BELLY-UP IN THE BAYOU, WHO'S THE CULPRIT?

PHYSICAL, CHEMICAL, AND BIOLOGICAL PARAMETERS OF OFFATTS BAYOU, GALVESTON, TX

A Senior Scholars Thesis

by

ALLISON CHRISTINE SKINNER

Submitted to the Office of Undergraduate Research
Texas A&M University
In partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2007

Major: Marine Biology

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ABSTRACT

Belly-Up in the Bayou, Who's the Culprit?
Physical, Chemical, and Biological Parameters of
Offatts Bayou, Galveston, TX (April 2007)

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Department of Marine Biology
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Offatts Bayou is an embayment in the Galveston Bay complex on the upper Texas coast. The bayou is approximately 4.8 km long with a maximum width of 1 km, and an average depth of approximately 5 m. A small created lake (Lake Madeline) is connected to Offatts Bayou by a short, narrow channel. Together, Lake Madeline and Offatts Bayou (LMOB) are an important nursery and habitat for many finfish, shellfish, birds and other fauna and flora. The low mixing environment of LMOB, due to its relatively deep basin and small mouth, make it an ideal study area for understanding the significance of phytoplankton blooms and hypoxia as the causal factors of the near annual fish kills in these systems. Physical, chemical and biological parameters were measured at up to 17 stations distributed across LMOB, twice weekly over the course of two summers. Low winds, little rain and a highly stratified water column isolated a phytoplankton bloom to the upper pycnocline in the late summer of 2005. Phytoplankton concentrations in Lake Madeline (246.89 µg/L) were 4 times higher than those in Offatts Bayou (58.69 µg/L).

The dominate phytoplankton species was an as yet, unidentified spherical cyanobacterium. The fish kill in August 2005 was associated with the decay of this bloom. Gulf menhaden (*Brevoortia patronus*) was the only fish species killed. Higher winds and more rain in the summer of 2006 resulted in a generally well mixed and oxygenated water column. Phytoplankton concentrations were low (13.22 µg/L) throughout the summer and a fish kill was not observed. The findings of this study supported the hypothesis that phytoplankton, either directly through harmful algal blooms/large quantities of biomass, or indirectly through low dissolved oxygen concentrations, are the primary causative factor of the fish kills occurring during the late summer months in LMOB. This study was unique in several respects: (1) two summers of physical, chemical and biological data were collected on fine spatial and temporal scales, (2) the phytoplankton community was identified to genus level revealing the identity of the bloom forming species, and (3) the cause of the fish kill could be clearly defined.

ACKNOWLEDGMENTS

Special thanks to Derek Shultz, Federico Alvarez, Mark London, and Amanda Thronson for helping collect the data. My appreciation also goes to Dr. Ayal Anis (TAMUG) for the use of his CTD. Winston Denton (TPWD) helped in the initial set up of this project. Recognition is also due to Keith Dupuis and Gaurav Singhal for their assistance with MatLab. My gratitude is also given to Andrew McInnes with the TAMUG Coastal Geology Lab for his assistance in collecting and processing the bathymetry data for the LMOB, as well as help with data collection in the summer of 2006. A Texas Institute of Oceanography (TIO) fellowship was awarded offering support in the latter stages of this study and in preparing the thesis and manuscript. Finally, I am indebted to Antonietta Quigg Ph.D. for her mentorship, support, and guidance.

NOMENCLATURE

LMOB	Lake Madeline and Offatts Bayou
NOAA	National Oceanic and Atmospheric Administration
PRISM	Pollution Response Inventory and Species Mortality
PSU	Practical Salinity Units
CST	Central Standard Time
CTD	Conductivity Temperature and Depth Instrument
DMSO	Dimethyl Sulfoxide
HCl	Hydrochloric Acid
GIS	Geographic Information System
Julian days	Day of Year

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CHAPTER I

INTRODUCTION

Fish kills are reported throughout the nation and much research is conducted in an attempt to determine the cause of these mortality events. The most common causes cited are low dissolved oxygen (hypoxic waters, under 50 µmol/Kg), eutrophication, followed by harmful algal blooms, and/or a combination of these factors (Granéli et al. 1989, Lowe et al. 1991, Reynolds-Flemming & Leuttich 2004). Beyond the obvious loss, large-scale fish kills are indications of serious ecological disturbances. They are an apparent sign that conditions within the affected water body have deteriorated to such a degree that fish life is no longer supported. The occurrence of a fish kill often affects other trophic levels, resulting in mass ecosystem dysfunction, public health risk(s), and economic losses.

Low dissolved oxygen concentrations are commonly reported as the cause of fish kills, as many organisms are unable to cope with the physiological stress associated with depleted oxygen conditions (Ritter & Montagna 1999). Hypoxia has been linked to water column stratification as well as decomposition of organic matter, extreme cases of the later being termed eutrophication. Low concentrations of oxygen are typically confined

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This thesis follows the style of the Marine Ecology Progress Series.

to deep waters, below the pycnocline, normally leaving the waters above this density gradient well mixed and oxygenated. This top part of the water column serves as a refuge for mobile fauna. Therefore, hypoxia alone as a cause of mass mortality events of mobile species seems unlikely. Ritter & Montagna (1999) offered a mechanism to account for the death of pelagic fishes due to hypoxic water; that is, one of wind-driven lateral upwelling/downwelling. This mechanism was observed in the Neuse River Estuary; winds forced a pile-up of oxygen rich water on the leeward shore, forcing oxygenated surface waters down, while the displaced surface water from the windward shore was replaced by hypoxic bottom water (upwelled) (Ritter & Montagna 1999).

Eutrophication begins with an increase in nutrient and dissolved organic matter loading, which leads to increases in particulate organic matter throughout the water column and on the benthos. The organic matter typically originates from bacteria, phytoplankton, and zooplankton in the water column. The amounts are of such high levels that it can not be diluted by the systems natural mechanisms and this excess organic matter sinks. On the way to the bottom, the matter is degraded by bacteria, which use up the oxygen during respiration. This degradation process is the primary culprit in the depletion of oxygen throughout the water column. Unless oxygen is re-supplied by physical mixing processes, this breakdown of the organic matter leads to hypoxia and /or anoxia (Gray et al. 2002, Wassmann & Olli 2004).

Harmful algae are those that cause a variety of deleterious effects on aquatic ecosystems, including negative aesthetic effects such as beach fouling and poisoning of various organisms, e.g., birds, manatees. Direct effects of some harmful algal blooms are oxygen deficiency, and clogging fish gills, which, in turn cause fish kills (Granéli et al. 1989). Harmful algal blooms are typically associated with toxin producing phytoplankton; this product is detrimental to plants and/or animals. The most commonly reported are paralytic, diarrhetic, amnesic and neurotoxic shellfish poisoning (Granéli & Turner 2006). Such toxicity can cause shellfish intoxication, leading to human fatalities, as well as vectorial intoxication whereby toxins are accumulated and transported through pelagic food webs. Toxin producing phytoplankton are found in all major Domains: Dinophyceae, Bacillariophyceae, Haptophyceae, Raphidophyceae, and Cyanophyceae. The most common and well known culprits involved in fish kills are the dinoflagellates *Gambierdiscus toxicus*, *Prorocentrum spp*., *Ostreopsis spp*., *Karenia brevis*, *Alexandrium spp*., and other *Pfiesteria*-like organisms (Wassmann & Olli 2004, Granéli & Turner 2006). *Prymnesium parvum,* or golden alga, produces toxins responsible for massive fish and bivalve deaths in brackish water bodies. In the last decade, this organism has spread vigorously throughout Texas (TPWD (2007) Golden Alga Index. Accessed 4 Apr. http://www.tpwd.state.tx.us/landwater/water/environconcerns/hab/ga). Of the cyanobacteria, *Microcystis sp.* is most commonly associated with human and livestock poisoning as well as fish kills. Under optimal conditions (such as high light and calm weather, usually in summer), *Microcystis sp.* forms blooms that are so dense, they appear to form a mat on the surface water (Granéli & Turner 2006). These blooms, regardless of the phytoplankton responsible, affect water quality as well as the health of humans and natural resources.

A study conducted by the US National Oceanic and Atmospheric Administration (NOAA) compiled the causes and locations of reported fish kills in the United States of America; Texas was the state reporting the most fish killed between 1980 and 1989 (Lowe et al. 1991). The largest number of fish killed in any one county occurred in Galveston County, Texas, reporting approximately 106 million dead fish during this period. Galveston County also holds the record of the most events consisting of over 1 million dead fish (Lowe et al. 1991). A recent meta-analysis of the Pollution Response Inventory and Species Mortality (PRISM) database for Texas found that in Texas bays, the majority of fish kills (53 %) between 1951 and 2006, were caused by low levels of dissolved oxygen in the water (Thronson & Quigg 2007). Second to this was physical damage or trauma (e.g. due to seismic testing) accounting for 18 % of the fish kill events, while biotoxins such as those produced by harmful algal blooms accounted for 14 % of deaths, and 12 % were attributed to temperature, typically cold snaps.

Gulf menhaden (*Brevoortia patronus*) are the most commonly killed species in Texas, accounting for 33 % of all fish killed (Thronson & Quigg 2007). Yellowtail snapper (*Lutjanus chrysurus*) and Atlantic spadefish (*Chaetodipterus faber*) make up 29 % of fish killed. The four Texas species of drum (Black-*Pagonias cromis*, Red-*Sciaenops ocellatus*, Star-*Stellifer lancolatus* and Banded-*Larimus fasciatus*) make up 1 % of the total fish killed (Thronson & Quigg 2007). All these fish species are important components of Texas' commercial and recreational fishery, and so their loss has major consequences for the economy and ecological welfare of this region.

Offatts Bayou was created by the city of Galveston in the early part of the 1900's as a borrow pit for land fill when the island was raised (references in Cooper & Morse 1996). The bayou is approximately 4.8 km long with a maximum width of 1 km, and an average depth of approximately 5 m (Figure 4). The study area also includes the adjoining Lake Madeline (in total the area is referred to as LMOB). Lake Madeline is a water body with similar characteristics and tends to magnify any anomalies that the adjoining Offatts Bayou may experience (Figure 4). Bayous like Offatts are important habitats for many finfish and shellfish; Offatts Bayou, in particular, also serves as an important recreational area for nearby residents and visitors. The multi-million dollar complex, Moody's Gardens sits on the banks of Offatts Bayou. The low mixing environment of LMOB, due to its relatively deep basin, small tidal inlet, and its isolation from nearby Galveston Bay complex, makes it an ideal study area for understanding the causes and effects of hypoxia and phytoplankton blooms, both of which may be significant factors in the cause of the near annual fish kills observed in this system.

This independent study tested the hypothesis that phytoplankton, either directly through harmful algal blooms/large quantities of biomass, or indirectly through low dissolved oxygen concentrations, are the primary causative factor of the fish kills occurring during the late summer months in Offatts Bayou. To test the stated hypothesis, a combination of physical, chemical and biological parameters were measured over the course of two summers (2005 and 2006). Fortuitously, a fish kill occurred in 2005 but not in 2006. Physical parameters measured included temperature (°C) and salinity (PSU) which were used to calculate buoyancy frequency (Brunt - Väisälä frequency). The only chemical parameter measured was dissolved oxygen concentrations (µmol/Kg). Biological parameters measured were dominant phytoplankton (plankton tows identified to Genus), chlorophyll *a* as a proxy for phytoplankton biomass, and phaeophytin *a* as an indicator of the breakdown material of a phytoplankton bloom. The fish kill observed early in the morning on August 26th, 2005 (Figure 2) occurred in Lake Madeline. *Brevoortia patronus* (Gulf Menhaden) were the only fish killed; those dead fish ranged from juvenile to adults (Figure 3).

CHAPTER II

METHODS

Collection of Data and Water Samples: Field work

Summer 2005

Fifteen sample sites were chosen throughout Lake Madeline and Offatts Bayou (LMOB) to provide a general swath of the system, in order to achieve an overview of the bayou’s water column (See Figure 1). A 17' Aluminum flat bottom boat with a 40 hp four stroke engine was launched at the 61st St. public boat ramp between East Bay site and Deep Hole site for each sampling trip. All trips were conducted between CST 0800-1200 hrs unless weather conditions were not permitting. Trips were performed twice weekly in order to capture short temporal changes in the LMOB.

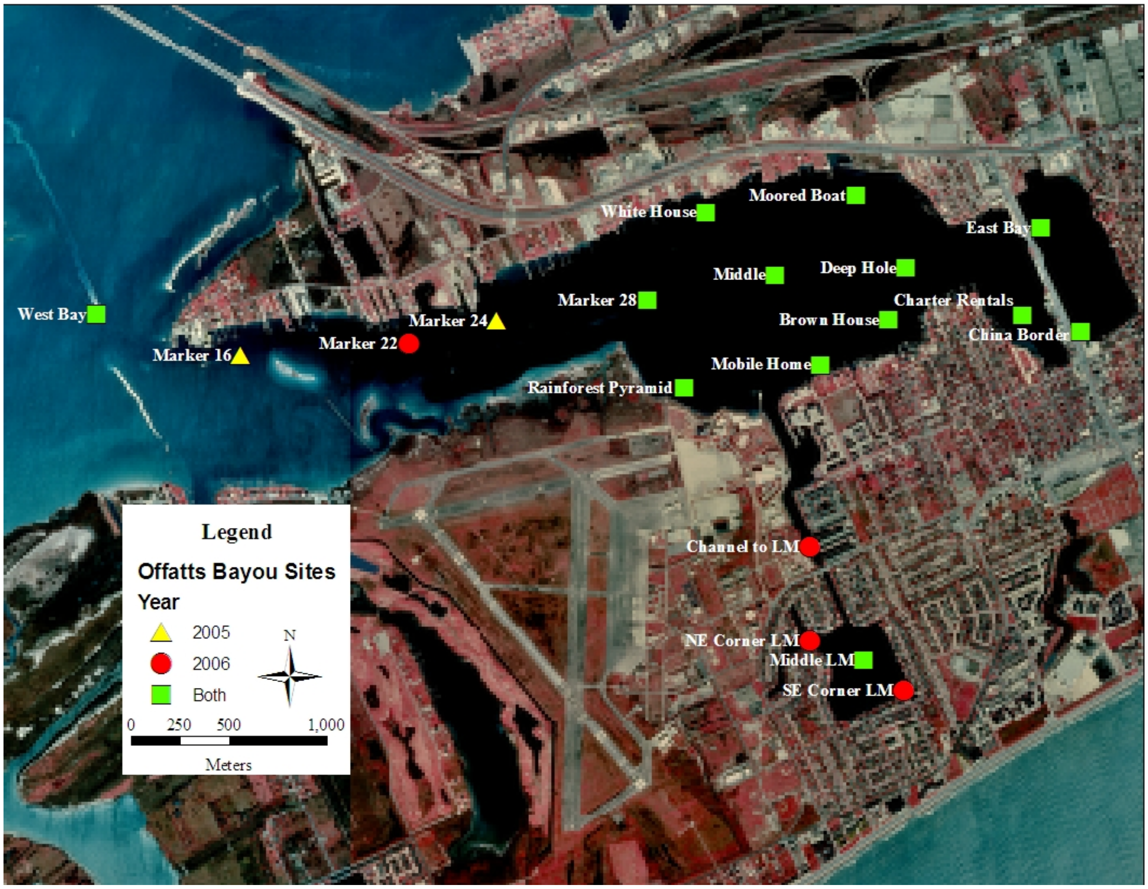

Fig. 1. Pictorial of Offatts Bayou with sites. Sites labeled by: Green squares indicate sites sampled both summers (2005 and 2006), yellow triangles indicate sites only sampled in 2005, red circles indicate sites sampled only in 2006.

At every site, secchi depth (m) was measured to assess water clarity. A Seabird 19 SBE Conductivity Temperature and Depth instrument (CTD, calibrated November 22nd, 2004) was used to collect temperature (°C), salinity (PSU), dissolved oxygen concentrations (µmol/Kg), and density measurements. The CTD was turned on and held at the surface for approximately 30 sec at every station to allow for flushing of the sensors. The instrument was then lowered slowly (approximately 0.15 m/sec) and data was collected every 0.25 sec and stored internally for post-sampling download in the lab. Water samples and plankton tows were also gathered from some sites where turbidity was observed to be high. Plankton samples were gathered with a 65 μm plankton net and stored in 50 mL translucent Fisherbrand plastic tubes and placed in a cooler of ice. Surface water samples were gathered from elbow depth into brown 1000 mL Nalgene bottles and placed in a cooler on ice. Each bottle was rinsed three times with sample water before collection of water to be processed.

Table 1. List of sampling sites and locations. Latitude, longitude, site number, year sampling took place (both includes 2005 and 2006), and description for all sites shown in Figure 1. Marker 24 data from 2005 was used for comparison with data from Marker 22 in 2006 (Considered the same site, 3, for comparison purposes).

Latitude	Longitude	Year	Site Number	Site Description
29.286	-94.845	Both	1	Moored Boat
29.286	-94.853	Both	2	White House
29.279	-94.877	2005		Marker 16
29.279	-94.868	2006	3	Marker 22
29.280	-94.864	2005	3	Marker 24
29.280	-94.885	Both	4	West Bay
29.282	-94.856	Both	5	Marker 28
29.278	-94.854	Both	6	Rainforest Pyramid
29.284	-94.849	Both	7	Middle
29.270	-94.847	2006	8	Channel to Lake Madeline
29.266	-94.847	2006	9	NW Corner of Lake Madeline
29.265	-94.844	Both	10	Middle of Lake Madeline
29.264	-94.842	2006	11	SE Corner Lake Madeline
29.279	-94.847	Both	12	Mobile Home
29.281	-94.843	Both	13	Brown House
29.283	-94.842	Both	14	Deep Hole
29.281	-94.836	Both	15	Charter Rentals
29.280	-94.833	Both	16	China Border
29.285	-94.835	Both	17	East Bay

Summer 2006

Sampling was performed essentially as described for summer of 2005 with some notable exceptions; seventeen sites were selected, fourteen of which were common to the previous summer’s collection. These changes are as follows: an extra site in the channel to Lake Madeline, two extra in Lake Madeline itself and one less in the main channel to the basin (Figure 1). The addition of these sampling sites in and around Lake Madeline was in response to the fish kill observed in this area in the summer of 2005. One site was taken out of the channel due to the relative consistency in data from this area.

Temperature, salinity, dissolved oxygen concentrations and density measurements were collected using the same Seabird SBE 19 CTD (calibrated January 20th, 2006). Water samples and plankton tows were collected from predefined sites, as opposed to the random sampling conducted in 2005, (West Bay, Marker 22, the Middle of the Main Basin, East Bay, the Deep Hole, and Lake Madeline) this summer in order to achieve more consistent and comparable data. Additional samples were collected when turbidity was high or other interesting phenomena were observed (such as obvious delineation in color of adjacent water masses Aug 24th). Plankton tows and water samples were gathered and stored in the same manner as described for the previous summer.

Initial Laboratory Processing of Samples

All water samples were filtered through Whatman 25 mm glass-fiber filters (GF/F), pore size of 0.7 µm. The filters were folded and placed in microcentrifuge tubes which were labeled with site and trip number then placed in the freezer (-20 ºC) for later processing. Plankton tows were preserved with formalin by making the total solution 3 % formalin, enabling the determination of dominant phytoplankton for each sample; phytoplankton were identified to Genus. CTD data was downloaded and converted from binary code to ASCII format using SBE software. This data was further processed by bin-averaging pressure for every 0.25 m; this format was the one used in all calculations and plots in subsequent post processing. Post processing and data visualization was achieved with Microsoft Excel 7.0 and MatLab 7.0.

Turner Fluorometer

Chlorophyll *a* (phytoplankton biomass) was estimated using a Turner Instruments 10-AU fluorometer. Frozen filtered samples were removed from the freezer and processing was continued on ice in a dark environment. This was achieved by keeping the samples under dark plastic on ice until run through the fluorometer. Filters were extracted and placed into 5 mL test tubes with a 50/50 solution of 90 % acetone/DMSO (Collins 1997). Filters were left in solution and placed in a dark refrigerator overnight (not longer than 24 hrs). The following day the filters were removed from the test tubes and then the test tubes were centrifuged to pellet all particulates in the sample. The samples were then placed in the fluorometer and readings were taken. Samples were then acidified with two drops of 10 M HCL and run again. Fluroescence is a relative number which can be used as a proxy for biomass. The readings gathered from this instrument are calibrated using the spectrophotometer so that a concentration number indicating total biomass can be calculated. Calibration was conducted by using a pure solution of chlorophyll *a* and running that sample through both the spectrophotometer and the fluorometer. Data obtained was used to calculate the response factor to be used in later calculations of biomass (Arar & Collins 1997).

$$F_s=C_s/R_s \tag{1}$$

F_s = response factor for sensitivity setting, S (number used in final calculations)

R_s = fluorometer reading for sensitivity setting, S (fluorometer)

C_s = concentration of chlorophyll a (spectrophotometer)

Pheaophytin *a* determinations were also made using the Turner Fluorometer. The same standards were used to calibrate for pheaophytin *a* as were for calibration of the chlorophyll *a*, however, once the initial readings were taken the standards were acidified. The numbers generated were used in the following equation and in the final calculation of the pheophytin *a* concentration (Arar & Collins 1997).

$$r = R_b/R_a \tag{2}$$

r = the ratio of fluorescence in the standard solution before and after acidification.

R_b = fluorescence of pure chlorophyll *a* standard solution before acidification

R_a = fluorescence of pure chlorophyll *a* standard solution after acidification

To generate a number for the total biomass concentration of chlorophyll *a* (µg/L) the following equation (3) from Arar & Collins (1997) was used:

$$C_{E,c} = F_s\,(r/r\text{-}1)\,(R_b\text{-}R_a) \tag{3}$$

It was also possible to calculate the pheophytin *a* concentration using the following equation:

$$P_E = F_s(r/r\text{-}1)(rR_a\text{-}R_b) \qquad (4)$$

and then,

$$P_s = \frac{P_E * \text{extract volume (L)} * \text{DF}}{\text{Sample volume (L)}} \qquad (5)$$

P_E = pheophytin *a* concentration (µg/L) in the sample extract

Ps = pheophytin *a* concentration (µg/L) in the whole water sample

DF is the dilution factor (Arar & Collins 1997).

Phytoplankton Identification

Preserved plankton tows were allowed to settle. One slide per sample was observed systematically and all phytoplankton present were identified to genus. This was carried out for all samples collected; less than one percent of phytoplankton could not be identified. Dominant phytoplankton were grouped by Domain for clear depiction of changes in composition through the sampling period. Simpson's diversity index was calculated for each sampling trip as well as the entirety of both summers, for an overall observation, using the equation:

$$D = \frac{\Sigma n_i\,(n_i - 1)}{N\,(N\text{-}1)} \qquad (6)$$

Where n_i is the number of individuals of species I which are counted per sample and N is the total number of individuals counted per sample. Values near zero indicate a highly diverse, heterogenous sample, whereas values near one indicate a low diversity, homogenous sample.

The Shannon index was also calculated for each sampling trip as well as the entirety of both summers, for an overall observation, using the equation:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i \qquad (7)$$

where S is the number of species, and p_i is the relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals in the community ($p_i = n_i/N$); n_i being the number of individuals in a species, and N being the total number of all individuals. H'_{max}, an estimate of the maximum number of species in an area, is calculated as ($H'_{max} = \ln S$). Species evenness is a number derived from the Shannon index and will give some indication of how evenly the proportions of taxa are distributed in a sample and is calculated as ($E = H'/H'_{max}$).

The primary benefit of using this diversity index in addition to Simpson's is that it is less biased by sample size; given that we are identifying only one slide per sample this number should be more representative of natural conditions than the one provided by Simpson's diversity index.

Post Processing and Calculations

The Brunt-Väisäla frequency (buoyancy frequency), calculated using the sea water toolbox for MatLab 7.0, represents the stability of the water column. Values above zero indicate stable water which is not prone to mixing unless energy is added, values of zero indicate neutral stability, and values below zero indicate water which is unstable and therefore prone to mixing. The hypoxia ratio was calculated using the following equation:

$$\frac{[\text{depth of the water column (m)}] - [\text{depth at which hypoxia began (m)}]}{[\text{depth of the water column (m)}]} \tag{8}$$

This calculation allows easy depiction of the percentage of the water column that is hypoxic (below 50 μmol/Kg) allowing for ease of data comparison for each site.

Meteorological Data

Wind data was obtained from the closest possible NOAA meteorological monitoring station (Galveston Pleasure Pier) over the entire sampling period for both summers. The data obtained included data for every hour; this data was averaged for each day and plotted using MatLab 7.0. Rainfall data was obtained from Scholes Field regional airport located on Offatts Bayou's south shore (the data was already averaged by day). Days which were recorded by the airport as "trace" were modified in this thesis from "trace" to represent 0.01 inches, for the purposes of visualizing the data. Meteorological data was plotted for every day during the sampling period using MatLab 7.0.

CHAPTER III

RESULTS

A fish kill was observed early morning on August 26th, 2005 in Lake Madeline (Figure 2). *Brevoortia patronus* (Gulf Menhaden) were the only fish observed to be affected - the dead fish ranged from juvenile to adults (Figure 3).

Fig. 2. Composite picture of fish kill observed on August 26th, 2005 in Lake Madeline. Large picture shows the primary concentration of fish, small picture shows a close up of the dead fish.

Though the dead fish were primarily concentrated in the southernmost finger of Lake Madeline, fish were observed dying in the channel to Lake Madeline as well as in the northernmost portion of Lake Madeline proper. The large concentration was primarily smaller fish, whereas the fish dying in the channel were larger fish; no other species were found.

Fig. 3. Two samples of fish collected on the day of the fish kill. Fish on the left was among the smaller fish observed (primarily concentrated in the southernmost finger of Lake Madeline); fish on the right was among the larger fish observed (collected in the channel to Lake Madeline).

Bathymetry

Offatts Bayou is deeper than the surrounding West Bay, with the deepest portion (indicated by the darkest blues, Figure 4) on the eastern side, rising to a shallow, narrow, sill-like inlet as the only means of exchange with neighboring waters.

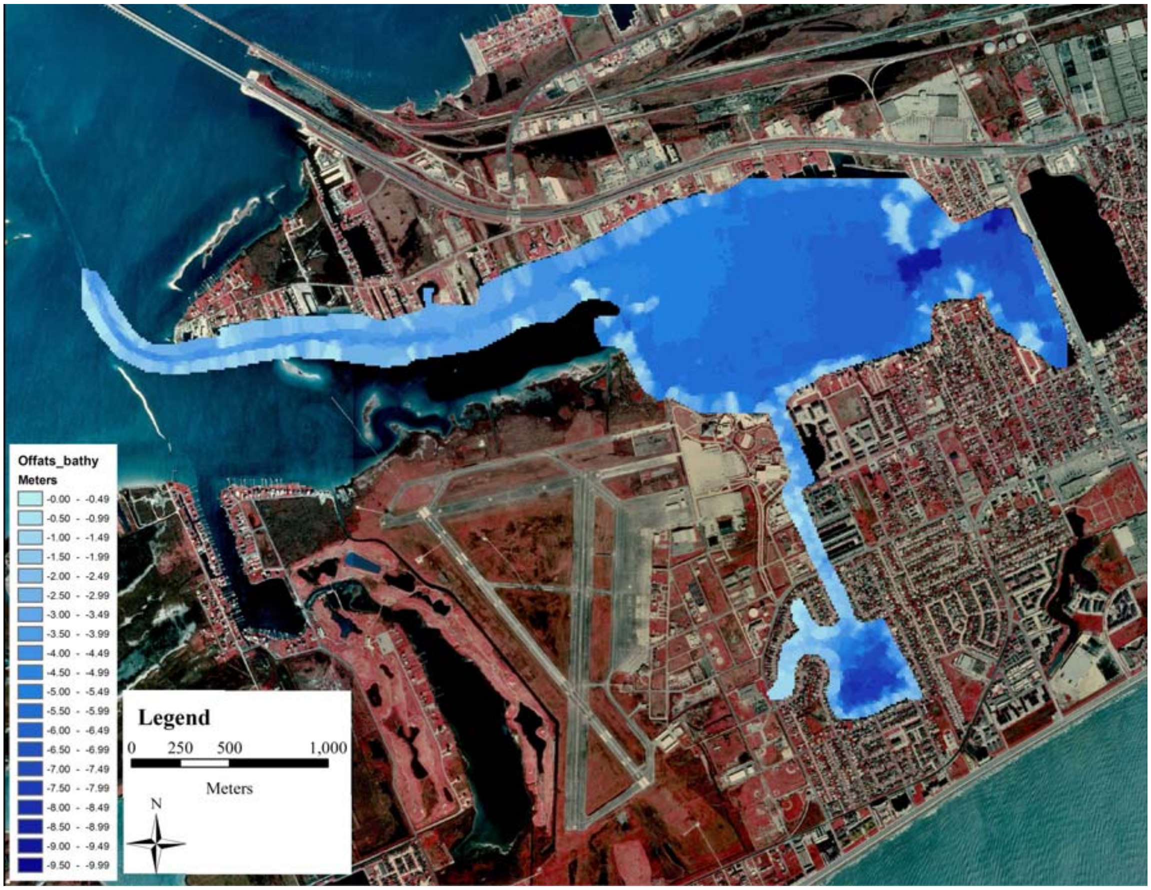

Fig. 4. GIS representation of Bathymetry data for Offatts Bayou and Lake Madeline. Darker color (blue) indicates deeper portions of the system.

Offatts Bayou is approximately 5 km long, 1km wide with an average depth (of the entire LMOB) of approximately 5 m. Lake Madeline, the area of the observed fish kill, is a small connected water body with a similar bathymetry and restricted exchange, to that of the main bayou; the deepest portion is the south-west corner, rising to a similar shallow, narrow, sill-like mouth, the only means for exchange between Lake Madeline and Offatts Bayou. The total volume of the LMOB, calculated using Bathymetry and the boundary polygon in GIS, is approximately 13,662,378.04 m^3.

Meteorological Data

Wind speed in knots was plotted as a function of Julian days for summers 2005 and 2006 (Figures 5.1 & 5.2). Average wind speeds (red line) for 2006 (4.92 knots) were higher than in 2005 (3.85 knots). In 2005, wind speeds ranged from 2.11 to 6.5 knots. On most days in the summer of 2005, wind speeds were plus or minus 1 knot from the average wind speed of 3.85 knots.

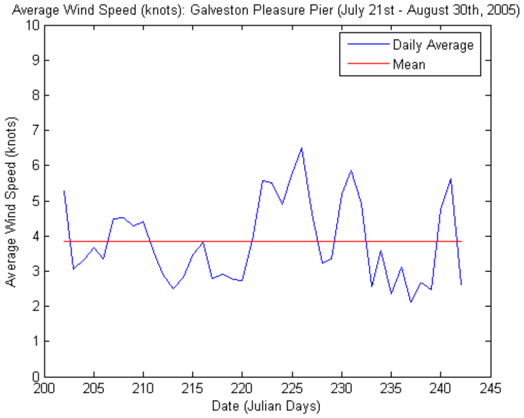

Fig. 5.1. Daily average wind speeds for 2005. Daily averages are indicated by the blue line; the red line shows the average wind speed for the entire study period in 2005. Data courtesy NOAA (Galveston Pleasure Pier).

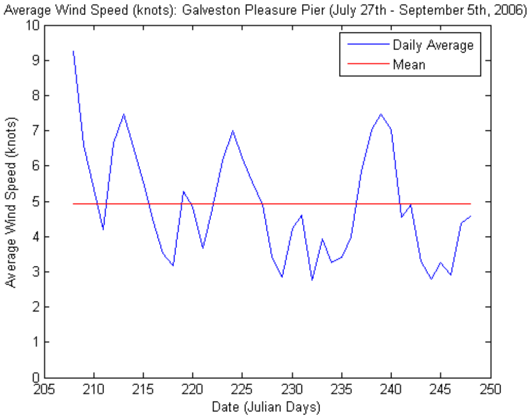

Fig. 5.2. Daily average wind speeds for 2006. Daily averages are indicated by the blue line; the red line shows the average wind speed for the entire study period in 2006. Data courtesy NOAA (Galveston Pleasure Pier).

During the summer of 2006, wind speed ranged from 2.75 to 9.26 knots, and was characterized as having a higher average of 4.92 knots (Figure 5.2). On five occasions in 2006, wind speeds were greater than 7 knots (Figure 5.2), a wind speed not attained at all in summer of 2005. The day of the fish kill, August 26th, 2005 (Julian Day 238), was preceded by several days of low wind (less than 3 knots). Such a prolonged time of low average wind speeds was not observed in 2006; the average wind speed in 2006 is often times higher than 2005 with only four days of low wind (less than 3 knots).

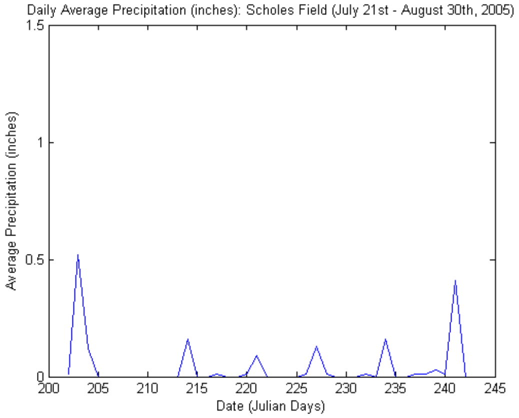

Fig. 6.1. Average daily rainfall for 2005. Data courtesy Scholes Field Airport, Galveston Island.

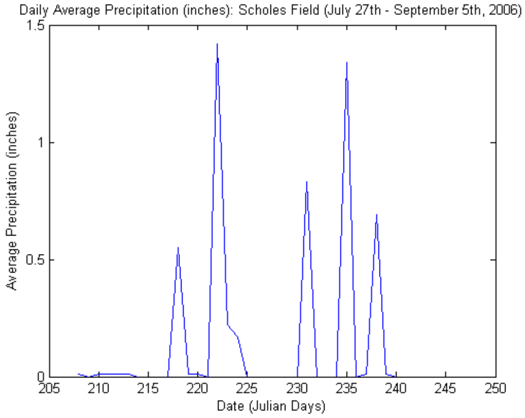

Fig. 6.2. Average daily rainfall for 2006. Data courtesy Scholes Field Airport, Galveston Island.

Precipitation, in inches, was plotted against Julian days for the summers of 2005 and 2006. Rainfall was greater in 2006 than 2005. Total rainfall for the 2006 study period was 5.31 inches. Total rainfall for the 2005 study period was 1.71 inches. Sporadic drizzles were common in 2005 and uncommon in 2006. Rainfall events in 2006 generally consisted of a more significant amount of rain; these episodes of freshwater input were not observed in 2005.

Water Quality Parameters (Physical and Chemical Parameters)

Surface Waters

Surface temperature (°C), salinity (PSU) and dissolved oxygen (μmol/Kg) were plotted for all sample days at all locations in LMOB; all were relatively constant throughout both summers. Despite some subtle differences between years, the temperatures between years were not significantly different (Figure 7). Surface temperature in the LMOB was relatively constant from 2005 to 2006. 2005 was warmer, with temperatures ranging from 28.9 – 39.8 °C, and an average surface temperature of 31.2 °C; 2006 surface temperatures ranged from 26.3 – 31.8 °C, having an average temperature of 30.2 °C. The warmest day in 2005 was August 26th (day 238), the date of the observed fish kill. July 25th, 2005 (day 206) was warmer at some stations but the overall average was cooler than the day of the observed fish kill.

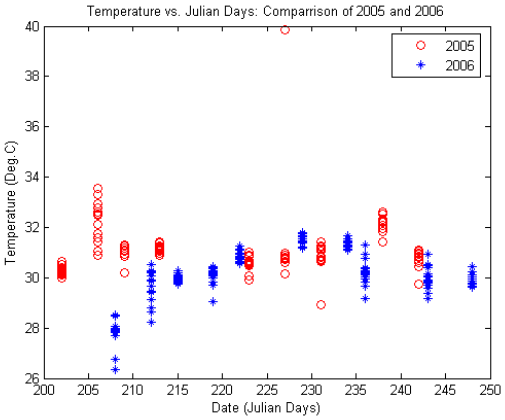

Fig. 7. Graph showing surface temperature (°C) variations throughout both summers.

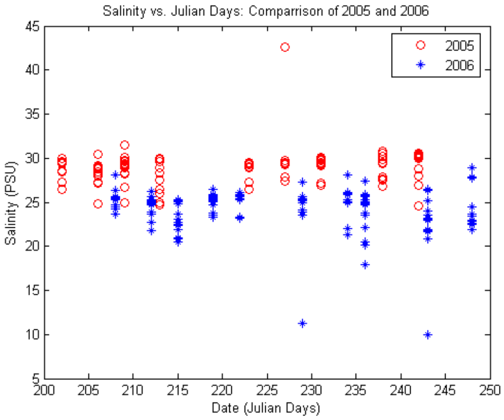

Fig. 8. Graph showing surface salinity (PSU) variations throughout both summers.

Salinities (PSU) of the surface waters were indicative of the estuarine nature of LMOB, with the nearby West Bay being its main source water. They were relatively high, ranging from 24.6 - 42.6 PSU in 2005 (Figure 8) and did not vary substantially around the mean of 29 PSU - corresponding to the small amount of rainfall that year (see Figure 6.1 above). Values were more variable in 2006, with a range of 9.9 to 28.9 PSU; few values were less than 20 PSU (average of 24.5 PSU). The generally lower surface salinities in 2006 may be been a function of the greater rainfall that year and wind driven mixing events (Fig. 5.2 & 6.2 above).

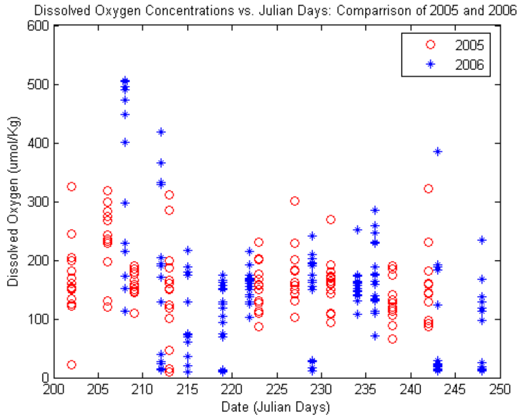

Fig. 9. Graph showing surface dissolved oxygen concentration variation throughout both summers.

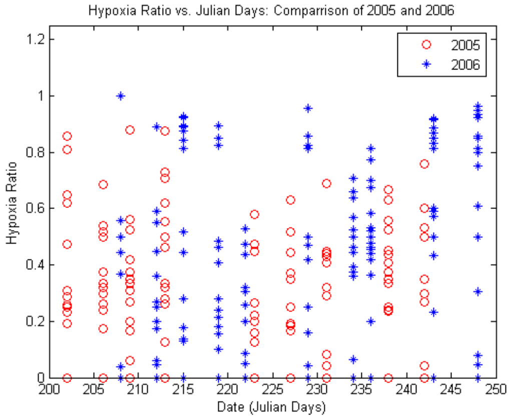

Fig. 10. Graph showing variation in the calculated hypoxia ratio throughout both summers.

Surface dissolved oxygen concentrations were similar in 2005 and 2006 (Figure 9). The oxygen concentration in 2005 ranged from 8.8 – 326.3 μmol/Kg with an average of 165.0 μmol/Kg. The surface concentrations in 2006 ranged from 8.9 – 506.9 μmol/Kg, averaging 146.9 μmol/Kg. The higher values of oxygen in 2005 are thought to be associated with a phytoplankton bloom which occurred on August 22nd, 2005 (see Figure 24.2 below).

In order to ascertain the level of hypoxia across LMOB during each summer, a hypoxia ratio was calculated. This ratio, on a scale of 0 to 1, shows that, there was little change in amounts of hypoxia during the period of the study (Figure 10). The average hypoxia ratio was 0.32 in 2005; relative to 0.37 in 2006. The amount of low oxygen water throughout the water column (depicted by the hypoxia ratio) was similar from one summer to the next, suggesting that hypoxia alone was not a factor in the fish kill in 2005.

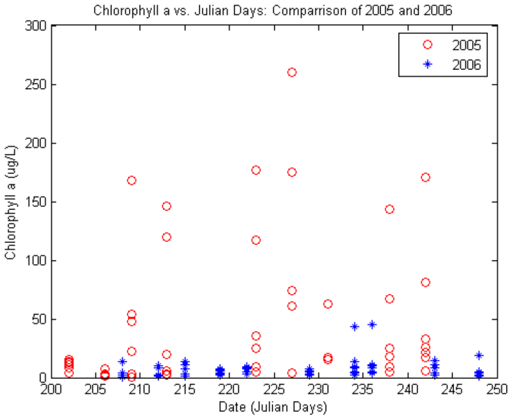

Fig. 11. Graph depicting chlorophyll *a* variation throughout both summers.

The overall trend in 2005 was an increase in chlorophyll *a* (Figure 11). This trend was not observed in 2006. Significantly more biomass was observed in the summer of 2005 than 2006, indicating that a phytoplankton bloom was present. The primary phytoplankton present were cyanobacteria in the summer of 2005 (Figure 26); whereas 2006 saw an almost equal dominance of cyanobacteria and diatoms (Figure 27).

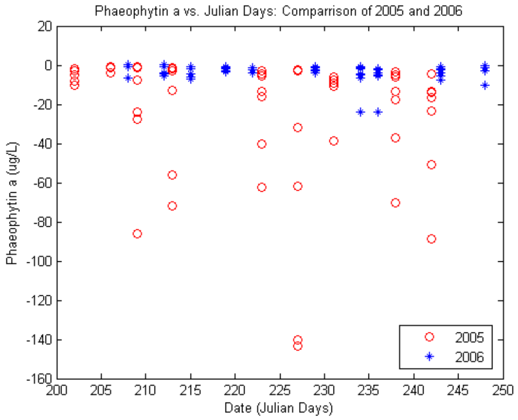

Fig. 12. Graph depicting phaeophytin *a* variation throughout both summers.

The amount of phaeophytin *a* was also notably different in 2005 than 2006 (Figure 12). Phaeophytin *a*, being an indicator of the breakdown of chlorophyll *a*, suggests that the amount of dead/dying phytoplankton in the water column was increasing through the date of the fish kill. Phaeophytin *a* is represented here as a negative number due to the calibration calculations of the Turner 10-AU fluorometer.

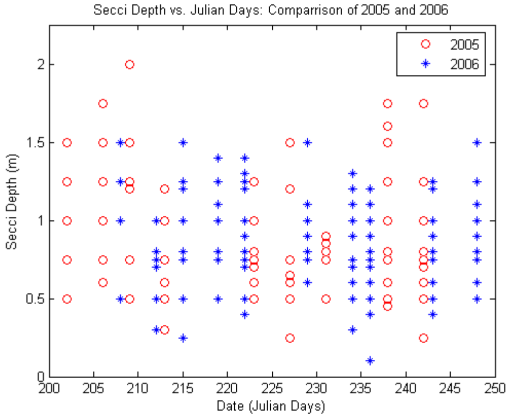

Fig. 13. Graph depicting secci depth variation throughout both summers.

Secci depth was consistent throughout both summers (Figure 13). Deepest depths occurring in early summer of 2005, these higher secci depths correspond to the low wind mixing and rain water input to the system (Figures 5.1 & 6.1), thus keeping overall turbidity low. The depth was lower where phytoplankton blooms were observed (primarily in Lake Madeline). The very shallow depth depicted on August 24th, 2006 (Julian day 236), was from a water mass observed near the Charter Rentals station; where a clear delineation from green water with a very deep secci depth was observed next to a mass of red water with a secci depth of only 1-2 inches. This water mass did not cause a fish kill as none were observed in the summer of 2006.

Entire Water Column

Figure 14 depicts temperatures generated by averaging the temperature for the entire water column at every station for each sampling trip in the summers of 2005 and 2006 (in contrast with the surface values depicted in Figure 7).

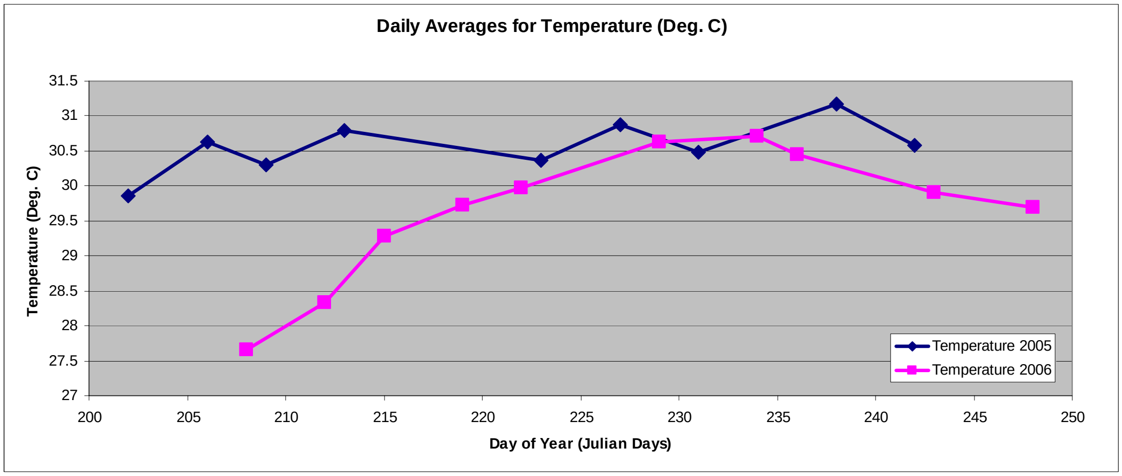

Fig. 14. Graph depicting daily average water temperature (°C) throughout the study area for 2005 and 2006. These averages include measurements taken throughout the water column, for and included every station on the day of sampling. Note the day of the fish kill in 2005 was August 26th (Julian Day 238).

This graph (Figure 14) shows a greater contrast in the temperature from one summer to the next. Temperature in 2006 is low at the start of the sampling period (corresponding to high wind mixing and low rainfall) and increases throughout the summer; temperature in 2005 was relatively constant and considerably higher than those measured in 2006 for the majority of the summer. Temperatures ranged 23.6 – 39.9 °C in the summer of 2005, and an average temperature of 30.5 °C; while in 2006 temperatures ranged from 20.4 – 32.3 °C, having an average temperature of 29.8 °C. The warmest day in 2005 was August 26th (day 238), the date of the observed fish kill. July 25th (day 206) was warmer at some stations but the overall average was not warmer than the day of the kill.

The warmest day of 2005 was August 26th, the day of the observed fish kill, with surface temperatures around 32-33 °C (Figure 15). Lake Madeline in particular increased in temperature from the day prior to the fish kill to the day of the fish kill (Figure 15), this is notable as it was the site of the observed fish kill. The high temperatures of nearly 39 °C on August 15th, 2005 were recorded in West Bay, a very shallow area. The weather prior to this day was that of very low rainfall and low wind mixing, thus increasing the temperature to such high levels. These high temperatures were observed for the entire water column at this station (and all other stations the CTD recorded temperatures that seemed reasonable) which indicates that this recording is not an anomaly or malfunction of the instrument. Temperatures rarely exceeded 31 °C in 2006 (Figure 16), corresponding to the higher wind mixing and rainfall (Figures 5.2 & 6.2).

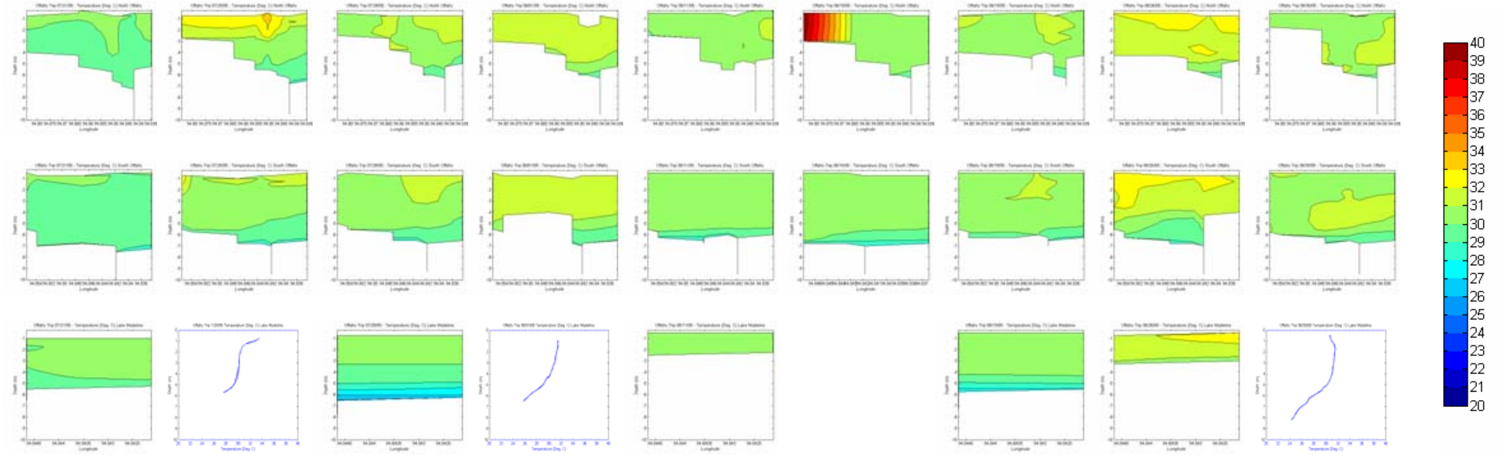

Fig. 15. Contour Plots depicting Temperature (°C) throughout the water column for 2005. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

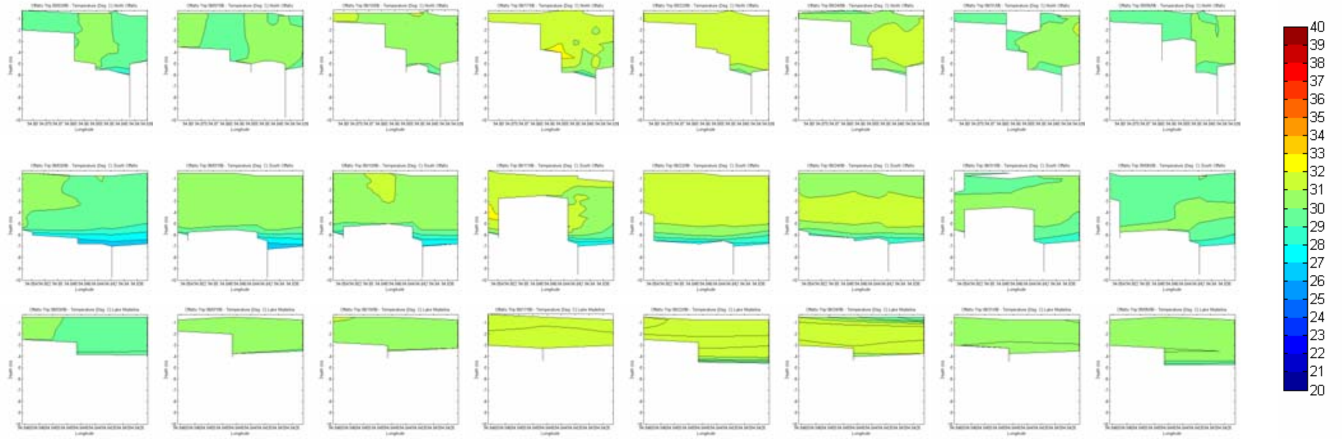

Fig. 16. Contour Plots depicting Temperature (°C) throughout the water column for 2006. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

Figures 15 and 16 depict temperatures (°C) throughout the water column for each day, separated into North Offatts Bayou, South Offatts Bayou and Lake Madeline for both summers. Salinities were higher in 2005 than 2006 (Figures 15 & 16).These contour plots clearly show that laterally wind-driven upwelling/downwelling was never observed in Offatts Bayou.

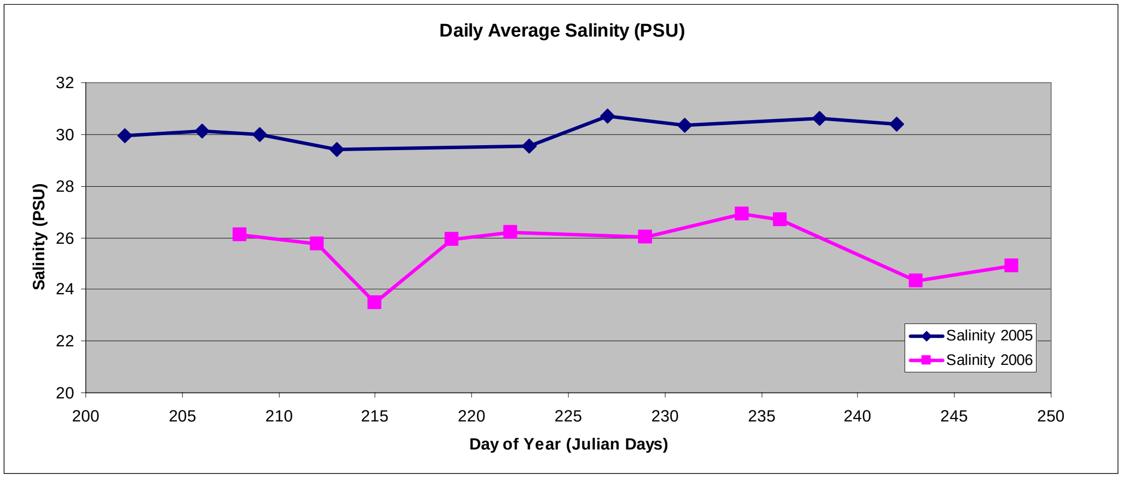

Fig. 17. Graph depicting daily average salinity (PSU) throughout the study area for 2005 and 2006. These averages include measurements taken throughout the water column, for and included every station on the day of sampling. . Note the day of the fish kill in 2005 was August 26th (Julian Day 238).

Figure 17 depicts salinity values generated by averaging the entire water column at every station for each sampling trip in the summers of 2005 and 2006. Figure 17 shows a clear difference in the overall salinity from 2005 to 2006; with 2005 being more saline by nearly 2 PSU throughout the summer (corresponding with the amount of wind-mixing and rainwater input). Salinities (PSU) were indicative of the estuarine nature of LMOB, with the nearby West Bay being its main source water. They were relatively high ranging from 23.2 - 47.6 PSU in 2005 (Figure 17) and did not vary substantially around the mean of 30 PSU, possibly as a result of little rainfall that year (see Figure 6.1). Values were more variable in 2006, falling in the range 3.7 to 30.4 PSU (Figure 17), few values were less than 20 PSU (average of 25.6 PSU). The generally lower salinities in 2006 may be been a function of the greater rainfall that year and wind driven mixing events (Fig. 5.1 & 6.1 above).

Figures 18 and 19 depict salinities (PSU) throughout the water column for each day, separated into North Offatts Bayou, South Offatts Bayou and Lake Madeline for both summers. Salinities were higher in 2005 than 2006 (Figures 18 & 19). These contour plots of salinity again do not indicate that laterally wind-driven upwelling/downwelling occurred in LMOB.

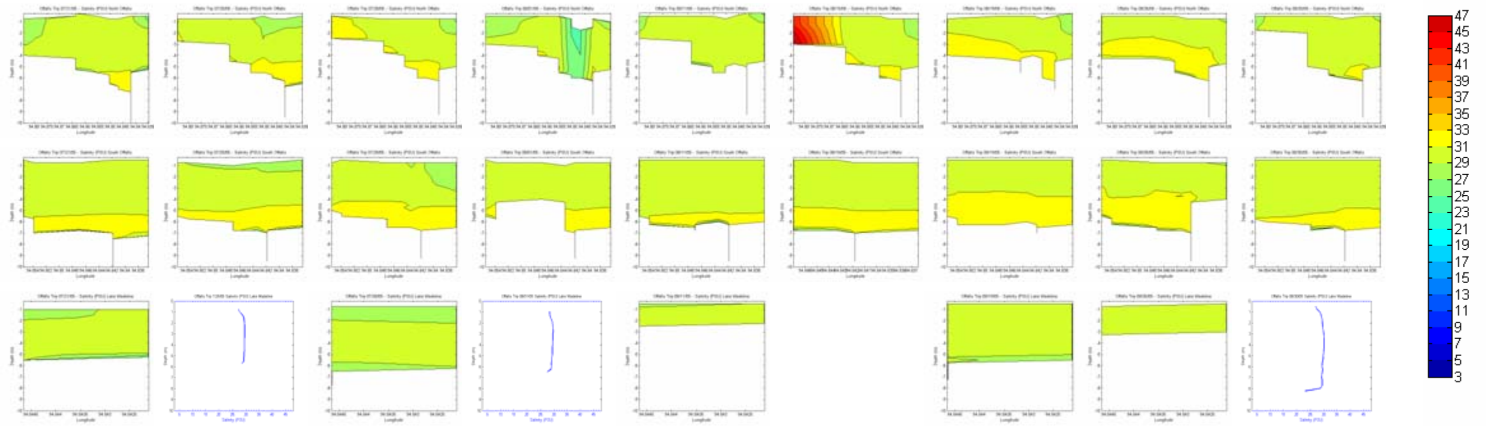

Fig. 18. Contour Plots depicting Salinity (PSU) throughout the water column for 2005. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

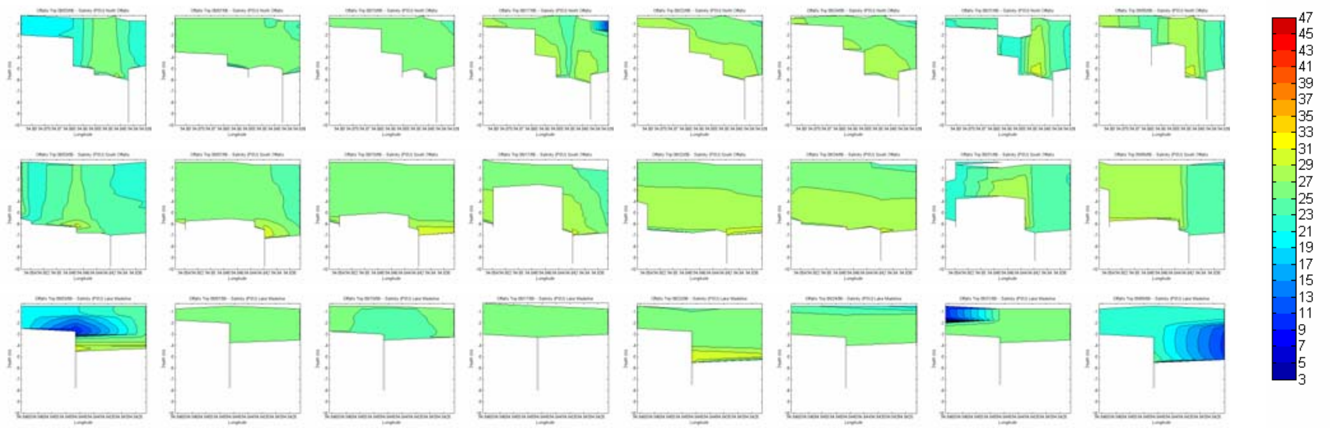

Fig. 19. Contour Plots depicting Salinity (PSU) throughout the water column for 2006. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

2005 consistently showed surface salinities around 30 PSU and bottom salinities around 32 PSU (Figure 18), which is appropriate as the more saline water is denser and will thus sink. The high salinities observed on August 15th, 2005, coincide with the high temperatures discussed above, and correspond to the low wind mixing and little rain fall prior to this sampling trip. Salinities in 2006 were lower than that of 2005, with salinities ranging from between 24 and 26 PSU in the surface waters to salinities near 28 PSU for the bottom waters (Figure 18). The higher salinities observed near the bottom due to the resultant higher density of the water. Very low salinities were observed in Lake Madeline August 31st, and September 5th, 2006 (Figure 19); these dates correspond to times of increased rainfall. Lake Madeline is surrounded by homes and manicured lawns thus increasing the amount of rain that will runoff into the water body (observed on the 31st). Low salinities were also observed in Lake Madeline on August 3rd, 2006 (Figure 19). The weather data obtained began just prior to this date does not show any rainfall that would be the cause of this, though the wind speeds were high.

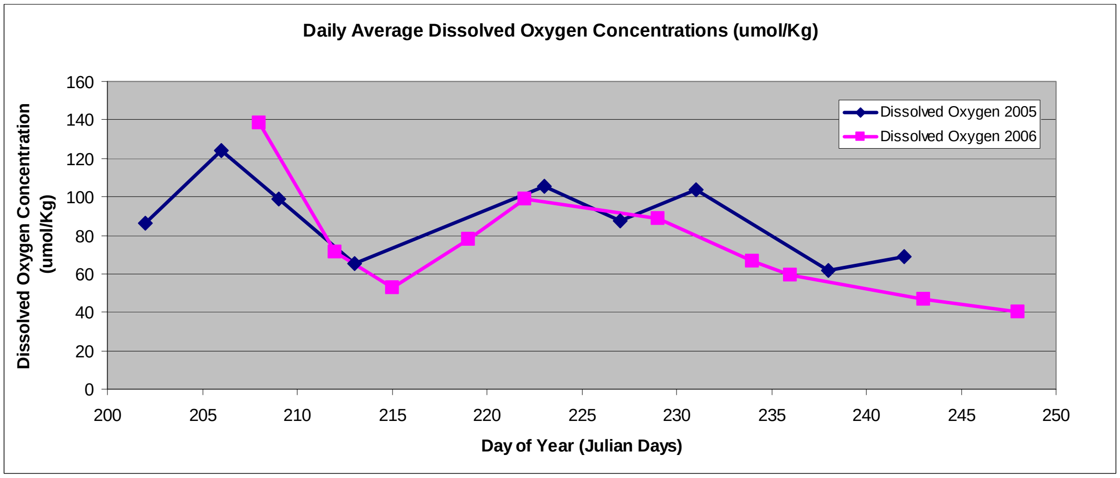

Fig. 20. Graph depicting daily average dissolved oxygen concentrations (μmol/Kg) throughout the study area for 2005 and 2006. These averages include measurements taken throughout the water column, for and included every station on the day of sampling. Note the day of the fish kill in 2005 was August 26th (Julian Day 238).

Dissolved oxygen concentrations during both summers declined steadily (Figure 20). These numbers were generated in the same way as figures 14, and 17, demonstrating again, the low variation from summer to summer, as was also depicted in the Figures 9 and 10, representing surface waters.

Figures 21 and 22 depict dissolved oxygen concentrations (μmol/Kg) throughout the water column for each day, separated into North Offatts Bayou, South Offatts Bayou and Lake Madeline for both summers. Both summers saw bottom waters which were hypoxic. The amount of oxygenated water (as indicated by colors other than purple in Figures 21 & 22) was less on the south side of Offatts Bayou and Lake Madeline, and the depth at which hypoxia began is much deeper on the north side. Plots and data for the summer of 2006 showed greater amounts of hypoxic waters (however some of the numbers, primarily for the final trip on the 5th of September, could be due to a false reading on the CTD).

The trend in oxygen concentrations in the summer of 2005 was one toward greater amounts of bottom water hypoxia (Figure 21) which corresponds to the shallowing of the pycnocline due to prolonged time periods of low wind mixing and small amounts of rainfall as seen in Figures 5.1 and 6.1. The data for the summer of 2006 show large amounts of hypoxic water throughout the sampling period (Figure 22). The higher amounts of dissolved oxygen in the water column observed on August 10th and August 17th, 2006 (Figure 22) correspond to times of higher wind mixing and rainfall (Figures 5.2 & 6.2).

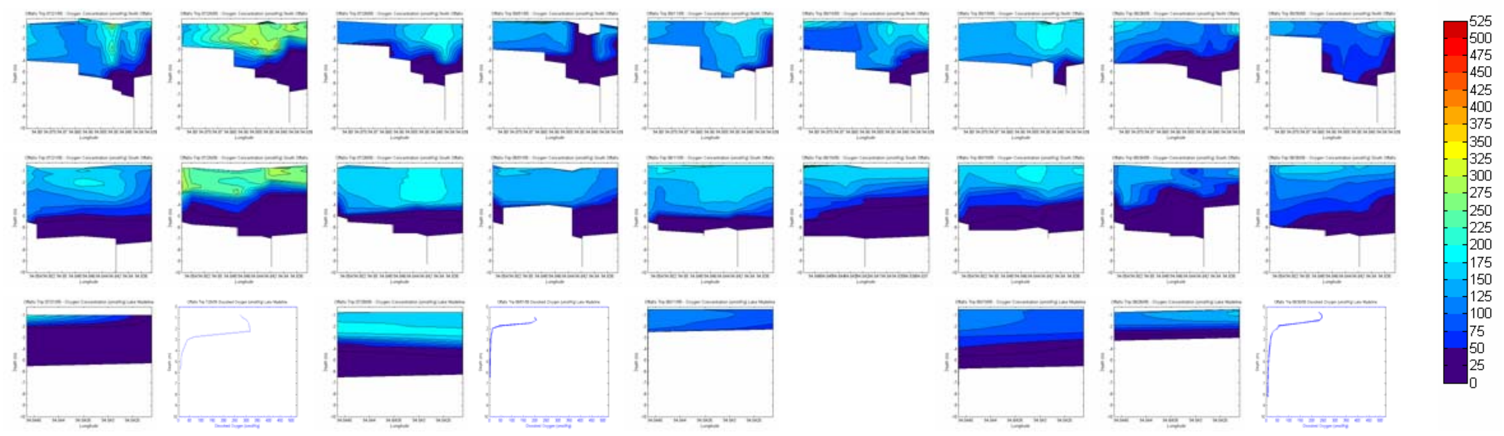

Fig. 21. Contour Plots depicting dissolved oxygen concentrations (μmol/Kg) throughout the water column for 2005. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

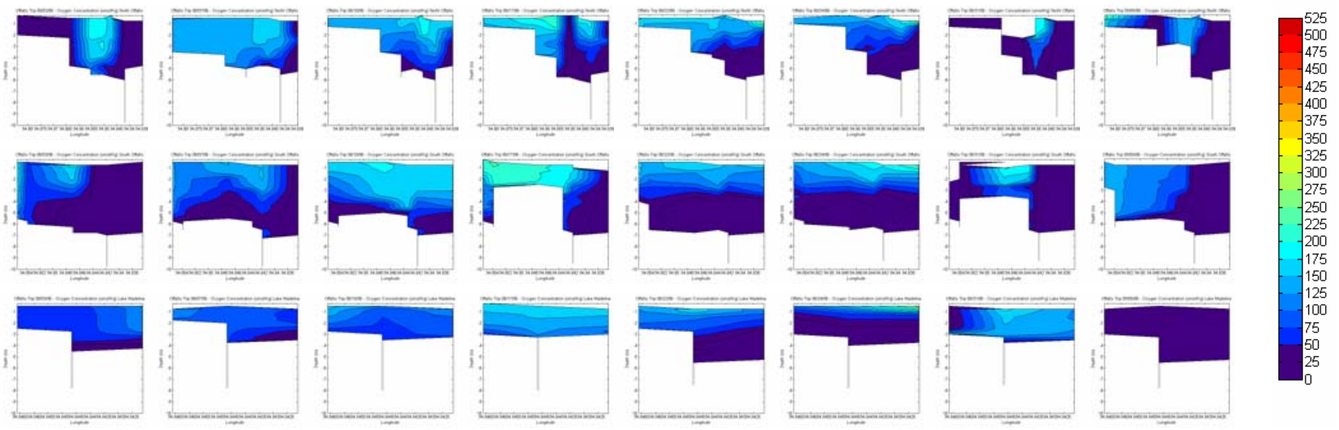

Fig. 22. Contour Plots depicting dissolved oxygen concentrations (μmol/Kg) throughout the water column for 2006. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 8/3, 8/7, 8/10, 8/17, 8/22, 8/24, 8/31, 9/5.

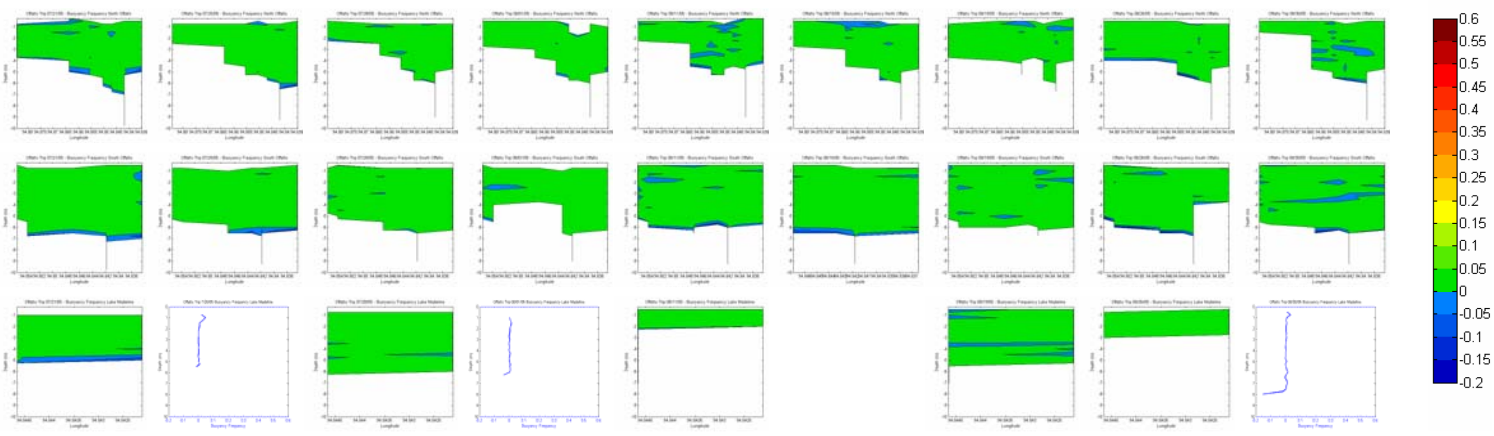

Fig. 23. Contour Plots depicting Buoyancy Frequency throughout the water column for 2005. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

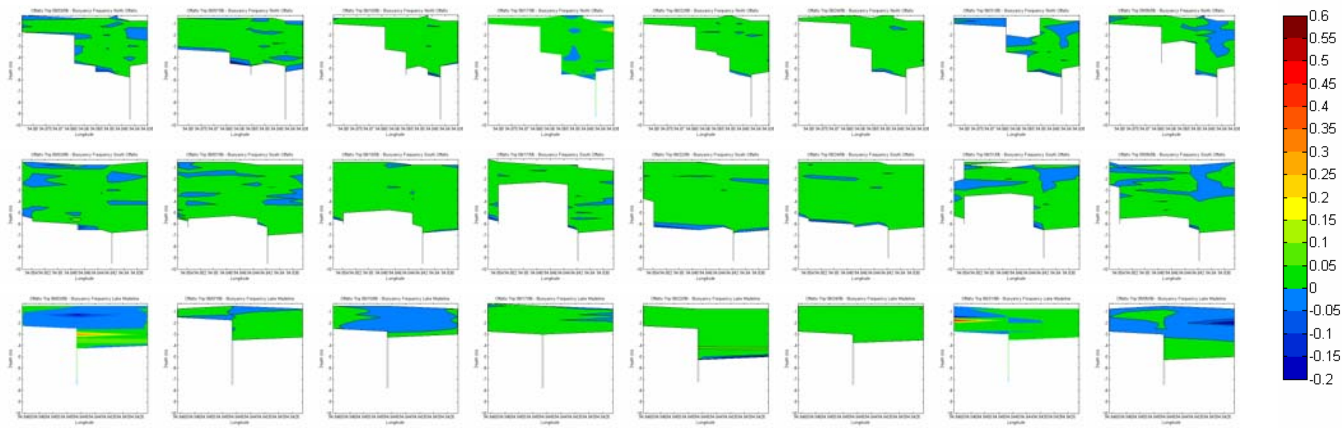

Fig. 24. Contour Plots depicting Buoyancy Frequency throughout the water column for 2006. North side (Top Row) indicates transect drawn through sites starting West Bay ending in East Bay (includes West Bay, Marker 16, Marker 22, Marker 28, White House, Moored Boat, Deep Hole, and East Bay, as seen in Figure 1). South Side (Middle Row) indicates transect drawn through the southern sites (Marker 28, Rainforest Pyramid, Mobile Home, Brown House, Deep Hole, Charter Rentals and China Boarder). Contours for Lake Madeline (Bottom Row) include as many sites possible (2006 included 3 sites, occasionally in 2005 the SW corner was sampled in addition to the middle and contour maps indicate a transect between the two). Dates for the above plots are 7/21, 7/25, 7/28, 8/1, 8/11, 8/15, 8/19, 8/26, 8/30.

Buoyancy frequency represents the stability of the water column; negative numbers indicate water which is prone to mixing while positive numbers indicating a stable water column. The water column was much more stable in the summer of 2005 (Figure 23) as indicated by the large amounts of green. The most stable day observed was August 26th, the day of the fish kill. This data corresponds to the low wind speeds and small amounts of rainfall, thus increasing the strength of the pycnocline and solidifying the positions of differing water masses within the study area. The summer of 2006 shows more negative numbers (Figure 24) indicating a water column which is easily mixed. This corresponds to the high input of fresh water from rain and mixing due to wind. The most unstable water columns were observed on August 3rd, 10th, 31st, and September 5th (corresponding to days of high wind mixing and rainfall, Figures 5.2 & 6.2).

Biological Parameters

Chlorophyll a and Phaeophytin a concentrations

Very small amounts of chlorophyll *a* and phaeophytin *a* were observed in the summer of 2006 (Figure 26.1 & 26.2) indicating that a bloom never occurred. High concentrations were observed in the summer of 2005 (Figure 25.1 & 25.2), primarily in Lake Madeline (Figure 25.2). These high numbers of chlorophyll *a* and phaeophytin *a*, indicate that a bloom did occur in Lake Madeline in 2005; peaking on August 22nd, four days prior to the fish kill. Table 2 also shows that the primary phytoplankter present was an unknown spherical cyanobacteria. The chlorophyll *a* and phaeophytin *a* concentrations are relatively low on August 26th, the day of the fish kill.

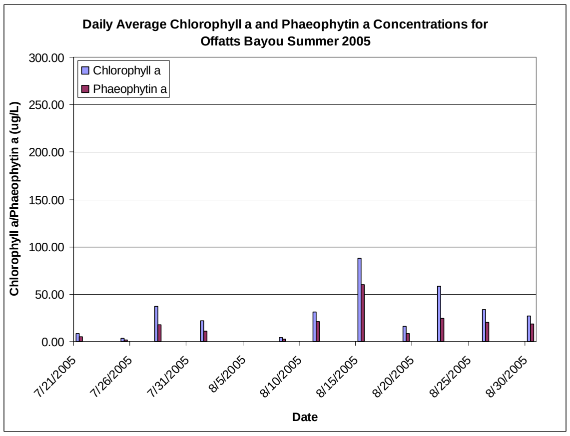

Fig. 25.1. Daily average chlorophyll *a* (blue) and phaeophytin *a* (purple) concentrations for Offatts Bayou summer 2005.

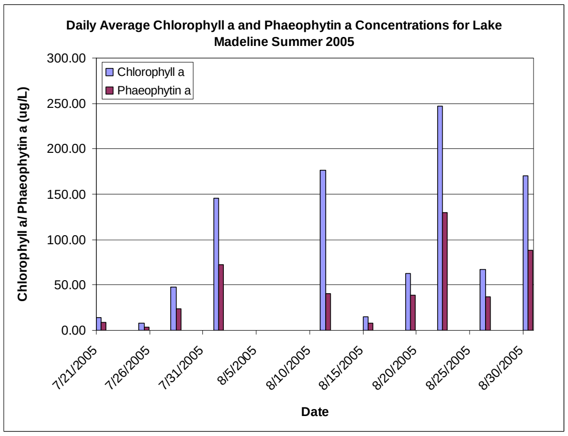

Fig. 25.2. Daily average chlorophyll *a* (blue) and phaeophytin *a* (purple) concentrations Lake Madeline summer 2005.

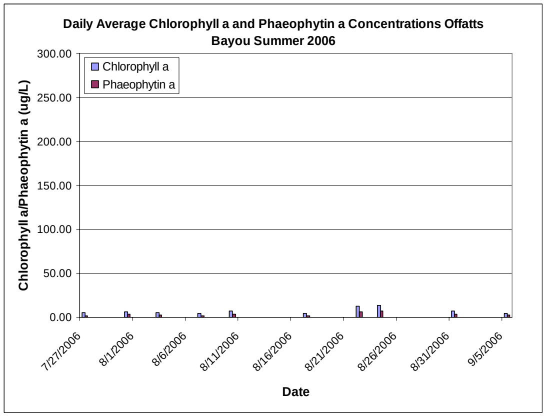

Fig. 26.1. Daily average chlorophyll *a* (blue) and phaeophytin *a* (purple) concentrations for Offatts Bayou summer 2006.

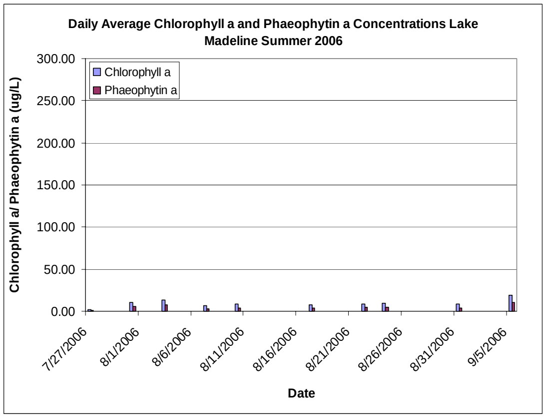

Fig. 26.2. Daily average chlorophyll *a* (blue) and phaeophytin *a* (purple) concentrations for Lake Madeline summer 2006.

Phytoplankton Counts

The summer of 2005 was dominated by the presence of cyanobacteria (Figure 27) in the form of unknown spherical cyanobacteria and *Microcystis sp*. (See Table 2). The summer of 2006 was also dominated by the presence of cyanobacteria, however diatoms were much more prevalent than the summer of 2005 (Figures 28).

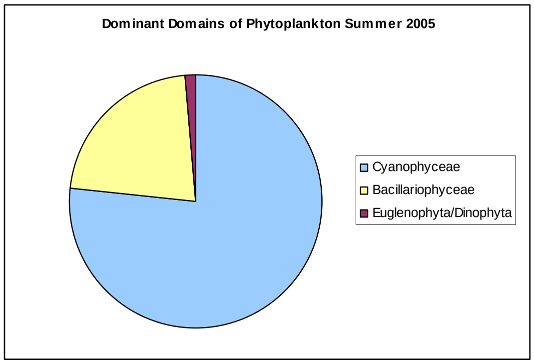

Fig. 27. Pie Chart depicting the dominant Domains of phytoplankton for the summer of 2005.

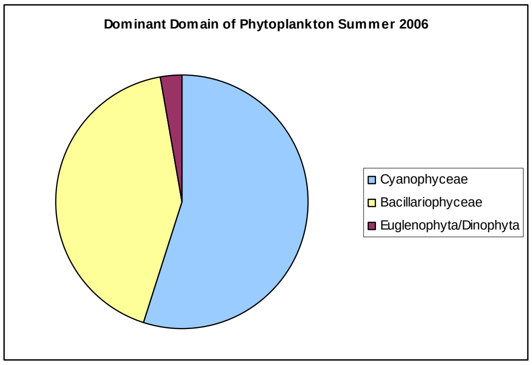

Fig. 28. Pie chart depicting dominant domains of phytoplankton for the summer of 2006.

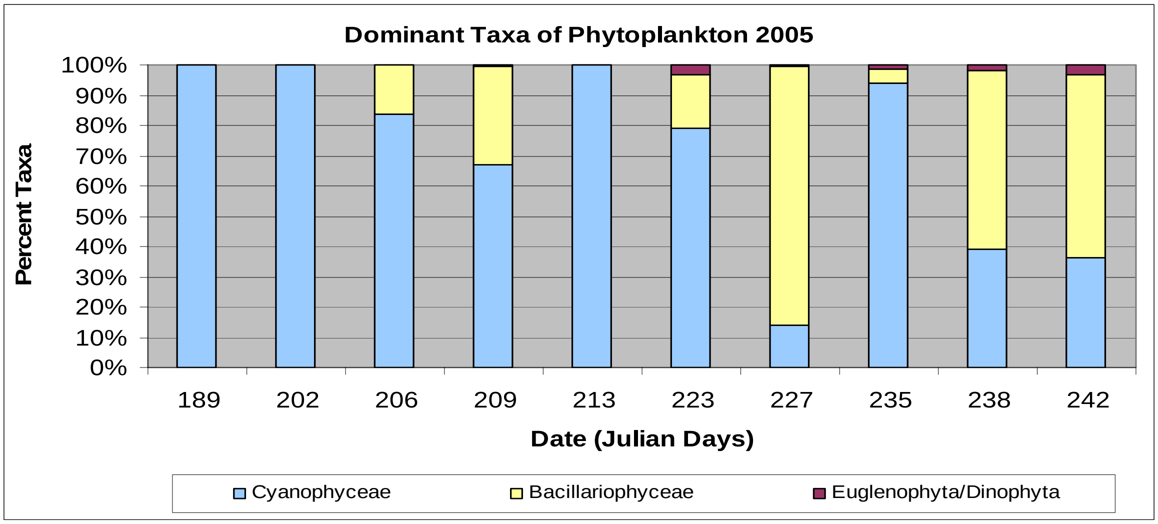

Fig. 29. Bar graph depicting dominant taxa of phytoplankton for the summer of 2005, separated by Domain.

Phytoplankton counts were conducted to determine the dominant phytoplankton present in the study area, thus enabling the determination of the presence or absence of toxic algae. The summer of 2005 was dominated by cyanobacteria (in the form of unknown spherical cyanobacteria and *Microcystis sp.* Table 2), changing toward the end to a dominance of diatoms (primarily *Coscinodiscus sp*., found on August 11th, 26th, and 30th, Table 2) (Figure 29). The large fluctuation on August 15th (Julian day 227) corresponds to increased wind mixing and very small amounts of rain (See Figures 5.1 & 6.1). Julian day 235 corresponds to an algal bloom (as depicted in Figures 25.1 & 25.2), thus the bloom, three days prior to the fish kill, was primarily cyanobacteria. August 26th, the day of the fish kill (Julian day 238), was dominated by diatoms, however cyanobacteria were still present in high numbers.

Table 2. Phytoplankton counts for summer 2005, identified to Genus level, separated by Domain.

	7/8	7/21	7/25	7/28	8/1/	8/11	8/15	8/23	8/26	8/30	**Total**
Cyanophyceae											
Anabaena sp.				5			3	4			**12**
Anthrospira sp.									2		**2**
Unknown spherical sp.				42	534	1602	115	3853	85		**6231**
Lyngbya sp.								9	10	9	**28**
Microcystis sp.	500	500	650	190	9	125	66	46	87	59	**2232**
Oscillatoria sp.			11	1		19	3	39	78	1	**152**
Trichodesmium sp.									2		**2**
Bacillariophyceae											
Auiacodiscus sp.									4		**4**
Azpeitia sp.				1							**1**
Chaetoceros sp.				7		40	279		12		**338**
Coscinodiscus sp.	1		45	56		284	662	143	357	103	**1651**
Cylindrotheca sp.			1	43		55	15	41	2		**157**
Detonula sp.				6		1				2	**9**
Ditylum sp.			2				13	1	1		**17**
Melosira sp.			2						3		**5**
Navicula sp.								1			**1**
Nitzchia sp.						1					**1**
Odontella sp.			10	2		2	56		10	10	**90**
Pleurosigma sp.								1	1		**2**
Pseudonitzschia sp.				1		3	47	4	6		**61**
Rhizosolenia sp.							57		1		**58**
Thalassonemia sp.			70								**70**
Euglenophyceae											
Euglena aeosformis						73		61		6	**140**
Dinophyceae											
Ceratium sp.							6	1	4		**11**
Peridinium sp.				1		1		1	8		**11**
Prorocentrum sp.				1							**1**
Daily Total	**501**	**500**	**791**	**356**	**543**	**2206**	**1322**	**4205**	**673**	**190**	

Table 3. Diversity indices for 2005, includes Simpson's diversity index and Shannon's index for each trip and overall for the entire summer.

	7/8	7/21	7/25	7/28	8/1	8/11	8/15	8/23	8/26	8/30	Summer
Simpson's	0.996	1.000	0.683	0.337	0.967	0.549	0.310	0.841	0.328	0.393	0.367
Shannon (H')	0.014	0.000	0.71	1	0	1.00	1.57	0.43	1.57	1	1.397
H'_{max}	0.693	0.000	2.197	2.565	0.693	2.485	2.485	2.639	2.890	1.946	3.258
Evenness (E)	1.437	0.000	0.311	0.131	1.396	0.221	0.125	0.319	0.113	0.202	0.113

Table 3 shows the Shannon and Simpson diversity indices for each sampling day as well as the entire summer of 2005. Simpson's diversity index (supported by the Shannon index) shows a trend from a homogenous ecosystem (in terms of phytoplankton) to one of a more diverse heterogeneous system. August 23rd, four days prior to the fish kill, a low diversity was again observed. This is also the day of the bloom indicated in Figures 25.1 and 25.2. This bloom primarily consisted of cyanobacteria in the form of the unknown spherical species.

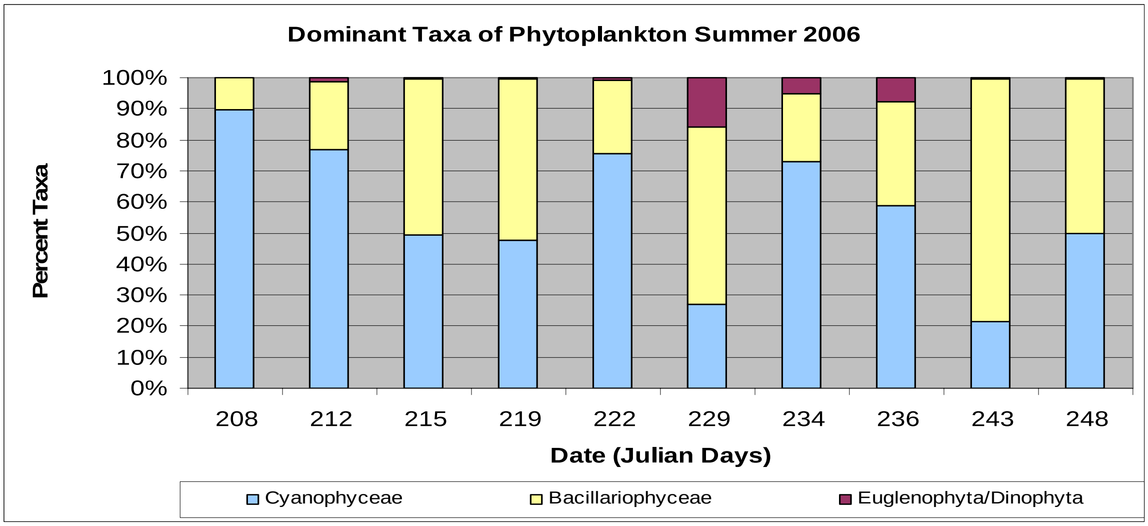

Fig. 30. Bar graph depicting dominant taxa of phytoplankton for the summer of 2006, separated by Domain.

Unlike the summer of 2005, diatoms were present throughout the summer of 2006 in large abundances (Figure 30) and in diverse assemblages (Tables 4 & 5). The increases of diatoms correspond to periods of higher wind mixing and rainfall (Figures 5.2 & 6.2). Julian day 215 follows the period of highest wind mixing; days 229 and 243 both follow periods of high rainfall. The dominant cyanobacteria in 2006 were again unknown spherical cyanobacteria accompanied by *Microcystis sp*., and the dominant diatoms were *Coscinodiscus sp*. and *Chaetoceros sp*. (Table 4). The Euglenophyta and Dinophyta were also higher in abundance than in 2005.

Table 4: Phytoplankton counts for summer 2006, identified to Genus level, separated by Domain.

	7/27	7/31	8/3	8/7	8/10	8/17	8/22	8/24	8/31	9/5	**Total**
Cyanophyceae											
Unknown spherical sp.	601	643	65	39	125	261	989	323	174	1111	**4331**
Lyngbya sp.	11	3	8	8		1		1		5	**37**
Microcystis sp.	93	687	573	1455	912	119	228	113	104	140	**4424**
Oscillatoria sp.	7	6	16	11	1	8	2	6	10	1	**68**
Bacillariophyceae											
Amphora sp.								2		1	**3**
Azpeitia sp.		1		5						19	**25**
Bacteriastrum sp.										39	**39**
Cerataulina sp.										37	**37**
Chaetoceros sp.	9	125	95	680	64	192	8	20	38	355	**1586**
Coscinodiscus sp.	50	225	235	561	163	384	129	76	266	6	**2095**
Guinardia sp.										1	**1**
Cyclotella sp.										1	**1**
Cylindrotheca sp.	4	12	12	47	6	8	7	29	5	7	**137**
Dactyliosolen sp.				1						1	**2**
Ditylum sp.	1			169	51	65	26	14	22	5	**353**
Gossleriella sp.					1					1	**2**
Grammatophora sp.			19	2							**21**
Hemiatus sp.	1								2	3	**6**
Leptocylindrus sp.										453	**453**
Lithodesmium sp.				1		1					**2**
Navicula sp.				1						5	**6**
Nitzchia sp.		2	17	19	3	3	7	2	2	4	**59**
Odontella sp.	8	3	13	104	16	33	26	23	15	1	**242**
Pleurosigma sp.		1	2		14		4			9	**30**
Pseudoguinardia sp.									6	34	**40**
Pseudonitzschia sp.	3	6	29	13	2	22	116	59	18		**268**
Rhizosolenia	4	5	185	9	5	13	11	7	482	236	**957**
Skeletonemia sp.			5	23		1	2				**31**
Thalassonemia sp.			67	10	2	99	25.00	18	185	28	**434**
Trachyneis sp.							1	6			**7**
Euglenophyceae											
Euglena sp.	1			4	7	228	89	57	3		**389**
Dinophyceae											
Alexandrium sp.		20	4	1	2	1				4	**32**
Ceratium sp.										3	**3**
Oxyphysis sp.										1	**1**
Polykrikos sp.										1	**1**
Prorocentrum sp		4								2	**6**
Protoperidinium sp.			1	4						1	**6**
Daily Total	**793**	**1743**	**1346**	**3167**	**1374**	**1439**	**1670**	**756**	**1332**	**2515**	

Table 5. Diversity indices for 2006, includes Simpson's diversity index and Shannon's index for each trip and overall for the entire summer.

	7/27	7/31	8/3	8/7	8/10	8/17	8/22	8/24	8/31	9/5	Summer
Simpson's	0.592	0.313	0.241	0.293	0.466	0.161	0.383	0.230	0.214	0.260	0.180
Shannon (H')	0.934	1.382	1.845	1.580	1.23	2.037	1.454	1.923	1.822	1.762	2.091
H'_{max}	2.565	2.708	2.833	3.091	2.773	2.833	2.773	2.773	2.708	3.434	3.611
Evenness (E)	0.231	0.116	0.085	0.095	0.168	0.057	0.138	0.083	0.079	0.076	0.050

Table 5 shows the Shannon and Simpson diversity indices for each sampling day as well as the entire summer of 2006. Simpson's diversity index indicates that the phytoplankton assemblage present in the summer of 2006 was consistently heterogeneous, with no group dominating the system at any time (this is supported by the Shannon index).

CHAPTER IV

DISCUSSION AND CONCLUSIONS

Discussion

Fish kills are a common occurrence world-wide as a result of one, or a combination, of the following: eutrophication, phytoplankton blooms, hypoxia, and a number of other reasons associated with industrialization, development and urbanization. Of the 22 coastal states in the U.S., Texas was ranked not only for having the greatest number of recorded fish kills, but also the only state in which more than a million were killed in any one incidence (Lowe et al. 1991). Galveston Bay, on Texas' upper coast, is the estuary in which the majority of the 5341 recorded fish kills, in Texas, occurred between 1951 and 2006 (Thronson and Quigg 2007). Within this complex is Lake Madeline and Offatts Bayou, connected to each other by a narrow channel, surrounded by residences and recreational activities. A fish kill comprising of Gulf Menhaden was observed in the early morning hours on August 26th, 2005, concentrated primarily in Lake Madeline. No fish kill was observed in 2006 in either Lake Madeline or Offatts Bayou. Not only did this allow a unique comparison of the LMOB system between years, but it also pin-pointed the likely cause of the 2005 fish kill.

Lake Madeline has a bathymetry which tends to restrict water movement between it and the adjoining Offatts Bayou, thus the waters are commonly subject to stratification. The summer of 2005 was met with little rainfall and little wind mixing, exacerbating the problem of restricted waters, leaving them strongly stratified as indicated by the buoyancy frequency (Figure 31).

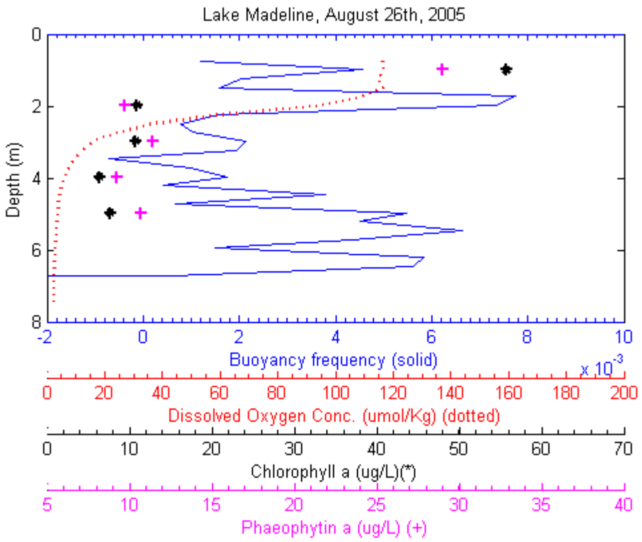

Fig. 31. Summary figure of buoyancy frequency, dissolved oxygen concentrations, chlorophyll *a*, and phaeophytin *a* concentrations for August 26th, 2006 in Lake Madeline.

Surface temperature and salinity were not drastically different from 2005 to 2006; however differences were seen when the entire water column was analyzed. 2006 showed waters of lower overall temperature which were also less saline - this being a result of the increased rainfall and thunderstorm activity experienced during the summer of 2006. The high salinity and stable water column in 2005 was likely a factor in the abundance of phytoplankton (primarily cyanobacteria) that season.

Surface dissolved oxygen concentrations are often used as indicators of water quality and ecosystem health; they are regulated by the interplay between both physical (e.g.

wind mixing) and biological (e.g. organism growth) factors in surface waters. Oxygen concentrations are often more variable than parameters such as temperature and salinity. As hypoxia was prevalent in the bottom waters during both summers (2005 in which a fish kill was observed and 2006 when this event was not observed) hypoxia was likely not a likely factor in the cause of the fish kill. The idea that laterally wind driven upwelling could bring these hypoxic waters to the surface, inundating the area where fish were previously confined, is also not likely; the summer with more potential to cause this upwelling due to the higher wind speeds and a less stable pycnocline was the summer in which no fish kills were observed, suggesting that low dissolved oxygen concentrations were not a likely factor (via any mechanism) in the cause of the fish kill observed in 2005.

Chlorophyll *a* concentrations can be used to determine the occurrence of a phytoplankton bloom by approximating biomass; phaeophytin *a* can likewise be used to determine the occurrence of a phytoplankton bloom that has been missed, as it is the breakdown material of chlorophyll *a*. Large amounts of chlorophyll *a* and phaeophytin *a* were observed on August 22nd, 2005, four days prior to the fish kill, indicating that a bloom was in progress. Diversity indices also indicate that on August 22nd, 2005, there was a phytoplankton bloom, with a resident assemblage of primarily one phytoplankter, indicating that the environment was more favorable to them and thus they were able to out-compete the other phytoplankton present and increase to bloom proportions. This bloom was especially concentrated in Lake Madeline (as indicated by both the chlorophyll *a* concentrations and the low diversity). The falling concentrations of chlorophyll *a* and phaeophytin *a* on the day of the fish kill can be explained by the fact that the waters tested for these concentrations were taken from approximately 0.4m - the crashing bloom could have been concentrated just below this depth, above the pycnocline, thus loading the upper water column with breakdown materials from the bloom just prior. This supports the hypothesis that a large biomass of phytoplankton could have been a major factor in the fish kill August 26th, 2005.

It has been established that eutrophication is common in embayments surrounded by developed land, due to surface runoff carrying increased levels of nutrients into the system. However, the increased nutrients are likely not the only culprit; because these areas are surrounded so closely by developments, wind mixing is often times rare, except for thunderstorm activity, thus leaving these systems to become increasingly stratified (as observed in 2005). This stratification causes, as observed in Figure 31, concentration of phytoplankton and their breakdown products. Thus a bloom, due to increased nutrients, is confined to a small area and the following crash is likewise confined. Therefore, if the phytoplankters are toxic their release of these toxins would be concentrated in this area as well; if they are not toxic the breakdown can cause increased depletion of the oxygen in this already restricted water, both of these cases could lead to fish mortality events. The presence of cyanobacteria in 2006, indicate that high nutrient levels were present. However, large amounts of mixing and fresh water input were also common and therefore, a fish kill was not observed. It is true that phytoplankton concentrations were never as high as they were in 2005, but this is likely due to the lack of strong pycnoclines throughout the 2006 summer and the phytoplankton were thus not confined to the surface waters, where the sampling occurred.

The very positive buoyancy frequency for 2005 is indicative of a stratified water column with the pycnocline located at approximately 1.8m. The stratification of the water column (pycnocline at depth of 1.8m) served as a concentrating mechanism for oxygenated water, nutrients, phytoplankton and their breakdown products (as seen in Figure 31). This figure also clearly depicts the concentration of oxygenated waters, phytoplankton, and the breakdown materials in these isolated surface waters. Oxygen concentrations, concentrations of chlorophyll *a* and phaeophytin *a* all fell dramatically below the pycnocline at 1.8m.

Conclusion

This study tested the hypothesis that phytoplankton, either through harmful algal blooms, large quantities of biomass, or low dissolved oxygen concentrations, are the primary causative factor of the fish kills occurring during the late summer months in LMOB. Low dissolved oxygen concentrations were present during both summers and did not vary markedly from one summer to the next, suggesting that hypoxia (through any mechanism) was not the cause of the fish kill. Small numbers of toxic phytoplankton were observed during both summers, however the bloom that occurred four days prior to the fish kill consisted of a nontoxic phytoplankton. Therefore, the crashing of this bloom did not release toxins to subsequently kill the fish. The bloom, and its subsequent crashing, was concentrated in the narrow sanctuary of top water where the Gulf Menhaden were residing. This exorbitant amount of detritus and organic matter suffocated the fish causing the mortality event on August 26th, 2005. It is the conclusion of this study that high amounts of biomass from the crashing bloom, in conjunction with the strong stratification of the water column present in Lake Madeline, was the cause of the fish kill.

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