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Summary

Here we report results from a study of water quality, including dissolved oxygen (D.O.) dynamics in Baffin Bay, Texas, a semiarid lagoonal estuary. On average, D.O. followed a typical seasonal pattern of lower D.O. levels during the warmer months and higher levels during winter. However, episodic hypoxia (<2.0 mg/L D.O.) was observed throughout the study period, and on several occasions the hypoxia lasted for multiple days. These prolonged episodes of hypoxia have the potential to impart significant stress on organisms who are unable to escape to more oxygenated refuges, either vertically or horizontally. For many of the dates noted above where prolonged hypoxia was observed, these episodes tended to correlate with periods of light winds. However, winds alone do not fully explain all of the hypoxia events. One possibility is that the hypoxia was driven by the breakdown of organic matter from a senescing phytoplankton bloom, which (phytoplankton biomass) were pronounced during these events. The high phytoplankton biomass is consistent with other recent studies that have shown high and increasing chlorophyll in the system. Overall, D.O. fell below TCEQ surface water quality criteria (4.0 mg/L) for a large portion of the sampling days. A considerable portion of days for both sites and depths were under the conventional hypoxia threshold (2.0 mg/L) as well, which was established based on studies suggesting that this level may provide insufficient D.O. to support marine life. These findings add to the growing body of evidence suggesting that Baffin Bay is undergoing nutrient-driven eutrophication, including high and increasing chlorophyll and nitrogen concentrations, episodic hypoxia and fish kills.

Acknowledgements

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Introduction

Hypoxia is a global problem that affects shallow estuarine and coastal systems in diverse climate zones ranging from tropical to temperate (Diaz and Rosenberg 2008). While hypoxia can result from natural variability (e.g., Levin et al. 2009; Rabalais et al. 2010; Zhang et al. 2010; Deutsch et al. 2011), numerous examples of long-term increases in hypoxia frequency and/or intensity are of concern to the management and scientific communities. Indeed, studies over the past several decades have documented decadal to multidecadal-scale declines in the dissolved oxygen (D.O.) content of coastal waterbodies, increasing duration of hypoxic events, and/or increasing spatial extent of hypoxia (e.g., Kemp et al. 2009; Murphy et al. 2011; Rabalais et al. 2014). In a significant fraction of these cases, the drivers of this change in D.O. content are well established. In particular, watershed land use changes in favor of activities that increase nutrient and/or organic matter loads to coastal systems are commonly linked to growing ecological footprint of hypoxia (Kemp et al. 2005; Howarth 2008).

Here we report results from a study of D.O. dynamics in Baffin Bay, Texas, a semiarid lagoonal estuary. The Baffin Bay-Upper Laguna Madre complex is of vital economic and ecological significance as a “hot spot” on the Texas coast for several commercially/recreationally important fish species (Lacson and Lee 1997). Nonetheless, there is growing evidence that the health of this ecosystem is being negatively affected by multiple stressors, namely those associated with high nutrient concentrations and “brown tide” algal blooms (e.g., Wetz et al. 2017). Hypoxia has also been observed, and has previously been linked to several large fish kills involving recreationally-important species (i.e., spotted seatrout, red drum, black drum) over the past ten years (Texas Parks & Wildlife Spills & Kills Team reports). There is a critical need to understand drivers of hypoxia in this system because it and other Texas estuaries have experienced a long-term water temperature increase of ~2^{o}C since the 1960’s (Applebaum et al. 2005; Montagna et al. 2011; Montagna and Palmer 2012), a trend that is expected to continue over the coming century. The most obvious consequences of this water temperature increase include amplification of temperature-dependent microbial respiration rates (Hopkinson and Smith 2005) and a reduction in the D.O. saturation state of coastal waters (Applebaum et al. 2005; Altieri and Gedan 2015).

Methods

Study Location – Baffin Bay (23 km long) is the main tributary for the Texas portion of the Laguna Madre, connecting at its mouth with the Upper Laguna Madre to the east (Fig. 1).

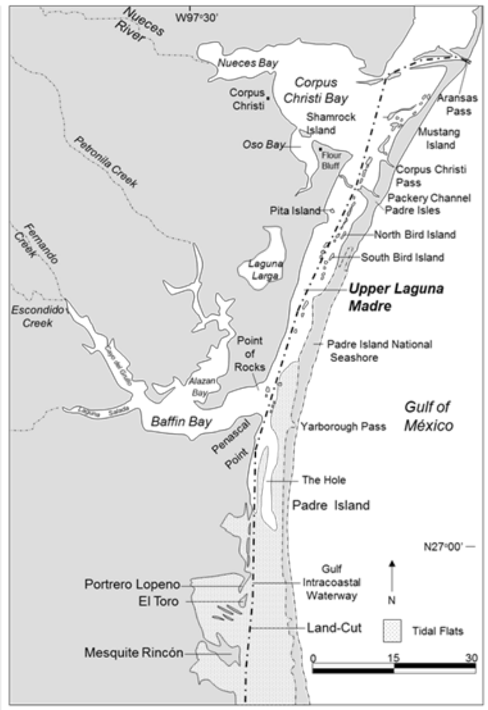

Figure 1. Map showing location of Baffin Bay (left) and study sites within Baffin Bay (right).

Watershed land use coverage for Baffin Bay is dominated by agriculture (44%), followed by scrub (35%) and grassland (8%) (NOAA Coastal Change Assessment Program). In comparison, human development is relatively limited within the watershed, with the city of Kingsville being the largest populated area (pop. 26,213).

Overall, Baffin Bay is shallow (<2-3 m), with 3 sub-tributaries of its own (Fig. 1). Because of the semiarid climate and "flashy" nature of rainfall in the region, the streams feeding these tributaries often do not flow except during high rainfall periods. This, coupled with high evaporation rates in the region, leads to hypersaline conditions in Baffin Bay-Laguna Madre. Winds can be relatively strong in the region and are thought to play a dominant role in hydrography of the system (Tunnell and Judd 2002). Wind direction is predominantly from the southeast from May-September, driving water to the north in Laguna Madre. In contrast, it is not uncommon to have winds out of the north in winter, which can alter the flow regime considerably (Tunnell and Judd 2002). The nearest inlets that allow for exchange between the Laguna Madre and Gulf of Mexico are Packery Channel (~41 km north of Baffin Bay), Aransas Pass (~70 km north of Baffin Bay) and Port Mansfield (~80 km south of Baffin Bay). These distances, along with diurnal tidal ranges of only ~2-3 cm, results in minimal overall tidal influence on the system. In fact, the dominant tidal signature is that of a long period, semiannual tide that results in changes in water level of ~50 cm. Additional water level change (10-20 cm) is driven by wind stress.

Sonde Water Quality Monitoring - Hydrolab DS5X sondes were deployed on the surface and bottom of two previously established and permanent TCEQ monitoring sites, channel marker 36 (CM 36; 27° 16.635' N 97° 37.492' W) and channel marker 14 (CM 14; 27° 15.937' N 97° 29.662' W) (Figure 1). Our original plan was to deployed sondes at a third location as well (Cayo del Grullo), however persistent maintenance issues limited the availability of sondes for this site. Data was collected at 20 minute intervals over the life of the study. Here we report daily averages of this higher frequency data for purposes of explaining broad scale trends in water quality variables, and also for purposes of comparing the data with TCEQ water quality criteria. Datasondes were calibrated prior to deployment, retrieved every 2-3 weeks and then underwent a rigorous post-deployment quality control check to identify data that was affected by biofouling, faulty probes, etc.

Meteorological Data- Daily wind speed and precipitation data from Kingsville's Naval Air Station (NAS) weather station were obtained from NOAA's National Center for Environmental Information.

Results and Discussion

Physical Conditions- Water temperature was similar between CM 14 and 36 (Figure 2). A clear seasonal pattern was evident, with highest temperatures observed in June through September (>30°C), and coolest temperatures observed in December-January (Figure 2). Rainfall was patchy during the study. Two rain events in mid-May each produced over 3 inches of precipitation (Figure 3). August, September, and early December also experienced one or more days with over 1 inch of precipitation (Figure 3). Despite the episodic high rainfall, only ephemeral decreases in salinity were observed. For example, after the two heavy rain events in mid-May, surface salinity dropped from ~35 to ~26 at CM 36, and from ~35 to ~25 at CM 14 (Figures 4, 5). Salinity remained in the mid-20's at CM 36 until late July, and thereafter increased to the mid-40's by the end of the study period (Figure 4). This sharp increase in salinity highlights the role that evaporation plays in terms of the overall water chemistry in Baffin Bay. Salinity-driven stratification was ephemeral at both stations throughout much of the year, although a period of prolonged stratification was observed at CM 36 in August 2016 (Figure 6), and at CM 14 in late June through early July as

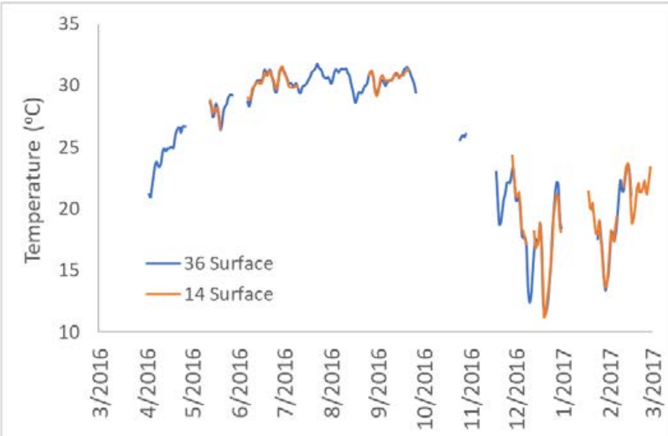

Figure 2. Surface water temperature at CM 36 and CM 14 in Baffin Bay.

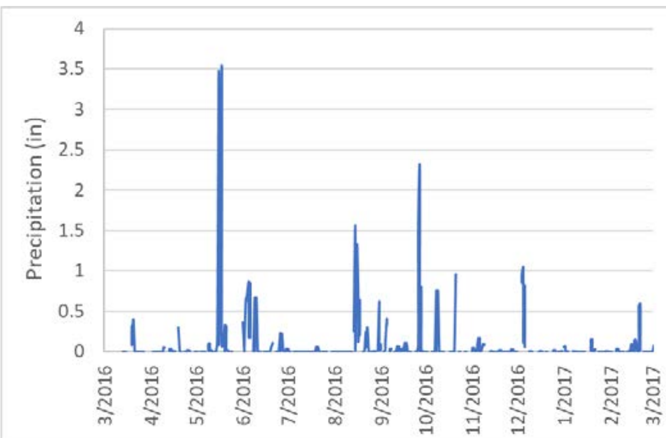

Figure 3. Precipitation measured at NAS-Kingsville.

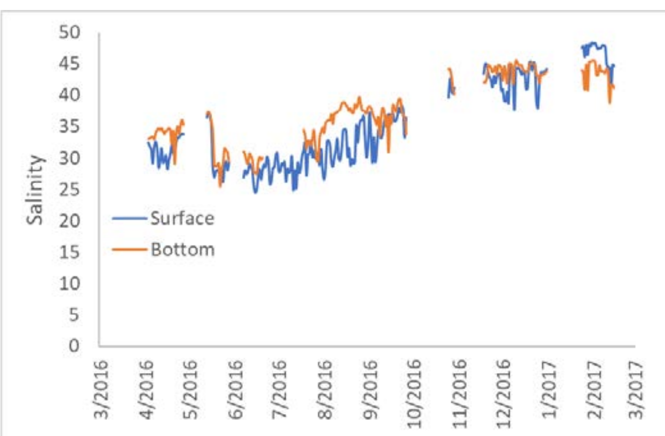

Figure 4. Salinity at CM 36 in Baffin Bay

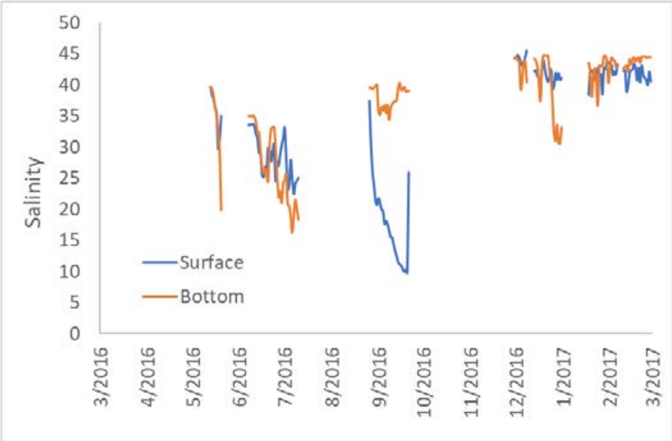

Figure 5. Salinity at CM 14 in Baffin Bay.

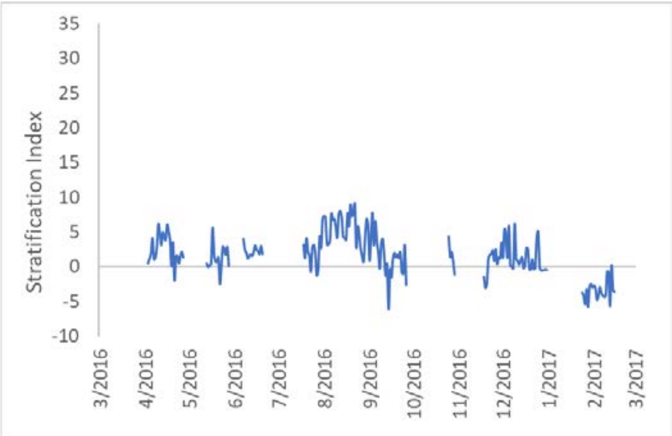

Figure 6. Stratification index at CM 36 in Baffin Bay.

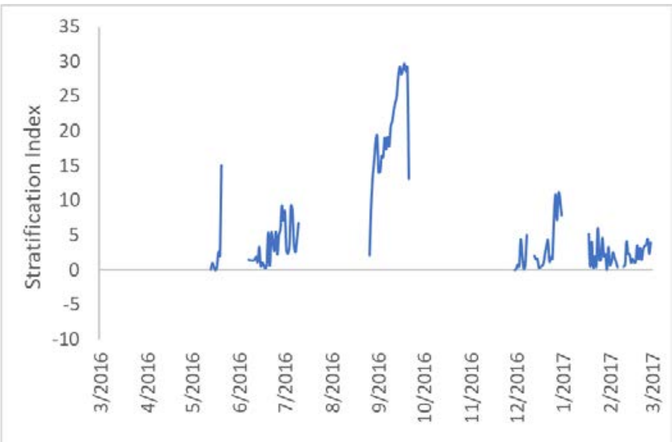

Figure 7. Stratification index at CM 14 in Baffin Bay.

well as September 2016 (Figure 7). Heightened stratification in late August through September 2016 appears to correlate with lowest wind speed (Figure 8), suggesting that a lack of wind driven vertical mixing was partially responsible.

Dissolved Oxygen Dynamics- On average, D.O. followed a typical seasonal pattern of lower D.O. levels during the warmer months and higher levels during winter (Figures 9, 10). However, episodic hypoxia (<2.0 mg/L D.O.) was observed throughout the study period, which was surprising given that hypoxia is typically not thought to occur during cooler months. On several occasions, hypoxia lasted for multiple days. For example, at CM 36, bottom-water hypoxia lasted 5 consecutive days from July 13-18, 2016, and 3 consecutive days from August 14-16 and August 31-September 2, 2016 (Figure 9). At CM 14, surface-water hypoxia lasted 3 days from June 9-11, 2016, 2 days from June 29-30, and 9 days from January 29-February 6, 2017 (Figure 10). These prolonged episodes of hypoxia have the potential to impart significant stress on organisms who are unable to escape to more oxygenated refuges, either vertically or horizontally (Diaz and Rosenberg 2008). Surprisingly, hypoxia was occasionally observed in both surface and bottom waters simultaneously. At CM 36 for example, this was observed on 6 dates during the study period (Figure 9). This was unexpected, as this phenomenon has not been previously documented in Baffin Bay, but may offer one explanation for past fish kills that were suspected of being caused by hypoxia (unpubl. Texas Parks & Wildlife Spills & Kills reports). Hypoxia that is limited to near bottom waters can be harmful to organisms living in the sediment, but mobile organisms can escape to more oxygenated refuges in surface water or through lateral movement (Eby and Crowder 2002; Vacquer-Sunyer and Duarte 2008). However, if surface and bottom water experience hypoxia simultaneously, this would essentially eliminate the vertical (water column) refuge and has potential to act as a serious stressor on nekton.

For many of the dates noted above where prolonged hypoxia was observed, these episodes tended to correlate with periods of light winds. Examples are shown in Figures 11 and 12. However, winds alone do not fully explain the hypoxia formation. For example, the 5-day long hypoxia observed at CM 36 in July, 2016, actually corresponded with relatively strong winds

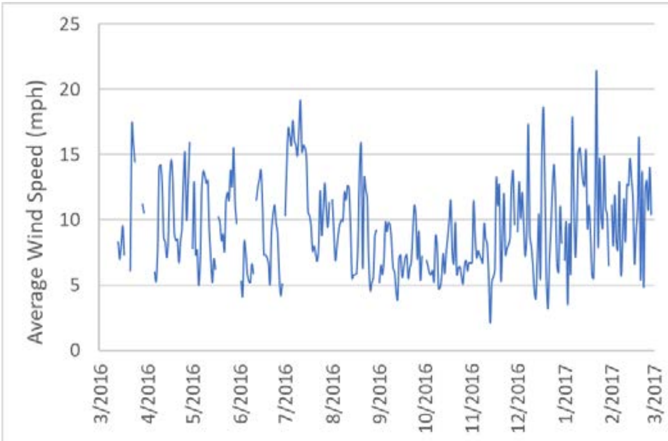

Figure 8. Average wind speed at NAS-Kingsville.

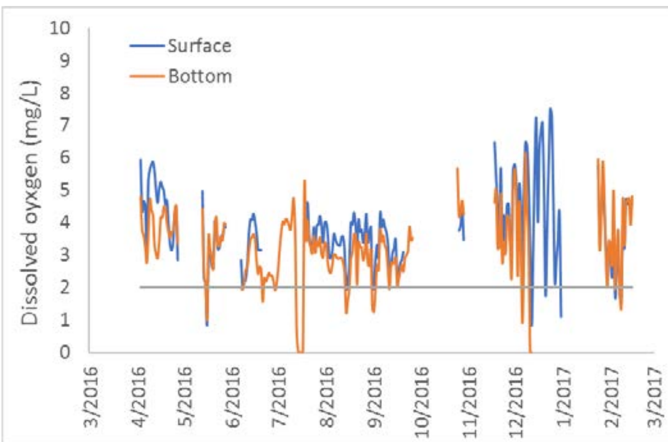

Figure 9. Dissolved oxygen at CM 36 in Baffin Bay. Gray line indicates 2 mg/L.

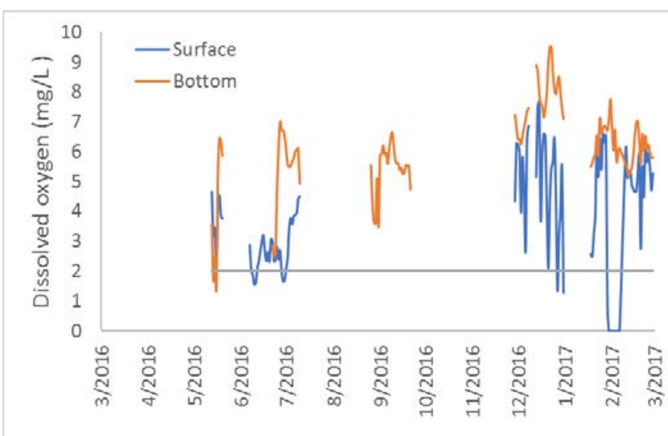

Figure 10. Dissolved oxygen at CM 14 in Baffin Bay. Gray line indicates 2 mg/L.

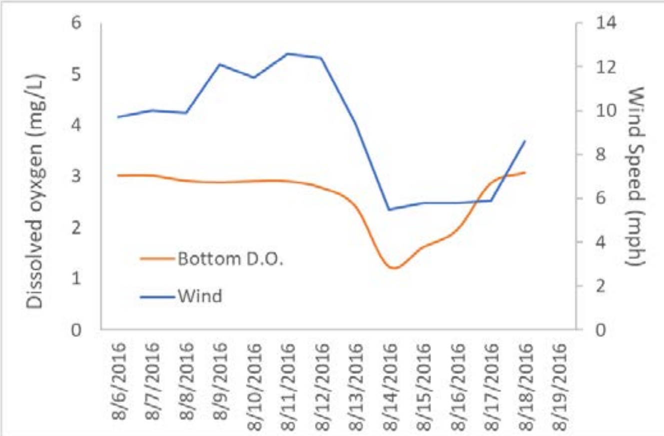

Figure 11. Relationship between wind speed and bottom water dissolved oxygen. From CM 36, August 2016.

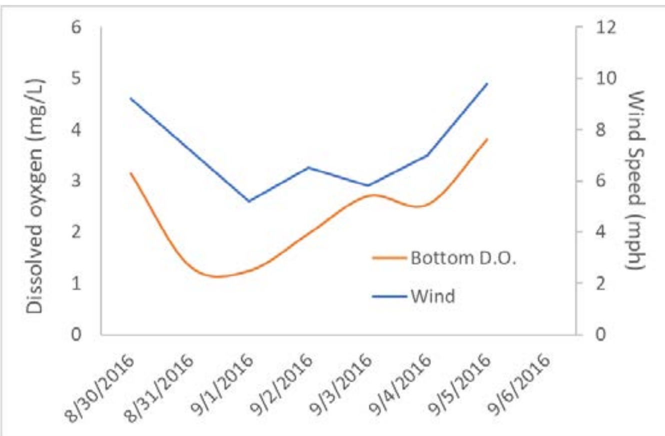

Figure 12. Relationship between wind speed and bottom water dissolved oxygen. From CM 36, August-September 2016.

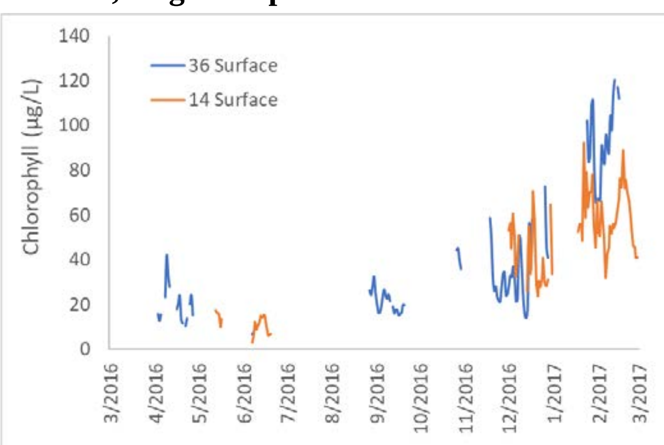

Figure 13. Surface chlorophyll concentration in Baffin Bay.

(Figures 8 and 9). One possibility is that the hypoxia was driven by the breakdown of organic matter from a senescing phytoplankton bloom. Although we do not have sonde chlorophyll data from that timeframe, chlorophyll data from the Baffin Bay volunteer water quality monitoring program found very high chlorophyll at the surface (25 µg/l) and bottom (72 µg/l) at CM 36 on July 13, 2016 (Wetz, unpubl. data). Another timeframe in which prolonged hypoxia could not be explained by winds, late January-mid February 2017, also coincided with a period of very high chlorophyll (Figure 13). This data was particularly perplexing however, as it was only the surface water at CM 14 that was hypoxic, and not bottom water. One possibility is that prolonged winds out of the north/northeast during this time of year pushed oxygenated water into the mouth of Baffin Bay at the bottom from seagrass beds in Laguna Madre. Thus, while the bottom water was oxygenated by this enriched (with O_2) water, surface waters saw D.O. depletion as the high phytoplankton biomass bloom that was in place decayed. Previous studies have shown that algal derived organic matter can be highly labile (Biddanda 1988; Harvey et al. 1995).

Overall, D.O. from both CM 36 and CM 14 was below TCEQ surface water quality criteria (4.0 mg/L) for a large portion of the sampling days (Table 1). A considerable portion of days for both sites and depths were under the conventional hypoxia threshold (2.0 mg/L) as well, which was established based on studies suggesting that this level may provide insufficient D.O. to support marine life (reviewed by Diaz and Rosenberg 1995).

Table 1. Summary of dissolved oxygen data in comparison to TCEQ criteria for estuarine waterbodies.

	CM 36 Surface	**CM 36 Bottom**	**CM 14 Surface**	**CM 14 Bottom**
Days of Data	196	249	114	167
% Days 2.0-4.0 mg/L	57.1	68.3	38.6	4.8
% Days <2.0 mg/L	5.6	10.4	14.0	1.2

Conclusions

Results from this study add to the growing body of evidence suggesting that Baffin Bay is undergoing nutrient-driven eutrophication, including high and increasing chlorophyll and nitrogen concentrations, and episodic hypoxia (Montagna and Palmer 2012; Wetz et al. 2017). The significance of the observed hypoxia and other symptoms of eutrophication on Baffin Bay ecosystem health cannot be overstated. For instance, hypoxia has been linked to several large fish kills involving recreationally-important species (i.e., trout, red drum, black drum) in Baffin Bay over the past ten years (Texas Parks & Wildlife Spills & Kills Team reports). In 2012-2013, a large portion of adult black drum (*Pogonas cromis*) were found to be starving. Anecdotal evidence suggests that there was a sharp decline in the abundance of their prey, the filter-feeding clam (*Mulinia lateralis*). However, black drum abundances were also very high at this time, thus it is not clear if overpopulation, water quality issues, or a combination of both caused the starvation event. An ongoing study of benthic organismal biomass and diversity (i.e., black drum prey) has demonstrated a strong relationship with D.O. conditions (Pollack, Wetz, et al., unpubl. data), consistent with studies from other systems.

Data showing potential for rapid onset of hypoxia, which was correlated with both physical processes and prior phytoplankton blooms, emphasizes the need to understand the relative importance of physical processes versus microbial respiratory processes on hypoxia formation to guide effective management solutions. A related study (funded by Texas Sea Grant), aimed at quantifying the lability of algal and watershed-derived organic matter, is nearing the end phase and when coupled with findings from the current study, should offer a comprehensive understanding of drivers of hypoxia in Baffin Bay.

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