River Shallow Transects
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
Figure 3.2.3.3: September Greenwich Bay Transects
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L.
Figure 3.2.3.4: September West Passage Transect
Indicates the spatial patterns of (a) temperature, (b) salinity, and (c) dissolved oxygen (color contours). Density contours are drawn and labeled in black. Measurement locations are denoted with black points or stars for DO concentrations less than 3.5 mg/L
3.3. The Snapshot Surveys in Temporal Context:

**Dissolved oxygen:**

Dissolved oxygen data from the Bullock’s Reach time series (bottom instrument) (Figs. 3.3.1.a-3.3.3.a) documents that hypoxic and near-hypoxic conditions were persistent in the Providence River during the summer of 2001. All three months show hypoxic events of varying duration ranging from 1 to 16 days with the 12 hour averaged DO concentration not rising above 40% saturation. The surveys capture moderate DO values relative to the rest of the time series. The bottom instrument at the Bullock’s Reach mooring was well below the oxygen minimum zone shown in the shipping channel transects in all three surveys and thus was not recording the minimum DO in the Providence River. In July DO averaged over 12 hours was below 50% saturation for 22 out of 31 days and below 40% saturation 7 days out of 31. August showed the most severe and longest duration hypoxic event lasting from the 15th to the 31st. During August the 12-hour averaged DO concentration was below 50% saturation 26 out of 31 days and below 40% saturation 21 days out of 31. In September DO didn’t rise much above 50% until the 17th but all hypoxia events were of short duration lasting no more than 2 days.

**Salinity and river flow:**

The river flow data (Figs. 3.3.1.b-3.3.3.b) indicates that both the July and August surveys were conducted shortly after the peak river flow for the month thus explaining the surface lens of low salinity that was present in these surveys. The September survey, in contrast, was conducted after a protracted period of low river flow, thus the relatively weak stratification observed in September.

Salinity data from the Bullock’s Reach mooring (Figs. 3.3.1.b-3.3.3.b) demonstrates how surface and bottom salinity in the Providence River responds to changes in river flow and gives an indication of the overall degree of stratification as the difference between surface and bottom salinity. Surface salinity appears to be closely linked to river flow with salinity minima recorded 1-2 days after peak flow from the Blackstone River for all months. Bottom salinity either remains constant or increases in
response to peaks in river flow. This result can be easily explained with a standard model of estuarine circulation in which increase freshwater influx produces increased flow of surface water out of the estuary, which is balanced by increased flow of oceanic water in at the bottom. This phenomenon of coastal water intrusion acts to increase vertical stratification in the estuary.

**Temperature:**

The relationship between atmospheric and water temperature from the Bullock’s Reach mooring is illustrated by Figs 3.3.1.c-3.3.3c. Surface water appears to respond quickly and directly to changes in atmospheric temperature with a short lag of 1-2 days in all three months. The response of bottom water is mediated by the degree of stratification. When stratification is weak (as judged by the difference between surface and bottom salinity) bottom water temperature responds positively to an increase in atmospheric temperature. When temperature maxima are coincident with peaks in river flow, the increased stratification and saltwater intrusion associated with these events, masks the relationship between atmospheric temperature and bottom water temperature often resulting in cooling of bottom water after a peak in atmospheric temperature.

**Tidal mixing:**

The survey dates were chosen to correspond with neap tides (Figs. 3.3.1.d-3.3.3.d) to minimize tidal mixing, which could reduce stratification and thus prevent the development of hypoxia. In all three months, maximum tidal amplitude coincides with reduced stratification (Figs. 3.3.1.b-3.3.3.b) as judged by the difference between surface and bottom salinity measured at the Bullock’s Reach mooring. However, tidal mixing appears to have limited ability to break up hypoxic events (Figs. 3.3.1.a-3.3.3.a). Spring tides correspond to the end of hypoxic events in July (Fig. 3.3.2.a) and September (Fig. 3.3.3.a), but had little effect on the hypoxic event in August (Fig. 3.3.2.a), which persisted through the end of the month.
Figure 3.3.1: July temporal context
(a) Dissolved oxygen data from the Bullock’s Reach buoy, bottom instrument: raw data shown in red, 12 hour moving average of measurements in black. (b) Surface and bottom salinity from the Bullock’s Reach buoy; river flow from USGS gauging stations on the Pawtuxet and Blackstone Rivers. (c) Surface and bottom salinity from the Bullock’s Reach buoy; air temperature data from NWS/NOAA average daily temperature data for Providence, RI. (d) Tidal height from Harbor Master Pro predictions for Nayatt Point, Narragansett Bay, RI.
Figure 3.3.2: August temporal context

(a) Dissolved oxygen data from the Bullock’s Reach buoy, bottom instrument: raw data shown in red, 12 hour moving average of measurements in black. (b) Surface and bottom salinity from the Bullock’s Reach buoy; river flow from USGS gauging stations on the Pawtuxet and Blackstone Rivers. (c) Surface and bottom salinity from the Bullock’s Reach buoy; air temperature data from NWS/NOAA average daily temperature data for Providence, RI. (d) Tidal height from Harbor Master Pro predictions for Nayatt Point, Narragansett Bay, RI.
**Figure 3.3.3:** September in temporal context

(a) Dissolved oxygen data from the Bullock’s Reach buoy, bottom instrument: raw data shown in red, 12 hour moving average of measurements in black. (b) Surface and bottom salinity from the Bullock’s Reach buoy; river flow from USGS gauging stations on the Pawtuxet and Blackstone Rivers. (c) Surface and bottom salinity from the Bullock’s Reach buoy; air temperature data from NWS/NOAA average daily temperature data for Providence, RI. (d) Tidal height from Harbor Master Pro predictions for Nayatt Point, Narragansett Bay, RI.

(a) **Bottom Dissolved Oxygen**

(b) **Salinity and River Flow**

(c) **Water and Air Temperature**

(d) **Tidal Height**
3.4. Aerial maps of DO on Density Surfaces:

The relationship between DO and density observed in the T-S diagrams and transects for all three surveys lead to this final analysis of the spatial extent of hypoxic regions in Narragansett Bay. Both the T-S diagrams and the transects indicate a mid-water oxygen minimum zone in much of the Bay. There is no plausible explanation for the formation of hypoxic waters at mid-depth since oxygen demand is expected to be greatest near the sediment surface due to decomposition of organic matter that settles there. The only good explanation for the observed mid-water oxygen minimum zone is advection of intermediate density low DO water from surrounding areas. Observations from the Providence River support this hypothesis; the mid-depth oxygen minimum zone observed in the shipping channel appears continuous with the near-bottom hypoxic zone in the adjacent shallow regions on either side of the channel. Furthermore, the density of the oxygen minimum zone exhibits two patterns that are consistent with the advection hypothesis: (1) the density of the oxygen minimum zone is relatively constant within a given region of the bay and (2) density and DO within the oxygen minimum zone increase gradually as you move seaward suggesting that mixing with well oxygenated coastal waters is occurring.

To capture spatial patterns of DO within the oxygen minimum zone I mapped DO onto isopycnal surfaces for the entire bay. Transects, T-S diagrams, and station-specific depth profiles were used to choose the appropriate density surface for each station. The density surfaces I chose reflect the patterns of salinity, temperature, and DO observed in the bay and divisions between density surfaces do not necessarily correspond to the regions of the bay that I defined at the beginning of the study (Fig. 2.1.1). Each of the 4 density surfaces that I used were applied across a broad region of the bay with the least dense surface used near the head of the estuary (Providence River, parts of the Upper Bay, Greenwich Bay, and West Passage) and the most dense surface used in the southern parts of East and West Passages. For some of the shallow stations in Greenwich Bay and the Providence River I used bottom measurements (indicated on the maps) because the water column didn’t include the density surface chosen for that region of the bay.
The aerial view maps (Figs. 3.4.1-3.4.3) illustrate spatial patterns of DO distribution within the oxygen minimum zone and allow comparison of the aerial extent of hypoxia between survey dates. Information about sources of hypoxic water in Narragansett Bay, and spatial patterns of advection can also be inferred from these maps.

In all surveys, hypoxic waters are asymmetrically distributed between the east and west sides of the bay with the majority of hypoxic waters located on the western side of the bay. This relationship suggests that the process of advection preferentially moves the intermediate density waters to the west side of the bay. Two regions of severe oxygen depression (< 20% sat) are apparent in the July and August surveys: the northern Providence River, and western Greenwich Bay (Figs. 3.4.1 & 3.4.2). In the September survey (Fig 3.4.3) hypoxia is absent from Greenwich Bay but the extent of the hypoxic region in the Providence River is comparable to that observed in July and August. The July survey (Fig. 3.4.1) indicates the most significant intrusion of hypoxic water into West Passage (also observed in the transects and T-S diagrams) while the August survey (Fig. 3.4.2) shows the most extensive intrusion of hypoxic water into the Upper Bay.
Figure 3.4.1: Aerial extent of hypoxia in July DO (% sat) mapped onto variable isopycnal surfaces. The density of the surface used is indicated in parentheses following the station name. Bottom measurements are denoted by (b) following the station name.
Figure 3.4.2: Aerial extent of hypoxia in August DO (% sat) mapped onto variable isopycnal surfaces. The density of the surface used is indicated in parentheses following the station name. Bottom measurements are denoted by (b) following the station name.
Figure 3.4.3: Aerial extent of hypoxia in September DO (% sat) mapped onto variable isopycnal surfaces. The density of the surface used is indicated in parentheses following the station name. Bottom measurements are denoted by (b) following the station name.
4. DISCUSSION:

During the summer of 2001 hypoxia was a persistent and widespread condition in upper Narragansett Bay. The synoptic surveys conducted in July, August and September indicate extensive hypoxic zones in the Bay on all three dates. Given the temporal context provided by Dana Kester’s time series data from the same period, hypoxic conditions captured in the snapshot surveys were clearly not rare or isolated events during the summer of 2001. Although hypoxic conditions have previously been documented in Greenwich Bay (Granger et al., 2000) and the Providence River during the summer time, this phenomenon was believed confined to these regions. Our study shows that although the Providence River and Greenwich bay may be the dominant sources of hypoxic water in the bay, this water regularly advected into adjacent regions of the bay (Upper Bay, and West Passage).

4.1. Origin of hypoxia in Narragansett Bay:

The T-S diagram analysis strongly supports the conclusion that hypoxic conditions develop within Narragansett Bay rather than hypoxic water entering the Bay through one of the inputs. Hypoxic and near-hypoxic DO measurements fall within a narrow density range that is specific to the estuary in all surveys. Furthermore, the strong and consistent relationship between DO concentrations and density in all parts of the bay suggests that hypoxic water has a limited number of sources. The most severe oxygen depression occurs in the Providence River and Greenwich Bay in all surveys except September when hypoxia was absent from Greenwich Bay. These regions also show the least dense hypoxic waters in all three surveys indicating that they could be the dominant sources of hypoxic water to Narragansett bay but that hypoxic water subsequently flows into adjacent regions of the bay (Upper Bay and West Passage) gradually gaining density and oxygen as it mixes through the estuary.

The shallow regions of Greenwich Bay and the Providence River may play an important role in the formation of hypoxic waters. In both July and August surveys, some of the lowest oxygen concentrations in the bay were recorded close to the sediment
surface in waters less than 5 m deep. In the Providence River, the hypoxic zone at the sediment surface on the subtidal flats was continuous with the oxygen minimum zone observed in the deeper shipping channel. Organic matter at the sediment surface has a greater potential for a high and persistent oxygen demand than particles suspended at intermediate depth (where the oxygen minimum zone occurs in the shipping channel). Further studies on the respiration rates at this surface need to be conducted to determine whether the sediment oxygen demand in these shallow regions is sufficient for the shallow flats of the Providence River and Greenwich Bay to be the dominant sources of hypoxic water in Narragansett Bay.

4.2. Conditions for Low DO:

Water column stratification plays an important role in the development of hypoxic conditions in Narragansett Bay. The July and August surveys were both conducted shortly after precipitation events that resulted in peak fresh water inputs for the month. In both surveys strong stratification was apparent with a shallow, clearly defined pycnocline separating the surface lens of relatively fresh water from the rest of the estuary and thus preventing aeration of bottom water through contact with the atmosphere. Below the pycnocline, dissolved oxygen concentrations dropped off sharply clearly illustrating the effectiveness of this pycnocline in preventing introduction of oxygen into the bottom water.

The dependency of development of hypoxic conditions on strong stratification was further illustrated by the September survey in which stratification was notably weakened and hypoxia was not observed in Greenwich Bay, or some of the shallow regions in the Providence River.

Tidal mixing during spring tides may disrupt stratification in some areas of the bay, leading to the termination or prevention of hypoxic events. However, the effect of tidal mixing on stratification appears to be limited. Stratification observed in the Providence River in mid-August was not disrupted by spring tides and hypoxic conditions consequently persisted through the end of the month.
4.3. **Freshwater inputs, nutrient loading, and hypoxia:**

The concentration of hypoxic waters in Greenwich Bay and the Providence River appear to be a result of nutrient loading combined with stratification due to freshwater inputs and warming of the surface waters. The wastewater treatment facility at Field’s Point may play an important role in formation of hypoxic water in the Providence River due to large discharge of freshwater and nutrients which simultaneously increases stratification and oxygen demand. In Greenwich Bay, the East Greenwich WWTF and the large unsewered population (Granger *et al.* 2000) are likely significant sources of nutrients to the system.

The assymetrical distribution of hypoxic waters along the western side of Narragansett Bay may be linked to estuarine circulation. If the intermediate density hypoxic waters are generally flowing out of the bay (south) coriolis force would act to deflect this flow to the west while inflowing oceanic waters at the bottom would be deflected to the east possibly producing the observed distribution of hypoxia.
5. CONCLUSIONS:

1) During the summer of 2001 extensive hypoxic regions were present in the bay in July, August and September surveys.

2) The buoy data collected by Dana Kester suggests that hypoxic conditions were persistent in the Providence River during the summer of 2001 and that the hypoxic events we captured in our snapshot surveys were not unique or even severe in the context of the rest of the summer.

3) The hypoxic waters observed in the surveys are forming in the bay rather than being introduced with oceanic or riverine waters.

4) Strong stratification of the water column and a shallow pycnocline (both as a result of a pulse of fresh water inputs) are important conditions leading to hypoxia in Narragansett Bay.

5) The shallow regions of the bay that receive high nutrient inputs (from sewage treatment plants and terrestrial runoff) may play an important role in formation of hypoxic water in Narragansett bay but only when the shallow water above these subtidal flats is sufficiently stratified to prevent mixing and introduction of atmospheric oxygen to the bottom waters.

6) Providence River and Greenwich Bay appear to be the dominant sources of hypoxic water in Narragansett Bay, however, hypoxia was not confined to these regions during the summer of 2001; Hypoxic waters were documented in the Upper Bay and West Passage during all three surveys.

7) During the summer of 2001 hypoxic conditions were concentrated along the western side of the bay due to the patterns of advection and estuarine circulation.
REFERENCES:


Lawrence, Corey R. – The effects of increased nutrient loading on macrobenthos communities of West Falmouth Harbor, Massachusetts – Marine Biological Laboratory, Woods Hole MA


