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A new perspective on coastal hypoxia: The role of saline groundwater

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ABSTRACT

Processes leading to the development of coastal hypoxia are usually attributed to anthropogenic nutrient loading. We present new evidence documenting a natural process capable of producing large-scale water masses undersaturated with respect to dissolved oxygen, independent of human-caused nutrient loading and subsequent nutrient-enhanced productivity. Along the heavily developed coastline of Myrtle Beach, South Carolina, the offshore discharge of saline, anoxic groundwater generates undersaturated bottom water masses which can be advected into nearshore waters. Highly elevated radium isotope activities measured in low-oxygen bottom waters cannot be supported by any known terrestrial source. Rather, discharge of cold, anoxic, high-radium water from offshore carbonate aquifers is the likely source. Density stratification inhibits mixing of these discharged waters during inshore transport. During a low-oxygen event in August 2012, this restricted mixing is likely the mechanism for the observed oxygen deficit in bottom waters. This discovery suggests benthic layers undersaturated with respect to dissolved oxygen may be considerably more prevalent than currently recognized, particularly around the carbonate-platform of the US East Coast.

1. Introduction

Severe dissolved oxygen (DO) depletion in coastal waters, a condition known as hypoxia, occurs in varied environments (Rabalais et al., 2010). The threshold for hypoxia is defined by the SCOR Working Group 128 to occur when dissolved oxygen concentrations drop below 62.5 μM (equivalent to 2 mg/L, 1.4 mL/L, or approximately 30% saturation; Levin et al., 2009; Rabalais et al., 2010; Zhang et al., 2010). In unrestricted coastal waters, hypoxia is most often attributed to nutrient-induced eutrophication (Diaz and Rosenberg, 2008; Rabalais et al., 2010). Nutrient sources may be local discharge of sewage, stormwater, or rivers draining excessively fertilized agricultural and municipal landscapes. Once in the coastal ecosystem, nutrients facilitate development of phytoplankton blooms. Under stratified conditions, the settling, consumption, and decay of this organic matter promote significant DO depletion in bottom waters that are unable to rapidly exchange oxygen with the atmosphere (Diaz and Rosenberg, 2008). Reduced DO concentrations negatively impact benthic and pelagic macrofauna and at the extreme, can cause extensive regional-scale ‘dead zones’ (Rabalais et al., 2002).

Zhang et al. (2010) characterize three major types of coastal ecosystems in which hypoxia is known to occur. The first type is in the receiving waters of a large river estuary (e.g., Mississippi River, Chesapeake Bay, and Yangtze River), where terrestrial nutrient loading combined with salinity-driven stratification can produce episodic and/or periodic hypoxic events. Another type of hypoxia occurs in semi-enclosed basins (e.g., Baltic and Black Seas, fjords), where water exchange with the open ocean (and therefore flushing) is limited, magnifying the effects of nutrient loading into hypoxic events that may be persistent. Finally, coastal hypoxia may occur at sites of oceanic upwelling, normally where western boundary currents impinge on narrow continental shelves, allowing elevated nutrient concentrations in these upwelled water masses to produce seasonal hypoxic events (Zhang et al., 2010). In each of these cases, oxygen may be consumed from both the water column and the sediments (Rabalais et al., 2010). The relative importance of benthic respiration has been shown to vary seasonally and inter-annually, but may dominate over water column respiration in some instances (Ostrom et al., 2005; Quiñones-Rivera et al., 2007, 2010; Wang et al., 2008).

Diaz and Rosenberg (2008) document a recent increase in recognized magnitude, frequency, and spatial extent of coastal hypoxia. These changes are largely attributed to anthropogenic nutrient loading through runoff and atmospheric inputs and often require a combination of biological (e.g., net respiration) and physical (e.g., stratification) mechanisms to reduce dissolved oxygen concentrations and maintain them at low levels.

Long Bay, South Carolina (Fig. 1), is one such coastal setting where episodic hypoxic conditions have been recognized since 2004. Long

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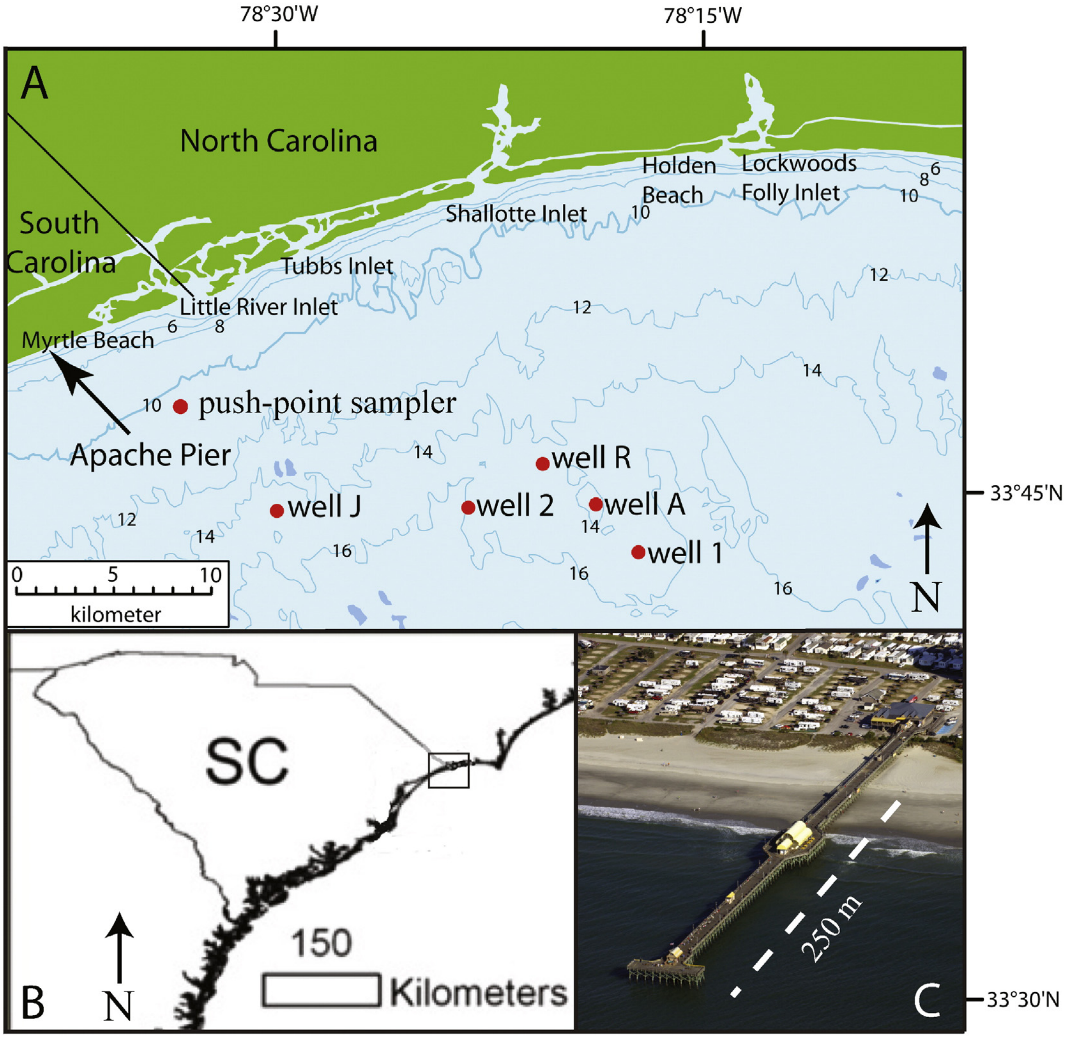

Fig. 1. Base map of Long Bay, SC, showing the developed urban center along the Grand Strand and Apache Pier (shown in inset C) where the low-DO water mass was sampled. Bathymetric contours are given in m below sea level. Offshore wells (Moore et al., 2002; Moore and Wilson, 2005) are set into sand and clay layers atop a carbonate basement. Radium data from Wells A and R are presented in Table 1 and Fig. 8C. In Sept. 2013, a PushPoint sampler deployed closer to shore found water with shallow porewater Ra activities similar to those observed in Wells A and R.

Bay is a concave embayment, stretching 160 km from Winyah Bay, South Carolina, to the Cape Fear River estuary, North Carolina. The center of Long Bay houses the Grand Strand — a highly urbanized stretch of beach containing the tourist center of Myrtle Beach.

Following the discovery of hypoxic conditions, continuous measurements of water quality parameters were initiated in surface and bottom waters at the seaward end of Apache fishing pier (Fig. 1), about 250 m offshore where water depths range from 5 to 7 m (Libes and Kindelberger, 2010). Two additional piers were similarly instrumented in 2012, providing spatial coverage of approximately 35 km along the coastline of Long Bay (Libes et al., 2014). Collectively, these observations document that the nearshore waters are characterized by short periods (hours to days) of low DO saturation in bottom water, often reaching hypoxic conditions, especially in August and September. The events of longest duration and lowest DO occur during and immediately after periods of sustained upwelling-favorable SW winds (Sanger et al., 2012).

The occurrence of low-DO conditions in Long Bay perplexed investigators, as it did not follow the generally-accepted environmental types outlined by Zhang et al. (2010). Two substantial river systems discharge at the edges of the bay, but their biogeochemical influence on central Long Bay is not well understood. Moreover, the geomorphology of Long Bay does not limit exchange and flushing with the ocean. Studies have demonstrated the potential for upwelling to transfer deeper ocean water onto the continental shelf of Long Bay (Sanay et al., 2008; Sanger et al., 2012), but this upwelled water would have to transit a long (100 km), shallow continental shelf before reaching nearshore waters. Attempts to document the spatial distribution of a hypoxic water mass in 2009, however, determined the low-DO waters to be isolated to within 2 km of the shoreline and directly offshore of the most urbanized shoreline (Sanger et al., 2012). No observations of reduced DO concentrations have been made beyond ~2 km from the shoreline, suggesting a localized, terrestrial source of the water quality degradations, or that such low-DO water masses were simply missed during sampling.

Investigators initially speculated that the hypoxic events were related to the engineered modification of stormwater pathways from the urbanized areas. Such modifications have aimed to better convey runoff to the coastal waters through outfall pipes and channelized tidal creeks. However, attempts to correlate rainfall events to the onset of hypoxic conditions have remained unsuccessful.

During a 2009 hypoxic event, however, McCoy et al. (2011) detected anomalously high activities of radon-222 (a tracer of groundwater discharge; see reviews by Burnett et al., 2006; Swarzenski, 2007; Charette et al., 2008) in bottom waters that were 5–6 fold higher in concentration than normal levels in this area. Radon activities subsided to background concentrations as DO concentrations increased throughout