Exploration of Biophysical Interactions Associated with Mesoscale Variability in the Central Gulf of Mexico

Katharine Celeste Woodard

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EXPLORATION OF BIOPHYSICAL INTERACTIONS ASSOCIATED WITH
MESOSCALE VARIABILITY IN THE CENTRAL GULF OF MEXICO

by

Katharine Celeste Woodard

A Thesis
Submitted to the Graduate School
of The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Master of Science

Approved:

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Maureen A. Ryan
Dean of the Graduate School

May 2014
ABSTRACT

EXPLORATION OF BIOPHYSICAL INTERACTIONS ASSOCIATED WITH
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by Katharine Celeste Woodard

May 2014

Bio-physical coupling in the Gulf of Mexico (GMx) is explored in this research using an integrated satellite sensor approach. Physical features are identified using Sea Level Anomaly (SLa) produced by Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO). Biological characteristics of the GMx have been recognized as ocean color identified by the satellites SeaWiFS and MODISA. A climatology data set and a chlorophyll anomaly (CLa) was made using the 14-year mean determined from the ocean color files. The hypotheses are that there will be an inverse relationship between SLa and CLa, that mesoscale SLa features will significantly modulate local biological variability compared to the typical seasonal conditions, and that interannual climate variability will influence this climatological state of biological variability. Using MATLAB, Generic Mapping Tools (GMT), and other programs, statistics were performed and images of both parameters were created. Individual images of SLa contours superimposed on CLa as well as Hovmöller diagrams allowed qualitative analysis with image analysis to aid in determining the hypotheses. Due to the non-parametric nature of SLa and CLa, a Spearman’s Rank Correlation was performed along lines of latitude and longitude and across the GMx in conjunction with the Ives-Gibbons dichotomous correlation, which allowed for magnitude to be dismissed. A significant inverse relationship was found between SLa and CLa. The second hypothesis of SLa...
modulating local biological conditions was also proven through qualitative and quantitative analysis, though the third hypothesis of interannual variability did not have enough data to support it.
ACKNOWLEDGMENTS

A number of people have lent their time and effort in contributing to the development of this thesis. I would first and foremost like to thank my advisor, Dr. Jerry Wiggert, without whom this thesis would never have made it to completion. I would also like to thank the members of my committee: Dr. Scott Milory and Robert “Bob” Arnone.

I would like to thank NOAA Integrated Ocean Observing System (IOOS) and the Southeastern Universities Research Association (SURA), as well as the Northern Gulf Coastal Hazards Collaboratory (NGCHC), which provided funding for this project.

I would like to extend my gratitude to both Jamie Davis and Brooke Jones for their support and assistance with scripting programs for image analysis. I would also like to thank the Goddard Earth Sciences Data and Information Services Center at the Goddard Space Flight Center in Greenbelt, Maryland for the production and distribution of ocean color data. I would like to thank AVISO: Archiving, Validation and Interpretation of Satellite Oceanographic data for the production and distribution of the Sea Level Anomaly data.

Finally, I would like to thank my family and friends for their endless support and encouragement, not only throughout this process but in all my endeavors.
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<tr>
<td>AVISO</td>
<td>Archiving, Validation, and Interpretation of Satellite Oceanographic data</td>
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<td>Chl</td>
<td>chlorophyll-a</td>
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<td>CLa</td>
<td>Chlorophyll Anomaly</td>
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<td>DAAC</td>
<td>Distributed Active Archive Center</td>
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<td>DCM</td>
<td>deep chlorophyll maximum</td>
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<td>EnviSat</td>
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<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
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<td>EOF</td>
<td>Empirical Orthogonal Function</td>
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<td>ERS</td>
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<td>Gulf of Mexico</td>
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<td>LCE</td>
<td>Loop Current Eddy</td>
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<td>MODISA</td>
<td>Moderate Resolution Imaging Spectroradiometer aboard the Aqua Satellite</td>
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<td>NaN</td>
<td>Not-a-Number</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NOMAD</td>
<td>NASA bio-Optical Marine Algorithm Dataset</td>
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<td>OBPG</td>
<td>Ocean Biology Processing Group</td>
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<td>OSCAR</td>
<td>Ocean Surface Currents Analyses – Real time</td>
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<tr>
<td>SeaBASS</td>
<td>SeaWiFS Bio-optical Archive and Storage System</td>
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<td>SeaWiFS</td>
<td>Sea-viewing Wide Field-of-view Sensor</td>
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<td>SLa</td>
<td>Sea Level Anomaly</td>
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<td>SSH</td>
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<td>SST</td>
<td>Sea Surface Temperature</td>
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<td>TOA</td>
<td>top of atmosphere</td>
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CHAPTER I

INTRODUCTION

Using an integrated satellite sensor approach, bio-physical coupling in the Gulf of Mexico (GMx) is explored in this analysis. Specifically, that mesoscale (hundreds of kilometers) physical parameters identified by sea level anomaly (SLa) affect biological features, such as chlorophyll fronts or blooms, identified by ocean color (chlorophyll-a). The hypotheses are as follows:

1. Negative SLa features such as cyclonic eddies will yield a positive chlorophyll anomaly (CLa) signature, while positive SLa features will yield a negative CLa signal.

2. That mesoscale SLa features will significantly modulate local biological variability compared to the typical seasonal conditions.

3. Interannual climate variability will influence this climatological state of biological variability.

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer aboard the Aqua satellite (MODISA) identified ocean color in the GMx. As ocean color identified chlorophyll-a (Chl), the chlorophyll anomaly data set was created in MATLAB using the chlorophyll-a 14-year mean as the reference climatology. SLa data for the GMx were extracted from a globally merged data set based on several satellite-based altimetry platforms available at AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data; http://www.aviso.oceanobs.com/duacs/). Anomaly fields are a measure of the parameter (in this case of chlorophyll and sea surface height) based on the climatological mean.
Positive anomaly would mean the parameter is above the climatological mean, while a negative anomaly would mean the parameter is below the climatological mean.

This research seeks to identify that a correlation between SLa and CLa/Chl exists in the GMx and the local implications of this correlation. This study will further understanding of the effects of mesoscale physical features upon the biological characteristics in the GMx open basin. Thus, large scale biophysical interactions will be investigated and their spatio-temporal variability characterized.
CHAPTER II
BACKGROUND

Mixed Layer Biology and Physics

Phytoplankton growth in the ocean is limited by light, temperature, or nutrient availability. These limiting nutrients are usually nitrate, iron, phosphate, or silicate depending on the location in the ocean and phytoplankton nutritional requirements. The open GMx has sufficient light throughout the mixed layer (Joliff et al. 2008). In the open GMx at the surface, the limiting nutrient is nitrate (Biggs and Müller-Karger 1994; Jochens and DiMarco 2008). This proves true for the entire year as “waters of the open GMx are permanently stratified and depleted of nitrate” (Dagg and Breed 2003: p. 133). The primary pool for nitrate is found below where phytoplankton growth occurs, the euphotic zone. This abundant pool of nitrate is below the nitracline, which usually coincides with the thermocline. The nitracline depth in the open GMx is approximately 90 meters (Dagg and Breed 2003). Acting as a barrier, stratification associated with the thermocline inhibits mixing of the waters above and below the thermocline’s density gradient. If this barrier uplifted (or physical mixing was stimulated) an influx of allochthnous nutrients into the euphotic zone would occur, relaxing nitrate-limitation and promoting phytoplankton growth.

The most important supply of nitrate to the upper mixed layer is that acquired through vertical mixing (Miller 2004). New production is the term given for primary production associated with newly available nitrogen (Dugdale and Goering 1967). This occurs in oligotrophic waters when nutrients from below the thermocline/nitracline in the GMx enter the euphotic zone. Recycled production is where organic matter is eaten,
respired, and excreted as ammonia to be re-incorporated by phytoplankton into organic matter (Dugdale and Goering 1967; Miller 2004). Primary production, new and regenerated, can be estimated from the chlorophyll distributions, though explicit distinction between new and regenerated production is not directly possible. Regenerated production comes as a result of ammonia that typically is associated with stratified, oligotrophic waters. New production is typically linked to nitrate enrichment from depth and fuels rapid accumulations of phytoplankton biomass (i.e., phytoplankton blooms) that appear prominently in the ocean color observations (Platt and Sathyendranath 2008).

With the assumption that regenerated production is at a steady state, phytoplankton blooms observed in the oligotrophic open waters of GMx could then be assumed to be a response of new production.

Different mesoscale physical mechanisms impact the depth of the nitracline or nutrient flux in general, impacting in turn the biological characteristics of an area. Eddy-eddy interactions, advection from areas of high to low concentration, eddy pumping, and eddy-topographic interaction all elicit biological responses throughout the entire domain of the GMx.

The rotational direction of eddies create upwelling or downwelling zones in the eddy core based on the direction of rotation, which can vertically entrain nutrients (Figure 1). In addition, the outer edges of eddies influence the surrounding waters, which can laterally advect nutrients from highly concentrated regions. Negative SLa will typically correspond with positive CLa within an eddy, while the opposite will hold true for positive SLa. “Cyclonic eddies are regions of greater vertical stabilization of the water column” according to Miller (2004: p. 12). This is due to sloping of the sea surface in the
middle of the cyclonic eddy bringing water from below, which in turn moves the thermocline to a shallower depth (Miller 2004). The thermocline shoals upward as a result of divergent flow at the surface, creating the sloping towards the center of the eddy. Water that is lost by this divergent flow needs to be replaced, requiring an upward vertical flow (Knauss 1997). This is one scenario of the phenomenon known as eddy pumping (Figure 1). More generally, eddy pumping is where cyclonic (anticyclonic) eddies induce upwelling (downwelling) within the eddy itself, increasing (decreasing) nutrient concentrations and stimulating (suppressing) phytoplankton growth in the euphotic zone. The upwelling (downwelling) occur due to divergent (convergent) flow at the surface. Previous GMx correlation studies have reported on how chlorophyll distributions were affected by anticyclonic-cyclonic eddy pairs along the western and southern coasts (Biggs and Müller-Karger 1994; Salas-de-León et al. 2004).

As a general rule of thumb, it is noted that for every one centimeter signature of SLa there is an inverse four meter isopycnal displacement (McGillicuddy et al. 1998). For example, with a SLa signature of 10 cm, isopycnals would be depressed by approximately 40 m. In the GMx specifically, cyclonic eddies of -10 to -20 cm magnitude typically upwell the thermocline to 50 – 60 m below the sea surface, while the nitracline is found near 50 – 70 m below the sea surface (Biggs and Müller-Karger 1994; Walker et al. 2005; Zimmerman and Biggs 1999).
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 Gulf (Biggs and Müller-Karger 1994; Toner et al., 2003). The Loop Current (LC) also plays a role in advection, entraining blooms from the Campeche Bank and the northern “wall” of the LC into the open GMx and the Atlantic Ocean (Toner et al. 2003).

Advection of coastal waters can also bring nutrients from the advected shelf water which helps to maintain the entrained phytoplankton stock (Mann and Lazier 2006; Toner et al. 2003). 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-marginal flow or upwelling can occur which will inject nutrients into the euphotic zone, sparking growth (Jochens and DiMarco 2008; Morey et al. 2003; Zimmerman and Biggs 1999).

Figure 1. Shape of isopycnals and the interface between two water masses of density, $\rho_1$, $\rho_2$ as affected by an a) anticyclonic, warm-core eddy and b) cyclonic, cold core eddy. The motion of rotation causes downwelling within the center of an anticyclonic eddy (a) and upwelling at the center of a cyclonic eddy (b). It can also be seen that the sea surface, $\rho_0$, is raised with the anticyclonic eddy and depressed at the cyclonic eddy. (Stewart 2008: p. 173).
Gulf of Mexico Dynamics

The Gulf of Mexico (GMx) is located between 18° – 32°N and 80° – 100°W (Figure 3). The dynamics of the GMx basin is characterized by three main physical features: the Loop Current (LC), Loop Current Eddies (LCEs), and cyclonic eddies. The bathymetry of the GMx is an important influence on these three main features.

The highly dynamic Loop Current is the dominant feature within the Gulf of Mexico. It enters the Gulf from the Caribbean Sea through the Yucatan Channel, propagates northward into the GMx basin, and then flows out through the Florida Straits. The average extension of the Loop Current as calculated by Leben (2005) is 26.2°N and 87.9°W. As the LC is highly dynamic, the northward extension of the LC into the GMx ranges from minimal, around 24.1°N, to penetrating sometimes as far north as 28.1°N with westward extension ranging from 85.8° – 93.1°W (Leben 2005; Vukovich 2007). It is the considerable northward extension which can lead to the formation of large anticyclonic eddies, known as Loop Current Eddies (Cherubin et al. 2006; Jochens and DiMarco 2008; Murphy et al. 1999). Along with the instability of the LC, it is also believed that cyclonic features can aid the formation of anticyclonic eddies (Cherubin et al. 2006; Vukovich, 1988, 2007). This is important when performing correlations of SLa and CLa in the GMx, as eddy-eddy interaction can be important in the advection of chlorophyll as well as in the mixing of the water column.

Loop Current Eddies (LCEs) are large anticyclonic eddies, around 250 – 400 kilometers in diameter, which break off from the LC and travel westwards. It can take months or years for a LCE to completely separate from the LC; however, the average frequency of ring separation events has been reported as occurring about every 6 and 11
months (Hamilton et al. 2002; Leben 2005; Oey 1995; Oey and Lee 2002; Ohlmann and Niiler 2005; Sturges and Leben 2000; Vukovich 1988, 2007), though the frequency of separation estimates are highly variable and exhibit dependence on the length of the data set used (Murphy et al. 1999; Vukovich 2007). Most LCEs have their centers located between 24°–26°N (Vukovich 2007), suggesting that they are guided by bottom bathymetry (Figure 2) (Welsh and Inoue 2000). LCEs will undoubtedly have a great effect on the GMx properties, as these large physical features will experience a strong eddy-bathymetry interaction along the western continental shelf (Hyun and Hogan 2008; Oey 1995). The collisions lead to the eddies changing course with directional change dependent on where the collision took place along the continental shelf as well as the magnitude of the shelf impact (Hyun and Hogan 2008; Vukovich 2007).

The LCEs will play a role on biological features within the Gulf through their circulatory dynamics and persistence. It is logical to expect that once in contact with the continental shelf the LCEs will advect chlorophyll away from the coastline into more oligotrophic waters (cf., Biggs and Müller-Karger 1994). It is also conceivable that in the open GMx, the spatial extent and westward propagation of LCEs will affect the low levels of phytoplankton already present there. Anticyclones, the Loop Current, and LCEs are all nutrient poor; however, interactions with cyclonic features and bottom bathymetry can stimulate biological growth by bringing nutrient-rich water to the euphotic zone in the aforementioned nutrient poor features (Jochens and DiMarco 2008).

Cyclonic eddies are another dominant feature in the GMx. These types of eddies are generally smaller than LCEs, with diameters on the order of 100 – 150 km (Hamilton et al. 2002; Vukovich 2007). They play a very large role on biological characteristics, as
noted previously, due to the doming of the nutricline induced by their rotation. Cyclonic eddies can form around the perimeter of the LC (Cherubin et al. 2006; Vukovich 1988, 2007; Zimmerman and Biggs 1999). These types of eddies also move westward in the GMx, with their centers being between 24.5° – 26.5°N (Vukovich 2007). It has also been noted that once a LCE comes into contact with the western boundary of the GMx, small-scale cyclones can form to the north due to the advection of potential vorticity by the circulation of the anticyclone (Frolov et al. 2004; Ohlmann et al. 2001; Vukovich 2007). The conservation of potential vorticity can be achieved in two ways. The first is that if an eddy is to remain at the same latitude it must change the water layer thickness and the

Figure 2. Bathymetry map of the Gulf of Mexico.
relative vorticity (Knauss 1997). The second is that the layer thickness remains the same but the latitude and the relative vorticity changes (Knauss 1997).

Cyclonic eddies also are often present in the eastern GMx near the Dry Tortugas (Oey 1996; Ohlmann and Niiler 2005; Vukovich 2007; Zimmerman and Biggs 1999). The southern GMx, around the Bay of Campeche, is usually associated with minor rings (i.e., cyclonic rings with diameters less than 150 km and anticyclonic rings less than 200 km). Complex patterns of upwelling along the Campeche Bank, riverine inputs that also impact the region, and the cyclonic gyre in the Bay of Campeche dominate this region making comparison of this region to the entire GMx more complicated, which contains larger mesoscale eddies and a dominate anticyclonic gyre (the LC) more difficult (DiMarco et al. 2005; Salmeron-Garcia et al. 2011; Schmitz et al. 2005; Vukovich 2007; Zavala-Hidalgo et al. 2003). Cyclonic eddies near the Bay of Campeche are formed at rates similar to LCE formations of every 6 to 11 months (Zavala-Hidalgo et al. 2003). According to Pérez et al. (1999), “friction between the Yucatan Current and the bottom of the continental shelf produces a speed gradient that creates a negative vortice of the current in the area” (p. 154). This process creates the cyclonic eddies. If the eddy migrates north, its lifespan is 3 – 15 months with the longest lifespans coinciding with those eddies that merge with other individual cyclonic eddies and the shortest lifespans associated with those cyclonic eddies that remain on the Campeche Bank (Zavala-Hidalgo et al. 2003).

As mentioned previously, bathymetry influences how physical features behave within the GMx. This will have a large significance in the GMx and this study, as the influence on physical features will in turn lead to how biology is affected in this area.
Biggs and Müller-Karger (1994), Welsh and Inoue (2000), Salas-de-León et al. (2004), and Hyun and Hogan (2008) found that bottom bathymetry greatly influences the evolution of eddy pairs within the GMx (Figure 2). Eddies translate predominantly westward in the central GMx due to the influence of the Coriolis force (Frolov et al. 2004; Leben 2005). This westward path will eventually lead to a collision with the continental shelf, if the eddy does not dissipate first. Once in contact with the continental shelf surface chlorophyll distributions indicate that offshore advection of more concentrated phytoplankton populations situated on the shelf begins to occur (Biggs and Müller-Karger 1994).

Within the open GMx the waters are always oligotrophic with the upper 100 m having extremely low levels of nitrate and, thus, chlorophyll concentrations, rates of primary productivity, and zooplankton biomass (Biggs and Müller-Karger 1994; Dagg and Breed 2003). Thus, if lateral advection from coastal waters or nutrient injection via upwelling occur due to physical processes, biological responses will be readily apparent. In previous studies, advection from areas of higher chlorophyll concentration to lower chlorophyll concentration have been perceived qualitatively in images, allowing the presence of advection to be inferred based on satellite imagery (Chu and Kuo 2010; Leterme and Pingree 2008).

**Satellite Sensors**

Multiple satellite platforms identified the different parameters (i.e., CLa, SLa) for this study. SeaWiFS and MODISA identified ocean color (chlorophyll-$a$), while a number of along-track satellites (see below) identified sea surface height from which SLa was calculated.
SeaWiFS was launched in August 1997 aboard the SeaStar spacecraft (Barnes et al. 1999; SeaWiFS Project 2013). It is a multi-spectral radiometer. SeaWiFS was in a sun-synchronous orbit with an orbital period every 99 minutes. SeaWiFS had a swath width of 2801 km LAC (Local Area Coverage) and 1502 km GAC (Global Area Coverage) (SeaWiFS Project 2013). Its spatial resolution was 1.1 km LAC and 4.5 km GAC (SeaWiFS Project 2013). Ocean color data are identified using eight different bandwidths centered on 412, 443, 490, 510, 555, 670, 765, and 865 nm. Spatial resolution is available at 1.1 km at nadir, with 9 km used for this study. The scanner has a tilt mechanism to avoid sun glint off of the ocean surface, while maintaining an along-track direction (Franz et al. 2005; SeaWiFS Project 2013).

MODIS was launched on board the Aqua satellite platforms in May 2002 with operations beginning in June 2002 (Franz et al. 2005; Savtchenko 2004). MODIS has 36 bandwidths for land, ocean color, and atmospheric measurements. Nine of these channels are used for ocean color: 412, 443, 488, 531, 551, 667, 678, 748, and 869 nm (Franz et al. 2005; MODIS Web 2013). Most bands (29) are 1 km resolution at nadir, with the other two being 250 and 500 m at nadir (MODIS Web 2013). MODISA, like SeaWiFS, has a sun-synchronous orbit and is a scanning radiometer (Franz et al. 2005). Unlike SeaWiFS, MODIS cannot tilt the optics to avoid sun glint (Franz et al. 2005; Savtchenko 2004). MODIS has a scan rate of 20.3 rpm, a cross track swatch of 2330 km by 10 km along track at nadir (MODIS Web 2013).

There is the thought that error could occur in using two different satellite platforms for a continuous data set. To see the implications of this, Franz et al. (2005) showcased that these two satellites do indeed provide a continuous ocean color time-
series, stating “ratio trends show that MODIS-Aqua and SeaWiFS global averaged deep-water [normalized water-leaving radiance] retrievals are in agreement to within 5% in the 400 – 600 nm range” (p. 8). Identical software and averaging methods were employed for Level-3 processing to generate spatial and temporal composites for both satellite platforms (Franz et al. 2005). The two satellites do still use different algorithms to derive ocean color. SeaWiFS uses OC4v4. OC4v4 uses maximum-bandwidth-ratio that incorporates 443, 490, and 510 nm (Ocean Color Web 2009). MODISA uses OC3M. OC3M also makes use of a maximum-bandwidth-ratio, but only incorporates 443 and 488 (Ocean Color Web 2009). As turbidity increases, the selected maximum-bandwidth migrates from shorter (blue) to longer (green) wavelengths (Ocean Color Web 2009). In the most turbid water, OC4v4 selects the wavelength of 510 nm, but OC3M remains at 488 nm (Ocean Color Web 2009). This results in a difference of the functional form, which could lead to a difference in estimated chlorophyll concentrations in turbid water (Ocean Color Web 2009). Both algorithms use the following formulas with differing coefficients:

\[ Rrs_1 = \text{blue wavelength (443, 490, or 510 nm)} \]  
\[ Rrs_2 = \text{green wavelength (547, 555, or 565 nm)} \]  
\[ X = \log_{10}(\frac{Rrs_1}{Rrs_2}) \]  
\[ chlor_a = 10^{a_0+a_1X+a_2X^2+a_3X^3+a_4X^4} \]

For SeaWiFS, \( a_0 = 0.3272, a_1 = -2.9940, a_2 = 2.7218, a_3 = -1.2259, \) and \( a_4 = -0.5683 \) are the coefficients in Equation 4. For MODISA, \( a_0 = 0.2424, a_1 = -2.7423, a_2 = 1.8017, a_3 = 0.0015, \) and \( a_4 = -1.2280 \) are the coefficients in Equation 4 (Ocean Color Web 2009).
Ocean color calculations require retrieving water-leaving radiance from the measured radiance at the top of the atmosphere (TOA) (Franz et al. 2005, Savtchenko 2004; SeaWiFS Project 2013). This requires not only the instrument to be well-calibrated, but algorithms to process the raw data (Franz et al. 2005). In accordance with the continuous ocean color time-series NASA designated the responsibility of consolidating ocean color processing, calibration, validation, and distribution to the Ocean Biology Processing Group (OBPG) (Franz et al. 2005). The OBPG took a common software approach to merge algorithms to use for both SeaWiFS and MODISA, applying a common atmospheric correction approach to both sensors (Franz et al. 2005, 2012). The OBPG maintains a repository of in situ oceanographic and atmospheric data known as SeaBASS (SeaWiFS Bio-optical Archive and Storage System) to support satellite data product validation, algorithm development, and climate-related inquiries (Werdell et al. 2003; http://seabass.gsfc.nasa.gov/wiki/article.cgi?article=System_Description). SeaBASS holds in situ data products such as apparent and inherent optical properties, phytoplankton pigment concentrations, water temperature, salinity, stimulated fluorescence, and aerosol optical thickness (Werdell et al. 2003). Within SeaBASS there is “a publicly available, global, high quality in situ bio-optical data set for use in ocean color algorithm development and satellite data product validation activities known as NOMAD” (NASA bio-Optical Marine Algorithm Dataset) (Werdell and Bailey 2005: pp.137; http://seabass.gsfc.nasa.gov/wiki/article.cgi?article=NOMAD). NOMAD data products include coincident observations of water-leaving radiances and chlorophyll-α concentrations to aid the OBPG in validation of satellite data (Werdell and Bailey, 2005).
Sea Surface Height (SSH) is a vertically integrated property based on density distributions (Landerer et al., 2006). SSH is measured with radar altimeters. The altimeter transmits short pulses of microwave radiation toward the surface of the ocean and then receives the reflected signal (Martin 2008). Microwave radiation can view the surface through cloud cover and is only obscured by heavy rain (Martin 2008). This return signal yields sea surface height after the signal has been corrected for atmospheric interference and instrument noise (Martin 2008). Altimeters measure the distance between the sea surface and the satellite altimeter (the instrument) in reference to the geoid. The geoid is the hypothetical shape of the earth, coinciding with mean sea level and its imagined extension under (or over) land areas. Sea surface height is described by the reference ellipsoid ($E_R$), which is “the shape of the time-independent uniform distribution of the Earth’s mass generated by gravitational and centrifugal forces” (Martin 2008: p. 300).

Due to the uneven distribution of the Earth’s mass, the equipotential sea surface must be defined relative to the ellipsoid (Martin 2008). This is referred to as the geoid undulation ($N$), with the geoid being a sum of $N$ and $E_R$ (Marin 2008). Thus, sea surface height is relative to the geoid and is defined as

$$\zeta(\chi, \psi, t) = h_s(\chi, \psi, t) - N(\chi, \psi) - E_R(\chi, \psi)$$

[Equation 5]

where $\chi$ is latitude, $\psi$ is longitude, $t$ is time, and $h_s$ is the height of the sea surface above the Earth’s center of mass (Martin 2008).

The AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data; http://www.aviso.oceanobs.com/duacs/) website provided access to a merged SLa product. AVISO reprocesses the altimetric data regularly in order to take new algorithms, corrections, parameters, and other factors into account.
AVISO uses altimetry data from ERS (European Remote-Sensing) 1/2, Topex/Poseidon, GFO (GeoSat Follow On), Jason 1/2, and EnviSat (Environmental Satellite). Level 4 data, which is utilized in this study, are cross-calibrated data. SLa was determined relative to a 7-year mean of SSH data collected from different altimeters. SLa data are available in 7-day increments starting in October 1992 through the present. Global merged SLa, based on several satellite platforms (see below), was used with the GMx region extracted from the data set. The spatial resolution is 1/3° x 1/3°.

ERS 1 and 2 were launched in 1991 and 1995 respectively. Their missions ended in 2000 and 2001, respectively (European Space Agency 2014; https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/satellite). They were both launched into a near-polar orbit at a mean altitude of 780 km with instrument payload comprising active and passive microwave sensors and thermal infra-red radiometer (European Space Agency 2014). Both had a period of 100 minutes with 14.3 orbits per day (European Space Agency 2014). Both ERS 1 and 2 had an absolute rate error of less than 0.0015 degree seconds with maximum errors of bias of 0.11 degree (pitch/roll) and 0.21 degree (yaw) (European Space Agency 2014). The radial orbital restitution is 5 m (European Space Agency 2014).

Topex/Poseidon launched in 1992 as a joint venture between CNES and NASA (www.aviso.altimetry.fr/en/missions/past-missions/topexposeidon/orbits.html). The mission ended in January 2006. It had an accuracy of 4.2 cm. It had global data coverage ranging from 66°N to 66°S. Topex/Poseidon has a reference altitude of 1336 km, circular,
with a 66˚ inclination. It has a 10-day repeat ground track and a ground scanning velocity of 5.8 km/s.

GFO or GeoSat Follow-On launched in 1998 to an altitude of 880 km. GFO followed the 17-day repetitive orbit of GeoSat (Radar Altimetry Tutorial 2011; http://www.altimetry.info/html/missions/gfo). GFO has an exact repeat mission orbit, which was a near-polar circular orbit. It has a 108˚ inclination, 0.001 eccentricity, and a 100 minute period.

Jason 1 and Jason 2 were also utilized for their altimeter data (www.aviso.altimetry.fr/en/missions/past-missions/jason-1.html). Jason 1 was in operation from 2001 – 2013. It has a 66˚ inclination, a 10-day repeat orbit, and was a joint venture between CNES and NASA. Jason 1 flew in formation with Topex/Poseidon, though Jason 1 trailed by 500 km. Jason 2 was launched in 2008. Jason 2 also follows Jason 1, but the two tracks differ by five days.

EnviSat (Environmental Satellite) launched into a sun-synchronous, near-circular orbit in 2002 (www.aviso.altimetry.fr/en/missions/past-missions/envisat.html). It has an inclination of 98.55˚ and an orbit period of 100.6 minutes, with an exact repeat cycle of 35 days. EnviSat follows the same ground track as that of ERS-2.

Previous Findings

Correlations between SLa and Chl/CLa have been studied numerous times throughout the world’s oceans. Wilson and Adamec (2001, 2002) studied the correlation of SLa and surface chlorophyll globally, including during the El Niño Southern Oscillation event of 1997-99. Chu and Kuo (2010) and Kahru et al. (2007) correlated SLa and chlorophyll-\(a\) in the western and eastern Pacific Ocean respectively. Leterme and
Pingree (2008) analyzed the spatial and seasonal structure of chlorophyll-$a$ and the eddy field along the North Atlantic’s spring bloom boundary. The impact of mesoscale eddies on new production in the Sargasso Sea was examined by McGillicuddy and Robinson (1997), McGillicuddy et al. (1998), and Siegel et al. (1999). Biggs and Müller-Karger (1994) and Salas-de-León et al. (2004) studied anticyclonic-cyclonic eddy pairs and their interaction on chlorophyll stocks along the western and southwestern coastlines in the GMx respectively.

However, basin-wide studies of SLa/CLa correlations are lacking for the GMx. Toner et al. (2003) used remote sensing to look at how cyclonic eddies affect chlorophyll dispersal in the GMx, coming closer to the basin-wide correlation aim of this current study. Toner et al.’s (2003) effort focused primarily on coastal waters to see specifically the role that cyclonic, cold-core eddies play in the advection of chlorophyll-rich waters from the shelf into the open GMx. Though using different parameters, Jolliff et al. (2008) conducted a GMx basin-wide correlation of upper ocean thermal energy and bio-optical properties of colored detrital matter and surface chlorophyll-$a$ concentration. Most SLa/CLa correlation studies, however, that have been performed in the GMx tend to be within coastal waters and focused on small areas. Some of these studies with more constrained research sites, like that of Biggs and Müller-Karger (1994), utilized ship-board measurements to augment the satellite data.

A good example of a previous SLa and CLa correlation study was by Leterme and Pingree (2008). The study was conducted in the North Atlantic during the spring bloom to explore biophysical effects. There was a significant overall inverse relationship between satellite derived chlorophyll anomalies and sea level anomalies. They concluded
that “main open ocean eddy influence is one of advection or a redistribution of the [chlorophyll-\(a\)] field by eddies” (Leterme and Pingree 2008: p. 180). While these results are expected in this open GMx study as well, it is assumed that bathymetry will exert greater influence. As discussed above, bathymetry does influence how eddies maneuver in the GMx, as well as where cross-shelf advection is most likely to occur. Instead of advection having the greatest effect on the boundary of the spring bloom, as is seen in Leterme and Pingree’s (2008) study in the North Atlantic, the continental shelf in the Gulf of Mexico will dictate this. The present analysis will also feature much smaller concentrations of chlorophyll and thus less prominent chlorophyll anomalies than the earlier study of Leterme and Pingree (2008) (~0.5 mg/m\(^3\) in the GMx compared to 1.5 mg/m\(^3\) in the North Atlantic).

Advantages versus Disadvantages of Remotely Sensed Data

Remotely sensed chlorophyll can only be seen down to the first optical depth.

\[
g(z) = \exp(-2Kz) \quad \text{[Equation 6]}
\]

is the equation for the factor \(g(z)\) by which chlorophyll is weighted to estimate the remotely sensed concentration, where \(K\) is the diffuse attenuation coefficient and \(z\) is depth (Robinson 2010). The equation to calculate remotely sensed chlorophyll concentration is

\[
c_{\text{sat}} = \frac{\int_0^{z_0} c(z)g(z)dz}{\int_0^{z_0} g(z)dz} \quad \text{[Equation 7]}
\]

where \(c(z)\) is the concentration of chlorophyll as a function of depth (Robinson 2010).

One of the short-comings of using remote sensing exclusively in this study is the existence of deep chlorophyll maxima (DCM), which are below the first optical depth. These DCM are responsive to, and can showcase, the effects of mesoscale physical
features without satellites noting the effect. An advantage of *in situ* measurements is that DCM distribution, phytoplankton speciation, nutrient concentration, and the thermocline depth can be determined. All of these characteristics could then be considered to assess whether eddy pumping was affecting primary production in the area. The downside to *in situ* sampling is that these measurements would take a significant amount of resources along with the disadvantage of being spatially constrained. Thus, for large scale basin wide studies such as this one, surface chlorophyll and sea surface heights will need to be interpreted and utilized.

Argo is an international project to collect temperature, salinity, and current data over the world’s oceans down to 2000 m. ([http://www.argo.ucsd.edu](http://www.argo.ucsd.edu)). Beginning in 2000 with the final floats deployed in 2007, there are over 3000 floats dispersed throughout the world’s oceans. These floats provide current information as well as temperature and salinity. The Argo project coincides with the Jason satellite altimeter mission, enhancing the altimeter through subsurface measurements over a large area. The data is free and available from two global data centers.

Unfortunately, Argos float trajectories do not commonly encompass the GMx. However, Ocean Surface Currents Analyses – Real time (OSCAR) is available from NASA’s PO.DAAC site ([http://podaac.jpl.nasa.gov](http://podaac.jpl.nasa.gov)) on either 1° or 1/3° degree grid spacing in 5-day increments. This data set is available from 1992 through the present. OSCAR calculates surface current velocities based on 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 ageostrophic component and a thermal wind adjustment.
Johnson et al. (2007) found that for locations above 10˚N there is a respectable correlation between OSCAR satellite-derived sea surface currents with ground truth data from *in situ* observations. Thus, current data from OSCAR can be used in place of Argos floats to reveal surface advection pathways occurring in the GMx much like Leterme and Pingree (2008) did in the North Atlantic with Argo.
CHAPTER III

METHODS

Data Acquisition and Processing

Chlorophyll

Chlorophyll-a data were collected as 8-day composites from SeaWiFS and MODISA satellite data repository of the Goddard DAAC (Distributed Active Archive Center) that is accessible via the Ocean Color Web (http://oceancolor.gsfc.nasa.gov/). The resolution is 0.09° x 0.09° (9 km). The time period for the data set used here matches that used for SLa, January 1998 – December 2011. SeaWiFS was collected from January 1998 – December 2002; MODISA was then used from January 2003 – December 2011. Through a consistent application of calibration and processing methodologies by the Ocean Biology Processing Group, a continuous ocean color time-series is available through SeaWiFS and MODISA, ensuring that data from both instruments can be used in a single study (Franz et al. 2005). Between the two instruments the normalized water-leaving radiance products are in agreement to 5% globally (Franz et al. 2005).

The Chl data was retrieved via the wget command in UNIX terminal window. Perl scripts invoking IDL routines distributed with SeaDAS were used to extract the data from the HDF files retrieved from the Goddard DAAC. To enable better data and statistical analyses, the Chl data was regridded to a courser grid matching that of the SLa data. MATLAB routines were used to generate this courser gridded chlorophyll-a data, which was established to match the SLa-employed Mercator grid.

Once this re-gridding was accomplished, 8-day chlorophyll climatology and anomaly data sets were generated based on the observational period. Climatology was
created by determining the 14-year mean at each time step for each location. The calculation would be:

$$Climatology_{(\chi, \psi,t)} = \frac{\sum_{t_{1998}}^{t_{2011}} Chl_{(\chi, \psi,t)}}{14}$$  \[Equation 8\]

where $\chi$ is latitude, $\psi$ is longitude, and $t$ is time. Thus, for each 8-day composite (e.g., January 1 – 8) at every coordinate in the data set there would be a set of 14 different chlorophyll concentrations (e.g., one for each January 1 – 8 for 1998 – 2011) that would be averaged to get the chlorophyll climatology (Figure 3).

Once the 8-day climatological data set was obtained, any missing (flagged) data values within the 14-year time-series were replaced with the coincident climatological value in order to produce a gap-free chlorophyll-$a$ data set. Five percent of the entire data set was changed from flagged data (NaN values) to the climatological mean. This was done to allow for application of statistical analyses that require a continuous time-series.

Higher surface chlorophyll is generally present in the open GMx during winter (> 0.1 mg/m3), defined by late November through March, and lower concentrations dominate in summer (April - November, Biggs and Müller-Karger 1994). During summer months, the GMx tends to become uniformly deplete of surface chlorophyll (Appendix A A1b, A2b, A3b, A4b, A5b), as well as uniformly warm in temperature; thus, eddy-related features are difficult to discern in SST distributions (Salmerón-García et al. 2011). This does not affect SLa calculations, which is part of the reasoning in choosing this parameter. By design, seasonal variability is removed from the chlorophyll and sea level observations, ensuring that anomalous biological (CLa) and physical (SLa) characteristics of the open GMx can be studied and correlated over any desired time frame within the 14-year coincident observational period. The CLa data set was calculated by
\[ CLa_{(\chi, \psi, t)} = Chl_{(\chi, \psi, t)} - \text{Climatology}_{(\chi, \psi, t)} \]  

[Equation 9]

where \( \chi \) is latitude, \( \psi \) is longitude, and \( t \) is time (Figure 3). Creating an anomaly field after replacing flagged values with the coincident climatological mean would create zero values where the previous flagged values occurred.

**Figure 3.** “Schematic for creating a climatology and anomalies based on weekly composites. Starting with 52 weekly composite images spanning \( T \) years, extract the \( n \)th weekly composite from each of \( T \) years and average them to produce the climatology for week \( n \). Repeat for each of the 52 weeks to produce 52 weekly climatology images. To produce the anomaly image for Week \( n \), Year \( N \), subtract the \( T \)-year climatology for Week \( n \), from the image for Week \( n \), Year \( N \).” (Robinson 2010: p. 199).
Sea Level Anomaly

SL$a$ 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 as weekly (7-day) composites. This study utilized data for the time period January 1998 – December 2011, to coincide with CL$a$ analyses. Sea Surface Height (SSH) was measured along-track using the ERS 1/2, Topex/Poseidon, GFO, Jason 1/2, and EnviSat satellites. SL$a$ was then calculated from a 7-year mean by Ssalto/Duacs and AVISO (1/3° x 1/3° resolution). The GM$x$ region was extracted from the globally merged data set. The data were obtained from the AVISO site using OPeNDAP (Open-source Project for a Network Data Access Protocol; http://www.opendap.org) calls within in-house generated MATLAB programs.

The SL$a$ data set did not need to be processed in-house like the Chl data. For the purposes of statistical analysis, missing values were treated as those in the Chl/CL$a$ data sets. For both CL$a$ and SL$a$, as stated above, the missing values were set to zero with the reasoning that filled values for the regular data sets (not anomalous data sets) would be climatological values. Using this logic, zero values replaced NaN (Not-a-number) values in the SL$a$ data set to create a completely continuous time-series of SL$a$ needed for statistical analysis purposes. These new continuous data sets, both CL$a$ and SL$a$, were used only for statistical purposes and not applied in the 2-D graphics described below, which did not necessitate a completely continuous data set.

Due to the mismatched time-frames of the two data sets (7-day SL$a$, 8-day CL$a$/Chl) overlap did occur. Two SL$a$ sets overlapped with some 8-day CL$a$/Chl time-frames. For the purpose of a continuous, non-duplicated data set, the first of the two SL$a$ data were utilized in quantitative and qualitative analysis. For example, in 2003 for the 8-
day CLa period of April 23 – 30 there would be two available SLa data for April 23 and April 30. In this case the SLa data for April 23 would be used. This was implemented over the entire 14-year time-series.

Generation of 2-D Graphics

Image processing was conducted using scripts that employed gridding and graphics routines included in Generic Mapping Tools (GMT). Chlorophyll-a (9km), Chl climatology (Regridded 1/3˚), SLa, and CLa (9 km and regridded 1/3˚) data were used to generate 2-D graphics that revealed spatial distributions of these parameters. In addition, SLa contours superimposed on spatial distributions, which provided qualitative insight into correlations between these fields.

Hovmöller diagrams of CLa and SLa were also created in GMT. Hovmöller diagrams reveal how a specific latitudinal or longitudinal section changes with time. In the context of GMx dynamics, this allows for discerning the lateral propagation of mesoscale features. For example, the signature of a westward propagating eddy in SLa would manifest as a diagonal line in the SLa Hovmöller diagram. If the corresponding CLa diagram has a similar signature, this suggests a correlation between the two parameters that represents a distinct chlorophyll anomaly propagating in conjunction with an eddy’s trajectory. The latitudes 24˚N, 27˚N and longitudes 94˚W, 90˚W, and 86˚W were chosen for Hovmöller diagrams (Figure 2), as together these create an adequate grid of the entire GMx basin that encompass distinct regimes. The major portion of all these cross-sections is composed of open, deep water in the GMx, which is the focal point of this study. Further distinction between these sections relates to the degree they are impacted by the Loop Current associations (LC, LCEs, and cyclonic eddies). Statistical
correlation analyses were also completed on these same latitudes and longitudes, testing the first hypothesis. Using these longer (14-year) time-series provides the means to assess Hypothesis 3 by providing an analysis of specific pixels for the entire time-series. Thus, a Hovmöller diagram can be used to visually identify anomalies within a specific region/area.

Individual months and years were analyzed based on the analysis of the Hovmöller diagrams. This provided a more in-depth examination of both quantitative statistical and qualitative correlation, and afforded the 2-D spatial perspective that Hovmöller plots lack. Monthly, seasonal, and annual analyses based upon data collected over a longer time-series, provide a way to measure local biological variation due to physical forcing, which in turn provides the framework to statistically test Hypothesis 2.

Statistical Analysis

The Spearman’s Rank Correlation and Kendall’s Rank Correlation are significance tests useful for testing associations among bivariate populations that are not normally distributed (Zar 1974). A Spearman’s Rank Correlation suits the data used for this study better than the Kendall’s Rank Correlation, as the former can accommodate larger data sets that the latter cannot (Zar 1974). However, due to the enormity of the data set (> 1,000,000 values for each parameter) the p-value will always yield significant results due to its small value (< 0.000001). It is still useful to determine the p-value, as not every test done for this study will be over the entire data set. Some statistical sets will be over a few weeks, taking a sub-set of the overall data set, which will mean the data set will be small enough to have the p-value be of use to determine significance. Previous studies correlating SLa and Chl, or Chl and Sea Surface Temperature (SST), have also
employed the Spearman’s Rank Correlation (cf., Leterme and Pingree 2008). This is propitious as Leterme and Pingree (2008) provide a precedent of significant $R$-values, which can then be compared with those produced here. Those analyses with too many data points to allow the $p$-value to be useful could use the $R$-values of past studies as a check point of significance. The correlation $R$- and $p$-values were calculated in MATLAB R2013a using the statistics toolbox over different spatial and temporal ranges in the GMx, with the latter ranging from seasonal to the complete 14-year period.

Another significance test used for correlation of SLa and regridded CLa is the Ives and Gibbons correlation (Zar 1974). The Ives and Gibbons correlation test is for dichotomous nominal data. Dichotomous nominal data are those data which have two possible outcomes, such as positive or negative, yes or no. By changing negative values in each parameter’s data set to a -1 and each positive value to +1, the magnitude of each is eliminated and identification of inverse relationships between SLa and CLa can be emphasized. In this case, zero values are placed with the negative values, given a -1 value. This is an arbitrary decision, as zero CLa and SLa values are not indicative of change due to any type of mesoscale physical feature. It could be noted that zero values are not a huge part of the data set (5%). These zero values could even be discarded from the data sets for this particular statistical test, though a continuous data set gives more value to the correlation coefficient calculated from the Ives and Gibbons test. After -1 and +1 values are attributed to each value for both parameters, the correlation coefficient can be calculated by

$$r_n = \frac{a-b}{a+b}$$

[Equation 10]
where $a$ is the number of cases in which either both variables have the value of +1 or both have the value of -1 (both factors present or both absent), and $b$ is the number of cases in which the values of the two variables disagree (Ives and Gibbons 1967; Zar 1974).

In addition to statistical tests, the mean, variance, and standard deviation were calculated for the regridded chlorophyll-$a$ data set. Mean and variance were calculated at each grid point for each month of every year of the time-series and for every month over the entire time-series (i.e., there would be 15 separate mean values for each grid point for a single month: 14 for each individual year and one for the 14-year mean for that month). These values were calculated in MATLAB with the statistics toolbox. GMT was used to plot these mean and variance values (a total of 15 images for each month) across the GMx. The overall monthly mean can be compared to the individual monthly means and variances to perceive biological variability in the open GMx.

MATLAB was used to identify the spatial bounds set by different choices for threshold isobaths to confine the data set for statistical testing, based on bathymetry of the GMx. The MATLAB function dsearchn allowed the set to remain intact, while shallower grid points could be omitted for analysis. The 200m, 300m, 1000m, and 2000m were all tested to determine if SLa and CLa would correlate better in the open GMx with coastal waters phased out. For statistical testing the 200m isobath was chosen to mask out data from coastal waters.
CHAPTER IV

RESULTS

Correlation between SLa and Chl/CLa can be seen both in long-term (years) and short-term (seasonal or monthly) in the GMx. Hovmöller diagrams showcase the evolution and changes in SLa and Chl/CLa due to a mesoscale event such as a LCE over a single line of latitude or longitude. Separate Hovmöller diagrams of four year and one year increments for 5 different latitudes and longitudes (see Figure 4 for Latitude/Longitude lines) were created for the variables of Chl, CLa and SLa. For figures of anomalies, the colorbar is designed to be balanced so that colors switch abruptly at zero, making the transition between positive and negative anomalies clear. Black colors represent data that is off the scale for both positive and negative values. Short-term results are best determined from analyzing individual images of SLa contours superimposed on color images of CLa. These images are useful in qualitatively evaluating the relationship between SLa and CLa. These Hovmöller diagrams show the seasonal cycle of chlorophyll with greater concentrations present in the winter (Appendix A A1b, A2b, A3b, A4b, A5b). The anomaly fields show how chlorophyll and sea level evolve in space and time, but with “the underlying geographical distribution and [their] typical seasonal variations removed” (Robinson 2010: p. 199).

Bio-physical Coupling along 24˚N

Figure 5 shows SLa along 24˚N for 1998 – 2002. From 87˚W to 84˚W there are strong signals of both positive and negative SLa, which reverse back and forth. These SLa reversals are the signatures of the loop current and those frontal eddies that are most
associated with it (e.g., LCEs, LC frontal cyclonic eddies). The coordinates for this LC signal (87°W to 84°W) are typical for the LC at 24°N (Leben 2005; Vukovich 2007).

In 1998 there is a positive SLa signal beginning at approximately 87°W in the beginning of April (1998.25). This feature (Figure 5, feature 1) travels westward reaching 94.5°W at 1998.5. This positive SLa feature, which travels westward and remains stationary next to the continental shelf upon reaching the western boundary is a LCE. This can be seen in Figure 6, with the LCE labeled H. In July, LCE H merges with another positive SLa feature, spreading across the western GMx (Figure 6c). This is identified in Figure 5 as the positive SLa stretching from 93°W to 98°W. In the Hovmöller (Figure 5), this large positive SLa feature remains in the same position for the rest of the year. In the individual images (Figure 5; some not shown) LCE H comes into contact with the western continental shelf and remains until the end of 1998 (Figure 6f).

The biological aspect of this feature, LCE H, can also be discerned in the Hovmöller of CLa for the same latitude and time period (Figure 7, feature 2) with mostly negative CLa detected for the spatial constraints of the LCE. This negative CLa within the boundaries of LCE H are also observed in Figure 6 with the exception of Figure 6a.

Another interesting feature occurs in 1998 between 85°W and 87°W. In Figure 5 there is a very large negative anomaly (feature 3) as seen by the black color within the center indicating SLa that is off the scale (< -50 cm). This feature can also be seen in the individual images of Figure 6, as the large ellipsoid feature with dashed contour lines (i.e., negative SLA) where the LC would normally be present with positive SLa signature in the center of the GMx (84.5°W to 87°W). Figure 7 has a similar feature but of positive CLa (feature 4), and this positive CLa is present in Figure 6 within the boundaries of the
negative SLa feature. It is interesting to note that this anomalous biophysical variability coincides with the prominent 1997/98 ENSO that exerted global climatic influence.

Potential connectivity of this event in the GMx will be explored further in the discussion.

Figure 4. Latitudes and longitudes that are featured Hovmöller diagrams of the GMx basin.
Figure 5. Hovmöller plot of SLa along 24°N for 1998 – 2002. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar. (1) Encloses LCE H’s westward movement across the GMx basin. (3) An ellipsoid of negative SLa with high magnitude.
Figure 6. Individual images of SLa (negative = dashed, positive = solid) superimposed on CLa (colored image) for LCE H in 1998. (a) March 30-April 6 (b) May 25-June 1 (c) July 12-19 (d) August 5-12 (e) November 9-16 (f) December 19-26, 1998.
Figure 7. Hovmöller plot of CLa along 24°N for 1998 – 2002. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar. (2) Encloses LCE H’s westward movement across the GMx basin. (4) An ellipsoid of positive CLa with high magnitude.
For the entire GMx basin along 24˚N for the year of 1998, the Spearman’s Correlation Coefficient is -0.36 \((p<0.00001)\), which is a significant inverse relationship between SLa and CLa. The Ives-Gibbons’ correlation coefficient is -0.24 for 1998 along 24˚N, again establishing a significant inverse relationship. For 1998, from 87˚W to 98.333˚W, where the LCE H passes through, the Spearman’s Correlation Coefficient -0.30 \((p<0.00001)\) and the Ives-Gibbons’ correlation coefficient is -0.23. The negative SLa/positive CLa feature seen in the Hovmöller and individual images (Figures 5 – 7) has a Spearman’s Correlation Coefficient of -0.29 \((p<0.00001)\) and Ives-Gibbons’ correlation coefficient of -0.22 along 24˚N. For the extent of Figures 3 and 4, the Spearman’s Correlation Coefficient \((1998.0 – 2002.0, 24˚N)\) is -0.22 \((p<0.00001)\).

In early August of 2006, an ellipsoid of negative SLa is located in the eastern GMx \((\sim 87˚W, 25˚N;\) Figure 6). As weeks progress, this feature gets larger in magnitude and area. The CLa encompassed within the boundaries of this negative SLa (Eddy I) is positive and also grows in magnitude as weeks progress (Figure 8). Once formed, Eddy I migrated southwestward towards the Yucatan Peninsula. The week of August 29 – September 5, 2006 (Figure 8b), Eddy I was stretched above the Yucatan Channel as it migrated westward. This same week, another negative SLa feature (Eddy J) appears in the north-central GMx \((87˚W, 26.5˚N;\) Figure 8b). Eddy I progresses westward until it is located above the eastward portion of the Yucatan Peninsula \((88˚W)\), then travels northward. Simultaneously, Eddy J migrates southward along the same line of longitude. During this time period of northward and southward progression of Eddies I and J, the LC is located on the east side of these cyclonic eddies, while an anticyclonic eddy (Eddy K) lies to the west of the two cyclonic eddies. Eddy K is a LCE that previously broke off
of the LC in August 2006 (seen 2006.65, 87.5˚W; Figure 9, labeled 5). LCE K is seen in the Hovmöller for 2006 along 24˚W. The LC can be distinguished at 2006.5, 87˚W (Figure 9, feature 5). This positive SLa feature (LCE K) is seen traveling westward throughout Figure 9 (feature 5).

Figure 8. Progression of Eddy I, Eddy J, and LCE K throughout the last half of 2006. The contour lines are SLa, dashed lines are negative SLa, and solid lines are positive SLa. Colors denote CLa with blues equating negative CLa and yellow/reds denoting negative CLa. Individual figures are: (a) August 13-20 (b) August 29-September5 (c) September 14-21 (d) November 1-8, 2003.
Figure 9. Hovmöller plot of SLa along 24°N for 2006.5 – 2007.5. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar. (5) Encloses LCE K’s westward movement across the GMx basin. (7) Cyclonic Eddy Q’s progression in the GMx basin.
Figure 10. Hovmöller plot of CLa along 24°N for 2006.5 – 2007.5. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar. (6) Encloses LCE K’s westward movement across the GMx basin. (8) Encloses Cyclonic Eddy Q’s progression within the GMx.
Seen in the individual images LCE K, this anticyclonic eddy follows bathymetry around 24°N maintaining position in the central GMx before traveling westward and colliding with the continental shelf around 2007.25 and remains there until July 20, 2007 (Figure 9, feature 5). Once it hits the slope, the LCE moves south then distorts from a circular feature into an ellipsoid. The week of July 4 – 11, 2007 is the last week with any sign of LCE K (images not shown).

Eddy I (situated off the Yucatan Peninsula) and Eddy J (moving southward from the central Gulf) merge into one large cyclonic eddy, Eddy Q, in the center of the GMx on September 14 – 21 (Figure 8c), both still containing a positive CLa signature within their boundaries. This is seen in the CLa Hovmöller at the 2006.7 (Figure 10, feature 8), though negative SLa can be seen at 2006.5 as Eddy I traveled westward towards the Yucatan and then more northward at 85°W (Figure 8; Figure 9, feature 7). Once formed, Eddy Q develops larger SLa in magnitude and spatially, still flanked on either side by Eddy K and the LC. Slowly Eddy Q migrates north, then westward before dissipating in April of 2007(images not shown). Eddy Q can be seen with slight negative SLa/positive CLa in the Hovmöller of 24°N (Figure 9 – 10, labeled 7 and 8 respectively), though it can also been seen in the Hovmöller of 27°N around 2006.5 – 2007.0 (Appendix A A2a, A2c).

For this time period (2006.5 – 2007.0) the Spearman’s Correlation Coefficient for the entire GMx is -0.34 and the Ives-Gibbons’ correlation coefficient is -0.41. Along 24°N for 2006.5 – 2007.5 the correlation coefficients are -0.19 (Spearman’s, p<0.00001) and -0.28 (Ives-Gibbons). Correlation statistics for 24°N Hovmöller diagrams covering 2002 – 2006 (Spearman, r = -0.26), 2006 – 2009 (Spearman, r = -0.17), and 2009 – 2012...
(Spearman, \( r = -0.32 \)) along 24°N are as noted. For the entire time-series (1998 – 2011) at 24°N the Spearman’s Correlation Coefficient is -0.25 \((p<0.00001)\). The Ives-Gibbons’ correlation coefficient over this complete observation period is -0.20, which suggests a significant inverse relationship between SLa and CLa as \( r \neq 0 \).

**Bio-physical Coupling along 27°N**

Figure 11 shows the 4-year (2002 – 2006) Hovmöller of SLa at 27°N. The longitude boundaries at this latitude are 82.3333°W to 98.3333°W, which includes coastal waters along the Texas and Florida shelves. For 2002 – 2006, for the boundaries mentioned above, the Spearman’s Correlation Coefficient is -0.21 and the Ives-Gibbons’ correlation is -0.15. Throughout this 4-year period, mesoscale SLa features with high magnitudes of both signs occur in a band ranging from 87°W to 90°W (Figure 11), indicating the LC and those mesoscale physical features associated with it (LCEs and cyclonic frontal eddies). This LC signature at 27°N is further west than that seen at 24°N (Figure 5), corresponding with the westward extension of the LC. The prominent switching between positive and negative SLa signatures from 87°W to 92°W corresponds with the opposite CLa signature, particularly for the time period of 2002.75 to 2004.5 (Figs. 11 and 12).

Around 2005.25 (April 2005) there is a signature of high magnitude positive SLa, which is a part of the LC but then becomes a separated LCE (Figure 13a, b), that appears from 88.5°W to 93°W (Figure 11, feature 9). This positive feature travels westward and fades from Figure 11 around 2005.75 (around September). Examining individual images (Figure 13), the LCE (labeled W) can be seen pinching off from the LC, traveling
westward then migrating southward (not seen in Hovmöllers) around the first week of October 2005 at 93°W. Continuing to move southwestward, LCE W comes into contact

Figure 11. Hovmöller plot of SLa along 27°N for 2002–2006. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar. (9) Encloses LCE W’s progression in the GMx along 27°N.
Figure 12. Hovmöller plot of CLa along 27°N for 2002 – 2006. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar. (10) Encloses LCE W’s CLa signature along 27°N.
Figure 13. Progression of LCE W in 2005. (a) April 15-22 (b) June 18-25 (c) August 5-12 (d) September 30-October 7 (e) November 1-8 (f) November 25-December 2, 2005.
with the continental shelf where it becomes a more oblong shape around November 2005 (Figure 13f). The magnitude of LCE W diminishes, with a slight signature still visible the last week of 2005, though it is not until February 26 – March 5, 2006 that there is no trace of LCE W visible upon the grid. LCE W correlates with negative CLa in the respective Hovmöller (Figure 12, feature 10). Figure 13 also shows LCE W with negative CLa within its boundaries until it disperses in 2006. The Spearman’s Correlation Coefficient for this feature for 27˚N, 82.6667˚W to 90˚W during 2005 is -0.35 (p<0.00001) with the Ives-Gibbons’ correlation coefficient being -0.38 for this confined area, both coefficients indicating a significant inverse relation. The correlation coefficients are different between the two tests due to one encompassing magnitude, while the other (Ives-Gibbons’ test) is dichotomous, testing if there is a true inverse relationship. There could be some difference because of this, as well as zero values being arbitrarily chosen to be in the negative group for the dichotomous test. These correlation coefficients are considered significant as compared with previous study periods. Leterme and Pingree (2008) had a lower correlation coefficient with fewer data points, so that this larger coefficient coupled with more data points leads to a significant coefficient conclusion.

There are also correlated SLa and CLa features in the 2006 – 2009 (Spearman, r = -0.24 p<0.00001) and 2009 – 2012 (Spearman, r = -0.25 p<0.00001) Hovmöller Diagrams. Along 27˚N in the GMx basin (82˚W - 98.3333˚W), for the entire time period of 1998 - 2011, the Spearman’s Correlation Coefficient is -0.20 (p<0.00001), with the Ives-Gibbons’ correlation coefficient -0.14 (Appendix A A2a, A2c).
From 2007.00 to 2007.25 (end of April), there is a negative SLa feature that stretches across the entire basin at 27°N (Figure 14, feature 11). Prior to this, from 2006.75 at 87°W there is a negative SLa signature that migrated west, eventually merging with the expansive negative SLa at 2007.00 (Figure 14, feature 11). These features can be discerned in the CLa Hovmöller at the same time, though the CLa signature begins slightly west (at 88°W) of the negative SLa feature in 2006.75 (Figure 15, feature 12). Examining the individual imagery, the westward migrating negative SLa feature is a cyclonic frontal eddy. The extensive negative SLa in the beginning of 2007 is actually multiple eddies, which then become a large negative SLa front from 26°N to the coastline. As the year progresses this front breaks down into singular rings of negative SLa.

Before and after (2006.25 – 2007.0 and 2007.25 – 2008.0) this negative SLa feature (Figure 11, feature 11), there are a very high magnitude positive SLa features apparent from 87°W to 90°W (Figure 14, features 13 and 15). The positive SLa feature seen from around 2006.25 (feature 15) is a LCE that detaches, reattaches, and detaches again from the LC and travels westward, as seen in the Hovmöller (Figure 14, feature 13). This coincides with negative CLa in the respective Hovmöller (Figure 15, feature 14). This same sequence of a LCE detaching, reattaching, and detaching from the LC occurs again in 2007, and is seen by the positive SLa from 2007.25 – 2008 (Figure 14, feature 15). Again, this highly positive SLa feature coincides with negative CLa in Figure 14 (feature 16). The Chl Hovmöller also exhibits heightened chlorophyll signature during 2007.00 – 2007.25 and very low (close to 0.00 mg/m³) chlorophyll indicated by dark blue colors where the positive SLa features appear (Figure 16, feature 17, 18, and 19).
The Spearman’s Correlation Coefficient from 2007 – 2007.25 for SLa and CLa (feature 11, 12) is -0.35 (pval<0.00001) along 27°N; for the same time period and spatial domain, the Spearman’s Correlation Coefficient is -0.31 (pval<0.00001) for Chl and SLa. The Spearman’s Correlation Coefficient along 27°N, 87°W - 93°W for the large positive SLa feature from 2006.25 – 2007 is -0.57 for CLa/SLA (features 13, 14) and -0.70 for Chl/SLa (features 13, 18). The Ives-Gibbons’ correlation during this same time period and longitude constraints between CLa and SLa is -0.62. From 2007 – 2008 along 27°N, 87°W - 93°W, the Spearman’s Correlation Coefficient for CLa/SLa is -0.53 and for Chl/SLa is -0.65. The Ives-Gibbons’ correlation coefficient of CLa/SLa for this time period is -0.49. For the entire time period of these features (2006.25 – 2008.0), the Spearman’s Correlation Coefficient along 27°N for CLa/SLA is -0.29 and between Chl/SLa is -0.27.

From 2008.75 – 2009.25, there is a negative SLa feature around 92°W – 95°W (Figure 14, feature 21) that corresponds with a positive CLa (Figure 15, feature 22) feature (Spearman, r = -0.31, p<0.001; Ives-Gibbons, r = -0.27). The individual spatial distributions reveal this signature to relate to a small negative SLa ring with positive CLa both within and entrained around it, which forms at the end of September 2008 and remains in the same location until the end of February 2009 (individual images not shown).

A less noticeable feature than those discussed previously along 27°N occurs in 2001. A positive SLa feature from ~ 89°W – 92°W occurs in the first half (2001 – 2001.5) of 2001 (Appendix A A2c) with coincident negative CLa (Appendix A A2a). The Loop Current eddy associated with these signatures can be deciphered better in the
individual images. The week of March 22 – 29, 2001 (Figure 17b), a high magnitude (>50 cm) LCE separates from the LC. This LCE (LCE M) moves westward, turning southwest the week of May 25 – June 1 (Figure 17d), coming into contact with the western continental shelf mid-August (Figs. 17c-e), and finally dissolving the second week of 2002 (not shown). Throughout its life cycle LCE M encompasses negative CLa. In 2001 throughout the GMx there are numerous patches of positive CLa, though LCE M retains its coherent negative CLa signature (Figure 17).
Figure 14. Hovmöller plot of SLa along 27°N for 2006 – 2010. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar. (11) Encloses a cyclonic frontal eddy migrating west 27°N (13) Encloses a LCE which detaches, reattaches, and detaches again before migrating westward. (15) Encloses a LCE which detaches, reattaches, and detaches before migrating westward. (21) A negative SLa feature which remains in the western GMx for its lifetime.
Figure 15. Hovmöller plot of CLa along 27°N for 2006 – 2010. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar. (12) Encloses a cyclonic frontal eddy migrating west 27°N (14) Encloses a LCE which detaches, reattaches, and detaches again before migrating westward. (16) Encloses a LCE which detaches, reattaches, and detaches before migrating westward. (22) A positive CLa feature which remains in the western GMx for its lifetime.
Figure 16. Hovmöller plot of Chl along 27°N for 2006 – 2010. (17) Encloses a cyclonic frontal eddy migrating west 27°N (18) Encloses a LCE which detaches, reattaches, and detaches again before migrating westward. (19) Encloses a LCE which detaches, reattaches, and detaches before migrating westward. (23) A cyclonic feature which remains in the western GMx for its lifetime.
Figure 17. Progression of Eddy M throughout 2001. The contour lines are SLa, dashed lines are negative SLa, and solid lines are positive SLa. Colors denote CLa with blues equating negative CLa and yellows/reds denoting positive CLa. (a) March 6-13 (b) March 22-29 (c) April 7-14 (d) May 25-June 1 (e) August 13-20 (f) December 19-26, 2001.
Bio-physical Coupling along 86˚W

The full 14-year Hovmöller diagrams for the line of longitude 86˚W (cf. Figure 4) show part of the Caribbean Sea (18˚– 22˚N), pass through the Yucatan Channel, traverse the Loop Current (24˚ – 27˚N), and end at 30.3770˚N (Appendix A A3a, A3c). This is a dynamic region, as can be seen in the imagery that has been shown. For the entire time-series at 86˚W for the GMx region (above 22˚N), the Spearman’s Correlation Coefficient is -0.2027.

The most remarkable feature that manifests in both SLa and CLa is in 2009, with most prominent presence being in the latter half of the year from 22˚ – 26˚N (Figure 18 – 19). Here there is a pronounced negative, northward propagating SLa signature (Figure 18, feature 25), which corresponds over the same latitudes to a notable positive CLa signal (Figure 19, feature 26). Two cyclones merge in late August of 2009 in the central GMx, much like what was seen when Eddies I and J merged in 2006. The range of this cyclone is the same that is seen for negative SLa in Figure 14 and positive CLa in Figure 15. This cyclone remains in the central GMx until the end of 2009 when it begins to migrate west. Once this cyclonic ring migrates, the LC propagates further into the GMx. This, the LC, is positive SLa signature seen in Figure 18 and negative CLa in Figure 19.

In the first half of 2010 there is negative SLa across the GMx, as well as positive CLa and high Chl. This signature can also be seen along 24˚N, 27˚N, 90˚W, and 94˚W (Appendix A A1a-c, A2a-c, A4a-c, A5a-c). Examining the 8-day images of CLa with SLa contours superimposed for 2010, the majority of the GMx (with exception to the LC) is replete with positive CLa. Around January 25 there is a front of negative SLa across the northern half of the GMx (26˚N – 31˚N). This front extends as far down as 24˚N.
Figure 18. Hovmöller of SLa for 2009.5 – 2010.5 along 86°W. Blues correspond with negative SLa, reds with positive SLa, while black colors represent SLa that is off the scale. (25) Negative SLa that is of interest, showing cyclonic features that merge in the central GMx and migrate north.
Figure 19. Hovmöller of CLa for 2009.5 – 2010.5 along 86°W. Blues correspond with negative CLa, reds with positive CLa, while black colors represent CLa that is off the scale. (26) Positive CLa that is of interest, showing cyclonic features that merge in the central GMx and migrate north.
Like that seen in 1998, this is an anomalous phenomenon compared with the entire study period. There is a seasonal cycle associated with chlorophyll-$a$ as seen in the Chl Hovmöller diagrams in the Appendix (Appendix A A1b, A2b, A3b, A4b, A5b). As seen in previous studies, winter in the open GMx has higher surface chlorophyll (>0.2mg/m$^3$) than in the summer (~0.05 – 0.15 mg/m$^3$) (Biggs and Müller-Karger 1994; Biggs et al. 2008; Müller-Karger et al. 1991). The 2010 signal of high chlorophyll extends through the week of June 26 – July 3, 2010, which is into the defined summer months of April – November (Biggs and Müller-Karger 1994; Biggs et al. 2008; Müller-Karger et al. 1991). The high chlorophyll signature has a significant inverse relationship with Spearman’s Correlation Coefficient of -0.6682, p<0.00001 and the Ives-Gibbons’ correlation coefficient of -0.4286.

Bio-physical Coupling along 90˚W

In the GMx, 90˚W ranges between 21˚N and 30˚N (cf. Figure 4). The open water of the GMx can be defined within the boundaries ~23.5˚N – 28˚N. The northern and southern ends of 90˚W extend on to the Louisiana/Yucatan shelf. SLa can be seen for the entire boundary, not just open water (Figure 18); however, observable CLa signatures in the plots for this longitude are within the open water boundaries (Figure 19). The lack of data on the shelf waters is due to the coastal waters being of higher productivity, thus the data was masked in this study. Like the diagrams of 86˚W and 24˚N, the Loop Current does play a role in the SLa and CLa signals for 90˚W, though the LC generally manifests further to the east in the GMx basin. LCEs and cyclonic frontal eddies can be seen in positive and negative SLa signatures from 24˚N – 27˚N. Statistical analysis for this line of longitude will stay between ~23.5˚N – 28˚N to avoid coastal waters impacting the
correlation between SLa/CLa as more factors, such as riverine input and upwelling, affect coastal chlorophyll variability. There is a lower significance along this area of the Gulf with the Spearman’s Correlation Coefficient being -0.29 (p<0.00001).

In the latter half of 2009 there is a positive SLa signature across 90°W, with the sign switching to negative for the first half of 2010 (Figure 20). In the corresponding CLa plot (Figure 21), negative CLa dominates late 2009/early 2010 coincident with the positive SLa. Subsequently a period of pronounced positive CLa manifests over the first half of 2010. This CLa signature is associated with notable negative SLa. Spatial maps reveal a negative SLa front across the northern and central GMx associated with positive CLa. As the year progresses this front decreases and is compacted to the central GMx. Interestingly, a later negative SLa feature (2011 – 2011.5) is of similar magnitude and spatial extent but the associated positive CLa feature is much less pronounced. Spatial maps indicate a cyclonic ring in the central GMx, though the CLa associated with this ring fluctuates between positive and negative with neither signal dominating within the ring itself (data not shown). The basin wide features from late 2009/early 2010 have a significant inverse relationship with the r = -0.62 (Spearman, p<0.001) and r_n = -0.51 (Ives-Gibbons, p<0.001).
Figure 20. Hovmöller of SLA for 2008–2012 along 90°W. Blues correspond with negative SLA, reds with positive SLA, while black colors represent SLA that is off the scale.
Figure 21. Hovmöller of CLa for 2008 – 2012 along 90°W. Blues correspond with negative CLa, reds with positive CLa, while black colors represent CLa that is off the scale.
Bio-physical Coupling along 94°W

The last latitude section analyzed, 94°W is dominated by open water and sits in the middle of the largely oligotrophic western half of the GMx. This area also has more of a qualitative correlation than the previous section, seen in the images as a clearer representation between the two parameters’ Hovmöller. The constraints for statistical correlation will be from 18°N - 29°N to diminish the impact of coastal waters on the analysis. There is low significance for this cross-section over the 14-years of analysis (Spearman, $r = -0.16$, p<0.00001; Ives-Gibbons, $r_n = -0.15$).

A prominent feature with physical and biological expression appears over this line of longitude in 2006.75 from 24°N - 28°N (Figure 22 - 23). Negative SLa dominated here for what appears to be the entirety of 2007 in the northern half of open water region of the GMx at 94°W (Figure 22, feature 27). At this same location in Figure 23, there is a similarly shaped feature composed of high positive CLa (feature 28). These signatures comprise a positive SLa cyclonic eddy and SLa front that occurs over this area of the GMx.

In 2007 there is a front composed of negative SLa and positive CLa in the western GMx. Corresponding to the feature in the Hovmöller for 94°W discussed above, there is a cyclonic ring that forms and migrates to the western GMx in October 2006 coinciding with the negative SLa at 2006.75 in Figure 22. This cyclonic ring becomes a part of a negative SLa front that begins in the last two weeks of 2006. This front stretches from 92°W to 96°W and 22°N – 28°N. During January 2007 this ellipsoid-like front keeps it shape, though only the northern area of this front, with a -20 cm circular SLa feature (feature R), holds positive CLa (Figure 24a). SLa feature R hovers over the same spot
(26°N, 94°W) through April 23 – 30, 2007 (Figure 24d). Throughout this period, positive CLa has also been present in this area. A broader negative SLa front, including the circular negative SLa and a larger cyclonic eddy (Eddy P) in the central GMx, was present from February 2 – 9, 2007 to March 20 – April 6, 2007 (Figure 24b-d). This front is of negative SLa from 26°N to the coastal waters of the northern GMx. Positive CLa is present also within this front. March 20 – April 6, 2007, the cyclonic eddy (Eddy P) is in the central GMx, with the -20 cm feature still present at 26°N and 94°W. It is now larger, extending to 93°W – 96°W, appearing more eddy-like. Throughout the time period this feature (R) is present, with values persistently less than -20 cm, positive CLa is also present within it. The first week of May, feature R splits into two smaller circular negative SLa features, both of which are -20 cm and encompassed by a SLa front that again extends across the GMx from 96°W – 85°W. The late April distribution captures the initial stages of this separation event (Figure 24d). All throughout 2007 there is a circular feature of negative SLa with positive CLa along 94°W, ranging from 24°N – 26°N (Figure 24). This can be seen in the Hovmöller for 94°W (Figure 22 – 23, feature 27, 28) as well as that of 26°N (images not shown).

Along this cross-section for 94°W, from 24° – 28°N in 2007, there is a moderately significant correlation between SLa and CLa of -0.56 (Spearman, p<0.00001) and -0.34 (Ives-Gibbons). For 2007, over the entire open water portion of this cross-section, there is a lower, but still significant correlation of -0.31 (Spearman, p<0.00001).
Figure 22. Hovmöller of SLa for 2006 – 2010 along 94°W. Blues correspond with negative SLa, reds with positive SLa, while black colors represent SLa that is off the scale. (27) Encloses a negative SLa front and cyclonic ring occurring in 2007.
Figure 23. Hovmöller of CLa for 2006 – 2010 along 94°W. Blues correspond with negative CLa, reds with positive CLa, while black colors represent CLa that is off the scale. (28) Encloses a front of positive CLa and negative SLA cyclonic ring with positive CLa within its boundaries.
Figure 24. Progression of SLa/CLa fronts and eddies in 2007. The contour lines are SLa, dashed lines indicate negative SLa, and solid lines indicate positive SLa. Colors denote CLa, with blues equating negative CLa and yellows/reds denoting positive CLa. Individual images are: (a) January 1 – 8 (b) February 2 – 9 (c) March 30 – April 6 (d) April 23 – 30, 2007.
Coastal Water Entrainment

Though Hovmöller diagrams presented above provide a good picture for the GMx overall, there are some sections and phenomena that these plots do not include. Coastal water entrainment or lateral advection usually occurs on time scales shorter than those that would be clearly observed in Hovmöller diagrams, as coastal advection usually occurs on weekly scales. In the GMx there are areas that have a high likelihood to have lateral advection due to mesoscale physical features (such as eddies) that are not necessarily covered along the latitudes and longitudes used for Hovmöller plots discussed in the previous section. These areas include the Yucatan Peninsula and the west Texas shelf near 24°N – 26°N.

Between 86°W and 90°W lies the edge of the Yucatan Peninsula (Figure 2; Figure 4). The LC passes closely to the eastern coast; thus, a strong potential exists for potentially lateral advection of coastal waters, with elevation in chlorophyll and nutrient concentration, into the open GMx. In 2003 there is an extensive lateral advection event due to the LC passing near the coast. A cyclonic eddy forms here, possibly initiated as a recirculation zone, which subsequently propagates northward. From March 5 to June 26, 2003 there is a visible signature of positive CLa coming off the Yucatan Peninsula following the outer contour lines on the west side of the LC. In early May of 2003 a cyclonic ring forms just above the Yucatan Peninsula, becomes larger over the next few weeks, and then begins to migrate north in late June (Figure 25). Examining OSCAR plots (Figure 26), the high magnitude current passes closely to the edge of the coast. The LC is the most prominent feature in these OSCAR plots (Figure 26). Due to the magnitude (indicated by arrow size) and proximity to the coast of the LC, it is logical to
believe this spawned the positive CLa signature extending from the Peninsula to the open GMx. The proximity of the LC to the Yucatan Peninsula revealed in the OSCAR plots (Figure 26) coincides with the advection event apparent in the spatial distribution plots (Figure 25), with the clearest correlation between Figures 25a and 26a as well as Figures 25d and 26d.

Also in 2003 in the western GMx there is another case of coastal entrainment. During the first week of 2003 there is a small, negative SLa feature in the western GMx (Eddy B in Figure 27) between 94˚W – 96˚W and 26˚N – 28˚N. Given the characteristics of its ellipsoid shape, SLa sign, and current paths shown in OSCAR images (Figure 28), Eddy B is considered a cyclonic eddy here. As weeks progress Eddy B becomes larger in area and magnitude. For the week of March 14 – 21, 2003 (Figure 27d) the feature is over the western continental shelf; it primarily encompasses negative CLa but also holds a thin strip of positive CLa. This line of positive CLa comes from coastal waters, flowing along the -20 cm isopleth of Eddy B. Figure 28b shows surface currents distribution for 18 – 22 March, 2006, and the cyclonic ring/current pattern is close to the continental shelf. Thus, the strip of positive CLa seen in Figure 27b is likely due to the currents of Eddy B close to coastal waters. The next image of March 22 – 29, 2003 (Figure 27c) shows Eddy B in the same location, with the CLa strip still originating from coastal waters, along the isopleths of negative SLa into the eddy, with a larger amount and magnitude. The matching OSCAR plot (Figure 28c) shows a similar pattern for the surface currents as that in the SLa distribution (Figure 27c). This continues to occur until April 15 – 22 (Figure 27d), when the coastal waters are phased out and Eddy B holds positive CLa
within its eastern half and negative SLa within its western half. From this time until August 13 – 20, 2003 (images not shown), Eddy B contains positive CLa.

Figure 25. Images of advection due to LC influence on the Yucatan Peninsula in 2003. The contour lines are SLa (dashed = negative SLa, solid = positive SLa). Colors denote CLa (blues = negative CLa, yellows/reds = positive CLa). The line of yellow and red aligning with the edge of the LC extending into the open GMx is an example of lateral advection. (a) March 22 – 29 (b) May 9 – 16 (c) May 25 – June 1 (d) June 18 – 25, 2003.
Figure 26. OSCAR surface velocity images to show the proximity and magnitude of the LC near the Yucatan Peninsula where lateral advection occurs. (a) March 23 (b) May 12 (c) May 28 (d) June 22, 2003.
Figure 27. Progression of Eddy B and its advection of coastal water throughout 2003. The contour lines are SLa (dashed = negative SLa, solid = positive SLa). Colors denote CLa (blues = negative CLa, yellows/reds = positive CLa). Figures are: (a) January 1 – 8 (b) March 14 – 21 (c) March 22 – 29 (d) April 15 – 22, 2003.
Figure 28. OSCAR surface velocity images to show the proximity and magnitude of the Eddy B near the Mexican/Texas Shelf where lateral advection occurs. (a) January 1 (b) March 18 (c) March 23 (d) April 17, 2003.
In 2006 there are multiple mesoscale features, Eddy Q, LCE K, and the LC, in the central GMx, as discussed above (Figure 10). The cyclonic features of Eddy I, Eddy J, and the merged Eddy Q are in the central GMx and help influence coastal advection. Eddy I approached the Yucatan Peninsula coastline as it migrated southwestward before shifting northward. The week of September 14 – 21, merging of Eddy I and Eddy J began. In the image of CLa and SLa, a streak of positive CLa can be seen extending from the tip of the Yucatan Peninsula to Eddy I. Following the merging of Eddies I and J, this extension of positive CLa from the Yucatan to Eddy Q persists for several weeks, with some weeks’ signatures being larger than others. One of the largest coastal advection signatures comes from the week of November 1 – 8, 2006 (Figure 10d). Examining the OSCAR images, the LC can be seen to be close in proximity to the Yucatan Peninsula and large in magnitude (Figure 29b). This suggests that these two factors of the LC influence the coastal waters and advect the coastal waters into the open GMx. The OSCAR currents also show how the LC loops in the central GMx near Eddy Q. Thus, this advected material could pass into Eddy Q, as the two mesoscale features are in close proximity to one another. Eddy Q is also a large cyclonic eddy with its own positive CLa signature that becomes more pronounced once this advected material begins to be incorporated within Eddy Q’s borders.
Figure 29. OSCAR surface velocity images to show the proximity and magnitude of the LC near the Yucatan Peninsula where lateral advection occurs. (a) September 16 (b) November 6, 2006.
CHAPTER V

DISCUSSION

The first Hypothesis that negative SLa features will yield a positive CLa signature, while positive SLa features will yield a negative CLa signature, can be seen qualitatively in the individual images and Hovmöller diagrams (Figures 5 - 27). Some of the more resilient features are noticeable in both the SLa and CLa Hovmöller diagrams.

The Spearman’s Rank Correlation and Ives-Gibbons’ statistical tests conducted along single lines of latitude and longitude indicate significance between the two parameters, from low to strong. Low significance for correlation coefficients is usually described as having an r-value of 0.01 – 0.29, moderate with an r-value of 0.3 – 0.59, and strong correlation is described as an r-value of 0.6 – 1 (Johnson, Pers. Comm.). Along with using values deemed significant in previous studies, this range of values was used to determine significance for data sets with too many data points to allow the p-value of the Spearman’s Rank Correlation to show significance. The Spearman’s Rank Correlation Coefficient and Ives-Gibbons’ Correlation Coefficient of prominent features discussed here are collected in Appendix B, where they are ranked from low (+), moderate (++), or strong (+++). Comparison of these values to the Spearman’s Rank Correlation Coefficient of Leterme and Pingree (2008) are also included.

In 2001, LCE M is a large (~2° x 2°, >50 cm SLa) anticyclonic eddy that migrates from 26°N, 90°W to 24°N, 95°W in 36 weeks (March 22, 2001 – January 8, 2002). LCE M’s migration path follows the bathymetry of the GMx. As Welsh and Inoue (2000) previously reported, bathymetry in the GMx greatly influences movements of mesoscale eddies by the principle of conservation of potential vorticity (Knauss 1997). For depths
along and above the 200 meter isobaths over the entire 36 weeks, there is a moderate inverse Spearman’s Correlation Coefficient of -0.31. This quantitative correlation is for the area between 24°N – 26°N, 95°W – 90°W throughout the 36-week lifetime of LCE M. While this is the area with LCE M, this quantitative correlation is for an area that is larger than the size of the LCE. While there are some fronts and SLa features within this area over the 36-week period, the images (Figure 17 and those not shown) reveal that LCE M is the only discernible fully formed eddy. The entire area of quantitative analysis is approximately 222 km x 555 km, with LCE M reaching approximately 222 km diameter at its largest. As LCE M is only a portion of the area used for quantitative analysis, and qualitative analysis shows a negative CLa signature within its borders, the -0.3088 Spearman’s Correlation Coefficient is determined significant. As the magnitude of SLa for LCE M is 50 cm, the thermocline could be depressed by 200 m based on McGillicuddy et al.’s (1998) calculations. With this large of a depression of isopycnals (i.e., downward displacement of the thermocline and nitracline), access within the euphotic zone to a pool of subsurface nutrients would be significantly reduced, thus suppressing phytoplankton growth and leading to the negative CLa signature. The motion of LCE M could also push the phytoplankton stock within the boundaries of LCE M below the surface as the anticyclonic motion downwells the interior waters. This, along with low nutrient availability, would cause a negative surface CLa signature.

In 2003 a small cyclonic eddy can be identified along the western continental slope of the GMx, from 94°W – 96°W, 26°N – 28°N. March 14 – 21, 2003 there is a thin strip of positive CLa extending from coastal waters along the -20 cm isoline of Eddy B. Qualitatively this indicates advection from coastal waters by Eddy B. Biggs and Müller-
Karger (1994) previously studied this area of the GMx; they found that both cyclones and anticyclones advect coastal waters when they make contact with the continental slope/shelf, potentially advecting material 200 km into the GMx, though advection of material has also been shown to progress thousands of kilometers. Wawrik and Paul (2004) found that the Mississippi River plume extended into the eastern GMx as far as the Dry Tortugas. In the present study, advection can be seen as the positive CLa strip follows this isoline further from the coast for a month, even curving with the -20 cm isoline of Eddy B (Figure 27, some images not shown). After lateral advection ceases the positive CLa signature remains inside Eddy B, even along misshapen contours (Figure 27d) in the open GMx waters. This perpetuating positive CLa within the boundary of Eddy B, but negative CLa outside of it, indicates that physical processes within Eddy B are promoting growth. The positive CLa seen in Eddy B is the stock of phytoplankton advected from coastal waters seen in earlier images. The persistence of positive CLa within Eddy B suggests that the phytoplankton population has nutrients to maintain the elevated Chl-a concentrations. The nutrients needed to maintain phytoplankton stock could have been laterally advected from the coastal waters along with the phytoplankton seen in satellite imagery. There is not a significant quantitative relationship for this area during this time period, making these conclusions speculative based on the imagery available.

The next SLa/CLa correlative feature of interest is in early August 2006. Eddy I, a small cyclonic ring, forms near the Dry Tortugas. It has been noted in prior studies that this is a common area for formation of cyclonic eddies (Oey 1996; Ohlmann and Niiler 2005; Vukovich 2007; Zimmerman and Biggs 1999). Eddy I then migrated southwest
towards the Yucatan Peninsula. Eddy J forms in the north-central GMx (87˚W, 26.5˚N). As seen in Figure 10c, Eddy I and Eddy J merge to form the larger Eddy Q. While eddies over the Yucatan Peninsula tend to move northward (Zavala-Hidalgo 2003), the presence of LCE K on the west and the LC on the east favor merging of the two cyclones.

The sequence of SLa/CLa distributions suggest that, acting as gears, LCE K and the LC push and pull Eddy I and Eddy J together, as the two cyclonic eddies also have no other areas to migrate to. The signatures of Eddy Q and the LC can be seen in the Hovmöller Diagram for 86˚W and 24˚N for both CLa and SLa during 2006. LCE K has a prominent signature in the 24˚N Hovmöller. From August 5 through the end of 2006 in the central GMx (83˚W – 90˚W, 22˚N – 28˚N), there is a significant inverse correlation between SLa and CLa of -0.44 (Spearman) and -0.42 (Ives-Gibbons). For the entire GMx basin over 200 m, for the duration of Eddy Q the correlation coefficient is -0.26 (Spearman), while the correlation coefficient for the duration of LCE K is -0.26 (Spearman). This shows that there is a significant inverse relationship between the two parameters, SLa and CLa, during this time period.

For the entire GMx basin outside the 200 m isobath over the 14-year time-series the Spearman’s Correlation Coefficient for SLa/CLa is -0.20 (p<0.00001), while the Ives-Gibbons’ correlation coefficient is -0.19. This correlation is slightly higher between SLa/Chl, with the Spearman’s Correlation Coefficient being -0.29. The correlation coefficients are similar to those in previous studies (Chu and Kuo 2010; Joliff et al. 2008; Kahru 2007; Leterme and Pingree 2008). Leterme and Pingree (2008), who studied correlation between SLa and chlorophyll with remote sensing (albeit for the Gulf Stream region), calculated the Spearman’s Correlation Coefficient. They found that a significant
overall inverse relationship occurred with an $r$-value of -0.34 (Leterme and Pingree 2008).

This, along with the other quantitative and qualitative analyses of SLa/CLa, allow the first Hypothesis that negative SLa features will yield a positive CLa signature, while negative SLa features will yield a negative CLa signature to be accepted. The mesoscale eddies and fronts showcased in Hovmöller diagrams and seen in individual imagery (i.e., LCE M, LCE K, Eddies I, J, Q, R) all showcase that distinctive physical features exist within the GMx. These same features also show, qualitatively and quantitatively, that the biological reactions are a result of mesoscale processes. Inverse correlation coefficients, as well as qualitative agreement seen in the Figures, demonstrate that negative SLa features elicit a positive biological response of growth seen in positive CLa within cyclonic eddies and that positive SLa features produce a negative or no response exhibited with negative CLa. Positive SLa features can exhibit two responses due to the downward shoaling of the thermocline/nitracline. When the center of a positive SLa feature is downwelled, everything that was held within the center, not just nutrients, is also downwelled. These include phytoplankton stocks that were in local surface waters prior to a positive SLa feature, such as a LCE, migrating into the area. The downwelling of phytoplankton stock is an example of a negative response. No response would occur if there was already not much in the local area (or that which could be discerned by remotely sensed ocean color sensors) and the positive SLa did not elicit a change in the local environment.

The second Hypothesis that mesoscale SLa features will significantly modulate local biological variability compared to the typical seasonal conditions builds upon the
acceptance of the first Hypothesis. This can be seen well in the Hovmöller diagrams. The open GMx has higher surface chlorophyll in the winter (> 0.2 mg/m$^3$) and low surface chlorophyll in the summer (~0.05 – 0.15 mg/m$^3$) (Biggs and Müller-Karger 1994; Biggs et al. 2008; Müller-Karger et al. 1991). This seasonal cycle is consistent throughout each Chl Hovmöller diagram presented over the 14-year study period (Appendix A A1b, A2b, A3b, A4b).

SLa impacts the typical seasonal conditions at open water locations due to nutrient injection, whether through advection or upwelling. According to Perez et al. (1999), upwelled water in the central GMx has nutrient concentrations of 6 to 13 µmol/l of nitrate (372 – 806 mg/m$^3$). This leads to high chlorophyll concentrations in the region of upwelling. If anomalously high (low) chlorophyll concentrations were to occur in summer (winter) due to the influence of mesoscale features, then Hypothesis 2 could be accepted. Also, comparing CLa would allow this seasonality to be discounted. Thus, if CLa is elevated (positive) in the open GMx accompanied by a mesoscale physical feature, it can be concluded that the physical feature did modulate the local biological variability of the area it is passing over.

In 2007, between 24˚N – 26˚N (Appendix A A4b), there is a Chl signature through the year that is higher than the normal winter signature. This same signature is seen in the CLa Hovmöller (Appendix A A4a), the SLa Hovmöller (Appendix A A4c), as well as Figures 22 and 23, discussed above. There is a front of chlorophyll anomaly/positive chlorophyll and negative SLa during this time period. There is also Eddy R (Figure 24), which lingers over 94˚W for four months, and encircles positive CLa and higher Chl than its surroundings. The areas labeled 1 – 4 in Figures 4 and 6 highlight
the relationship of SLa and CLa. It is clear here and in the other Hovmöllers (see Appendix A) that CLA, SLa, and Chl share an inverse relationship due to physical features modifying local characteristics and allowing a biological response such as growth to ensue.

Focusing on smaller time-series of CLa, SLa, and Chl also show results of SLa impacting typical biological conditions (see above). As mentioned previously, LCE M lasts for 8.5 months from mid-March 2001 to the second week of January 2002. While much of the open GMx during this time period has a positive CLa signature in the images (Figure 15; some images not shown), within LCE M there is negative CLa. This type of association between parameters also occurs in 2003 (Eddy B, Figure 27) and 2006 (Eddy Q and LCE K, Figure 10). As previously discussed, these features give significant inverse correlation between SLa and CLa for Eddy Q and LCE K in 2006. These features (LCE K with Eddy Q’s signature following) can also be discerned in the 14-year Hovmöller of 27°N for the latter half of 2007, when Eddy Q had migrated to the central north GMx then westward.

The ability to discern these CLa responses to mesoscale SLa features qualitatively in Hovmöllers as well as individual imagery, in addition to quantitative statistical analysis on these same areas, allows the second Hypothesis to be accepted. While not every SLa feature elicits a significant quantitative or qualitative CLa response, there is enough evidence presented in the Results chapter to support the hypothesis that mesoscale SLa features will significantly modulate local biological variability compared to the typical seasonal conditions.

The El Niño event of 1997-1998 was the strongest El Niño event in over 50 years of gathering data (http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/eln/rcnt.rxml). This had globally reaching effects. The northern Gulf of Mexico has excessive rainfall during El Niño conditions (Kovats et al. 2003). High precipitation and heightened river discharge could lead to elevated nutrient loading to the northern GMx which would increase phytoplankton biomass (Müller-Karger et al. 1989; Yoder and Kennelly 2003). During this event, waters were up to 2°C warmer in 1997 than usual in the northern GMx, with excess rainfall in 1998 (Krishnamurti et al. 2000). This warm water, along with nutrient loading, could also provide conditions for a phytoplankton bloom to occur earlier than expected. This could be a contributing mechanism associated with the massive CLa signature in the winters of 1998, 2007, and 2010.

Though this anomalous behavior in the GMx during early 2010 was observed, interannual climate variability poses a challenge to quantitative characterization due to prominent variability at higher frequency. An attempt was made using Empirical Orthogonal Functions (EOFs), similar to the analysis of Wilson and Adamec (2001, 2002). However, EOF analysis on SLa primarily accounted for the variability of the Loop
Current, with lower frequency variability difficult to discern. The LC is a large, variable feature in the GMx, and though other processes may be active, such as cyclonic eddies or LCEs, the EOF accounted for only that variability produced by the LC. In addition, the EOF modes of CLa analysis accounted for the highly variable coastal regions especially that near the delta of the Mississippi River, when waters shallower than 200 m were masked. Thus, the null hypothesis for this particular hypothesis must be accepted, as it was not quantitatively demonstrated.

Limitations

The responses and associations seen in this study are based on the idea that these SLa features are promoting new production due to nutrient injection. As the open, surface GMx is not light limited, mechanisms that inject nutrients would stimulate new production. The phytoplankton bloom based on new production would subsequently excrete ammonia, and recycled nitrogen could act to maintain phytoplankton populations. 

*Prochlorococcus* is an abundant cyanobacterium in subtropical waters, which utilizes recycled nitrogen (Mann and Lazier 2006). This cyanobacterium could be a component of the CLa blooms seen correlating with mesoscale SLa eddies; however, 

*Prochlorococcus* is very efficient in low light, and is thus a major contributor to subsurface chlorophyll maxima (Mann and Lazier 2006). As the remote sensing methods used in this study account for only the first optical depth, a subsurface chlorophyll maximum (alternatively referred to as deep chlorophyll maximum, DCM) would not be included. It could potentially be accounted for if the thermocline and nitracline is uplifted into the first optical depth.
The DCM could also be responsible for why the correlation is not higher between SLa and CLa. As every 1cm of SLa displaces isopycnals by 4 m, if the magnitude of the mesoscale eddies is not very anomalous, the doming of the nitracline will be enough to cause growth in the euphotic zone but not high enough to cause growth within the first optical depth. If this occurs, the satellite sensors will not observe the phytoplankton signal. The first optical depth is 30 – 50 m in clear water in the GMx (Biggs et al. 2008). The nitracline in the GMx is approximately 90 m (Dagg and Breed 2003), thus the SLa magnitude must be at least 10 – 15 cm for the nitracline to be uplifted to the euphotic zone based on McGillicuddy et al.’s (1998) calculations. Previous studies found that GMx cyclonic eddies typically uplift the nitracline to 50 – 70 m below the sea surface, which is just at the cusp of the first optical depth (Biggs and Müller-Karger 1994; Walker et al. 2005; Zimmerman and Biggs 1999). If the nitracline is uplifted only to 50 – 70 m due to cyclonic eddies, the DCM due to upwelled nutrients would most likely not be discerned by satellite remotely sensed ocean color. Very strong cyclonic eddies in the GMx will uplift the nitracline further into the first optical depth, allowing signatures to be observed by satellite platforms, while smaller magnitude cyclonic eddies may not shoal the thermocline or nitracline enough for phytoplankton blooms to be detected.

Nitrogen fixing organisms are also of concern within this study. Some phytoplankton (Diazotrophs) are able to fix their own nitrogen in the GMx, which enables their growth and proliferation without the aid of mesoscale physical features affecting the depth of the nitracline. These populations could contribute to some of the CLa seen in images, as well as cause other phytoplankton to bloom with subsequently regenerated nitrogen from excretion. Mulholland et al. (2006) quantified the uptake and
release of NO$_3$/NH$_4$ by *Trichodesmium* and found that in the GMx this supplement to the nitrogen budget can sustain small blooms. This might not affect the current study, however, as *Trichodesmium* is seen in shallower waters in the eastern GMx and may not be prevalent in the oligotrophic waters (Mulholland et al. 2006).

It is assumed in this study that using CLa removes the seasonal signal from the chlorophyll field. It is possible that bloom timing is asynchronous over multiple years, which could introduce anomalies if a bloom for a given year is shifted from the climatological state. That is, timing of seasonal events, such as the spring bloom, are not annually persistent. Thus, if these events are shifted temporally (arriving later or earlier than “normal”) anomalies could be introduced.
CHAPTER VI
CONCLUSIONS

The first Hypothesis that SLa inversely corresponds to CLa in the GMx was accepted due to quantitative and qualitative analysis. Statistical analyses performed on prominent SLa features to calculate if a significant correlation exists with CLa could be compared to prior studies which had accepted an inverse relationship between Chl and SLa (Appendix B). As seen in Appendix B, the prominent features in this study have the same significance magnitude (++) as the Leterme and Pingree (2008) study, while comprising more data points than the Leterme and Pingree (2008) study. Though some features have a lower significance with the Ives-Gibbons’ test, the Spearman’s Rank Correlation Coefficient matches or exceeds the magnitude of that from Leterme and Pingree (2008). Leterme and Pingree (2008) determined SLa and Chl to be significantly correlated. Based on this conclusion and the results of the statistical analyses performed for this study, Hypothesis 1 could be accepted. This hypothesis has been tested and accepted throughout the world’s oceans (Benitez-Nelson et al. 2007; Biggs and Müller-Karger 1994; Chu and Kuo 2010; Joliff et al. 2008; Kahru et al. 2007; Leterme and Pingree 2008; McGillicuddy et al. 1998, 2007; McGillicuddy and Robinson 1997).

Bottom bathymetry does influence this correlation, as most mesoscale physical features, such as mesoscale eddies, are forced by the conservation of vorticity to keep their centers located between 24˚N and 26˚N, which is observed in this study.

The acceptance of the first Hypothesis was necessary to prove the next two Hypotheses. The second Hypothesis, that mesoscale SLa features will modulate local biological variability compared to typical seasonal conditions, is connected with the first
Hypothesis. Thus, much of the data used to prove the significance of the inverse relationship of SLa and CLa is also used to prove the significance of SLa affecting local biological characteristics. If negative (positive) SLa features correlate with positive (negative) CLa, then local seasonal characteristics will be altered by this relationship, thus allowing the second Hypothesis to be accepted. Using chlorophyll anomaly allows the second Hypothesis to be accepted, as changes relative to the usual local conditions are emphasized with the use of the anomaly field. Some of the features noted in Appendix B have greater statistical correlation (classified as strong in this study) than the baseline used here of the overall correlation coefficient of Leterme and Pingree (2008). As seen in the features noted in Appendix B and those referenced above in the Results chapter, it can be determined that SLa does modulate local biological variability in the GMx.

Significant interannual variability related to climate modes was more difficult to demonstrate. While events that are temporally coincident with El Niño are observed in the data set, no significant quantifiable relationship was validated. Empirical Orthogonal Functions (EOFs) were attempted as a means of establishing an ENSO linkage, but due to the high frequency variability of the Loop Current and chlorophyll near the coastal regions and Mississippi Delta, EOF modes did not obviously reveal specific relationships to external climate influences. There is a positive SLa signature in late 2009, which switches in 2010. This could be due to onshore winds brought on by El Niño that then switch to offshore winds in January – March, 2010. Similar responses were seen along the coastal GMx from Galveston, TX to St. Petersburg, FL in a study done by Kennedy et al. (2007). Onshore winds due to fronts are likely to occur October – December during El Niño years, with winds switching directions from January – March (Kennedy et al. 2007).
Meteorological conditions can affect sea level pressure, which then modulates SLA. The initial onshore winds would create a downwelling zone in the northern GMx and a positive SLa signature. The winds would then switch to offshore, changing the northern GMx to an upwelling zone with a negative SLa signature. This upwelling zone would provide nutrient loading, stimulating phytoplankton growth and the positive CLa signature across the GMx. Such a response was not demonstrated in this study; thus, the null hypothesis of interannual variability must be accepted.

The research presented contributes to our understanding of the effects of mesoscale physical processes on biological responses within the GMx. The data presented establishes a strong association in the GMx between mesoscale physical processes identified through SLa and biological signatures identified through CLa. The location of physical processes affects whether these features actively trigger a biological response or whether the associated biological signature is a product of physical entrainment by mesoscale features. The observations suggest that the former holds true in open, oligotrophic waters of the GMx, while the latter effect is a more active response in coastal regions of the GMx. Future research should also aim to better understand interannual variability related to climate modes within the GMx. Refining the EOF analysis attempted here through application of low-pass filtering techniques could help to achieve this. Another research aim suggested by this study is a thorough exploration of the temporal variation of seasonal events (e.g., timing of the spring bloom) over the entire GMx basin through time-series analysis, which would improve interpretation of the CLa fields. Finally, the LC’s interaction with shelf waters of the Yucatan Peninsula reveal biophysical variability associated with the frontal boundaries of mesoscale eddies in the
central Gulf, which represents a largely unexplored topic that could benefit from future investigation.
Figure A1a. CLa along 24°N for 1998 – 2011. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar.
Figure A1b. Chl-a along 24°N for 1998 – 2011.
Figure A1c. SLa along 24°N for 1998 – 2011. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar.
Figure A2a. CLa along 27°N for 1998 – 2011. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar.
Figure A2b. Chl-a along 27°N for 1998 – 2011.
Figure A2c. SLa along 27°N for 1998 – 2011. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar.
Figure A3a. CLa along 86°W for 1998–2011. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar.
Figure A3b. Chl-a along 86°W for 1998–2011.
Figure A3c. SLa along 86°W for 1998 – 2011. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar.
Figure A4a. CLa along 90°W for 1998 – 2011. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar.
Figure A4b. Chl-a along 90°W for 1998 – 2011.
Figure A4c. SLa along 90°W for 1998 – 2011. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar.
Figure A5a. CLa along 94°W for 1998 – 2011. Reds/yellows correspond with positive CLa, blues with negative CLa, black with CLa magnitudes that are off the scale bar.
Figure A5b. Chl-a along 94°W for 1998–2011.
Figure A5c. SLa along 94°W for 1998 – 2011. Reds correspond with positive SLa, blues with negative SLa, black with SLa magnitudes that are off the scale bar.
### APPENDIX B

#### COMPARISON OF CORRELATION COEFFICIENTS TABLE

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<tr>
<th>Feature Name</th>
<th>Spearman’s Correlation Coefficient (SLa/CLa)</th>
<th>Ives-Gibbons’ Correlation Coefficient (SLa/CLa)</th>
<th>Leterme &amp; Pingree (2008) Correlation Coefficient</th>
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<tr>
<td>Feature 21&amp;22</td>
<td>++</td>
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<td>(Figures 14 – 15)</td>
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<tr>
<td>2009-2010, 90°W</td>
<td>+++</td>
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<td>(Figures 20 – 21)</td>
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<tr>
<td>Feature 27&amp;28</td>
<td>+++</td>
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<td>(Figures 22 – 23)</td>
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</table>

Compares the correlation coefficients of prominent features in the GMx with the correlation coefficient of Leterme and Pingree (2008). +, ++, and +++ represent low (0.01 - 0.29), moderate (0.30 – 0.59), and strong (0.6 – 1) correlation coefficients respectively.
REFERENCES


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