Observations of Dissolved Oxygen Variability and Physical Drivers in a Shallow Highly Stratified Estuary

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ABSTRACT

Evaluating the role of long-term anthropogenic changes on dissolved oxygen (DO) in coastal systems is often a challenge due to variability in a system and measurement sensitivity to spatial and temporal trends. Physical processes can significantly modify the DO variability and act as a major driver of uncertainty when it comes to quantifying the bio-chemical changes associated with the DO budget. Stratification has been observed to be a dominant factor in controlling the hypoxic conditions that can develop in Mobile Bay, AL, a shallow highly stratified estuary prone to episodic hypoxia. Using CTD transect data and long-term water quality monitoring stations the variability of DO was examined throughout Mobile Bay. This study examined the physical drivers of these trends and highlighted the role stratification, temperature, and advection play in driving the bay wide variability. Under stable conditions, the spatial trend in Mobile bay will reflect the along-estuary gradient. When stable conditions don't occur due to random episodic mixing events and cross estuary exchange, the Bay can be driven by a number of factors: the along-estuary gradients, time since the previous mixing event, level of stratification, and biochemical oxygen demand. The combination of these elements provides an increased understanding of the complex dynamics driving low DO in this system. Long-term trends show the DO is decreasing in Mobile Bay based on changes in DO in the shipping channel, northern region, and Bon Secour region.

Keywords: highly stratified, estuarine hydrodynamics, dissolved oxygen, shallow estuary

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Introduction

Evaluating the role of long-term anthropogenic changes on dissolved oxygen (DO) in coastal systems is often a challenge due to natural variability in a system and inadequate spatial and temporal sampling. Natural variability may include changes that occur over seasonal, episodic, and daily time scales. The oxygen budget is fundamentally driven by biological processes associated with the production (photosynthesis) and consumption (respiration) of oxygen, but physical processes (e.g. solubility, physical forcing) can drive large changes in the variability of DO. In systems with high natural variability, long-term trends of anthropogenic change can be difficult to observe and separate from natural variability. This natural variability can occur on various time scales ranging from hours to years due to both biochemical and physical processes. Identifying long-term deteriorating DO trends is of interest to researchers and coastal managers because of the impact of low DO on marine organisms (Vaquer-Sunyer and Duarte 2008) and biogeochemical cycles associated with changing redox conditions (Middelburg and Levin 2009). At very low concentration levels, a system becomes hypoxic (DO $\leq$ 2 mg l^{-1}) which is detrimental to some aquatic organisms and alter benthic community structure (Diaz and Rosenberg 1995)

Hypoxic conditions in bottom water during summer is a common occurrence in many estuaries (Kemp et al. 2009). The first national assessment of oxygen conditions in U.S. waters identified the Gulf of Mexico regions as having a high percentage of hypoxic systems that continue to be present today (CERN, 2010). Generally, hypoxic conditions can be attributed to stratification (limiting the vertical diffusive transport of oxygen), the rate of flushing, and the extent of organic loading. Of the 38 Gulf of Mexico estuaries reviewed by Bricker et al. (2007), 16 were identified as having high influencing factors due to high nutrient loads and high susceptibility to eutrophication. A number of these estuarine systems from Texas to the Florida panhandle (e.g., Corpus Christi Bay, TX, Lake Pontchartrain, LA, Mississippi Sound, MS, Mobile Bay, AL, and Perdido Bay, FL/AL) have been identified as areas of concern based on previous hypoxia observations (Engle et al. 1999). Per Kemp et al. (2009), these shallow estuarine systems may be broadly classified as episodically hypoxic estuaries, where hypoxia may typically last for days to weeks. In comparison, in relatively deep estuaries (>10 m) DO can decline steadily to hypoxic levels during spring to summer as stratification, warming temperature, phytoplankton, and organic matter loading increases, and hypoxia, once established, can last for months. At the other end of this classification spectrum, in very shallow estuaries (1-5 m) with low turbidity and low stratification, hypoxic events last hours over diel cycles when DO is lowest right before dawn. The episodic systems experience large variability in DO concentrations that can range on temporal and spatial scales associated with both physical (tides, river discharge, and wind) and biological (organic matter inputs and production and respiration) components resulting in intermittent hypoxia and DO trends that may be less predictable.

Understanding the drivers of episodic hypoxia is fundamental to improving the analysis of DO long-term trends and predictions of future DO dynamics. In estuaries that experience large variability over the course of days to weeks it can be difficult to discern long-term patterns especially when the drivers are poorly understood and/or there are limited long-term observations available. The focus of this paper is to examine the spatial and temporal variability of DO in Mobile Bay, a shallow, highly stratified estuary prone to episodic hypoxia driven by interactions between physical and biogeochemical processes. In this study, data from summer bay-wide transects and long-term continuous water quality monitoring stations were used to assess the variability in DO dynamics and the relevant physical forcing conditions driving variability in this system.

Study Site

Mobile Bay is a shallow, microtidal (range <0.8m) estuary in the northern Gulf of Mexico. The average depth is 3 m and the bay has uniform bathymetry with the exception of a 12 m deep, 120 m wide ship channel that runs the length of the estuary (Fig. 1). Mobile Bay has a river discharge of 1,516 $m^3 s^{-1}$ (2000–2016). During summer and early fall the average river discharge falls to less than 500 $m^3 s^{-1}$ (Coogan et al. 2019). During this low discharge period, the residence time is 20-54 days (Du et al. 2018) and strong stratification as high as 20 PSU m^{-1} in the pycnocline (Coogan et al. 2020) can occur throughout the bay. This strong stratification and long residence time, along with high water temperature, can contribute to the development of hypoxia (May 1973; Schroeder and Wiseman 1988; Cowan et al. 1996; Park et al. 2007).

In the northern part of Mobile Bay, Park et al. (2007) observed DO variations on time scales ranging from hours to days associated with stratification changes. Early reports of low DO in Mobile Bay focused on Jubilee events where crabs, shrimp, and several fish species would concentrate on the shoreline during predawn to escape low DO that formed deeper in the bay overnight (Austin 1954; Loesch 1960). Loesch (1960) noted that stratification allowed for the development of low DO values, with observations as low as 0.5 mg l^{-1}, and that this low DO could be advected towards shore corralling marine organisms trying to escape the hypoxic conditions. May (1973) reviewed local newspaper articles to find mentions of Jubilee events going back to 1867. He concluded that the low DO events were natural and were associated with organic matter loads from the watershed rather than increases in nutrients and subsequent cultural eutrophication.

Park et al. (2007) examined timeseries measurements of oxygen in the summer and found the bottom water DO concentrations were hypoxic 99% of the time when the vertical salinity gradient was > 8 PSU (over a vertical distance of 2.5 m with total depth of 4 m) while hypoxia rarely occurred when the salinity gradient was < 3 PSU. Sediment oxygen consumption (SOC) and nutrient loading measured by Cowan et al. (1996) also highlighted that the nutrient loading and SOC rates (0.1-1.25 g O_2 m^{-2} d^{-1}) were modest in Mobile Bay and prolonged hypoxia was due to strong stratification. This modest SOC rate from data was collected in 1993 and 1994 is comparable to unpublished observations from 2019 in the same region and estimates by Coogan et al. (2019) in the ship channel. It should be noted though that hypoxic conditions can develop rapidly, within a few hours to days, and based on the SOC rates by Cowan et al. (1996), Park et al. (2007) estimated it would take 5.2 days for the water column to decrease to hypoxic levels and not the hours to days that are observed. Their estimated total (both water column and sediment) oxygen consumption rate, 7.4 g O_2 m^{-2} d^{-1}, fall at the upper limit of previously reported ranges. This variability between studies and methods in the same system highlights the challenges in solving the DO budget and uncertainty when trying to analyze significant long-term changes in frequency and duration of hypoxic conditions.

Data and Methods

Data Sources

Multiple datasets were used to examine the DO variability in Mobile Bay, including data from nine long-term water quality stations maintained by the Dauphin Island Sea Lab and Alabama Marine Resources Division (red dots in Fig. 1), and the four short-term deployment stations that collected data from July 12 to August 2, 2016 (black dots). Data collected at these stations included salinity, temperature, DO, and pressure data. Long-term data sensors maintained by the Dauphin Island Sea Lab are swapped on average every 30 days and sensors maintained by Alabama Marine Resources Division are swapped on average every 14 days. Data was corrected with post calibration data. When sensors showed poor post calibration (>±15%), the data was flagged as bad and not included in this dataset. Twelve of the stations were fixed near bottom sites 0.25-0.5 m above the sea floor. The only non-fixed station was MB (in the center of the bay) that collected vertical profile data over 0.5 m intervals throughout the water column. Data was collected at 60, 30, and 10 min frequencies depending on the site and were subsequently averaged to 1-hour tidal, 50-hour subtidal, 7-day, and monthly averages for processing. Timeseries data was analyzed over three time periods: the short-term deployment (July 12 to August 2, 2016), a one-year deployment (August 2016 to August 2017), and long-term data for stations MB (2005-2017), MP (2003-2019) and BS (2010-2019). Wind data was also collected at the MB station (Fig. 1) at 1-min intervals and averaged to 30-min and 6-hr data for analysis.

In addition to the timeseries data, hydrographic surveys were conducted from small boats in July 2016 and from April to October in 2019. These surveys captured the spatial variability of stratification and DO in the bay. Table 1 shows the details of the surveys (dates, number of CTD casts, and tidal phase), and changes in DO that occurred at the monitoring time series stations during the course of the survey. The 2016 surveys were conducted on July 14, 19, 21, 28, and 30. In 2019, bay-wide surveys were conducted monthly except in August, when sampling was approximately weekly. The surveys took place on April 22-23, May 20-21, June 25-26, July 25-26, August 1, 7, 16, 29-30, September 23-24, and October 28. Each survey involved measuring vertical profiles with a CTD cast (Seabird SBE 25) throughout the bay (Fig. 2). In 2016, six transects were surveyed, and in 2019 the survey was expanded to include nine transects. Single day surveys began at first light and took between 6-8 hours to complete (1/4-1/3 of the tidal cycle). Note, the impacts of ebb and flood tidal changes were not examined due to the long duration of the surveys. In 2019, six of the surveys were conducted over the course of 2 days. The average change in DO observed at the water quality stations over the course of a survey was 1.8 mg l^{-1} and the largest change 5.2 mg l^{-1} occurred on the July 19, 2016 survey at station KL. A total of 1,011 vertical profiles were collected during these 2 years to provide a robust suite of spatial observations.

Table 1: Bay wide survey dates are listed with the number of CTD cast, tidal phase, and comparison of change in DO with water quality stations throughout the bay over the course of the survey.

Date	Cast	Tidal Phase	DO change over Survey Period (mg l^{-1})				
			DN	KL	DI	MP	BS
July 14, 2016	33	Neap	1.5	2	2.3	1.8	4.7
July 19, 2016	57	Spring	1.5	5.2	3.8	3.2	0.5
July 21, 2016	62	Spring	0.5	N/A	1.9	0.3	2.8
July 28, 2016	58	Neap	1.3	3	2.6	2.8	2.4
July 30, 2016	60	Neap	1.4	1.4	2.4	0.2	0.4
April 22-23, 2019	68	Spring	0.8	5.1	1.7	0.5	1
May 20-21, 2019	70	Spring	2.1	2.3	1.4	2.5	2.3
June 25-26, 2019	69	Neap	4.9	3.4	2.7	0.3	1.4
July 25-26, 2019	72	Neap	0.6	1	2.9	1.6	2.9
August 1, 2019	67	Spring	0.2	1.9	0.4	0.9	4.3
August 7, 2019	67	Neap	0.2	0.9	1.1	1.3	3.2
August 16, 2019	67	Spring	2.8	0	3.4	0.9	1
August 29-30, 2019	76	Spring	4.3	0.1	1.7	1.4	1.5

September 23-24, 2019	70	Neap	0.6	0.2	2.2	0.1	0.1
October 28, 2019	52	Neap	0.7	1.2	0.4	1.6	0.8

Analysis

The extent of the hypoxic area in Mobile Bay was calculated from a linear interpolation of 65 CTD cast across 9 transects (Fig. 2). The CTD cast data was first linearly interpolated to 0.25 m depths vertically. The data was then horizontally interpolated over a triangulation-based linear interpolation. The farthest interpolation was 4.1 km. In regions where depth changes (i.e. a hole or in the ship channel) prevented interpolation or near shorelines where extrapolations were necessary, a nearest neighbor interpolation was used. Because of the broad shallow nature of Mobile Bay this nearest neighbor interpolation was primarily used to keep DO constant to the shoreline from the nearest CTD cast location and to fill holes with constant DO values across depth contours. Note the surveys took one to two days to complete and are a representation of the hypoxic area during that survey period, not a single point in time.

To analyze the oxygen concentration changes a measured concentration (O_{obs}) and apparent oxygen utilization (AOU) value were examined. AOU was calculated as the DO deficit relative to the saturation concentration (O_{sat}):

$$AOU = O_{sat} - O_{obs} \tag{1}$$

The AOU allowed for the changes in saturation vs oxygen demand to be accounted for and retains units that are the same as the measured concentration. To analyze the impact of stratification the buoyancy frequency (N),

$$N^2 = -\frac{g}{\rho_o}\frac{\Delta\rho}{\Delta z} \tag{2}$$

was calculated, where g is gravity, ρ_o is the depth average density, and $\Delta\rho$ is the change in density over the change in depth Δz. To analyze long-term DO timeseries, a Mann Kendall test was used to test the null-hypothesis that there is no monotonic trend in the series.

Results

Spatial DO Observations

During the summer of 2019, hypoxic conditions were observed in 9 out of 10 surveys. The maximum hypoxic ($\leq$ 2 mg l^{-1}) area calculated was 34% of the bay on August 16, and low DO ($\leq$ 3 mg l^{-1}) observed in 53% of the bay on that same day (Fig. 2d and Fig. 3). This large region of hypoxia and low DO was coupled with strong stratification that measured as large as 20 PSU m^{-1} and had a bay wide depth average of 2.7 PSU m^{-1} on August 16. The episodic nature of hypoxia in this estuary was also evident in Fig. 2 and 3 where over the course of a month the hypoxic area fluctuated from 4% to 34%. Starting on July 25-26, relatively sporadic hypoxia was observed throughout the bay that covered 3% of the system. A week later the bay transitioned to a modest hypoxic area of 15% in the northern region of the bay (August 1). The following week, the hypoxic area was concentrated in the western portion of the bay (August 7). By August 16, the hypoxic area spread back throughout the bay reaching its peak extent of 34% and a week and a half later the bay returned to its starting concentration of 3% (August 29-30). Of the 65 total stations sampled during these surveys, hypoxia was observed at 41 stations (63%) during at least one of the 2019 surveys.

To highlight the spatial trends in this system, vertically averaged (from surface to bottom or to 5 m depth in the ship channel) DO maps were calculated for 2 periods: April-May (a high discharge period with $> 1{,}500$ m^3 s^{-1}) and June-October (a low discharge period with $\leq 1{,}500$ m^3 s^{-1}). During the low salinity (high discharge) period, the bay had spatially variable DO with little to no bay wide patterns (Fig. 4e). This is in contrast to the high salinity (low discharge) period when a broad along estuary DO pattern was observed with lower DO present in the northern part of the estuary. This along estuary trend was observed for both the low and high discharge periods in the ship channel (Fig. 4g,h) but had an increased gradient during the low discharge period.

These spatial trends were further examined with subtidal timeseries in July 2016 from the 13 water quality stations for 5 regions (delta, north, central, south, and Bon Secour in Fig. 1). The data in Fig. 5 was converted to AOU units to remove the impact of changes in saturation on the trends observed (note the spatial maps in Fig. 4 were kept as concentration to limit the uncertainty associated with interpolating temperature and salinity spatially in calculating AOU). The bay-wide average showed a general increase in AOU until July 25 with a decrease around July 20, followed by a larger decrease till July 28 and finally increased toward the end of July (Fig. 5). The northern region had the highest AOU peaking at 6.3 mg l^{-1}. Further down-estuary, the AOU decreased in the central and south (near the estuary mouth) regions. This highlights a similar trend to the DO spatial data from CTD cast, that an increasing AOU (decreasing DO concentration) was observed moving up the estuary. The exceptions of this trend occurred in the delta and Bon Secour region. The delta did not follow the increasing up-estuary trend, but it did follow the same general trend of rises and falls with respect to the average AOU signal. Bon Secour followed its own unique pattern during this time where on July 17 and 20 the AOU trend moved in the opposite direction of the bay wide average.

The along estuary trend was also observed in the long-term data for both high (> 1,500 $m^3 s^{-1}$ greater than the average discharge) and low (≤ 1,500 $m^3 s^{-1}$) discharge periods (Fig. 6). The high and low discharge periods are the same low and high discharge distinction in Fig. 4. The yearlong AOU data in Fig. 6 showed the same north-south along estuary spatial trend of decreasing DO concentrations at up-estuary sites. The outliers of this trend were again MP (the delta region) and BS (the Bon Secour region). During high discharge the difference in AOU between MP and BB was relatively small when compared to the low discharge difference between these two sites. A shift between the high and low discharge trend can also be seen in the salinity data where the horizontal gradient between MP and BB was 1.2 PSU km^{-1} during low discharge and 0.5 PSU km^{-1} when discharge was high. These changing gradients with discharge are similar to those seen in the ship channel (Fig. 4g,h).

Temperature and Stratification

The relationship between stratification and DO from the CTD cast data showed that with increasing stratification DO generally decreases and AOU increases (Fig. 7). When the maximum stratification exceeded 0.25 s^{-1} hypoxia was observed 24% of the time for all the CTD data collected in 2016 and 2019. When CTD data from the southern region was not included, the percent of hypoxia increased to 35%. The southern sites near the mouth of Mobile Bay (blue dots in Fig. 7) had a lower AOU but still followed the increasing AOU with increasing stratification trend. The sites near the mouth had on average higher levels of stratification but had a less steep trend of increase in AOU. Two time periods, marked by low and high discharges, were used to distinguish the two plots in Fig. 7 and remain consistent with previous analysis. Both the low and high discharge periods showed similar trends.

The importance of stratification in Mobile Bay was further analyzed over 11 years of profile data from station MB. The bin averaged data showed low DO concentrations in Mobile Bay were dependent on the occurrence of both stratification and high temperatures (Fig. 8). Out of the 11 years of data, low DO (≤ 3 mg l^{-1}) was observed only when the temperature was greater than 19.4°C regardless of the level of stratification. When periods with low stratification were evaluated ($N < 0.05$), then low DO only occurred when the temperature was greater than 28.0°C. This trend of coupled temperature-stratification dependence was also seen in the annual signal, where stratification at station MB is highest in January and low DO concentrations do not regularly occur until June when both stratification and temperature are high (Fig. 9).

Wind

Wind was also included in the analysis to evaluate its role in modifying the episodic trends. At a central site in the bay (station MB), observations at the surface showed increasing wind speed reduced the absolute value of AOU (Fig. 10) as increasing wind leads to increasing air sea flux of oxygen. Near the bottom of the water column this same trend is observed, however there is a limited response where no trend is observed until the wind speed reaches ~10 m s^{-1}. This lack of initial response was due to stratification at the site where low wind speeds did not have enough mixing energy to break down the strong stratification, but as the wind increased a decrease in stratification was observed.

At low wind speeds when the mixing energy was not enough to break down the stratification, the wind stress still played a role in modifying the current structure in this system. Fig 11 shows across-estuary wind (East / West) plotted with the dissolved oxygen difference between stations KL and DN (water quality stations on opposing sides of the estuary) from July 1, 2019 to August 16, 2019, a period of low wind speeds (average 4.1 m s^{-1}). During this relatively low wind period, the westward winds were correlated with a decrease in DO concentration on the eastern side of the bay, as cross-estuary flow drove upwelling on the eastern side of the bay and longer fetch on the western side of the bay increased wind mixing. Under eastward winds, the opposite occurred as cross-estuary winds on August 7 drove a tilting of the pycnocline and advected all the near bottom low DO water to the western side of the bay (Fig. 2c).

Long-term Changes

Long-term changes in DO were examined at two water quality stations (MP and BS). Both MP and BS had a monotonic increase for AOU when evaluated with a Mann Kendall trend test (Fig. 12). The AOU at MP increased from 0.4 in 2004 to 1.6 (mg l^{-1}) in 2019. The AOU at BS increased from 1.0 in 2010 to 1.6 (mg l^{-1}) in 2019. There were no significant trends for salinity or temperature over this same time period at stations MP or BS (not shown).

Discussion

Spatial Variability

In 2019, hypoxic (DO $\leq$ 2 mg l^{-1}) conditions in Mobile Bay fluctuated from 34% of the bay experiencing hypoxia (during strong stratification in the summer to 0% in the spring and fall. During the month of August when this maximum extent of hypoxia was reached, hypoxic conditions varied rapidly in magnitude and location during the preceding weeks (Fig. 2). Had there been no weekly surveys in August, the maximum extent of hypoxic area observed in 2019 would have been 4% (dashed line in Fig. 3 based on end of month sampling schedule). This large level of variability due to the episodic nature of Mobile Bay makes evaluation of long-term trends difficult since the magnitude of change in long-term trends are often small in comparison with the magnitude of the observed short-term variability. The connection of hypoxia to stratification and mixing has been previously observed in Mobile Bay by research going back to the 1950s (Austin 1954; Loesch 1960; Cowan et al. 1996; Park et al. 2007), but observations of the spatial extent of hypoxia in Mobile Bay are sparse and the episodic nature makes them difficult to directly compare. The maximum area of hypoxia was estimated to be 37% of the bay in 1971 (May 1973), 34% of the bay was estimated to be below 2.8 mg l^{-1} in 1978 (Schroeder and Wiseman 1988), and 41% of the bay was observed to be hypoxic in 1993 (Carlton et al. 1998). Although direct comparisons of these estimates are difficult due to the large variability highlighted previously (Park et al. 2007) and in this study, the spatial resolution of the surveys and general trends can be noted for future analysis. Regions likely undergoing long-term change of deteriorating water quality are the Bon Secour region, the ship channel, and the northern end of the bay. In the 1970s, no hypoxia was observed in Bon Secour, although May (1973) notes it was not extensively sampled. In 1993, hypoxia was observed in Bon Secour (Carlton et al. 1998) and again in 2016 and 2019 with this study. This change over previously unreported hypoxia from the 1970s and the long-term observations (Fig. 12) suggest there is a change in the spatial extent of hypoxia in Mobile Bay, potentially the along-estuary DO gradient is expanding both into the delta (based on the long-term changes at MP) and southeastward into Bon Secour.

Other areas of increased hypoxia include the ship channel, where May (1973) found no evidence of oxygen depletion, although it is unclear the extent to which the channel was sampled. Data from 2016 and 2019 in this study observed hypoxia in the northern (up-estuary) section of the channel during all 5 CTD surveys in 2016 and 9 out of 10 surveys in 2019. Additional surveys conducted from 1993-1995 observed hypoxic conditions in the up-estuary section of the channel 2 out of the 3 years that surveys were conducted (Pennock et al. 1996). Drivers of these hypoxic changes are unclear but Coogan et al. (2019) found that temperature and DO changes in the channel were associated with advection of water from offshore. This suggests the development of hypoxic water in the channel may be a result of both offshore changes and local changes inside the estuary. Previous studies (e.g., Kuo et al. 1991; Park et al. 1996) in other systems have shown that even when the incoming bottom water is oxygen-rich, it can become hypoxic if oxygen consumption exceeds DO replenishment (vertical mixing too weak to reach to the bottom water) as it is advected upstream, and offshore changes may not be needed to develop hypoxia in the channel if the internal changes are great enough. Work on the channel since the 1970s includes the deepening of the channel from 12.1 to 13.7 m in 1989 (Byrnes et al. 2013). These changes may have also contributed to the observed increased hypoxia in the channel where deepening the channel would increase salt intrusion, stratification, and reduced vertical mixing. Deepening the channel though would also lead to increases in gravitational circulation and reduce the time for biochemical processes to consume DO in the bottom water leading to reduced hypoxia. The drivers of the increased hypoxia in the ship channel are unclear and may be a result of a number of changes including the physical ones listed here as well as biochemical changes.

One area that has experienced little to no hypoxia in both the historic studies and the 2016 and 2019 data was the region near the estuary mouth. Figure 7 highlights that this region followed a smaller slope from the rest of the bay with respect to stratification. The southern region had on average greater levels of stratification but lower levels of AOU. This trend was the result of offshore advection being the dominant driver of the DO signal for this region of the bay since it was within the tidal excursion length (5-10 km). As water is advected further up-estuary by subtidal circulation, internal drivers of hypoxia (stratification and biochemical oxygen demand) dominate the signal and drive down the DO concentration (Coogan et al. 2019).

The along estuary DO gradients described in this paper have been observed in other systems such as the Pamlico River estuary, which also experiences a low tidal energy and strong stratification (Stanley and Nixon, 1992). Scavia et al. (2006) used a simple model to predict longitudinal DO profiles in Chesapeake Bay based on the decay of organic matter being advected by subtidal up-estuary flow and vertical exchange flux. The model conceptually follows surface organic matter (from the river and primary production) that travels down estuary and slowly sinks. These sinking particles can then settle to the sea floor or be transported back up the estuary via the density driven estuarine circulation where the major source of the organic matter in Chesapeake Bay was found to be surface layer primary production. Although the average residence time is much smaller in Mobile Bay, 34 days (Du et al. 2018) compared to 180 days in Chesapeake Bay (Du and Shen, 2016), similar to Chesapeake Bay, Cowan et al. (1996) suggested that phytoplankton were a major component of particulate carbon and particulate nitrogen in Mobile Bay. During low discharge, down-estuary regions of Mobile Bay can become nutrient limited (Pennock et al. 1999), but regions adjacent to tributaries can be heavily influenced by eutrophication that is present in a number of the sub-estuaries of Mobile Bay (Lehrter, 2008).

While this study focuses on addressing the physical component, advection, driving the along estuary gradient, the along-estuary nutrient and organic matter gradients can also enhance the up-estuary decreasing DO trend. The along-estuary advection has also been observed by Coogan et al. (2019) in the channel where DO decreased at a rate of 0.17 g O_2 m^{-3} d^{-1} as it was advected up-estuary by a near bottom subtidal velocity of 8.7 to 10.5 cm s^{-1}. These along-estuary processes are further complicated by changes in stratification where changes in the gravitational circulation and mixing can alter and interrupt the along-estuary trend. The strength of gravitational circulation and relative importance between biological oxygen demand and vertical diffusion were highlighted by Kuo et al. (1991) and Lin et al. (2006) and are crucial components in the longitudinal spatial changes of DO concentration in estuaries.

The Delta and Bon Secour regions fell outside this trend due to advection from the river driving the DO signal at the northern end, and separate circulation dynamics in Bon Secour from the rest of the bay. These hydrodynamic differences have been modeled by Webb and Marr (2016) and Du et al. (2018) and show weak flushing in the Bon Secour region due to a separate circulation cell. Du et al. (2018) estimated that the average water age in this region is > 48 days at low discharge, longer than the bay wide average of 34 days.

These trends are further complicated by wind dynamics that can both break down stratification and modify the current structure. Previous work has shown wind is a dominant physical forcing condition in this estuary (e.g. Kim and Park 2012, Schroeder et al. 1990), and wind direction can lead to asymmetric responses through current interaction (Coogan and Dzwonkowski, 2018). The wind-driven cross-estuary exchange highlighted in Fig. 11 has also been observed in Chesapeake Bay (Sanford et al. 1990), and Neuse River Estuary (Reynolds-Fleming and Luettich, 2004). The estuary response and sensitivity to these changes of wind direction and magnitude add to the complexity of understanding the episodic variability of hypoxia.

Based on the new understanding in spatial variability of hypoxia, Mobile Bay can be divided into five zones (Fig. 13). In the northern end of the bay including the delta (Zone I), the DO signal is dependent on advection from the delta and varies in size based on river discharge. Zone II is driven by local changes in stratification, temperature, and oxygen demand dynamics. Zone III is influenced by advection from offshore. Zone IV is driven by local changes in stratification, temperature, and oxygen demand dynamics similar to Zone II but the circulation dynamics are distinct from the rest of the bay. Zone V, the shipping channel, is influenced by advection from offshore, temperature, residence time in the channel and oxygen demand dynamics. These zones do not include the impact of winds that can drive cross-estuary currents and impact stratification. Under stable conditions, the spatial trend will reflect the along-estuary gradient, but with random episodic mixing events and cross estuary exchange, the bay will be driven by a number of trends: the along-estuary gradients, time since the previous mixing event, level of stratification, and biochemical oxygen demand. These changes make teasing apart the physical drivers of variability difficult to predict beyond the general trends discussed in this paper.

Climate change and other long-term DO trends

Nearly 94% of oxygen depleted regions are expected to experience a 2°C temperature increase by the end of the century (Altieri and Gedan 2015). On the Gulf of Mexico coast a 1.1°C water temperature increase is predicted for future climate change scenarios (Laurent et al. 2018; Lehrter et al. 2017), and several studies have highlighted warming trends are already occurring (e.g. Allard et al. 2016, Turner et al. 2017). With this increased temperature, changes in oxygen saturation and biological temperature dependent decay will continue to drive down the DO concentration following the pattern highlighted in Figs. 8 and 9.

The role of both stratification and temperature being important factors in driving DO changes has been observed in a number of systems (Kuo and Neilson 1987; Stanley and Nixon 1992; Park et al. 1996 and 2007; Borsuk et al. 2001; Buzzelli et al. 2002; Lehrter et al. 2017; Laurent et al. 2018). In the Neuse River estuary, NC, stratification and water temperature explained 30% and 23% of the variance in DO, respectively (Buzzelli et al. 2002). In systems where strong stratification and warm temperatures coincide, future climate change scenarios will be relatively straight forward. This study highlights that the highest stratification in Mobile Bay occurred in January (Fig. 9), but hypoxic conditions did not develop until June when stratification and temperature were both high. Systems similar to Mobile Bay, where peak stratification occurs earlier in the year, may present more complex scenarios of climate change impact on DO dynamics.

In addition to warming, climate related changes that are predicted to impact Mobile Bay are increased heavy rainfall events (USGCRP 2018) though observations of average discharge have shown the river discharge has been decreasing from 1,800 $m^3 s^{-1}$ in the 1975-1989 to 1,500 $m^3 s^{-1}$ in 2000-2018 (based on data from USGS station 02428401 and 02469762). Any long-term changes in river discharge due to climate change and ongoing changes in hydrology from urbanization are likely to impact stratification and nutrient delivery to the bay. These changes coupled with the observed importance of temperature, along-estuary gradients, and stratification from this study make it clear that changes in river discharge magnitude can alter the physical forcing conditions in the bay, alter the magnitude and timing of organic matter and nutrient loads. These interactive effects will complicate impacts associated with changing climate impacts.

Some stations in Mobile Bay have already shown long-term changes in DO. The Bon Secour region as previously discussed had hypoxia that was not observed in the 1970s and station MP was observed in this study to be decreasing in DO concentration (Fig. 12). The mechanism of this change in DO could not be determined from the available data, however salinity and temperature changes could be ruled out. The decrease of DO could be due to nutrient driven eutrophication or terrestrial organic matter runoff. Osterman and Smith (2012) observed eutrophication has been increasing in the bay since the 1950s based on changes in microfauna assemblages from sediment cores. Decreasing foraminiferal densities starting in the 1980s suggested a negative response in the microfauna community to this eutrophication. The changes observed at MP in this study since 2003 may reflect this continuing change or more recent anthropogenic changes. Establishing the reasons for these water quality changes is crucial for management of the estuary and improving water quality. Both the long-term trends in BS and MP should be the focus of future research.

Conclusions

Spatial and temporal DO trends are highly variable in Mobile Bay as a result of the episodic nature of stratification and its impact on DO dynamics. This study focused on the physical drivers of these trends and highlighted the role stratification, temperature, winds, and advection play in driving bay wide variability. The combination of these elements provides an increased understanding of the complex dynamics driving low DO in shallow, stratified systems. Long-term trends suggest the spatial extent of hypoxic area and low DO in Mobile Bay is increasing from changes in the Bon Secour region, ship channel, and northern region (station MP). A combination of decreasing DO in the bay and future changes associated with climate change make evaluating the contribution and uncertainties associated with stratification, and temperature on the DO budget critical for evaluating long-term changes in estuaries.

Acknowledgments

Long-term data was collected by the Tech Support Group at the Dauphin Island Sea Lab, including Kyle Weis, Roxanne Robertson, Alan Gunter, Mike Dardeau, G. Lockridge, Hunter King, Y. Hintz and L. Linn (Data available at www.mymobile.com). Additional data sources were also made available by the Alabama Department of Natural Resources-Marine Resource Division. This paper is a result of research funded by the National Oceanic and Atmospheric Administration's RESTORE Science Program under awards NA17NOS4510101 and NA19NOS4510194 to the University of South Alabama and Dauphin Island Sea Lab and by the Center for Environmental Resiliency at the University of South Alabama.

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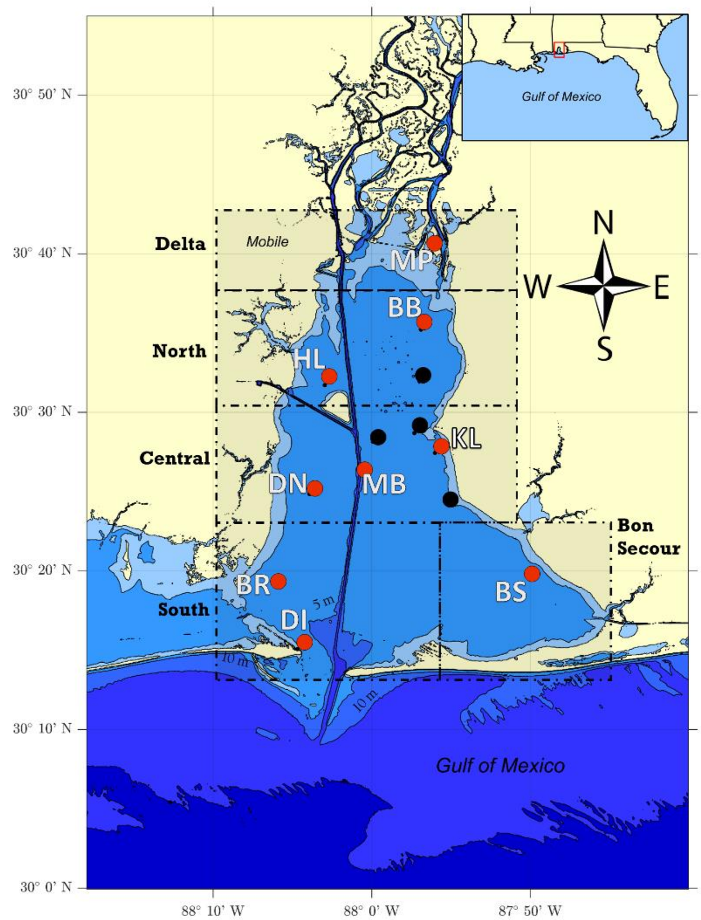

FIG. 1. Map of Mobile Bay with color contours marking the 2, 5, 10 and 20 m isobaths and the location of nine long-term water quality stations (red dots), four short-term water quality stations (black dots), and five regions (Delta, North, Central, South, and Bon Secour) used to average DO data and analyze trends.

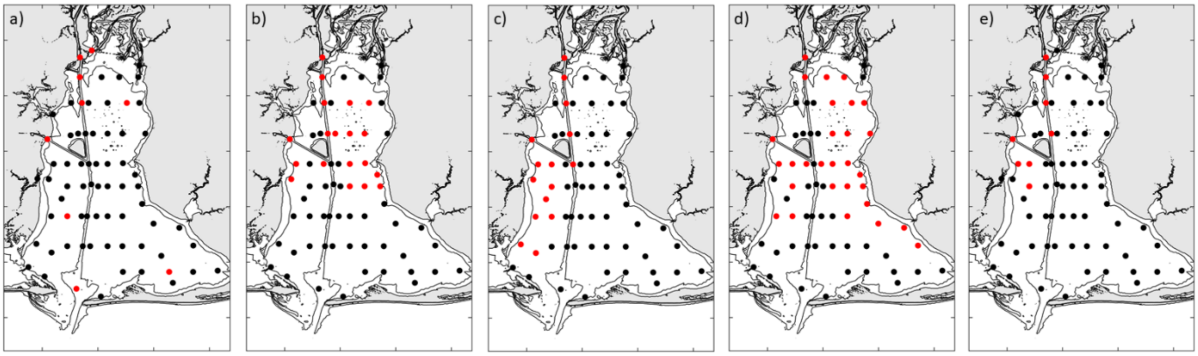

FIG. 2. Bay wide CTD surveys conducted on (a) July 25-26, (b) August 1, (c) August 7, (d) August 16, and (e) August 29-30, 2019, showing the minimum DO concentration from the CTD cast with DO ≤ 2 mg l^{-1} (red dots), and DO >2 mg l^{-1} (black dots).

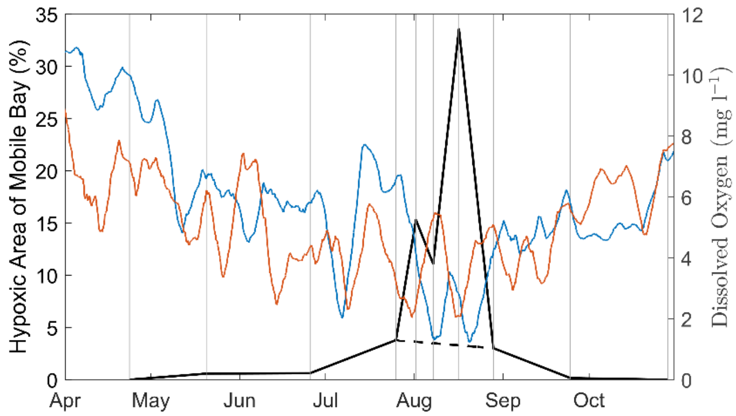

FIG. 3. Time series of the hypoxic (< 2 mg l^{-1}) area in Mobile Bay during 2019 calculated from bay wide CTD surveys (solid black line). The dashed black line indicates that the monthly sampling would have completely missed the wide spread hypoxia. Right axis shows a 7-day low pass filtered DO time-series at stations DN (blue) and KL (red). Vertical gray lines denote CTD bay wide survey dates.

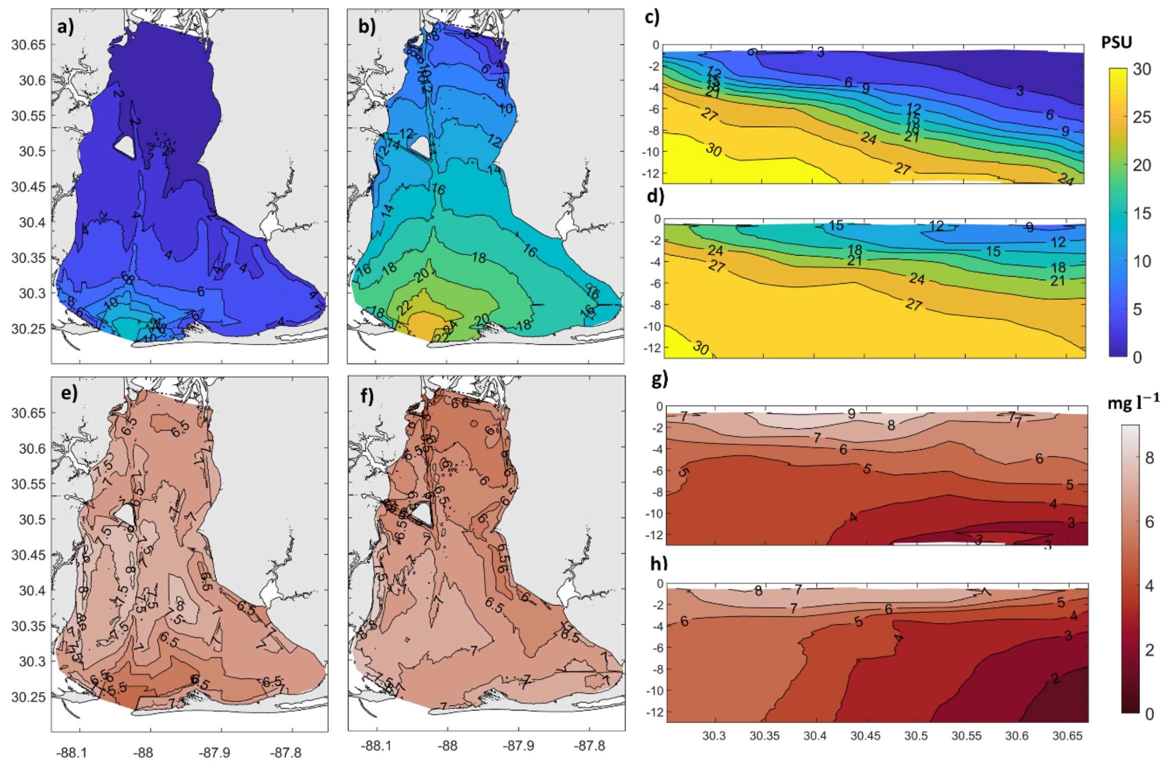

FIG. 4. Spatial maps of salinity (PSU) averaged vertically from surface to bottom (or to 5 m depth in the channel) from the (a) April-May and (b) June-October surveys, and along the ship channel over the (c) April-May and (d) June-October surveys, and the corresponding spatial maps of DO concentration (mg l^{-1}) (e-h).

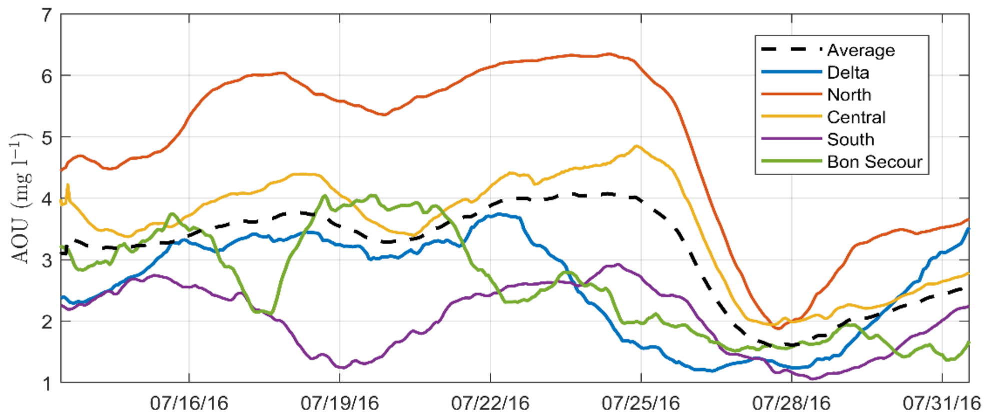

FIG. 5. Subtidal timeseries of near bottom DO in July 2016 for the averages over the entire bay and five regions based on the data from 13 mooring stations (see Fig. 1 for the locations of regions and stations). The data was converted to AOU units to remove the impact of changes in saturation on the trends observed.

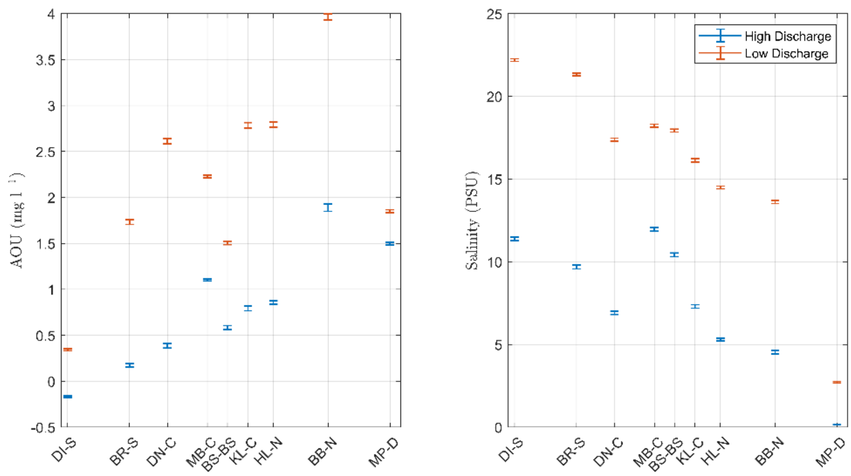

FIG. 6. Near bottom AOU, and salinity at nine long-term stations showing averages of one-year (August 2016 to August 2017) data for high (> 1500 m^3 s^{-1}) and low (≤ 1500 m^3 s^{-1}) discharge periods. In the *x*-axis, the 2-letter station ID's are organized by distance from the estuary mouth (where DI-S is 0 km from the estuary mouth and MP-D is 47 km from the estuary mouth) and the last 1 or 2-letter ID indicating the station regions (see Fig. 1 for their locations).

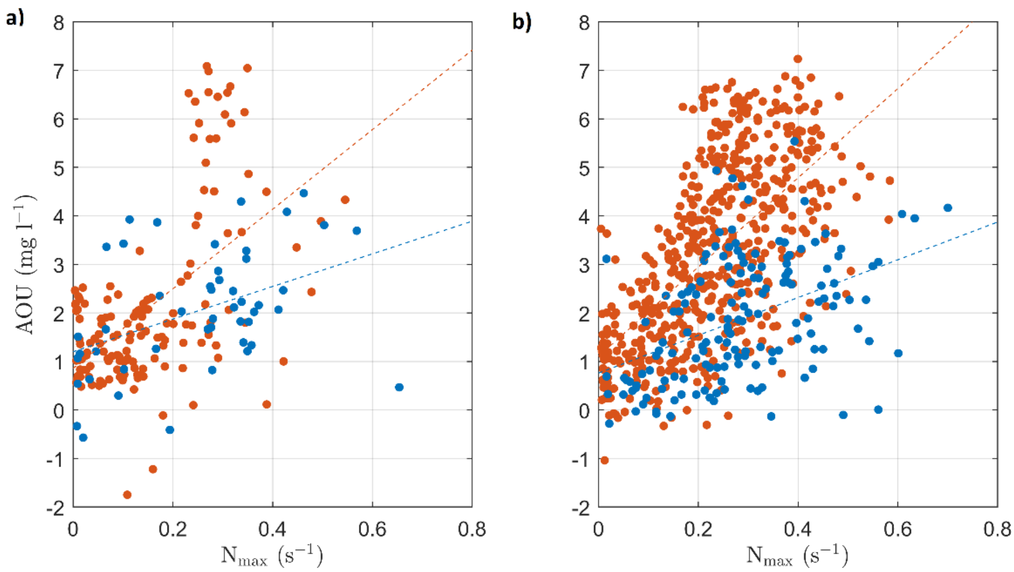

FIG. 7. Relationship between CTD profile minimum AOU and maximum stratification for the near mouth region of the bay (blue dots: South in Fig. 1) and everywhere else (red dots) for the (a) high discharge period (April-June) and the (b) low discharge period (July-October). Linear best fit lines are also plotted as red (r=0.56, $p<0.05$ and r=0.62, $p<0.05$ for high and low discharge, respectively) and blue (r=0.43, $p<0.05$ and r=0.43, $p<0.05$ for high and low discharge, respectively) dashed lines.

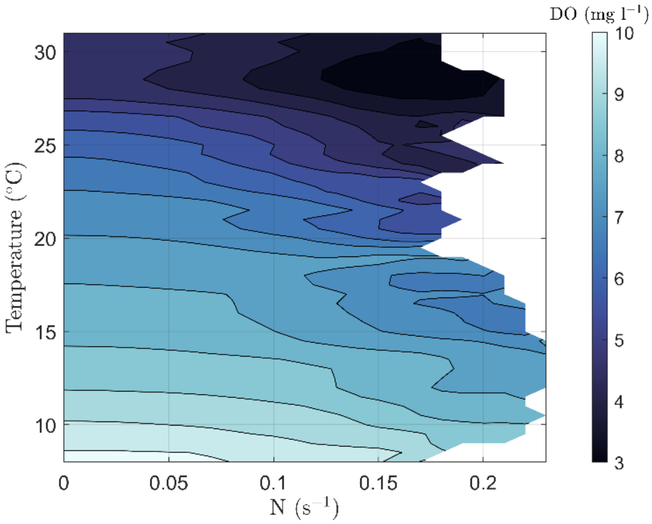

FIG. 8. The near bottom DO concentration as function of temperature and depth averaged stratification at station MB from 11-years of observations (2005-2017). The contour interval is 0.5 mg l^{-1}.

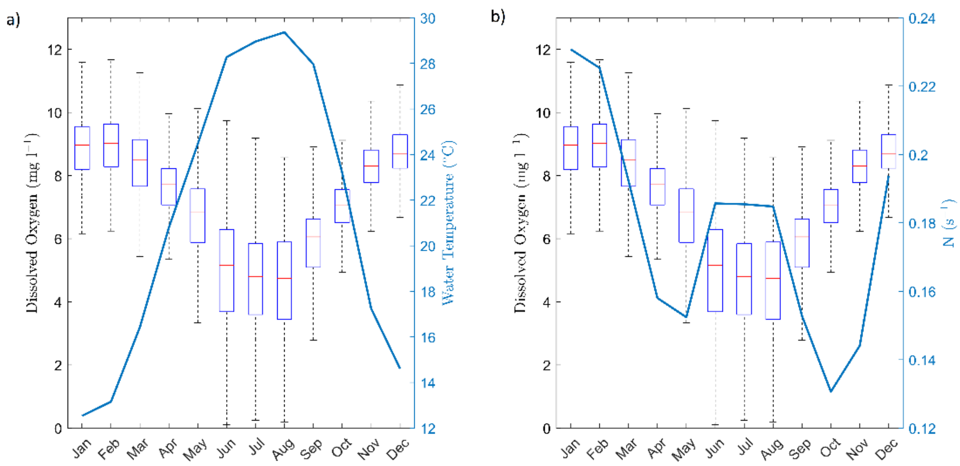

FIG. 9. Boxplot of monthly near bottom DO concentration from the data in 2005-2017 at station MB with (a) water temperature and (b) stratification.

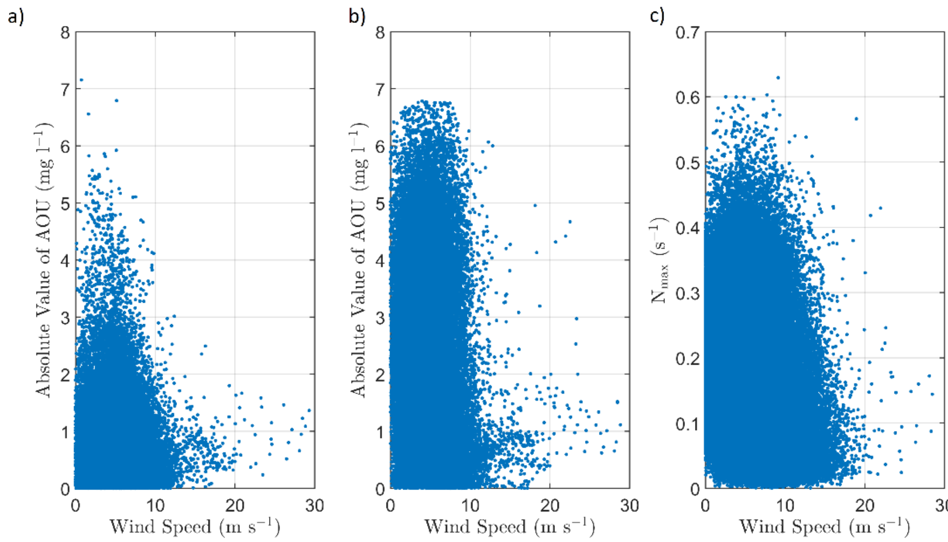

FIG. 10. Absolute wind speed plotted with the absolute value of AOU at the (a) surface and (b) bottom and (c) stratification for station MB during June, July, and August over 11 years of hourly data.

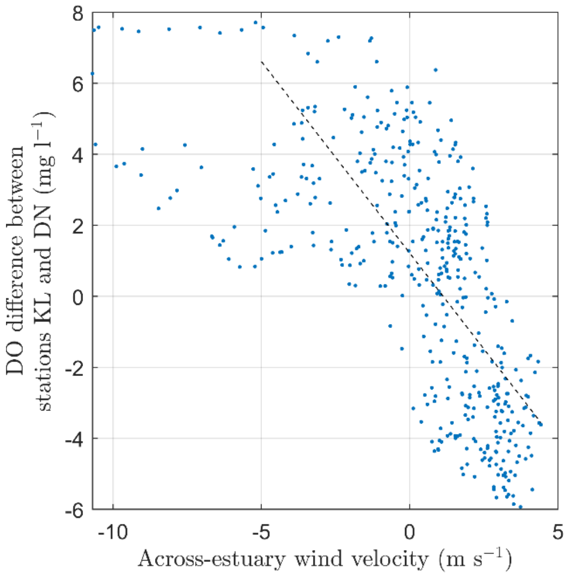

FIG. 11. Across-estuary wind velocity where positive values are eastward winds and negative values are westward winds during a relatively low wind period from July 1 to August 16, 2019 plotted with the DO difference between stations KL and DN (water quality stations on opposing sides of the estuary) where positive (negative) values are associated with higher oxygen concentrations on the western (eastern) side of the bay.

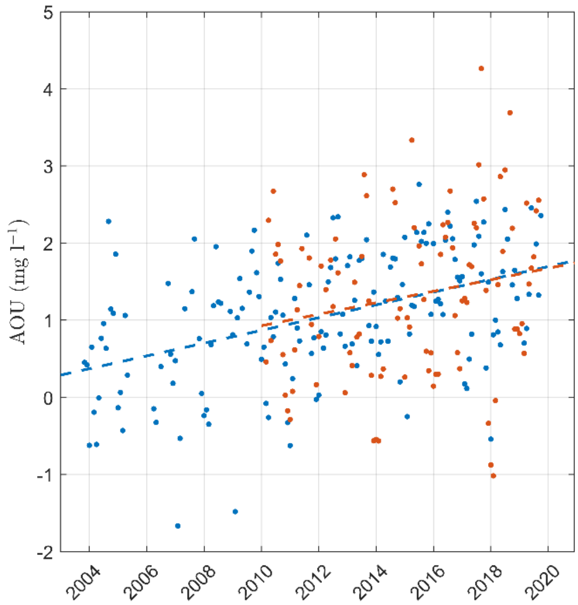

FIG. 12. Long-term trends at station MP (blue dots) and BS (red dots) showing monthly averaged AOU. Dashed lines show the linear best fits of the long-term trends.

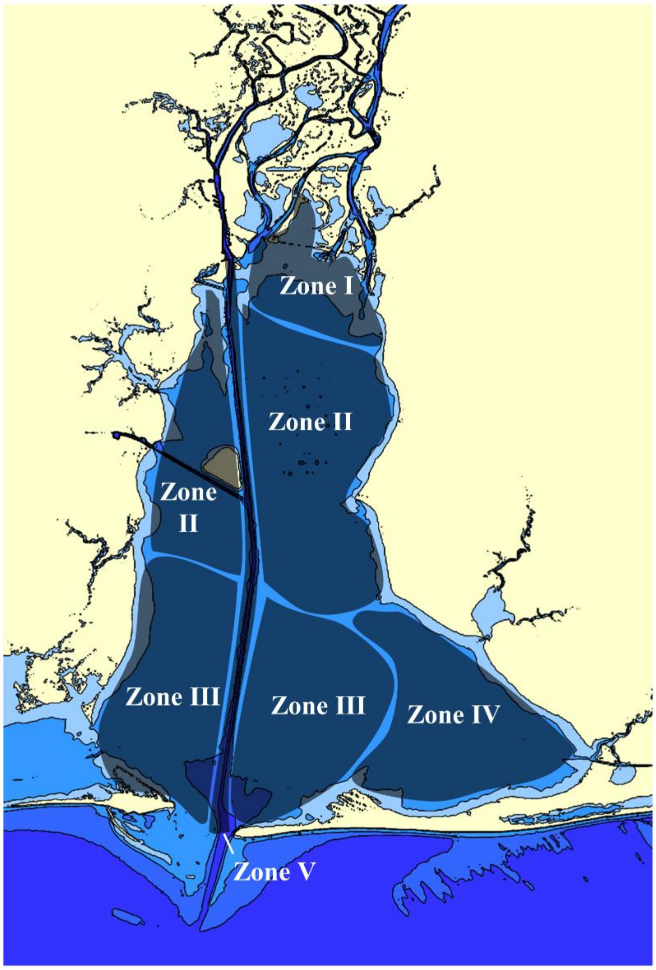

FIG. 13. Map of Mobile Bay showing the main physical drivers of near bottom DO: advection from the delta (Zone I), stratification and internal dynamics (Zone II), advection from offshore (Zone III), residence time and stratification (Zone IV), advection from offshore and residence time in the channel (Zone V)