Monitoring Dissolved Oxygen in New Jersey Coastal Waters Using Autonomous Gliders: Multi-year Trends and Event Response

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***Abstract*- While low Dissolved Oxygen (DO) concentrations are not uncommon in the coastal ocean, what is less understood is how the location and size of these low DO regions vary and what impact that variability has on ecosystem health. Therefore alternative sampling strategies are needed to continuously map these low DO areas in a way that quantifies this variability. This project applies a series of Autonomous Underwater Vehicle (AUV) deployments from Sandy Hook to Cape May, NJ to address this need by mapping the subsurface DO concentration in near real-time within the near coastal ocean. The scales of variability of the DO concentration observed over these two seasons were on the order of 60-80 km in space and 3-4 days in time. The strongest gradients were observed across the thermocline with surface waters usually much more oxygenated than the bottom waters. Based on these missions, we have begun to sample the dynamic coastal ocean environment at the scales of known variability. The results show that while there are persistent patterns in the dissolved oxygen fields off our coasts, rapid changes can occur with varied effects across the region.**

Index Terms - Oceanographic Techniques, Robot Sensing Systems, Oxygen

I. Introduction

The coastal ocean is a highly variable system with processes that have significant implications on the hydrographic and oxygen characteristics of the water column. The spatial and temporal variability of these fields can cause dramatic changes to water quality and in turn the health of the ecosystem. Both the U. S. Environmental Protection Agency (EPA) and the New Jersey Department of Environmental Protection (NJDEP) have prioritized monitoring the coastal waters off New Jersey in their long-term strategic plans as an essential component of the decision-making process. Of particular interest are the spatial and temporal characteristics of dissolved oxygen (DO). In response to this need to better understand the dynamics, we put together a program to augment existing monitoring with targeted deployments of glider Autonomous Underwater Vehicles (AUVs) equipped with sensors to map coastal dissolved oxygen and hydrographic conditions in near-real time along the New Jersey inner-shelf.

Monitoring for DO in the coastal ocean off New Jersey has typically been done through lab analyses of discrete water samples collected from boats or helicopters. Between 1979 and 2005 this sampling identified DO concentrations below 5.0 mg/L every year off the coast of New Jersey. While these low values are not uncommon, what is less understood is how the location and size of these low DO

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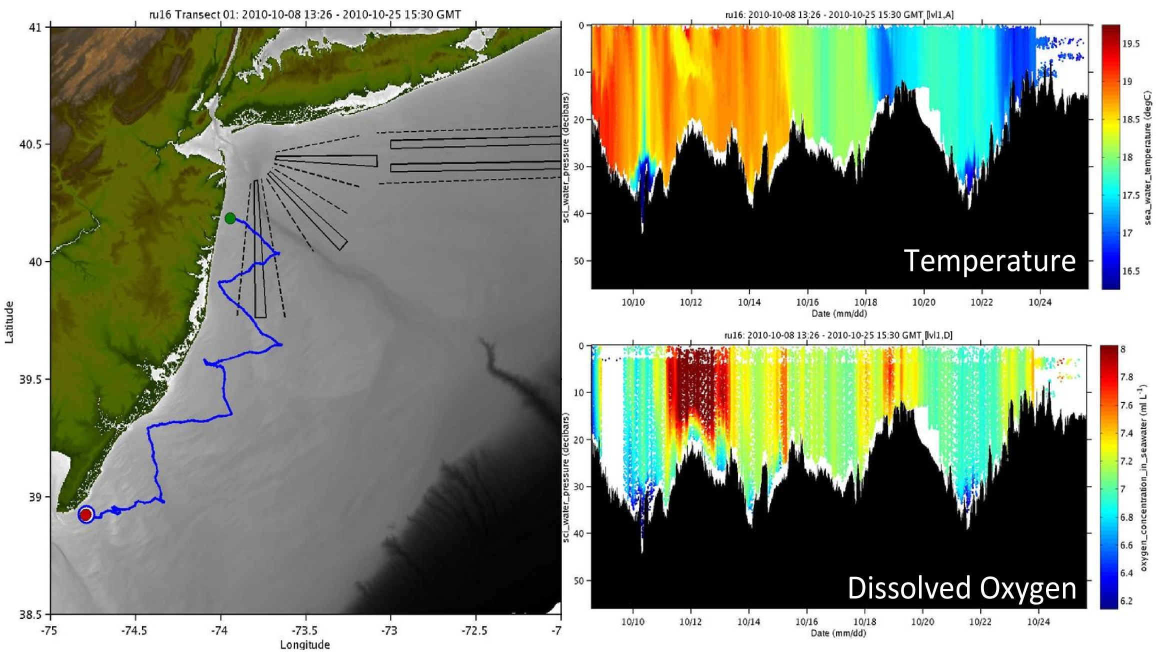

Figure 1 Temperature (upper right) and dissolved oxygen concentration (lower right) collected during a coastal run along the New Jersey coast from October 8, 2010 through October 25, 2010

regions vary and the impact that variability has on ecosystem health [1]. Therefore, alternative sampling strategies are needed to map the low DO areas in a way that quantifies this variability. Here we apply a series of AUV transits from Sandy Hook to Cape May, NJ to map the subsurface DO concentration in near real-time within the near coastal ocean (Figure 1). The primary users for the data generated through these missions are the EPA and the water monitoring division of the NJDEP. During each mission the real-time data was used to map dissolved oxygen and water column stratification along the New Jersey coast.

II. Shallow Glider AUV Missions

Continuous ocean observations are derived from a series of glider deployments along the inner-shelf of the waters off the New Jersey coast. The buoyancy-driven propulsion of these vehicles affords high efficiency and deployment endurance approaching 30 days with alkaline batteries [2]. These particular gliders have been operated jointly by Rutgers University Coastal Ocean Observation Lab (RU COOL) scientists and Teledyne Webb Research Corporation engineers in science experiments since 1999, transitioning to sustained deployments by the COOL Operations Center in 2003.

The Rutgers University Institute of Marine and Coastal Sciences (RU/IMCS) in collaboration with MARACOOS, the Mid-Atlantic regional component of IOOS, the NJDEP Division of Water Monitoring and Standards, and the EPA Region II have demonstrated the use of the Slocum glider to observe temperature, salinity, and dissolved oxygen concentrations off the coast of New Jersey. With these missions, we tracked the evolving fields of dissolved oxygen and hydrography through upwelling and coastal storm events [3]. Throughout the missions, the gliders surface and connect via an onboard satellite modem to the glider center at regular intervals, typically 3 hours. These surfacings provide an opportunity to download the most recent subset of the data segment from the glider and send new mission commands as needed to the glider. The most recent data transferred back from the gliders are automatically processed in real-time and visualized on the lab website (http://rucool.marine.rutgers.edu/).

Each deployment takes about 21 days to complete. For each coastal run, the glider is deployed off Sandy Hook, NJ and completes a zigzag track down the coast toward Cape May, NJ (Figure 1&2). The precise location of the track is dependent on environmental conditions and accessible water depths. For each deployment the glider is equipped with two main sensors, a pumped Sea-Bird CTD (Model GPCTD) and an Aanderraa Optode (Model 3835/5014W). The CTD samples conductivity, temperature and pressure a rate of 0.5 Hz throughout the mission. The pressure is used to calculate depth. These data map ocean temperature, salinity and density along the track. The optode measures phase shifts across a calibrated foil that when combined with measured temperature from the CTD gives dissolved oxygen concentration and percent saturation at a rate of 1 Hz (Figure 2). Data is stored locally on the glider and a subset of science data is sent back to Rutgers in real-time via the satellite link. The subset consists of every third data point within every third up and down profile. The resulting resolution of this subset is approximately 0.9m in the vertical and 110m in the horizontal. After recovery of the glider, all data are run through sensor specific QA/QC verifications detailed in an executed Quality Assurance Project Plan before delivery to NJDEP and EPA. The development of this Quality Assurance Project Plan with details of the operating procedures is another accomplishment that will be particularly useful as the government agencies move forward with incorporating AUV data into environmental decision-making.

III. Dissolved Oxygen Variability

This analysis focuses on two missions in 2011 and four in 2012 (Figure 2). In each mission completed over the two years, DO concentrations were observed below 5 mg/L. The lowest values were seen during the late summer in 2012 with absolute minimum values below 1.0 mg/L. In general the mean bottom concentrations were 3.0 mg/L less than the surface. In the remaining sub-sections we describe the details of the observed variability in the DO fields within and between deployments and years.

A. Spatial/Temporal Distribution

Similar to the thermal structure, the DO fields over the summer months were best characterized as a two-layer system with higher concentrations above the thermocline and lower concentrations below (Figure 3). The summer of 2011 was subject to a large phytoplankton bloom that was interrupted by two significant rain events (Hurricane Irene and the remnants of Tropical Storm Lee) while the summer of 2012 was much less eventful. The lowest values were seen in July, August and September 2012 with some values below 1.0 mg/L. In August of 2011, the lowest concentrations were seen near the seafloor closer to the coast. This mission coincided with a large the entire

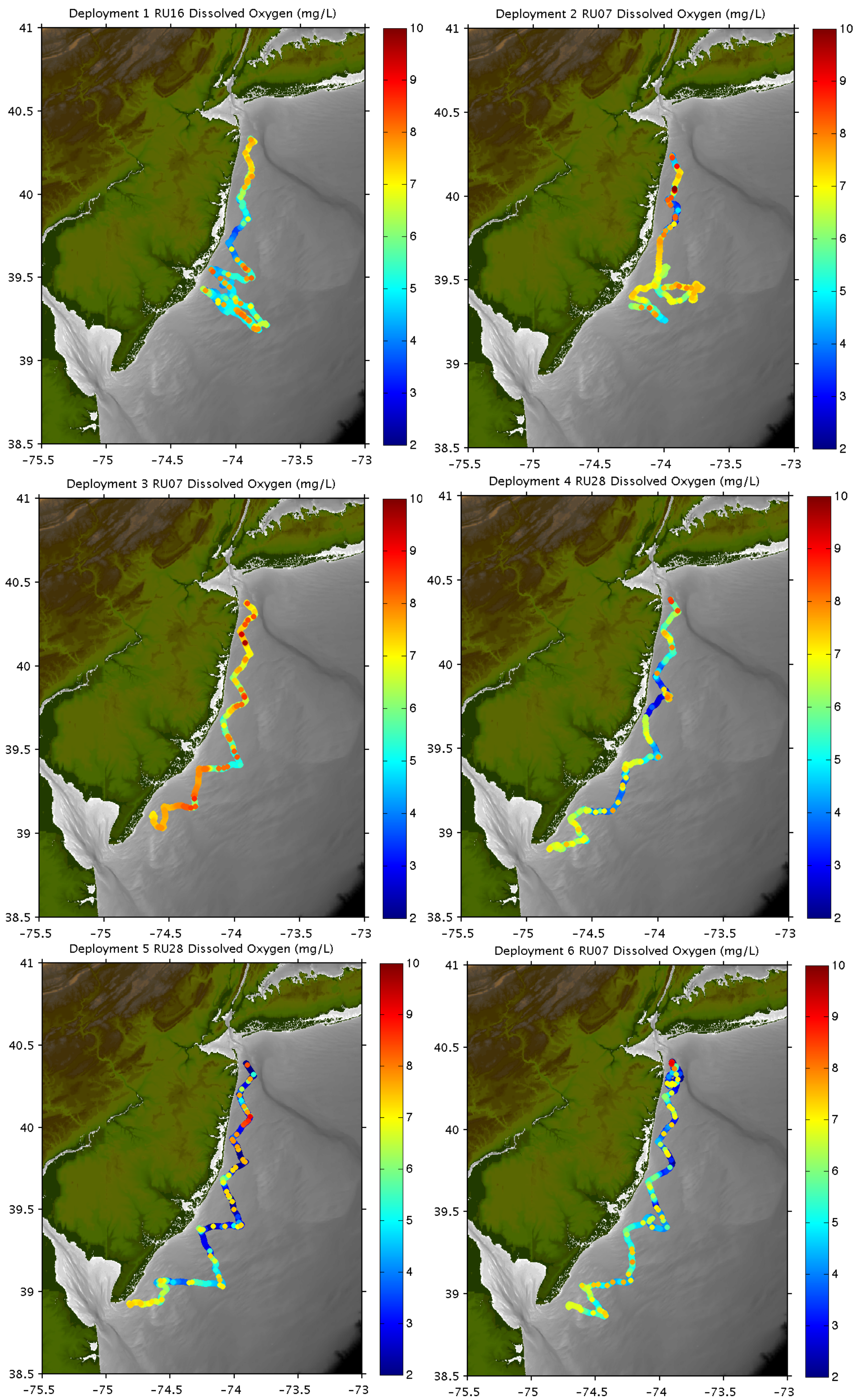

Figure 2: The path for each deployment completed in August 2011 (upper left), October 2011 (upper middle), June 2012 (upper right), July 2012 (lower left), August 2012 (lower middle), and September 2012 (lower right). The path color indicates the lowest Dissolved Oxygen concentration observed for each profile along the track.

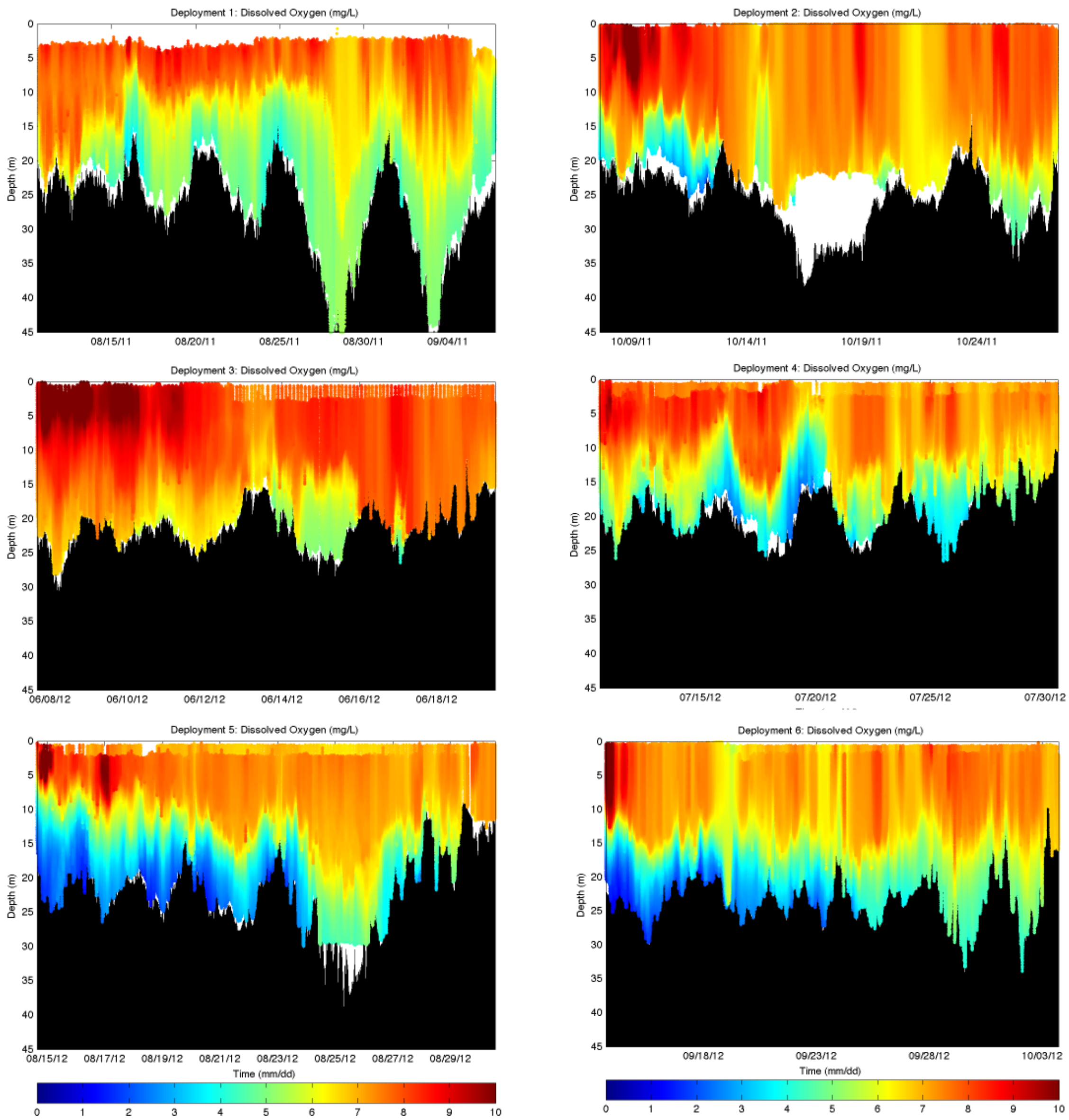

Figure 3: Cross-sections of dissolved oxygen concentration for the deployments completed in August 2011 (upper left), October 2011 (upper right), June 2012 (middle left), July 2012 (middle right), August 2012 (lower left), and September 2012 (lower right).

domain. Even with the large expanse of the bloom, the lowest values, all above 3.8 mg/L, were limited to waters shallower than 20 m. Following Hurricane Irene (August 28, 2011), the large salinity gradient, setup by Irene's rains, maintained the stratification into the fall. This maintained the boundary between the lower oxygen concentration of the bottom layer and the surface. As the October mission progressed, even this late stratification broke down and the lower layer readily mixed with the higher concentrations of the surface layer. Over the four missions in 2012 we see the progression from a relatively well-oxygenated water column in June with all values above 4.5 mg/L (Figure 3, middle left) to a more bimodal distribution in the late summer and early fall. The summertime lows in the bottom layer were 1.88 mg/L in July and 0.94 mg/L in August (Figure 3). In general there was a tendency for the lowest values to occur along the northern coast of NJ, within the 25-m isobath. For all missions, the DO concentration in the surface layer was never below 5 mg/L and was seen as high as 12 mg/L. For the bottom layer all DO concentrations were between 0.82 mg/L and 8.5 mg/L. From the two years of data we can see that the late summer condition in each year both show a bimodal distribution with higher concentrations in the surface layer and lower concentrations in the lower layer. While the surface peak is the same between the two years, we do see lower DO concentrations in the lower layer in 2012 (peak approximately 3 mg/L) compared to 2011 (peak approximately 5 mg/L) in 2012 (Figure 3).

B. Decorrelation scales

Since the glider is a non-stationary platform it is important to state that it is simultaneously sampling temporal and spatial change. It is difficult to differentiate a measured change in DO concentration as a change in time or a change in space when looking at the glider data in isolation. Using autocorrelation we calculated the decorrelation time and length scales for each deployment. The decorrelation scale is defined as the scale, in time or space, in which the autocovariance coefficient falls below 0. These scales describe the time and space over which the DO variability becomes uncorrelated. For example, a decorrelation length scale of 50 km indicates that the DO observations at any point are correlated with DO observations within 50 km. Similarly, a decorrelation time scale of 5 hours indicates that the DO observations at a particular time are correlated with DO observations at that point for 5 hours before and after the measurement. These scales can be used to guide the sampling required in time and space to capture the variability of DO along the coast. For the remainder of this report, the DO concentrations of the surface layer will be represented as those sampled between 3 m and 4 m below the

Table 1. Decorrelation scales for time and space for each deployment. The scales are calculated separately for the surface and bottom data.

	Space Scales (km)		**Time Scales (Days)**	
	Surface	**Bottom**	**Surface**	**Bottom**
Deployment 1: August 2011	62.0	70.6	3.19	3.70
Deployment 2: October 2011	76.7	77.5	3.74	3.79
Deployment 3: June 2012	77.9	74.1	3.45	3.24
Deployment 4: July 2012	49.8	62.9	2.78	3.70
Deployment 5: August 2012	97.9	107.5	4.53	5.53
Deployment 6: September 2012	38.0	162.8	1.78	7.81
Project Average	**67.1**	**92.6**	**3.2**	**4.6**

surface and the DO concentration of the bottom layer will be represented by those sampled between 3m and 4m above the seafloor. The average spatial decorrelation scales for all the deployments are 67 km for the surface and 92 km for the bottom (Table 1). This scale is approximately the length of a glider leg from offshore to onshore and likely reflective of the persistent difference seen between the nearshore and offshore dissolved oxygen vertical structure. The 2011 deployments showed similar scales for the surface and bottom, all within 10 km of the project mean. The 2012 data show a larger spread in the values of the length scales between surface and bottom as well as between different deployments. For each 2012 deployment the surface scale was smaller than the bottom scale. There is also a general trend toward longer length scales in the bottom layer later in the season.

The mean temporal scale across all deployments was 3.2 days for the surface and 4.6 days for the bottom layer. Similar to the space scale, the bottom layer had longer decorrelation time scales than the surface. With an average glider speed of approximately 20-24 km/day, it would take the glider about 2.8 to 3.3 days to cover the mean spatial decorrelation scale. While we feel that these temporal scales are more reflective of the time it takes for the glider to move through the variation in space rather than a measured local change over time, we do observe faster changes in time that are more episodic and predominately due to mixing induced by local winds.

IV. Event Response: Hurricane Irene

In late August 2011 Hurricane Irene tracked directly over the inner New Jersey Shelf. The routine sampling of the coastal glider deployed along the New Jersey coast captured this significant forcing event. Prior to the storm passing, we modified the glider mission to maintain a cross-shelf line coordinated so that the glider was in deeper water at the peak of the storm. In so doing we were able to capture, in near real-time, the evolution of the hydrographic and dissolved oxygen fields before, during and after the storm (Figure 4). A dramatic impact of Hurricane Irene is seen in the temperature data. This section shows how quickly the water column was

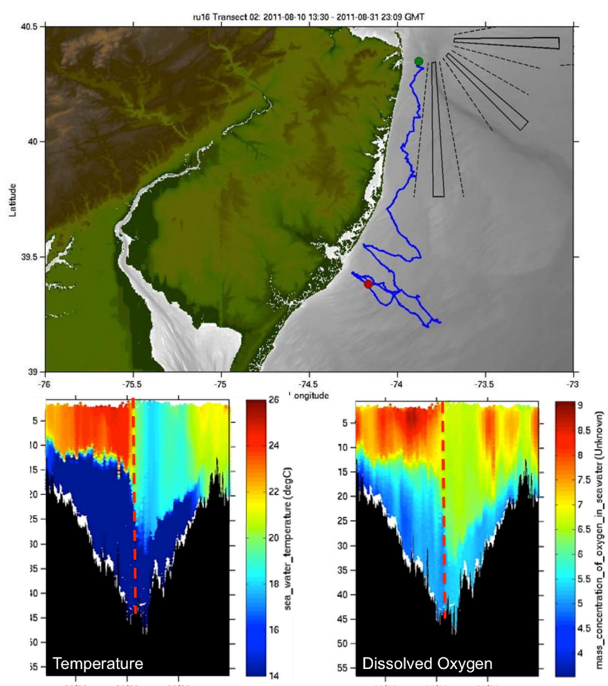

Figure 4: Glider path during August 2011. The temperature (C) (lower left) and dissolved oxygen concentration (mg/L) (lower right) collected during Hurricane Irene along the cross-shelf line at the southern end of the path. The timing of the storm is shown as a red dashed line in each cross-section.

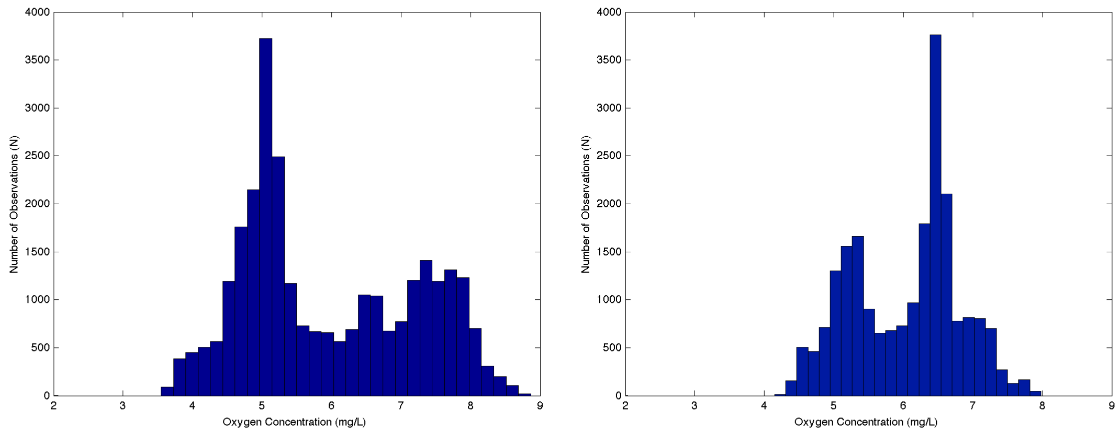

Figure 5: Distribution of dissolved oxygen measurements collected in the above cross-sections before (left) and after (right) the passing of Hurricane Irene.

mixed, transitioning for a strongly stratified water column before the storm to a deeper and weaker thermocline following the storm. This section gave us our first look at how quickly the inner-shelf was impacted by a hurricane at the temporal and spatial resolution provided by the underwater glider.

Similarly the structure of the dissolved oxygen fields underwent a significant transformation through the storm. Before the storm, there was a large gradient through the water column with higher concentrations near the surface separated from lower oxygen values below the thermocline. Following the storm, the intense mixing weakened the strong dissolved oxygen gradient allowing higher oxygen concentration to penetrate closer to the seafloor. The distribution of oxygen values in the pre-storm and post-storm sections shows a shift toward the middle of the range (Figure 5). After the storm there are no observed concentrations below 4 mg/L or above 8 mg/L. There is still a bi-modal distribution but it has shifted from the pre-storm peaks of 5 mg/L and 7.5 mg/L to about 5.2 mg/L and 6.5 mg/L for the bottom and surface layers respectively. The largest peak in the distribution has also shifted from the lower concentrations of the bottom layer to the higher concentrations of the surface layer.

V. Conclusions

The sampling provided through the glider AUV showed that the concentrations of dissolved oxygen were highly variable in the vertical, horizontal, and through time. The strongest gradients were observed across the thermocline with surface waters usually much more oxygenated than the bottom waters. These gradients were weaker closer to the coast and significantly weakened following several strong wind events. Spatial variability explained most of the variability with more mixed conditions in the shallow waters near the coast and more stratified conditions in the deeper water offshore. It was in the deeper waters offshore that most of the lower DO concentrations were found below the thermocline. The scales of this variability observed over these two seasons was on the order of 60-80 km in space and 3-4 days in time. We conclude that these decorrelation scales are representative of the distance over which the water depth varied. The time scale is more an indicator of the time it takes the glider to cover this distance rather than a change across all space in time.

There were observed changes in time, predominately caused by strong (Hurricane Irene) and moderate wind events that mixed the more oxygenated surface water with the deeper less oxygenated water. During Hurricane Irene we saw rapid mixing of the more oxygenated surface waters across the thermocline and into the bottom waters. In addition, events like Irene and the coastal bloom in 2011 highlighted the capability to adapt pre-determined missions to respond to these events. This allowed us to ensure that observations were taken relative to the bloom throughout the storm. Since this was all done in real-time the monitoring data was immediately available to NJDEP and EPA to inform their response to these events.

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