Monitoring Bio-physical Coupling in the Open Gulf of Mexico Using an Integrated Satellite Sensor Approach

Katharine C. Woodard and Jerry D. Wiggert
Department of Marine Science
University of Southern Mississippi
Stennis Space Center, MS 39529
katharine.woodard@eagles.usm.edu

***Abstract* - In the autumn of 2006 (September 20 – December 20, 2006) two cyclonic rings merged to form a larger cyclonic ring in the central Gulf of Mexico (GMx). An anticyclonic ring and the Loop Current aided this merger. The different rotational rings were compared in sea level anomaly (SLA) magnitude as well as chlorophyll anomaly (CLA) signal. The cyclonic ring encompasses positive CLA, while both the anticyclonic ring and loop current usually feature negative CLA. Coastal advection also occurred in this time frame, with a large CLA signature that extended from the Yucatan Peninsula to the large cyclonic ring. Throughout the entire autumn of 2006, the respective positive and negative SLA features in the central GMx possess negative and positive CLA indicating a qualitative correlation is present during this time.**

Keywords—Sea level anomaly; chlorophyll; chlorophyll anomaly; eddies; Gulf of Mexico; SeaWiFS; MODISA

I. INTRODUCTION (*Heading 1*)

Sea level anomaly (SLA) and chlorophyll (chl) / chlorophyll anomaly (CLA) have been correlated throughout many parts of the world oceans. Physical mechanisms such as nutrient pumping, advection, and cross-marginal flow play a large role in influencing biological characteristics, identified by chl/CLA. The objective of this study is to identify if certain mesoscale physical parameters (SLA) will impact biological features (ocean color) in the open Gulf of Mexico (GMx) using remote sensing methods.

Light, temperature, and nutrient availability are all limiting factors for phytoplankton growth in the ocean. The limiting nutrients are usually nitrate, iron, phosphorus, or silicon depending on the location in the ocean and phytoplankton nutritional requirements. In the open Gulf of Mexico at the surface, the limiting nutrient is nitrate [1, 2]. There are multiple mechanisms that allow mesoscale physical features such as eddies to significantly impact biological characteristics in an area. Eddy-eddy interactions, lateral advection, eddy pumping, and eddy-topographic interaction all elicit biological responses throughout the entire domain of the GMx.

The motion of eddies create upwelling or downwelling zones in the eddy core based on the direction of rotation, which can internally bring up or externally advect nutrients as well as chlorophyll from highly concentrated regions. Negative SLA will usually correspond with positive CLA within an eddy, while the opposite will hold true for positive SLA. Due to the sloping of the sea surface in the middle of cyclonic eddies bringing water from below, in turn moving the thermocline to a shallower depth, cyclonic eddies are considered regions of greater vertical stabilization of the water column [3]. This is eddy pumping. Cyclonic (anticyclonic) eddies induce upwelling (downwelling) within the eddy itself, increasing (decreasing) nutrient concentrations in the surface and stimulating (suppressing) phytoplankton growth in the euphotic zone.

Advection of chlorophyll from areas of higher concentration, such as coastal waters, by eddies has been shown to move chlorophyll up to 200 kilometers into the open GMx [1, 4]. The Loop Current (LC) also plays a role in advection, “pulling” blooms from the Campeche Bank and the northern “wall” of the LC into the open GMx and the Atlantic Ocean [4]. Advection of coastal waters can also bring nutrients from the advected shelf water which helps to maintain the phytoplankton stock transported [4]. Eddy-eddy interaction is also an important mechanism that drives biology. When two eddies are near one another and cross over the continental shelf, cross-margin flow or upwelling can occur which will inject nutrients into the euphotic zone sparking growth [3, 5].

Topography can influence how physical features behave within the GMx. This will have a larger significance in the GMx and this study, as the influence on physical features will lead to how biology is affected in this area. Bottom topography greatly influence eddy pairs within the Gulf of Mexico [1, 6, 7]. Eddies translate predominantly westward in the central GMx due to the influence of the Coriolis force [8, 9]. Cyclonic and anticyclonic eddies also generally have their centers between 24.5˚-26.5˚N due to topography as they translate to the west in the GMx [11] (Fig. 1). This westward path will eventually lead to a collision with the continental shelf, if the eddy does not dissipate first. Once in contact with

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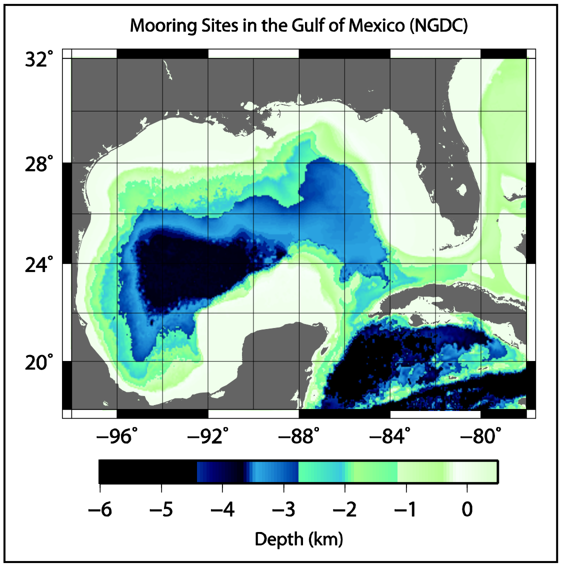

Fig. 1. Topography of the Gulf of Mexico.

the continental shelf, advection of chlorophyll begins to occur [1].

Loop Current Eddies (LCEs) are large anticyclonic eddies with diameters on the order of 250-400 kilometers. These eddies break off from the LC and travel westwards. Collisions of LCEs with the continental shelf lead to the eddy changing course, with direction dependent on where along the shelf the collision took place [7, 10]. Along with directional changes, contact with the western boundary by an LCE has also been shown to produce small-scale cyclones [8, 11]. Cyclonic eddies are generally smaller than LCEs with diameters on the order of 100-150 meters [10, 12]. They play a large role on biological characteristics due to the doming of the nutricline induced by their rotation. Cyclonic eddies can form around the perimeter of the LC [11, 13, 14, 15], in the eastern GMx near the Dry Tortugas [15, 16, 17, 18], and in the southern GMx, around the Bay of Campeche [10, 19].

The collision of a LCE or cyclonic eddy with the western continental shelf or subsequent eddy pair can lead to advection from the coastal waters into the open Gulf. If lateral advection from coastal waters or nutrient injection via upwelling occur due to physical processes, it should be easy to observe a biological response. Previous studies of advection from areas of higher chlorophyll concentration have been perceived qualitatively in images [20, 21]. This qualitative observation of advection will also be utilized in this study.

The objective of this paper is to show qualitatively that mesoscale SLA features will significantly impact local biological variability compared to typical seasonal conditions, as well as an inverse relationship between SLA and CLA.

II. Methods

SLA data products have been produced by Ssalto/Duacs and distributed by AVISO, with support from CNES (http://www.aviso.oceanobs.com/duacs/). The data set is available from October 1992 through the present in weekly (7-day) increments. This study utilized data for the time period January 1998-December 2011. SSH was measured along-track using the ERS 1/2, Topex/Poseidon, GFO, Jason 1/2, and EnviSat satellites. SLA was then calculated from a seven-year mean by Ssalto/Duacs and AVISO. The resolution is 1/3° x 1/3°. The GMx region was extracted from the globally merged data set.

Chlorophyll-a data was obtained as 8-day composites from SeaWiFS and MODISA satellite data holdings of the Goddard DAAC. The resolution is 0.09˚ x 0.09˚ (9km). The time period for the Chl data set matches that of SLA: January 1998 – December 2011. SeaWiFS data was collected from January 1998 – December 2002; MODISA was then used from January 2003 – December 2011.

The Chl data set was regridded to match the 1/3˚ grid of SLA data. A chlorophyll anomaly (CLA) data set was then created using the 14-year mean. CLA helps to ensure seasonality does not bias the results, as surface chlorophyll is higher in the winter than in the summer in the GMx [1].

Ocean Surface Currents Analyses – Real time (OSCAR) is an ocean surface currents product available from NASA PO.DAAC site (http://podaac.jpl.nasa.gov) on a 1˚ grid. This data set is available from 1992 through the present. OSCAR calculates surface velocities from satellite sea surface height, wind, and temperature. The surface currents calculated from the model average the top 30m of the ocean using a quasi-steady geostrophic model with an eddy viscosity based wind-driven ageostophic component and a thermal wind adjustment (http://www.esr.org/oscar_index.html). This current data can be used to aid in showing surface advection occurring in the GMx.

All products used for this study were DAP-accessible data.

Images of SLA superimposed over CLA were processed and allowed a qualitative analysis to be conducted. Images were also processed of SLA superimposed over Chl. 2006 and 2007 results will be discussed here.

III. Results

Beginning the week of August 5, 2006 (prior to autumn 2006), a negative SLA feature is presented in the southeast GMx, near the Loop Current positive SLA feature. This cyclonic eddy (Eddy A) encompasses positive CLA within its boundaries (Plate 1). As the weeks progress, larger CLA signatures are seen within Eddy A. Eddy A then moved westward to a location just above the Yucatan Channel (~-87˚W, 23˚N). Another cyclonic feature, Eddy B had formed at this time in the northern, central GMx (~-88˚W, 27˚N). Eddy B also encompassed positive CLA.

Plate 1

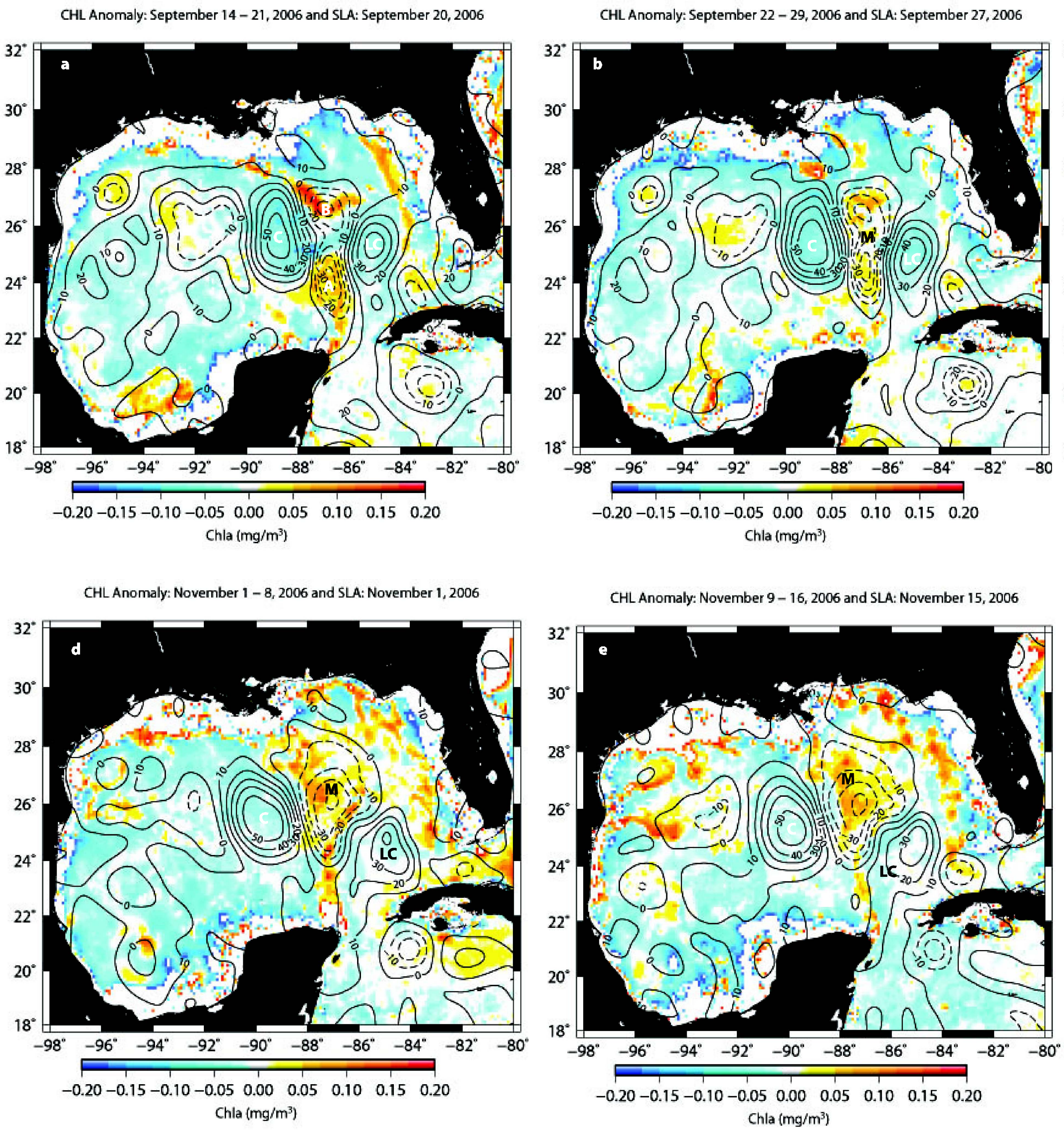

Plate 1. 9 Chlorophyll anomaly (CLA) colored images, with reds and yellows representing positive CLA and blues representing negative CLA with sea level anomaly (SLA) contours superimposed. Dashed contour lines represent negative SLA with solid lines representing positive CLA. (a) CLA of September 14-21, 2006 with SLA from Sept. 20. This image shows Eddies A and B beginning to merge to form Eddy M. (b) CLA of Sept. 22-29, 2006 and SLA Sept. 27, 2006, showing Eddy M has now formed. (c) CLA of October 8 - 15 with SLA Oct. 11. This shows a the "stream" of CLA extending from the Yucatan Peninsula to Eddy M. (d) CLA of November 1 - 8 and SLA of Nov. 1, 2006. (e) CLA of Nov. 9 - 16 and SLA of Nov 15, 2006.

September 6 – 13, Eddy A proceeded to move northward, while Eddy B migrated south, both along the same line of latitudes (~-87˚W). The following week, Eddy A and Eddy B begin to merge together to form a larger, cyclonic SLA feature – Eddy M (Plate 1, a). Eddy M becomes a large, both in magnitude and area throughout its life; with SLA ~ -40cm and an area stretching form 24˚N – 27.5˚N, a width from -86˚W – -88˚W at times, Eddy M still encompassed positive CLA that exceeded 2 mg /m3at times.

Eddy C, the anticyclonic eddy towards the west of Eddy M, is usually holding a CLA signature of 0 - -0.1 mg/m^3, though some values can reach ~ -0.2 mg/m^3 (Plate 1). Values within the Loop Current are similar. There are some weeks in which there is positive CLA throughout much of the GMx. This could be due to an error in the Chl data from the instruments or interpolation error in the programming.

A notable CLA signature (0.05 - > 0.2 mg/m^3) appears off of the Yucatan Peninsula the week of October 8-15, 2006 (Plate 1,c). It is a "stream" of CLA extending from the coastlines of Mexico into the Eddy M. Looking at the OSCAR plot for the same time frame, the "stream" of SLA extending into the GMx follows the path of the Loop Current (Fig. 2). The high velocity current passes close to the coastlines of the peninsula before flowing into the open GMx. The CLA signature coming from the coast to the open GMx remains through the end of 2006.

IV. DISCUSSION

Beginning the week of August 5, 2006, a negative SLA feature is presented in the southeast GMx, near the Loop Current positive SLA feature. This cyclonic eddy (Eddy A) holds some positive CLA within its boundaries, but not a large amount. As the weeks progress larger CLA signatures are seen within Eddy A. There is also an interesting positive CLA signature (not shown) over the boundary of the west Florida shelf, which includes part of Eddy A. Eddy A could be laterally advecting some of this strong (>0.2 mg/m^3) CLA signature, as well as nutrients from this region, from the west Florida shelf into its boundaries. This could seed Eddy A with more Chl and nutrients, so that the phytoplankton population is enhanced and becomes more prominently apparent to the sensors. The phytoplankton population within Eddy A could then be sustained by the nutrients being pumped into the center of the eddy.

Eddy A moves westward in the GMx to just above the Yucatan Peninsula fully engrossed with positive CLA (0.05 – 0.15 mg/m^3). Again, this positive CLA signature is a product of eddy pumping and the additional phytoplankton population added to the original from the advection of shelf waters. Eddy A then proceeds to translate northward beginning to merge with Eddy B the week of September 14 (Plate 1). As

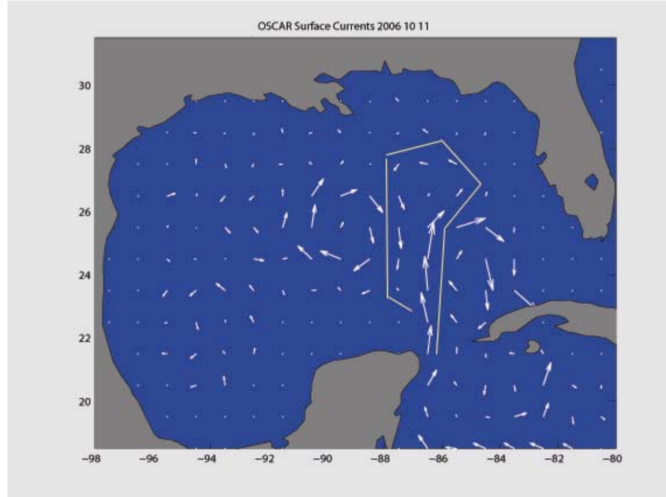

Fig. 2. OSCAR currents foe October 11, 2006. Enclosed is yellow is the beginning of the Loop Current passing closely to the Yucatan Peninsula moving northward, as well as Eddy M, highlighting the path of the advected material.

images show, there are two large positive SLA features to the west and east of Eddy A and Eddy B. As they are of opposite rotation, the merging of these two cyclones into Eddy M could be influenced by Eddy C pulling Eddy B southward and the Loop Current pushing Eddy A northward. It must be acknowledged that the presence of Eddy C and the Loop Current, in conjunction with topography, made it hard for Eddy A or B to translate another way besides north and south respectively.

Once merged, Eddy M continues to hold positive CLA. The "stream" extending from the Yucatan Peninsula into Eddy M for the latter half of autumn can be attributed to advection from the Loop Current (Plate 1, Fig. 2). As seen in the OSCAR image (Fig. 2), the high magnitude of the Loop Current flows close to the coastal waters of the peninsula. Due to this high magnitude, the Loop Current can advect highly concentrated coastal waters into the open GMx. As Eddy M is located in the central Gulf in close proximity to the Loop Current, the advected water is diverted into Eddy M by coming into contact with the cyclonic eddy's different rotational flow. The highly concentrated water also shows to be seeding Eddy M with more phytoplankton, as CLA signatures begin to rise once the "stream" of advected material is in contact with the eddy. Along with phytoplankton, this advected material can also be carrying nutrients which help to sustain the phytoplankton once out in the oligotrophic open GMx waters.

V. CONCLUSIONS

It can be concluded that mechanisms such as lateral advection, eddy pumping, and cross-marginal flow all came into play in the central GMx in the autumn of 2006. As seen through satellite imagery, these processes can be identified through qualitative analysis. Though it is not a perfect correlation between chlorophyll anomaly and sea level anomaly, the dominant features in the central GMx during this time period are clear enough to suggest that physical processes affecting sea surface height play a role on local biological variability.

Quantitative results should be obtained on this time period, as well as the entire 14-year period for which the chlorophyll anomaly was based upon to reinforce the qualitative analysis reported here.

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