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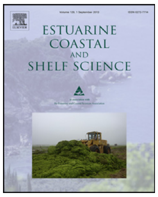

Optical variability along a river plume gradient: Implications for management and remote sensing

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ABSTRACT

Effective assessment and management of seagrass distributions require a thorough understanding of the water environment, in particular the inherent optical properties (IOPs) of the water column, and the linkage with environmental forcing such as coastal run-off. Coastal waters off the Suwannee and Steinhatchee rivers in the northeastern Gulf of Mexico where seagrass is abundant were sampled regularly in 2010 and 2011 during periods ranging from normal spring flooding to record-low flow conditions associated with widespread drought. Relationships between surface salinities, chlorophyll a concentrations (Chl-a), and IOPs were examined to characterize the optical variability of this region as well as its connection with river discharge and wind forcing. Significant spatial and temporal variability was observed for Chl-a (0.285–14.4 mg m^{-3}), colored dissolved organic matter (CDOM) absorption at 443 nm, $a_{\mathrm{CDOM}}(443)$, (0.042–7.53 m^{-1}), and particulate backscattering at 660 nm, $b_{\mathrm{bp}}(660)$, (0.002–0.067 m^{-1}) with gradients evident between nearshore (riverine) and offshore (oceanic) waters. Overall, CDOM was the dominant optically significant constituent (OSC), contributing ~74–75 ± 11% to total (non-water) absorption at 443 nm and 555 nm. CDOM was mainly controlled by river flow, with an inverse correlation observed between $a_{\mathrm{CDOM}}(443)$ and salinity ($r^2 = 0.66$). Chl-a showed less direct dependence on flow, exhibiting elevated concentrations (>5 mg m^{-3}) mainly during the summer. Particulate backscattering in this region was relatively low and largely controlled by non-algal particles, as was evident by the strong relationship between $b_{\mathrm{bp}}(660)$ and detrital absorption at 443 nm, $a_{\mathrm{d}}(443)$ ($r^2 = 0.71$). Compared with other coastal waters in the eastern Gulf of Mexico, $a_{\mathrm{CDOM}}(443)$ was ~3–5 times higher and $b_{\mathrm{bp}}(660)$ was ~50% lower, making the study region very dark. Given that the optical properties of coastal waters in this region are strongly influenced by CDOM derived from terrestrial discharge, remote-sensing algorithms for determining long-term Chl-a trends should focus on utilizing wavebands less influenced by CDOM.

1. Introduction

1.1. Background and relevance

Coastal ecosystems worldwide are increasingly threatened by a variety of human stressors (e.g. pollution, eutrophication, urbanization, and overfishing) as well as natural disturbances (e.g. hurricanes, El Niño). Increased sediment loads and algal blooms are just a few examples of such negative impacts that can lead to degradation in water quality, causing declines in submerged aquatic vegetation including seagrass beds (Kemp et al., 1983; Hale et al., 2004). Seagrasses are essential to the health of nearshore coastal ecosystems as they provide important refuge and forage habitat for ecologically and economically important fish and shellfish species. These areas stabilize bottom sediments helping to prevent coastline erosion and also improve water clarity by removing water column nutrients. While loss of these communities has been attributed to several different factors, deterioration in water quality resulting in light limitation is the major factor affecting seagrass survival given their high light requirements (Ralph et al., 2007).

Light limitation in natural waters is primarily caused by changes in the inherent optical properties (IOP) of the water column which include spectral absorption, $a(\lambda)$, and scattering, $b(\lambda)$, coefficients at near-UV (~300–400 nm) and visible (~400–750 nm) wavelengths, λ. IOPs are controlled by the concentration and composition of both the particulate and dissolved materials in the water column. $a(\lambda)$ is the sum of absorption contributions made by major optically

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significant constituents (OSCs), including water molecules, phytoplankton, detritus, and colored dissolved organic matter (CDOM). Phytoplankton cells which contain both light-harvesting and photoprotective pigments (e.g., chlorophylls and carotenoids) preferentially absorb blue (~440 nm) and red (~675 nm) light strongly. Non-living detrital particles composed mainly of decayed organic material and CDOM derived primarily from terrestrial discharge also absorb blue light strongly, but exhibit exponentially decreasing absorption with increasing wavelength. The amount of light scattered by particles (both living and non-living) in the backward direction or the particulate backscattering coefficient, $b_{bp}(\lambda)$, is dependent on particle size and index of refraction with smaller, more highly refractive particles (e.g. inorganic suspended sediment) generally exhibiting increased $b_{bp}(\lambda)$ (Wozniak and Stramski, 2004). Understanding the specific cause of light limitation (e.g. algal blooms, CDOM, or turbidity) is useful for coastal resource managers charged with protecting coastal ecosystems because certain factors impacting light availability, and hence ecosystem health, can be regulated and controlled (Dennison et al., 1993; Morrison et al., 2006).

Given the increased stress currently being placed on coastal and estuarine ecosystems, effective water quality monitoring programs are needed. Current water quality monitoring data are prone to spatial and temporal aliasing because they rely mainly on annual, quarterly, and sometimes monthly in situ measurements at a limited number of sites. Satellite remote-sensing optical water quality (RSOWQ) data products, as provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) (Esaias et al., 1998), offer the advantage of more synoptic and frequent measurements, allowing for improved determinations of long-term mean and anomaly states of optical water quality (Hu et al., 2004; Harding et al., 2005; Chen et al., 2007a,b). These data products include chlorophyll a concentrations (Chl-a in mg m^{-3}, an indicator of algal biomass), $a_{CDOM}(\lambda)$, $b_{bp}(\lambda)$, and diffuse attenuation coefficients ($K_d(\lambda)$ in m^{-1}, a measure of water clarity). While several different types of algorithms exist for determining RSOWQ data products from satellite ocean color measurements, the validity of these algorithms for optically complex coastal waters needs to be verified before reliable RSOWQ data products can be developed (Carder et al., 1989; Wozniak and Stramski, 2004; Harding et al., 2005; Cannizzaro and Carder, 2006).

The Big Bend region of northwest Florida (USA) is located on the west Florida shelf (WFS) in the northeastern Gulf of Mexico and is home to more than 106,000 ha of mapped, nearshore seagrass beds (Carlson et al., 2010). This region consists of a low-energy, wide, shallow continental shelf with terrestrial input from several river and stream systems, including the Suwannee River. Although relatively undeveloped compared to other seagrass-rich areas along Florida's coastline, several growing concerns in this region exist, including increased nutrient concentrations in surface waters and groundwater due to changes in land use. Hornsby (2007) showed that nitrogen loads have risen nearly 10-fold over the past 50 years in coastal rivers discharging into the Big Bend region. Increased nutrient loading may affect seagrass health by increasing phytoplankton abundance in the water column, thus changing water clarity characteristics of the region (Hale et al., 2004). Significant seagrass bed loss and thinning in Florida's Big Bend region were observed following the extremely active 2004–2005 hurricane season and was attributed to degradation in water quality associated with increased run-off (Carlson et al., 2010). However, whether this loss was caused by light limitation due to increased turbidity and CDOM directly associated with the river plume or phytoplankton blooms stimulated by riverborne nutrients could not be determined based on limited field data provided by existing water quality monitoring programs.

The purpose of this study was to examine the temporal and spatial variability of Chl-a and IOPs in the Big Bend region of northwest Florida using field data collected regularly over a two-year period. Relationships amongst Chl-a and optical properties were examined in conjunction with local river discharge in order to determine the main factor(s) controlling light availability to the bottom in this region. Implications for resource management needs in nearby seagrass-rich regions are discussed and the potential accuracies of existing remote-sensing algorithms for estimating RSOWQ data products to complement existing field monitoring efforts are also examined.

1.2. Geographic setting

Based on the hydrology of its stream systems, the Big Bend region can be separated into the "Springs Coast" (~28.2–29.1°N) and the "Big Bend Proper" (~29.1–30.1°N) with the focus of this study on the latter region (Fig. 1). Seven rivers (Suwannee, Steinhatchee, Fenholloway, Econfina, Aucilla, St. Marks, and Ochlockonee) empty into the Big Bend Proper. The hydrology of these systems is dominated by surface run-off during high or flood flows and groundwater inflow from springs during low or base flows (Mattson et al., 2007). Seasonally, river flow patterns vary widely in Florida with northern rivers traditionally experiencing higher flows during spring as is typical for much of the southeastern USA and southern rivers experiencing higher flows during summer and fall as a result of increased convectional and tropical storm activity. Several river systems in the Big Bend Proper, including the Steinhatchee and upper portions of the Suwannee, are located in a transition zone where annual river discharge often exhibits a bi-modal flow pattern with two distinct peaks during the spring and summer (Kelly and Gore, 2008). Interannual variability in river discharge in Florida is largely driven by El Niño/Southern Oscillation (ENSO)-related climatic variability in the Pacific with higher (lower) than normal precipitation and discharge occurring during El Niño (La Niña) years (Sun and Furbish, 1997).

The annual mean discharge for the Suwannee River (~10,000 cfs) is highest for this region and second highest in Florida. Originating in the Okefenokee Swamp of southeastern Georgia, this river drains an area encompassing ~28,500 km^2 of both southern Georgia and north-central Florida. Given the low-lying relief of this region, the Suwannee River is mainly swamp-fed, carrying high concentrations of tannin-rich dissolved organic material from soil and decayed plant material and minimal sediments. Hence, it is often referred to as a blackwater river system.

Once on the shelf, mixing occurs between river and marine end-member waters from the Gulf of Mexico. Distributions of particulate and dissolved materials in the water column are also influenced by various physical processes such as currents, winds, and tides. Seasonally, wind-driven circulation in this region is to the south during winter (October–March) and to the north during summer (April–September) (Yang and Weisberg, 1999). Storm systems that occur regularly during the winter (e.g., frontal systems) and more intermittently during the summer and fall (e.g., tropical storms and hurricanes) can also affect distributions of materials on the shelf as increasing winds lead to temporary (<1 week) increases in sediment concentrations within the water column which, in turn, cause increases in particulate backscattering (Walker and Hammack, 2000; Lohrenz et al., 2008).

2. Data and methods

2.1. Field data

Field data were collected bimonthly between March 2010 and November 2011 from stations located off the Suwannee ($n = 18$) and Steinhatchee rivers ($n = 13$) (Fig. 1). Temperature, conductivity, pH, and dissolved oxygen (DO) were measured at each station from ~0.25 m below the surface and ~0.5 m above the bottom using a

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