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An analysis of diffuse light attenuation in the northern Gulf of Mexico hypoxic zone using the SeaWiFS satellite data record

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ABSTRACT

The Sea-viewing Wide Field-of-View Sensor (SeaWiFS) derived diffuse light attenuation along the Louisiana continental shelf (LCS) was examined at monthly scales from 1998 to 2007 to characterize temporal and spatial patterns, and responsible physical forcing conditions. The SeaWiFS diffuse light attenuation ranged from 0.10 to 2.64 m^{-1}. Stepwise multiple linear regression analysis suggested that spatial and temporal patterns in diffuse light attenuation were influenced by wind speed, nutrient loading, and river discharge from the Mississippi and Atchafalaya River Basin. SeaWiFS daily integrated surface photosynthetically active radiation (PAR, 400–700 nm) and diffuse light attenuation were used to calculate the absolute PAR and percentage of surface PAR that reached the sediment water interface (SWI) on the LCS. Large portions of the LCS were euphotic to the SWI especially during April and May. This finding implied that significant primary production was possible beneath the pycnocline during spring and early summer. In addition, this study was the first to demonstrate that the euphotic depth was correlated to the depth at which the water column turned hypoxic on the LCS. The development of hypoxic waters may be influenced by decreased light availability below the pycnocline in addition to aforementioned physical forcing.

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1. Introduction

The Louisiana continental shelf (LCS) is strongly influenced by the discharge of the Mississippi and Atchafalaya River Basin (MARB). Nutrient-rich water is delivered to the LCS through the MARB, with maximum concentrations occurring in the spring. Two thirds of the Mississippi River flow enters the Gulf of Mexico through the Mississippi River bird-foot delta, whereas the remaining third is delivered from the Atchafalaya River (Dale et al., 2010). Historical records indicate that nutrient concentrations in the Mississippi River increased approximately 2-fold during a 25-year period beginning in the mid-1950s (Goolsby et al., 2001). However, there was no significant change in river nutrient concentrations from 1979 to 2007 (Greene et al., 2009).

River nutrient loading increases primary productivity, phytoplankton biomass and therefore organic matter within the river plume and adjacent coastal waters (Lohrenz et al., 1997, 2008; Turner & Rabalais, 1991). The effects of nutrient enhanced productivity across the shelf region have been inferred from modeling (Bierman et al., 1994; Justic et al., 1996; Scavia et al., 2003) and by sediment geochemical measures (Eadie et al., 1994; Rabalais et al., 2004, 2007; Turner et al., 2004). The transport and downward flux of organic matter to the sub-pycnocline waters is believed to fuel microbial metabolism that consumes oxygen, thus contributing to hypoxic conditions below the pycnocline (Redalje et al., 1994; Wysocki et al., 2006). This net oxygen consumption contributes to the largest zone of oxygen-depletion in the United States coastal waters, averaging 13,800 km^2 between 1985 and 2008 based on annual July surveys (http://gulfhypoxia.net).

The net consumption of oxygen in below-pycnocline waters and the sediments is the primary cause of hypoxia. Potential mechanisms offsetting oxygen consumption below the pycnocline are processes such as lateral and vertical oxygen flux, and in situ oxygen production via light driven photosynthesis (Justic et al., 1996; Lehrter et al., 2009). Light below the pycnocline can support both phytoplankton and the microphytobenthic (MPB) net production. MPB assemblages can persist at light levels as low as 0.1% surface irradiance (Cahoon, 1999), whereas phytoplankton typically become light-limited at 1% of surface irradiance (Kirk, 1994). While diffuse light attenuation is high within the Mississippi River plume (Lohrenz et al., 1999), it decreases with increasing salinity such that large portions of the LCS, where hypoxia occurs, are euphotic throughout the water column and to the sediment water interface (SWI) (Lehrter et al., 2009). The Bierman et al.'s (1994) deterministic mass balance model suggests that light penetrating below the pycnocline is an important factor influencing organic matter production and dissolved oxygen concentrations. Dortch et al. (1994) estimated

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that photosynthesis at the sediment–water interface contributed up to 57% of the lower water column photosynthesis. In this respect, an increased understanding of light availability on the LCS is critical to understanding the relative contributions of water column and SWI photosynthesis to the supply of carbon and oxygen in the hypoxic zone.

In this paper we examine shelf-wide synoptic estimates of diffuse light attenuation, absolute daily integrated photosynthetically active radiation (PAR, 400–700 nm), and the percentage of daily integrated PAR at the SWI using satellite observations. We characterize the timing, location, and physical forcing impacts on diffuse light attenuation and PAR reaching the SWI. While surface PAR and diffuse light attenuation on the LCS are routinely measured through a variety of ship-based surveys, these observations are typically limited to a few stations per day spatially and only a few weeks at a time temporally. In addition, field surveys in the northern Gulf of Mexico are biased towards the spring and summer months when hypoxia is prevalent. Therefore field observations are inadequate to fully describe water column diffuse light attenuation across the entire LCS over the entire annual cycle. In contrast, satellite-derived data provide synoptic coverage, once properly validated against shipboard or buoy observations. The goals of this study are: (1) validate the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) daily integrated surface PAR, (2) adjust the SeaWiFS Kd_{490} diffuse light attenuation coefficient product to represent Kd_{PAR} with field observations of Kd_{PAR}, (3) estimate the spatial and temporal patterns of absolute and percentage surface PAR at the SWI, (4) interpret how the euphotic depth relates to hypoxia, and (5) examine relationships between SeaWiFS diffuse light attenuation and wind speed, MARB discharge, and nutrient loading from 1998 to 2007.

2. Methods

Field observations were used from EPA Gulf Ecology Division shelf-wide surveys (Fig. 1), Louisiana Universities Marine Consortium (LUMCON) July surveys (Fig. 1, unpublished data, NOAA NODC, www.nodc.noaa.gov), and the LUMCON Lake Pontchartrain station (Fig. 1).

2.1. EPA Gulf Ecology Division field observations

Seven research cruises were conducted from 2005 to 2007 on the LCS where hypoxia routinely occurs (Fig. 1). Three cruises were conducted in the spring (March 2005, April 2006, and April 2007) and 4 cruises were conducted during summer months (September 2005, June 2006, September 2006, and August 2007). The March 2005 cruise was aboard the R/V *Longhorn* and the remaining cruises were aboard EPA's Ocean Survey Vessel *Bold*. With the exception of the September 2005 cruise, a Sea-Bird 911 CTD (Sea-Bird Electronics, Bellvue, WA, USA) was deployed to measure vertical profiles of temperature, salinity, dissolved oxygen, and photosynthetically active radiation (PAR, Biospherical Instruments, QSP-200, San Diego, CA, USA). A Sea-Bird 43 dissolved oxygen sensor on the CTD was used to estimate the depth at which the water column turned hypoxic (defined as <2 mg $O_2\ L^{-1}$, 1.4 ml $O_2\ L^{-1}$, or ~62 O_2 μmol kg^{-1}). Secchi depth was recorded at each station occupied during daylight hours.

Surface PAR (400–700 nm) (E_0) was measured continuously with a 2π LI-COR LI-190 irradiance sensor and averaged at 15 min intervals. The diffuse light attenuation coefficient (Kd_{PAR}, m^{-1}) determined from the CTD was calculated as the slope of $\ln(E_z/E_0)$ versus depth (z) where E_z was the PAR at depth z and E_0 was the PAR measured at the surface. The reciprocal of Secchi depth (SD) was regressed against Kd_{PAR} at Gulf Ecology Division sites. The regression coefficients were then used to estimate Kd_{PAR} at all LUMCON sites.

2.2. LUMCON field observations

Secchi depth was used to estimate diffuse light attenuation coefficients during LUMCON surveys because PAR measurements were not reported at LUMCON sites. SeaWiFS surface daily integrated PAR

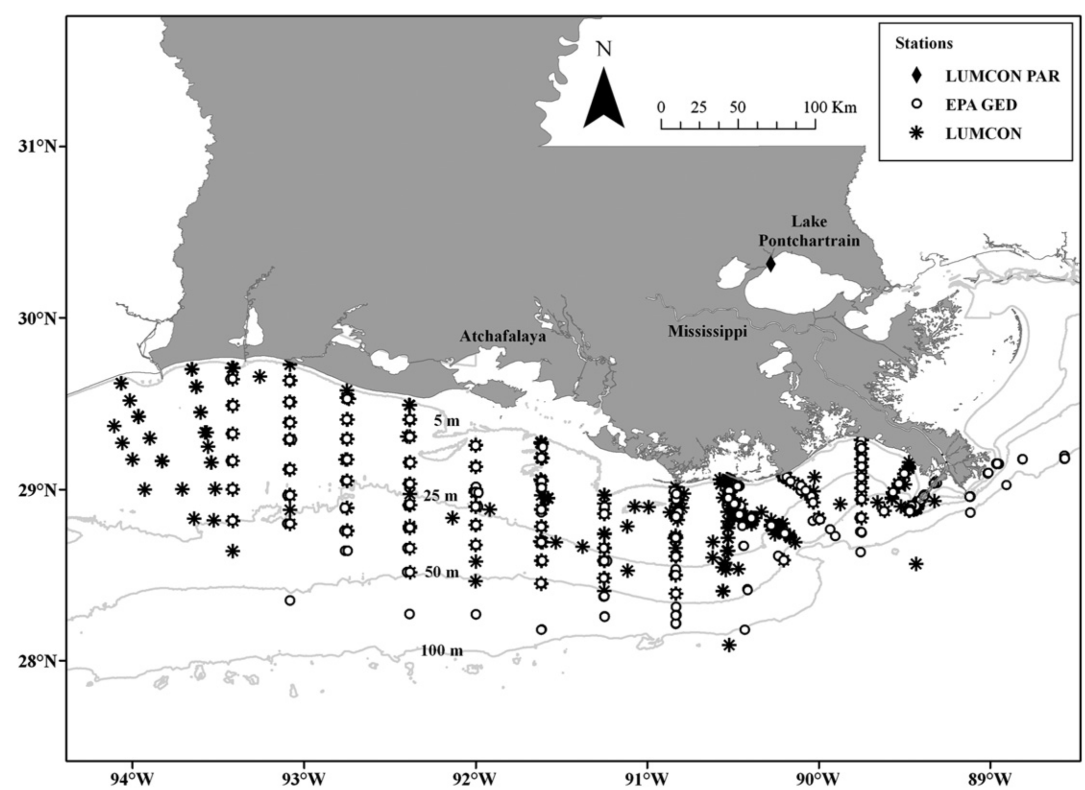

Fig. 1. Map of study region in the northern Gulf of Mexico. Locations of all EPA Gulf Ecology Division (GED) sample stations are indicated in open circles, LUMCON sample stations are indicated with asterisks, and the LUMCON Lake Pontchartrain monitoring station is indicated as a diamond.