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Toward connecting subtropical algal blooms to freshwater nutrient sources using a long-term, spatially distributed, in situ chlorophyll-*a* record

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ABSTRACT

Harmful algal blooms are increasing in tropical estuaries which can have complex morphologies and hydrologic regimes while being less well studied than temperate estuaries. Spatial and temporal patterns of algal bloom occurrence in Florida Bay were examined to evaluate the potential contribution of the various freshwater inputs to the subtropical bay as nutrient sources. Monthly water quality data, from 1989 to 2009, at 28 sampling stations across the bay were analyzed at the station-month level, aggregated into hydrologic Zones of Similar Influence and based on annual rainfall seasons. The Zones of Similar Influence are linked to the geomorphology of the bay with western areas being more directly connected to the Southwest Florida Shelf waters than eastern areas. Correlation analysis suggested that inputs of phosphorus were the predominant factor in the initiation of elevated chlorophyll a (chl-*a*) levels but was also consistent with higher nitrogen limitation in western Florida Bay as reported in literature. Differences in mean monthly chl-*a* indicated a seasonality of algal blooms with elevated chl-*a* concentrations following heavy precipitation months for stations in the north-central and western areas of the bay where algal blooms have been re-occurring. Differences in stations' chl-*a* concentrations showed stations to the northwest as having significantly higher concentrations than more interior stations during the dry season but not during the rainy season (when algal blooms are occurring). Mapping the sampling stations atop the bathymetry of Florida Bay highlighted the importance of coastal morphology in evaluation of potential nutrient pathways for estuarine algal bloom sources. The specific factors resulting in the seasonal cycles of blooms remained unresolved but portions of the bay and times of year were identified as important areas for further research. This study indicates that illustrating the interplay of geomorphology and winds and rains at fine temporal and spatial resolution is required to describe nutrient circulation for systems with complex morphologies such as those associated with reefs, island matrices and headlands.

1. Introduction

Tropical harmful algal blooms (HABs) are increasing in frequency and intensity, and are substantially affecting marine communities, as a result of increased coastal eutrophication, changes in oceanic climate and enhanced long-distance dispersal in ballast water (Bauman et al., 2010). While human activity has significantly altered water discharges throughout the world, the impacts within any particular estuarine system depend critically on the nature of the coastal sea such as its flushing characteristics (Jickells et al., 2014). The complex morphology associated with reefs, island archipelagos, capes and headlands can play an important role in determining the ecological function of coastal waters. Regions inshore of reef and island matrices are isolated by varying degrees from adjoining offshore oceanic waters, potentially leading to localized physical and biogeochemical processes and to large variations in the function of planktonic ecosystems over small spatial areas (Jones et al., 2014). Control of HABs in these types of systems, therefore, depends on information of adequately fine scale and resolution in order to determine the influence of the complex morphologies on water mass properties.

Florida Bay is recognized for its productivity, diversity and role as a marine nursery (Bulter et al., 1995). Bounded on the east and south by the Florida Keys and to the west by the Gulf of Mexico on the southwest Florida shelf, the bay is a critical part of a complex system involving freshwater marshes, mangrove ecotones and islands, seagrass meadows and coral reefs. The Florida Bay—Everglades ecosystem is unique among North American estuaries because of its carbonate sedimentary environment, restricted tidal regime and subtropical climate (Sutula et al.,

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2003). Tropical and subtropical estuaries are typically dominated by calcium carbonate sediment, as opposed to silicate or clay-dominated sediments of temperate coastal regions (Koch et al., 2001), which generally leads to phosphorus limitation as calcium carbonate scavenges phosphate from seawater (Brand, 2002).

In the late 1980s, algal blooms began to be documented as a new threat to Florida Bay, especially in association with ecosystem degradation and decline in commercially important species including seagrass, corals and sponges as well as fish and lobster (Bulter et al., 1995; Phlips et al., 1999). Prolonged pico-cyanobacterial blooms are believed to now threaten the ecological health of this system (Gilbert et al., 2009a, 2009b) and many genera of cyanobacteria are known to produce toxic compounds (O'Neil et al., 2012). While HABs have been reoccurring into the present in western and north-central regions of the bay, the direct chain of events leading to the initiation and persistence of HABs in the estuary remains unclear (Boyer et al., 2009; Brand, 2002; Bulter et al., 1995; McCarthy et al., 2009; Richardson and Zimba, 2002) as in other tropical estuaries around the world (Bauman et al., 2010). Of particular interest is the source of nutrients for these blooms. Uncertainty about the specific factors leading to the HABs limits the management of the estuary and could allow for eutrophication here and in other estuaries experiencing similar problems.

While spring phytoplankton blooms are ubiquitous in temperate coastal systems, phytoplankton blooms in fall and summer have gained attention in recent years as a consequence of their increasing recurrence (Guinder et al., 2013). These events have been related to climate trends such as changes in rainfall (Briceño and Boyer, 2010) and temperature (McCarthy et al., 2009) and to anthropogenic disturbance (Gilbert et al., 2009a, 2009b), however the underlying causes remain a matter of debate. Importantly, there is consensus that HABs are complex events, typically not caused by a single environmental driver but rather multiple factors occurring simultaneously (O'Neil et al., 2012). Assessing the systematic effect of factors influencing the occurrence of fall HABs in Florida Bay can provide information that is relevant to other estuaries facing eutrophication especially since considerably less is known about how tropical coastal ecosystems function compared to their temperate counterparts (Gilbert et al., 2009a, 2009b).

The objective for this work was to evaluate the spatial and temporal dynamics of chlorophyll-*a* (chl-*a*) concentrations, indicative of phytoplankton biomass, in the study area using a 20 year-long in situ data record. Chl-*a* concentrations from 28 stations divided in 6 zones were analyzed. Correlations between chl-*a*, at the resolution of monthly measurements at individual stations, and potential driving forces were tested and then assessed in light of the study area's morphology and hydrologic regime. The chl-*a* concentrations were compared across stations and months to assess the magnitude and timing of algal bloom occurrence in relation to location. Completion of these objectives is expected to provide information that will be useful in assessing the causes of tropical algal blooms through the identification of seasonal patterns in phytoplankton biomass and by substantiating connections with potential nutrient sources.

2. Methods

2.1. Study site

Florida Bay (Fig. 1) is a shallow lagoon located off the southern tip of the Florida peninsula with depths of less than 4 m throughout (Phlips et al., 1995). It is bounded by the Everglades to the north and is open to the Gulf of Mexico along its western margin. The main line of the Florida Keys, a Pleistocene reef, separates Florida Bay from the Atlantic Ocean (Boyer and Fourqurean, 1997; Wanless and Tagett, 1989).

South Florida's subtropical climate can be subdivided into dry (November through May) and wet (June through October) seasons (Steinman et al., 2002). The annual average precipitation for South Florida (Lake Okeechobee and south) for 1976–2001 was 132 cm (52 in.). In Florida Bay, the lowest mean monthly temperature occurs during the dry season (20 °C in January) and the highest monthly mean temperature coincides with the wet season (28 °C in August) (Briceño and Boyer, 2010).

Florida Bay is at the downstream end of the Kissimmee River–Lake Okeechobee–Everglades watershed and can therefore be affected by any changes that occur in that hydrological system (Brand, 2002). The Everglades, one of the largest freshwater wetlands in North America, are highly oligotrophic with phosphorus (P) being the limiting macronutrient (Childers et al., 2002). The two important drainage areas making-up the remaining wetlands of the Everglades are Taylor Slough in the southeast and the much larger Shark Slough to the north and west.

Changes in the timing and magnitude of water entering the Everglades have been caused by anthropogenic development in South Florida, where a vast network of levees, pumps and canals now cover South Florida. The majority of freshwater that historically flowed from Lake Okeechobee south through the Everglades has been diverted to the Atlantic Ocean and Gulf of Mexico by a network of 2400 km of canals (SFNRC, 2012).

2.1.1. Florida Bay hydrogeology

Florida Bay is made up of ecologically disparate basins (varying in sediment type, sediment depth, and benthic vegetation) that are structurally defined by a network of mudbanks (Phlips et al., 1995). The banks are broad with gently sloping flanks and cover a majority of the area in the western portions of the bay whereas banks in the eastern portions of the bay are narrow and discontinuous with steep windward flanks (Taylor and Purkis, 2012; Wanless and Tagett, 1989). Direct freshwater runoff into Florida Bay is largely restricted to the northeast portions where Taylor Slough and the C-111 canal drainage basins meet the estuary.

In Florida Bay, the hydrology of the system dominates the ecological and geochemical dynamics (Gilbert et al., 2009a, 2009b) with the various regions of the bay being associated with differing hydrologic regimes and therefore differing geochemical dynamics. The network of mudbanks impedes water circulation within the bay as well as tidal exchange with the adjacent Gulf of Mexico and Atlantic Ocean (Briceño and Boyer, 2010). The southeastward flow connecting the Gulf and Atlantic entrains freshwater outflows from the Everglades' Shark Slough and results in a low salinity band extending along the coast and into northwestern Florida Bay (Lee et al., 2002). Shelf waters are periodically directed into the bay interior by prevailing currents (Briceño and Boyer, 2010; Gilbert et al., 2009a, 2009b). Being semi-isolated, the central and eastern basins have longer residence times than the more open southern or western regions (SFNRC, 2012). Seasonal variations in wind direction and magnitude were shown by Lee and Smith (2002) to lead to predictable changes in the direction and volume of flow through the middle Keys at the south of Florida Bay.

Groundwater is gaining increasing attention as a source of inputs to the Everglades and Florida Bay. The Biscayne aquifer, which extends from Palm Beach County and underlies Florida Bay and the Florida Keys (Chen et al., 2010), is one of the most productive karst aquifers in the world with its thickness increasing in a southeasterly direction from a feather edge in northwestern Shark Slough to over 65 m thick along the southeastern coastline (Price et al., 2006). Salt water intrusion into the porous aquifer creates a mixing zone where the more dense seawater mixes with the less dense, inland freshwater. Several studies have found brackish groundwater discharge to occur in the mixing zone (Spence, 2011). The position and extent of the mixing zone and the flux of its associated brackish groundwater discharge are governed by many factors such as rainfall, groundwater withdrawals, irrigation, evapotranspiration, waves, and changes in sea level (Price et al., 2006). Significant exchange has also been documented from the aquifer beneath the Florida Keys into Florida Bay due to differences in surface