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Characterization of a high chlorophyll plume in the northeastern Gulf of Mexico

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ABSTRACT

In the northern Gulf of Mexico (NGMx), plumes of high chlorophyll shelf waters have been observed to extend across the shelf-break to the central basin. Prior research has shown an association between this cross-shelf flow of water and materials and the adjacent rotation of cyclonic and anticyclonic eddies. Satellite remote sensing data were used here to identify such an eddy-driven plume and to detect and characterize both the mechanisms driving the plume and its biogeochemical impacts. Satellite imagery included chlorophyll (CHL), fluorescence line height (FLH) and chromophoric dissolved organic matter (CDOM) measurements from SeaWiFS and MODIS-Aqua, sea surface temperatures from MODIS-Terra, QuikSCAT wind fields and a merged multi-platform sea surface height product (SSHa). In early June 2007 images, a prominent high-CHL plume (HCP) was seen extending from the continental shelf of the NGMx. A comparison of the CHL and SSHa fields revealed that the HCP was coincident with a cyclone–anticyclone pair, thus linked to an apparent cross-shelf transport. Nearest to the shelf, the CHL values associated with the transport fell within the usual CHL temporal and magnitude range for the summer CHL maximum. Further offshore, the HCP-associated CHL increase was temporally offset, occurring several weeks earlier than expected seasonal CHL peaks. Within the HCP, the relationship of CHL:CDOM:FLH notably diverged from the climatological status, supporting the hypothesis that the HCP composition includes modified shelf waters. Estimates of primary productivity across the study region revealed significant increases in productivity within the HCP's boundaries.

1. Introduction

Circulation in the northern Gulf of Mexico (NGMx) is largely influenced by the Gulf of Mexico Loop Current (LC) and its associated eddy field (Morey, Martin, O'Brien, Wallcraft, & Zavala-Hidalgo, 2003; Ohlmann, Niiler, Fox, & Leben, 2001; Schmitz, Biggs, Lugo-Fernandez, Oey, & Sturges, 2005). The LC is a rapid current bringing warm water into the Gulf of Mexico (Gulf) via the Yucatan current and exiting the Gulf as the Florida current, thereby forming an important link in the Atlantic Gulf Stream system (Schmitz et al., 2005). Extension of the current into the Gulf fluctuates aperiodically (Alvera-Azcárate, Barth, & Weisberg, 2009; Hyun & Hogan, 2008; Sturges, Lugo-Fernandez, & Shargel, 2005). The extension of the LC is responsible for the highly energetic eddy field associated with the LC and the variable nature of the LC extension results in a complex circulation–biota relationship for the Gulf.

Directly linked to the LC extension is the shedding of Loop Current eddies (LC eddies), formed as the distal end of the current intrusion pinches off forming an anticyclonic eddy (Oey, Ezer, & Lee, 2005; Schmitz et al., 2005; Sturges, Hoffmann, & Leben, 2009). The shedding of eddies by the LC varies temporally (Alvera-Azcárate et al., 2009; Hyun & Hogan, 2008; Sturges et al., 2005, 2009) along with the variable extension of the main body of the LC with LC eddy formation intervals reported as ranging from 3 to 17 months (Morey, Martin, O'Brien, Wallcraft, & Zavala-Hidalgo, 2003). Cyclonic eddies tend to form near the edges of the LC or LC eddies and often continue to interact with these features (Hyun & Hogan, 2008), at times leading to the formation of counter-rotating cyclone–anticyclone systems or pairs. Such eddy pairs (sometimes referred to as dipole eddies) have been observed and investigated both throughout the Gulf (Hamilton, Berger, & Johnson, 2002; Salas-de-León, Monreal-Gómez, Signoret, & Aldeco, 2004) and in energetic ocean systems worldwide (de Ruijter et al., 2004; Feng, Majewski, Fandry, & Waite, 2007; Pegau, Boss, & Martinez, 2002).

In addition to the biogeochemical impact of each eddy (Falkowski, Ziemann, Kolber, & Bienfang, 1991; McGillicuddy et al., 1998; Siegel, Peterson, McGillicuddy, Maritorena, & Nelson, 2011), interaction between the members of the eddy pair can potentially alter biogeochemical conditions of the water column. Cyclone–anticyclone pairs can cause environmental and ecosystem impacts due to interactions with the water column, bottom topography, and other circulatory features including other eddies (Biggs & Muller-Karger, 1994; Toner et al.,

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2003). The confluence of the counter-rotating pairs can result in an offshore current of up to 80 cm/s (Schiller, Kourafalou, Hogan, & Walker, 2011). A typical volume transport of ~30 Sv (Biggs & Muller-Karger, 1994; Brooks & Legeckis, 1982) observed between these pairs is of similar magnitude to that of the nearby Florida Current. Flow associated with these currents or jets can persist for days (Teague, Jarosz, Carnes, Mitchell, & Hogan, 2006), moving water masses seaward across the shelf break and into deep waters (Jochens & DiMarco, 2008; Ohlmann et al., 2001; Teague et al., 2006). Morey, Martin, O'Brien, Wallcraft, and Zavala-Hidalgo (2003) showed that specific areas of the NGMx are frequent pathways for these cross-shelf flows, including the western side of the DeSoto Canyon. This is likely due to the fact that cyclonic eddies are often near the canyon (Wang, Oey, Ezer, & Hamilton, 2003), thus available to pair with LC eddies. Cross-shelf flows induced by eddy pairs have been shown to contribute to the advection of shelf material into the central Gulf (Chassignet et al., 2005; Hamilton & Lee, 2005; Hamilton et al., 2002). Freshwater, sediments and coastal suspended particulates can be transported across the shelf to the slope and central basin when the causative eddy pairs are sustained for sufficient time and positioned over the continental slope (Chassignet et al., 2005; Hamilton & Lee, 2005; Morey, Martin, O'Brien, Wallcraft, & Zavala-Hidalgo, 2003; Toner et al., 2003). The transport of slope water and materials is observable via satellite ocean color as plumes or tongues of elevated chlorophyll-a composition (Brooks & Legeckis, 1982; Schiller et al., 2011), features herein referred to as high-chlorophyll plumes (HCPs). Although dependent on the aperiodic presence of eddy pairs, HCPs exhibit a seasonal pattern, present primarily in late spring and summer months (Morey, Schroeder, O'Brien, & Zavala-Hidalgo, 2003; Teague et al., 2006). This is due to the influence of the Mississippi River plume on the regional shelf waters. Understanding the relationship between the Mississippi River plume and NGMx wind stress provides insight into this seasonal dependence.

The Mississippi River contributes ~13,000 m^3/s of freshwater to the NGMx (Morey, Martin, O'Brien, Wallcraft, & Zavala-Hidalgo, 2003), which is more than half of the total freshwater input to the Gulf (Hitchcock et al., 1997; Jochens & DiMarco, 2008). The waters near the source spread out as a low-salinity (~26.25) surface layer plume on the surrounding shelf (Hitchcock et al., 1997; Salisbury et al., 2004). Unlike open ocean surface waters, the buoyant riverine plume is enriched in dissolved organic matter, particulates and nutrients (Yuan, Miller, Powell, & Dagg, 2004). The potential for the Mississippi River plume to influence community structure and primary productivity far from the shelf was demonstrated by Wawrik et al. (2003). Dispersal of these riverine waters is dependent on wind stress, which tends to direct the plume to the northwest during fall and winter and to the east during spring and summer (Hitchcock et al., 1997; Morey, Martin, O'Brien, Wallcraft, & Zavala-Hidalgo, 2003; Morey, Schroeder, O'Brien, & Zavala-Hidalgo, 2003; Salisbury et al., 2004; Teague et al., 2006). When the plume's propagation is eastward, these lower salinity waters are prone to entrainment by the eddy field in the vicinity of DeSoto Canyon (Jochens & DiMarco, 2008; Morey, Martin, O'Brien, Wallcraft, & Zavala-Hidalgo, 2003; Morey, Schroeder, O'Brien, & Zavala-Hidalgo, 2003). An excellent description of a similar marine system in the South China Sea is given by Tang, Kawamura, Van Dien, and Lee (2004) who used SeaWiFS ocean color measurements to characterize an HCP generated by wind-mediated cross-shelf upwelling. Similarly to corresponding features in the NGMx, this HCP appeared to be a jet or filament of riverine-enriched coastal waters extending offshore due to both seasonal wind forcing and offshore circulatory features.

The purpose of this work was to consider the biological impact from the flow of water and materials across the shelf break due to a counter-rotating eddy pairs. Only with the advent of the synoptic, upper ocean bio-optical observations provided by the Coastal Zone Color Scanner (CZCS), did it become possible to obtain holistic views of the impact of mesoscale features on biological patterns (e.g., Biggs & Muller-Karger, 1994; Denman & Abbott, 1994). Even today, full understanding of the physical–biogeochemical interactions associated with eddy pairs remains incomplete due to the complexity of the associated three-dimensional mixing patterns. Despite the constraints imposed by the imaging limitations of CZCS technology, Biggs and Muller-Karger (1994) demonstrated that eddy pairs were responsible for increased offshore productivity and for the transport of shelf waters and particulates to the central Gulf.

The present study builds upon these previous efforts to further an understanding of how cross-shelf HCPs affect phytoplankton biomass and primary productivity both near and offshore. To achieve this, observations from satellite ocean sensors are used to measure bio-physical parameters, giving the advantage of large-spatial, short-temporal scale analysis. A combined time series of SeaWiFS and MODIS-Aqua CHL data, as well as the addition of CDOM and FLH from MODIS-Aqua observations, provides a long-term dataset to evaluate bio-optical properties associated with NGMx HCPs. The relationships among CHL, FLH and CDOM were expected to vary greatly between shelf and offshore waters and to be significantly altered by the HCP. A consistent CHL:FLH:CDOM signature along the HCP would suggest surface shelf water advection and the transport of shelf/riverine phytoplankton to the offshore environment. To further consider the biogeochemical impact of these events, the contribution of an observed HCP to a net primary productivity (NPP) budget was determined.

This paper is comprised of four sections. Following the background presented in the Introduction, the Data section describes the types of data analyzed in the present study and denotes how each dataset was employed. The Results section presents a detailed HCP feature study including HCP detection, bio-physical interactions concurrent with HCP formation, HCP-associated bio-optical observations and finally HCP-associated enhanced NPP estimates. The final Discussion section provides a summary of the findings and their implications.

2. Data

Animated time series of 8-day composite ocean color fields from NASA's Ocean Color Web (http://oceancolor.gsfc.nasa.gov/) were created to detect temporal patterns and anomalous features, such as filamentous HCPs associated with cross-shelf transport. The animated data included MODIS-Aqua 2003–2011 4 and 9 km resolution chlorophyll concentration (CHL), normalized fluorescence line height (FLH) and chromophoric dissolved organic matter (CDOM), and SeaWiFS (1998–2002) CHL only. Standard algorithms were used for CHL to minimize bias between platforms. Hu et al. (2003) report a percent error of less than 50% for spring–summer NGMx satellite to in situ measurements. Utilization of 8-day composite data allows for the elimination of most cloud interference, however, error could potentially be introduced due to uneven averaging across the spatial domain. CDOM is reported as a unitless index value based on the algorithm given by Morel and Gentili (2009).

Sea surface temperature (SST) fields processed from MODIS-Terra data files were used in seasonal evaluation, to verify eddy presence and to detect upwelling. These data consisted of 8-day averaged L3 mapped grids from 2001 to 2009 with 4 km spatial resolution.

Sea surface height (SSH) fields generated by the Colorado Center for Astrodynamics Research Group (CCAR) were accessed from the GOMEX-PPP data products site (http://abcmgr.tamu.edu/gomexppp/) to identify eddies and advective paths associated with cross-shelf flow. The data consist of 1/4° merged multi-platform SSH fields from 2004 to 2010 described in Leben, Born, and Engebreth (2002).

SeaWiFS and MODIS-Aqua based 8-day Carbon based Productivity Model (CbPM) net primary productivity (NPP) estimates, described in Behrenfeld et al. (2009) and Westberry et al. (2008), were accessed through Oregon State University's Ocean Productivity website (http://www.science.oregonstate.edu/ocean.productivity). CbPM estimates were found to be more consistent with reported in situ NPP estimates for the NGMx.