

HYPOXIA IN THE NEARSHORE COASTAL WATERS OF SOUTH CAROLINA ALONG THE GRAND STRAND

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Abstract. In July 2004, hypoxic conditions were discovered in the nearshore waters of Long Bay, a coastal embayment that borders the sandy beaches of the Grand Strand in northeastern South Carolina. Since dissolved oxygen (DO) levels were not being routinely monitored in Long Bay, first efforts at assessing local hypoxia focused on characterizing temporal and spatial dynamics. To do this, datasondes were deployed at the seaward end of a fishing pier to collect continuous measurements of temperature, salinity and DO. Based on these observations, Long Bay appears to be a net heterotrophic system, with a monthly mean percent saturation of DO less than 100% nearly year round. Strong semidaily oscillations reflect local production of DO during the day by phytoplankton, with larger amplitudes observed during the summer and in the surface waters. Hypoxic events occur during the summer. They are brief, lasting from periods of hours to days, and result from a convergence of particular physical and biogeochemical conditions. Since 2004, the most intense and persistent periods of hypoxia were observed during the summer of 2009, with anoxic conditions present over two multi-day periods in August and September. Changes in local conditions, such as ocean warming associated with global climate change and increased terrestrial loadings of nutrient and organic matter resulting from population growth, could increase the frequency and intensity of low DO events. Therefore, management interventions could be useful in maintaining DO levels in the nearshore waters of Long Bay.

INTRODUCTION AND BACKGROUND

Low levels of dissolved oxygen (DO) in Long Bay were first documented in July 2004 in response to reports of a “flounder jubilee” during which numerous large flounder were being caught from the fishing piers and surf zone. Fishermen were also finding that their bait fish, suspended in buckets at mid depth, were dying. Surveys performed by Coastal Carolina University researchers determined

that bottom water DO levels were less than 2 mg/L, suggesting that the flounder were moving into the surface waters and surf zone in pursuit of waters with higher DO. During and since that time, low DO waters have only been observed in the immediate nearshore, i.e., within 0.8 km of the coast in water depths of 5 to 10 m.

During the 2004 event, DO levels fell below the threshold for “hypoxia”, a condition commonly referred to as a “dead zone”, such as occurs in the Gulf of Mexico and Long Island Sound. Reports of coastal regions experiencing hypoxia are increasing (Diaz and Rosenberg, 2008). Once a coastal region experiences hypoxia, the frequency and intensity tend to increase over time. Low DO has a negative impact on fish and bottom-dwelling organisms, reducing population numbers and altering ecosystem structure. This can lead to the proliferation of nuisance organisms, such as large jellyfish (Rabalais and Turner, 2001). Coastal areas experiencing low DO are also prone to acidification, another biological stressor (Fabry et al. 2008).

Long Bay is one of several embayments located along the southeastern continental shelf of the USA. As shown in Figure 1, the Cape Fear River marks its northern extent. The southern boundary is created by Winyah Bay, which is the third largest estuary, in terms of watershed area, on the eastern seaboard. Other waters that discharge into Long Bay include: (1) 14 tidal creeks, locally known as swashes, whose watersheds include freshwater and saltwater marshes and Carolina Bays, (2) stormwater runoff that is funneled through hundreds of pipes that terminate on the beachface and seven ocean outfalls that discharge 300 m offshore in water depths of 5 to 10 m, (3) several small inlets such as Murrells Inlet and Little River Inlet, and (4) submarine groundwater discharges. Land use in Long Bay is dominated by the Grand Strand, which includes the densely populated municipalities of Myrtle Beach, North Myrtle Beach, Surfside, Briarcliffe Acres, Atlantic Beach and unincorporated areas of Horry County, including Garden City. The Grand Strand is a major tourist destination, hosting over 14 million visitors a year.

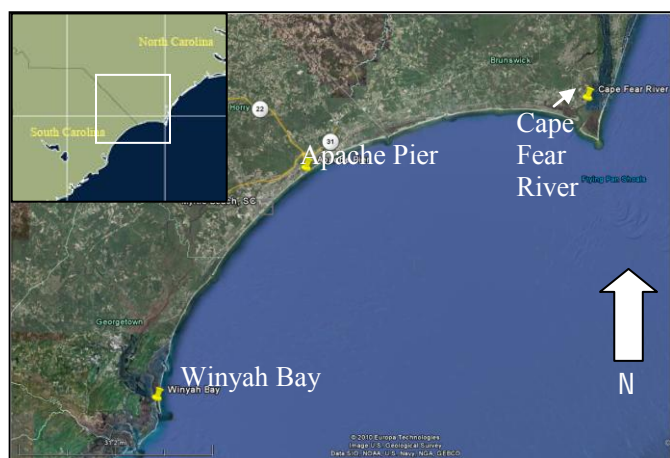


Figure 1. Long Bay. Copyright Google 2009

As a result, much of the region is highly urbanized, with impervious coverage in the coastal watersheds ranging from 17 to 42%.

Scientists were initially puzzled by the occurrence of hypoxia in Long Bay as this phenomenon had not been reported in similar environmental settings, i.e., shallow waters off sandy beaches distant from rivers. The only information on prior DO levels in Long Bay is anecdotal reports of infrequent fish jubilees that occurred during the 1950s through 1970s. To address this lack of information, two multiparameter datasondes have been deployed in the surface and bottom waters at the seaward end of the Apache fishing pier in Long Bay since June 2006. The goals of this deployment are to provide: (1) scientific data to help establish the frequency and causes of hypoxia in Long Bay, (2) year-round real-time information to the fishing public, and (3) an early alert to local natural resource managers of hypoxic conditions.

METHODS

At the north end of Myrtle Beach, near the northern limit of the low DO observations made in July 2004, two sondes have been continuously deployed from the seaward end of Apache Pier (33.7615 N 78.7798 W) since June 2006. The pier is 385 m long and the water depth at its seaward end varies from 5 to 7 m depending on the tides. One sonde is deployed approximately 1 m above the seafloor. The other is floating about 1 m below the sea surface. Each sonde is housed in a 7.6-cm ID perforated PVC standpipe coated with antifouling paint.

The sondes collect and transmit DO, salinity and temperature measurements every 15 min to YSI's Econet data server which displays the data at: <http://www.ysiiconet.com/public/WebUI/Default.aspx?hidCustomerID=131>. A meteorological station records wind direction and speed, air temperature, barometric pressure,

humidity, and rainfall. All these data can be downloaded as .csv files from the YSI Econet website.

The sondes are YSI 600R's outfitted with conductivity, temperature, and Clark cell DO sensors. The latter are salinity, pressure, and temperature compensated, enabling onboard computation of percent saturation of DO, defined as $\%DO = [DO]_{\text{observed}}/[DO]_{\text{NAEC}} \times 100$, where NAEC is the equilibrium DO concentration at 1 atm total pressure and in-situ measurement temperature and salinity. In-situ measurement uncertainties are: salinity = ± 0.4 ppt, DO = ± 0.4 mg/L, $\%DO = \pm 5\%$, and temperature = $\pm 0.1^\circ\text{C}$. To validate the data, post-deployment calibration checks are performed in the field. A performance check is also performed using a datasonde manually deployed outside the standpipe. Data grading is performed with Aquarius InformaticsTM time series software. A corrected dataset is created by removal of measurements that failed quality control checks.

RESULTS AND DISCUSSION

DO concentrations in Long Bay were generally undersaturated ($\%DO < 100\%$) year round, suggesting a continuing presence of organic matter that is being degraded by aerobic microbes. Potential sources of this organic matter include the blackwater rivers whose discharges bracket Long Bay, i.e. Winyah Bay's outlet which lies 70 km southwest of Apache Pier and that of the Cape Fear River, located 70 km northeast. Volumetrically smaller, but closer, discharges that drain the urbanized core of the Grand Strand's coastline, a 45-km length of beachfront extending from Garden City to North Myrtle Beach, include: (1) Little River Inlet, 23 km northeast of Apache Pier, (2) 8 tidal creeks, and (3) the aforementioned stormwater pipes and ocean outfalls.

Time Scales of Variability

DO concentrations in Long Bay, as characterized by measurements at Apache Pier, exhibit unique patterns of variability over time scales of days, seasons, and years (interannually). While surface DO concentrations tend to exceed bottom concentrations, similar timings were exhibited at both depths for DO declines across all timescales. The co-occurrence of low DO in the surface and bottom waters suggests the presence of a very large and active DO sink in the water column, given the opportunity for O_2 resupply via exchange across the air-sea interface.

On a daily timescale, DO concentrations tend to decline at night and increase during the day. The amplitude of the diel oscillation is larger in summer than in winter. It is also larger in the surface water as compared to the bottom water, presumably reflecting the timing and location of higher net photosynthetic rates. This is notable given the frequent observation of chlorophyll maxima in the bottom waters of Long Bay (Koepller et al., 2010).

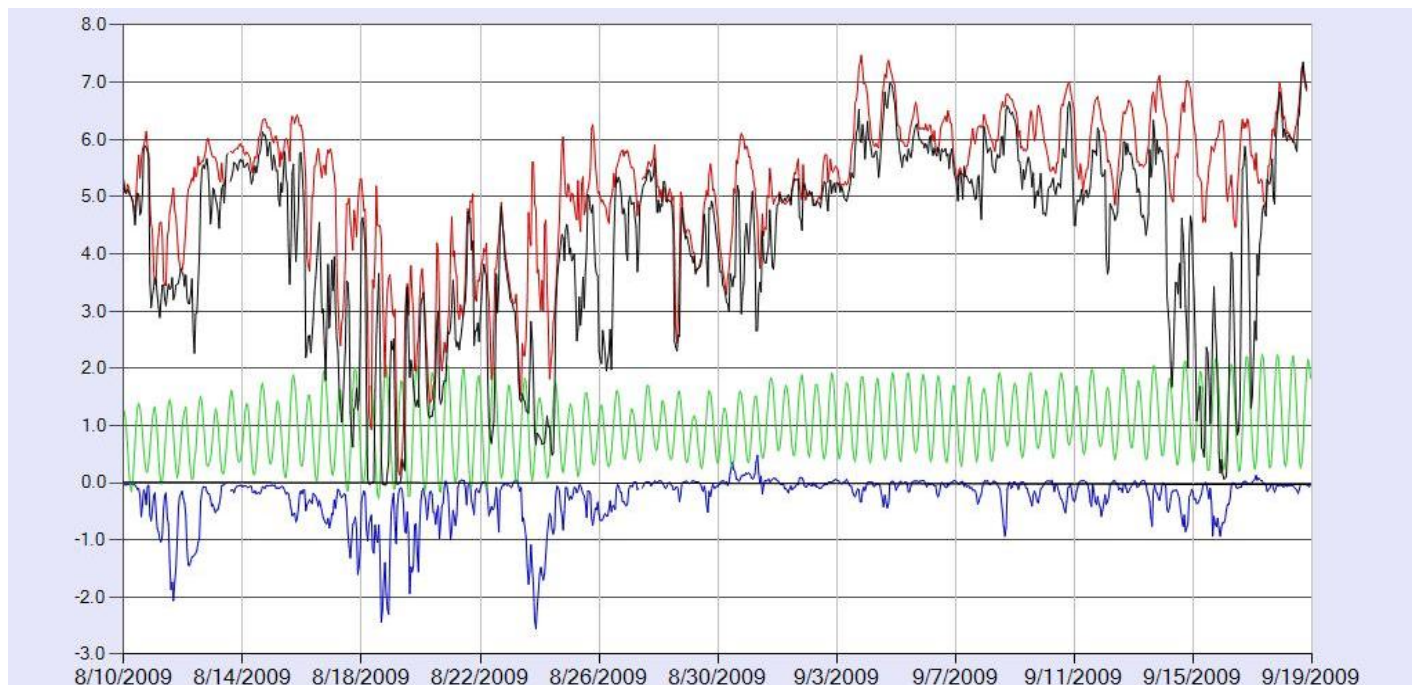


Figure 2. The water conditions at Apache Pier during the 2009 hypoxia event in Long Bay: (1) surface (red) and bottom (black) DO concentrations in mg/L, (2) temperature stratification (bottom temperature – surface temperature) in °C (blue), and (3) sea level (green) in meters as measured at Springmaid Pier, 29 km southwest of Apache Pier.

On a seasonal timescale, the period of lowest DO is broadly May through October, with July and August tending to be the peak times of lowest concentrations. The maximum difference in monthly mean DO amongst the seasons is on the order of 4 mg/L. The seasonal variation arises from temperature-driven changes in gas solubility and respiration rates, with the latter also likely influenced by seasonal fluctuations in availability of degradable organic matter and nutrients. This supports a larger DO sink during warm weather, as evidenced by occurrence of the lowest %DO's during this period.

The typical low DO events (<4 mg/L) observed during July and August were sustained over timescales of hours to days and followed periods of upwelling favorable conditions. The latter arise from oscillating wind stress and diurnal solar heating when moderate-speed winds blow alongshore, i.e., out of the southwest (Voulgaris, 2010). The resulting upwelling brings colder marine waters inshore causing lower water temperatures and higher salinities in the bottom waters. This creates vertical density stratification and frontal conditions that inhibit dispersion of freshwater discharged into Long Bay.

On an interannual basis, significant differences were observed amongst the summer seasons of 2006, 2007, 2008, and 2009. The frequency and duration of low DO events during the warm weather months of 2007 were significantly less than observed in 2006, 2008, and 2009. This difference is attributed to lower rain accumulation in

2007, associated with an historic drought, and to fewer days of upwelling favorable oscillatory winds.

Occurrences of Hypoxia

DO concentrations less than 2 mg/L were observed multiple times during June 2006 and during August and September 2008 for periods of a few hours. In all cases, hypoxia occurred following sustained periods (few days) of upwelling-favorable winds. Not until the summer of 2009 was another low DO event observed that had a duration and intensity equal to the one documented in 2004. As shown in Figure 2, hypoxic conditions, with brief periods of anoxia, were observed in the bottom and surface waters from Aug 17-26 and Sept 14-17, 2009.

The development of anoxia was preceded by the intrusion of cold saline water inshore over a period of several weeks as observed by sondes deployed off Winyah Bay and North Myrtle Beach as part of the Palmetto Wind Research Project (<https://bcmw.coastal.edu/palmetto-wind-research-project>). The intrusion of marine waters was driven by upwelling favorable winds. Both the August and September events occurred during a spring tide. In both cases, DO's oscillated in phase with the semidaily tide. During the August event, the lowest DO coincided with high tide whereas in September, the lowest DO coincided with low tide. The abrupt nature of these tidal oscillations reflects the role of tidal currents in transporting waters of low DO to and fro in the nearshore.

Observations made by manual deployments of a datasonde at other fishing piers documented that hypoxic conditions were widespread but patchy over time and space. These suggest that the low DO conditions were maintained within a cohesive water mass, or masses, that moved around in the nearshore of Long Bay over small spatial and temporal scales. The influence of frontal conditions in preventing the dispersion of nearshore waters was also supported by the presence of unusually high ²²²Rn concentrations that were inversely correlated with DO concentrations (Clay McCoy, pers. comm.).

CONCLUSIONS AND IMPLICATIONS

Observations from datasondes deployed from Apache Pier in Long Bay have documented that DO concentrations exhibit a wide range of temporal variability, including (1) diel oscillations with higher concentrations during the day, (2) seasonal variations with lowest concentrations during the summer, and (3) interannual differences that appear to be associated with physical forcing (winds, currents, tides) and terrestrial discharges. The physical forcing serves to restrict movement of the nearshore water, preventing its dispersion offshore. An additional mode of temporal variability is associated with tidal influences that could involve tidal pumping across the seafloor, within the swashes and nearshore sediments.

The continuous observations presented herein support a working hypothesis, as developed by the Long Bay Working Group, that hypoxia is a consequence of marine and terrestrial processes impacting a system with a minimal threshold for development of low DO (Koepler et al., 2010; Sanger et al., 2010; Smith et al., 2010; Voulgaris et al., 2010).

The potential role of terrestrial materials in the development of hypoxia in Long Bay suggests that management actions could be adopted to reduce the flow of these substances and thereby prevent further degradation of water quality. This is timely for three reasons. First, the municipalities of the Grand Strand are now required to implement stormwater management programs to reduce pollutant flows into natural water bodies. Second, projected increases in the population along the Grand Strand are likely to lead to increased sources of organic matter and nutrients, requiring better stormwater management to prevent contamination of local waters. Third, the effects of global climate change, including higher water temperatures, will by itself lead to an increased frequency and intensity of low DO events in Long Bay due to decreased DO solubility and increased microbial respiration rates. This alone necessitates future careful management of pollutant inputs, including those of organic matter and nutrients.

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