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Abundance and Distribution of Early Life Stage Blue Crabs (*Callinectes sapidus*) in Lake Pontchartrain

Lissa Lyncker
University of New Orleans

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Abundance and Distribution of Early Life Stage Blue Crabs (*Callinectes sapidus*) in Lake
Pontchartrain

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Master of Science
In
the Department of Biological Sciences

by

Lissa Lyncker

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ABSTRACT

I conducted a 12-month study of near-shore habitats in Lake Pontchartrain to assess spatiotemporal variation in the abundance of early life stage blue crabs (*Callinectes sapidus*). Collections were made using a 1 m² throw trap and data showed that *C. sapidus* numbers varied over time and among sites. Two recruitment events occurred during the study. During the first recruitment in May-June, *C. sapidus* entered Lake Pontchartrain via the Inner Harbor Navigational Canal. In September-October, *C. sapidus* entered the Lake Pontchartrain via the Rigolets and Chef passes. My data suggest that *C. sapidus* utilize water circulation within the Lake Pontchartrain as a means of transportation throughout the estuary. MODerate-resolution Imaging Spectroradiometer (MODIS) 250 m data were analyzed to gain a large-scale view of suspended sediments patterns within Lake Pontchartrain and quantify water movement. Field sampling along with remote sensing proved to be beneficial when assessing estuarine-wide *C. sapidus* post-larval dispersal processes.

Keywords: *Callinectes sapidus*, blue crab, crab migration, crab transport, *Callinectes sapidus* transport, nursery habitat, dispersal, post-larval dispersal, post-settlement dispersal, recruitment, SAV, Lake Pontchartrain, mass water movement, remote sensing, MODIS 250 m data, MODIS 250 m satellite images, estuarine dependent species, suspended sediment

INTRODUCTION

By definition, estuarine-dependent species employ complex life cycles, moving through and using different estuarine habitats as they develop. Various developmental life stages can undergo periods of planktonic, nektonic, and benthic existence and each can use a spatially distinct habitat (Perry et al. 1984; Etherington and Eggleston 2000). This life history strategy involves the large-scale movement of these various life stages and estuarine-dependent species tend to occupy multiple habitats throughout the entire estuary. Dispersal is imperative for these species to complete their life cycle and they have evolved to effectively utilize those transport mechanisms that drive dispersal, such as wind and tidally driven water movement (Tankersley et al. 1998; Welch and Forward 2001). These mechanisms help estuarine dependent species move within an estuarine system and allow them to reach appropriate habitat and necessary resources. Water movement events that span the length of the entire estuary serve as both large and small-scale means of transport throughout the entire system. Wind and tidally driven water movement events are common means of dispersal for planktonic stages that enter into an estuary from offshore habitat and often determine abundance and distribution patterns (Etherington and Eggleston 2000).

The blue crab, *Callinectes sapidus*, is an estuarine-dependant species of great ecological and commercial importance that has evolved to take advantage of such large-scale water movement events. This species is widely distributed and uses estuaries from Nova Scotia, down the east coast of North America, off Bermuda, throughout the Gulf of Mexico and the Caribbean Sea, including the Antilles Islands, and down the east coast of South America to northern Argentina (Guillory and Elliot 2001). In these estuaries, *C. sapidus* plays prominent roles as both predator and prey and serves as a means of energy transfer throughout the system (Hill et al.

1989). Larval crab zoea feed on dinoflagellates, copepod nauplii, and other plankton whereas post larval megalope consume fish larvae, small shellfish, and aquatic plants. Juvenile and adult *C. sapidus* are also voracious benthic omnivores that feed on a wide array of plants and demersal animals, including smaller individuals of their own species. While playing an important ecological role as a generalist predator in estuaries, *C. sapidus* also serve a more vital role as prey species for numerous other animals. Fishes often target the egg mass attached to a mature female (Hill et al. 1989) and fishes, shellfish, jellyfish, comb jellies, and other estuarine planktivores eat free-swimming larvae. Juvenile and adult *C. sapidus* are preyed upon by birds and mammals in shallow water, whereas fishes such as spotted sea trout (*Cynoscion nebulosus*), red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), sheepshead (*Archosargus probatocephalus*), striped bass (*Morone saxatilis*), and American eel (*Anguilla rostrata*) prey upon *C. sapidus* throughout their estuarine habitats (Hill et al. 1989). *Callinectes sapidus*' wide distribution throughout an estuary, maintained by dispersal via mass water movement, in conjunction with these critical predator-prey interactions within the estuarine system is the key to the ecological importance of the species. Not only is this species widely spread and abundant, it is a key ecological component in many processes, which occur in habitats along the entire salinity gradient.

Mass water movement within an estuary (estuarine circulation) is an important means of transportation for *C. sapidus* at all life stages. Once females make their final pubert molt to maturity, mate, and store sperm, they will use currents to migrate down-estuary to higher saline waters. Egg-carrying females, called sooks, enter more saline waters and release their eggs at the peak of high tide. Gravid females travel up to 300 km seaward to release their eggs (Millikan and Williams 1980; Forward et al. 2003). Females selectively use currents for migration down-

estuary and synchronize larval release specifically at the peak of nocturnal flood tides to reduce predation during transport of larvae to offshore habitat (Tankersley et al. 1998; Morgan 1990; Power 1997). Larval *C. sapidus* transported out to higher saline waters are approximately 0.25 mm in size and metamorphose through 7 to 8 larval stages lasting 30 to 50 days before the final larval molt to the megalopal stage. The megalopal stage ranges from 1.5 to 2.5 mm in size and lasts 6 to 60 days.

Environmental cues, such as an increase in salinity and turbulence from an approaching flood tide, stimulate megalope to ascend in the water column and swim. By rising into the current, megalope exploit tidal movement to be transported back into the estuary and near shore, shallow habitats. Conversely, lower salinity and reduced turbulence within the estuary cues megalope to descend and settle. Ebb tide turbulence does not stimulate them to swim and leave the estuary because the salinity change is not there to cue the ascension into the water column (Welch and Forward 2001). Once settled, megalope molt into the first instar crab stage, which is the first stage that resembles an adult crab (Hill et al. 1989). Early juvenile planktonic movement back into and throughout the estuary is a key determinant of the distribution and abundance of *C. sapidus* throughout estuarine systems (Forward et al. 2003; Millikan and Williams 1980). A secondary, post-settlement planktonic dispersal, driven by density dependent processes, is another key factor influencing abundance and distribution of *C. sapidus* (Etherington and Eggleston 2003).

A number of other factors also influence primary and secondary post-larval dispersal and settlement processes. Habitat type (whether it is complex or not) also greatly influences variation in abundance and distribution of *C. sapidus*. Other factors such as location within the estuary, habitat accessibility, and substrate type can determine the value of a nursery habitat

(Etherington and Eggleston 2000). Environmental forces such as wind velocity, wind direction, tidal stage, and storm events (varying wind velocities and direction that can interact synergistically with the tidal flux) not only influence but can also drive *C. sapidus* recruitment events.

The capacity of an estuary to serve as a nursery for can be estimated by understanding what habitat types are available, identifying where valuable habitats are located within the system, and determining how accessible those habitats are to *C. sapidus*. In addition, assessing the means to reach valuable habitat via system-wide estuarine circulation patterns that transport the early life stage crabs into upper estuarine areas is imperative to understanding how *C. sapidus* uses an estuarine system. Though field investigation of habitat type and habitat proximity to the inlets of an estuary may be feasible, investigation of estuarine circulation and the influential environmental forces is much more difficult. Large-scale field studies conducted to assess water circulation throughout a large body of water, though thorough, are time intensive and expensive. Various methods have been used to monitor water movement, though not all of them are time or cost-effective or of adequate scale to completely capture estuarine-wide dynamics. Since recruitment dynamics within estuaries are reliant on water circulation patterns and planktonic dispersal, they are highly variable spatially and temporally. Therefore, the scale of investigation could greatly affect the interpretation of research results. That is, what is observed at one scale might not be evident at a smaller scale (Wessman 1992; Etherington and Eggleston 2000; O'Connell et al. 2006).

One approach that has been demonstrated to be a cost-effective means to study estuarine dynamics is to use remote sensing techniques to track and measure mass water movement within important coastal waters and bays (Miller et al. 2005). For example, remote sensing techniques

can be used to monitor the transport of suspended material within the water column (Miller and McKee 2004). Comparing images of water turbidity, which is suspended material within the water column usually consisting of both organic and inorganic material, can be used to monitor large-scale sediment transport and mass water movement dynamics within environments such as estuaries (Miller et al. 2005). One type of remote sensing data that can be used to measure turbidity is Moderate-resolution Imaging Spectroradiometer (MODIS) 250 m data. These 250 m resolution data provide a synoptic, all encompassing view of areas such as estuaries via two satellites that pass over every day. The two satellites, Terra and Aqua, are in sun-synchronous orbits, which cross the equator and each latitude at the same local solar time each day. Terra crosses the equator at 1030 hours (10:30 a.m.) local time traveling descending node (north to south), while Aqua crosses over the equator at 1330 hours (1:30 p.m.) local time traveling ascending node (south to north) offering two views of the estuary within a single day (Miller et al. 2005). The satellites are orbiting the earth in such a way (circling the poles while the earth spins on its axis) that by the time they cross where one is located, it is 1030 and 1330 hours (10:30 a.m. and 1:30 p.m., respectively).

The moderately high resolution, near daily (1.5 days) revisit time, and two daily overpasses that offer once or even twice daily images, provide MODIS 250 m data adequate to monitor estuarine processes in large coastal waters and bays. The MODIS band 1 data (bandwidth of 620-670 nm) is beneficial to monitor suspended sediment transport, since suspended sediments reflect brightly in the red region (~650 nm) of the electromagnetic spectrum in contrast to non-turbid, clear water. Because of this difference in reflectance, which creates a visual difference between brightly reflecting suspended sediment and darker less turbid water within a MODIS 250 m band 1 image, water movement can be monitored through

suspended sediments features. A “feature” in a MODIS 250 m band 1 image is a distinguishable characteristic in a water body that can be monitored through time. This is achieved by overlaying consecutive MODIS 250 m band 1 images and then conveying information about the physical processes that occurred prior to or at the time the data were recorded. A feature can consist of a bold line or meandering pattern created by the differences in suspended sediment patterns throughout a body of water. Tracking naturally dynamic features (e.g., large amounts of re-suspended sediment moving throughout a body of water or a plume dispersing from a river mouth) provides an understanding of the physical processes dominating water movement. One can also calculate the rate at which these processes are occurring. Finally, the images can be used to suggest possible implications of system-wide transport of particular suspended particles within masses of water (Miller et al. 2005).

Remote sensing techniques, specifically the application of MODIS 250 m band 1 data, are useful to monitor mass water movement in highly productive estuarine environments such as Louisiana coastal waters. The Mississippi River, with its numerous tributaries, is a constant source of nutrients and sediment into Louisiana waters and the result is a highly turbid coastal environment. With an abundance of suspended organic and inorganic material within Louisiana waters such as Lake Pontchartrain, wind and tidal induced currents create a system-wide mosaic or pattern of features that can offer insight into local influential processes. Monitoring those features and patterns within Lake Pontchartrain is important in order to gain an understanding of the sources of input into the system and local influential processes that likely help create the highly productive estuarine environment of Louisiana.

Because of this nutrient rich, highly productive coastal environment, Louisiana provides optimal nursery habitat for many ecologically and commercially important, estuarine dependent

species, such as *C. sapidus*. There are many factors that contribute to the considerable production and harvest of *C. sapidus* in the Louisiana and more specifically Lake Pontchartrain. In addition to the nutrients from the Mississippi River and other tributaries, coastal Louisiana provides an optimal nursery habitat because of the subtropical climate, abundant rainfall, large inputs of fresh water, low coastal wave activity, daily tidal flushing, low tidal amplitudes, and large amounts of marsh edge available as essential habitat (Day et al. 1973; Thomas et al. 1990). As a result of these ideal conditions, *C. sapidus* landings for Louisiana averaged 19.5 million kilograms in the 1990's, which were 72.7% of the total Gulf of Mexico production for that decade (Guillory 2002). In 2002, Louisiana *C. sapidus* landings neared 22.7 million kilograms, which was 28% of the national *C. sapidus* harvest for that year (Guillory and Perret 1998; Guillory et al. 1998). These data emphasize the link between Louisiana's productive estuaries and its equally productive *C. sapidus* fisheries.

Studying the connections between these biotic and abiotic factors in Louisiana is especially important now because of excessive land loss rates that are constantly changing the geology and hydrology of the area. Land loss rates are on the order of $> 64.75 \text{ km}^2$ per year as interior fresh and brackish marsh are converted to saline marsh and saline marshes are converted to open water (Boesch et al. 1994). Within other estuaries, *C. sapidus* settlement and recruitment varies significantly over time and space (Etherington and Eggleston 2000). In these systems, conducting a broad spatial investigation of influential environmental factors, system circulation, and storm events was the key to understanding local *C. sapidus* recruitment dynamics (Etherington and Eggleston 2000). Within Lake Pontchartrain there is a need to use a similar approach to identify those areas where initial settlement and recruitment occurs, determine the distribution and abundance of *C. sapidus* post larvae over time, and assess how the species uses

water circulation within the system. This information is vital for the proper management of the fisheries and the continued conservation of the species.

While the commercial and ecological importance of *C. sapidus* and the species' dependence on estuarine circulation in Lake Pontchartrain is well established, little is known about the spatial and temporal abundance and distribution of *C. sapidus* or their use of water circulation in the system. Also lacking is an understanding of what environmental factors influence *C. sapidus* settlement and recruitment within Lake Pontchartrain. Lastly, as hurricanes continue to threaten the Louisiana coastline and coastal communities, hurricane protection and restoration projects are going to be constructed. These have the potential to alter valuable coastal habitat and migration pathways from the Gulf of Mexico to inland waters bodies that serve as juvenile nursery habitat, such as Lake Pontchartrain. The importance of system-wide water movement and the imposing, near future threat of altering important ecological processes such as transport coupled with water movement emphasizes the need to fully understand water movement patterns in Lake Pontchartrain with regards to recruitment dynamics of ecologically and commercially important species, such as *C. sapidus*. The key to gaining an understanding of vital estuarine-wide processes is conducting a large-scale investigation of the system (Etherington and Eggleston 2003). Therefore, my specific objectives in this study were to 1) determine spatiotemporal distribution and abundance of *C. sapidus* early life stages (i.e., settlers and recruits) in Lake Pontchartrain; 2) identify abiotic and biotic factors influencing *C. sapidus* settlement and recruitment within Lake Pontchartrain; and 3) use remote sensing as a tool to identify large scale patterns of water flow that correspond with peaks in recruitment of *C. sapidus*.

MATERIALS AND METHODS

Study System and Sampling Sites

My study area was located within Lake Pontchartrain, an estuarine ecosystem that encompasses large expanses of near-shore, vegetated, and non-vegetated habitats. Lake Pontchartrain has a surface area of 1630 km² and is relatively shallow with an average depth of 3.7 m (Georgiou and McCorquodale 2002). There are three inlets into the Lake that allow tidal exchange with the Gulf of Mexico. Rigolets and Chef Menteur passes are natural inlets located in the eastern region of the Lake, whereas the Inner Harbor Navigation Canal (IHNC) is a non-natural, dredged pass located farther west in the southeastern region of Lake Pontchartrain. A comparison of tidal exchange through the three inlets has shown that the Rigolets Pass is a flood tide dominated channel, while the other two channels are ebb dominated (Sikora and Kjerfve, 1985). Lake Pontchartrain is considered a predominantly wind driven system with the majority of tidal influences limited to near the tidal inlets (Georgiou and McCorquodale 2002). Daily tides within this estuary are diurnal and have a mean range of < 0.3 m (Baumann 1987; Byrne et al. 1993). Tidal influence near the inlets is characterized by changes in water level elevations of 13-14 cm and velocities greater than 10 cm/s, whereas areas in the middle of the Lake are characterized by changes in water level elevations of 2-4 cm and velocities of 1.5 cm/s (Georgiou and McCorquodale 2002). Though tidal influence is greatest near inlets, wind induced currents are influential throughout the system and create various water movement patterns associated with specific wind velocities and directions and water depths in different regions of the Lake (Georgiou and McCorquodale 2002).

O'Connell et al. (2004) identified five ecologically discernable regions in Lake Pontchartrain based on varying combinations of natural and anthropogenic influences (Figure 1).

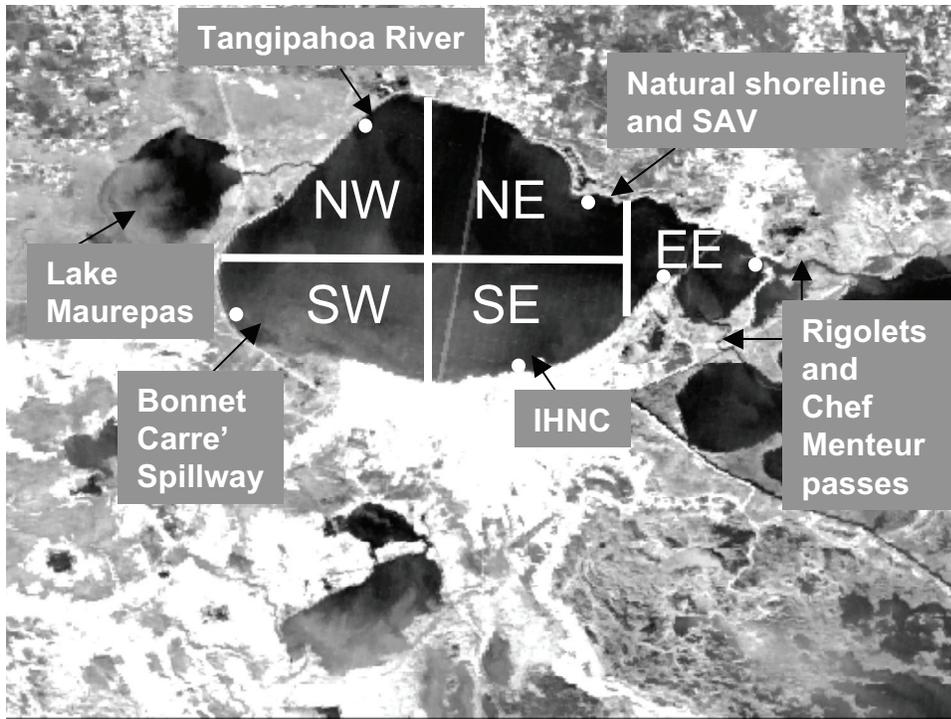


Figure 1. Five ecologically discernable regions within Lake Pontchartrain, the major regional influences, and the six sampling locations, which are designated with white circles (O'Connell et al. 2004).

The northwest region of Lake Pontchartrain is greatly influenced by runoff from the Tangipahoa River. This tributary provides freshwater input into Lake Pontchartrain causing salinity reduction in the northwest region. An increase in agriculture in this region also introduces excess fertilizers and animal waste products into Lake Pontchartrain. The northeast region of Lake Pontchartrain contains the largest expanse of submerged aquatic vegetation (SAV) and the least altered shorelines. Submerged grass beds in this region consist of wigeon grass (*Ruppia maritima*) and marsh edge consists of smooth cord grass (*Spartina alterniflora*). The Bonnet Carre' Spillway is the major influence in the southwest region of Lake Pontchartrain. When the Mississippi River is at flood stage (cresting at approximately 5.2 m), the Bonnet Carre' Spillway is opened and water is diverted into Lake Pontchartrain resulting in drastic salinity reduction, eutrophication, and transport of fine sediments into Lake Pontchartrain. There is a great amount of remnant sediment near the Bonnet Carre' Spillway that is easily re-suspended into the water column during wind events. The southeast region of Lake Pontchartrain is greatly influenced by the highly urbanized New Orleans Metropolitan area. Urban runoff, large expanses of artificial embankment, and navigation canals, such as the Mississippi River Gulf Outlet (MRGO), the Gulf Intracoastal Water Way (GIWW) and the Inner Harbor Navigation Canal (IHNC), which allow for salt water intrusion far into the estuary, have greatly impacted this region. Finally, two natural tidal passes, the Rigolets and Chef Menteur passes, which are imperative to tidal exchange and natural estuarine circulation, are located in the eastern most region of the Lake.

Sampling locations were selected from each of these five regions (O'Connell et al. 2004). I sampled at these locations to assess *C. sapidus* density throughout Lake Pontchartrain spatially and temporally and to potentially compare the *C. sapidus* data I collected with *C. sapidus* data acquired by O'Connell et al (2004; unpublished data). While one sampling location was chosen

in each region, I decided to also sample a sixth site where Rigolets Pass opens into Lake Pontchartrain (Figure 1). The Rigolets Pass sampling location was selected because the channel accounts for the majority of flood tide flow and could serve as the main entrance route of early life stage *C. sapidus* into the Lake Pontchartrain.

The substrate and habitat type available within each site throughout Lake Pontchartrain is another ecological component that likely influences the variation in *C. sapidus* distribution and abundance on a large spatial scale. Densities of *C. sapidus* are greater in complex, structured habitat when compared to non-structured habitat and densities are similar regardless of the type of complex structured habitat (Etherington and Eggleston 2000). There are differences in substrate and habitat type throughout Lake Pontchartrain as a result of the previously mentioned regional ecological differences. For example, the Tangipahoa River site (located in the northwest region of the Lake) is non-vegetated, with a soft mud-silt-clay bottom and sparse amounts of small Rangia clam (*Rangia cuneata*) shells. The shoreline consists of larger *R. cuneata* shells, some patches of common reed (*Phragmites australis*), and a few individual black willow (*Salix nigra*) near the water's edge. In contrast, Goose Point (in the northeastern region) is shallow, with both vegetated and non-vegetated areas over a sandy bottom, with *R. cuneata* and American oyster (*Crassostrea virginica*) shells intermittently scattered throughout. The shoreline is natural marsh edge consisting of mostly smooth cord grass (*Spartina alterniflora*.) The Bonnet Carre' Spillway site (southwestern region) is shallow, non-vegetated mud-silt-clay bottom, with scattered *R. cuneata* shells throughout. The shoreline consists of steep, eroded mud banks with some introduced concrete rock piles. Pontchartrain Beach, the southeastern site is non-vegetated with sandy substrate and many small *R. cuneata* shells mixed throughout. The shoreline is a gradually sloping beach face consisting of sand, pebbles, and detritus. The site

located in the eastern part of Lake Pontchartrain near Irish Bayou is shallow with vegetated (mostly sparse beds of widgeon grass, *Ruppia maritima*) and non-vegetated habitats with *R. cuneata* shells. There is also sand, clay, and mud substrate in some areas. The shoreline consists of some sand but mostly piles of intact and crushed *R. cuneata* and *C. virginica* shells. The last and most eastern site is located at the Rigolets Pass and has silty-sandy soft substrate. The shoreline consists of patchy sand beaches and extensive *S. alterniflora* marsh edge. The presence of sand, submersed aquatic vegetation (SAV), and natural marsh edge increases moving eastward across the Lake. The western region of the Lake is predominantly non-structured, mud bottom habitat.

Sampling Methods

I wanted to assess the spatial and temporal variation in abundance of early life stage *C. sapidus* in Lake Pontchartrain and to quantify biotic and abiotic factors that may affect their distribution and abundance. Multiple studies focusing on fishes and decapod crustaceans in shallow habitats have utilized a variety of gear types (Jordan et al. 1997; Rozas and Minello 1997; O'Connell et al. 2004; Steel et al. 2006). With intentions to compare *C. sapidus* abundance and distribution data collected within my study to *C. sapidus* data collected by O'Connell et al. (2004; unpublished data), I initially planned to use a comparable gear type, a seine (O'Connell et al. 2004). However, I decided to use an enclosure throw trap for my study based on literature review and the preliminary results from a study I conducted on gear type efficiency. The study consisted of sampling at each site throughout August 2005 using a seine adjacent to an enclosure trap making sure that 1) the two gear types were sampled within the same habitat type within the site (e.g., both gear types deployed within a single SAV bed) and 2) deploying the seine and throw trap next to one another did not interfere with the sample collected

by either gear type (i.e., the seine was pulled in a way not to disturb the adjacent area that was then sampled using the throw trap). A 4.6 m wide, 1.8 m tall, 1 mm mesh, 18.14 kg weighted seine was pulled 3 times and each pull covered a 60 m distance. A 1 m², 0.75 m tall, aluminum enclosure trap was deployed 3 times adjacent to each seine pass, which produced a total of nine throw trap samples. Throw traps collected higher densities of *C. sapidus* than seines (Figure 2). Therefore, I quantified the density of early life stage *C. sapidus* using a 1 m² enclosure throw trap at each of the six sites throughout a twelve month sampling period, March 2006 – February 2007. While previous studies of *C. sapidus* abundance and distribution in other estuaries focused on sampling during those months considered to have the highest post larval influx (August through October; see Mense et al. 1995; Perry et al. 1995; Rabalais et al. 1995; van Montfrans et al. 1995; Perry et al. 1998), I chose to sample for 12 months at all of my sites because *C. sapidus* post larval dynamics were not well understood in Lake Pontchartrain, and I wanted to gain a more complete assessment of the *C. sapidus* life history dynamics in this particular estuarine system.

Once the sampling location, temporal scale, and gear type were chosen, the remaining components of the experimental design, such as sampling frequency of each site per month, amount of sample replication, and replication within each sample, were decided. Three samples were collected from each site once a month. A single sample at each site consisted of three traps within a sub-plot. Thus, three subplots each consisting of three traps were sampled at each site per month. The subplots were arbitrarily chosen anew each month ensuring that the entire sampling location was assessed (Etherington and Eggleston 2000; Rozas and Minello 2006). Each trap was thrown in 0.5 m - 0.75 m deep water, making sure it effectively penetrated the substrate to ensure no organism could escape and was then cleared with a 1.0 mm mesh bar

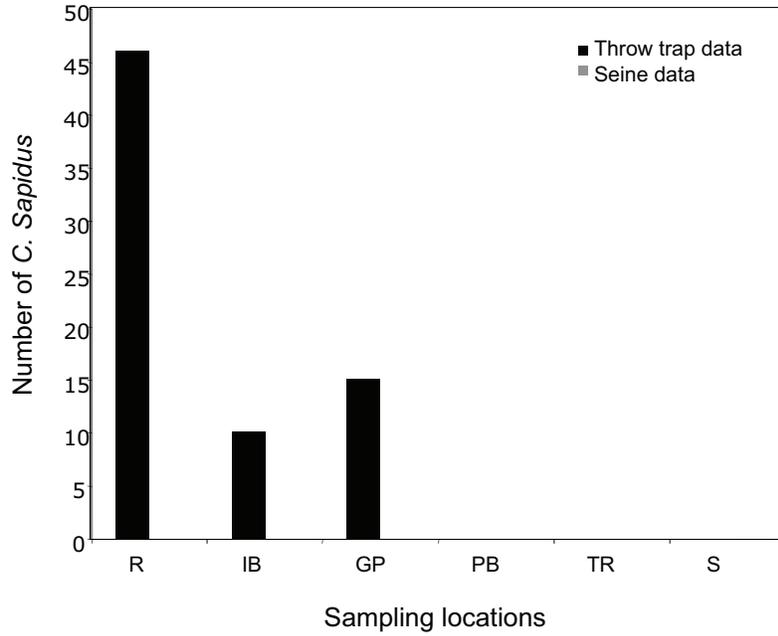


Figure 2. A gear type comparison between an enclosure throw trap and a seine conducted during August 2005. Though both gear types were sampled adjacent to one another in the same habitat, the seine did not collect *C. sapidus* at any of the sampling locations. Sample sites are arranged from east to west across Lake Pontchartrain: R = Rigolets, IB = Irish Bayou, GP = Goose Point, PB = Pontchartrain Beach, TR = Tangipahoa River, S = Spillway.

seine. The bar seine was swept through the trap until three consecutive empty sweeps (i.e., no organisms recovered in three sweeps) were achieved. All crabs, fishes, and shrimp, were placed in a zip-lock bag labeled for that specific trap and was stored in an ice chest. Samples were then transported to the laboratory for processing. Along with quantifying *C. sapidus* densities at each site, environmental parameters such as dissolved oxygen, salinity, water temperature, turbidity, and bottom water velocity were measured at the time of sampling. Wind data were retrieved for dates pertaining to the sampling period from the LUMCON weather data that were collected from a LUMCON buoy in Lake Pontchartrain (30° 18.894' N, 90° 16.831' W). Tidal data were retrieved for dates pertaining to the sampling period from United States Geological Survey (USGS) tidal gauges that are attached to the Highway 90 Bridge that crosses the Rigolets Pass near Slidell, LA.

Sample Processing

Throw trap samples were preserved in a 10% formalin solution in individually labeled glass jars. *Callinectes sapidus* were counted and carapace width (CW; point to point between lateral spines) and body weight were measured. Carapace width was measured to the nearest 0.01 mm using electric calipers (Mitutoyo SR44) and a dissecting microscope (Leica S6E). *Callinectes sapidus* were then categorized into size classes (0-2, 3-5, 6-9, and > 9), which were derived from instar stages. Instar stages (1-9) were previously determined from various growth studies on laboratory-reared early life stage *C. sapidus* (Pile et al. 1996) and represent the stage between molts. Thus, the instar stage ranging from 1 to 9 represents the number of molts required to reach an associated carapace width (Table 1). The instar stage can be used to categorize early life stage *C. sapidus* since growth is relatively uniform until they reach approximately 10 mm CW (Pile et al. 1996). For this study, *C. sapidus* smaller than instar 1

Table 1. Instar stage and associated carapace width (CW) in millimeters (mm). The instar stage represents the numbers of molts to attain the associated carapace width.

Instar	CW (mm)
First	2.2 - 3.0
Second	3.1 - 4.2
Third	4.3 - 5.9
Fourth	6.0 - 7.4
Fifth	7.5 - 9.1
Sixth	9.2 - 10.6
Seventh	10.7 - 12.6
Eighth	12.7 - 14.1
Ninth	14.2 - 16.1

were classified instar 0 because they were megalopae that had not molted into a first crab stage. *Callinectes sapidus* larger than instar 9 were labeled instar > 9, because the crabs molted greater than nine times to reach the various carapace widths measured at the time of collection. Instar 0-2 stage crabs were considered new settlers. These crabs were the most recent to arrive in the region and were estimated to have been at the site for 0-16 days. Instar 3-5 stage crabs were considered early recruits. These had settled, molted, and had been in the region for 14-46 days. Instar 6-9 stage crabs were considered later recruits that had been in the region for 41-113 days (Pile et al. 1996; Etherington and Eggleston 2000; 2003). I also recorded the total number and CW range (smallest and largest) of another crab species, the estuarine mud crab (*Rhithropanopeus harrisi*) when it occurred in samples. The total number and total length (TL) ranges (smallest and largest) of each shrimp species were determined for all shrimp, while total number and standard length (SL) ranges (smallest and largest) of each fish species were also determined. All fish species identifications were confirmed using Hoese and Moore (1998).

Statistical Analyses

Each site was considered to be unique and independent for statistical purposes. Three samples were obtained for each site each month. A sample consisted of three traps within each of the three subplots. Data were transformed ($\log [x+1]$) to approximate more closely the normal distribution for analytical purposes. StatView (Abacus Concepts 1996) was used to conduct analyses of variance (ANOVA) to test for the effects of sampling period and sampling location on the following response variables:

- C. sapidus* density,
- C. sapidus* carapace width,
- C. sapidus* individual size class density,

total number of species,
density of *Litopenaeus setiferus*,
density of *Farfantepenaeus aztecus*,
the density of total *R. harrisii*,
water temperature (°C),
salinity (ppt),
dissolved oxygen (mg/L),
turbidity (NTU),
and bottom water velocity (m/s).

Following ANOVA, post-hoc testing was conducted in StatView using the Bonferroni-Dunn procedure to determine which means differed significantly from each other. In addition, StatView was used to conduct regression analyses to test for relationships between environmental parameters and *C. sapidus* density. Wind velocity, wind direction, and barometric pressure (environmental variables associated with the passage of frontal systems) were obtained from the LUMCON platform in Lake Pontchartrain and plotted in Microsoft Excel to demonstrate trends over time. Tide gauge height data were obtained from the USGS tide gauge located in the Rigolets Pass were also plotted in Microsoft Excel to demonstrate trends over time.

Satellite Image Processing

Once trends from the field data were revealed, I then acquired all MODIS 250 m data for 2006 to 2007. I inventoried the data for those images that could potentially be used in the study, classifying them by image quality (hazy / not hazy / cloudy / semi cloudy / cloud free / glint / glint free). Images cannot be used if they are hazy, distorted because the area of interest is located near the edge of the swath, if cloud cover masks the area of interest, or if sun glint

interferes with the sensor. I compiled a set of images that could be used and from that set I extracted images associated with times during the sampling period when *C. sapidus* entered Lake Pontchartrain and were distributed throughout the system. The MODIS 250 m data for 15-18 May 2006, and 14, 15, 25, and 26 September 2006 were then analyzed using HDFLook 4.1 software.

My analysis using HDFLook software consisted of using a batch scripts developed by Miller et al. (2005) to extract the region of interest over Lake Pontchartrain (29.6 to 30.5° N, -90.7 to -89.5° W) from the main MOD02QKM file. I then converted the data from at-sensor radiance (calibrated radiance) to surface reflectance, assigned latitudinal and longitudinal coordinates to the image, georeferenced the image, and outputted the data as a generic two band HDF file. The HDF files for 15-18 May 2006 and 14, 15, 25, and 26 September 2006 were then further processed and analyzed using ENVI 4.3 software. Within ENVI, images from consecutive days were overlaid and linked, then the movement of the suspended sediment features that were identified within the consecutive images was tracked over time. To track a suspended sediment feature over time using consecutive images, a leading edge of a particular feature was identified. Identifying the leading edge, an area that would indicate movement of the feature and net transport, depended on environmental parameters such as the velocity and direction of wind induced currents and the extent of tidal exchange and required the assessment of those data in conjunction with the MODIS 250m band 1 data. An identifiable feature in an image is the result of differences in reflectance/turbidity within the water column in which a darker (lower reflectance/less turbid) region is adjacent to a brighter (higher reflectance/ more turbid) region creating a line or “edge” where the two regions meet. Once the leading edge was identified in each image, I determined the location of the edge. An example of this method

involves the feature identified in the 15-18 May 2006 images, which was a plume (Figure 3). The plume was vertically bisected, from north to south, to create western and eastern halves. The eastern half of the plume was then bisected horizontally, from west to east, to create a north and south part, and 20 points were then measured, 10 in each half (Figure 3). Though difficult to make sure a specific point within the edge of a feature from one image is the exact same point on the edge of the feature in consecutive images, an attempt was made to match the points as closely as possible. It was assumed that recording evenly spaced data points (location points) along the edge of a feature was enough data to represent the location of the feature and to calculate the distance the edge of the feature moved from one day to the next. After identifying the feature and recording the location of the edge of the feature, I quantified the distance the water moved between each day and the total movement across a period of days.

To investigate the wind and tidal influences, wind speed and direction data, barometric pressure data, and tidal data were analyzed in conjunction with the remotely sensed data. Wind velocities and direction, and barometric pressure for dates 15-18 May 2006 and 14, 15, 25, and 26 September 2006 were assessed to determine wind influences and the passage of frontal systems for the time that coincided with the MODIS 250 m data used in this study. Tidal data were assessed for dates 15-18 May 2006. Tidal data were not available for the 14, 15, 25 and 26 September and tidal stage prediction tables were used to best estimate tidal influence during September. Typical effects of the passage of a frontal system include a switch in wind direction from south to north with a corresponding increase in wind speed during the front's passage. Often there is a temporary increase in wind speed as the front passes with high wind gusts and then a gradual decrease to low wind speeds during a high-pressure stationary system (Miller and McKee 2004). The wind, pressure, and tide data were analyzed together to better understand the

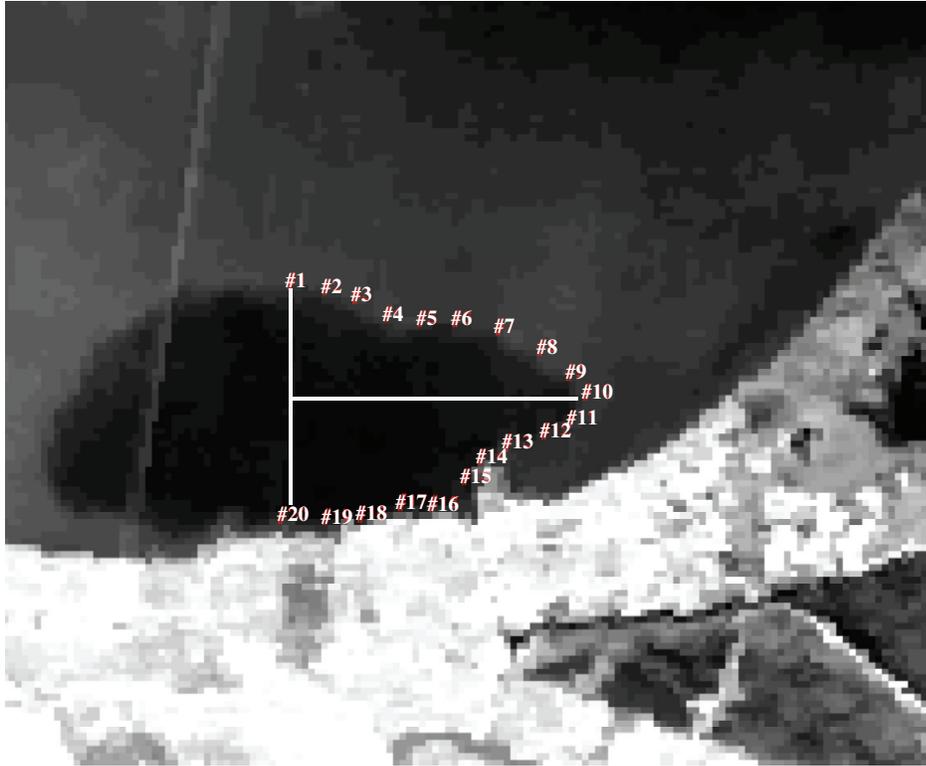


Figure 3. The MODIS 250m band 1 data satellite image (15 May 2006) illustrating where 20 point locations were measured to acquire the feature edge location. The identified feature, a plume, was bisected into western and eastern halves, and the eastern part was bisected into upper and lower regions. Ten points were measured in the upper and lower regions.

role of individual factors that drove the system-wide physical processes, which impacted the water movement portrayed in the MODIS 250 m band 1 data and the *C. sapidus* distribution revealed through field investigation.

RESULTS

Variation in Abundance and Distribution of C. sapidus

A total of 1,910 *C. sapidus* (instar stages 0-2, 3-5, 6-9, >9) was recovered from 216 independent samples collected between March 2006 and February 2007. Of the 216 samples (representing 648 traps), *C. sapidus* were present in 104 samples (313 traps) for a frequency of occurrence of 48%. There were 260 instar 0-2 stage crabs, 590 instar 3-5 stage crabs, 642 instar 6-9 stage crabs, and 418, > 9 instar stage crabs collected throughout the sampling period. The smallest *C. sapidus* carapace width was 1.1 mm (instar stage 0) and was collected at Pontchartrain Beach in May, while the largest carapace width was 123 mm (instar stage > 9) and was collected at Irish Bayou in June.

Early juvenile *C. sapidus* were present in all regions of Lake Pontchartrain. However, *C. sapidus* densities were significantly different among sampling locations ($F_{5,144} = 30.468, p < 0.0001$). The species was more abundant at sites in the eastern region of Lake Pontchartrain (Figure 4). Early juvenile *C. sapidus* were present during all months of the sampling period, however, densities varied significantly among months ($F_{11,144} = 11.520, p < 0.0001$). The species was most abundant during two events: one event in May-June and one event in September-October (Figure 5). *Callinectes sapidus* density was greater during the May-June recruitment event than the September-October event. There was also a significant month by site effect on in mean *C. sapidus* densities (event by site: $F_{55,144} = 2.247, p < 0.0001$; Figure 6). Large numbers of *C. sapidus* reached certain sampling locations before others, and those sampling locations that received *C. sapidus* first during the first recruitment event were not the same sampling locations that received *C. sapidus* first during the second recruitment events. During the first recruitment

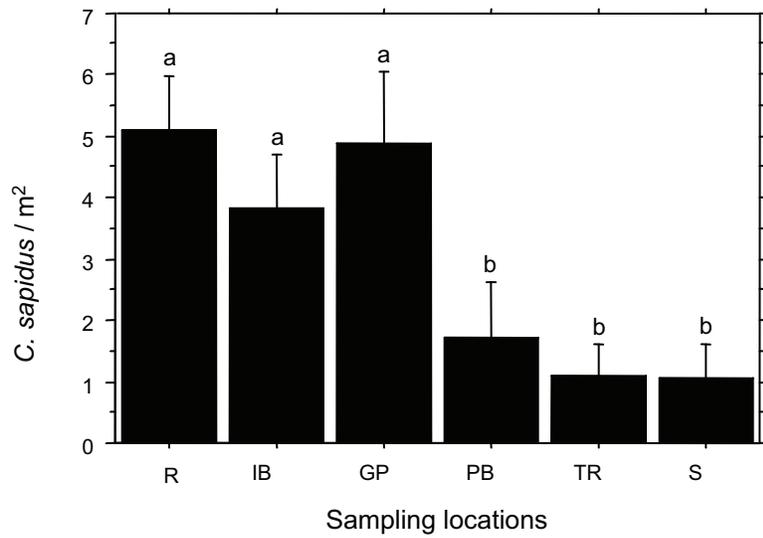


Figure 4. Mean (± 1 SE) density of *C. sapidus* among sampling locations. There was a significant difference in early life stage *C. sapidus* density among sites ($F_{5,144} = 30.468$, $p < 0.0001$). Significant differences in means denoted by a or b. Sample sites are arranged east to west, reading left to right: R = Rigolets, IB = Irish Bayou, GP = Goose Point, PB = Pontchartrain Beach, TR = Tangipahoa River, S = Spillway.

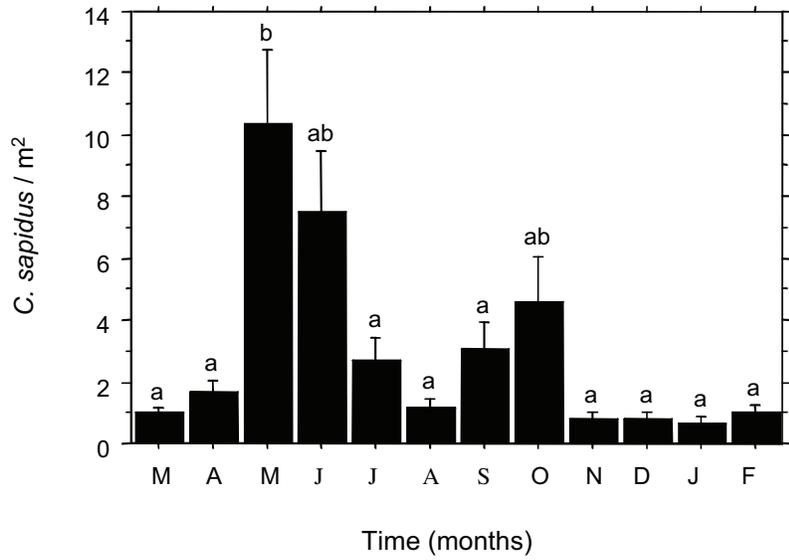


Figure 5. Mean (± 1 SE) density of *C. sapidus* overtime. There was a significant difference in early life stage *C. sapidus* density throughout the 12-month sampling period from March 2006 – February 2007 ($F_{11,144} = 11.520, p < 0.0001$). Significant differences in means denoted by a, b, or ab.

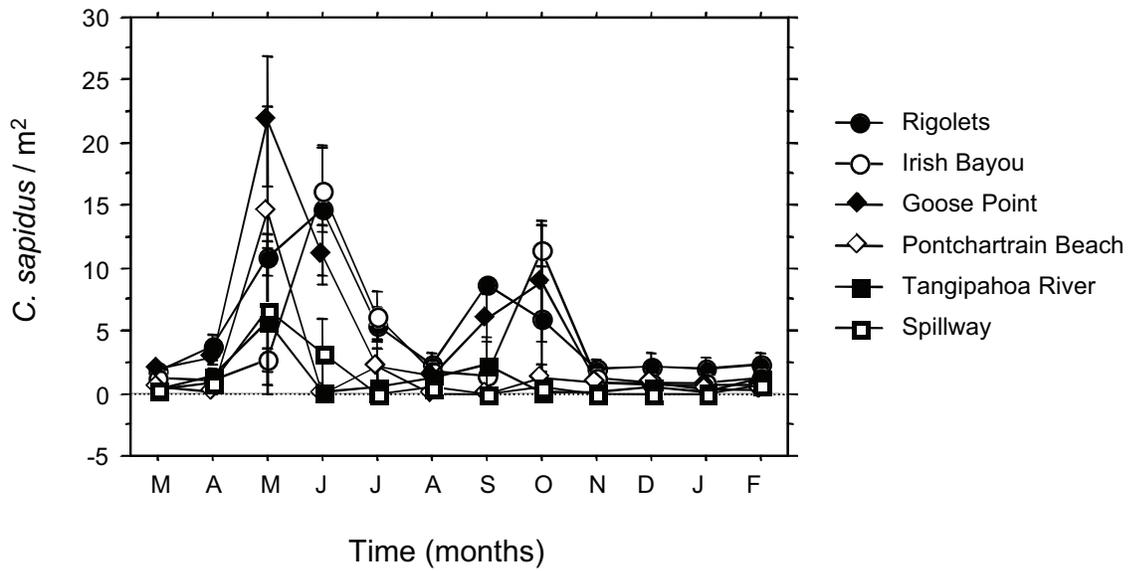


Figure 6. Mean (± 1 SE) density of *C. sapidus* overtime and among sites. There was a significant difference in mean *C. sapidus* density over time and among sampling locations and also as a result of the interaction of time by site (time: $F_{11,144} = 11.520$, $p < 0.0001$; site: $F_{5,144} = 30.468$, $p < 0.0001$; time by site: $F_{55,144} = 2.247$, $p < 0.0001$).

event, large numbers of early life stage *C. sapidus* were first collected in May at Goose Point, Pontchartrain Beach, and the Bonnet Carre' Spillway, and large numbers of *C. sapidus* were not collected at Irish Bayou and Rigolets Pass until the following month in June. During the second recruitment event, large numbers of early life stage *C. sapidus* were collected first at the Rigolets and were not collected at Irish Bayou and Goose Point until the next month in September. These differences in recruitment peaks among sites explain a significant interaction between sampling location and sampling period. The interaction likely suggests that there were differences in mean carapace width among sites but only during certain months or vice versa.

When looking at mean carapace width, there were significant differences among sampling locations ($F_{5,144} = 2.664$; $p < 0.0001$) and among months ($F_{11,144} = 2.756$, $p = 0.0029$). Larger *C. sapidus* were mainly collected in the eastern region (Figure 7). Carapace width decreased during those two events when *C. sapidus* density increased, indicating those two increases in *C. sapidus* density were likely two recruitment events of early life stage crabs into the estuary (Figure 8). In addition, there was a significant site by month interaction for mean carapace length ($F_{55,144} = 1.484$; $p = 0.0330$).

Callinectes sapidus were most abundant in the eastern region of Lake Pontchartrain and were most abundant during the two recruitment events. Distribution and abundance patterns of individual size classes (0-2, 3-5, 6-9, >9) followed similar trends with the exception of instar 0-2 stage crabs. Though there were no significant differences in mean instar 0-2 crab density among sampling locations ($F_{5,144} = 2.043$; $p = 0.0761$), the smallest instars, instar 0-2, were only collected near the inlets into Lake Pontchartrain, the Rigolets, and the IHNC (Figure 9). There were significant differences in mean instar 0-2 density among months ($F_{11,144} = 13.648$; $p < 0.0001$). Individual class sizes of instars 0-2 stage crabs were collected during both recruitment

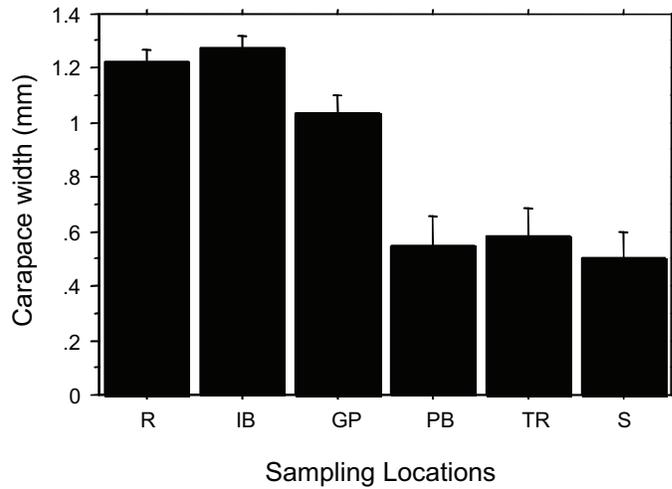


Figure 7. Mean (+1 SE) *C. sapidus* carapace width among sampling locations. The mean carapace width differed significantly among sampling locations ($F_{5,144} = 2.664$; $p < 0.0001$). Sample sites are arranged east to west, reading left to right: R = Rigolets, IB = Irish Bayou, GP = Goose Point, PB = Pontchartrain Beach, TR = Tangipahoa River, S = Spillway.

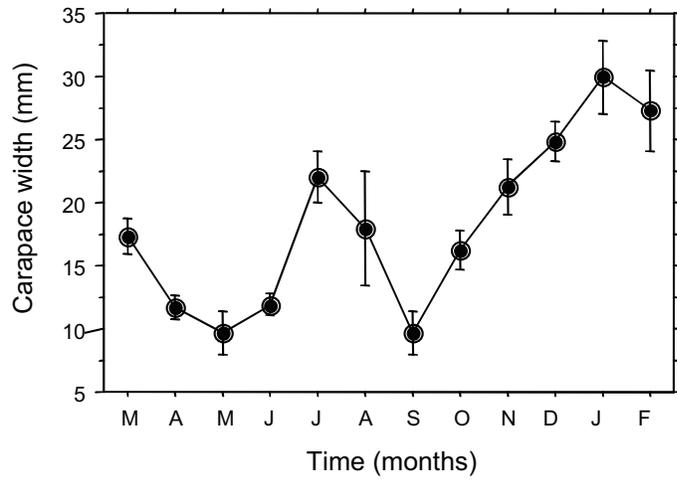


Figure 8. Mean (± 1 SE) *C. sapidus* carapace width over time. The mean carapace width differed significantly throughout the 12-month sampling period from March 2006 – February 2007 ($F_{11,144} = 2.756, p = 0.0029$).

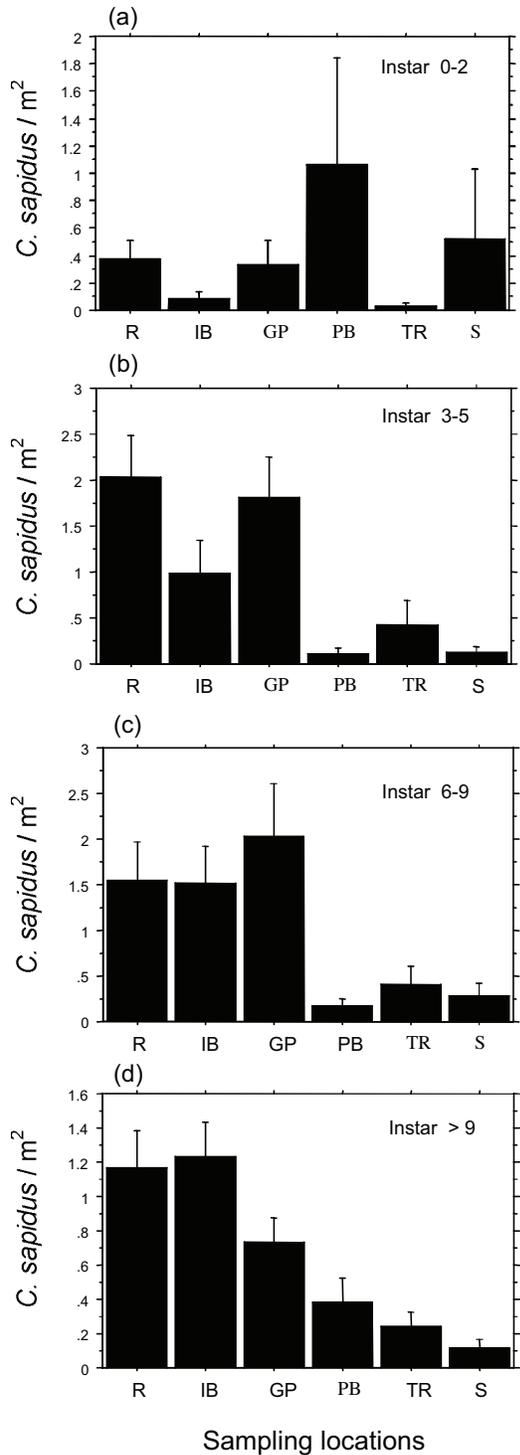


Figure 9. Mean (+1 SE) *C. sapidus* instar (0-2, 3-5, 6-9, >9) density among sampling locations. There was no significant difference of instars 0-2 mean density among sites ($F_{5,144} = 2.043$; $p = 0.0761$). There were significant differences in mean instar density among sites for the larger crabs: (b) Instars 3-5 ($F_{5,144} = 35.765$; $p < 0.0001$), (c) Instars 6-9 ($F_{5,144} = 15.604$; $p < 0.0001$), (d) Instars >9 ($F_{5,144} = 17.856$; $p < 0.0001$).

events but were most abundant during May (Figure 10). There was also a significant site by month interaction ($F_{55,144} = 1.928$; $p = 0.0010$), which suggested that the mean instar 0-2 stage crabs varied among months but only within certain sampling locations.

Instars 3-5, 6-9 and > 9 stage crabs were most abundant in the most eastern sites within Lake Pontchartrain (Figure 9). Mean instar 3-5, 6-9, and >9 densities differed significantly among sampling locations (3-5: $F_{5,144} = 35.765$; $p < 0.0001$; 6-9: $F_{5,144} = 15.604$; $p < 0.0001$; >9: $F_{5,144} = 17.856$; $p < 0.0001$) and among months (3-5: $F_{11,144} = 21.252$; $p < 0.0001$; 6-9: $F_{11,144} = 14.753$; $p < 0.0001$; > 9: $F_{11,144} = 3.344$; $p = 0.0004$). Instar 3-5, 6-9, and >9 stage crabs were collected in nearly all months, though instar 3-5 were most abundant in May, June, and September, instar 6-9 stage crabs were most abundant in June and in October and > instar 9 crabs were most abundant towards the end of the first recruitment event in July (Figure 10). Though crabs larger than instar 9 were most abundant in July, considerable numbers of > 9 instar stage crabs were also collected during the second recruitment event in October and throughout the winter, November to February. There were also significant site by month interactions for mean instar 3-5 density ($F_{55,144} = 5.311$; $p < 0.0001$) and 6-9 density ($F_{55,144} = 3.796$; $p < 0.0001$) suggesting that there are differences in mean instars among sites but those differences occur within certain months or vice versa.

I specifically noted that during the first recruitment event, instar 0-2 and 3-5 stage crabs were most abundant in May, instar 6-9 stage crabs were most abundant in June, and > 9 instar stage crabs were most abundant in July. During the second recruitment event, instar 3-5 stage crabs were most abundant in September, instar 6-9 stage crabs were most abundant in October, and > 9 instar stage crabs were most abundance in October, though > 9 instar stage crab densities remained constant throughout the winter months, November 2006 – February 2007.

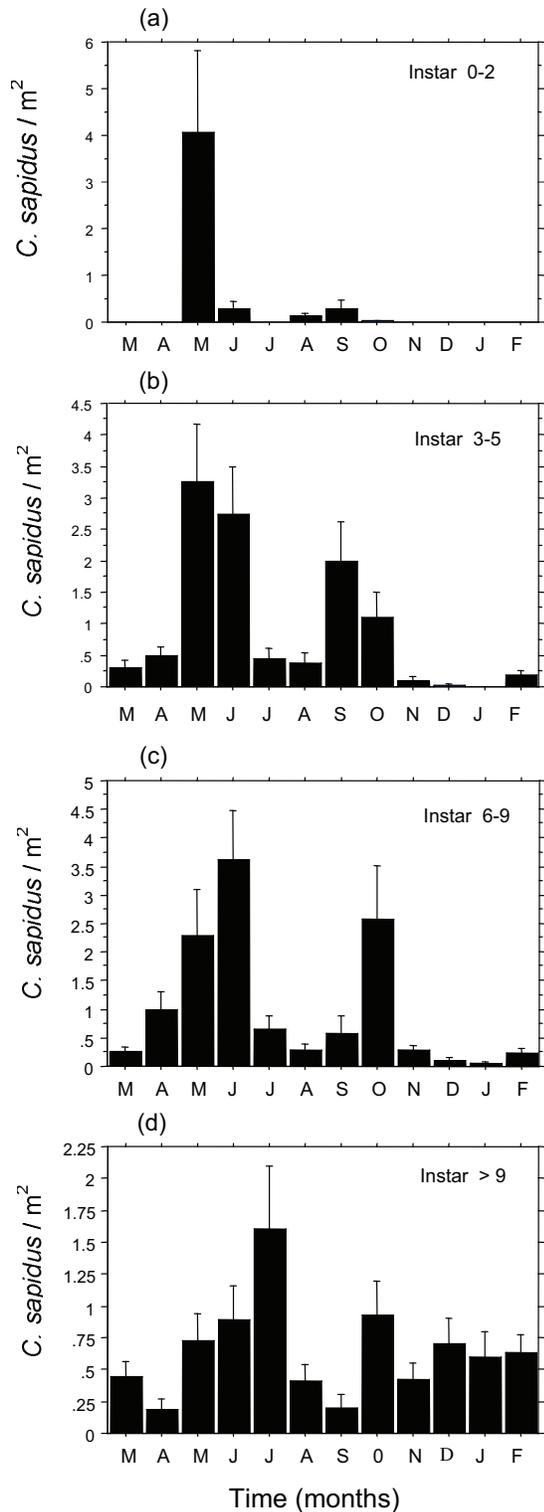


Figure 10. Mean (+1 SE) *C. sapidus* instar (0-2, 3-5, 6-9, >9) density over time. There were significant differences in mean instar density throughout the 12-month sampling period from March 2006 – February 2007: (a) Instars 0-2 ($F_{11,144} = 13.648$; $p < 0.0001$), (b) Instars 3-5 ($F_{11,144} = 21.252$; $p < 0.0001$), (c) Instars 6-9 ($F_{11,144} = 14.753$; $p < 0.0001$), (d) Instars >9 ($F_{11,144} = 3.344$; $p = 0.0004$).

Variation in Abundance and Distribution of Other Species

A total of 38 species were collected with *C. sapidus* during this study (Table 2). The number of species collected among sampling location was significantly different ($F_{5,144} = 32.377$; $p < 0.0001$). The majority of all species were located in the eastern region of the Lake at the Rigolets, Goose Point, and Irish Bayou. There were only half as many species in the farther westward regions. The most species were collected at the Rigolets, while the least number of species were collected at Pontchartrain Beach. The number of species collected also varied significantly among months ($F_{11,144} = 10.266$; $p < 0.0001$). There was a large increase in the total number of species collected from the spring to early summer months with a peak in the number of species collected in June.

Brown shrimp (*Farfantepenaeus aztecus*) densities varied significantly among sampling locations ($F_{5,144} = 5.845$; $p < 0.0001$) and among months ($F_{11,144} = 11.154$; $p < 0.0001$).

Farfantepenaeus aztecus were mainly collected at Goose Point and were only collected in May and June. White shrimp (*Litopenaeus setiferus*) densities also varied significantly among sites ($F_{5,144} = 23.547$; $p < 0.0001$) and among months ($F_{11,144} = 18.517$; $p < 0.0001$). The Rigolets Pass site was the only location that considerable numbers of *L. setiferus* were collected. *Litopenaeus setiferus* were collected mostly in June though the species was collected from August through October. *Rhithropanopeus harrisi*, a resident crabs species of Lake Pontchartrain, was collected in all sampling locations although the density varied significantly among sampling locations ($F_{5,144} = 5.561$; $p = 0.0001$). Considerable numbers of *R. harrisi* were collected at all sites except Pontchartrain Beach and the Spillway. This species was most abundant near the Tangipahoa River and as common at the sites in the eastern region of the Lake. Mean *R. harrisi* density also differed significantly among months ($F_{11,144} = 6.831$; $p < 0.0001$). The mean density

Table 2. Other species collected with *Callinectes sapidus* at each sampling location throughout the sampling period. The table provides the total number of each species collected and the total number of each species collected at each sample site.

Species	Total # collected	Rigolets	Irish Bayou	Goose Point	Pontchartrain Beach	Tangipahoa River	Spillway
<i>Anchoa hepsetus</i>	9	1	0	7	0	1	0
<i>Anchoa mitchilli</i>	1370	494	48	243	66	176	343
<i>Bairdiella chrysura</i>	76	46	16	10	4	0	0
<i>Brevoortia patronus</i>	99	71	0	1	8	19	0
<i>Chasmodes bosquianus</i>	8	1	7	0	0	0	0
<i>Chasmodes saburrae</i>	1	0	1	0	0	0	0
<i>Citharichthys spilopterus</i>	12	12	0	0	0	0	0
<i>Cynoscion nebulosus</i>	29	13	9	7	0	0	0
<i>Cyprinodon variegatus</i>	13	7	0	2	4	0	0
<i>Eucinostomus gula</i>	6	5	0	0	1	0	0
<i>Farfantepenaeus aztecus</i>	35	6	3	25	0	0	1
<i>Fundulus grandis</i>	1	0	0	1	0	0	0
<i>Gambusia affinis</i>	2	0	0	1	1	0	0
<i>Gobiesox strumosus</i>	71	24	29	9	5	3	1
<i>Gobiosoma bosc</i>	966	245	334	91	20	179	97
<i>Hyporhamphus unifasciatus</i>	1	0	0	1	0	0	0
<i>Lagodon rhomboides</i>	4	1	0	2	1	0	0
<i>Limulus polyphemus</i>	1	0	0	1	0	0	0
<i>Litopenaeus setiferus</i>	264	199	20	34	0	6	5
<i>Lucania parva</i>	15	3	6	2	4	0	0
<i>Menidia beryllina</i>	68	9	3	17	38	0	1
<i>Menticirrhus littoralis</i>	1	0	1	0	0	0	0
<i>Microgobius gulosus</i>	8	3	0	5	0	0	0
<i>Micropogonias undulatus</i>	49	22	5	1	10	4	7
<i>Myrophis punctatus</i>	13	1	7	2	3	0	0
<i>Oligoplites saurus</i>	2	2	0	0	0	0	0
<i>Opsanus beta</i>	1	1	0	0	0	0	0
<i>Paleomonetes pugio</i>	3482	1540	856	1046	20	3	17
<i>Paralichthys lethostigma</i>	3	2	0	0	1	0	0
<i>Poecilia latipinna</i>	1	0	0	0	1	0	0
<i>Rhithropanopeus harrisi</i>	1589	322	431	265	40	420	111
<i>Sphoeroides parvus</i>	4	0	3	0	1	0	0
<i>Squilla empusa</i>	1	1	0	0	0	0	0
<i>Strongylura marina</i>	1	0	0	1	0	0	0
<i>Symphurus plagiusa</i>	35	13	16	6	0	0	0
<i>Syngnathus louisianae</i>	122	3	12	100	7	0	0
<i>Syngnathus scovelli</i>	155	0	44	110	0	1	0
<i>Trinectes maculatus</i>	5	0	0	1	0	3	1

of this species demonstrated a seasonal variation in abundance and was greatest from May to October. There were significant site by month interactions for *F. aztecus* ($F_{55,144} = 3.544$; $p < 0.0001$), *L. setiferus* ($F_{55,144} = 8.559$; $p < 0.0001$), and *R. harrisii* ($F_{55,144} = 1.903$; $p < 0.0001$) suggesting for each species there was a difference in mean among sampling locations though only during certain months.

Environmental Variables

Water temperature did not vary significantly among sampling locations ($F_{1,192} = 0.252$; $p = 0.6162$), but did vary significantly among months ($F_{11,192} = 28.036$, $p < 0.0001$). Water temperature followed seasonal patterns, increasing in spring months, peaking in June and gradually decreasing until January 2007. Salinity also varied significantly among sampling locations ($F_{1,192} = 43.315$, $p < 0.0001$). Salinity decreased moving westward across the Lake away from the Rigolets and Chef Menteur passes with the exception of saltwater intrusion that occurs via the IHNC along the south shore of Lake Pontchartrain. While the average salinity for the majority of the regions ranged from 8.5 ppt in the east, to 6 ppt in the southwest, the site in the northwest region consistently had very low salinities with an average of 3 ppt due to the influence of fresh water from the Tangipahoa River. Salinity did not differ significantly among months ($F_{11,192} = 1.327$, $p = 0.2120$). Dissolved oxygen did not vary significantly among sampling locations and was generally high in all regions of the Lake ($F_{1,192} = 1.097$; $p = 0.2963$). Dissolved oxygen (DO) differed significantly among months ($F_{11,192} = 10.950$, $p < 0.0001$) and followed seasonal patterns demonstrating an inverse relationship to water temperature. Dissolved oxygen decreased throughout the spring and summer months with the lowest value recorded in August at a value of 5.5 mg/L and then increased during the early fall and winter months. Turbidity was another environmental parameter that varied significantly among

sampling locations ($F_{1,192} = 50.172, p < 0.0001$) but did not vary significantly among months ($F_{11,192} = 1.638, p = 0.0909$). There is an east to west turbidity gradient. Turbidity increased moving westward across Lake Pontchartrain. The greatest turbidity was recorded during the winter months in the western-most region of Lake Pontchartrain. Lastly, bottom water velocity differed significantly among sampling locations ($F_{1,192} = 5.316; p = 0.0222$) but did not vary significantly among months ($F_{11,192} = 0.715; p = 0.7238$). However, there was a significant site by month interaction for water bottom velocity ($F_{11,192} = 1.922; p = .0387$) suggesting that bottom water velocity varied among sites but only during certain months. The highest bottom water velocity occurred during March 2006 at the Rigolets.

There were significant relationships between *C. sapidus* density and several environmental variables such as water temperature, salinity, and turbidity ($F = 16.081, p < 0.0001$). These three variables contributed to the explanation of 26% of the variation in *C. sapidus* spatiotemporal abundance. There was a positive relationship between *C. sapidus* density and water temperature, and as water temperature increased, the number of *C. sapidus* increased. There was a positive relationship between *C. sapidus* density and salinity, and as salinity increased moving west to east across Lake Pontchartrain, the number of *C. sapidus* collected increased (west to east across Lake Pontchartrain). Lastly, there was a negative relationship between *C. sapidus* density and turbidity, and as turbidity increased (from east to west across Lake Pontchartrain), the number of *C. sapidus* collected decreased (from east to west). Relationships between *C. sapidus* density and the environmental variables are summarized in Table 3. Though these environmental variables were significantly related to *C. sapidus* density, there were also interactions between the variables themselves. Water temperature is related to temporal, seasonal changes. Both turbidity and salinity are related to one another and more importantly are related to the increase

Table 3. Regression values demonstrating the relationships between mean *C. sapidus* density and *in situ* measured environmental variables. The regression analyses were significant ($F_{5,210} = 16.081$; $p < 0.0001$) and these environmental variables helped to explain 26% of the variation in *C. sapidus* abundance and distribution.

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	- 0.859	0.766	- 0.859	- 1.122	0.2632
Water temp	0.788	0.276	0.33	2.853	0.0048
Salinity	0.46	0.122	0.259	4.117	< 0.0001
DO	0.559	0.424	0.147	1.318	0.189
Turbidity	- 0.402	0.09	- 0.274	- 4.486	< 0.0001
Water velocity	4.221	2.221	0.114	1.909	0.0576

of distance away from the eastern region in Lake Pontchartrain. Thus, the effect of water temperature on *C. sapidus* density appears to be confounded within the effect of time, and the effects of salinity and turbidity on *C. sapidus* density appear to be confounded within the effect of increasing distance away from the eastern region of Lake Pontchartrain.

MODIS 250 m Band 1 Data

The MODIS 250 m band 1 (620 - 670 nm) data collected from dates 15-18 May 2006 and 14, 15, 25, and 26 September 2006 demonstrated water movement features that influenced *C. sapidus* distribution and abundance in Lake Pontchartrain during the first and second recruitment events, respectively, and provided information to quantify the net transport of suspended sediment, water, and *C. sapidus* during those time periods. The feature identified and tracked in May 2006 (Figures 11 - 14) was a clear water plume emerging from the IHNC along the south shore of Lake Pontchartrain. The leading edge of the plume was tracked over the course of the five days through consecutive MODIS 250 m band 1 data images. The feature identified and tracked from 14-15 September 2006 was a mass of suspended sediment near Irish Bayou in the eastern region of Lake Pontchartrain (Figures 15 and 16). The feature identified and tracked from 25-26 September 2006 was a small, clear plume-like figure near the IHNC (Figures 17 and 18). The leading edges of both suspended sediment features in September were tracked over the two-day periods.

The net transport, movement of the leading edge of the plume, from 15-16 May 2006 was 3.68 km to the NE (Figures 11 and 12), from 16-17 May 2006 was 1.98 km to the NE (Figures 12 to 13), and from 17-18 May 2006 was 1.21 km to the NE (Figures 13 to 14). The total net transport of the leading edge of the plume from 15-18 May 2006 was 6.87 km to the N-NE. The net transport for the suspended sediment feature from 14-15 September 2006 (Figures 15 and 16)



Figure 11. MODIS 250 m band 1 data collected on 15 May 2006 at 11:35am. The wind direction at this time was from the north-northwest at 3.676 m/s. The box indicates the leading edge of the feature. This image illustrates the approximately 100 km² clear water plume the day it emerged from the IHNC.

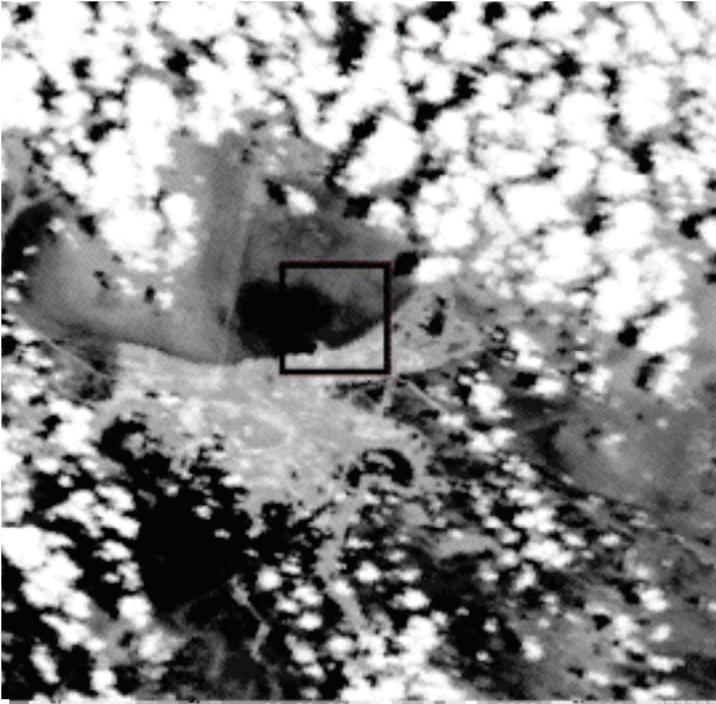


Figure 12. MODIS 250 m band 1 data collected on 16 May 2006 at 12:15pm. The wind direction during this time was from the north-northwest at 2.431 m/s. The box indicates the leading edge of the feature. The leading edge moved 3.68 km from the previous day.

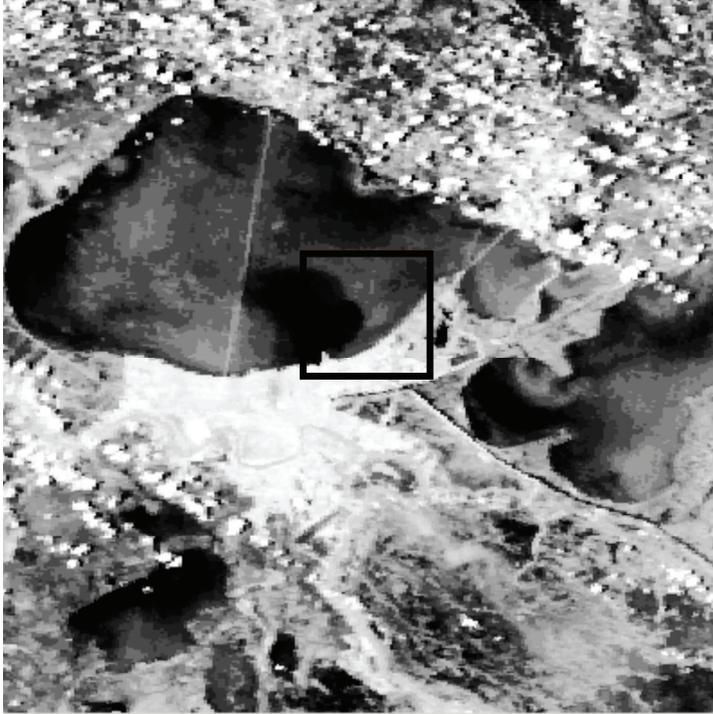


Figure 13. MODIS 250 m band 1 data collected on 17 May 2006 at 11:20am. The wind direction during this time was from the north-northwest at 2.277 m/s. The box indicates the leading edge of the feature. The leading edge moved 1.98 km from the previous day and moved a total of 5.66 km from 15-17 May 2006.

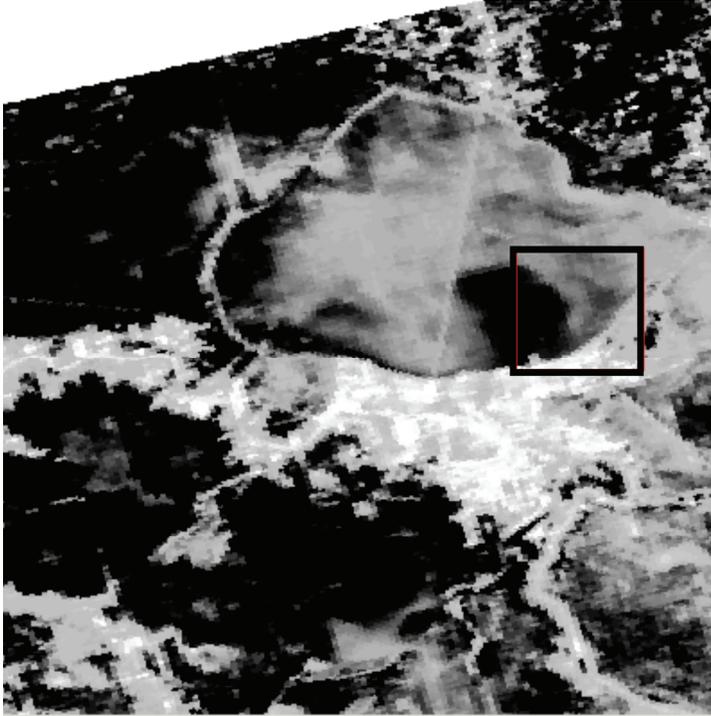


Figure 14. MODIS 250 m band 1 data collected on 18 May 2006 at 1:40pm. The wind direction during this time was from the north-northwest at 1.833 m/s. The box indicates the leading edge of the feature. The leading edge moved 1.21 km from the previous day and moved a total of 6.87 km from 15-18 May 2006.

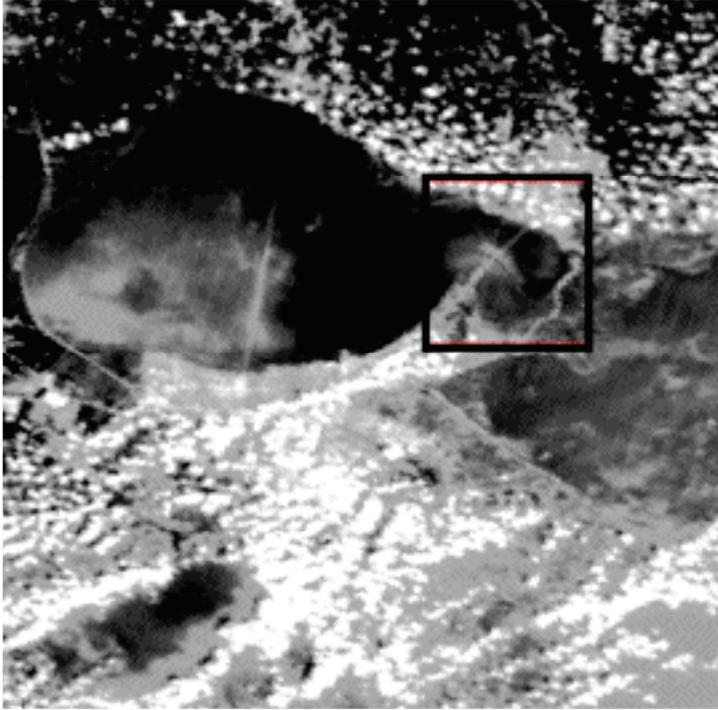


Figure 15. MODIS 250 m band 1 data collected on 14 September 2006 at 12:10pm. The wind direction during this time was from the northeast at 2.384 m/s. The image illustrates the suspended sediment feature in the eastern region, which is designated by the black box.

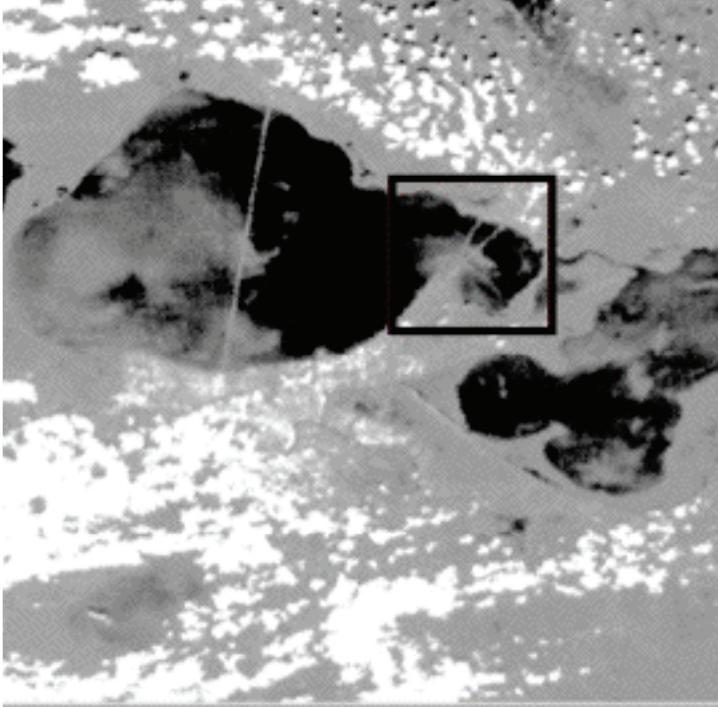


Figure 16. MODIS 250 m band 1 data collected on 15 September 2006 at 2:30pm. The wind direction during this time was from the southeast at 2.732. The image illustrates the suspended sediment feature, which is designated by the black box. The leading edge moved 0.97 km from the previous day.

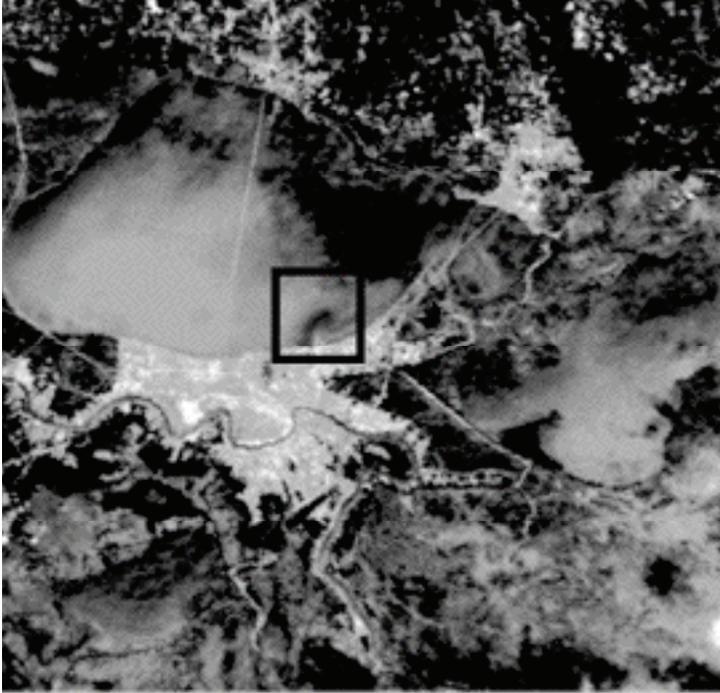


Figure 17. MODIS 250 m band 1 data collected on 25 September 2006 at 11:55am. The wind direction during this time was from the north-northeast at 5.96 m/s. The image illustrates the suspended sediment feature, which is designated by black box.



Figure 18. MODIS 250 m band 1 data collected on 26 September 2006 at 2:10pm. The wind direction during this time was from the north-northeast at 5.332 m/s. This image illustrates the suspended sediment feature, which is designated by the black box. The leading edge moved 2.57 km from the previous day.

was 0.97 km to the W-SW and the net transport for the suspended sediment feature from 25-26 September 2006 (Figures 17 and 18) was 2.57 km to the W-SW.

Wind and Tidal Data

The wind direction from 15-18 May 2006 was predominantly from the north-northwest and wind velocity rarely fell below 2 m/s throughout that five-day time period. The tidal exchange throughout the five-day period consisted of daily ebb tides and nocturnal flood tides (Figures 19-20). The wind direction and velocity on 14 September 2006 varied throughout the day (Figure 21, Images a and b). On 15 September 2006, there was a constant east-southeast wind, and the wind velocity increased during the second half of the day from approximately 1330 to 1600 (Figure 21, Images a and b). In general, from 14-15 September 2006, the wind velocities remained relatively high and gusty from the east-northeast (Figure 21, Images a and b). The wind direction on 25-26 September 2006 was constant throughout both days from the north-northeast (Figure 22, Images b). The wind velocities during the two-day period remained high at approximately 6 m/s (Figure 22, Images a).

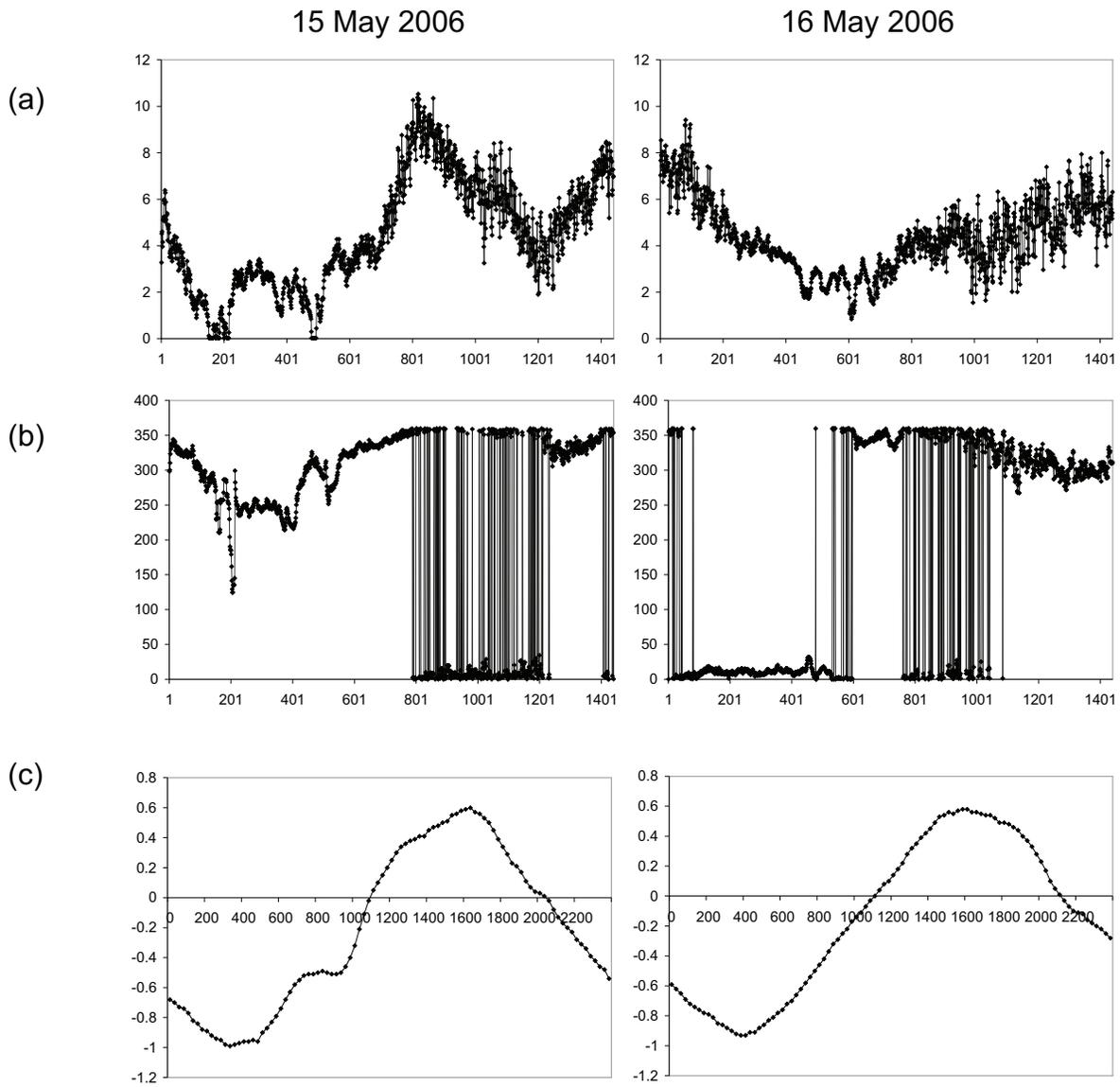


Figure 19. Image (a) wind speed (m/s), Image (b) wind direction ($^{\circ}$ N), and Image (c) tidal gauge height for 15-16 May 2006. Time (a-b = min; d = hours) is on the x-axis for all variables.

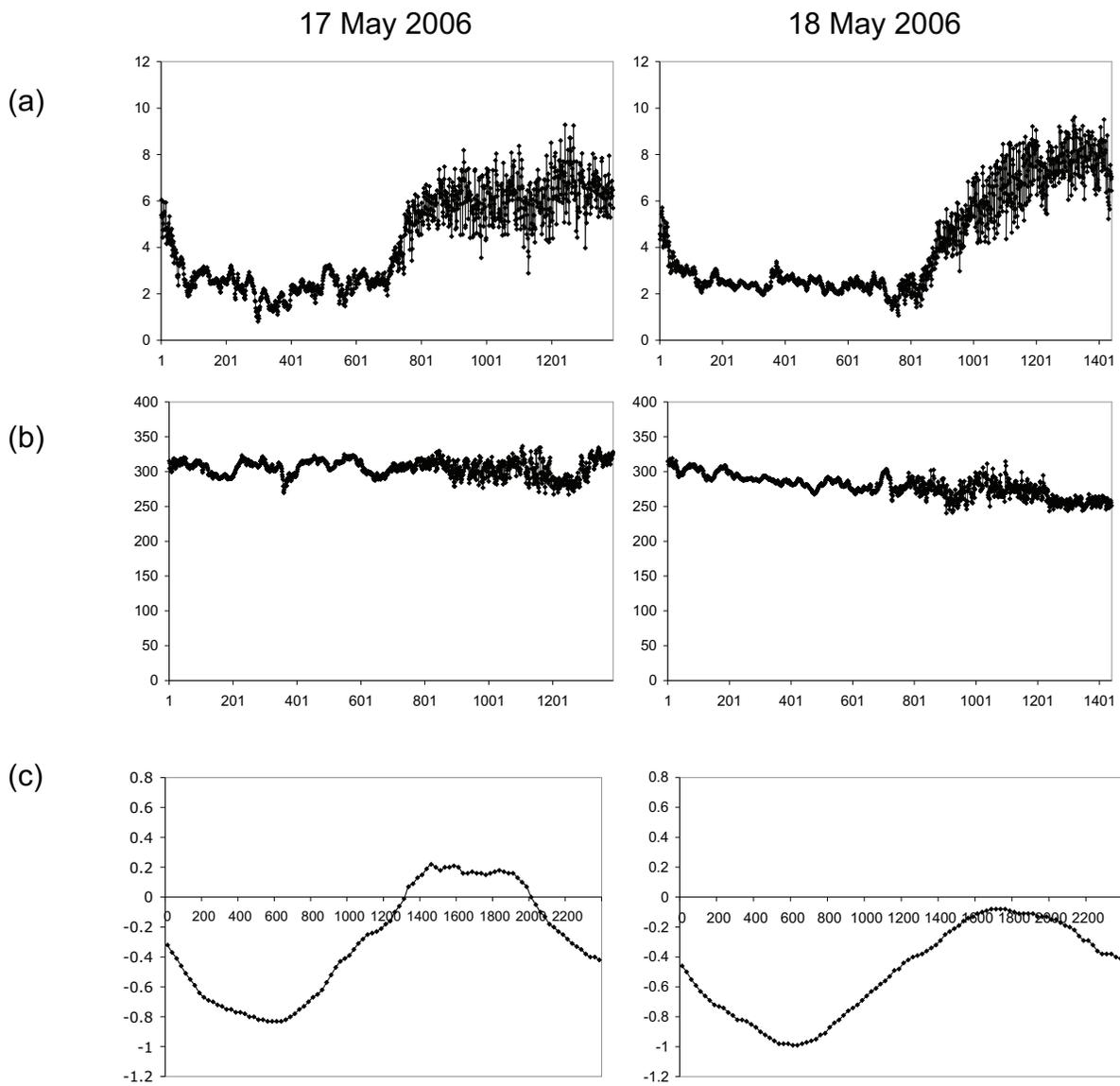


Figure 20. Image (a) wind speed (m/s), Image (b) wind direction ($^{\circ}$ N), and Image (c) tidal gauge height (ft) for 17-18 May 2006. Time (a-b = min; d = hours) is on the x-axis for all variables.

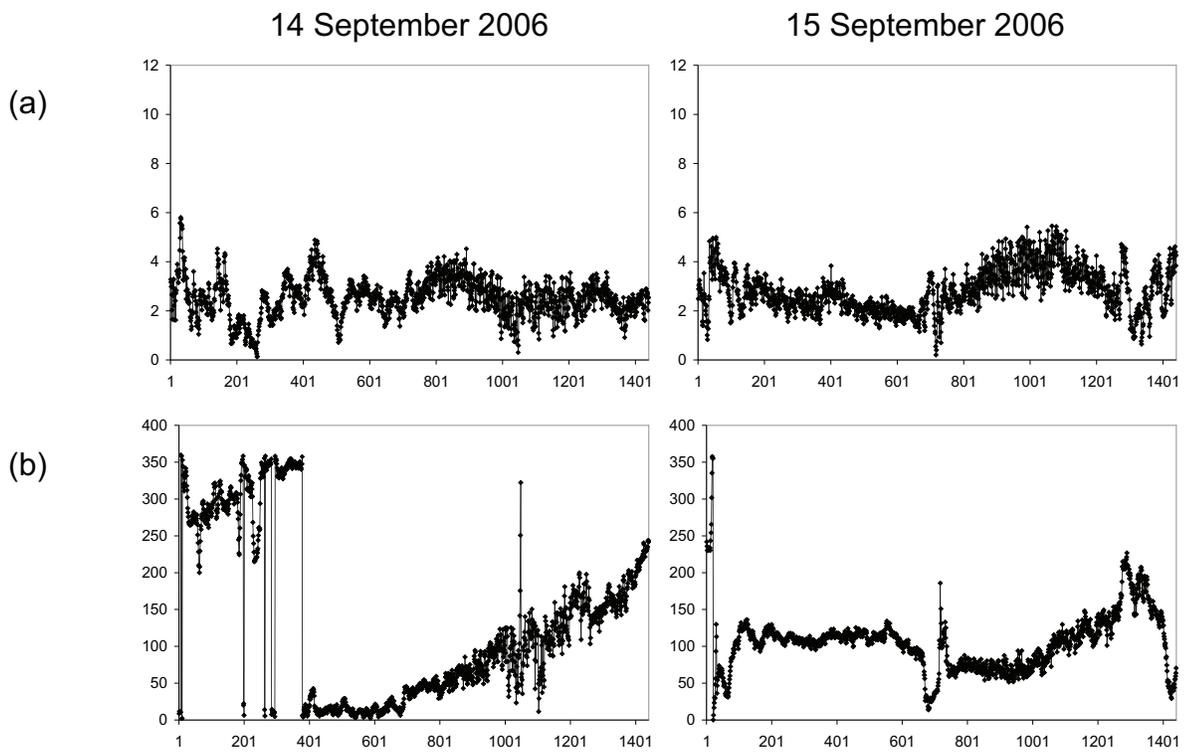


Figure 21. Image (a) wind speed (ms) and Image (b) wind direction ($^{\circ}$ N) for 14-15 September 2006. Time (min) is on the x-axis for both variables.

25 September 2006

26 September 2006

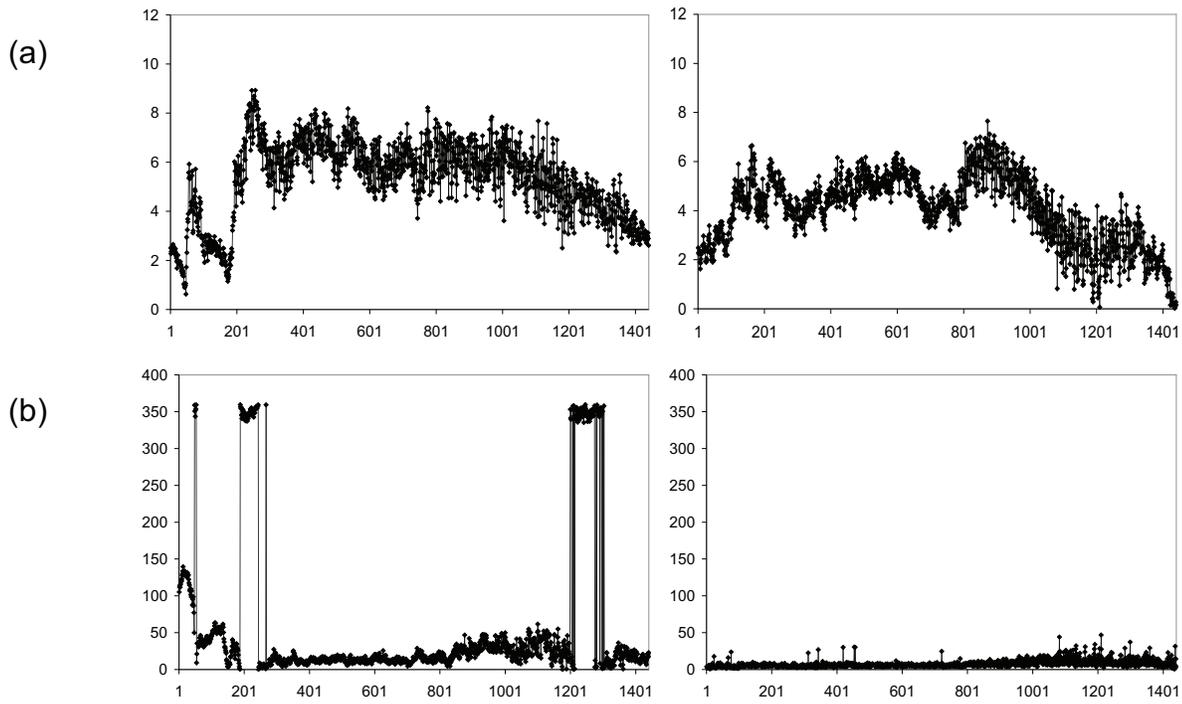


Figure 22. Image (a) wind speed (ms) and Image (b) wind direction ($^{\circ}$ N) for 25-26 September 2006. Time (min) is on the x-axis for all variables.

DISCUSSION

Two Recruitment Events

Recruitment into Lake Pontchartrain by *C. sapidus* is contingent upon water movement throughout the estuarine system. Variations in those recruitment events (i.e., differing migration routes, recruitment sizes, average carapace length of recruits, etc.) are related to the changes in those environmental factors and conditions, which influence water movement. During the sampling period within this study, environmental conditions favored the rapid transport of a large group of early life stage *C. sapidus* into Lake Pontchartrain via a shorter, more direct migration route, while later in the year conditions favored the more gradual transport of a smaller group of later stage, early juveniles via another migration route (Figure 23). During those two events certain conditions aligned with early life stage crabs; however, under another set of conditions, *C. sapidus* may have been transported differently or not transported at all. Etherington and Eggleston (2003) referred to this as a “stochastic likelihood” that a large group of crabs could line up with the right conditions (wind, tidal, storm frontal systems) and could be transported due to the right combination of environmental forces or conditions. Instinctually, the species selects tidal phase and nocturnal versus day transport to ensure optimal transport, but the species’ dispersal can also greatly depend on large-scale, highly variable environmental conditions. Potentially these conditions may line up in unfavorable combinations that could prove harmful to the species. In a similar scenario, the recruitment of acorn barnacles (*Semibalanus balanoides*) in Mt. Hope Bay, Rhode Island appears to be also driven by physical forces, such as wind direction. If the wind blew from the south, *S. balanoides* recruited to the southern areas and vice versa (Bertness 1999). The species was forced to recruit to the area that environmental conditions selected irrespective of what benefited the population.

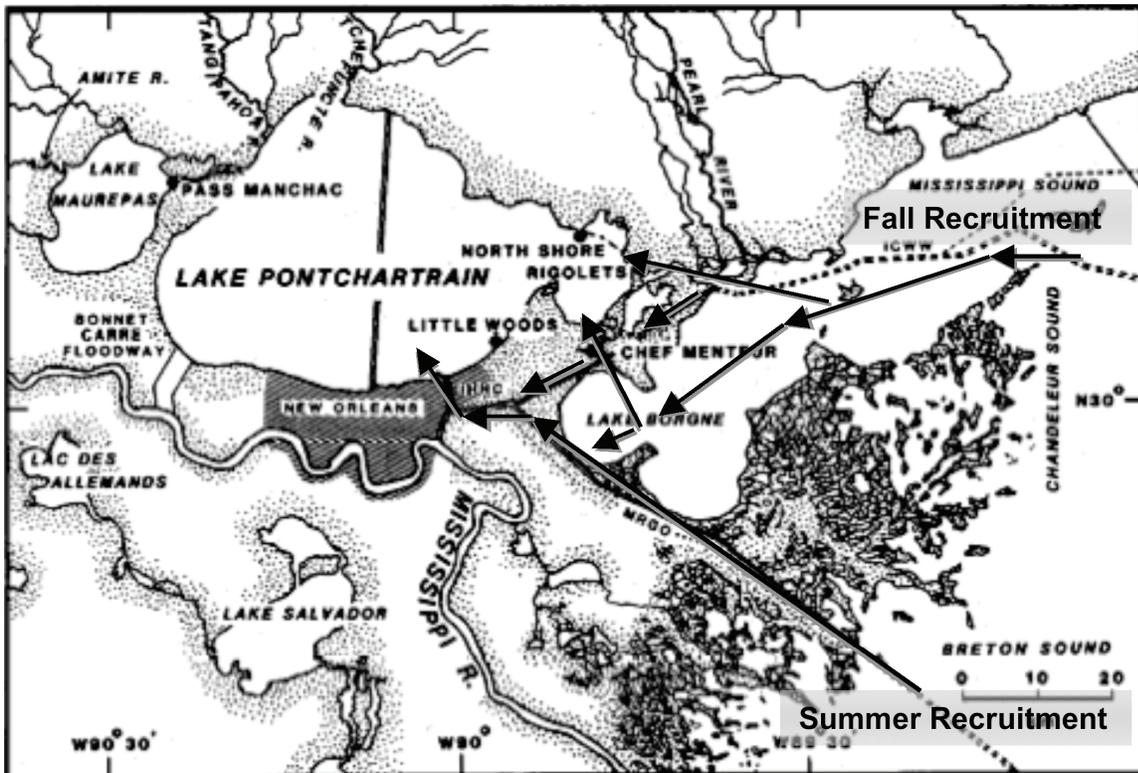


Figure 23. Image of Lake Pontchartrain and surrounding water bodies demonstrating the two differing routes of early life stage *C. sapidus* recruitment into Lake Pontchartrain during the summer and fall recruitment events. Image modified from Sikora and Kjerfve (1985).

Callinectes sapidus density varied temporally in Lake Pontchartrain as has been found in previous studies. Darnell (1959) reported early life stage *C. sapidus* recruitment in Lake Pontchartrain occurred in May and later in the fall, though the study did not emphasize which recruitment event was larger. McClintock et al. (1993) reported an increase of early life stage crabs in August of 1989 and March of 1991 in Weeks Bay, AL. The earlier recruitment event in Weeks Bay indicated a very early spring spawn or very late fall spawn, which suggested overwintering of early life stage crabs from the fall spawn. Atlantic Coast estuaries also exhibit two *C. sapidus* recruitment events, with the early May event representing a minor influx compared to the larger event from August to November (Etherington and Eggleston 2000). However, other more recent studies of megalopal settlement in the northern Gulf of Mexico in Mississippi Sound showed minimal recruitment during April, May, and June (Perry et al. 1998). In these cases, large numbers of megalopae were collected in plankton samples in barrier island passes during spring months (Perry et al. 1995; Rabalais et al. 1995). Inland settlement was low suggesting that the megalopae were available offshore but not yet transported inland (Perry et al. 1995; Rabalais et al. 1995). Duffy (1997) also reported peak densities of early life stage crabs in October and low densities during the summer. Therefore, the bi-modal recruitment events I observed suggest atypical forces are acting on *C. sapidus* movement within Lake Pontchartrain.

The temporal distribution and abundance of early life stage *C. sapidus* appears to be largely influenced by life history strategies in which females synchronize larval release with ebbing tides during certain times of the year to ensure larvae are transported offshore during those months when predation is highest. Upon metamorphosing into the post larval stage, large numbers of early life stage *C. sapidus* recruit into the lower saline, calmer Lake Pontchartrain

estuarine waters starting within two months of female spawning using nocturnal flood tides. However, in the case of *C. sapidus* in Lake Pontchartrain, the temporal and spatial patterns of abundance and distribution may be altered. The more direct artificial connections to seaward habitats (like the MRGO) create “short cuts” in and out of Lake Pontchartrain. Ultimately, the abundance and distribution patterns of *C. sapidus* in Lake Pontchartrain were influenced by the time of year, migratory route, wind and tide induced circulation, and habitat type.

Two Migration Pathways

Two differing sets of environmental conditions resulted in *C. sapidus* transport through two different pathways. The first recruitment event was associated with the same hydrodynamics that accounted for the large plume of water, which emerged from the IHNC. Saltwater intrusion from the IHNC can create 0.3 - 0.6 m deep plumes of water that can periodically cover up to 250 km² of Lake Pontchartrain (Poirrier 1978 ; Georgiou and McCorquodale 2002). Though strong northerly winds during the May-June recruitment event may seem counter intuitive to transport into Lake Pontchartrain, the physical conditions, which induced plume expansion and *C. sapidus* transport were consistent with hydrologic transport models conducted specifically for the IHNC. With northerly and westerly winds, models predicted the high saline plume would expand to the north and west, while with a southerly winds, the plume would be compressed to the south shore and expands laterally to the east and west (Georgiou and McCorquodale 2002). The surface water being moved by wind currents is transported in the with-wind direction, whereas the water near the bottom of Lake Pontchartrain is transported in the opposing-wind direction. Thus, the plume extending from the IHNC along the bottom of Lake Pontchartrain is moved in the opposite direction of the wind. In addition,

when a northerly wind is combined with a flood tide, only 15% of the flow is with the wind, and 85% of the flow is towards the north against the wind (Georgiou and McCorquodale 2002).

Tidal movement during this first recruitment period opposed reported recruitment conditions in which tidal transport of estuarine species typically occurs at night via nocturnal flood tides (Perry et al. 1998). The tide during this period rose throughout most of the day and fell throughout most of the night. Daily flood tides and nightly ebb tides are more characteristic of larval movement out of the estuary. Larval release by females is synchronized with nocturnal ebb tides to reduce larval predation rates and ensure tidal transport to higher saline waters (Tankersley et al. 1998; Forward et al. 2003; Morgan 1990). With the environmental conditions in place and a daily flood tide, the results of this study support that *C. sapidus* were likely transported into Lake Pontchartrain during the day. The hydrologic conditions, water movement driven by both wind and tide, during this time period appeared to have induced a divergence from instinctual behavior (i.e., the species was transported during the day when chances of predation were greater).

The physical conditions associated with the transport of *C. sapidus* during the second recruitment event were different than the earlier event and induced transport via the natural inlets into Lake Pontchartrain. The general wind directions, tidal estimates, and the influx of early life stage crabs to eastern sites in September were consistent with literature on the life history of *C. sapidus* in Louisiana coastal waters (Perry et al. 1998). Predominantly easterly winds coupled with large nocturnal flood tides are the conditions during that time of year in which post-larvae in Mississippi Sound, the large body of water adjacent to the natural inlets in the eastern part of the Lake, are transported into Lake Pontchartrain via the Rigolets and Chef Menteur passes (Perry et al. 1998).

Callinectes sapidus Most Abundant in the Eastern Region

My results also support the idea that throughout the course of these large scale ecological processes, there are other processes occurring at smaller scales. Etherington and Eggleston (2000) emphasize the importance of scale in a system-wide investigation. In addition to a Gulf wide and coastal wide scale *C. sapidus* movement, smaller scale, geographically specific processes can also influence distribution and abundance. Larger scale transport processes are impacted by a combination of physical forces and abundance of larvae ready to be transported inland during a given period when conditions induce inland transport. However, once the early life stage *C. sapidus* are brought into and then distributed within the system, smaller scale, estuarine-wide processes likely determine succession. Etherington and Eggleston (2000; 2003) reported that accessibility of suitable habitat is a key component, which determines the value of that habitat.

In Lake Pontchartrain, though, there are three inlets and extensive circulation patterns such that early life stage *C. sapidus* have access to all regions of the Lake. The surface water in the middle of Lake Pontchartrain typically moves in the opposite direction of the wind, while the shallow water near the shoreline flows with the direction of the wind. This normally creates two large gyres that depend on wind direction in the middle of the Lake. A third gyre is produced on the Lake floor in the shallow western region during northerly and southerly winds or in the shallow north end during easterly and westerly winds (Georgiou and McCorquodale 2002). These large gyres, which account for circulation to nearly all areas within Lake Pontchartrain likely transported *C. sapidus* from the southern central location to westward, north and eastward locations during the first recruitment event and from the eastern region to the further westward locations during the second recruitment event. Other processes besides dispersal likely limit *C.*

sapidus abundance and distribution within Lake Pontchartrain as my results suggest that it is possible for crabs to disperse to all portions of the Lake; they are not spatially limited. Habitat type, substrate, resources, and post-settlement processes such as competition and predation likely play a role in where these early life stage crabs settled and remain. However, analyses of unpublished data revealed no negative relationships among the size classes suggesting low levels of intraspecies competition.

Though not specifically addressed through field investigation in this study, substrate and habitat differences between the eastern and western regions of Lake Pontchartrain likely played a major role in abundance and distribution patterns along with post-settlement processes such as predation. The lack of *C. sapidus* I observed in the western region of Lake Pontchartrain is possibly due to the lack of suitable habitat, which subjects early life stage crabs to higher predation rates and potentially limited resources. With no structured habitat for the crabs to use as refuge or which to adhere to, crabs that dispersed westward were likely consumed by predators or transported with wind events until reaching more optimal habitat. When looking at the abundance and distribution of the species collected along with *C. sapidus* within this study, the number of potential predatory species was greatest during the early summer influx of early life stage *C. sapidus* into the non-structure central and western regions.

Sites in the eastern regions consist of extensive natural marsh edge, and SAV, which provides structure and protective habitat. Western sites consist of concrete or riprap embankment, eroded mud banks, and non-complex, non-protective open sand or mud bottoms (refer back to site descriptions in the Materials and Methods). These complex habitats such as marsh edge and SAV are known to offer refuge and increased resources for many estuarine species (Pile et al. 1996). Complex habitat is essential for the survival of early life stage *C.*

sapidus because predation rates are higher in open bottom unstructured habitat (Heck and Thoman 1981; Pile et al. 1996; Etherington and Eggleston 2000).

When looking more closely at a study conducted in the eastern region of Lake Pontchartrain which looked at differences in macrofaunal community structure between certain native and invasive SAV and compared vegetated versus non-vegetated habitat, the study further emphasize microhabitat processes such as strong selection for vegetated, structured habitat over adjacent non-vegetated, open bottom habitat (Duffy 1997). *Callinectes sapidus* will remain in complex structure until, due to size increases, predation rates become equal to non-structured habitat, driving the species to inhabit adjacent non-structured habitat (Pile et al 1996). Though Atlantic Coast studies report instar 5 stage crabs and larger moving out of protective complex habitat over open substrate (Pile et al. 1996), studies within the northern Gulf of Mexico report that *C. sapidus* no smaller than 10 mm in size actually move outside of vegetated habitat (Williams et al. 1990).

Furthermore, studies conducted in estuaries in the northern Gulf of Mexico report that large recruitments of early life stage crabs do not result in increased abundance of later stage juvenile abundance (Guillory and Prejean 1997; Heck et al. 2001; Perry et al. 1998, and Morgan et al. 1996). In Mobile Bay and Mississippi Sound, there were no significant relationships between megalopal supply and juvenile abundance, except right after few large recruitment events of early life stage crabs. Even with large influxes of early life stage crabs, within two weeks crab density in those areas of large recruitment returned to the previous density. Similar events likely occurred in Lake Pontchartrain during the first recruitment event when large numbers of early life stage *C. sapidus* settled in May and none were collected the next two months. Even within an upper estuary, protective area that provides nursery habitat, such as

Lake Pontchartrain, there was a lack of relationship between early life stage crabs and later stage early juveniles. However, within Atlantic Coast estuaries, megalopal and early juveniles are strongly correlated with adult population (Olafsson et al. 1994; Pile et al. 1996).

The abundance of gravid females, larval crabs, and post larval crabs does not appear to limit *C. sapidus* populations in the northern Gulf of Mexico (Guillory et al. 1998). Megalopal abundance is 10 - 100 times greater in the northern Gulf of Mexico estuaries than the Atlantic Coast estuaries (Rabalais et al. 1995). However, later juvenile abundances are similar between Gulf Coast and Atlantic Coast estuaries demonstrating a large decrease of crabs from one life stage to the next for Gulf of Mexico populations. High predation rates in the Gulf of Mexico, which can be 85-95% a day, are the major limiting factors for *C. sapidus* populations (van Montfrans et al. 1995; Morgan et al. 1996; Heck et al. 2001). These factors may even negate the effects of greater post larval abundance along with greater expanses of marsh edge that serve as nursery habitats within the northern Gulf of Mexico (Guillory et al. 1998).

Post Settlement Planktonic Dispersal

The younger *C. sapidus* that occurred in high numbers at Pontchartrain Beach in May 2006 and the larger crabs found at Irish Bayou and the Rigolets a month later were likely of the same cohort. Etherington and Eggleston (2003) found that densities of recent settlers (instar 0-2 stage crabs) from August and recent recruits (instar 5 stage crabs) from September that were determined to have settled at the same period of time within the recruitment event were associated and could define a cohort. They looked at the time-since-settlement data for instar 0-2 and instar 5 stage crabs and assessed the relationship from the first month to the second month to determine if there was an overlap in the time period both groups settled. Instar 0-2 stage crabs would have settled within 0-16 days and instar 5 stage crabs would have settled within 30-46

days. I collected instar 0-2 stage crabs on May 30th and 31st, thus the instars could have initially settled on or around May 16th and 17th. In June, I collected instar 3-5 stage crabs on the 20th, 21st, and 22nd, thus the larger instars could have initially settled on or around May 7th and 8th. These settlement dates were within 10 days of one another and indicate that the two groups of instars collected in May and June more than likely represent a single cohort. The time since settlement dates are based on laboratory studies conducted by others and growth rates were reported to be higher in field than the laboratory (Epifanio et al. 1994; Welch and Epifanio 1995).

During the second recruitment event, as in the first recruitment event, there was evidence of a cohort arrival followed by a second planktonic dispersal. Instar 0-2 stage crabs were collected in Lake Pontchartrain on September 26th indicating settlement on September 10th and 11th. Between October 24th and 30th, 3-5 instar crabs were collected indicating a settlement between September 9th and 19th. These instar 0-2 stage crabs collected in September and instar 3-5 stage crabs collected in October appear to be of the same cohort (Figure 5). Instar 3-5 stage crabs were most abundant in September and instar 6-9 stage crabs were most abundant in October. The > 9 instar crabs were also present in October and appeared to continue to grow gradually throughout the winter months, November 2006 – February 2007.

Growth Trends

Growth trends were also evident within the *C. sapidus* abundance and distribution data. *Callinectes sapidus* growth is related to temperature (Hill et al. 1989) and when the early life stage crabs entered Lake Pontchartrain as instar 0-2 or 3-5 stage crabs during the recruitment event in May, warm water temperatures likely induced rapid growth resulting in an immediate increase of the next size class the next month. However, there were low numbers of any size *C.*

sapidus collected in August and September following the recruitment event. Low *C. sapidus* density during those months possibly resulted because this cohort of *C. sapidus* either grew and moved away from shallow habitat, were subjected to predation, or better avoided capture by the throw trap because they were larger. The second recruitment peak was during fall and early winter when water temperatures were declining and metabolic activity for most ectothermic organisms was also declining. For *C. sapidus* growth rate is highly affected by decreases in temperature (Hill et al. 1989). Growth rates following the second recruitment period would not be constant and rapid like during the first recruitment event in the summer. Throughout the winter months, growth would be more gradual and result not in a peak but in small additions of larger *C. sapidus* over time. Growth has been shown to cease over the winter months or, in the case of mild winters as experienced in the northern Gulf of Mexico, growth continues but at a reduced rate (McClintock et al. 1993). These data suggest gradual growth of the cohort over the winter or the prolonged presence of > 9 instar stage crabs due to a decrease in growth or a decrease in predation rates (or both) during winter months.

Overall C. sapidus trends

Over the last 30 years, an increase in megalopal and early juvenile *C. sapidus* settlement and recruitment has occurred farther inland. The increase in smaller *C. sapidus* farther inward is speculated to be related to habitat degradation, barrier island deterioration, coastal erosion and land loss, and also tidal inlet widening (Guillory et al 1997; Georgiou et al. 2005). Though, as *C. sapidus* are transported inland in search of protective habitat, internal habitat degradation, (i.e., loss of SAV and structured habitat within inland bodies of water) are also impacting *C. sapidus* populations. In the 1960s, 8097 ha of SAV were present in Lake Pontchartrain, and in 1973, only 810 ha were present. By 1985, only 397 ha were present (Montz 1978). The loss of SAV

in Lake Pontchartrain is directly related to the loss of nursery habitat in the system and is likely negatively impacting *C. sapidus* populations over time.

In general, commercial crab landings and fisheries independent data suggest Louisiana *C. sapidus* populations are declining. Factors such as over fishing, increased fishing efficiency, increased demand, increased number of fishermen, increased number of traps per fishermen, and habitat loss throughout the entire estuary are responsible for the decline (Guillory 1997). Large influxes of *C. sapidus* into MRGO could possibly be further indicative of decreasing coastal habitat in a naturally degrading delta environment highly impacted by anthropogenic influences and hurricanes.

MRGO and Hurricane Risk Reduction Structures

There are both positive and negative implications to estuarine dependent species when considering a proposed closing of the MRGO. The negative implications pertain to closing a migratory corridor that provides another, more direct route for the transport of commercially and ecologically important species into Lake Pontchartrain. The water-way was dredged nearly 45 years ago (Sikora and Kjerfve 1985) and since that time estuarine dependent species could and have depended on it as a migratory corridor (as I have demonstrated here). However, the alternate pathway and this highly altered environment may be disrupting or negating entrained behavior and instinct for species that select to migrate during certain times of the year and during certain times of the day. Allowing the alternate corridor to close may have great positive implications to estuarine dependent species, i.e., restoring more natural transport and migration events. Forcing the species to enter Lake Pontchartrain through the natural inlets in the eastern region would drive settlement and recruitment in areas of suitable habitat. Completely closing the channel at Bayou La Loutre would also reduce salt-water intrusion. In addition, a previous

study reported decreasing salt-water intrusion restricted predators less tolerant of lower saline water to farther seaward habitat (Guillory 2000). In general, it would seem that an addition of early life stage *C. sapidus* via the IHNC into the central and western regions of Lake Pontchartrain would increase *C. sapidus* abundance and benefit the overall population in Lake Pontchartrain; however, the increase of *C. sapidus* densities into those areas was not sustained as available habitat was not suited to sustain life at those early stages. Further studies must be conducted to gain a better understanding of the positive and negative impacts of the MRGO on Lake Pontchartrain commercial and ecologically important estuarine dependent species.

Furthermore, with the threat of each hurricane season, plans are being developed to reduce the risk of storm surge impacts throughout the Greater New Orleans Metropolitan Area (GNOMA). Though risk reduction is crucial for human populations, the impacts of flood control structures across the MRGO, GIWW, and potentially even the Rigolets and Chef Menteur passes could change natural system-wide ecological processes and such alterations must be carefully considered. Migratory patterns could be altered and estuarine dependent species populations within Lake Pontchartrain could decline significantly. Migratory corridors in and out of Lake Pontchartrain are important for maintaining populations of important estuarine dependent species and are essential for ultimately maintaining the fisheries in Lake Pontchartrain. Besides potential impacts to transport throughout the system, proposed project would further disturb and remove important nursery habitat in the eastern region. Though habitat loss would be accounted and mitigated throughout the construction of the hurricane risk reduction system, the loss of habitat in the interim may be too great since the impacted area would consist of the majority of nursery habitat currently available.

MODIS 250 m Band 1 Data

In addition to gaining insight into *C. sapidus* distribution and abundance, migration pathways and the influential physical forces, this study also demonstrated the utility and limitations of ecological application of MODIS 250 m data within highly productive, turbid coastal waters such as Lake Pontchartrain. With two spacecrafts providing one and sometimes two images a day that can demonstrate estuarine water movement, one can acquire an instant overview, a “snap shot” of system-wide processes that may not be evident in smaller scale field sampling or may be missed in the case of an ephemeral event that could have occurred in between sampling periods, e.g., the plume emergence during the first recruitment event. However, as demonstrated in the case of the second recruitment event, the utility of MODIS 250 m data are limited and are not applicable under any suite of environmental conditions. The utility of the data was limited by image quality and the number of quality images available during a desired time period. When considering the time period during both recruitment events, only 30% of the images that clearly displayed Lake Pontchartrain could be used. The utility of the MODIS 250m images were also limited by the high wind velocities that continually mixed the system and caused system wide sediment re-suspension. Significant re-suspension occurs within Lake Pontchartrain with winds speeds greater than 4 m/s (Miller et al. 2005). With increased sediment re-suspension in nearly 75% of Lake Pontchartrain, net transport and local re-suspension were not easy to distinguish, and local re-suspension can mask net transport (Miller et al. 2005).

My results also suggest that when large-scale ecological events are coupled with less evident, natural, large-scale physical processes, such as *C. sapidus* recruitment and water

circulation, more than a qualitative approach, (i.e., viewing water movement within MODIS 250m data) may be required to discern influential factors to recruitment within a system. The MODIS 250 m band 1 data available during the second recruitment period were not as useful in distinguishing influential water movement features because this more natural recruitment event via the natural inlets into Lake Pontchartrain was coupled with tidal and wind events that usually occur during those fall months. In addition, the hydrodynamics and sediment transport near the eastern region of Lake Pontchartrain and within the Rigolets and Chef passes were also nearly impossible to decipher because of the data resolution. *In situ* measured environmental data along with remotely sensed data can better indicate those significant water movement events.

Etherington and Eggleston (2003) looked at the duration of wind from a certain direction to determine what specific wind events influenced *C. sapidus* recruitment. They calculated the time since settlement (0-12 days for instar 1-2 stage crabs and 1-25 days for instar 3-5 stage crabs) and looked at the duration of wind from a certain direction for 0-12 and 1- 25 days to determine what specific wind events influenced recruitment of those size crabs within the system. I did not need to use such an approach during the first recruitment event, when the MODIS 250 m band 1 data images provided not only quantitative water movement data, but also indicated qualitatively what appeared to influence *C. sapidus* distribution and abundance. Assessing wind direction for the respective time since settlements was more helpful during the second recruitment event when the images did not offer a visual indication of an influential event.

SUMMARY

Although there were two recruitment events throughout the sampling period, time specific wind and tidal patterns within each event induced transport of early life stage *C. sapidus* into Lake Pontchartrain via two different migration pathways. The alternate migration path influenced primary and secondary dispersal during the first recruitment event, and the natural passes into Lake Pontchartrain influenced primary and secondary dispersal during the second recruitment event. While environmental conditions of the late summer and early fall *C. sapidus* recruitment have been illustrated in various reports in the northern Gulf of Mexico, conditions underlying the first recruitment noted in this study via the MRGO have not been thoroughly explored and require further investigation.

Habitat accessibility does not limit distribution and abundance within Lake Pontchartrain. My results suggest that the lack of suitable nursery habitat through Lake Pontchartrain is the major influence on *C. sapidus* populations in the system. Crabs are transported throughout the entire Lake, as I have shown here, and suitable habitat is the limiting factor in Lake Pontchartrain. With the great amount of wind and tidal induced currents within Lake Pontchartrain, crabs are transported throughout the system, though beyond the eastern and northeastern regions, there is no complex, structured habitat for protection. The continued decrease in SAV and structured, protective nursery habitat will likely result in the decrease of *C. sapidus* populations in Lake Pontchartrain. In addition, the majority of crabs in these vulnerable early life stages are collected in the east, and altering habitat in the eastern region of Lake Pontchartrain (i.e., proposed Rigolets Pass closure structures) will only continue to cause *C. sapidus* population decline in Lake Pontchartrain. In the end, altering the natural hydrology of an estuary could disrupt or negate instinctual behavior for species that select to migrate during

certain times of the year and even certain times of the day to reduce predation rates and ensure transport to suitable nursery habitat. For example, the selective nocturnal flood tide transport was negated and large numbers of early life stage *C. sapidus* were flushed into Lake Pontchartrain within a day time flood tide event via the IHNC earlier in the year during my study.

In addition, this approach for applying remote sensing techniques to ecological investigation appears to be a very useful tool in monitoring important large-scale estuarine processes, which impact large-scale ecological processes. As established by this study, MODIS 250 m data can be used to monitor large-scale influential water movement patterns utilized as means of transportation during *C. sapidus* recruitment events. Acquiring daily “snapshots” of Lake Pontchartrain is extremely useful in demonstrating significant ephemeral events that smaller scale sampling can overlook or not detect at all. This study which combined field and remote sensing investigation, highlighted the MRGO as an important corridor of migration between upper and lower estuarine habitats, but further investigation is required to fully understand the positive and negative implications of estuarine dependent species utilizing this is migration route. Ultimately, remote sensing techniques were and can be used to more completely understand *C. sapidus* and possibly other estuarine species recruitment dynamics and variations in distribution and abundance patterns within Lake Pontchartrain.

Lastly I realize my twelve months of data are limited and only limited conclusions can stem from this study and these results. Temporal replication, investigating early life stage *C. sapidus* within Lake Pontchartrain for multiple years would be necessary to distinguish between reoccurring processes and anomalies. Hopefully this study to acquire baseline data on *C. sapidus* recruitment, distribution, and abundance within Lake Pontchartrain for conservation and

management purposes will create a foundation on which to create criteria for maintaining and preventing the alteration of those system-wide, ecologically important processes, which influence ecologically and commercially important estuarine species.

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VITA

Lissa Lyncker was born in New Orleans, Louisiana, on January 22, 1982. She grew up in Irish Bayou, a small commercial fishing community in the eastern outskirts of New Orleans. Her father and other family members in the area were all commercial fishermen. She grew up working on shrimp and crab boats, and she developed a love and respect for the water and aquatic organisms at an early age. She graduated from Pope John Paul II high school in May 2000. Later that year she enrolled in Loyola University New Orleans in New Orleans, Louisiana. She majored in Biology and graduated Cum Laude with a Bachelor of Science degree in May 2004. In August 2004, she entered the Biological Sciences program in the Graduate School of the University of New Orleans.