PHYSICAL OCEANOGRAPHIC CONSTRAINTS CONTRIBUTING TO THE DEVELOPMENT OF LOW OXYGEN EVENTS IN LONG BAY, SC

George Voulgaris¹ and Rosario Sanay²

AUTHORS: ¹Professor, Department of Earth and Ocean Sciences, University of South Carolina, Columbia, SC 29206, USA
²Investigator, Institute of Marine Science and Fisheries, University of Vera Cruz, Vera Cruz, Mexico

Abstract. Lately episodic low oxygen events (<3mg/L) are not unusual during summer seasons off Long Bay, SC, USA, an area with high economic importance. In fact, there were two severe hypoxic events that occurred in the summer of 2004 and 2009. In this presentation, the physical conditions that prevail during the occurrence of these events are examined through the use of observational and numerical modeling data. The analysis indicates that low oxygen events coincide with upwelling favorable wind conditions (i.e., winds from the S-SW). It has been found that solar radiation and the oscillatory nature of upwelling-favorable wind-stress play the most important role keeping the inner shelf (<10m) stratified during an upwelling event. These conditions are common during summer and define the prerequisite conditions for the development of a low oxygen event. The coincidence of these conditions with low oxygen events leads to the development of three possible scenarios explaining the low oxygen events: (i) the upwelling condition creates a trapping zone for terrestrial/nearshore organic material resulting in enhanced oxygen consumption rates; (ii) organic material is advected from further offshore (inner, mid-shelf) under this upwelling conditions; and (iii) a combination of (i) and (ii). In any case, the increment of biological activity at the bottom layer near the coast and the lack of oxygen exchange with the atmosphere might lead the low oxygen events in Long Bay where the severity depends on the persistence of the upwelling-favorable oscillatory wind field.

INTRODUCTION

The occurrence of hypoxia events in coastal seas has been related to upwelling systems that deliver nutrient-rich oceanic water to the continental shelf (Glenn et al., 1996; Grantham et al., 2004) and to increased runoff of nutrients from land (Wisman et al., 1997; Naqvi et. al., 2000; Turner et al., 2005). Both intrusion of oceanic water and runoff from land to coastal waters enhance vertical stratification, a condition necessary for formation and maintenance of low oxygen events in the bottom layer.

According to climatological data (Blanton et al., 2004), upwelling favorable winds are common during the summer-seasons in the South Atlantic Bight (SAB). Furthermore, Atkinson et al. (1986), Lee and Pietafsa (1987), and Hamilton (1987), have shown that the presence of the Gulf-Stream cold water (GSW) at the outer shelf bottom layer is also a common feature during summer seasons in the SAB. Once the GSW is present on the outer-shelf, upwelling-favorable winds can transport it across the shelf (Hoffman et al., 1980; 1981). The magnitude of the intrusion depends on the characteristics (e.g., intensity, duration) of the southwesterly wind events. The cross-shore advective scales of the cold-water on the inner-shelf (e.g., distance from the shore) might depend on prevailing stratification (Nelson et al., 2004; Aretxabareta et al., 2005) as this inhibits water column mixing, and can further support Gulf Stream water intrusions landward all the way to the inner-shelf.

Figure 1. Study region. Long Bay, SC extends from Cape Fear, NC to Cape Romain, SC. Caro-COOPS stations are indicated by yellow dots. The 10, 20, 40 and 200m isobaths are shown. (Image from http://nautilus.baruch.sc.edu/carocoops_website/index.php).
Long Bay is located in the South Atlantic Bight (SAB) and extends from Cape Fear, NC, to Cape Romain, SC (see Figure 1). Episodic low oxygen events (<3 mg/L) have been observed in summer seasons off this bay. One of the most evident events occurred on summer of 2004, were the fish were found lethargic, the bottom water featured an anomalous low temperature and the water column showed a significant vertical stratification (Sanger et al., 2010). Preliminary examination of meteorological data carried out by the author, revealed that the summer 2004 low oxygen event occurred during a period of upwelling-favorable winds that coincided with an “anomalous” water-cooling and a stratified water column. In order to assess these issues, a series of process-oriented numerical simulations were carried out. Additionally, two years (2006 and 2007) of meteorological, current velocity, and hydrographic data from four stations located at the SAB were analyzed.

METHODS

Current velocity, salinity and water temperature data near the surface and near the seabed were obtained from four stations (SUN2, SUN3, CAP2, CAP3) located in the nearshore off the coast of South Carolina (Figure 1) and operated by Carolinas Coastal Ocean Observing and Prediction Systems (Caro-COOPS, NOAA). The SUN2 and CAP2 stations were located at 10 m water depth while the other two were in approximately 20 m water depth. The hydrographic data analyzed corresponds to the summer seasons of 2006 and 2007. Observations of atmospheric conditions were obtained from the Caro-COOPS buoy SUN2. Additionally, dissolved oxygen (for the period of 2006-2007) and bottom water temperature (for the period of 2001-2007) were obtained from the SC Nearshore Monitoring Station at Springmaid Pier (Voulgaris et al., 2008).

All current, wind, dissolved oxygen, temperature and salinity time-series were pre-processed to eliminate bad data, fill gaps in the records and then they were low-pass filtered to remove variations occurring at periods less than 33 hours (Beardsley et al., 1985). The velocity and wind vectors were oriented into an along/across-shore orthogonal coordinate system. Salinity data from stations SUN2 and CAP3 for the year of 2007 were discarded completely due to data quality issues.

The numerical model used in the simulation is the Regional Ocean Model System (ROMS). ROMS is a primitive equation, free-surface, hydrostatic, sigma-coordinate model. The model setup included all the terms of the primitive equations except horizontal viscosity. A third order and upstream biased advection scheme was used, so no explicit horizontal viscosity was required (Haidvogel et al., 2000). Vertical turbulence mixing was parameterized with the Generic Length Scale (Umlauf and Burchard, 2003) momentum turbulence closure submodel.

The numerical experiments were carried out on an idealized domain that is 700 and 200 km long in the alongshore and cross-shore directions, respectively. The domain simulates a concave-shaped bay (300 km long) bounded by a cape to the north and one to the south. A straight coastline (200 km long) configuration was implemented to the north of the northern cape and to the south of the southern cape to allow continuation in the side boundaries. The characteristics of the central part of the domain resemble the morphological features of Long Bay, SC from Cape Fear, NC to Cape Romain, SC, and from the coast (5 m depth) to about 150 km offshore (55 m). Offshore the 55m isobath bathymetry is uniform. The length of the straight parts of the coastline was selected such that the wind-driven circulation at the northern and southern parts were identical to each other, so that no artificial alongshore pressure gradients were setup due to imperfection at the open boundaries. The across-shore bathymetric profile of the middle of the bay and the straight parts of the coast is consistent with that of Long Bay, SC.

In both horizontal directions, the grid resolution varies from 1.5 km to 3 km. In the cross-shore direction the highest resolution is near the coast and decreases offshore, while in the alongshore direction, the highest resolution is at the bay and decreases toward both north and south. The domain consists of 160 x 231 horizontal grid points and 30 vertical levels with a vertical resolution varying from 0.12 m near the coastline and 3.0 m in the deepest parts. The initial density field used resembles typical summer conditions as observed in the South Atlantic Bight (Austin and Lentz, 2002), which is a thermally stratified water column consisting of a well-mixed surface and bottom layers and a linear stratified thermocline in between. The model is forced with a spatially uniform northward (upwelling-favorable) wind stress that either remains constant over time or oscillates in a sinusoidal fashion. In the first case the wind stress is ramped-up linearly for 6 hours up to a maximum value (0.1 N m$^{-2}$) and then it remains constant for the duration of the model run. The oscillatory pattern has a period of three days and oscillates from 0.01 to 0.2 N m$^{-2}$. The direction, magnitude and duration of the wind patterns used in the simulations are consistent with those observed in South Atlantic Bight.

RESULTS

Temperature data from bottom layer at Springmaid Pier for the period of 2001-2007 identify recurrent pulses of anomalous cold water at the coast during
summer seasons mainly (not shown here). The strongest event was observed during summer of 2003. This event, according to Nelson et al. (2004), was evident along much of the U.S. eastern seaboard and was found to be highly correlated with upwelling favorable wind conditions. Less pronounced pulses were observed during summer of 2004, 2005 and 2006, while during summer of 2007 there is no noticeable cold water intrusion.

Temperature – Salinity (T-S) diagrams of data obtained from the hydrographic stations SUN3 and CAP3 for 2006, and from station SUN3 for 2007 have confirmed the existence of GSW in the middle shelf during the summer. Additionally, the T-S diagram from station SUN2 in 2006 suggests that the GSW reaches the inner-shelf by July and mixes with the coastal waters. The presence of the GSW at station CAP2 is not confirmed, due to the “contamination” of the signal by fresh water discharge. The T-S diagrams suggest that the origin of the “anomalous” pulses of cold water observed at the inner-shelf, are or coincide with pulses of GSW which is also nutrient-rich and features a dissolved oxygen concentration (DO) of ~5 mg/L (Atkinson et al., 1987).

Time series of wind stress, temperature, salinity, and alongshore and across-shore currents from the surface and near bottom for summer 2006 at station SUN2 (not shown here) has confirmed the prevalence of upwelling favorable winds. Three upwelling events longer than 5 days were identified where the wind intensity oscillated between near zero to 8 m/s with a periodicity of approximately 3 to 4 days. These phenomena seem to coincide with the occurrence of lower oxygen concentrations recorded at the Springmaid Pier, SC.

A series of process-oriented numerical simulation was carried out in order to elucidate the physical conditions that lead to stratification of the coastal waters during an upwelling event. In order for the Gulf Stream water to reach the inner-shelf a cross-shore circulation needs to develop. This will require adequate wind energy to develop upwelling conditions but is limited to levels inadequate to mix the water column and inhibit such circulation. Several numerical experiments were carried out to elucidate the physical conditions under which the GSW can reach the inner-shelf. The physical forcing examined included different levels of: (i) initial vertical stratification, (ii) river discharge, (iii) wind pattern (constant and oscillatory), and (iv) solar radiation. The ranges of these conditions were typical of those found during the summer in the South Atlantic Bight.

The numerical simulations demonstrated that cross-shore circulation in the inner-shelf was minimal to non-existent under constant wind stress conditions, independently of the initial vertical thermal stratification, river discharge and solar radiation (not shown here). Similar results were obtained even for the cases of oscillatory wind forcing, except when solar radiation was considered. This latter case is shown in Figure 2 where a cross-section (view toward north) of temperature and velocity fields of the inner-shelf is shown for four different time steps. A few hours after the maximum wind stress (see time=8 days in Fig. 2), the water column close to the coast is homogeneous and there is no cross-shore circulation. Further offshore the water column remains stratified and Ekman transport is present. When the magnitude of the wind stress decreases, the inner-shelf water column starts to thermally stratify again due to solar irradiance, and Ekman transport is re-established. This Ekman transport moves cold water toward the coast at the bottom layer and further enhances stratification. As the wind stress increases again, the Ekman transport is intensified and so is vertical stratification, until the wind-stress becomes strong enough to break the stratification and mix the water column.

The above numerical experiments prove that the only conditions under which cooler and potentially nutrient-rich offshore water can make it to the nearshore is under oscillatory wind stress conditions and intense solar radiation. The latter is higher in the summer, which might explain why the low oxygen events are present only in the summer.

CONCLUSIONS

We studied the physical conditions that lead to hypoxia events in Long Bay, SC. Our study was based on
three-dimensional processes - oriented numerical simulation and current, hydrographic and meteorological in-situ measurements for the years 2006 and 2007. The 2006 data set revealed that low-oxygen (< 3 mg/l) events on the coastal bottom layer are likely to occur during summer season (high solar radiation and low river discharge) and under long periods (more than 15 days) of upwelling favorable wind conditions. The water column remained stratified most of the time (a physical process that limits oxygen exchange with the atmosphere), due to solar radiation and to cold water intrusions from the middle-shelf bottom layer (i.e., GSW) via Ekman dynamics. In contrast, during summer of 2007 there was no low-oxygen events observed near the coast. During summer of 2007, the water column remains thermally homogeneous most of the time and there was no evidence of cold water intrusions. Wind data for that summer showed upwelling favorable conditions. Similar conditions were observed for the 2009 event although that event coincided with extremely high tidal ranges (Libes and Kindelberger, 2010) that have modified the processes slightly.

According with the numerical results, the response of a highly stratified inner-shelf to constant upwelling favorable wind forcing, was the formation of a coastal front and associated jet that moves offshore with time. Inshore of the front, the water column became homogeneous, while offshore of the front Ekman transport takes place, carrying cold water toward the coast at the bottom layer. The numerical experiments showed that the only physical conditions that can contribute to the cross-shore transport of colder and nutrient rich water (e.g., GSW) to the nearshore is a combination of oscillatory upwelling wind conditions and thermal stratification by solar radiation. The cold water intrusions help to keep the water column stratified even under strong wind stress, a condition that enhances the Ekman transport and then vertical stratification which may lead to low oxygen events.

Although the oceanographic conditions alone favor the hypothesis that low oxygen water is advected from offshore, the spatial limited extent of low oxygen in the study area (see Koepfler, 2010) indicates that this is not the case. Instead biology seems to provide an important role in regulating the observed hypoxic conditions (Smith et al., 2010). The upwelling conditions certainly provide an important role by eliminating the exchange of oxygen with the atmosphere while the GSW might help to provide the tipping point on a system already at crucial point. In any case the increment of biological activity at the bottom layer near the coast and the lack of oxygen exchange with the atmosphere might lead the low oxygen events in Long Bay where the severity depends on the persistence of the upwelling-favorable oscillatory wind field.

ACKNOWLEDGEMENTS

This work was funded primarily by the SC Sea Grant Consortium (Project R/CP-12). Additional support was provided by the National Science Foundation (Awards OCE-0451989 and OCE-0535893).

LITERATURE CITED


