APACHE PIER SENSORS

Contract Number 655065

Final Report

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INTRODUCTION

Funding was provided to maintain datasondes deployed at a fishing Pier in northern Myrtle Beach, SC. These datasondes were designed to provide continuous measurement of dissolved oxygen, temperature and salinity. They are part of a Hypoxia Alert Network established by SECOORA, SC DNR, SC DHEC OCRM and SC Sea Grant Consortium in response to a hypoxic event which occurred in July 2004. The data collected are also being used to better understand the causes and impacts of hypoxia in Long Bay. This work was performed in coordination with several other related projects funded by the SC Sea Grant Consortium and SC DHEC OCRM. During the initial phase of this project, Coastal Carolina University’s Environmental Quality Lab maintained a datasonde at Springmaid Pier with funding from SECOORA. This project enabled continued operation of the Springmaid data sonde through Sept 2007 and provided operational support to maintain the two datasondes (surface and bottom water) installed by SC DNR at Apache Pier in Spring 2006.

In this report, we provide the complete data record collected by the Apache Pier sondes through December 2008 along with summary statistics, correlations amongst parameters and a brief description of the current working hypotheses regarding the causes of the low DO observed in the nearshore waters of Long Bay.

FUNDING HISTORY

In 2006, SC DNR contracted with AMJ, Inc and YSI Econet for the installation of two datasondes at Apache Pier. CCU’s EQL provided maintenance under funding agreements summarized in Table 1. SC DNR has also been covering, until February 2009, the annual YSI Econet subscription for web-based delivery of the raw data in near real time from the Apache Pier datasondes. OCRM funding enabled
purchase of two backup YSI datasondes and extended warrentees through 2011. SC DNR provided funding for a lightening upgrade and installation of a meteorology station in December 2006.

Table 1. Funding History

<table>
<thead>
<tr>
<th>Date</th>
<th>Funded</th>
<th>Amount</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>Installation and Econet Service for 3 years effective Feb 2006. Voltage diffuser.</td>
<td>NA</td>
<td>SC DNR</td>
</tr>
<tr>
<td>10/23/06 to 2/28/08</td>
<td>Dissolved Oxygen Assessment along the Grand Strand Using Pier Based In-Situ Sensors</td>
<td>$50,766</td>
<td>OCRM</td>
</tr>
<tr>
<td>9/1/2007 to 8/31/2008</td>
<td>WWA Nearshore WQ Study: Maintain WQ Sensors at Apache Pier, Amendment 1</td>
<td>$26,212</td>
<td>SC DNR-Coop NA04NMF4720306</td>
</tr>
<tr>
<td>8/31/2008-8/31/2009</td>
<td>WWA Nearshore WQ Study: Maintain WQ Sensors at Apache Pier, Amendment 2</td>
<td>$12,000</td>
<td>SC DNR-Coop NA04NMF4720306</td>
</tr>
<tr>
<td>3/16/09-3/15/10</td>
<td>Temporal and Spatial Variability of Dissolved Oxygen in Long Bay as characterized by pier-based in-situ sensors</td>
<td>$8,000</td>
<td>Sea Grant</td>
</tr>
<tr>
<td>4/15/09-9/15/09</td>
<td>Interagency Funding Agreement</td>
<td>$8,000</td>
<td>SC DNR</td>
</tr>
<tr>
<td>4/2009</td>
<td>Plasma Screen Display</td>
<td>NA</td>
<td>Santee Cooper</td>
</tr>
</tbody>
</table>

*Also included a deployment of a Hydrolab datasonde at Springmaid Pier

**OPERATIONAL DETAIL**

**Installation, Deployment, and Repair**

The installation and deployment history of the sondes is summarized in Table 2. The sondes are deployed at the seaward end of Apache Pier which is 1260 ft long (Figures 1 through 3). The sondes are housed in two 4” ID PVC standpipes that extend from sea floor to the pier decking which is about 25 ft above sea level. The standpipes are fastened to pier pilings. They are painted with antifouling paint and perforated with 1” diameter holes to promote water exchange.

Table 2. Parameters, deployment depths and deployment dates

<table>
<thead>
<tr>
<th>Latitude and Longitude</th>
<th>Parameters</th>
<th>Depth(s)</th>
<th>Deployment dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.7615 N 78.7798 W</td>
<td>DO, %DO, temperature, salinity</td>
<td>Surface and 1 m from bottom (4 to 6 m)</td>
<td>6/20/06 – present</td>
</tr>
<tr>
<td></td>
<td>wind direction and speed, air temperature, barometric pressure, humidity, and rainfall</td>
<td>Approximately 5 m above sea level</td>
<td>1/4/2007 - present</td>
</tr>
</tbody>
</table>
Figure 1. Long Bay, South Carolina. The position of the pier is shown by the arrow head.

Figure 2. Northern Myrtle Beach, SC. The position of the pier is shown by the arrow head. The swash to the south is Singleton Swash.
Figure 3. Apache Pier. The location of the sonde standpipes is shown by the arrow head.

A concrete reef was constructed in the 1990s under the pier to improve fishing. The water depth at the end of the pier is 5 to 7 m depending on the tidal range. The original installation was performed in spring 2006 via a contract from SC DNR to AMJ, Inc. and YSI Econet. This location at the northern end of Myrtle Beach, SC is near the northernmost extent of the hypoxic zone observed in July 2004. The sondes became fully operational on 6/20/06. One sonde is deployed approximately 1 m from the bottom and the other is positioned near the surface via attachment to a float.

The sondes collect and transmit real-time dissolved oxygen, salinity and temperature measurements every fifteen minutes to YSI’s data server which uploads the information to a public website: http://www.ysieconet.com/public/WebUI/Default.aspx?hidCustomerID=131. A meteorological station was installed in December 2006 and became operational on 1/4/07. These data (wind direction and speed, air temperature, barometric pressure, humidity, and rainfall) are also reported at YSI Econet’s Apache pier website.

Major periods of outage and their causes are listed in Table 3. Pursuant to the lightening damage in 2006, SC DNR contracted with AMJ, Inc to add two pom-pom diffusers that are each independently grounded to the ocean beneath the pier. Once enhanced lightening protection was installed at this site in December 2006, no further lightening damage has been sustained except on March 17, 2008 during a thunderstorm. Repairs required replacement of circuit boards in both deployed sondes and was ascribed to ‘voltage regulation’ issues. One of the sondes was still under warranteed and its repair was covered by this warranteed.
Table 3. Major Outage Periods

<table>
<thead>
<tr>
<th>Dates</th>
<th>Length of Outage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/7– 8/17/06</td>
<td>10 d</td>
<td>Both sondes out due to lightening.</td>
</tr>
<tr>
<td>9/3 – 9/9/08</td>
<td>5 d</td>
<td>Sondes were removed as a precautionary measure in advance of Tropical Storm Hannah</td>
</tr>
<tr>
<td>1/30/09 to 4/16/09</td>
<td>75 d</td>
<td>Standpipes were lost from the pier although both sondes were recovered. New standpipes were installed on 4/21/09</td>
</tr>
</tbody>
</table>

The original standpipes were lost from the fittings that held them to the pier in on 1/30/09. New standpipes were constructed and installed. The sondes were redeployed on 4/16/09 in two new standpipes. One of the grounding wires has been ripped from its fittings to the piers twice, probably by fishing hooks. The wire has been re-secured twice. The other wire is currently broken at a depth 1 foot below the high water level. A new wire (cell phone tower grounding strap) has been ordered and will be installed ASAP.

Standard Operating Procedures

The datasondes are YSI model 600Rs outfitted with conductivity, temperature and Clark cell DO sensors. The DO sensors are salinity, pressure and temperature compensated, enabling onboard computation of %DO, i.e. \( \text{%DO} = \frac{\text{DO}_{\text{observed}}}{\text{DO}_{\text{NAEC}}} \times 100 \) where NAEC is the normal atmospheric equilibrium concentration, i.e., the dissolved oxygen concentration which would be present in the seawater if it had reached equilibrium with atmospheric gases at a total atmospheric pressure of 1 atmosphere and the in-situ temperature and salinity of the sample. Temperature is measured with a thermistor.

Salinity values are reported in units of ppt although they are measured conductimetrically and should theoretically be reported as psu (practical salinity unit based on the PSS-1978). Dissolved oxygen is reported in units of mg/L. Temperature is reported in °F for the benefit of the fishermen who use these data.

Maintenance and calibration procedures for the salinity and DO sensors are documented in a laboratory SOP (Appendix A). No maintenance or calibration work has been performed on the meteorological station or the temperature sensors. The latter are checked when the units are returned to YSI.

All maintenance and calibration activities are documented in a log (Appendix B). The DO sensors are calibrated against air saturated water. A post calibration check is performed in water saturated seawater. This is done in the lab immediately after calibration and periodically during deployment (field post calibration check). The salinity sensors are calibrated against a KCl standard of known conductivity. A post calibration check is performed in a Laboratory Control Sample (filtered seawater of known salinity). This is done in the lab immediately after calibration and periodically during deployment (field post calibration check). Minimal cleaning is done prior to performing a field post calibration check.

From March to October, field post-calibration checks are performed at least once per week. From October to March, post-calibration checks are performed at least once every other week. The sondes are redeployed if their post calibration checks are in control for salinity and DO. After two weeks of deployment, or failure of a post calibration check, the sondes are exchanged with ones that have been freshly calibrated in the lab. The retrieved sondes that are returned to the lab are thoroughly cleaned and new DO membranes installed. The DO sensors are periodically reconditioned. During the winter of
2008-2009, all four sondes were sent to YSI for their winterization special which involved cleaning, checking, and repair of any problems.

The standpipes are painted with antifouling paint. They are periodically cleaned by scraping internally with a specially configured weight set and the PVC surfaces have been coated with antifouling paint. Over the years, additional measurements have been taken to reduce biofouling. In 2008, we began covering exposed surfaces with adhesive backed copper tape that is periodically replaced. In 2009, we began covered the sonde guard vents with wide mesh copper gauze.

Based on deployment history and YSI instrument specifications, in-situ estimates of measurement errors are: salinity = ±0.4 ppt, dissolved oxygen = ±0.3 to ±0.5 mg/L, %DO = ±5%, and temperature = ±0.1C. Noise in the salinity signal was observed during warm weather months. Efforts were made with YSI to determine the cause of this noise but due to its sporadic nature, a diagnosis has yet to be made. A likely possibility is that small slits in the DO membrane give rise to rapid fluctuations in salinity. Confusingly, this noise will spontaneously resolve. Sporadic problems have also arisen with deployment of the surface sonde in which it appears that the sonde has been stuck in the standpipe above the water surface for short (15 to 30 min) periods.

**Data Management**


Web links to the YSI Econet site include:

- Long Bay Near-shore Water Quality Management website ([http://www.carocoops.org/longbay/realtime.php](http://www.carocoops.org/longbay/realtime.php)) which is maintained by the Carolinas Coastal Ocean Observing and Prediction System (Caro-COOPS), the Southeast Atlantic Coastal Ocean Observing System (SEACOOS), and the Southeast Coastal Ocean Observing Regional Association (SECOORA).
- SECOORA also hosts a link at [http://secoora.org/maps/inventory/](http://secoora.org/maps/inventory/) as shown in Figure 4.
The raw data are downloaded quarterly from the YSI Econet website into a .csv file. Aquarius time series software (Aquarius Informatics, Inc.) is used to edit records based on information provided by the Maintenance and Calibration log. Additional data reduction is described in the next paragraph. The corrected data records are used for all statistical analyses and publication quality graphing. Aquarius software is used for some of this as well as time averaging, such as production of hourly and monthly averages. The potential exists for posting of these corrected records at the SECOORA website. For an additional $1200 per annum, Econet can also post these data at their Apache Pier website.

Data correction was performed as follows: (1) signals collected during calibration periods were eliminated as the sondes were not located at their proper sampling locations, (2) signals where a known problem caused field post calibration check failures, such as a slit in a DO membrane, were eliminated and (3) signals that were grossly mismatched to adjacent signals, such as 0 ppt salinity were eliminated. Measurements were left in the record in cases where field post calibration checks revealed that a sensor was out of control with no known cause. No effort was made to back correct any signals. Also, no effort was made to “smooth” signals to correct for acceptable sensor drift.
Due to a very high degree of DO membrane failures during the summer of 2009, an additional field post calibration check was performed. This consisted of the independent measurement of DO, temperature and salinity with a manually deployed Hydrolab datasonde just prior to field post calibration check of the YSI sondaes. If the YSI readings agreed with the Hydrolab measurements, the YSI data were retained regardless of whether the field post calibration check was in control. In many instances, it appeared that the DO membrane was damaged during sonde retrieval and had been operating correctly during the deployment. This highlights the need to replace the sondes with units that have LDO sensors which are less prone to biofouling over two week deployments and do not have membranes.

OUTREACH AND OTHER ACTIVITIES

Hypoxia Alert Network

- The Apache pier YSI Econet account is programmed to send out a hypoxia alert via email to the project PI’s and agency contacts when DO concentrations fell below 4 mg/L and %DO falls below 60%.

Publications and Technical Reports


Presentations

- Koepfler, Eric, Lake, Sam, Smith, Erik M., Bennett, Joe, and Libes, Susan, Examination of Inner Shelf Water Quality in Long Bay, South Carolina, using Dataflow. (2008) Southeastern Estuarine Research Society, 3/13-14/08, Fort Johnson Marine Science Center in Charleston, SC (poster)
- Libes, S. (2008) Looking Upstream: How Watershed Processes affect the coastal ocean, Keynote speaker, Litchfield SC Marine Educators Association, Fall Annual Conference, 10/14/08, Litchfield Golf and Beach Resort, Litchfield, SC (oral)
- Libes and Bennett (2008) Low Dissolved Oxygen in Long Bay: Dissolved Oxygen Assessment along the grand strand using pier-based in-situ sensors, SC Sea Grant Consortium Long Bay Working Group Workshop and NOAA in the Carolinas site visit, BMFL, Georgetown, SC, 12/9/08 (oral)

Publicity

• SC Sea Grant Consortium (2009) Scientists working to understand water-quality anomaly, Vol. 23, No. 3, Coastal Heritage: Cold-Water Corals
• R. Morris (7/13/08) Fishing for a Dead Zone, The Sun News
• Holshouser, G. (2006) Local Efforts aimed at answering the many questions the ocean offers. The Sun News, Friday, July 21, 2006, p. 4B.
• The weekly fishing column in The Sun News written by Gregg Holshouser routinely notes the water temperatures as reported by the Apache Pier data station.
• An informational poster was developed and shown at the Burroughs and Chapin Center for Marine and Wetlands Studies Open House held at Ripley’s Sea Aquarium, Myrtle Beach, SC on Oct 11, 2007.

Festivals

• Graduate and undergraduate students have hosted informational booths at Customer Appreciation Day festivals held by the Apache Campground and Pier owners at Apache Pier.
• An informational booth was staffed at Kids Appreciation Day in April 2009 to explain the pier monitoring.

Outreach materials

• The brochure shown in Figure 5 was designed and produced at the request of the Apache Family Campground & Pier. They have also requested a brief written explanation of what all the parameters show by the website mean.

Figure 5. Brochure advertising YSI Econet website
• Santee Cooper’s wind power study has funded purchase of a plasma screen display that is located in the fish tackle shop. This enables all passersby to see the Econet website and real-time data.

Graduate Student Training

• A graduate student, Emma Wear, has been assisting with sensor maintenance and received a research assistantship for her efforts.
• Another graduate student, Christian Johnson, performed a fishing effort survey at Apache Pier using a video cam. He has also obtained and collated fishing data from the Grand Strand Fishing Rodeos held since the 1970s on all the fishing piers of the Grand Strand. These data are being used for time series analysis along with SC DNR records of fishing effort (number of people fishing on the piers).
• The sensor data were used by another graduate student, J. Mull, who performed a flounder survey for SC DNR during Summer 2007.

Site Visits

• SC DHEC OCRM conducted a site visit at Springmaid Pier on 8/6/07.
• Apache Pier Campground, SC DNR and AMJ met at Apache Pier on 12/9/08 to transfer YSI Econet responsibilities to CCU.

Leveraged Funding

• A request for continued operational funding was submitted as part of a SEACOOS proposal in April 2007 by Lynn Leonard, UNC-W. The grant was funded but not at a high enough level to provide support to the Apache Pier operations.

The following proposals made use of the Apache Pier dataset:

• Sanger, McCoy, Voulgaris, Wilder, Libes, Koepfler, Libes, Bennett, Wenner, Conrads, Pirhalla, Davis: The Relative Importance of Regional and Local Influences on Nearshore Dissolved Oxygen Levels in a Southeastern Coastal Embayment. NOAA CHRP 2007, July 1, 2007 to June 30, 2010, $1,375,611 declined
• Koepfler, E., Libes, S., Smith, E., and Bennett, J . Identification of Coastal Hypoxia Mechanisms and Hypoxia Monitoring in Inner Shelf Waters of Long Bay, South Carolina 2/1/06 – 7/31/09 Funded by the SC Sea Grant Consortium and SC DHEC OCRM at $153,114
• Koepfler, E. Pilot Study to Expand Ongoing Efforts to Explain Coastal Hypoxia in Long Bay: Remus Study. (July-August 2008) Funded at $10,975 by the SC Sea Grant Consortium and SC DHEC OCRM. This funded deployment of an AUV and glider through the Southeast and Gulf of Mexico Regional Center for NOAA’s Undersea Research Program and the Mid-Atlantic Bight Regional Center for NOAA’s Undersea Research Program.
• Santee Cooper has provided funding to maintain temperature, salinity and CDOM sensors at three buoys deployed in a transect perpendicular to Apache Pier. These buoys were deployed in August 2009 and will be in place for 1 year.
RESULTS AND DISCUSSION

The data reported herein represent the first continuous record of DO levels in the nearshore of Long Bay. The only other DO data are those collected via grab sampling at a number of sites during the July 2004 hypoxic event and a continuous deployment of a Hydrolab datasonde from Jan 2006 to Sept 2007 at Springmaid Pier. The latter is located at the southern end of Myrtle Beach, SC. The observations from this sonde are described in Libes and Bennett (2008). This report includes an analysis of the data collected at Apache Pier through March 2008. At both sites, DO variability has been observed to occur over multiple temporal and spatial scales. An evaluation of horizontal spatial variability is possible via comparison of the Apache Pier sondes to the one deployed concurrently at Springmaid Pier in approximately 6 to 7 m water depth. Vertical spatial variability can be evaluated via comparison of the surface and bottom water sondes at Apache Pier.

At Apache Pier, the sondes were deployed in June 2006, providing a 3-year record although the first year was marked by significant data loss during June and July (2006). As described in Operational Detail: Installation, Deployment, and Repair, this loss was due to lightening damage and motivated installation of additional protection which has thus far protected against further incidents. Other data losses were caused by Tropical Storm Hannah in 2008 and loss of the standpipes in January 2009. The latter were replaced in April 2009 and the sondes redeployed. Routine field post-calibration checks that were out of control led to rejection of data. The net effect on the entire data set is shown in Figure 6 for the period from 6/20/06 to 11/31/08 as the percent of the 15-minute observations which were recovered and of sufficient quality for data analysis. This data set was used to generate the statistics and graphs shown in this report. The 2009 data will be similarly evaluated and available in January 2010.

![Figure 6. % dissolved oxygen data recovered at Apache Pier based on the bottom water sonde.](image)

1 The units of mg/L DO and mg DO/L are used interchangeably herein.
Time Scales of Variability in DO

DO concentrations have been observed to vary over time scales of days, seasons, and interannually. The nature and causes of these degrees of variability are unique and distinct. The seasonality of DO concentrations is shown in Figure 7 in terms of the monthly means. The period of lowest DO is broadly May through October, with July and August tending to be the peak times of lowest concentrations. In 2008, the period of very low DO extended through October. Seasonal variations of the monthly mean DO are on the order of 4 mg/L. They are caused by temperature-driven changes in gas solubility, with the atmosphere providing a buffering reservoir of O₂. A second influence of temperature is due to an increase in respiration rates with increasing temperature. This provides a faster DO sink during warm weather. As shown in Figure 7, the surface monthly mean at Apache Pier has generally been equal to or greater than that of the bottom mean.

![Monthly Mean DO](image)

**Figure 7.** Monthly Mean DO. Note the lowest monthly mean was observed during Jul 06 during a period of limited data collection.

Has Hypoxia Been Observed?

The threshold for hypoxia is 2 mg/L, but several sources report significant impacts to fisheries at DO concentrations less than 3 to 5 mg/L. Diaz and Rosenberg (2008) use a 2 mL/L threshold that is equivalent to 3 mg/L. Bricker et al. (2007) in the National Estuarine Eutrophication Assessment classifies waters with DO concentrations of 2 to 5 mg/L as biologically stressed and 0 to 2 mg/L as hypoxic. USEPA (2008a) in the third National Coastal Condition Report classifies waters with 2 to 5 mg/L as fair and < 2 mg/L as poor. In Long Island Sound, concentrations below 5 mg/L are “potentially harmful” with fish leaving the area at concentrations less than 3 mg/L (USEPA 2008b).

At Apache Pier, DO concentrations less than 4 mg/L were observed seasonally during all years, starting in Apr/May and ending in Sept/Oct. The cumulative amount of time within each month that the bottom water DO has been less than 4 mg/L is shown in Figure 8a in units of days. Due to significant data loss in June-July 2006 and September 2008, during periods of low DO, the durations shown in Figure 8a for...
these periods are likely under estimates. This makes very clear the higher frequency of low DO (< 4 mg/L) during 2006 and 2008 as compared with 2007.

Similar observations were made at Springmaid Pier where during July – August 2006, during which 30% of the observations of DO were less than 4 mg/L. The lowest DO observed was 1.8 mg/L. At Apache Pier, DO’s less than 2 mg/L were observed during August 2006 for 1 hr collectively (4 records) and during August and Sept 2008 for a total of 30 hrs. The lowest observed DO at Apache Pier has been 1.2 mg/L (bottom water on 8/31/08 at 10:30 AM). The lowest surface water DO observed has been 2.2 mg/L (9/10/08 at 11:00 AM). In summary, hypoxic conditions have been observed at Springmaid and Apache Piers in 2006 and 2008 but do not appear to have been sustained for a period as long as the event which caused the flounder Jubilee in July 2004.

**Figure 8.** Bottom DO concentration (a) days below 4 mg/L with periods of significant data loss in light blue and (b) Minimum observed concentration and duration below 2 mg/L. The latter was determined by summing the 15-min observations of DO < 2 mg/L. The red line marks the threshold for hypoxia.
Seasonal Variability in DO

Strong evidence for a biogeochemical source of the low DO is provided by the % saturation of DO observations. (At the temperatures characteristic of the warm weather months, 60% saturation is approximately equivalent to 4 mg DO/L.) As shown in Figure 9, the monthly mean %DO has been less than 100% with the exception of slight supersaturations in the surface water during March 2007 and February 2008 and in the deep water during February 2008. Undersaturations reflect a net O₂ sink, i.e., that the uptake of O₂ via respiration in the water column and/or surface sediments is greater than the combined rate of supply from in-situ production via photosynthesis and physical transport.

Based on the observations from June 2006 through November 2008, Long Bay is a net heterotrophic system. This is thought to reflect high loads of natural DOM from adjacent blackwater river systems. The latter include: (1) Winyah Bay, which is about 40 mi to the south of Apache Pier, (2) Little River Inlet, which is 10 mi north, and (3) the Cape Fear River, which is 40 mi to the north. Apache Pier is near Singelton Swash, which is one of 8 tidal creeks that discharge into the ocean within a 20 mi distance that extends from Surfside Beach to North Myrtle Beach.

Figure 9. Monthly Mean %DO. Error bars reflect 1 SD around the mean. The green line marks 100% saturation. At this level, the DO concentration is equal to that of the normal atmospheric equilibrium concentration specific to the in-situ temperature and salinity.

The lowest %DO observations occurred in the deep water during warm weather months suggesting this is the location and timing of the most intense O₂ demand. Undersaturations in %DO reflect an excess of

2 Preliminary results from 2009 suggest that supersaturations have been more common than seen in 2006-2008. Supersaturations observed in the surface and bottom waters during the summer months suggest unusually high rates of photosynthesis in 2009.
O$_2$ loss via respiration with respect to O$_2$ supply. Since respiration rates increase with increasing temperature (as do rates of photosynthesis), higher oxygen demand is expected to occur during the warm weather months. Physical mechanisms by which O$_2$ is transported within and into seawater include advection, turbulent mixing (especially across the air-sea interface), and molecular diffusion. Vertical density stratification tends to inhibit reoxygenation by reducing the vertical movement of waters and hence communication with the atmosphere.

Vertical profiles collected during periods of low DO indicate that concentrations decline with increasing depth to the seafloor (an example is provided in Figure 21 from King et al. (2006)). At Apache Pier, the oxycline tends to be positioned 3 to 4 m below the sea surface in a total water depth of 7 m. This is consistent with the surface sediments serving as a significant source of O$_2$ demand. Oxygen demand from the sediments could be the result of secondary effects. This is suspected because the water column concentrations of all phosphorus species (TP filtered and unfiltered, ortho-phosphate and dissolved organic phosphorus) increase with increasing depth (Koepfler et al. 2008). This coincides with deepwater maxima in chlorophyll concentrations with chlorophyll to phaeopigment ratios that are greater than 1 (Koepfler et al. 2008). Both findings suggest that the sediments are a diagenetic source of phosphorus that helps stimulate benthic primary production. The resulting biomass is a potential later source of oxygen demand. Because measurements of primary production have not been made, the only information on the net balance between photosynthesis and respiration is provide by the %DO record, which clearly reflects net respiration (at least through 2008).

**Interannual Variability in DO**

The frequency of low DO observations during the warm weather months of 2007 was significantly less than observed in 2008 and probably in 2006 (data loss during 2006 biases this year’s statistical summaries to low values). This interannual difference is attributed to a lower rain accumulation in 2007 as shown in Table 1 and to fewer days of upwelling favorable oscillatory winds. According to Sanay and Voulgaris (2008) and Voulgaris (2009), the former conditions result from oscillating wind stress and diurnal solar heating during the summer months when moderate speed winds blow alongshore, i.e., out of the southwest. The resulting upwelling brings colder marine waters inshore causing lower water temperatures and higher salinities. This is subsequently overlain by a low density surface water mass whose temperature is elevated by solar heating and whose salinity in depressed by terrestrial runoff of freshwater, particularly after rain events. The conditions that lead to upwelling are associated with low pressure systems and hence rainfall, making it impossible to dissociate the combined effects of the oscillatory winds and rainfall in the development of low DO in Long Bay.

Table 1. Meteorological comparison amongst observation years. Rain data are from the NCDC station (WBAN#93718) at North Myrtle Beach. Lat 33.816 N Long 78.721 W Elevation: 10.1 m

<table>
<thead>
<tr>
<th>Year</th>
<th>May through November</th>
<th>June through August</th>
<th>Tropical Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>38”</td>
<td>28”</td>
<td>Alberto &amp; Ernesto</td>
</tr>
<tr>
<td>2007</td>
<td>22”</td>
<td>17”</td>
<td>None</td>
</tr>
<tr>
<td>2008</td>
<td>35”</td>
<td>24”</td>
<td>Hannah</td>
</tr>
</tbody>
</table>

When rainfall accumulations are reduced, lesser amounts of stormwater runoff and surficial groundwater discharge will enter Long Bay. These sources of water are hypothesized to convey significant fluxes of chemicals that contribute to oxygen demand, including nutrients and organic matter. Stormwater loading of oxygen demand is presumed likely due to the chronic contraventions of bacterial indicator levels (Enterococci) along the coastline of Long Bay, especially in and near the
swashes. As a result, many of these swashes are on the federal 303(d) list of impaired water bodies and the remainder will be listed in 2010 (SC DHEC 2008). Furthermore, grab sampling from all of the swashes, has demonstrated that the waters discharging from these features have elevated concentrations of nutrients, TOC, and BOD (Koepfler et al. 2008).

During periods of reduced freshwater discharge from land, salinities should be higher than during periods of higher rainfall and enhanced terrestrial runoff. Figure 10 suggests this was the case in 2007, which was a period of record drought for northeastern South Carolina. Reduced discharges of terrestrial runoff should result in a lower input of oxygen-demanding substances, resulting in higher %DO and DO concentrations as observed in 2007.

**Figure 10.** Monthly Mean Salinity. Error bars reflect 1 SD around the mean. The green line marks 35 psu.

**Low DO Events with Duration of Days to Weeks**

All of the periods in which %DO declined below 60% had durations no longer than two and half weeks. The events seen in 2008 are illustrated in Figure 11 which depicts the hourly average % Saturation of DO and salinity in the bottom water for April through November. The lower panel depicts the warm weather period from September through November. (The gap in early September is from Tropical Storm Hannah). Major low DO events (<60% saturation) occurred on: (1) 7/21-27, (2) 8/3-8/17, (3) 8/28-9/1, (4) 9/8(?)-9/10 and (5) 9/28-10/2. As shown in Figure 8, hypoxic conditions were observed in 2008 during August and September for cumulative periods of 1, 21, and 9 hours, respectively. The lowest 15-min DO concentration of the entire period of record was observed during this period, i.e., 1.2 mg/L on 8/31/08 at 10:30 AM.

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3 The start date of this event is uncertain as the sondes were removed from their deployments on 9/3 as a precautionary measure in advance of then Hurricane Hannah.
Figure 11. 2008 record of bottom water % Saturation of DO and salinity based on hourly averages: (a) May through November and (b) Sept through November. Yellow arrows mark rains events and total accumulations based on NCDC data. Four events are marked by yellow stars. Rain data are from the NCDC meteorological site at the North Myrtle Beach airport.

Min DO = 1.4 ppm
The association of rainfall with depressions in %DO is shown in Figure 11(b) for the period of September through November, with the dates and accumulations marked by the labeled yellow arrows. In most cases lag times are short, on the order of hours. The ensuing drops in salinity and %DO are abrupt and significant. For example, a 2.5” rainfall in late September (9/23/08) resulted in a 1 psu drop in salinity and a decline in %DO from 100 to 60% in a matter of 2 days. Within 5 to 6 days, the %DO reached levels as low as 40%. The largest single rain event during the summer of 2008 was Tropical Storm Hannah, in which 4.3” of rain fell. Once the sondes were reinstalled at Apache Pier 5 days after this event, extremely low %DO and DO concentrations were observed, although similarly low values had been observed a few days immediately prior to this tropical storm. The other two events of significant marked by stars on Figure 11(b) are discussed further below.

First, the events marked with stars in Figure 11(b) appear to be associated with movement of discrete water masses on time scales of days. Evidence for this is seen in the inflections and mixing relationships present on a T-S diagram constructed from the hourly means observed in the surface and bottom waters (Figure 12).

![Figure 12](image)

**Figure 12.** TS diagrams for bottom and surface water at Apache Pier from 9/9/08 to 10/6/08 based on hourly records. The region within the gray dashed box is shown in Figure 14.

During a period of dry weather, salinity declined from 9/21 to through 9/25. A further decline can be attributed to a 2.5” rain event on 9/25-26. From 9/19 to 9/23, the T-S data plot as a well defined mixing line which starts with a sharp inflection at 9/19. During this period, %DO ranged from 95 to 100%. After the 2.5” rain event on 9/25, a further reduction in salinity was accompanied by a concurrent rapid drop.
in %DO from 100 to 60%. After a few days, the salinity began increasing, but %DO continued to decline to a minimum of 40%. On 10/2, the %DO began to recover with a well defined diurnal oscillation suggesting an increase in deepwater primary production. The TS data from 10/2 form a unique region in the plot in Figure 12 suggesting the presence of a distinct water mass with relatively low temperatures for its salinity.

Role of Vertical Density Stratification in the Development of Low DO

The vertical density stratification within the water column was computed as the difference of the hourly mean density (sigma t) between the deep and surface waters. A positive value indicates a stable density stratification in which the bottom water is denser than the surface water. Values near zero are referred to as neutrally stratified. The vertical density stratification for July through October 2008 is presented in Figure 13(a). During late July and August, a stable vertical density stratification was present. The major low DO event which occurred during the first weeks of August was time of very high stable stratification as was the period immediately preceding Tropical Storm Hannah. During both of these periods, % DO declined to 20%. Stratification was also high immediately post Hannah, also coinciding with a period of very low DO.

A lesser period of increasing and sustained vertical density stratification occurred from 9/20 to 10/2 as shown in Figure 13(b). This period was characterized in the previous section as beginning with a period of declining salinity in the bottom waters. The increasing stratification was due to higher salinities in the bottom water (Figure 14(c)). This slightly stable stratification was destroyed by the 2.5” rainfall on 9/25. A period of increasing stratification recommenced on 9/27 and continued through 9/30. The T-S diagram in Figure 15 shows that the temperature and salinity in the surface and bottom waters were both increasing during 9/26 to 9/27 when %DO dropped rapidly from 100 to 60%. A stable stratification was produced by a higher salinity and lower temperature in the bottom water as compared to the surface water (Figure 14(c-d)). As shown in the T-S diagram, evidence for mixing of 2 to 3 bottom water masses is present. This suggests intrusion of marine waters and diel solar heating led to the development of stratification.

From 9/30 to 10/2 stable density stratification persisted at a constant level. On 10/1, %DO declined to 40%. This low DO event was remarkable for having occurred in October, making it the latest that such low %DO has been observed. This period is also notable for having followed on the heels of Tropical Storm Hannah (9/5-9/6). After 10/2, vertical stratification began increasing again, but the %DO recovered with a well defined diurnal oscillation, suggesting an increase in deepwater primary production. Several similar low DO events occurred in October and November 2008, i.e., 10/11 after 0.7” of rain, 10/24 after 3.5” of rain, and 11/30 after 1.6” rain (Figure 11(b)). The minimum %DOs during these events were about 60%. Lower values were probably prohibited from developing as water temperatures had cooled off from their summer time maxima (Figure 14).
Figure 13. Density stratification during Summer 2008 as projected by $\Delta \sigma_T$ during: (a) 7/27/08 to 9/31/08 and (b) Post tropical storm Hannah: 9/16/08 to 10/5/08.
Figure 14: Apache Pier from 9/15/08 to 10/15/08 based on 15-min records: (a) Surface water temperature and salinity, (2) Bottom water temperature and salinity, (c) Bottom and surface water temperature and del T (Surface – Bottom), and (d) Bottom and surface water salinity and del salinity (Bottom - Surface).
Figure 15 TS diagrams for bottom and surface water at Apache Pier from 9/26/08 to 9/27/08 based on 15-min records.

Low DO in Surface Waters

Diel oscillation in DO and %DO are commonly observed in the surface waters during the warm weather months and is attributed to the result of phytoplankton to sunlight (Figure 16). This frequency of periodicity is less evident in the bottom water except after rain events as previously noted. (Beginning in May 2009, Secchi depths are now being measured at the time of field post calibration checks.) The amplitude of the diel oscillation is larger in summer than in winter and in the surface water as compared to the bottom water, reflecting the timing and location of higher net photosynthetic rates. This is notable given the observation of chlorophyll maxima in the bottom waters (Koepfler et al. 1008). (2009 is likely to be an exception to this trend with much more frequent observations of supersaturations and diel cycling of DO in the bottom waters as compared with 2006 through 2008).

Figure 16 also shows that the surface waters express the same broad declines in DO seen in bottom water. The correlations of %DO in the surface and bottom waters for the warm weather months of 2006, 2007 and 2008 are shown in Figure 17. The correlation is significant in all three years (p = 0.00), but the degree to which the %DO in the bottom water explains that in the surface water ranges from $R^2$ of 0.64 in 2006 to 0.20 in 2007. The low $R^2$ in 2007 probably reflects the smaller range in %DO observed in that year, i.e., the relative lack of low DO events.
Figure 16. % Saturation of DO in surface and bottom waters during low DO seasons of 2008.

The lowest surface water DO observed during this period of record was 2.2 mg/L on 9/10/08 at 11:00 AM (as marked by the yellow star). The occurrence of such low DO in the surface waters suggests that vertical density stratification is not required for the establishment of hypoxic conditions. Instead significant oxygen demand must have been present in the surface waters. Alternatively the water column was well enough mixed for the oxygen demand in the bottom waters and/or sediment to support a deep DO undersaturation in the surface waters.

Figure 17. % Saturation of DO in surface versus bottom waters during low DO seasons of 2006, 2007 and 2008 using hourly mean values. Also shown are linear regression lines, r² and p values.
Influence of Winds

The role of upwelling favorable winds in the development of the intense low DO event in early to mid August 2008, during which hypoxic conditions were present, is illustrated in Figure 18. The upper panel of this figure shows the wind direction and speed along with the vertical density stratification as $\Delta \sigma_T \times 100$ (%). Antecedent rain included 2” on 7/23-24 and 1” on 7/31. As previously shown in Figure 13(a), a period of enhanced vertical density stratification encompassed the period from 8/7 to 8/16. Winds from the southwest (200°) were present on a diurnally oscillating basis from 8/7 to 8/12 with fairly low winds speeds (averaging 10 mph). The resulting bottom water DO concentration during the period of intense vertical stratification is shown in Figure 18(b), illustrating that concentrations were generally below 4 mg/L with hypoxic conditions present from: (1) 8 PM on August 8 to 9 AM on 8/9, (2) on 8/10 from 8 AM to noon, and (3) briefly during midnight and 6 AM on 8/12.

The role of upwelling in development of this low DO event is complicated. As shown in Figure 19, temperatures began a sustained decline in the surface and bottom waters on 8/4 that persisted through 8/9. The diurnal temperature oscillations were dampened in the bottom water during this period leading to a large vertical stratification in temperature during daylight hours. The salinity of the bottom water began increasing on 8/4, rising from 34.75 to 36.25 by 8/9. This suggests that upwelling drew marine waters inshore during this period. The surface water salinity was not as dramatically affected, rising from 35.5 from 35.75 during this period, which is not likely significant. Because the salinity measurements have an uncertainty of 0.5 psu, it is suggestive, but not certain, that the low DO event in August 2008 coincided with a period in which the bottom water salinity was about 0.5 psu greater than the surface salinity.

The hypoxic conditions observed in July 2006 exhibit a similar relationship with vertical density stratification as seen in 2008. These conditions were also associated with lower bottom water temperatures and higher bottom water salinities as shown in Figures 20 and 21. A heterotrophic microbial respiration rate measurement made on 7/11/06 at Apache Pier corroborates that very high rates of $O_2$ uptake were present (Smith et al. 2008).
Figure 18. Low DO events 7/28-8/23 in 2008. (a) Wind direction and speed (mph) along with $\Delta \sigma_t \times 100$ (%). (b) Bottom DO concentration (mg/L).
Figure 19. Low DO events 7/26- 8/17 in 2008. (a) Surface and Bottom water temperature and (b) Surface and Bottom water salinity.
Figure 20. Low DO events June-July 2006. % DO in surface and bottom waters. Del Temperature and rain dates and accumulations.

Figure 21. Vertical profile on DO observed during July 2006. Data are from King et al. (2006)

CONCLUSIONS

The results from the Apache Pier sensors in conjunction with other field measurements conducted since 2005 (Koepfler et al. 2008) have demonstrated that Long Bay is a net heterotrophic system with %DO less than 100% nearly year round. Low DO events are now being observed routinely during warm weather months and appear to result from convergence of necessary physics, chemistry and biology. This brings into question references to the hypoxic event of 2004 as an anomaly.

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4 Preliminary results suggest that this trend has not been seen during the warm weather months of 2009.
From a management perspective, Long Bay appears to have low assimilative capacity for O₂-demanding substances and is likely at a tipping point where hypoxia could become more frequent if hydrographic conditions promote enhanced vertical density stratification and/or terrestrial loading of nutrients and organic matter increases. The former is likely given current trends in global climate change. Another related impact could derive from ocean acidification which is likely to alter microbial community structure and function.

Low DO is a concern to local recreational and commercial fisheries. As noted by Holshouser (2007), a much higher abundance of king mackerel were present along the Grand Strand’s fishing piers in 2007 as compared to 2006. This was been attributed to lower DO concentrations in 2006 and a poorer water clarity. Local fisheries are already stressed as documented by sharp declines in the fish catch at the fishing piers since the 1970s (C. Johnson, pers. comm. based on Grand Strand Fishing rodeo fishing logbooks. ⁵) Low DO also has the potential to alter microbial community structures and hence select for undesirable ecosystem outcomes, such as HABs (Glibert et al. 2005).

Diaz and Rosenberg (2008) have inventoried all known marine waters subject to hypoxic conditions. Long Bay is included in this list. These authors have also documented that hypoxic conditions follow a trajectory in which rare episodes increase in frequency and eventually become persistent unless management changes are made to reduce terrestrial loading of nutrients and organic matter. This is of particular concern in Long Bay due to likely impacts on recreational and commercial fisheries which rely on hard-bottom benthic communities for at least part of their food source. Because the most DO-depleted waters have been found in contact with the seafloor, benthic communities are deemed to be most at risk as compared to pelagic nektan that are capable of swimming to more oxygen-rich waters. The impact of low DO conditions on sediment diagenesis is also a concern. For example phosphorus and iron rich precipitates tend to undergo geochemical cycling at redox boundaries, suggesting that they could be mobilized by increasing occurrence of hypoxia. Both have the potential to stimulate algal growth, with iron being known to enhance the occurrence of harmful algal blooms in coastal waters (Naito et al. 2005).

In Long Bay, increasing coastal development is likely to result in increased nutrient and organic matter loading in the form of polluted stormwater runoff and surficial ground water seeps. The stormwater treatment practices in current use focus on directing stormwater flows out into the ocean. Some efforts have been made at treatment prior to discharge, but the performance of these best management measures (BMPs) is of unknown effect. Plans are underway to tie together the discharges from hundreds of stormwater pipes that now discharge terrestrial runoff onto the beach face thereby merging their flows. These discharges will be emitted into a few stormwater outfalls located approximately 1000 ft offshore. This is the location where low DO has been most commonly observed. It is unclear as to whether any additional treatment devices will be installed as part of these outfall pipes.

The current trajectory of climate change will result in warmer coastal waters, thereby lowering DO solubility and enhancing respiration rates. The higher surface water temperatures could lead to increased vertical density stratification. As noted above, concurrent acidification from dissolution of atmospheric CO₂ coupled with lower DO will likely alter microbial structure and function regardless of the impacts from increased terrestrial loading of nutrients and organic matter.

Since no routine monitoring of dissolved oxygen had been conducted in the nearshore region of Long Bay prior to this work, all data collected herein represent wholly new insights. Although this project was motivated by the occurrence of an extended period of widespread hypoxia in the shallow nearshore of

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⁵ http://www.myrtlebeachinfo.com/mb-cvb/Vacations_Getaways/Fishing_Rodeo.html
the Grand Strand as inferred from the duration of a flounder Jubilee in July 2004 (Sanger et al., in prep), a repetition of these conditions has not observed. On the other hand, periods of DO with concentrations less than 4 mg/L have been frequently observed seasonally during the months of May through October with the most significant oxygen deficiencies occurring during July through September. Hypoxia was briefly observed during 2006 in June and in 2008 during August and September. While hypoxia is technically defined as DO concentrations Diaz and Rosenberg (2008) use a 2 mL/L threshold that is equivalent to 3 mg/L. Bricker et al. (2007) in the National Estuarine Eutrophication Assessment classifies waters with DO concentrations of 2 to 5 mg/L as biologically stressed and 0 to 2 mg/L as hypoxic. USEPA (2008a) in the third National Coastal Condition Report classifies waters with 2 to 5 mg/L as fair and < 2 mg/L as poor. In Long Island Sound, concentrations below 5 mg/L are “potentially harmful” with fish leaving the area at concentrations less than 3 mg/L (USEPA 2008b).

%DO in the surface water at Apache Pier is broadly correlated with that in the bottom water, suggesting similar biogeochemical and physical controls are at work throughout the water column. During periods of lowest DO, diurnal cycles in DO concentration are largest, reflecting high biological activity, i.e., production from photosynthesis causing supersaturations during the day followed by net aerobic respiration at night resulting in intense undersaturations (<60%). The large amplitude of these diurnal swings is expected to be stressful to animals.

The most intense oxygen deficits were sustained for time periods that ranged from hours to days to weeks. While the Hydrolab sonde was operating at Springmaid Pier during 2006-2007, it recorded many of the low DO events observed at Apache Pier. Most of the low DO events (< 4 mg/L) were associated with vertical density stratification arising from a few degree C difference between surface and bottom water temperatures and a salinity gradient of 1 psu or so. The temperature and salinity records are consistent with upwelling driven by longshore (southwesterly) winds. The ensuing Ekman transport brings cold saline water inshore. These waters are capped by a less dense surface layer created by diel solar heating and terrestrial runoff of freshwaters. The resulting vertical density stratification promotes O₂ deficiency in the bottom water by inhibiting attainment of gaseous equilibrium with atmospheric O₂. This mechanism explains why DO deficiencies develop in the bottom water, assuming that these waters or the underlying sediments have a sufficient source of O₂ demanding substances. But it does not explain the low DO concentrations concurrently observed in the surface waters.

Overall DO’s during the warm weather months were lower in 2006 and 2008 than 2007, although this conclusion is limited by the extended outages in 2006. Most of the low DO in 2006 was associated with a long-lived event extending from late June to early July. The interannual differences are ascribed to the record drought which occurred in 2007. Since upwelling favorable conditions are typically accompanied by low pressure cells, it is not possible to isolate the oceanographic driving forces from terrestrial run-off in the development of low DO in Long Bay.

The following is a brief summary of what is known regarding the sources and inputs of terrestrially driven organic matter and nutrients to Long Bay. Nutrient, BOD, DOC, turbidity, and chlorophyll distributions in Long Bay were characterized in the summer months of 2006 and 2007 in tidal creeks (swashes) and nearshore waters from grab sampling and dataflow surveys (Koepfler et al. 2008 and Bennett et al. 2009). The results demonstrate that concentrations of nutrients, particulates and organic matter increase with proximity to the coast and generally with depth. DO distributions exhibit an inverse relationship. Concentrations of phosphorus, BOD and chlorophyll were elevated, causing some of the waters to be rated as “fair” under the US EPA’s NCCR III coastal water quality classifications. Molar TDIN-to-DIP ratios ranged from 6.4 to 7.9, suggesting a high degree of phosphorus loading and that the phytoplankton could be N limited. A large fraction of the nutrients were present in particulate form. Bioassay amendments have demonstrated that the indigenous aerobic heterotrophic microbes
are nutrient and carbon limited. All of this evidence suggests that periods of low DO in Long Bay are associated with the input of chemical feedstock's from land-based sources. This input enhances the biological activity of aerobic heterotrophic microbes resulting in DO deficits. This mechanism for the development of hypoxia is significantly different from those observed elsewhere, such as Chesapeake Bay and the Gulf of Mexico, with commence with phytoplankton-based eutrophication.

**RECOMMENDATIONS FOR FUTURE WORK**

Several processes that are likely important to the development of low DO in Long Bay remain uninvestigated due to lack of funding. These include: (1) sedimentary processes, such as diagenesis, porewater advection and benthic photosynthesis and (2) primary production rates and temporal variations. The strong diel oscillations in %DO during the warm weather months in the surface waters, and often the bottom waters, suggest that in-situ O₂ production is significant. This is also supported by frequent observations of very high chlorophyll concentrations in the deep waters (Koepfle et al. 2008). 6 Notably the chlorophyll concentrations are inversely related to the DO. The chlorophyll to phaeopigment ratios are high, suggesting that the phytoplankton are viable. Regardless, the cellular POM associated with this chlorophyll is a small fraction of the total POM and DOM in the water column, emphasizing the importance of other sources of O₂ demand in this system besides detrital POM from phytoplankton.

Although the marine influences on development of low DO in Long Bay seem to be fairly well understood, the source(s) of allochthonous organic matter fueling net heterotrophy are not. These sources could include: (1) terrestrial runoff via swashes, beach pipes, outfall pipes, and groundwater, (2) flows from blackwater rivers and (3) in-situ production within the water column and/or sediments. The relative roles of POM versus DOM in fueling microbial respiration are also not known. Data are suggestive that hypoxia develops in Long Bay via a route unique from that observed in other systems where phytoplankton eutrophication is the critical first step. For example, bioassay work has shown that bacterial growth (and therefore organic matter degradation and O₂ demand) in Long Bay is often resource limited. This limitation is mostly due to phosphorus, but not always as C, N, and P have all frequently shown significant growth-enhancing effects (Smith et al. 2008 and Smith and Buck 2009). The causes of the observed variability in resource limitation are unknown. One possibility is that the dominant source/type of allochthonous organic matter is temporally and spatially variable. High resolution dataflow surveys and grab sampling were performed in the swash adjacent to Apache Pier (White Point Swash) during the summer of 2008 to better characterize allochthonous sources of nutrients and organic matter (Koepfle, pers. comm.) but far more definitive work needs to be done in this arena.

Preliminary estimates of DOC and nutrients fluxes from groundwater seeps into Long Bay were made in the summer of 2008 and suggest that these inputs could be significant. Other sedimentary sources of O₂ demand include diagenetic release of phosphorus and iron, particularly from hard bottoms, where phosphorite deposits are abundant. These inputs provide an indirect source of O₂ demand if they support benthic primary production or enhance microbial heterotrophy. Another potential source of sedimentary O₂ demand is organic matter present in the seabed. A layer of peat is found at the 3 m bathymetric contour along most of the Grand Strand. It was deposited during the last period of low sea level during the late Holocene (P. Gayes, pers. comm.). 7 These peat deposits are periodically covered

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6 CDOM sensors were deployed in a transect perpendicular the coastline off Apache Pier in July 2009 as part of a Santee Cooper funded wind power project (P. Gayes, pers. comm.). These sensors should provide information on the extent of the deep chlorophyll maximum in the nearshore waters. Reports of chlorophyll maximum in deeper waters on the continental shelf have been reported by Jahnke et al. (2008).

7 This is also the depth at which the waves in the surface zone break.
and uncovered by lenses of sand. When uncovered they are subject to erosion. The resulting peat fragments are observable as black particles suspended in the water column. The degree of their lability to microbial degradation is unknown.

Given the precarious nature of the oxygen balance in Long Bay and the extreme interannual variability observed thus far, continuing the operation of at least one set of surface and bottom DO sensors at a fishing pier in Long Bay is highly recommended, preferably Apache Pier due to the longevity of its existing record. Availability of the data to the public through the YSI Econet website and a plasma screen at the Apache Pier bait shop has served to inform and alert the public to the occurrence, causes, and impacts of low DO in Long Bay.

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