Temporal and Spatial Variability of Phytoplankton Biomass in Coastal Mississippi Waters

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The University of Southern Mississippi

TEMPORAL AND SPATIAL VARIABILITY OF PHYTOPLANKTON BIOMASS IN COASTAL MISSISSIPPI WATERS

by

Lorin Matthew Dornback

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

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August 2011
ABSTRACT

TEMPORAL AND SPATIAL VARIABILITY OF PHYTOPLANKTON BIOMASS IN COASTAL MISSISSIPPI WATERS

by Lorin Matthew Dornback

August 2011

Chlorophyll concentrations were measured in western Mississippi coastal waters to determine the spatial and temporal variability of phytoplankton. Nutrients (nitrate, silicate, phosphate), river discharge, temperature, salinity, stratification, tides, currents and winds were measured in concert with the phytoplankton concentrations. The purpose of this study was to determine the seasonal variability in phytoplankton and what was driving the variability. This study was comprised of a three year (September 2007- November 2010) time series where samples were taken once a month for eight stations. Profiles of each station were taken using a Conductivity, Temperature and Depth (CTD) sensor and a WET Labs FL-3 for in situ chlorophyll fluorescence. In addition, nutrient samples were taken by hand and peristaltic pump at each station. River discharge, tidal change, current and wind data was collected from various monitoring stations operated by Federal Agencies (USGS, NOAA, and NRL). Transect data was broken down into three sections (Inner Sound, Cat Island Pass, and Mississippi Bight) in order to assess the spatial variation on the Mississippi coast. Temporal variation was assessed by a comparison of time series data using Spearman’s Rank Correlations.

Average chlorophyll concentrations were found to decrease with distance from the shore. Seasonality was present through every location on the Mississippi
coast. Spring blooms in May were a defining feature of every area studied while fall blooms were present inside the Barrier Islands. Temperature was correlated to chlorophyll concentrations in the Inner Sound (p<0.01) and stratification was correlated to chlorophyll in the Mississippi Bight (p<0.05). In the transition zone of the Cat Island Pass, chlorophyll concentrations were correlated to temperature (p<0.01) and stratification (p<0.01). Chlorophyll concentrations did not correlate to nitrate, phosphate or river discharge. Silicate concentrations showed a seasonality opposite to chlorophyll concentrations. Lower silicate concentrations occurred during high chlorophyll cocentra
tions. Biological uptake was considered the reason for the lower silicate levels. Silicate was positively correlated to low salinities in the Inner Sound (p<005) and the Mississippi Bight (p<0.01). The Biloxi Bay was presumed to be a source for phosphate. High discharges from the Wolf and Pearl River would dilute phosphate concentrations in the western Mississippi Sound. Thus, phosphate was negatively correlated to low salinities (p<0.01) and river discharge (p<0.01). Nitrate appeared to have higher concentration pulses coming from Biloxi Bay and from the Mississippi Bight, but most of the year concentrations were below 0.5 umol L\(^{-1}\). The mechanism behind the high nitrate pulses was undetermined.
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I am very grateful to Sumit Chakraborty for his advice through my years here at USM, Kevin Martin and everybody who has worked on the NGI project for my data, and Allison Mojzis for her statistical advice and her diligent proofreading.

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CHAPTER I

INTRODUCTION

Phytoplankton populations are a critical component of aquatic ecosystems because of their role as primary producers and as principle energy suppliers for the marine food web. The highest abundances of phytoplankton typically occur in near shore coastal ecosystems, especially in estuarine environments (e.g., Cole & Cloern 1987; Day et al. 1989). In addition, phytoplankton abundances in estuarine environments are highly dynamic, resulting in a high amount of spatial and temporal variation in phytoplankton biomass.

The distribution and abundance of phytoplankton are largely influenced by variability in physical factors such as light, salinity, and temperature. Water chemistry plays a role in phytoplankton abundance as well. Phytoplankton growth requires an adequate supply of nutrients (e.g., NO$_3$, PO$_4$, SiO$_3$) to grow and reproduce. The availability of light and nutrients are considered the main limiting factors to phytoplankton growth (Harding et al. 1986; Cole & Cloern 1987; Malone et al. 1988; Smith & Harrison 1991). These limiting factors are highly variable in estuarine environments, thereby contributing to the dynamic nature of phytoplankton populations in these ecosystems. Light and nutrients influence the level of phytoplankton biomass present in an estuary, but in turn, these factors are influenced by the phytoplankton. Higher abundances of phytoplankton can decrease the available light by self-shading (Bannister 1974) and the available nutrient levels by population uptake (Cloern 1996). Phytoplankton consumption of nutrients can result in a decline
in nutrient concentrations beyond that associated with conservative mixing between high nutrient freshwater inputs and low nutrient oceanic waters (Cloern 1996).

Phytoplankton abundance and productivity is generally higher and more variable in coastal environments as compared to offshore waters (Ryther 1963; Walsh 1988). In particular, high productivity in coastal waters can generally be attributed to some combination of physical conditions that are conducive to accumulation of biomass (convergence, low mixing rates, etc.) and conditions favoring high growth of phytoplankton. In estuarine environments, the highest phytoplankton biomass typically occurs along the salinity mixing gradient between the freshwater and oceanic water masses (Malone et al. 1980; Pennock & Sharp 1986). The low salinity water mass is characterized by high nutrients, high turbidity and the marine water mass is characterized by low nutrients, low turbidity and high salinity. The characteristics of the low salinity water mass will vary with the rate of flow of rivers and streams into the estuary and associated inputs while the marine water mass changes with tides, wind forcing (Day et al. 1989), and offshore circulation patterns. The interface between the low salinity and marine water masses is highly dynamic. In the transition zone, there are ample amounts of nutrients and light to foster phytoplankton growth. This creates an area known as an “optimal growth zone” (DeMaster & Pope 1996; Smith & DeMaster 1996) where phytoplankton reach higher abundances than elsewhere along the mixing gradient.

Significance of Study

The northern Gulf of Mexico is a highly productive coastal environment strongly influenced by freshwater input from various sources including the
Mississippi, Atchafalaya, and Mobile Rivers. Prior studies have documented temporal and spatial patterns of chlorophyll in the northeastern Gulf of Mexico related to riverine outflow. The spatial distribution and abundance of chlorophyll have been shown to be related to the input of freshwater (Qian et al. 2003). In addition, there have been extensive studies of primary production in coastal areas off the Mississippi and Atchafalaya Rivers (Riley 1937; Sklar & Turner 1981; Lohrenz et al. 1990; Lohrenz et al. 1999; Lohrenz et al. 2008).

High amounts of phytoplankton biomass can be beneficial as a food source to higher trophic levels, but excessive phytoplankton biomass can be detrimental to an estuarine ecosystem. Excessive phytoplankton biomass can contribute to oxygen depletion in bottom waters (Stanley & Nixon 1992; Justic et al. 2005; Rabalais et al. 2007). Phytoplankton blooms that flourish in upper layers of the water column can eventually sink to the bottom. The associated large input of organic carbon can lead to high rates of microbial respiration in bottom waters, which can result in an oxygen deficit below the pycnocline. An extremely low level of oxygen (<2.0 mg L$^{-1}$) is considered hypoxic and can have harmful effects on local fauna (Rabalais & Turner 2001; Breitburg et al. 2009). Additionally, some non-toxic algal species are responsible for harmful algal blooms. Excessively high abundances of phytoplankton can have a potentially negative impact on ecosystem health. Too much biomass of any phytoplankton species can shade light from benthic primary producers (Onuf 1996; Okey et al. 2004), reduce larvae recruitment (Bricelj & MacQuarrie 2007), and reduce gill function (Landsberg 2002).
Studies in nearby estuarine systems have shown relationships among phytoplankton abundances, physical and chemical conditions, and ecosystem health. In Mobile Bay, Alabama, Holiday et al. (2007) showed a correlation between known dinoflagellate and diatom abundances and sea surface temperature, salinity, and nitrate and phosphate levels. In Perdido Bay Florida, point source and non-point source nutrient loading has been linked to elevated phytoplankton biomass (Livingston 2007), and associated phytoplankton blooms were linked to declines in fish, invertebrate, and infauna species abundance and diversity.

The Mississippi Sound provides an ideal site for the study of phytoplankton processes in a dynamic estuarine ecosystem. The Sound is a shallow estuarine environment that supports rich shrimp, oyster, and menhaden fisheries and a thriving tourism economy. Despite its socio-economic importance, little is known about the patterns of phytoplankton abundance in this region and its relationship to physical and chemical environmental conditions. The lone study of phytoplankton in the area comes from a National Aeronautics and Space Administration (NASA) remote sensing study (Atwell 1973) that used boat based water sampling to provide ground truth observations. That study lasted slightly over a year with no consistent temporal or spatial sampling regime, and provided few insights about the mechanisms controlling phytoplankton dynamics. Given the vital economic dependence on the Mississippi Sound ecosystem, it is important to study and understand the dynamics of phytoplankton.
Objectives

To address the need for a better understanding of factors influencing phytoplankton abundance in Mississippi coastal waters, this study will examine the temporal and spatial variability of in situ chlorophyll concentration in conjunction with a series of monthly cruises funded through the National Oceanic Atmospheric Administration (NOAA) Northern Gulf Institute project “Monitoring and Assessment of Coastal and Marine Ecosystems in the Northern Gulf.”

The first objective of this study was to describe the seasonal and spatial distributions of phytoplankton abundance in Mississippi coastal waters. Chlorophyll concentrations and chlorophyll fluorescence will be used as a proxy for phytoplankton abundance. The second objective is to determine relationships between environmental variables (riverine output, temperature, salinity, wind, currents, and stratification), and nutrients and chlorophyll concentrations in the Mississippi coastal waters. The environmental variables were chosen to address as many potential factors influencing chlorophyll concentrations and nutrients as possible.

The Mississippi coastal NGI transect is located in a highly variable coastal environment. Based on hydrological, chemical, and biological criteria, the transect stations were grouped into three distinct categories: the Inner Sound, the Cat Island Pass, and the Mississippi Bight. The bases for these groupings are described in the following paragraphs.

River inputs by two small rivers (Wolf and Jourdan) flow into the Bay Saint Louis and may substantially influence conditions in the bay. Depending on the riverine discharge the Bay has a flushing time ranging from hours to months. Sawant
(2009) calculated Jourdan and Wolf riverine discharges of 799, 50, and 6 m$^3$ s$^{-1}$ to flush the Bay in 0.3, 4.1, and 32.7 days. Wind may also play a role in Bay Saint Louis flushing, in addition to causing mixing in the shallow bay (<4 m). Due to the shallow nature of the Bay Saint Louis a well mixed water column should be present most of the year.

The 10 km wide Cat Island Channel is strongly subject to the influence of the microtidal transport between the Mississippi Bight and Mississippi Sound. In addition to the Wolf and Jourdan Rivers, Pearl River outflow to the east of Bay Saint Louis represents a substantial freshwater source. The Pass depth increases from 3 to 8 m moving away from shore. Thus, the combination of tidal and wind-driven mixing is important at shallower depths, but not sufficient to overcome the seasonal stratification at the deeper stations.

In the open shelf waters of the Mississippi Bight area, coastal currents as well as seasonal variations play a major role in influencing the physical conditions. Seasonal stratification is prevalent between the 10 m and 20 m isobaths.

Hypotheses

A. Due to the close proximity to land, the narrow pass and the shallow depth, chlorophyll and nutrient concentrations in the Inner Sound (Stations 1 and 2) will lack a clear seasonal pattern and instead be dominated by episodic events related to riverine, tidal, and wind forcing.

B. Due to the narrow pass, moderate distance to land and increasing depth, chlorophyll and nutrient concentrations in the Cat Island Pass (Stations 3, 4,
and 5) will have a distinct seasonal pattern, controlled by tidal flux, seasonal stratification and the buffered influence of riverine discharge.

C. Due to Gulf of Mexico influenced waters, temporal patterns of chlorophyll concentration in the Mississippi Bight (Stations 6, 7, and 8) will be characterized by a spring maximum related to nutrient availability and influenced by coastal current patterns and seasonal stratification.

Background

The Mississippi Sound is a sub-tropical, barrier island, estuary with the majority of the length (150 km) contained within Mississippi state boundaries. The eastern end of the Sound is enclosed by Dauphin Island and Heron Bay in Alabama with the western end enclosed by Lake Borgne and the Rigolets in Louisiana. A chain of barrier islands (Petit Bois, Horn, Ship, and Cat Islands) encloses the southern boundary of the Sound, with the islands ranging 7-15 km from the Mississippi coastal shoreline. The semi-enclosed area between the mainland and the barrier islands comprises 400,000 acres. Depths inside the Sound range from >1 m closer to mainland to 17.5 m on the northern edge of the barrier islands. Shipping channels are maintained at a 15 m depth from the mainland ports through some of the barrier island passes into the Mississippi Bight.

The western Mississippi Bight is an unusual coastal bight due to the Mississippi River delta to the west. The Chandeleur Islands form the western boundary and the Mississippi Barrier Islands form the northern boundary. This creates a right angle in the coastal geography. The sediments are largely composed of silt and mud due to outflow from the Mississippi Sound and the relict St. Bernard
Delta (now the Chandeleur Islands and Sound, Kennicutt 1995). The 20 m isobath also forms a right angle in the bight. The 20 m isobath roughly follows the 30 °N and 88.8 °W, paralleling the Mississippi Barrier Island and Chandeleur Island chains and terminating at the coordinates above.

Climatological Conditions

The southern Mississippi climate is intermediate between warm temperate and sub-tropical (Christmas 1975). Rainfall averages 150 cm yr\(^{-1}\) but differences in yearly totals can be as high as 141 cm. Winds during the summertime are primarily southeasterly. The wind patterns reverse during the winter months and winds mainly come from the northeast. Water temperatures range from 3.4 °C to 36.5 °C. The monthly water temperature maximum is normally during August and the minimum is normally during January or February. Vertical water temperature profiles are within three degrees from top to bottom, but variations of up to seven degrees were found with salinity gradients present (Christmas 1975).

Freshwater Input and Tides

Freshwater inputs into the western Mississippi Sound include; the Jourdan and Wolf Rivers that enter the western Mississippi Sound via Bay Saint Louis, the Pearl River that flows directly into the far western side of the Sound, and Lake Borne which form the western edge of the Sound and is fed by inputs into Lake Pontchartrain and the Mississippi River discharge. The Pearl River has the largest quantified freshwater input with a discharge of 365 m\(^3\) s\(^{-1}\). The Jourdan River and Wolf River have much smaller impacts with discharges of 20 and 21.5 m\(^3\) s\(^{-1}\) respectively. The Mississippi River does not have a direct input into the western
Mississippi Sound. The Mississippi River’s influence is through “leakage” of freshwater through the surrounding delta wetlands into the Sound, water flow through the locks of the Industrial Canal into the Mississippi River Gulf Outlet and into Lake Pontchartrain (Sikora & Kjerfve 1985). Coastal circulation can also carry Mississippi River outflow north and east from the Bird-foot delta into the Chandeleur-Breton Sound into the Mississippi Sound and Bight (Walker et al. 2005).

The Bonnet Carre Spillway is a human controlled discharge of the Mississippi River. Historically opened on an average of once every 10 years for two weeks to a month, the flood control measure is only used when the Mississippi River is at flood stages threatening New Orleans. Bonnet Carre Spillway flow rates can exceed 7000 m$^3$ s$^{-1}$ but rate is dependent on river flood levels. The excess water entering into Lake Pontchartrain will exit through the Rigolets into the western Mississippi Sound.

The Mississippi Sound has diurnal tides with a range of 0.46 m (Kjerfve 1983). Tidal flushing and influence from the more saline central Mississippi Sound keep the salinities in the western Sound around 20-25. Salinities reaching zero can be found near the mouth of Bay Saint Louis after large rainfall events and outgoing tides. Higher salinities closer to 35 are found inside the Sound during low rainfall periods and salinities of 35 are consistently found in the Mississippi Bight.

Nutrients

A study of nutrients entering the Mississippi Sound (Eleutarius 1975) reported that the primary sources of nitrate and phosphate were associated with freshwater inputs, with the highest concentrations coming from Bayou Cassotte near Pascagoula. The study also showed elevated levels of nitrate flowing from the Chandeleur
Sound/Mississippi Bight. Bayou Cassotte is located near an industrial canal that is home to the Mississippi Phosphates Corporation. Western Mississippi Sound rivers (Biloxi, Jourdan, and Pearl) were not a significant source of nitrate or phosphate, but higher concentrations of silicate were found to be imported by local rivers (Eleutarius 1975). Eleutarius (1975) also found that the western Mississippi Sound nitrate never exceeded 0.2 μmol L⁻¹ and that phosphate concentrations were inversely correlated with riverine discharge.

*Currents*

The averaged flow vectors on the east and west sides of Cat Island, show surface and bottom currents flowing into the Sound at rates of 2-4 cm s⁻¹ (Kjerfve 1983). However, diurnal tidal currents can be influential to the current speed and direction observed in confined passes between bodies of water.

Mississippi Bight surface currents have been reported to flow in a counter-clockwise direction. Though the overall flow might be counter-clockwise, wind and riverine outflow can influence the Mississippi Bight current direction episodically as well (Lohrenz & Verity 2004).

*Phytoplankton*

Phytoplankton biomass appears to be lowest in the winter and spring, gradually rise through the summer and peak in the fall (Atwell 1973). These peaks tend to be variable in their lateral distribution across the sound with no consistent pattern forming. The one consistent feature is a general decrease in phytoplankton abundance moving away from the mainland shoreline (Atwell 1973).
CHAPTER II
MATERIALS AND METHODS

In this project we analyzed data from monthly cruises conducted from September 2007 to November 2010 in the western Mississippi Sound and Mississippi Bight. Cruise samples included water samples for laboratory analyses and in situ optical and physical profiles of the water columns. Laboratory analyses of water samples were conducted for chlorophyll and nutrients (NO₃, PO₄, SiO₃). Sampling and data analyses are conducted through Northern Gulf Institute (NGI) funding of The University of Southern Mississippi’s (USM) project “Monitoring and Assessment of Coastal and Marine Ecosystems in the Northern Gulf”. Additional environmental data is provided courtesy of the National Oceanic and Atmospheric Administration’s (NOAA) National Data Buoy Center (NDBC) buoys and tide stations, and the United States Geological Survey (USGS) stream gauging stations.

Monthly Transect Cruise

The monthly cruise consists of eight stations starting from the mouth of Bay St. Louis, Mississippi, continuing past the western edge of Cat Island, and terminating at USM buoy 42067 (Fig. 2.1). The majority of the monthly cruises utilize the USM research vessel Lemoyne, but a small number of cruise measurements have been taken onboard the research vessels Tom McIlwain and Cape Hatteras.
Vertical Profiles of Physical and Optical Properties

Vertical profiles of in situ physical and optical properties were acquired using a Seabird SBE 49 CTD along with a WET Labs ECO FL-3 fluorometer taking water column profiles for each station. Data were acquired during both the downcast and upcast. Normally only data from the upcast were used due to the potential of bubbles interfering with optical measurements. The data were acquired using a WET Labs DH-4 data acquisition module and logged on a laptop computer via a cable to the surface.
CTD measurements were used for salinity, temperature and pressure measurements. $\sigma_t$ was calculated using a potential density script written in Matlab (Seawater toolkit CSIRO release 3.3 http://www.cmar.csiro.au/datacentre/ext_docs/seawater.htm). Subtracting the surface density from the bottom density and dividing the difference by the total depth gave a value for stratification.

An ECO FL-3 provided measurements of chlorophyll fluorescence (excitation wavelength 470 nm; detection wavelength 695 nm), phycoerythrin fluorescence (excitation wavelength 540 nm; detection wavelength 570 nm), and colored dissolved organic matter fluorescence (excitation wavelength 370 nm; detection wavelength 460 nm). For the purposes of this study, only the chlorophyll fluorescence was considered.

The FL-3 chlorophyll fluorescence counts were calibrated at WET Labs by measuring the signal output from the FL-3 (chlorophyll equivalent concentration or CEC) in relation to a fluorescence proxy of 25 mg m$^{-3}$. A scale factor was calculated by dividing the 25 mg m$^{-3}$ concentration by the CEC minus the dark count. The dark count is the baseline output of the FL-3 in the absence of light and in clean de-ionized water (WET Labs 2008). WET Labs calibrated the FL-3 three times during the study (August 2007, September 2008, and October 2009).

All data collected were processed through a series of Microsoft Excel macros, which were used to convert the instrument data files into calibrated output in the NASA SeaBASS format (Werdell & Bailey 2002). All subsequent data manipulation and graphical visualization was performed in Matlab.
ECO FL-3 Comparison

The ECO FL-3 was compared to chlorophyll concentrations determined for water samples taken from the surface and at depth. Chlorophyll concentrations were determined using two methods: High Performance Liquid Chromatography or HPLC (Wright et al. 1991) and by methanol extracted fluorescence (Welschmeyer 1994). Comparing the various methods provides a vicarious method for validating the measurements of FL-3 chlorophyll.

HPLC Chlorophyll Analysis

HPLC chlorophyll concentrations were measured from September 2007 to November 2009 following the method of Wright et al. (1991). Water samples were filtered using 47mm GF/F filters (0.7 μm nominal pore size) at a low vacuum (< 100 mm Hg). Pigment extraction was conducted using 90% acetone and a filtration through 0.2 μm Teflon syringe filter. The sample was analyzed using a Waters 600 Controller and Pump HPLC and the absorption spectra chromatograms were acquired using a Waters 2996 Photodiode Array Detector HPLC. All of the HPLC chlorophyll information was obtained with permission from the thesis work of Luz Molina (unpublished).

Fluorometric Chlorophyll Analysis

Fluorometric analyses of chlorophyll samples were conducted according to Welschmeyer (1994) using a Turner Design 10AU fluorometer. The 10AU instrument automatic adjusts sensitivity and is equipped with a digital readout. The samples were filtered through a 25 mm diameter, 0.7 μm-nominal pore size GF/F filter under low vacuum (≤100 mm Hg). The filter was placed in a Nanopure® water-
rinsed 10 mL borosilicate cuvette filled with 5 mL of 100% methanol. The pigments were allowed to extract in darkness and refrigerated conditions for 24 hours. After 24 hours, the cuvette was removed and vortexed for 10 seconds. The filter was removed from the methanol and discarded, and the cuvette was centrifuged for 10 minutes. The cuvette was carefully removed from the centrifuge and placed in the fluorometer. Chlorophyll samples were read three separate times for each cuvette and an average of the three readings was taken. In addition, a cuvette containing pure methanol was read to correct for instrument blank.

Chlorophyll was calculated with Equation 1.

\[
\text{Equation 1: Concentration} = \frac{F - 0.275 \times \left( \frac{6600}{F} \right)}{814.26}
\]

The chlorophyll equation was derived from Ritchie (2008), where \( F \) is the fluorometric value read from the fluorometer and \( V \) is the volume of sample filtered.

Comparison of Chlorophyll Measurements

Comparison of the FL-3 to the laboratory chlorophyll concentrations at surface, middle and bottom depths (Fig. 2.2A and 2.2B) showed generally good agreement although there was considerable scatter in the regressions. The FL-3 fluorescence measurements were taken from the closest depth to the water sample. The water samples were acquired from predetermined depths that were consistent for every cruise. This scatter was likely due to the vertical variability of phytoplankton and the difficulty of obtaining samples from the precise depth in the water column. Lower in situ fluorescence for surface samples might be due to photoinhibition. Despite the outliers, we conclude that the FL-3 provided a reasonable estimation of
chlorophyll concentrations in the study area.

![FL3 Fluorescence vs HPLC Chlorophyll](image1)

![FL3 Fluorescence vs Turner Fluorescence](image2)

**Fig. 2.2.** A comparison of FL-3 chlorophyll fluorescence to measurements of HPLC (A) and extracted chlorophyll fluorescence (B) chlorophyll concentrations. The solid line represents the geometric mean regression fit to the data (Model II).

**Water Sample Collection**

All seawater samples were stored in 10% HCl washed, Nanopure rinsed, and sample rinsed Nalgene bottles. Surface water samples were taken by hand at stations one, four, and eight. Station eight also includes sampling at middle and bottom depths. Depth samples were taken using weighted hosing (rinsed with seawater for five minutes) and a peristaltic pump. A depth sensor (In-Situ Inc. TROLL 9500) was attached to the end of the hose to determine the proper sampling depth. Each water sample was stored in a cooler on ice until samples could be returned to the laboratory for further analysis.
Laboratory Analysis

All filtration and analyses use clean techniques that involve washing all of the filtration apparatus and storage containers with 10% HCl and rinsing with nanopure water.

Nutrients

Nutrient samples were pre-filtered through a 25 mm diameter, 0.7 μm nominal pore size GF/F filter, running at low vacuum (≤100 mm Hg). The filtrate was collected in an acid washed flask, stored in a 125 mL Nalgene bottle, and frozen until time of analysis. For analysis the samples were returned to room temperature and all nutrients were measured using fluorometric (N species) and spectrophotometric (PO₄ and SiO₃) methods with an Astoria-Pacific A2+2 nutrient auto-analyzer (Method #A179, A027, A205, and A221; Astoria-Pacific International, Oregon USA).

Environmental Data Collection

Coastal Monitoring

Weather and tide data were attained from the NOAA National Data Buoy Center (www.ndbc.noaa.gov). Wind speed/direction and tide data were collected from the stations and integrated with the cruise data. The monitoring stations were, WYCM6 (near station 1), GPOM6 (north of Ship Island), and 42007 (station 7) (Fig. 2.1). This project used WYCM6 for tidal height measurements in the Bay Saint Louis. GPOM6 and 42007 were used to collect wind speed and direction.

Wind data was broken into the $u$ and $v$ vectors using equation 2. The $u$ vector is the zonal component and the $v$ vector is the meridional component. The $u$ and $v$ vectors used wind speed ($s$) in m s$^{-1}$ and wind direction ($d$) in degrees.
The average of each vector was taken for the 24 hours proceeding and during the cruise. Monitoring station 42007 was used for wind measurements from 2007-2008. 42007 was decommissioned after 2008. GPOM6 was established in late 2008 and was used for wind measurements during 2009 and 2010. The 24 hour average was used in all calculations. A five day average was used for Figure 3.2.

Mean tidal height was measured on an hourly basis from station WYCM6. The tidal rate of change was calculated by subtracting the current tidal height (for the sampling) from the tidal height of the previous hour. This provided the change in height over time. This was applicable to stations one and two, due to the proximity to the tidal station, but the other six stations would experience tidal change at different times. To resolve this problem, NOAA tide predictions (http://tidesandcurrents.noaa.gov/tide_predictions.shtml) were used for Cat Island, Ship Island, and Horn Island. The average time of high tide for the remaining six stations was determined and compared to the time of high tide at WYCMG. Compared to the Bay Saint Louis high tide, station three and four were one hour earlier, five and six were two hours earlier, and seven and eight were three hours earlier. The additional time was taken into account and added to the sampling time for each station when considering relationships to tidal effects. The rate of tidal change for the remaining stations was calculated from the adjusted hourly tidal height provided by WYCM6.

\[
\begin{align*}
    u &= -s \times \sin \left( \frac{\pi x d}{180} \right) \\
    v &= -s \times \cos \left( \frac{\pi x d}{180} \right)
\end{align*}
\]
With the multitude of factors that influenced tidal height, it is important to note that using tidal heights from Bay Saint Louis for the outer six stations was an approximation. Nevertheless, these approximations should provide a good indicator of the tidal direction during sampling.

Current Data

Current data was obtained from the NRL Northern Gulf of Mexico Ocean Nowcast/Forecast System (Ko et al. 2008). The netcdf file format was extracted using Matlab and plotted using the quiver command. A 3x3 box containing nine grid points from current model was overlaid on each transect station. The nine points were averaged together to create a single hourly average of $u$ and $v$ for each station. A 48 hour average was taken for the $u$ and $v$ current components at each point. The 48 hour time period applied to each cruise day and the preceding day. Data for April through August 2010 was not available due to Natural Resource Damage Assessment litigation issues.

USGS Streamflow and Gauge Height Data

Freshwater inputs to the western Mississippi Sound include five rivers and one tidally influenced lake. Table 2.1 details relevant USGS monitoring stations.

<table>
<thead>
<tr>
<th>Input</th>
<th>Location</th>
<th>USGS Station #</th>
<th>Streamflow</th>
<th>Gauge Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Bay Biloxi</td>
<td>Biloxi, MS</td>
<td>02481270</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Biloxi River</td>
<td>Wortham, MS</td>
<td>02481000</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Jourdan River</td>
<td>Bay St. Louis, MS</td>
<td>02481660</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Pearl River</td>
<td>Bogalusa, LA</td>
<td>02489500</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Tab. 2.1. (continued).

<table>
<thead>
<tr>
<th>Input</th>
<th>Location</th>
<th>USGS Station #</th>
<th>Streamflow</th>
<th>Gauge Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigolets Hwy 90 Bridge</td>
<td>Slidell, LA</td>
<td>301001089442600</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Wolf River</td>
<td>Landon, MS</td>
<td>02481510</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Every station monitors gauge height but three stations were missing streamflow measurements. All three stations that do not include streamflow are tidally influenced stations. This makes any measurements from these stations a poor proxy for freshwater input into the Mississippi coastal area. The remaining stations with discharge data were used to quantify the flux of freshwater into the Mississippi Sound (Fig. 2.3).
Statistical Analysis

Due to the non-normal distribution \((p \leq 0.05)\) of much of the data according to the Shapiro-Wilk test, non-parametric tests were conducted to determine the correlations and variance in the data. These statistical tests were run using IBM SPSS® 14.0 statistical software package. Each region averaged 2-3 stations into one region. No transformations were used on the regional averages.

Spearman’s Rank correlation analysis was conducted to compare all of the variables in the data set. Principal Components Analysis (PCA) was performed to simplify the variables into independent (orthogonal) components that describe the variance in the system. In the PCA, orthogonal rotation was performed with Varimax (variance maximizing). Ideally, varimax rotation will associate each variable with one factor and make the results easier to interpret. Stepwise Multiple Linear Regression (SMLR) was used to determine the major predictors of variation in the dependent variable, chlorophyll. A stepwise regression was used to maximize the residual sum of squares with the available dependent variables. A SMLR is technically a parametric test, but the test is mainly based on the normality of the residuals (Barry & Feldman 1995). Residuals are the difference between the predicted and observed parameters. The test is valid if the residuals have a normal distribution. A Shapiro-Wilk test was performed on the residuals to test for normality and all residuals were normal.

Regional medians and ranges were also used to characterize the differences between the Inner Sound, Cat Island Pass, and Mississippi Bight. Those calculations were made using Microsoft Excel.
CHAPTER III

RESULTS

The first objective of characterizing temporal and spatial patterns in chlorophyll was addressed by examining horizontal sections of chlorophyll fluorescence along the transect for selected cruises. Additionally temporal and spatial patterns were examined by comparing time series variations in chlorophyll fluorescence for the different subsets of stations organized into three major regions: Inner Mississippi Sound, Cat Island Pass, and Mississippi Bight.

The second objective involved characterizing relationships of chlorophyll to environmental variables in an effort to better understand possible mechanisms influencing dynamics of phytoplankton abundance in this region. Horizontal sections were presented initially to allow comparisons among different seasonal periods. The horizontal sections of chlorophyll fluorescence provided seasonal “snapshots” organized according to seasons and a representative cruise was selected to represent winter, spring, summer and fall conditions for each of the three years of the time series. Subsequently, time series of chlorophyll fluorescence and environmental variables were examined. The regional time series variables include chlorophyll, nutrients, salinity, temperature, tidal rate of change, and water current vectors. In addition to the regional time series for each of the three years of cruise data, time series of winds and river discharge were also examined.

For the regional time series, stations were grouped into the three distinct regions that included the Inner Sound, Cat Island Pass, and Mississippi Bight. The Inner Sound (Stations 1 and 2) is the shallow transition zone between the Bay St.
Louis and the Mississippi Sound. The Cat Island Pass (Stations 3, 4 and 5) is the transition zone between the Mississippi Sound and the Mississippi Bight. The Mississippi Bight (Stations 6, 7 and 8) is the region directly south of the Mississippi barrier islands and is strongly influenced by the northern Gulf of Mexico. Separating the transect into regions was an attempt to isolate the spatial variation inherent in estuarine systems.

In addition to the ship-based observations, data for tidal rate of change and surface current vectors were obtained from a NOAA tide station and an NRL current model. These data were parsed by time and location and compared to the regional time series. Some gaps in the regional time series occurred due to poor weather conditions.

Horizontal Sections of Chlorophyll Fluorescence

The horizontal sections serve to illustrate patterns in phytoplankton abundance and seasonal stratification across the time series transect (Fig. 3.1). Contours of vertical distributions of chlorophyll fluorescence and $\sigma_t$ along the transect from Bay St. Louis to the Mississippi Bight were provided for selected cruises representative of different seasons. The representative cruise was chosen based on availability (whether there were data that month), completeness (how many stations were sampled), and distinguishing characteristics (distinct features and trends seen in the data). In addition to the selected horizontal sections for the four seasonal periods, fifteen additional transect profiles, not shown in Fig. 3.1 were included in Appendix A.

The classic patterns of a spring phytoplankton bloom with the onset of vertical stratification and a fall phytoplankton bloom with the breakdown of stratification
were evident in the horizontal sections for 2008 and 2010. The 2009 data differed from the other years in that a near surface pycnocline was present for most of the year in the Pass and Bight. Spring chlorophyll fluorescence levels were also lower in 2009 than in 2008 and 2010, but the fall of 2009 had the highest levels of all three years. The density structure along the transect showed the expected pattern of weak or no stratification in winter (Fig. 3.1A) followed by the development of strong stratification in spring and summer (Figs. 3.1B and 3.1C). The latter was accompanied by elevated chlorophyll fluorescence in surface waters. During 2008 and 2010, there was also evidence of upwelling of higher density subsurface water in spring and summer. Higher chlorophyll concentrations were observed in summer 2008 (Fig. 3.1C) than the spring (Fig. 3.1B), but the overall spatial range was smaller. A breakdown in stratification was evident in the fall (Fig. 3.1D, H and K), and distributions of chlorophyll fluorescence were less vertically heterogeneous and characterized by a horizontal gradient with higher values in the Inner Sound and the Cat Island Pass and decreasing in the Mississippi Bight. Patchy distributions in summer chlorophyll fluorescence (summer 2008, Fig. 3.1C and spring and summer 2010, Fig. 3.1I and J) was probably due to mixing of different water masses along the transect. Elevated chlorophyll fluorescence in near bottom waters was evident in Cat Island Pass during winter 2008 (Fig. 3.1E) and was also evident in some other periods, possibly an indication of bottom resuspension of pigments.

Conditions during 2009 differed from the other two years as was already noted, including the lack of strong stratification and relatively low chlorophyll
fluorescence in spring. In addition, levels of chlorophyll fluorescence in fall 2009 displayed the high chlorophyll fluorescence in the Inner Sound and Cat Island Pass in conjunction with the breakdown of vertical stratification.

Temporal Variations

Temporal patterns were examined in the ship-based observations as well as in the regional winds and river discharge. The wind and discharge data are presented initially for river discharge data from the Biloxi, Pearl, and Wolf Rivers, and wind vectors from NOAA buoys in the Mississippi Sound and Mississippi Bight. This is followed by an examination of the time-series of surface water chlorophyll fluorescence, nutrients, water temperature, salinity, water column stratification, tidal rate of change, and surface current vectors for each of the three regions: Inner Mississippi Sound, Cat Island Pass and Mississippi Bight.
Fig. 3.1. Horizontal sections of chlorophyll fluorescence and sigma-t. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise. The vertical black lines through each transect represent the stations sampled during that cruise.
Wind and River Discharge Time Series

The climate time-series data was taken from automated measurement devices for wind (NOAA buoys WYCM6 near station 1, GPM6 north of Ship Island, and 42007 station 7, see Fig. 2.1) and for river discharge (USGS discharge stations, Table 2.1). The data for 2007 through 2010 were included for winds (Fig. 3.2) and river discharge (Fig. 3.3).

Overall, the winds were generally from the southwest during the spring and summer and from the northeast during the fall and winter (Fig. 3.2). Though, this was not always the case, yearly wind patterns were variable. Spring and fall eastern winds occurred during 2007 and 2008. During 2008-2010, there was a consistent pattern in which the winds had shifted from predominantly south and west components to predominantly north and east components.

Variations in the Biloxi (Fig. 3.3A), Wolf (Fig. 3.3B), and Pearl River (Fig. 3.3C) discharge data were generally consistent among all the rivers. Largest discharge was characteristic during the winter and spring for all rivers. The years 2009 and 2010 were wetter than 2007 and 2008. The year 2009 had the highest combined discharge totals of the four years.
Fig. 3.2. Wind vector time series. Gaps in the data were due to instrument failure. Each panel represents observations from a different year: A and B) 2007, C and D, 2008, E and F) 2009 and G and H) 2010. Each vector line represents an average of five days.
Fig. 3.3. River discharge time series. The Biloxi (A), Wolf (B) and Pearl (C) River discharges (m$^3$ s$^{-1}$) were plotted from 2007 through 2010. Note the difference in Pearl River discharge scale. Vertical dashed black lines represent the cruise dates.
Regional Time Series

As stated previously, the time-series were organized into three regions, the Inner Sound, the Cat Island Pass, and the Mississippi Bight. For each region, patterns in chlorophyll and nutrient data were examined along with the environmental data. Ranges and median values of chlorophyll, silicate and phosphate progressively decreased from the Inner Sound to Cat Island Pass and finally to the Mississippi Bight (Table 3.1). In contrast, median values of salinity and stratification increased from the Inner Sound through Cat Island Pass and to the Mississippi Bight (Table 3.1).

**Tab. 3.1.** The median and range of the Inner Sound, Cat Island Pass, and Mississippi Bight variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Inner Sound</th>
<th>Cat Island Pass</th>
<th>Mississippi Bight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Chlorophyll</td>
<td>mg m⁻³</td>
<td>3.64</td>
<td>2.95</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.35-8.31</td>
<td>1.05-6.70</td>
<td>0.63-5.45</td>
</tr>
<tr>
<td>Surface Nitrate</td>
<td>µmol L⁻¹</td>
<td>0.07</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.00-0.38</td>
<td>0.00-2.84</td>
<td>0.00-2.21</td>
</tr>
<tr>
<td>Surface Silicate</td>
<td>µmol L⁻¹</td>
<td>43.26</td>
<td>18.09</td>
<td>4.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.03-110.64</td>
<td>1.01-47.09</td>
<td>0.60-16.39</td>
</tr>
<tr>
<td>Surface Phosphate</td>
<td>µmol L⁻¹</td>
<td>0.67</td>
<td>0.49</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14-1.88</td>
<td>0.07-1.08</td>
<td>0.03-1.02</td>
</tr>
<tr>
<td>Surface Temp.</td>
<td>ºC</td>
<td>20.44</td>
<td>25.47</td>
<td>27.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.51-32.28</td>
<td>13.32-32.10</td>
<td>14.01-31.46</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>ratio</td>
<td>11.67</td>
<td>18.62</td>
<td>22.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.59-22.32</td>
<td>3.13-28.75</td>
<td>13.89-35.07</td>
</tr>
<tr>
<td>Stratification</td>
<td>Akg m⁻³</td>
<td>1.89</td>
<td>4.99</td>
<td>9.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.03-14.63</td>
<td>0.00-20.50</td>
<td>0.03-18.02</td>
</tr>
<tr>
<td>Tidal Flux</td>
<td>m h⁻¹</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.08-0.07</td>
<td>-0.08-0.07</td>
<td>-0.06-0.07</td>
</tr>
<tr>
<td>Current u</td>
<td>m s⁻¹</td>
<td>0.03</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.01-0.06</td>
<td>-0.02-0.03</td>
<td>-0.10-0.21</td>
</tr>
<tr>
<td>Current v</td>
<td>m s⁻¹</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.03-0.03</td>
<td>-0.06-0.04</td>
<td>-0.12-0.05</td>
</tr>
</tbody>
</table>
Relationships among chlorophyll and other variables were examined using Spearman’s Rank correlation analysis (Appendix A). In addition, the internal structure of variation in the data was described using PCA (Appendix D) and SMLR was used to identify any significant predictors of chlorophyll and nutrients (Appendix C).

*Inner Sound*

The Inner Sound chlorophyll fluorescence tended to be higher in summer and early fall periods (Fig. 3.4A). Chlorophyll fluorescence was generally low in winter months. Surface chlorophyll was correlated positively with temperature (Fig. 3.5A) \( (p<0.01) \), a reflection of high chlorophyll concentrations coinciding with warm water temperatures in the well mixed Inner Sound. Tidal rate of change (Fig. 3.5D) was a significant predictor of chlorophyll concentrations according to SMLR \( (p<0.05) \) (Appendix C). Outgoing tides were associated with higher levels of chlorophyll fluorescence and incoming tides were associated with lower fluorescence. No significant relationships were found between chlorophyll concentrations and the Inner Sound nitrate, silicate and phosphate (Appendix A). However, the macronutrients did exhibit significant relationships with other environmental factors. Chlorophyll, tidal flux, temperature, and stratification were all associated with the first principal component from principal component analysis (PCA) (Appendix D). This component accounted for 23.70% of Inner Sound variance. This was consistent with the view that variability in chlorophyll was influenced by physical processes in this region.

Surface nitrate concentrations (Fig. 3.4B) were consistently low during the study. The median nitrate concentration was 0.07 \( \mu \text{mol L}^{-1} \). Inner Sound surface
silicate concentrations varied (Fig. 3.4C) with generally higher values in spring and summer as compared to fall and winter months. Values of silicate were correlated negatively \( (p<0.01, \text{Appendix A}) \) with surface salinity (Fig. 3.5B), consistent with a freshwater source of silicate. The median surface silicate concentration was 43.26 \( \mu \text{mol L}^{-1} \). Spring concentrations of silicate were above the Inner Sound median on a consistent basis. Silicate concentrations during 2008 and 2009 were lowest in the fall. The Inner Sound experienced a major increase in silicate concentration during the summer and fall of 2010. Silicate concentrations in 2010 approached 80 \( \mu \text{mol L}^{-1} \) during June (77.84 \( \mu \text{mol L}^{-1} \)), July (79.85 \( \mu \text{mol L}^{-1} \)), and September (79.70 \( \mu \text{mol L}^{-1} \)) and peaked in October with a concentration of 110.64 \( \mu \text{mol L}^{-1} \). These concentrations were higher during these months than at any other point during the three-year study. In contrast to the negative correlation between silicate and surface salinity, the high silicate concentrations in late 2010 were during a very low river discharge period (Fig. 3.3), an indication that the rivers were not the primary source of silicate during that time.

Concentrations of phosphate were generally higher during summer and fall (Fig. 3.4D). The median phosphate concentration was 0.67 \( \mu \text{mol L}^{-1} \). Surface phosphate concentrations were correlated significantly \( (p<0.05) \) with surface salinity, which could be explained by a dilution by freshwater inputs. This is reinforced by a negative correlation \( (p<0.01, \text{Appendix A}) \) with the Pearl and Wolf River outflows (Fig. 3.3B & 3.3C).

Surface currents (Fig. 3.5E & 3.5 F) in the Inner Sound were predominantly eastward with a median current speed of 0.03 m s\(^{-1}\). The along shelf component of
currents was primarily eastward. No seasonal patterns were apparent in the Inner Sound surface currents, but the zonal and meridional components of surface currents were correlated ($p<0.01$) with the corresponding zonal and meridional components of wind (Fig. 3.2 and Appendix A).
Fig. 3.4. Inner Sound chlorophyll and nutrients. Surface chlorophyll (A) concentration (mg m⁻³), and surface nitrate (B), silicate (C) and phosphate (D) concentrations (µmol L⁻¹). Each concentration bar represents a cruise date during the time-series. The dark grey horizontal line represents the median Inner Sound value.
Fig. 3.5. Inner Sound physical time series. Surface temperature (A), surface salinity (B), water column density change (C), tidal rate of change (D), and average along shelf (E) and cross shelf (F) currents. Negative tidal rates of change corresponded to the outgoing tide. Positive values of zonal currents \( u \) were eastward and positive values of meridional \( v \) were northward. Each vertical bar represents a cruise sampling day. The dark grey horizontal line represents the median Inner Sound value.
Cat Island Pass

Temporal patterns in chlorophyll fluorescence in Cat Island Pass (Fig. 3.6A) were similar to that in the Inner Mississippi Sound with highest surface chlorophyll concentrations occurring May through September. The median surface chlorophyll was 2.95 mg m\(^{-3}\). Tidal flux (Fig. 3.7D) was a significant predictor \((p<0.01)\) of chlorophyll concentrations according to SMLR (Appendix C). The majority of the above median chlorophyll samples were taken on an outgoing tide, while the majority of below median samples were taken on an incoming tide. Surface chlorophyll concentrations were correlated significantly with surface temperature (Fig. 3.7A) \((p<0.01)\) and stratification (Fig. 3.7C) \((p<0.05)\). No significant correlations were found between chlorophyll concentrations and the nutrients. The first component from the PCA was associated with variation in chlorophyll, temperature, stratification, and salinity, accounting for 29.48% of Cat Island Pass variance (Appendix D).

Surface phosphate concentration in Cat Island Pass was correlated negatively \((p<0.05,\ \text{Appendix A})\) with Pearl River discharge (Fig. 3.3C). Zonal currents were a significant \((p<0.05)\) predictor of phosphate according to the SMLR (Appendix C). There was no apparent seasonal pattern in surface phosphate concentrations (Fig 3.6D). Low concentrations of Cat Island Pass surface phosphate in 2009 coincided with high discharge from the Pearl River.

The Cat Island Pass nitrate concentrations (Fig. 3.6B) reached episodic high values, but were otherwise generally low with a median of 0.08 μmol L\(^{-1}\). The high concentrations occurred during the late fall/early winter and late spring, but the source of these peaks was not clear.
Cat Island Pass surface silicate values (Fig. 3.6C) were lower than the Inner Sound with a median of 20.95 $\mu$mol L$^{-1}$. Values above 30 $\mu$mol L$^{-1}$ were observed in fall of 2007, 2009, and 2010. The broad range was due to the large influx of silicate that occurred during the fall. Fall 2008 was the exception to this trend. Lower than median concentrations were measured in November 2008, but that was the only fall month sampled.

Cat Island Pass median surface currents were generally low, but showed a seasonal pattern of northeastward flow (positive zonal and meridional components) in spring (Fig. 3.7E and 3.7F). Stratification (Fig. 3.7 C) was correlated significantly ($p<0.05$, Appendix A) with cross shelf flow in spring.

No significant relationships between tides (Fig. 3.7D) and Cat Island Pass currents or nutrients were observed. However, as mentioned above, SMLR indicated that tides were a significant predictor of chlorophyll concentrations (Appendix C).
Fig. 3.6. Cat Island Pass chlorophyll and nutrients. Surface chlorophyll (A) concentration (mg m$^{-3}$), and surface nitrate (B), silicate (C) and phosphate (D) concentrations (μmol L$^{-1}$). Each concentration bar represents a cruise date during the time-series. The dark grey horizontal line represents the median Cat Island Pass value.
Fig. 3.7. Cat Island Pass physical time series. Surface temperature (A), surface salinity (B), water column density change (C), tidal rate of change (D), and surface currents (E & F). Negative tidal rates of change corresponded to the outgoing tide. Positive values of zonal currents ($u$) were eastward and positive values of meridional ($v$) were northward. Each vertical bar represents a cruise sampling day. The dark grey horizontal line represents the median Inner Sound value.
Mississippi Bight

The Mississippi Bight median surface chlorophyll (Fig. 3.8A) varied seasonally with an increase in spring and summer peak in 2008 and 2010, although values were generally lower than the concentrations seen in the Cat Island Pass (Fig. 3.6A and Table 3.1) and the Inner Sound (Fig. 3.4A and Table 3.1). Median chlorophyll was 1.55 mg m\(^{-3}\). Similar to other regions, chlorophyll fluorescence was generally lower during 2009. Mississippi Bight median surface chlorophyll was correlated (\(p<0.05\)) with stratification (Fig. 3.9C). Results of SMLR demonstrated that zonal currents were a significant predictor of chlorophyll concentrations (\(p<0.05\), Appendix C). Strong stratification could contribute to conditions favorable for the development of increased phytoplankton abundance in surface waters. Eastward currents would presumably be transporting water from nearshore areas with high chlorophyll concentrations. The first component in the Mississippi Bight PCA accounted for 39.96\% of the variation. The first component was associated with chlorophyll, zonal currents, stratification, and silicate (Appendix D).

Surface nitrate concentrations (Fig. 3.8B) in the Mississippi Bight were low generally as for the other regions. Three major peaks in nitrate were observed in June 2008, May 2010, and June 2010. These peaks corresponded with eastward currents (Fig. 3.9E) in the Mississippi Bight. The overall median was 0.06 \(\mu\)mol L\(^{-1}\).

Mississippi Bight surface silicate concentrations (Fig. 3.8C) peaked in spring and early summer with an overall median of 4.70 \(\mu\)mol L\(^{-1}\) (Table 3.1), lower than the other regions. Surface silicate was correlated positively (\(p<0.05\)) with surface
temperature (Fig. 3.9A) and negatively correlated with \((p<0.05)\) surface salinity (Fig. 3.9B) (Appendix A).

Mississippi Bight surface phosphate (Fig. 3.8D) was higher during 2008 than during 2009 and 2010. Surface phosphate was correlated \((p<0.05,\) Appendix A) with surface salinity (Fig. 3.9B), an apparent consequence of low river discharge in 2010 (Fig. 3.3).

The zonal component of Bight surface currents were eastward in spring primarily (Fig. 3.9E) and westward during the fall (Fig. 3.9F). The meridional component shifted northward during summer in 2008 and 2009 (Fig. 3.9F). The eastward component of surface currents was correlated \((p<0.01,\) Appendix A) with stratification (Fig. 3.9C) and was a significant predictor of chlorophyll concentrations in the Mississippi Bight.
Fig. 3.8. Mississippi Bight chlorophyll and nutrients. Surface chlorophyll (A) concentration (mg m$^{-3}$), and surface nitrate (B), silicate (C) and phosphate (D) concentrations (μmol L$^{-1}$). Each concentration bar represents a cruise date during the time-series. The dark grey horizontal line represents the median Mississippi Bight value.
Fig. 3.9. Mississippi Bight physical time series. Surface temperature (A), surface salinity (B), water column density change (C), tidal rate of change (D), and surface currents (E & F). Negative tidal rates of change corresponded to the outgoing tide. Positive tidal rates of change corresponded to the outgoing tide. Positive values of zonal currents (u) were eastward and positive values of meridional (v) were northward. Each vertical bar represents a cruise sampling day. The dark grey horizontal line represents the median Inner Sound value.
CHAPTER IV
DISCUSSION

The objectives of this study were to describe the seasonal and spatial distributions of phytoplankton biomass, and to determine relationships between environmental variables, nutrients and phytoplankton biomass in coastal Mississippi waters. Time series observations of these variables across a coastal transect were made during the first three years of the Northern Gulf Institute “Monitoring and Assessment of Marine and Coastal Ecosystems.”

Findings confirmed that the Mississippi coastal region is a complex ecosystem subject to a variety of different environmental influences. Variations in phytoplankton biomass and associated productivity provide an index of the biological variability in this coastal ecosystem. This biological variability was likely influenced by a host of environmental factors. Correlations of chlorophyll concentrations with temperature, stratification, and currents were observed, an indication of the strong influence of physical dynamics on phytoplankton. In contrast, expected correlations between chlorophyll concentrations and nutrients were not observed, which could be a consequence of the complex suite of factors influencing. The results highlight the dynamic nature of this coastal ecosystem. In the remainder of this discuss, the observed correlations are considered in the context of mechanisms regulating chlorophyll concentrations and phytoplankton abundance in this coastal regime.

Evaluation of Hypotheses

The first hypothesis was that the Inner Sound would lack a clear seasonal pattern and instead be dominated by episodic events related to riverine, tidal, and
wind forcing due to it’s shallow depth and close proximity to the mainland. Variability in these factors (river discharge, tidal flux, and wind) in the Inner Sound was postulated to overshadow any seasonality in the chlorophyll and nutrients. In fact, this was not the case, as chlorophyll concentrations were significant correlated with water temperature in the Inner Sound (Table A.1) and consequently exhibited strong seasonality (Fig. 3.4). Tidal flux was a significant predictor of chlorophyll concentrations, probably due to outgoing tides carrying high chlorophyll water from near shore, but this would not have contributed directly to the seasonal patterns. Spring and fall blooms could be detected as well as high summer chlorophyll concentrations. Inner Sound nutrient concentrations also showed distinct seasonality. The silicate concentrations rose and fell with a similar seasonal pattern to the chlorophyll. This could be due to other nutrients, such as nitrate, being imported to the system along with the silicate. Silicate import would outpace uptake, increasing concentration as phytoplankton responded to higher nitrate concentrations. Also, sediment to water silicate import is higher during the warmer temperatures due to a variety of microbial, chemical, and physical processes (Srithongouthai et al. 2003). This would have correlated the high chlorophyll season with high silicate concentrations due to temperature. Phosphate concentrations were highest during the summer and fall when riverine inputs were low. Due to the low concentrations through most of the study, nitrate was the only Inner Sound concentration that lacked a clear seasonal pattern. Even though riverine and tidal forcing did influence phytoplankton and nutrients in the Inner Sound, the hypothesis of a lack of
seasonality was not valid. Clear seasonal trends were evident in chlorophyll, silicate and phosphate.

The second hypothesis was that the Cat Island Pass would have a distinct seasonal pattern, influenced by tidal and riverine forcing, and seasonal stratification due to deeper water depths and larger distance from the mainland. A seasonal pattern in chlorophyll concentrations was observed in Cat Island Pass and was correlated with stratification. Though again not a contributor to the observed seasonal pattern, tidal flux was a significant predictor of chlorophyll concentrations. Outgoing tides would carry higher chlorophyll concentrations into the Cat Island Pass stations. Spring blooms were present and summertime concentrations were relatively high, but fall blooms were not observed. Riverine and tidal forcing were factors that likely influenced stratification in the Cat Island Pass, thus, influenced the chlorophyll concentration indirectly. A seasonal trend was also evident in silicate, which appeared to rise and fall in contrast to the seasonal phytoplankton signal. This was opposite of the Inner Sound, stratification may have prevented sediment silicate inputs in the surface. Seasonal variations in phosphate concentrations were characterized by high concentrations during Pearl River discharge lows. Nitrate was almost always low in the Cat Island Pass and did not exhibit any seasonal change. All three factors (river discharge, tidal flux, and stratification) exhibited seasonal trends. As was the case for the Inner Sound, temperature was not considered in the original formulation of the hypothesis, but was significantly correlated with chlorophyll. It was concluded that chlorophyll, silicate, and phosphate in Cat Island Pass varied on seasonal timescales in concert with variations in freshwater inputs and physical forcing mechanisms.
The third hypothesis that the Mississippi Bight would be characterized by a spring maximum related to nutrient availability and influenced by coastal current patterns and seasonal stratification was supported by the observations. Chlorophyll concentrations in the Mississippi Bight were characterized by a consistent spring maximum. Correlations were significant between chlorophyll concentrations and stratification, which supported the hypothesis. Zonal currents were a significant predictor of chlorophyll, and there was a correlation between currents and stratification. Eastward currents likely carried high chlorophyll concentrations and fresher, warmer waters from the Cat Island Pass and Chandeleur Sound. This would have led to higher chlorophyll concentrations and stratification. Chlorophyll concentrations in the Mississippi Bight were consistently lower than in the other regions, but this could not be attributed to lower nutrient concentrations.

In summary, several key patterns emerged in the dynamics of chlorophyll fluorescence and its relationship to environmental variables. This included a consistent seasonal pattern in chlorophyll fluorescence, periodic high inner shelf chlorophyll in fall, and interannual variability. Each of these of aspects is considered further in the remainder of this discussion.

Seasonal Variability

Higher levels of chlorophyll fluorescence were observed during the late spring (Figs. 3.5-3.7), which was consistent with the classical spring bloom pattern related to seasonal stratification and enhanced growth of phytoplankton in the stratified upper water column as seen in many other estuarine systems (Malone et al. 1988; Lohrenz et al. 1999; Cloern & Jassby, 2010). The significant correlation between Mississippi
Bight and Cat Island Pass surface chlorophyll and density stratification (Tables A.2 and A.3) provided evidence in support of this. This was again consistent with the view that stratification influenced phytoplankton concentrations, presumably by subjecting the phytoplankton to more light (Pennock & Sharp 1994; Anderson & Taylor 2001; Xu *et al.* 2010).

Additionally, the Inner Sound and Cat Island Pass surface chlorophyll was correlated strongly with surface temperature (Tables A.1 and A.2), possibly due to higher solar irradiance during the warmer temperatures. Tidal flux was a significant predictor of chlorophyll concentration (Appendix C). Furthermore, ebbing tidal flow (Fig. 3.7D) was correlated with temperature and stratification, both of which were correlated with Cat Island Pass chlorophyll concentrations (Table A.2). A relationship between surface temperature and chlorophyll was also reported by Holiday *et al.* (2007) in the eastern Mississippi Sound. Similar relationships between chlorophyll concentrations and surface temperature have been observed in Beaufort, NC (Thayer 1971); Moreton Bay, Australia (O’Donohue & Dennison 1997); Mobile Bay AL; and the eastern Mississippi Sound (Holiday *et al.* 2007). As is the case for the Inner Sound, all of these other locations are shallow, well-mixed estuaries.

The potential was considered for nutrients as controlling factors contributing to the seasonal trends in chlorophyll variations. Seasonal patterns were evident in phosphate and silicate in all regions and nitrate in the Inner Sound, which was consistent with the patterns observed for chlorophyll. However, relationships between chlorophyll fluorescence and nutrients were not significant. Nitrate was generally low in concentration at all sites. The highest median surface concentrations of nitrate were
observed in Cat Island Pass followed by the Mississippi Bight, indicating that freshwater was not the primary source for nitrate. A previous study observed a similar trend of higher nitrate levels seaward of the barrier islands and showed the Pearl River discharge to be nutrient-poor relatively (Eleutarius 1975). The same study noted that Bayou Cassotte, near the Pascagoula River, had high concentrations of nitrate due to local industrial releases. EPA water discharge permits for nitrogen discharge are currently issued for wastewater, seafood processing and concrete plants in the Biloxi Bay and Bay Saint Louis areas (http://www.epa.gov/enviro/facts/qmr.html). Whether the source of nitrogen was from Biloxi Bay and Bay Saint Louis or offshore sources was not clear.

Peaks in nitrate concentration were observed in Cat Island Pass and the Mississippi Bight, (Figs. 3.7 and 3.8), but did not correspond between regions. This was most likely due to the movement of water masses in and around the sampling area. Sampling during two cruises, nine days apart, during May 2010 illustrated how quickly concentrations could change as shown by a nearly 3 μmol L⁻¹ difference. These observations were made during the Macondo Well oil spill that started after the blowout, explosion and subsequent sinking of the Deep Water Horizon offshore drilling rig (http://media.nola.com/news_impact/other/oil-cause-050710.pdf). While it seems unlikely that the oil or dispersants were responsible for the higher nitrate concentrations, it is possible that Mississippi River freshwater diversions that were opened on May 12, 2010 to prevent oil from reaching the Louisiana marshes could have contributed. Over 400 m³ s⁻¹ of Mississippi River water was diverted into Breton Sound (http://www.wlf.louisiana.gov/news/30675). Average winds for May 2010
were out of the south (Figure 3.2A). The Breton Sound diversion water could have passed through the Chandeleur Sound and into Cat Island Pass, resulting in the higher nitrate concentrations.

Upwelling could be another mechanism for higher nitrate concentrations in the outer stations. A study of winds and currents in the Mississippi-Alabama shelf found that the northward shift in winds during the summer created upwelling off the barrier islands (Dzwonkowski et al. 2011). Wind induced upwelling was weaker when stronger stratification was present. This could explain the why high nitrate concentrations appear to have no pattern. Given the monthly sampling rate, the high nitrate concentrations seen in the Cat Island Pass and Mississippi Bight appear random, but may in fact be related to short timescale circulation events. There was evidence of upwelling during spring and summer of 2008 and 2010 as evidenced by higher density water extending inshore (Fig. 3.1). These some of these times corresponded with generally south winds and the high nitrate concentrations.

Silicate declined going from the Inner Sound to the Mississippi Bight and was correlated negatively with surface salinity except in Cat Island Pass (Tables A.1-A.3). Riverine inputs (Fig. 3.3) were clearly an important source for silicate the Mississippi coastal area, as rivers are the source of up to 80% of oceanic silicate (Tréguer et al. 1995). The Inner Sound and Cat Island Pass silicate decreased with the spring bloom, but silicate concentrations increased through the summer and fall. This may have been due to diatoms dominating the winter and spring bloom and other phytoplankton species dominating for the rest of the year (Egge & Aksnes 1992). Mississippi Bight silicate concentrations generally increased in concert with increases in chlorophyll
concentrations. Higher silicate concentrations could have been related to coastal sources coming from the Mississippi Sound and other inland waters.

Phosphate also decreased going from the Inner Sound to the Mississippi Bight. The Inner Sound phosphate concentrations were correlated negatively with the Wolf and Pearl River discharges, while the Cat Island Pass phosphate concentrations were only correlated negatively to the Pearl River discharge. The Inner Sound and Mississippi Bight phosphate concentrations were correlated with surface salinity (Tables A.1-A.3). This pattern was consistent with a freshwater dilution of phosphate. Seasonal highs in phosphate concentration were during low river discharge periods, reinforcing the idea that the Mississippi Sound was a source for phosphate. Westward currents were also a significant predictor of high phosphate concentrations (Appendix C). Eleuterius (1975) found that elevated concentrations of phosphate were coming from the same area (Bayou Casotte) as the high nitrate concentrations. This may still be the case today or another source of phosphate could exist in the Mississippi Sound. EPA water discharge permits for phosphate are issued to waste water treatment plants in the Biloxi Bay. In addition, Mississippi Phosphates Corporation© has a diammonium phosphate production facility near the Pascagoula River in the eastern Mississippi Sound. Diammonium phosphate is widely used as a phosphate fertilizer. This may be the current source of phosphate seen in the Mississippi Sound.

Seasonal variations in winds were also potentially a factor in contributing to observed patterns. Winds were predominantly from the northeast for all of the years, but during the late spring through summer, winds shifted to out of the south for 10-12 weeks (Fig. 3.2). This was accompanied by a shift in currents to the north and east...
(Fig. 3.9 and Table A.3), and such currents may have carried low salinity water from the Mississippi River delta region. Walker et al. (2005) reported summer winds out of the southwest off the Mississippi Delta for 4-6 weeks during their study. Kjerve (1983) also observed a similar pattern in the Mississippi Sound, where southwest winds were recorded from late spring to fall. Differences in wind patterns during this study from prior observations could have been partially due to the location of the wind stations. Daytime thermal convection can lead to stronger northerly winds during the warmer months. The wind stations for this study were 28 km (2007-2008) and 18 km (2009-2010) from the mainland, decreasing the impact of warmer land surfaces on wind measurements. Two of Kjerve’s stations were less than 1 km from the shore. Even so, the southwestern shift in wind patterns is well documented for this region and can be attributed to the summertime westward oscillation of the North Atlantic Subtropical High or the Bermuda High (Li et al. 2011). The Bermuda High moves westward across the subtropical Atlantic during the summer. The western side of the high penetrates into the northern central Gulf of Mexico. The anticyclonic winds of the high pressure system redirect the northeast winds to the southwestern direction in the summer. A subtropical branch of the jet stream draws moisture from the north Pacific and carries it to the northern Gulf of Mexico during the winter and early spring (Mo et al. 2005). This jet stream influence was the most likely reason why local river discharges were higher during the winter and early spring.

River discharge (Fig. 3.3), while not correlated significantly with chlorophyll fluorescence, may have influenced dynamics of chlorophyll through transport of nutrients and effects on stratification. In the coastal Mississippi waters, salinity has
been found to be the dominant factor influencing density (Kjerve 1983) and river discharge may have contributed to stratification. River discharge may also contribute to nutrient loading (Harding 1994; Cloern 1996; Qian et al. 2003).

*Inner Shelf Chlorophyll Dynamics*

In addition to the consistent pattern of increased chlorophyll in spring and summer, high chlorophyll fluorescence also occurred in inner shelf waters in fall (Figs. 3.1, 3.5 and 3.6). This pattern was associated with reduced stratification in Mississippi Bight waters (Figs. 3.1 and 3.7). Such a pattern of elevated inner shelf chlorophyll is a common observation in many coastal ecosystems. For example, Chen et al. (2000) observed a similar pattern off the Louisiana-Texas shelf in November 1993, and attributed this to circulation patterns that retained chlorophyll and supplied nutrients to the inner shelf waters. The higher chlorophyll values may have been related to tidal action (Cloern 1996) transporting materials from the Bay Saint Louis. Outgoing tides would carry higher Inner Sound chlorophyll concentrations out of the Cat Island Pass. In the process, warmer, lower salinity water was carried out too. Increased bottom stress due to tidal currents may also result in bottom sediment resuspension as has been observed near the mouth of Mobile Bay (Lohrenz 2003). Such a process would resuspend phytoplankton and detrital pigments (Boss & Zaneveld 2003) and may also increase available nutrients for phytoplankton growth (Lohrenz et al. 2008; Briceno & Boyer 2010). The coarse temporal resolution of sampling during this study makes it difficult to determine clear relationships between elevated chlorophyll concentrations and episodic variations in winds and tides.
Atwell (1973) made three observations about the chlorophyll dynamics in the Mississippi Sound study area: chlorophyll concentrations decrease with distance from the shore during the summer; fall coincided with patchy distributions of chlorophyll concentrations; and areas of low chlorophyll concentrations were observed near Bay Saint Louis in winter. These findings were generally consistent with those of the current study, with the exception that patchy distributions occurred year round in the Mississippi coastal zone and were not confined to the fall season (Figs. 3.1C, 3.1D, 3.1F, 3.1J).

The significant covariates with and predictors of chlorophyll concentration were temperature, stratification, ebbing tides, and eastward currents (Fig. 4.1). However, none of these factors were significant in every region. Temperature was correlated with chlorophyll in the Inner Sound and Cat Island Pass. Stratification was correlated with chlorophyll in the Cat Island Pass and Mississippi Bight. It was evidence of transitional nature of the study area that only adjacent regions shared significant influences. Physical dynamics were important as well. Tides were significantly correlated with chlorophyll in the narrow pass while currents were significantly related to chlorophyll in the open waters of the Mississippi Bight.
Fig. 4.1. Significant correlations with chlorophyll concentrations along the NGI transect. Warmer temperatures and outgoing tides were correlated with Inner Sound and Cat Island Pass chlorophyll. Stratification was correlated with chlorophyll in the Cat Island Pass and Mississippi Bight. Eastward currents were correlated with chlorophyll in the Mississippi Bight. Symbols: Sun=Temperature, Red Arrows=Tidal Flux, Green Layers=Stratification, and Black Waves/Arrow=Currents/Direction.

Interannual Variability

Another finding of this study was the interannual variability in multiple observations over the three year time series. This was particularly evident in the continuous time-series of winds (Fig. 3.2) and river discharge (Fig. 3.3), but was also reflected in the chlorophyll and environmental time series. Chlorophyll levels were generally lower during spring and summer 2009 in the Mississippi Bight compared to other years (Fig. 3.8). Peaks in chlorophyll were also observed in June 2008, June 2009, September 2009, and May 2010. These changes may be attributed to fluctuations in the El Niño/Southern Oscillation (ENSO). Based on the reported
Multivariate ENSO Index (MEI)
(http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/), there was an El Niño event during summer, fall and winter 2009.

River discharge may have contributed to interannual variability, although the multiple freshwater sources in this region makes it difficult to discern effects of any one of them. The average annual discharge of the Biloxi, Wolf and Pearl Rivers increased every year between 2007 and 2009 (Fig. 3.3). Phosphate concentrations were correlated significantly and negatively with the Pearl River discharge in both the Inner Sound and Cat Island Pass regions (Tables A.1 and A.2). This was likely due to dilution of anthropogenic phosphate from the eastern Mississippi Sound. Discharge in 2008 was the second highest yearly average due to multiple small discharge peaks throughout the year. In 2010, the highest winter discharge of the four years was observed, but there were no large outflow events after the winter. A study of average monthly discharges of the Jourdan, Biloxi and Pearl during 1951-1966 (Christmas et al. 1975) found highest discharge occurred during the months of February and March. This was in agreement with the 2007-2010 river discharge data for which the highest discharge rates occurred during the winter and early spring. The September 2008 high outflow was likely due to hurricane Gustav. The hurricane made landfall as a category 2 storm in Cocodrie Louisiana on September 1, 2008 (Beven & Kimberlain 2009). The Biloxi and Wolf Rivers had a sharp spike in discharge on September 1. A more gradual increase in discharge was seen for the Pearl River, possibly a consequence of its larger drainage basin.
Phytoplankton washout may have been the cause of the lower chlorophyll concentrations during spring 2009. The increased riverine discharge would flush phytoplankton out of the estuary and decrease chlorophyll concentration (Abreu et al. 2010; Valdes-Weaver 2010). Observations in other microtidal estuaries have observed that chlorophyll concentrations were related to river discharge (Monbet 1992; Abreu et al. 2010). In the present study, high discharge rates seen during the spring of 2009 appeared to keep phytoplankton from accumulating in the typical spring stratified layer (Fig. 3.1F). When river flooding occurs, it is expected that phytoplankton washout will happen (Abreu et al. 2010; Valdes-Weaver 2010). This occurs when the estuary turns into an extension of a swollen river and phytoplankton are carried off shore. This may be a reason for the higher chlorophyll fluorescence during June 2010 in the Mississippi Bight (Appendix A).

Research Recommendations

Solar radiation is a critical source of energy for phytoplankton and was not quantified in this study. In addition to seasonal changes in light intensity on the surface, estuarine environments are highly variable in available light due to turbidity (Cloern 1987) and phytoplankton self shading (Bannister 1974). Information about variability in solar radiation may help to better understand phytoplankton dynamics. For future research efforts, depth integrated photosynthetically active radiation should be measured in order to quantify relationships between light and phytoplankton biomass.

Zooplankton grazing on phytoplankton may be an important top-down constraint on phytoplankton abundance (Fahnenstiel et al. 1995; Murell & Lores
It would be valuable to understand the zooplankton feeding dynamics in Mississippi waters. In addition to better understanding of phytoplankton abundances, zooplankton studies could yield insight into linkages between phytoplankton and higher trophic levels.

Short-term, high temporal resolution studies would be helpful in understanding the variability of the coastal Mississippi phytoplankton and nutrients in relationship to shorter time scale forcing. For instance, if sampling were conducted at one station for seven days, this would be useful in determining the role of tidal flux, shifts in wind direction/speed and nutrient chlorophyll relationships. High sampling rate, short period studies should be conducted on a seasonal basis to resolve some of the short-term variability in the region.

Long-term effects should also be characterized. Keeping this time series functioning is a large and expensive task, but this study is unique to the Mississippi coast. With a longer time series, comes a better view of climate (Livingston 2007; Briceno & Boyer 2010) and phenological (Kromkamp & Engeland 2010) changes affecting the coastal ecology. It is also important to have preliminary data in an area in case of an unforeseen disaster. Natural and anthropogenic ecological disturbances occur on a regular basis. Having a data set of “baseline” environmental conditions prior to any disturbance will be an asset to any recovery efforts. Comparisons of pre- and post-disturbance conditions can be used to find changes to the local ecology and determine the consequences to the biological system.

Lastly, satellite imagery of chlorophyll abundances should be considered in conjunction with this coastal time-series. Using satellite imagery in combination with
the water column profiles from this study, a synoptic view of variability in chlorophyll can be produced. Using this strategy would grant a better understanding of where blooms are forming and where phytoplankton are moving in Mississippi coastal waters.

Conclusions

This study described seasonal and spatial phytoplankton variations, where chlorophyll concentrations were high during the spring and fall blooms and decreased in concentration going seaward. These results also provided an important baseline of environmental variables and insights into the relationships between phytoplankton, nutrients and the environmental variables. Water temperature and stratification were important variables related to the seasonal patterns observed in chlorophyll concentrations. However, multiple variables interacted to influence nutrient and chlorophyll concentrations highlighting the complex nature of this estuarine system.
## APPENDIX A

### SPEARMAN’S RHO CORRELATIONS

#### Spearman’s Rho Correlations

| SurfChl | SurfN | SurfSi | SurfP | Windu | Windv | Currentu | Currentv | SurfTemp | SurfSal | DenChl | Biloxi | Pearl | Wolf | TidalRate |
|---------|-------|-------|-------|-------|-------|----------|----------|----------|---------|--------|--------|-------|------|-------|-----------|
| SurfChl |       |       |       |       |       |          |          |          |         |        |        |       |      |        |           |
| SurfN   | 0.032 |       |       |       |       |          |          |          |         |        |        |       |      |        |           |
| SurfSi  |       | 0.907 |       |       |       |          |          |          |         |        |        |       |      |        |           |
| SurfP   | 0.119 | 0.919 |       |       |       |          |          |          |         |        |        |       |      |        |           |
| Windu   | 0.558 | 0.861 | 0.774 | 0.914 | 0.182 |          |          |          |         |        |        |       |      |        |           |
| Windv   |       |       |       |       |       |          |          |          |         |        |        |       |      |        |           |
| Currentu| -0.109 | -0.366 | -0.132 | -0.411 | -0.775 | 0.234 |        |          |         |        |        |       |      |        |           |
| Currentv| 0.036 | 0.092 | 0.058 | 0.030 | 0.600 | 0.314 |        |          |         |        |        |       |      |        |           |
| Currentu| 0.022 | 0.208 | 0.195 | 0.199 | 0.044 | 0.823 | -0.172 |          |         |        |        |       |      |        |           |
| Currentv|       |       |       |       |       |          |          |          |         |        |        |       |      |        |           |
| SurfTemp| 0.540 | 0.001 | 0.668 | 0.317 | -0.237 | 0.142 | -0.333 | 0.391 |        |         |        |       |      |        |           |
| SurfSal | 0.001 | 0.997 | 0.689 | 0.064 | 0.276 | 0.851 | 0.063 | 0.074 |        |         |        |       |      |        |           |
| DenChl  |       |       |       |       |       |          |          |          |         |        |        |       |      |        |           |
| Biloxi  | 0.141 | 0.283 | 0.659 | -0.369 | 0.236 | 0.094 | 0.207 | 0.060 | -0.192 | -0.326 | 0.000 |       |      |        |           |
| Pearl   | 0.502 | 0.173 | 0.742 | 0.976 | 0.262 | 0.892 | 0.344 | 0.795 | 0.356 | 0.109 | 1.000 |       |      |        |           |
| Wolf    | 0.163 | -0.114 | -0.017 | -0.714 | -0.262 | 0.194 | 0.381 | 0.103 | -0.271 | -0.472 | 0.172 | 0.142 | 0.873 |       |           |
| TidalRate| 0.072 | 0.041 | 0.079 | 0.021 | 0.269 | 0.066 | 0.035 | 0.007 | 0.817 | 0.030 | 0.846 |       |      |        |           |

* Correlation is significant at the 0.01 level (2-tailed).
* * Correlation is significant at the 0.05 level (2-tailed).

Tab. A1. Inner Sound Spearman’s rho Correlations for surface chlorophyll, surface nitrate, surface silicate, surface phosphate, wind u vector, wind v vector, surface current u vector, surface current v vector, surface temperature, surface salinity, density change (stratification), Biloxi River discharge, Pearl River discharge, Wolf River discharge, tidal rate of change.
### Spearman's rho Correlations

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<td>0.176</td>
<td>0.176</td>
<td>0.176</td>
<td>0.176</td>
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<td>0.326</td>
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<tr>
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</tbody>
</table>

* Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

**Tab. A2.** Cat Island Pass Spearman’s rho Correlations for surface chlorophyll, surface nitrate, surface silicate, surface phosphate, wind u vector, wind v vector, surface current u vector, surface current v vector, surface temperature, surface salinity, density change (stratification), Biloxi River discharge, Pearl River discharge, Wolf River discharge, tidal rate of change.
Mississippi Bight Spearman’s rho Correlations for surface chlorophyll, surface nitrate, surface silicate, surface phosphate, wind u vector, wind v vector, surface current u vector, surface current v vector, surface temperature, surface salinity, density change (stratification), Biloxi River discharge, Pearl River discharge, Wolf River discharge, tidal rate of change.

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<thead>
<tr>
<th>Variable A</th>
<th>Correlation Coefficient</th>
<th>Sig. (2-tailed)</th>
<th>N</th>
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</thead>
<tbody>
<tr>
<td>Chlorophyll</td>
<td>0.199</td>
<td>0.374</td>
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<tr>
<td>Nitrate</td>
<td>0.048</td>
<td>0.191</td>
<td>22</td>
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<tr>
<td>Silicate</td>
<td>0.435</td>
<td>0.236</td>
<td>22</td>
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<tr>
<td>Phosphate</td>
<td>0.215</td>
<td>0.143</td>
<td>22</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.206</td>
<td>0.163</td>
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<tr>
<td>Salinity</td>
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<td>Density</td>
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<td>0.050</td>
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<tr>
<td>Biloxi</td>
<td>0.205</td>
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<td>22</td>
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<tr>
<td>Pearl</td>
<td>0.159</td>
<td>0.094</td>
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<tr>
<td>Wolf</td>
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<td>Tides</td>
<td>0.307</td>
<td>0.000</td>
<td>22</td>
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</tbody>
</table>

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Tab. A3. Mississippi Bight Spearman’s rho Correlations for various oceanographic and hydrographic variables.
APPENDIX B

CHLOROPHYLL Profiles

Fig. B1. Cruise transects for September 2007 (A), October 2007 (B), November 2007 (C), and December 2007 (D). Warmer colors indicate higher chlorophyll (mg m$^{-3}$) and isolines represent sigma T (11, 14, 17, 20, 23).
Fig. B2. Cruise transects for February 2008 (A), March 2008 (B), April 2008 (C), May 2008 (D), June 2008 (E), July 2008 (F), August 2008 (G), and November 2008 (H). Warmer colors indicate higher chlorophyll (mg m$^{-3}$) and isolines represent sigma T (11, 14, 17, 20, 23).
Fig. B3. Cruise transects for January 2009 (A), March 2009 (B), April 2009 (C), May 2009 (D), June 2009 (E), August 2009 (F), September 2009 (G), November 2009 (H). Warmer colors indicate higher chlorophyll (mg m$^{-3}$) and isolines represent sigma T (11, 14, 17, 20, 23).
Fig. B4. Cruise transects for March 2010 (A), May 2010a (B), May 2010b (C), June 2010 (D), July 2010 (E), September 2010 (F), October 2010 (G), and November 2010 (H). Warmer colors indicate higher chlorophyll (mg m$^{-3}$) and isolines represent sigma T (11, 14, 17, 20, 23).
APPENDIX C

MULTIPLE LINEAR REGRESSIONS

Inner Sound Regression (All Variables)

Variables Entered/Removed(a)

<table>
<thead>
<tr>
<th>Model</th>
<th>Variables Entered</th>
<th>Variables Removed</th>
<th>Method</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>Stepwise (Criteria: Probability-of-F-to-enter &lt;= .050, Probability-of-F-to-remove &gt;= .100).</td>
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</table>

Model Summary(b)

<table>
<thead>
<tr>
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<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
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</thead>
<tbody>
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ANOVA(b)

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<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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</thead>
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<tr>
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<td>36.108</td>
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<td></td>
<td>Residual</td>
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<td>21</td>
<td>2.363</td>
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</tr>
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<td></td>
<td>Total</td>
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<td>22</td>
<td></td>
<td></td>
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</table>

Coefficients(a)

<table>
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<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
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</thead>
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<td></td>
<td>B</td>
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</tr>
<tr>
<td>1</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(Constant)</td>
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a Dependent Variable: SurfChl
### Excluded Variables (b)

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<th>t</th>
<th>Sig.</th>
<th>Partial Correlation</th>
<th>Collinearity Statistics</th>
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</thead>
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<td>-.593</td>
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<tr>
<td></td>
<td>Currentu</td>
<td>.103(a)</td>
<td>.578</td>
<td>.570</td>
<td>.128</td>
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<tr>
<td></td>
<td>DenChg</td>
<td>.179(a)</td>
<td>1.062</td>
<td>.301</td>
<td>.231</td>
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a Predictors in the Model: (Constant), SurfTemp  
b Dependent Variable: SurfChl

### Residuals Statistics (a)

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<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
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a Dependent Variable: SurfChl
### Inner Sound Regression (Temperature)

**Variables Entered/Removed(a)**

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<td>1</td>
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a Dependent Variable: SurfChl

**Model Summary(b)**

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a Predictors: (Constant), TideRate
b Dependent Variable: SurfChl

**ANOVA(b)**

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<th>Sig.</th>
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a Predictors: (Constant), TideRate
b Dependent Variable: SurfChl

**Coefficients(a)**

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a Dependent Variable: SurfChl
### Excluded Variables(b)

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<th>Partial Correlation</th>
<th>Collinearity Statistics</th>
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*a Predictors in the Model: (Constant), TideRate  
b Dependent Variable: SurfChl

### Residuals Statistics(a)

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*a Dependent Variable: SurfChl*
Cat Island Pass Regression (All Variables)

Variables Entered/Removed(a)

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a Dependent Variable: ChlSurf

Model Summary(b)

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<th>Adjusted R Square</th>
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a Predictors: (Constant), SurfT
b Dependent Variable: ChlSurf

ANOVA(b)

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<th>Mean Square</th>
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<th>Sig.</th>
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a Predictors: (Constant), SurfT
b Dependent Variable: ChlSurf

Coefficients(a)

<table>
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<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
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<td></td>
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<td>Std. Error</td>
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a Dependent Variable: ChlSurf
### Excluded Variables(b)

<table>
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<th>Sig.</th>
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<th>Collinearity Statistics</th>
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a Predictors in the Model: (Constant), SurfT

b Dependent Variable: ChlSurf

### Residuals Statistics(a)

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<th>Std. Deviation</th>
<th>N</th>
</tr>
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a Dependent Variable: ChlSurf
### Variables Entered/Removed(a)

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a Dependent Variable: ChlSurf

### Model Summary(b)

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<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
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a Predictors: (Constant), Tides  
b Dependent Variable: ChlSurf

### ANOVA(b)

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<th>Mean Square</th>
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<th>Sig.</th>
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<tr>
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<td>1</td>
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<tr>
<td></td>
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<td>23</td>
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a Predictors: (Constant), Tides  
b Dependent Variable: ChlSurf

### Coefficients(a)

<table>
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<tr>
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<th>Unstandardized Coefficients</th>
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<th>Sig.</th>
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<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
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a Dependent Variable: ChlSurf
### Excluded Variables(b)

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<th>Collinearity Statistics</th>
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<tr>
<td>1</td>
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<td>-.227(a)</td>
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<tr>
<td></td>
<td>DenChg</td>
<td>.137(a)</td>
<td>.596</td>
<td>.558</td>
<td>.129</td>
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<tr>
<td></td>
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<td>-.014</td>
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<td>SurfP</td>
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<td>.886</td>
<td>.032</td>
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<tr>
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<td>.774</td>
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<tr>
<td></td>
<td>Currentv</td>
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*a* Predictors in the Model: (Constant), Tides  
*b* Dependent Variable: ChlSurf

### Residuals Statistics(a)

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
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<th>Std. Deviation</th>
<th>N</th>
</tr>
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*a* Dependent Variable: ChlSurf
### Variables Entered/Removed(a)

<table>
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<tr>
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<th>Variables Entered</th>
<th>Variables Removed</th>
<th>Method</th>
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<td>Stepwise (Criteria: Probability-of-F-to-enter &lt;= .050, Probability-of-F-to-remove &gt;= .100).</td>
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a Dependent Variable: ChlSurf

### Model Summary(b)

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<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
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a Predictors: (Constant), Currentu
b Dependent Variable: ChlSurf

### ANOVA(b)

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<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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<tr>
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<td>6.166</td>
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a Predictors: (Constant), Currentu
b Dependent Variable: ChlSurf

### Coefficients(a)

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
</tr>
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a Dependent Variable: ChlSurf
### Excluded Variables(b)

<table>
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<tr>
<th>Model</th>
<th>Beta In</th>
<th>t</th>
<th>Sig.</th>
<th>Partial Correlation</th>
<th>Collinearity Statistics</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>SurfSal, .004(a)</td>
<td>.016</td>
<td>.987</td>
<td>.004</td>
<td>.670</td>
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<tr>
<td></td>
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<td>.905</td>
<td>.031</td>
<td>.536</td>
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<tr>
<td></td>
<td>SurfS, -.148(a)</td>
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<td>.564</td>
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<td>.756</td>
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*a* Predictors in the Model: (Constant), Current 

*b* Dependent Variable: ChlSurf

### Residuals Statistics(a)

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
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<td>.000</td>
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<td>.000</td>
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*a* Dependent Variable: ChlSurf
## INNER SOUND

### Factor Analysis

<table>
<thead>
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<th>Component</th>
<th>Initial Extraction</th>
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<tbody>
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<td>SurfChl</td>
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<tr>
<td>SurfN</td>
<td>1.000</td>
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<tr>
<td>SurfS</td>
<td>1.000</td>
</tr>
<tr>
<td>SurfP</td>
<td>1.000</td>
</tr>
<tr>
<td>Windu</td>
<td>1.000</td>
</tr>
<tr>
<td>Windv</td>
<td>1.000</td>
</tr>
<tr>
<td>SurfTemp</td>
<td>1.000</td>
</tr>
<tr>
<td>SurfSal</td>
<td>1.000</td>
</tr>
<tr>
<td>DenChg</td>
<td>1.000</td>
</tr>
<tr>
<td>Wolf</td>
<td>1.000</td>
</tr>
<tr>
<td>TideRate</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Extraction Method: Principal Component Analysis.

### Total Variance Explained

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial Eigenvalues</th>
<th>Total % of Variance</th>
<th>Cumulative %</th>
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<tbody>
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<td>23.696</td>
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<td>68.288</td>
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<td>1.039</td>
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<td>77.738</td>
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<td>0.838</td>
<td>7.617</td>
<td>85.354</td>
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<td>0.750</td>
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<td>92.172</td>
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<td>0.394</td>
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<td>0.259</td>
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<td>0.669</td>
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</table>

Extraction Method: Principal Component Analysis.

### Extraction Sums of Squared Loadings

<table>
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<th>Total % of Variance</th>
<th>Cumulative %</th>
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<tbody>
<tr>
<td>1</td>
<td>2.607</td>
<td>23.696</td>
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<tr>
<td>2</td>
<td>2.032</td>
<td>18.472</td>
</tr>
<tr>
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<td>1.605</td>
<td>14.590</td>
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<tr>
<td>4</td>
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<td>11.530</td>
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<td>1.039</td>
<td>9.450</td>
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<td>0.838</td>
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<td>6.818</td>
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<tr>
<td>8</td>
<td>0.394</td>
<td>3.562</td>
</tr>
<tr>
<td>9</td>
<td>0.259</td>
<td>2.358</td>
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<tr>
<td>10</td>
<td>0.134</td>
<td>1.219</td>
</tr>
<tr>
<td>11</td>
<td>0.074</td>
<td>0.669</td>
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Extraction Method: Principal Component Analysis.

### Component Matrix(a)

<table>
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<th>3</th>
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<tr>
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<td></td>
</tr>
<tr>
<td>SurfChl</td>
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</tr>
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<td>SurfN</td>
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<td></td>
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<tr>
<td>SurfP</td>
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<tr>
<td>SurfS</td>
<td>-0.504</td>
<td>0.535</td>
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<td>Windu</td>
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<tr>
<td>SurfSal</td>
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Extraction Method: Principal Component Analysis.

---

a. 3 components extracted.
### Rotated Component Matrix(a)

<table>
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<th>Component 2</th>
<th>Component 3</th>
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<tbody>
<tr>
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<td>SurfTemp</td>
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</tr>
<tr>
<td>TideRate</td>
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<td></td>
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<tr>
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<tr>
<td>SurfSal</td>
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</tr>
<tr>
<td>Wolf</td>
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<td>Windv</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Windu</td>
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Extraction Method: Principal Component Analysis.

a. Rotation converged in 5 iterations.

### Component Transformation Matrix

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Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.
## Factor Analysis

### CAT ISLAND PASS

#### Communalities

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial</th>
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<tbody>
<tr>
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<tr>
<td>SurfS</td>
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<td>0.886</td>
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<tr>
<td>Currentv</td>
<td>1.000</td>
<td>0.762</td>
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#### Total Variance Explained

<table>
<thead>
<tr>
<th>Component</th>
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<td>Total</td>
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<td>3</td>
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<td>13.337</td>
</tr>
<tr>
<td>4</td>
<td>1.083</td>
<td>10.832</td>
</tr>
<tr>
<td>5</td>
<td>0.926</td>
<td>9.256</td>
</tr>
<tr>
<td>6</td>
<td>0.722</td>
<td>7.220</td>
</tr>
<tr>
<td>7</td>
<td>0.448</td>
<td>4.487</td>
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<td>1.229</td>
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#### Total Variance Explained

<table>
<thead>
<tr>
<th>Component</th>
<th>Extraction Sums of Squared Loadings</th>
<th>Rotation Sums of Squared Loadings</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>% of Variance</td>
</tr>
<tr>
<td>1</td>
<td>2.940</td>
<td>29.479</td>
</tr>
<tr>
<td>2</td>
<td>2.022</td>
<td>20.224</td>
</tr>
<tr>
<td>3</td>
<td>1.334</td>
<td>13.337</td>
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<tr>
<td>4</td>
<td>1.083</td>
<td>10.832</td>
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<td>5</td>
<td>0.926</td>
<td>9.256</td>
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<tr>
<td>6</td>
<td>0.722</td>
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<tr>
<td>7</td>
<td>0.448</td>
<td>4.487</td>
</tr>
<tr>
<td>8</td>
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<td>1.474</td>
</tr>
<tr>
<td>10</td>
<td>0.123</td>
<td>1.229</td>
</tr>
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</table>

#### Component Matrix(a)

<table>
<thead>
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<th>Component</th>
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<th>3</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
</tr>
<tr>
<td>SurfT</td>
<td></td>
<td>0.761</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SurfSal</td>
<td></td>
<td>-0.697</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ChlSurf</td>
<td></td>
<td>0.627</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Currentv</td>
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<td>0.546</td>
<td>0.539</td>
<td></td>
</tr>
<tr>
<td>Currentu</td>
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<td>0.844</td>
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<tr>
<td>SurfP</td>
<td></td>
<td>-0.671</td>
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<td></td>
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<tr>
<td>Pearl</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SurfN</td>
<td></td>
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<tr>
<td>SurfS</td>
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Extraction Method: Principal Component Analysis.

a. 3 components extracted.
### Rotated Component Matrix(a)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SurfT</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DenChl</td>
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<td>ChlSurf</td>
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<tr>
<td>SurfSoil</td>
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<td>0.923</td>
<td></td>
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<tr>
<td>Current</td>
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</tr>
<tr>
<td>SurfN</td>
<td></td>
<td>0.785</td>
<td></td>
</tr>
<tr>
<td>SurfS</td>
<td></td>
<td>0.695</td>
<td></td>
</tr>
<tr>
<td>Pearl</td>
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Extraction Method: Principal Component Analysis.
Rotation converged in 6 iterations.

### Component Transformation Matrix

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<th>3</th>
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<tbody>
<tr>
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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
## Factor Analysis

**Communalties**

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<thead>
<tr>
<th>Component</th>
<th>Initial</th>
<th>Extraction</th>
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<tbody>
<tr>
<td>ChiSurf</td>
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<td>SurfN</td>
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</tr>
<tr>
<td>SurfS</td>
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<td>0.579</td>
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<tr>
<td>SurfP</td>
<td>1.000</td>
<td>0.785</td>
</tr>
<tr>
<td>Currentu</td>
<td>1.000</td>
<td>0.736</td>
</tr>
<tr>
<td>Currentv</td>
<td>1.000</td>
<td>0.633</td>
</tr>
<tr>
<td>SurfTemp</td>
<td>1.000</td>
<td>0.799</td>
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<tr>
<td>SurfSal</td>
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<td>0.830</td>
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<td>DenChq</td>
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</tr>
<tr>
<td>Biloxi</td>
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<td>0.803</td>
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Extraction Method: Principal Component Analysis.

### Total Variance Explained

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<tr>
<th>Component</th>
<th>Initial Eigenvalues</th>
<th>Total</th>
<th>% of Variance</th>
<th>Cumulative %</th>
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<td>39.956</td>
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<td>1.247</td>
<td>12.466</td>
<td>69.284</td>
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<tr>
<td>4</td>
<td>1.083</td>
<td>10.597</td>
<td>79.881</td>
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<tr>
<td>5</td>
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<td>8.220</td>
<td>98.100</td>
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<td>6</td>
<td>0.495</td>
<td>4.947</td>
<td>93.052</td>
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<td>0.431</td>
<td>4.313</td>
<td>97.366</td>
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<tr>
<td>8</td>
<td>0.152</td>
<td>1.523</td>
<td>98.889</td>
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<tr>
<td>9</td>
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<td>0.981</td>
<td>99.869</td>
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<td>0.131</td>
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</table>

Extraction Method: Principal Component Analysis.

### Total Variance Explained

<table>
<thead>
<tr>
<th>Component</th>
<th>Extraction Sums of Squared Loadings</th>
<th>Rotation Sums of Squared Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>% of Variance</td>
<td>Cumulative %</td>
</tr>
<tr>
<td>Component</td>
<td>Extraction Sums of Squared Loadings</td>
<td>Total</td>
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<tr>
<td>2</td>
<td>1.686</td>
<td>16.862</td>
</tr>
<tr>
<td>3</td>
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<td>1.083</td>
<td>10.597</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
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<tr>
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<td>9</td>
<td>0.098</td>
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<tr>
<td>10</td>
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</table>

Extraction Method: Principal Component Analysis.

### Component Matrix

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
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<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>DenChq</td>
<td>-0.899</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SurfSal</td>
<td>-0.859</td>
<td>0.711</td>
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<td>SurfTemp</td>
<td>0.691</td>
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<tr>
<td>Currentu</td>
<td>0.686</td>
<td>0.599</td>
<td>0.822</td>
</tr>
<tr>
<td>Currentv</td>
<td>0.599</td>
<td>0.686</td>
<td>0.711</td>
</tr>
<tr>
<td>ChiSurf</td>
<td>0.899</td>
<td>-0.859</td>
<td>0.691</td>
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<td>Biloxi</td>
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<td>0.686</td>
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<td>SurfN</td>
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<tr>
<td>SurfP</td>
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<td>0.686</td>
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</table>

Extraction Method: Principal Component Analysis.

a. 3 components extracted.
### Rotated Component Matrix(a)

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
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</tr>
</thead>
<tbody>
<tr>
<td>SurfSal</td>
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<td></td>
</tr>
<tr>
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<tr>
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<td>SurfT</td>
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<tr>
<td>ChlSurf</td>
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<td>SurfTemp</td>
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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 12 iterations.

### Component Transformation Matrix

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
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<th>3</th>
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</thead>
<tbody>
<tr>
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<td>3</td>
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<td>0.663</td>
<td>0.825</td>
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</tbody>
</table>

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
BIBLIOGRAPHY


58. Ritchie, R.J. 2008. Universal chlorophyll equations for estimating chlorophylls a, b, c, and d and total chlorophylls in natural assemblages of


