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Hypoxic Events in Narragansett Bay, Rhode Island, during the Summer of 2001

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ABSTRACT: Bottom water hypoxic events were observed in Narragansett Bay, Rhode Island during the summer of 2001 using a towed sensor, vertical casts at fixed stations, and continuous monitoring buoys. This combination of approaches allowed for both extensive spatial and temporal sampling. Oxygen concentrations below the U.S. Environmental Protection Agency (EPA) acute hypoxia criterion of 2.3 mg l^{-1} were observed in the northern parts of Narragansett Bay, including the Providence River. We estimate 39% of the area of the Providence River was affected by acute hypoxia between July and September 2001. All other regions experienced only small areas of acute hypoxia ($< 5\%$), and no acute hypoxia was observed from Quonset Point south. The area encompassing oxygen concentrations below the EPA chronic hypoxia criterion of 4.8 mg l^{-1} was much more extensive in the upper half of Narragansett Bay, sometimes covering the majority of the region, though it is unclear whether exposure to concentrations below this criterion persisted long enough to significantly affect marine species in these areas. Vertical profiles of dissolved oxygen typically exhibited a mid water oxygen minimum near the pycnocline, followed by a slight increase in oxygen with depth. The surface waters above the pycnocline were typically supersaturated with oxygen. The northern portions of the Bay where the most extensive hypoxia was observed corresponded to the regions with both the greatest thermohaline stratification, the highest nutrient inputs, and the highest primary productivity.

Introduction

Recently, bottom water hypoxic events have been found to occur at the northern end of Narragansett Bay, Rhode Island (Fig. 1), between July and September. Such summer hypoxic events are found in many estuaries, but the events in Narragansett Bay appear to be more episodic than in many other locations. In this study we characterize the spatial extent and timing of hypoxic events in Narragansett Bay, and the relationship between these events and other parameters, such as stratification and temperature, using data from fixed site and spatially intensive surveys conducted during the summer of 2001.

When the organic matter produced by photosynthesis sinks into deeper waters and is consumed through aerobic respiration, dissolved oxygen (DO) is depleted. If mixing or photosynthesis do not replenish the DO in these waters quickly enough, hypoxia may occur. Thermohaline stratification, a shallow euphotic zone, and extended periods of weak mixing, all slow the replenishment of DO in the deeper water and may promote hypoxia. Anthropogenic nutrients represent another risk factor because they can lead to enhanced primary production, increasing the supply of organic matter.

During summer the water is warmest, DO solubility is reduced, and respiration rates increase. Summer is also the period of highest primary productivity in Narragansett Bay (Oviatt et al. 2002), and the organic carbon produced creates an increased biological oxygen demand (BOD).

Narragansett Bay is a temperate and relatively well mixed estuary. It has a mean tidal range of 1.4 m at the northern end and 1.1 m at the mouth (Levine 1972) and a mean depth of 8.6 m (Chinman and Nixon 1985). The Narragansett Bay estuary can be divided into several subregions including the Providence River, Mt. Hope Bay, Greenwich Bay, and the East and West Passages (Fig. 1). Most of the freshwater flow into the estuary enters either the Providence River in the northwest or Mt. Hope Bay in the northeast. Because of the higher local freshwater flow, these two regions typically exhibit a well defined halocline.

In Narragansett Bay the primary source of anthropogenic nutrients is from sewage. Three wastewater treatment plants in the Providence River region account for 70% of the wastewater nitrogen discharged directly into Narragansett Bay (Nixon et al. 1995; Carey et al. 2005).

In the late 1990s several researchers began to observe summer hypoxic events in Narragansett Bay, particularly when tidal mixing was minimal (Magnuson 1997; Bergondo et al. 2005; Deacutis et al. 2006). It was not until a major fish kill event in

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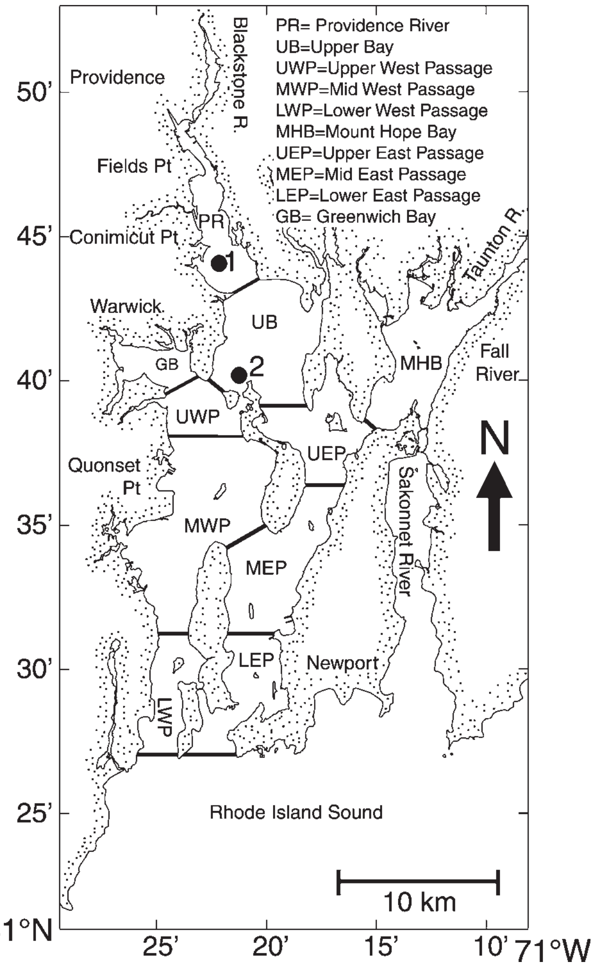

Fig. 1. The regions of the Narragansett Bay, Rhode Island, modified from Kremer and Nixon's (1978) model with the addition Greenwich Bay and Mt Hope Bay as subregions. The URI monitoring buoy locations are the points marked 1 and 2 and represent Bullock Reach and North Prudence, respectively.

Greenwich Bay during August 2003 (RIDEM 2003) that this issue attracted much attention outside of the research community.

Prior to the observations of hypoxia in Narragansett Bay during the late 1990s it is unclear whether hypoxia was merely going unnoticed or if there has been a change in the system. One of the earliest records of hypoxia in Narragansett Bay appears in a study by the U.S. Public Health Service (1960). They found a pattern of hypoxia and near anoxia in Upper Narragansett Bay in 1959 very similar to the pattern observed in the late 1990s. Indirect evidence suggests hypoxia may have been a occurring in the 1980s. Benthic studies by Valente et al. (1992) during August 1988 found a significant reduction in, or even absence of, benthic macrofauna in parts of the Upper Bay, especially near wastewater treatment plants where there was high nutrient loading. Such a change in the benthic community would be consistent with the effects of hypoxic events, although other stressors cannot be ruled out.

Several major studies of DO have been conducted in Narragansett Bay since hypoxia was directly observed. These studies included a monthly towed sensor transect of Narragansett Bay performed by the National Marine Fisheries Service (NMFS) and University of Rhode Island (URI), a 124 station nighttime survey of DO by the Narragansett Bay Estuary Program (NBEP) and volunteers from a number of other institutions, and an array of monitoring buoys deployed by URI. This research will focus on data collected in 2001 when there was overlapping coverage from all of these efforts.

In this study, the U.S. Environmental Protection Agency's (EPA) DO criteria for coastal waters from Cape Cod to Cape Hatteras (USEPA 2000) was used as the definition for hypoxia. This definition of hypoxia was chosen because the State of Rhode Island is currently developing new DO criteria based on the EPA approach. The EPA defines multiple hypoxia thresholds based on the degree of protection they provide to marine organisms. One threshold is the acute hypoxia criterion of 2.3 mg l^{-1}, below which DO does not meet the minimum standards for protecting larval and adult animal stages from mortality. A second hypoxia threshold is the EPA chronic threshold of 4.8 mg l^{-1}. If measurements fall between 2.3 and 4.8 mg l^{-1}, prolonged exposure may result in chronic effects. If exposure is limited there may be no significant effect. In such cases further study is required to assess the duration frequency and biological effect of these conditions.

Materials and Methods

The NMFS Narragansett Laboratory, in cooperation with the URI and Rhode Island Department of Environmental Management have been conducting regular monthly surveys of Narragansett Bay since 1998 using a Chelsea Technologies Group NvShuttle 500 undulating towed sensor array (Berman and Sherman 2001).

The cruise track began at Quonset Point heading south and returning to Quonset Point after circling the entire bay. Because the sensor was undulating through the water column, it needed a minimum of 6 m of water to operate safely. As a result, the cruise track was restricted to the channels. The sensor was towed at a maximum depth of either 20 m or within 1 to 2 m of the bottom, whichever was shallower. Cruises were performed on the URI vessel R/V *Captain Bert* and were targeted as close to the neap tide as possible between June and September in order to catch the worst hypoxic events.

DO was measured by a Seabird SBE-43 DO sensor. Prior to each cruise the DO sensor was calibrated in a bath of seawater at equilibrium with the air and with a known DO concentration determined by titration. During each cruise, samples were also collected for titration to check for instrument drift. All titration samples were analyzed using the azide modified Winkler method (Strickland and Parsons 1972).

NBEP, with the help of volunteers, measured DO at a number of different stations in the upper half of the Bay (Deacutis et al. 2006). The surveys were performed late at night and into the early morning predawn hours so that there would be no photosynthesis and DO would be near minimum levels. Dates were targeted for neap tides when conditions were most favorable for hypoxia to occur. Multiple boats participated in each survey to increase the area that could be covered in a single day. The number of stations observed in each survey varied depending on the number of volunteer boats available.

Crews were equipped with YSI 6,920 or YSI 600XL DO sondes with 650 DM loggers. The sondes were equipped with the YSI high sensitivity membranes. The calibration of the sensors was checked at each station by taking a reading with the sensor wrapped in a wet towel as recommended by YSI. In order to provide the best comparison between individual boats and sensors, the boats met prior to the survey and compared readings in a tub with the sondes side by side. At each station readings were taken at 1.5-m intervals.

Another monitoring effort in this region was a series of fixed YSI monitoring buoys operated by URI (Fig. 1). The buoys provided measurements of DO, chlorophyll, salinity, and temperature for the surface and bottom at 15-min intervals. The buoys used YSI 600XL or 6,000 sondes. Approximately every 2 wk the sensors were switched and serviced. For more details about the methods see Bergondo et al. (2005).

The area covered by concentrations below 2.3 and 4.8 mg l^{-1} in Narragansett Bay was estimated. The shallowest depth of hypoxia was determined for each vertical profile performed. The minimum depths of hypoxia for the stations within each of the regions of the Bay shown in Fig. 1 were averaged to determine the mean depth of hypoxia for each region. An assumption was made that all water below this mean depth was hypoxic. The percentage of the area of the regions below the hypoxic depth was determined according the depth-area relationships presented in Chinman and Nixon (1985).

Results

All surveys indicated periodic hypoxic events during neap tides in the July–September period of 2001 in portions of Upper Narragansett Bay. The lowest DO concentrations typically occurred in the Providence River, Upper Narragansett Bay, and Greenwich Bay.

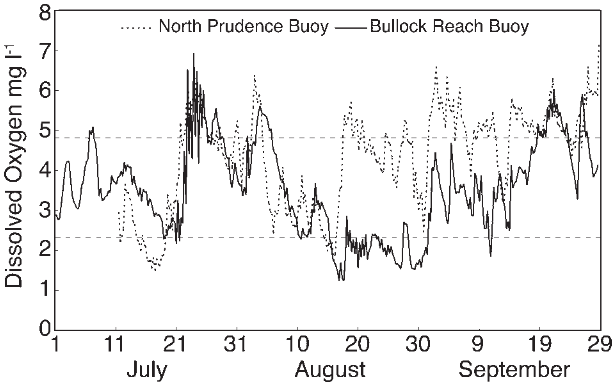

Fig. 2. Bottom oxygen data from the North Prudence and Bullock Reach monitoring buoys averaged over 6-hour intervals.

Monitoring buoys in the upper parts of Narragansett Bay indicated that the bottom water of this area had the lowest DO concentrations during neap tides (Fig. 2). Even when there was no neap tide, bottom water DO in the Providence River remained < 4.8 mg l^{-1} 77% of the July–September period and < 2.3 mg l^{-1} 17% of the time. Typically, periods with concentrations < 2.3 mg l^{-1} corresponded to neap tides. Values < 2.3 mg l^{-1} also corresponded to strong surface supersaturation of DO, indicating high rates of primary productivity.

A common feature observed in the deeper parts of the Upper Bay and in the Providence River channel was a mid water low in DO, rather than a low directly at the bottom. This oxygen minimum was often situated just below the pycnocline.

The spatial distribution of hypoxic conditions followed a similar pattern in all summer months. Typically the minimum DO was observed in the Providence River and Greenwich Bay regions with frequent observations < 2.3 mg l^{-1}. DO increased to the south, corresponding to decreasing stratification, water temperature, and surface water chlorophyll concentrations. A regression of stratification against minimum water column DO for all vertical profiles performed by the NMFS survey in July and August for the years from 2000 to 2003 produced an r^2 of 0.51 (Fig. 3). Hypoxic conditions were typically absent in the East Passage, but concentrations < 4.8 mg l^{-1} were observed as far south as Quonset Point in the West Passage. Hypoxia was observed in Mt. Hope Bay, but DO was typically higher than in the Providence River.

An example of this pattern is shown for surveys conducted in August 2001 (Fig. 4). A volunteer survey on August 15, 2001, sampled near the time

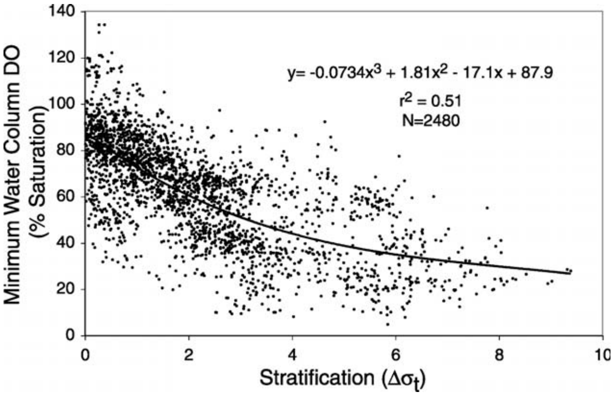

Fig. 3. A regression was performed between the degree of stratification and minimum water column dissolved oxygen (DO) percent saturation for all vertical profiles sampled by the NMFS surveys in July and August for the years 2000–2003. DO is given in percent saturation to normalize for the effects of varying salinity and temperature between stations on oxygen solubility.

that the minimum DO concentrations were observed at the buoy sites (Fig. 2). There were widespread measurements < 2.3 mg l^{-1} in Greenwich Bay, Providence River, and Upper Bay. The lowest DO in the Upper Bay region was concentrated along the western shore. Mt. Hope Bay and the Upper West Passage had DO ranging from > 4.8 to < 2.3 mg l^{-1}. The Middle West Passage had DO < 4.8 mg l^{-1} along the western edge but most of the region was > 4.8 mg l^{-1}. One day later on August 16, the NMFS survey was conducted (Fig. 4). Conditions were generally similar to those observed by volunteer surveys, with the notable exception that DO along the western side of the Upper Bay increased, as did DO in the West Passage. This was consistent with increasing tidal range and increased DO at the North Prudence Buoy (Fig. 2) and demonstrates how rapidly DO can change in this region.

The percentage of area below the EPA 4.8 mg l^{-1} criterion, including values below 2.3 mg l^{-1} in different regions of the Bay, was estimated for the months of July through September of 2001 (Fig. 5). There were no measurements < 4.8 mg l^{-1} in the lower East or West Passages. In the mid West Passage the area with DO < 4.8 mg l^{-1} was confined to 2% or less of the region's area in all surveys. In the mid East Passage DO < 4.8 mg l^{-1} was not

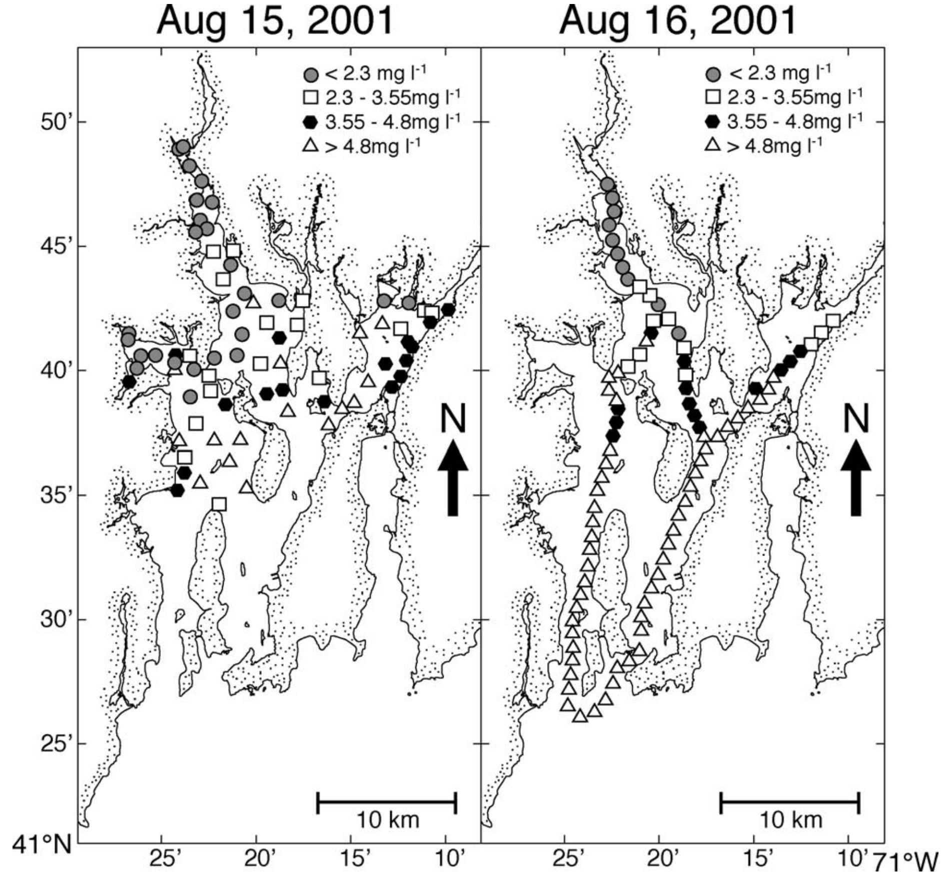

Fig. 4. The minimum water column dissolved oxygen for stations in Narragansett Bay during the August 15, 2001, NBEP survey and the August 16, 2001, NMFS cruise.

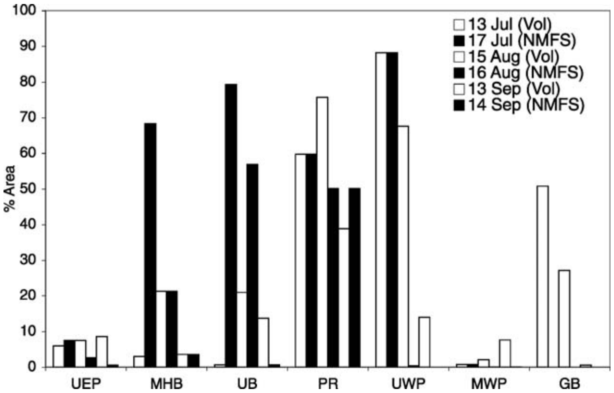

Fig. 5. The area covered by oxygen concentrations below the U.S. Environmental Protection Agency chronic hypoxia criterion of (< 4.8 mg l^{-1}) was estimated for the different regions of Narragansett Bay. The lower East Passage, lower West Passage, and mid East Passage were not observed to have any oxygen concentrations below the EPA criteria and are not shown. Other locations indentified in Fig. 1.

observed, with the exception of September 14, 2001, when hypoxia covered 0.3% of the region. The upper East Passage experienced DO < 4.8 mg l^{-1} in all months, covering 0.5–9% of the area. Mt. Hope Bay had DO < 4.8 mg l^{-1} during all surveys, covering 3–68% of the area. The Upper Bay had DO < 4.8 mg l^{-1} covering 0.7–79% of the area. The upper West Passage had DO < 4.8 mg l^{-1} covering 88% of the area during July 2001. The coverage of hypoxic conditions changed rapidly in this region. Between August 15 and August 16, DO < 4.8 mg l^{-1} went from covering 88% of the area to 0.4%. Greenwich Bay had DO < 4.8 mg l^{-1} covering 0.6–51% of the area. The percentage of Providence River's area with DO < 4.8 mg l^{-1} was 39–76%.

Only the Providence River showed extensive areas with DO < 2.3 mg l^{-1}, covering 27–39% of the area. The coverage was < 1% of the area in the mid and upper West Passage as well as in the Upper Bay. In Greenwich Bay, coverage was 0–4% of the total area, with DO < 2.3 mg l^{-1} occurring in two of the three surveys in that area. This may seem to contradict the fact that the majority of stations in July and August in Greenwich Bay had DO < 2.3 mg l^{-1} (Fig. 4), but the hypoxic stations tended to be deep spots and the resulting estimated average depth of hypoxia was deeper than much of the rest of the region. Mt. Hope Bay had DO values below 2.3 mg l^{-1} covering 0.5–2.5% of its area.

Discussion

The general increase in the severity of hypoxia on a northward gradient up Narragansett Bay can largely be explained by a corresponding increase in stratification (Fig. 3) that inhibits the mixing of the well oxygenated surface waters to the bottom. Periods of reduced wind and tidal mixing with their associated increase in stratification can be expected to have the lowest DO, as was observed by the buoys (Fig. 2). In parts of the Bay where hypoxia occurs but does not persist, such as the West Passage (Fig. 4), it appears that periods of below average mixing are required for hypoxia to occur at all. In other locations such as the Providence River where the degree of stratification is higher, hypoxic conditions may persist throughout the tidal cycle in some instances (Fig. 2).

Inhibited mixing of oxygenated waters due to stratification is exacerbated by the fact that most of the wastewater nitrogen flux into the Bay passes through the Providence River (Kremer and Nixon 1978; Carey et al. 2005), the region of greatest stratification. This in turn leads to elevated primary productivity (Oviatt et al. 2002) and the associated BOD from the organic matter produced in the northern parts of the Bay. As a result the areas of highest BOD and stratification are coincident.

Another compounding factor is that we found the water temperatures in the West Passage and upper parts of Narragansett Bay were typically between 1–3°C warmer those at the mouth of the Bay during the 2001 NMFS surveys. Warmer temperatures result in both higher respiration rates and lower oxygen solubility.

Bergondo et al. (2005) found that the greatest risk of hypoxia occurred when the tidal range was below 1 m. They state that periods of low tidal mixing reduced the transfer of DO from the surface to the bottom and also increased primary production due to the increased stability of the water column.

Since stratification is not governed by tides alone but also by other factors such as freshwater input from rain events and wind mixing, these factors will also contribute to the risk of hypoxic events. The importance of freshwater input can be shown by the relationship between stratification and DO (Fig. 3). Bergondo et al. (2005) found that strong winds, particularly from the north, tended to enhance mixing and reduced hypoxia at the buoy sites while reduced wind-driven mixing promoted hypoxia.

The Bullock Reach buoy showed an exception to the pattern of neap tide hypoxia in August 2001 (Fig. 2). The onset of acute hypoxia at this station corresponded to a neap tide, but hypoxia persisted through the following spring tide. In regions of higher stratification in the northern parts of the bay, tidal mixing was not always sufficient to reoxygenate the bottom waters. In this location, thermohaline stratification, higher surface productivity, and warmer water temperatures appeared to allow hypoxia to persist longer than elsewhere in the Bay. In contrast to Bullock Reach, the North Prudence buoy showed a steep rise in bottom water DO corresponding to the spring tide on August 18, 2001.

During the summer of 2002 there was a drought that reduced salinity driven stratification, but oxygen values in the Providence River were lower than those seen during the 2001 study period. Since the drought reduced salinity driven stratification this may appear to contradict the relationship between stratification and hypoxia. As a possible explanation for this event, Deacutis et al. (2006) suggested that reduced estuarine circulation due to the drought conditions may have been a factor in this event. Another explanation may be found in the NMFS data that show that the mean surface water temperature in Providence River where the worst hypoxia occurred was 1.6°C warmer in August 2002 than was seen in August 2001 and the mean bottom temperature was 1.5°C warmer. Given the effect of temperature on respiration rates and oxygen solubility, this would certainly have contributed to the lower observed oxygen concentrations.

The presence of DO < 4.8 mg l^{-1} in the mid West Passage as far south as Quonset Point (Fig. 4) can be contrasted to the similarly stratified mid East Passage were DO remained > 4.8 mg l^{-1}. Stratification is a contributing, rather than a predictive factor for hypoxia in Narragansett Bay. A major reason for the difference was that the bottom water in the East Passage was over 3°C colder than in the West Passage during the July–September 2001 period. The colder bottom water held more oxygen and the temperatures slowed metabolic rates for respiration. Another difference is that the East Passage is the deepest part of Narragansett Bay with a larger volume, while the total depth integrated productivity is not higher than in the shallower West Passage (Oviatt et al. 2002). This means that the BOD from the organic matter produced is distributed over a much larger volume of water.

The EPA criteria call for areas experiencing DO between 4.8 and 2.3 mg l^{-1} to be evaluated to determine if there are chronic effects on marine species. Monitoring buoys can aid in this by determining the length of exposure to reduced DO, but the existing buoys were located in areas that dropped below 2.3 mg l^{-1} and would fall under the acute criterion. Where the acute criterion applies, there is no requirement for evaluation of possible chronic effects. Of the regions affected by DO < 4.8 mg l^{-1} (Fig. 5), only the upper East Passage and mid West Passage never fell below 2.3 mg l^{-1} and should be evaluated under the chronic criterion. The chronic effects, if any, of the DO levels in those two regions are impossible to estimate based on the data collected. There were no measurements of DO outside of the two days covered by the volunteer or NMFS surveys each month, so the length of exposure to DO $<$ 4.8 mg l^{-1} is unknown. These surveys were conducted during the periods of lowest tidal mixing to try to observe the lowest oxygen concentrations, so there is a strong possibility that the DO did not remain < 4.8 mg l^{-1} for an extended period.

In locations where DO < 2.3 mg l^{-1} was observed, periods where the DO was between 2.3 and 4.8 mg l^{-1} would represent an additional stress to an already impacted system. The Bullock Reach buoy data indicated that the water was only above 4.8 mg l^{-1} for 23% of the entire July–September period (Fig. 2). The North Prudence results indicate that although the hypoxia was less frequent than at Bullock Reach, periods of DO < 4.8 mg l^{-1} surrounding periods of DO < 2.3 mg l^{-1} also occurred in the Upper Bay region. Although there was no buoy in Greenwich Bay, the other region prone to major acute hypoxic events, it seems likely that a similar pattern may exist.

Hypoxia in Narragansett Bay demonstrated some interesting similarities and differences when compared with other estuaries. Western Long Island Sound, which is geographically close to Narragansett Bay and experiences similar climatic conditions, suffers from seasonal hypoxia during periods of thermal stratification (Parker and O'Reilly 1991). As in Narragansett Bay, this hypoxia has been found to be episodic and tied to both bottom water ventilation through mixing and delivery of carbon from surface blooms (Anderson and Taylor 2001). The amount of stratification was 1.2–2.7 $\Delta\sigma_t$ between the surface and bottom during the hypoxic episodes (Welsh and Eller 1991). This was significantly less than the maximum stratification observed in the upper parts of Narragansett Bay where stratification can exceed 9 $\Delta\sigma_t$ (Fig. 3). As in Narragansett Bay, in western Long Island Sound the BOD occurs primarily in the water column, rather than in sediments, and a mid water low was typically observed (Parker and O'Reilly 1991; Anderson and Taylor 2001).

The risk of hypoxia in Narragansett Bay generally follows the north to south gradient of stratification, temperature, nutrient inputs, and productivity, with the lowest DO observed in the Providence River and Greenwich Bay. The deeper, colder waters of the East Passage are less susceptible to hypoxia than the warmer shallower waters of the mid West Passage. Tidal forcing plays a major role in the timing of hypoxia in Narragansett Bay, with the lowest DO corresponding to periods of minimal tidal mixing. Wind, rainfall, and temperature also play roles in controlling stratification and limiting the reoxygenation of bottom waters. This complex set of variables makes precise prediction of these episodic events difficult, but the periods and regions of higher risk for hypoxia in Narragansett Bay can be identified with our current understanding. The combination of high frequency observations from fixed monitoring sites and targeted spatially intensive surveys during the predicted risk periods during this study was found to be a useful approach for monitoring DO.

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