EFFECT OF VARIATION IN FRESHWATER INFLOW ON PHYTOPLANKTON PRODUCTIVITY AND COMMUNITY COMPOSITION IN GALVESTON BAY, TEXAS

A Thesis

by

AMANDA MAE THRONSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Zoology

EFFECT OF VARIATION IN FRESHWATER INFLOW ON PHYTOPLANKTON PRODUCTIVITY AND COMMUNITY COMPOSITION IN GALVESTON BAY, TEXAS

A Thesis

by

AMANDA MAE THRONSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Co-Chairs of Committee,	Duncan MacKenzie Antonietta Quigg
Committee Members,	William Neill Jay Rooker
Head of Department,	Vincent Cassone

December 2008

Major Subject: Zoology

ABSTRACT

Effect of Variation in Freshwater Inflow on Phytoplankton Productivity and Community Composition in Galveston Bay, Texas. (December 2008)

Amanda Mae Thronson, B.S., Texas A&M University at Galveston

Co-Chairs of Advisory Committee: Dr. Duncan MacKenzie
Dr. Antonietta Quigg

Freshwater inflows are essential to the health of estuaries and minimum discharge levels must be maintained in order to sustain a healthy ecosystem. Due to the predicted 50% increase in urban population growth along the Texas coastline by the year 2050, water regulators and managers are faced with the challenge of meeting human needs, while maintaining essential freshwater inflows into estuarine ecosystems. Galveston Bay is of particular concern because 10 million people currently living within its watershed.

Freshwater inflows into Galveston Bay during 2006 were determined by using daily discharge data from a United States Geological Survey (USGS) sampling gauge in the Trinity River. Changes in water quality parameters, primary productivity, and phytoplankton community structure in response to freshwater inflows, were monitored monthly to determine how the phytoplankton community responded to inflow events.

Freshwater inflow into Galveston Bay during 2006 was indicative of a low-inflow year, with seven large (>7,000 $ft.^3$ sec^{-1}) inflow events occurring throughout the year. There were significant differences in phytoplankton biomass (Fm), photosynthetic efficiency (alpha), and photosynthetic potential (yield) of the phytoplankton community, between wet (January-April and October-December) and dry (May-September) months. Significant differences in the biomass of phytoplankton groups also occurred with cyanobacteria being present in higher concentrations during the dry months and diatoms & dinoflagellates during the wet months. Low flow periods favored cyanobacteria, which lead to decreased secondary productivity, while pulsed inflow events resulted in enhanced secondary productivity by favoring diatoms and dinoflagellates. Resource Limitation Assays (RLAs) indicated that nitrogen was a potential limiting nutrient in Galveston Bay during spring/summer, with light limitation of phytoplankton communities possibly occurring near the mouth of the Trinity River.

This study demonstrates the role of freshwater inflows in determining the primary productivity and community composition of the phytoplankton in Galveston Bay over an annual cycle. Inter-annual studies are needed to elucidate the impact of freshwater inflows in years with higher inflows to Galveston Bay and determine which of these impacts need to be incorporated into water management decisions to maintain a healthy ecosystem.

DEDICATION

To my parents:

Who gave me the courage to pursue my dreams,

and the love and support to reach them.

ACKNOWLEDGEMENTS

I thank my advisor, Dr. Antonietta Quigg, for all the comments, suggestions, advice, and encouraging me to get out of the lab and try new things.

I also thank my co-chair, Dr. Duncan MacKenzie, and my other committee members, Drs. Jay Rooker and William Neill, for sticking with me through the project changes, and for the comments and suggestions to improve the quality of my thesis.

Thanks to everyone who helped out in the field and in the lab, including but not limited to Leslie, Erin, Calvin, George, Jamie, Federico, and Allison.

I also thank everyone in the Phytoplankton Dynamics Laboratory for keeping me sane by acting crazy, and for all being a little OCD.

Lastly, I thank my family and friends for being there for me through this entire process, and for being the fun and amazing people that they are!

NOMENCLATURE

Chl *a*	Chlorophyll *a*
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
ETR	Electron Transport Rate
Fm	Maximum Fluorescence
GBEP	Galveston Bay Estuary Program
GPS	Global Positioning System
HDPE	High Density Polyethylene
HPLC	High Performance Liquid Chromatography
MANOVA	Multivariate Analysis of Variance
N	Nitrogen
NOAA	National Oceanic and Atmospheric Administration
P	Phosphorus
PHA	Port of Houston Authority
PhytoPAM	Phytoplankton Pulse Amplitude Modulated Fluorometer
*Rel*ETR	Relative Electron Transport Rate
RLA	Resource Limitation Assay
RLC	Rapid Light Curve
TN	Total Nitrogen
TP	Total Phosphorus

TOC	Total Organic Carbon
TSS	Total Suspended Solids
TWDB	Texas Water Development Board
USGS	United States Geological Survey

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

1. INTRODUCTION

Freshwater inflows contribute physically (i.e., sedimentation, resuspension, and advection), chemically (i.e., nutrient enrichment) and biologically (i.e., enhanced productivity, recruitment gains, and losses via low-salinity tolerance) to an estuarine system, and are essential to the health of the estuary (Montagna and Kalke 1992). According to Longley (1994), freshwater inflows moderate the dilution of seawater to brackish water, bay temperatures, and the creation of a salt wedge and mixing zone due to tidal action. Reduced freshwater inflows caused by drought, dams, or diversions of freshwater could cause increased salinity, reduced mixing, and stratification of the water column, leading to changes in the community structure of the estuary. Given the predicted 50% increase in urban population along the Texas coast by 2050 (TWDB 2001), water regulators and managers are faced with the challenge of meeting human needs, potentially by freshwater diversions, while maintaining critical freshwater inflows into estuaries to preserve their overall ecosystem health.

Galveston Bay is the largest estuary (ca. 1456 km^2) on the Texas coast (Engle et al. 2007). It is the focus of conservation concern due to the high density of industrialization and urbanization in its watershed. About 47% of the total state population (almost 10 million people) live within the watershed (Moulton et al. 2004). The five counties bordering Galveston Bay have over 4 million people living in them, using an estimated 1.4 billion gallons of freshwater daily (TWDB 2007). Galveston Bay is the most productive of all Texas' estuaries with an oyster production that is

---

This thesis follows the style of *Estuaries and Coasts.*

unsurpassed in the U.S. (ca. 1,800 metric tons with a value of $8 million), a commercial fishery industry that is the source of one third of the state's commercial fishing income (Galveston Bay contributed ca. $99 million from 1994-1998), and a recreational fishery that made a gross direct contribution to the local economy of $171.5 million in 1986 (GBEP 2001; Lester and Gonzalez 2002; Pinckney 2006; TWDB 2007). Galveston Bay is home to important recreational and commercial fisheries consisting of oysters (2 species), shrimps (13 species), crabs (17 species) and fishes (over 150 finfish species, Lester and Gonzalez 2002). The Port of Houston, located on the northwestern section of Galveston Bay, moves more than 200 million tons of cargo annually (PHA 2006). Dredging for the Houston ship channel, as well as for two smaller ports (Texas City and Galveston) and various other activities have greatly altered circulation patterns in this shallow system (average depth 2 m).

Freshwater inputs into Galveston Bay are mainly from the Trinity River (83%; Fig. 1) and the San Jacinto River (8%). Most of the tidal exchange (ca. 80%) occurs through Bolivar Roads at the mouth of the bay, with a tidal range of 40cm. Only 7.7% of the tidal water volume is exchanged via tidal processes, indicating winds are more important than tides for inducing circulation (NOAA 1989; Pinckney 2006). Studies in Texas have shown that increases in freshwater inflows brought higher levels of terrestrial inputs that contributed significantly to the diet of migratory juvenile brown shrimp, increased photosynthetic activity in dominant halophytes, increased percent cover of annual marsh plants, and increased benthic macrofaunal density and biomass which

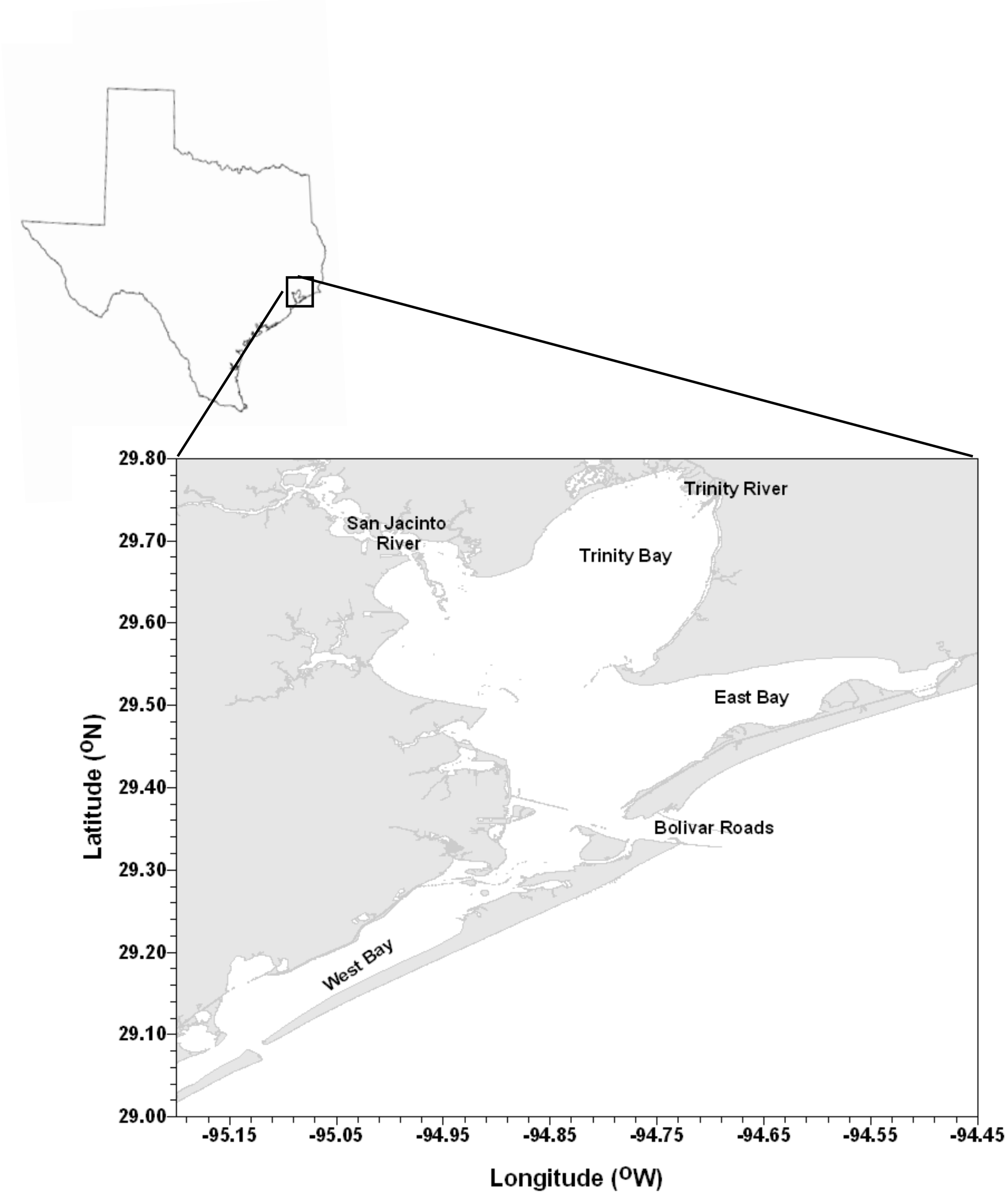


Fig. 1: Map of Galveston Bay showing sources of freshwater inflows and area of tidal exchange.

stimulates secondary production (Montagna and Kalke 1992; Heilman et al. 1999; Riera et al. 2000; Dunton et al. 2001; Ward et al. 2002; Pinckney 2006). In order to properly manage the state's freshwater resource, we need to understand how the present Galveston Bay ecosystem responds to freshwater inflow pulses during high and low flow periods. This will aid in understanding the downstream ecological effects of changes to freshwater inflows and modes of nutrient loading into the system.

Specific nutrients that are transported into the system via freshwater inflows will have an effect on the phytoplankton community. Generally, phosphorus (P) and nitrogen (N) limit freshwater and marine primary production, respectively. The limiting effects of nutrients can be exacerbated by reduced light availability (Arhonditsis et al. 2007), but Galveston Bay has a generally well-mixed, shallow water column that enables the phytoplankton to sustain photosynthesis due to vertical mixing processes (Pinckney 2006). Excessive nutrient loading in aquatic systems can increase oxygen demand. Major N (in the form of nitrate) loading events are directly related to Trinity River discharge (Pinckney 2006), indicating that during periods of high inflow there should be an increase in phytoplankton biomass. Huisman and Weissing (1995) found that short-term pulses may favor diatoms and longer periods of low loading would favor smaller phytoplankton.

Other important factors include the magnitude of flushing and nutrient loading, the mode of nutrient loading (e.g., continuous vs. pulsed flows, and frequency of pulsed flows), and the ratios of potentially limiting nutrients within the load (Malone et al. 1988; Chan and Hamilton 2001). Increased water removal would result in a decrease in the total volume of freshwater inflow, and also the number and magnitude of freshwater pulses. Buyukates and Roelke (2005c) showed that the mode of nutrient delivery impacts the plankton community composition. During times of high nutrient loading caused by pulsed inflow events some phytoplankton species are able to uptake and store nutrients at a rate greater than their reproductive rate, resulting in enhanced secondary productivity (Buyukates and Roelke 2005b). Nutrient loading also causes an increase in more edible forms of phytoplankton (Buyukates and Roelke 2005a; Buyukates and Roelke 2005c). Roelke et al. (2004) found that during a dry year (indicating continuous inflow) the phytoplankton community was dominated by cyanobacteria, resulting in low secondary productivity and diminished light penetration. A decrease in secondary productivity indicates that higher trophic levels would also be affected by differences in freshwater inflows.

This project involved high-resolution mapping of primary production and community composition of phytoplankton in Galveston Bay, along with water quality parameters in order to determine the impacts of changes in freshwater inflow and nutrient loading on the base of the food chain. This approach provided a more comprehensive understanding of the relationships between the nature of inflow events and estuarine ecosystem health in Galveston Bay, and findings from this study will be useful to state resource and water managers attempting to optimize diversions of freshwater.

1.1 Objectives

1. Monitor changes in water quality, primary productivity, and phytoplankton community structure in response to freshwater inflows in Galveston Bay.
2. Conduct a pilot study to define the limiting resources (nitrogen, phosphorus, silica, light) at key locations throughout Galveston Bay using resource limitation assays (RLA).
3. Develop improved, process-based understanding of the linkages between the variations in freshwater inflows and nutrient loading on phytoplankton community structure and productivity for Galveston Bay.

1.2 Hypotheses

H_0: There is no effect of variation in freshwater inflows on primary productivity and phytoplankton community structure in Galveston Bay.

H_1: Variation in freshwater inflows affects primary productivity and phytoplankton community structure in Galveston Bay.

2. MATERIALS AND METHODS

2.1 Freshwater Inflow Data

A sampling gauge operated by the United States Geological Survey (USGS) was used to determine the amount of freshwater discharged into Galveston Bay. The gauge (USGS 08066500; 30°25'30" N, 94°51'02" W) was located in the Trinity River in Liberty, Texas. This gauge recorded the daily discharge of the river in ft.^{3} sec^{-1}. All data collected from the USGS station were reviewed and approved by USGS personnel for accuracy before being published.

2.2 Field Procedures

High-density sampling surveys were conducted monthly in Galveston Bay from January to November 2006. No water was collected during the January trip for processing with the PhytoPAM. The survey was not done in December due to technical difficulties. An extra sampling survey was conducted mid-month after a large rain event in July to determine if there was an immediate effect on the phytoplankton community. Each sampling trip required one day for the north half of the bay (stations 1-20) and one day for the south half (stations 21-41; Fig. 2). The sampling occurred on consecutive days (weather permitting) and all trips were made from 07:00-17:00 hrs. The March and mid-July trips only have data for the north half of the bay due to unsuitable weather conditions on subsequent days. The sampling trips followed tightly gridded transects, stopping at 41 stations as shown in Fig. 2. The Dataflow (see *2.2.1 Dataflow*) recorded data continuously and water was collected at the 41 stations for analysis using the PhytoPAM (see *2.2.2 PhytoPAM*).

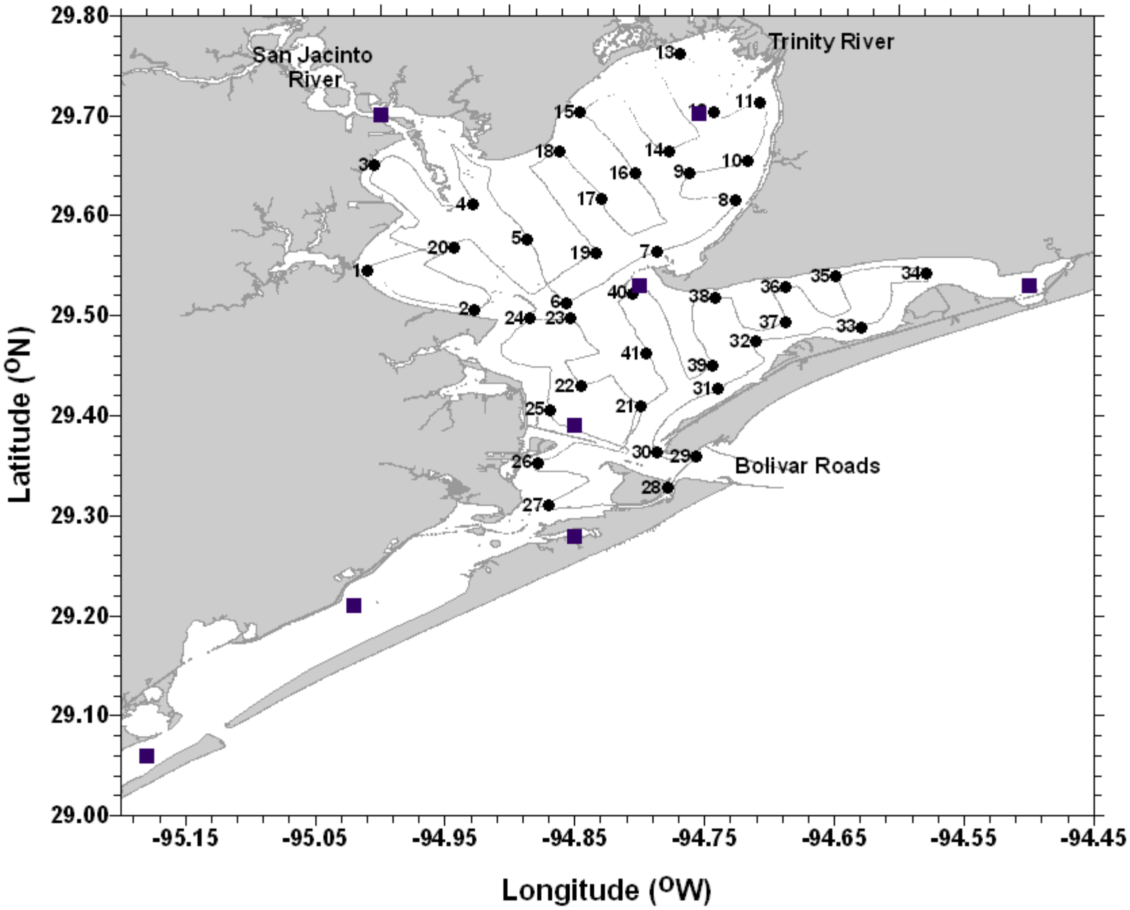


Figure 2: Map of sampling sites in Galveston Bay, Texas, including the GPS gridded transects (gray line), the 41 stations where PhytoPAM data were collected (black circles), and the stations for the resource limitation assays (blue boxes). Stations 1-20 were in the northern portion of the bay and stations 21-41 were in the southern portion.

2.2.1 Dataflow

A flow-through Dataflow unit (Madden and Day 1992) was mounted on a boat that was steered along tightly gridded transects through the bay as shown in Fig. 2. A ram was mounted vertically on the stern of the boat so it extended about 10cm below the waterline. As the boat moved forward, water was forced up the ram and run through a de-bubbler to prevent bubbles moving through the sensors. The Dataflow unit measured chlorophyll *a* (chl *a*; *in situ* fluorescence), pH, salinity, dissolved organic matter (DOM; *in situ* fluorescence), water temperature, and transparency. These measurements were taken every 40m (every 4 seconds at 18-22 knots) and surface waters were continuously pumped across the sensor array. The global positioning system (GPS) unit attached to the Dataflow allowed geo-referencing of transects with samples.

2.2.2 PhytoPAM

As the boat traveled along the gridded transects, water samples were collected at the 41 stations shown in Fig. 2 for analysis using the Phytoplankton Pulse Amplitude Modulated Fluorometer (PhytoPAM, Walz, Germany). GPS points were taken for all PhytoPAM samples allowing for geo-referencing of all measurements. These samples were collected in amber bottles and kept in an insulated container at ambient temperatures until the end of each field day.

2.3 Lab Procedures

Samples were stored at ambient temperatures until processing in the laboratory was completed. All samples were processed within 24 hours upon returning from the field.

2.3.1 Dataflow

The Dataflow data were downloaded to a laptop at the end of each sampling day and the data examined to reject outliers and other erroneous information. Data for chl *a*, DOM, and transparency were recorded as a voltage reading. The following equations were used to convert them into appropriate units:

(1) Chl *a* (ug/L) = Volt. * 25

(2) DOM (mg/L) = (Volt. * 194) - 10.088

(3) Transparency (%) = (Volt. - 0.059) / (4.798 - 0.059) * 100%

All other parameters were used without manipulation.

2.3.2 PhytoPAM

The PhytoPAM determines the content of active chl *a* in surface waters (Jakob et al. 2005). Four excitation wavelengths (470nm, 520nm, 645nm and 665nm) are used to differentiate between the differently pigmented groups of freshwater and marine algae (green algae, diatoms and dinoflagellates, cyanobacteria). These wavelengths do not correspond to the peak wavelengths of absorption of the pigment groups, but instead the ratios of the fluorescence yields of each group show differences upon excitation with these wavelengths, enabling the separation of algae into their respective groups. The photosynthetic performance and light-adaptational state of the various types of phytoplankton can be assessed, providing an indication of the physiological status of the phytoplankton (Jakob et al. 2005). Dark acclimated samples were homogenized before being placed in the PhytoPAM for analysis. In order to generate rapid light curves (RLC), an inbuilt program stepped through 20 actinic light levels between 0 and 764 μmol photons m^{-2} s^{-1} for 20 seconds each. RLCs were used to then determine the productivity and efficiency of the phytoplankton community. Alpha, calculated from the initial slope of a RLC, is a function of both light-harvesting efficiency and photosynthetic energy conversion efficiency of a phytoplankton community (Quigg and Beardall 2003). The PhytoPAM calculates the relative electron transport rate (*rel*ETR) from the plateau region of RLCs; this provides an estimate of the maximum photosynthetic rate (White and Critchley 1999). Yield (rel. units) is a measure of the maximum photosynthetic potential and provides information on how the phytoplankton community may be poised to respond to perturbations in the environment; in this case, freshwater inflows into Galveston Bay. A yield greater than 0.4 rel. units generally indicated that the phytoplankton community was photosynthesizing efficiently and had a sufficient amount of light and nutrients while a yield less than 0.4 rel. units indicated the phytoplankton community was stressed from lack of nutrients or light (Raven and Falkowski 1997). It is not yet possible to distinguish if nutrients or light create the limitation at this stage. After a minute in darkness, the sample was pulsed again with a single short saturating pulse to determine maximum fluorescence (Fm). Fm is used as a proxy for chl *a* biomass, which in turn is used as a proxy for phytoplankton biomass. Relative units are assigned to most of the parameters measured by the PhytoPAM; this is because of the nature of the measurement itself (fluorescence) and not due to a lack of calibration or other data transformation.

2.3.3 Chlorophyll a Analysis

Between 500 to 1000 mL of the water collected from the 41 stations was filtered onto 47mm GF/F filters to determine chl *a* concentrations. The filters were stored flat in petri slides and frozen until analysis. Filters were thawed on ice and placed in a DMSO/90% acetone (40:60) solution in the dark in a fridge for up to 24 hours. Chl *a* fluorescence was measured using a calibrated Turner 10AU fluorometer. Concentrations of chl *a* (corrected for phaeopigments) were determined according to Lohrenz et al. (1990).

2.4 Resource Limitation Assays

Resource limitation assays (RLAs) were performed at eight stations (Fig. 2) chosen to give a representative view of the entire Galveston Bay system. The procedure for the RLAs was modified from that of Rawlence (1988) and more recently, Fisher et al. (1999). RLAs were used to determine the factor potentially limiting primary productivity: nutrient (N as nitrate, phosphate, and/or silica) and/or light. Water samples (20L) were collected from the surface (0 to 0.3m) in an acid washed carboy and kept cool and dark until returned to the lab. Water quality parameters (salinity, temperature, DO and pH) and GPS location were recorded from sampling sites.

Stocks of nutrients were prepared at the following concentrations: 10 mM NO_3, 1 mM PO_4 and 10 mM Si (final concentrations were an order of magnitude lower). The sample water was divided into 8 cubitainers and the corresponding nutrients added to each treatment: control (no addition), +N (9mL of NO_3 stock), +P (6mL of PO_4 stock), +Si (9mL of Si stock), +NP (9mL of NO_3 stock, 6mL of PO_4 stock), +NSi (9mL of NO_3 stock, 9mL of Si stock), +PSi (6mL of PO_4 stock, 9mL of Si stock), +NPSi (9mL of NO_3 stock, 6mL of PO_4 stock, 9mL of Si stock). Cubitainers were transferred to a floating holding corral and incubated for 2-5 days at ambient water temperatures. Screening covered the floating enclosure, reducing PAR by 50% of ambient.

An initial sample (time = 0 hrs) was taken for chl *a* and PhytoPAM analysis in the lab. These steps were performed as described above (section *2.3.1* and *2.3.2*). Water samples were collected from all cubitainers and sampled for chl *a* and PhytoPAM every 12 hours for 48 hours and then every 24 hours ending after 5 days. The limiting resource was determined according to criteria described in Fisher et al. (1999).

2.5 Statistical Analysis

Multivariate analysis of variance (MANOVA) tests were performed on the water quality and PhytoPAM data using SPSS Version 14.0. Dataflow and PhytoPAM parameters were tested for temporal (wet vs. dry months) and spatial (north vs. south) differences, and univariate tests were used to test individual parameters. Wet months

(January-April, October-December) were classified as those in which the daily discharge into Galveston Bay was >3,700 ft.^{3} sec^{-1}; all other months were classified as dry months (May-September). Stations 1-20 and stations 21-41 (Fig. 2) were grouped together and classified as north and south Galveston Bay, respectively. All parameters were initially tested to meet normality assumptions, and those that did not were log (base 10) transformed (temperature, chl *a*, DOM, transparency, Fm, alpha, yield). Parameters that still did not meet normality assumptions were still considered in the analysis due to the large sample size (> 400 samples, Pallant 2007). Bonferroni adjustments of alpha values gave an adjusted alpha of 0.010 for the Dataflow parameters and 0.0125 for the PhytoPAM parameters. Independent samples t-tests were used to compare differences in the PhytoPAM parameters for the phytoplankton groups (cyanobacteria vs. diatoms/dinoflagellates) and temporal differences within the groups. Independent samples t-tests were also used to compare the control to each of the treatment groups at each station for the RLAs. Alpha values were set at 0.025 for the t-tests. All errors of means were calculated as standard deviations using Microsoft Office Excel 2003.

3. RESULTS

3.1 Freshwater Inflows

Daily discharge in the Trinity River was recorded by USGS gauge 08066500 in Liberty, Texas. The annual mean daily freshwater discharge was 2,629 ft.^{3} sec^{-1} (Fig. 3). The wet months were October through April and the dry months were May through September. The wet months had a range of freshwater inflows between 721 – 32,200 ft.^{3} sec^{-1}, a daily mean of 3,713 ft.^{3} sec^{-1}, and a daily median value of 1,685 ft.^{3} sec^{-1}. The dry months had a range of daily discharge rates between 768 – 2,450 ft.^{3} sec^{-1}, a mean of 1,101 ft.^{3} sec^{-1}, and a median value of 1,090 ft.^{3} sec^{-1}. In wet months, daily freshwater discharge varied 2-3 fold, while in dry months freshwater inflows to Galveston Bay remained relatively consistent and low (Fig. 3). During 2006, there were seven major inflow events (Fig. 3); these were all greater than 7,000 ft.^{3} sec^{-1}. According to the NOAA website (2008), July 2006 was the 9th wettest July in Galveston since 1889, with 9.39 in. of rain (average for July is 3.45 in.).

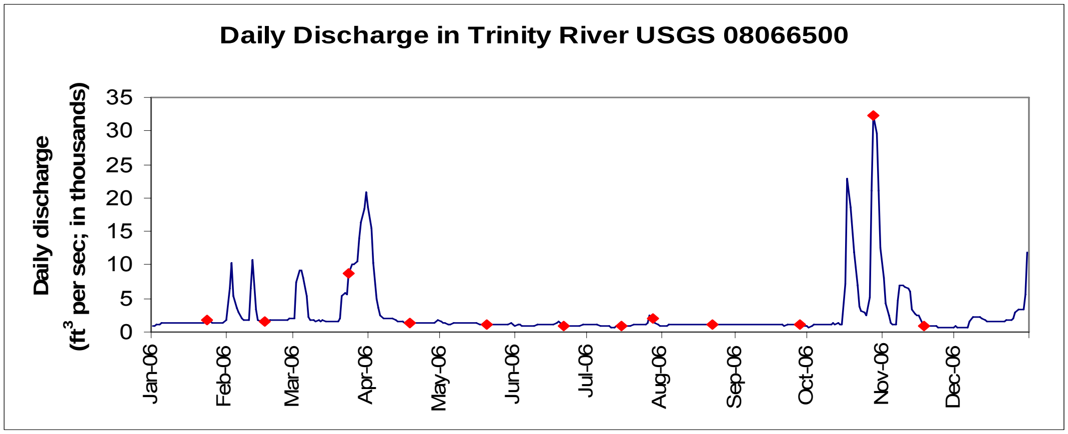


Figure 3: Freshwater inflow data from USGS gauge 08066500 for 2006. Red diamonds indicate days sampling trips were performed.

3.2 Water Quality Parameters – Dataflow Data

3.2.1 Temporal Trends

In 2006, temperature ranged from 8.3-32.8°C (Table 1). The mean average daily temperature for the year was 22.4°C. The wet months (Oct.-Apr.) had a mean temperature of 16.7°C and a range from 8.3-27.7°C. The dry months (May-Sep.) had a mean temperature of 27.7°C and a range from 23.9-32.8°C. The mean salinity for the year was 20.8 psu and ranged from 0.7 to 46.5 psu. Salinity during the wet months had the same range (0.7-46.5 psu) as the annual salinity, but the mean was 24.4 psu. Salinity during the dry months ranged from 2.6-33.7 psu, with a mean of 17.5 psu. Chl *a* concentrations for the year ranged from 4.3-106 μg L^{-1}, with a mean of 25.4 μg L^{-1}. The mean concentration of chl *a* was lower during the wet months (24.9 ± 16 μg L^{-1}) than during the dry months (25.9 ± 19 μg L^{-1}), but was not significantly different. The range in chl *a* concentrations during the wet months was 4.3 to 106 μg L^{-1} and the range during the dry months was 8.0 to 104 μg L^{-1}. The annual mean for DOM was 371 mg L^{-1}, with a 10-fold range over the year (83.0-960 mg L^{-1}). The mean DOM concentration during the wet and dry months was 383 ± 257 mg L^{-1}, and 359 ± 197 mg L^{-1}, respectively. The DOM concentrations were not statistically different between wet and dry months. The mean annual transparency was 24%, with a very large range across Galveston Bay from 0.02-76.2%. During the wet months, transparency varied from 0.02 to 64.4%, with a mean of 15.9 ± 15.63%. The range during the dry months was 0.02-76.2%, with a mean of 31.2 ± 16.75%, indicating there was not a significant difference.

A transect of stations from the mouth of the Trinity River to the Gulf of Mexico (Fig. 4A) was used to map the water parameters to determine whether distance from the freshwater inflow was influencing the water quality parameters on the y-axis, and time (month) on the x-axis. The distance of each station relative to the Trinity River is included in Fig. 4A as a reference. A subset of the 41 stations was chosen to provide a straight (relatively) line across Galveston Bay. Fig. 4B shows that temperature was influenced by time of year as would be predicted based on seasonality. Salinity was affected by distance from the Trinity River (Fig. 4C). Small peaks in daily discharge (approximately 10,000 $ft.^3$ sec^{-1}) of freshwater decreased the overall salinity in the northern part of Galveston Bay during the first few months of the year. The large (>20,000 $ft.^3$ sec^{-1}) inflow event that occurred in April caused a decrease in salinity which reached the southern part of the bay as well. Chl *a* concentrations did not show a definite trend along the transect from the mouth of the Trinity River to the Gulf of Mexico (Fig. 4D). DOM and transparency also did not show a trend with freshwater inflows (Fig. 4E, 4F). The mean transparency value for the dry months (31.2%) was 2-fold higher than the mean value for the wet months (15.9%).

A MANOVA was performed to investigate temporal differences in the water quality parameters measured by the Dataflow at each of the 41 stations. The dependent variables were temperature, salinity, chl *a*, DOM, and transparency. The independent variable was wet or dry month. There was a significant difference between wet and dry months on the combined dependent variables (Pillai's trace: $p \sim 0.000$). When the results were considered separately using a Bonferroni adjusted alpha level of 0.010, a statistically significant difference was seen between wet and dry months for temperature ($p \sim 0.000$). There was not a statistically significant difference between wet and dry

Table 1: Dataflow data for 2006. Wet indicates the period of high inflow from Oct – Apr. Dry indicates the period of low inflow from May – Sep. Jul (H) is the sampling survey conducted after a large rain event during mid-July.

		Year	**Wet**	**Dry**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul (H)**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Temp (°C)	Mean	22.39	16.57	27.66	13.21	11.98	14.43	24.06	24.79	27.27	30.88	28.21	30.49	25.68	20.25	15.82
	Min	8.27	8.27	23.89	8.27	8.27	13.34	22.53	23.89	25.62	29.39	26.80	29.10	24.54	17.95	13.91
	Max	32.84	27.72	32.84	14.42	15.78	15.79	24.84	27.32	29.55	32.30	29.76	32.84	26.94	27.72	18.60
	Median	24.53	15.18	27.43	13.19	11.39	14.31	24.00	24.56	27.12	31.11	27.94	30.41	25.68	20.05	15.60
Sal (psu)	Mean	20.78	24.36	17.54	33.97	35.82	24.46	23.14	23.35	18.56	11.90	15.73	14.08	19.17	10.64	14.09
	Min	0.71	0.71	2.62	12.73	15.20	6.04	6.31	11.57	5.84	4.01	2.62	3.61	12.66	1.28	0.71
	Max	46.54	46.54	33.74	44.62	46.54	30.14	34.92	33.74	32.42	17.94	32.43	27.05	29.59	29.16	27.64
	Median	20.04	25.71	17.47	34.03	38.09	28.10	25.02	23.55	18.22	12.75	14.95	13.41	18.59	8.57	13.83
Chl *a* (µg L^{-1})	Mean	25.43	24.86	25.95	20.16	17.19	18.80	21.52	20.71	15.60	15.98	38.45	18.08	41.86	26.78	43.90
	Min	4.28	4.28	8.00	7.63	7.23	6.45	6.50	8.25	8.35	8.00	9.20	9.00	12.73	4.28	9.50
	Max	106.15	106.15	104.55	38.98	41.95	48.90	40.93	42.38	28.50	38.25	104.55	36.85	74.00	106.15	83.10
	Median	20.35	21.40	19.33	19.45	15.43	14.08	21.30	18.58	14.70	12.75	26.28	17.63	44.59	23.90	46.74
DOM (µg L^{-1})	Mean	370.57	383.06	359.38	245.22	165.33	254.06	231.14	238.63	271.12	281.30	491.00	345.30	484.27	721.12	688.94
	Min	83.03	83.03	83.03	125.71	83.03	199.43	139.29	83.03	84.97	170.33	110.19	88.85	255.69	284.79	552.51
	Max	959.91	959.91	959.91	467.15	317.77	350.75	335.23	393.43	628.17	515.65	959.91	944.39	959.91	959.91	950.21
	Median	282.85	257.63	300.31	227.56	154.81	234.35	245.99	232.41	236.29	248.90	397.31	309.04	432.23	769.79	648.54
Trans (%)	Mean	23.96	15.91	31.25	15.35	11.44	7.24	10.41	15.34	31.35	34.64	19.74	46.43	40.81	17.70	30.58
	Min	0.02	0.02	0.02	0.02	0.44	0.23	0.23	0.02	14.37	4.24	1.50	22.81	1.92	0.02	0.44
	Max	76.20	64.38	76.20	57.21	31.67	21.76	28.51	61.64	48.77	62.27	34.21	76.20	62.69	59.95	64.38
	Median	21.76	10.99	31.25	6.88	9.31	4.45	7.83	8.67	30.83	33.04	20.49	47.39	41.17	11.63	31.04

months for salinity (p = 0.305), chl *a* (p = 0.907), DOM (p = 0.117), or transparency (p = 0.029).

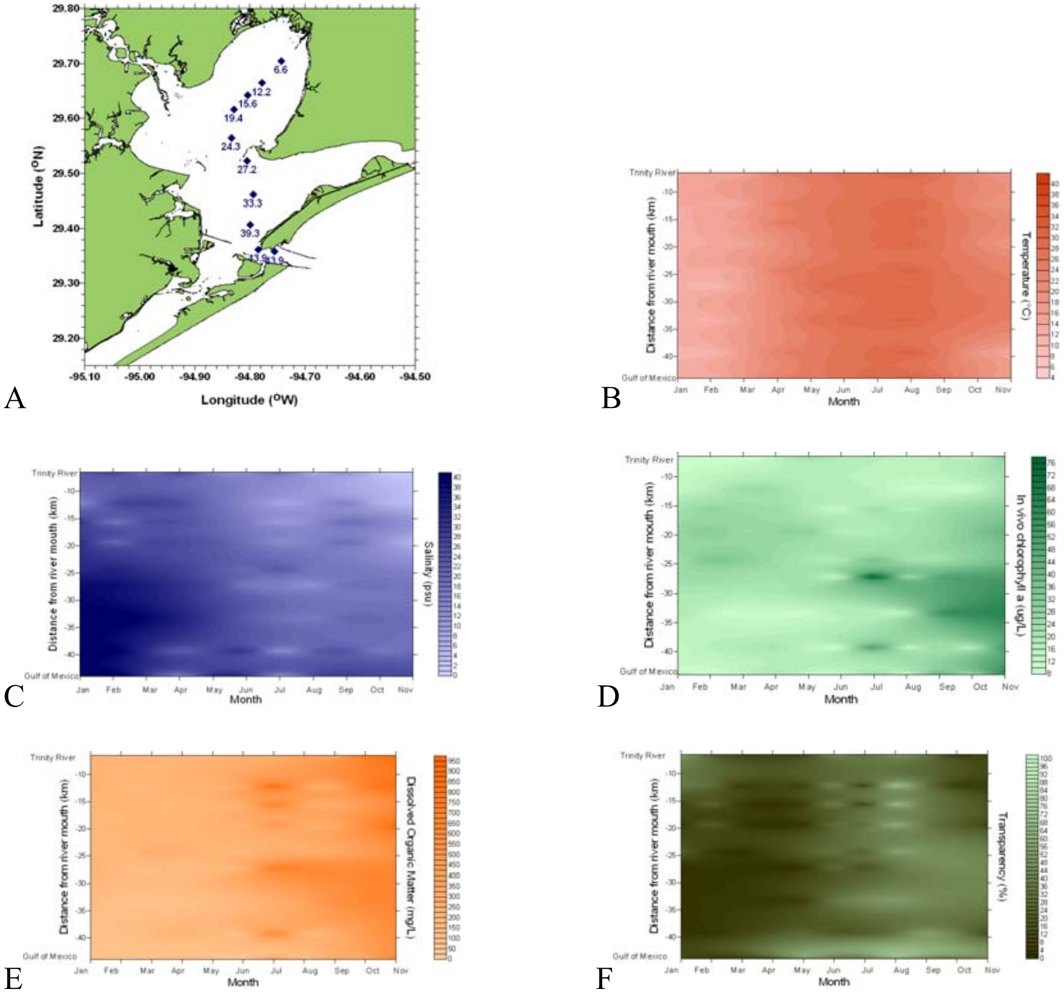


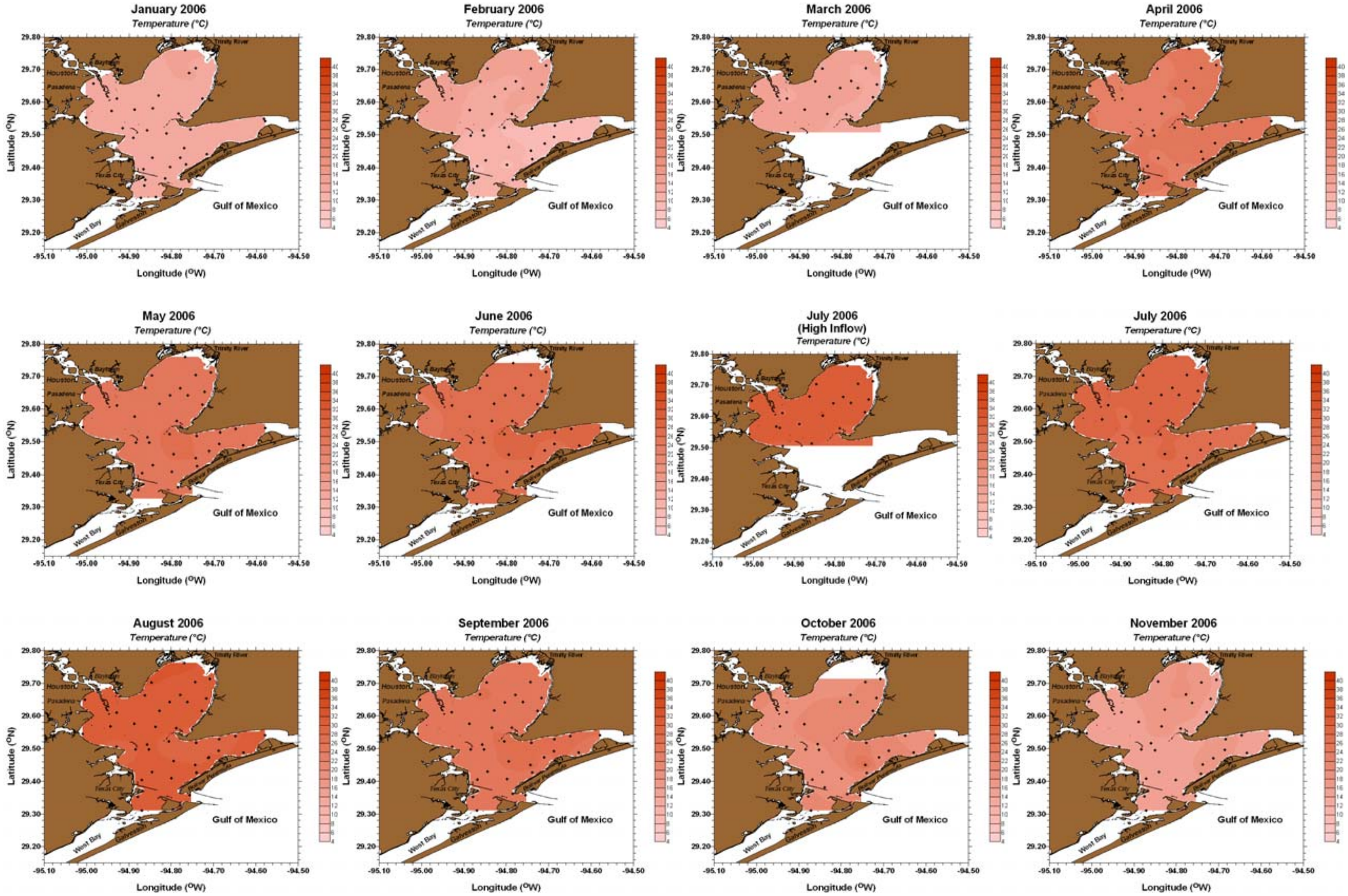
Figure 4: Dataflow data from a transect running from the mouth of the Trinity River to the Gulf of Mexico. A shows the stations in the transect. In B-F, distance from the Trinity River is shown along the primary y-axis. Month is shown on the x-axis. The parameter being mapped is shown along the secondary y-axis.

3.2.2 Spatial Trends

The water quality parameters varied spatially throughout the year as shown in Fig. 5-9. Surface water temperature was fairly uniform throughout the bay (Fig. 5). Salinity was always lower in the northeast portion of the bay near the mouth of the Trinity River

(Fig. 6). Chl *a* and DOM had fairly uniform distributions throughout Galveston Bay, but occasionally had areas in which 2-fold higher concentrations were observed, particularly in the fall (Fig. 7, 8). However, these were not associated with blooms of any specific phytoplankton (pers. obs.). Transparency levels were either fairly uniform or slightly lower in the northern portion of the bay, consistent with greater turbidity near the Trinity River (Fig. 9).

A MANOVA was performed to investigate if there were statistically significant patterns in the spatial distribution of the water quality parameters measured by the Dataflow. The dependent variables were temperature, salinity, chl *a*, DOM, and transparency. The independent variable was north or south. There was a significant difference between north and south on the combined dependent variables (Pillai's trace: $p \sim 0.000$). When the results were considered separately using a Bonferroni adjusted alpha level of 0.010, a statistically significant difference was seen between the north and south portions of the bay for salinity ($p \sim 0.000$). The average salinity in the north portion of the bay was 17.5 psu and 24.6 psu in the southern portion. None of the other variables were statistically significant (temperature: $p = 0.539$; chl *a*: $p = 0.045$; DOM: $p = 0.067$; transparency: $p = 0.337$).


January 2006

February 2006

March 2006

April 2006

May 2006

June 2006

July 2006
(High Inflow)

July 2006

August 2006

September 2006

October 2006

November 2006

Fig. 5: Monthly spatial distribution of temperature in Galveston Bay.

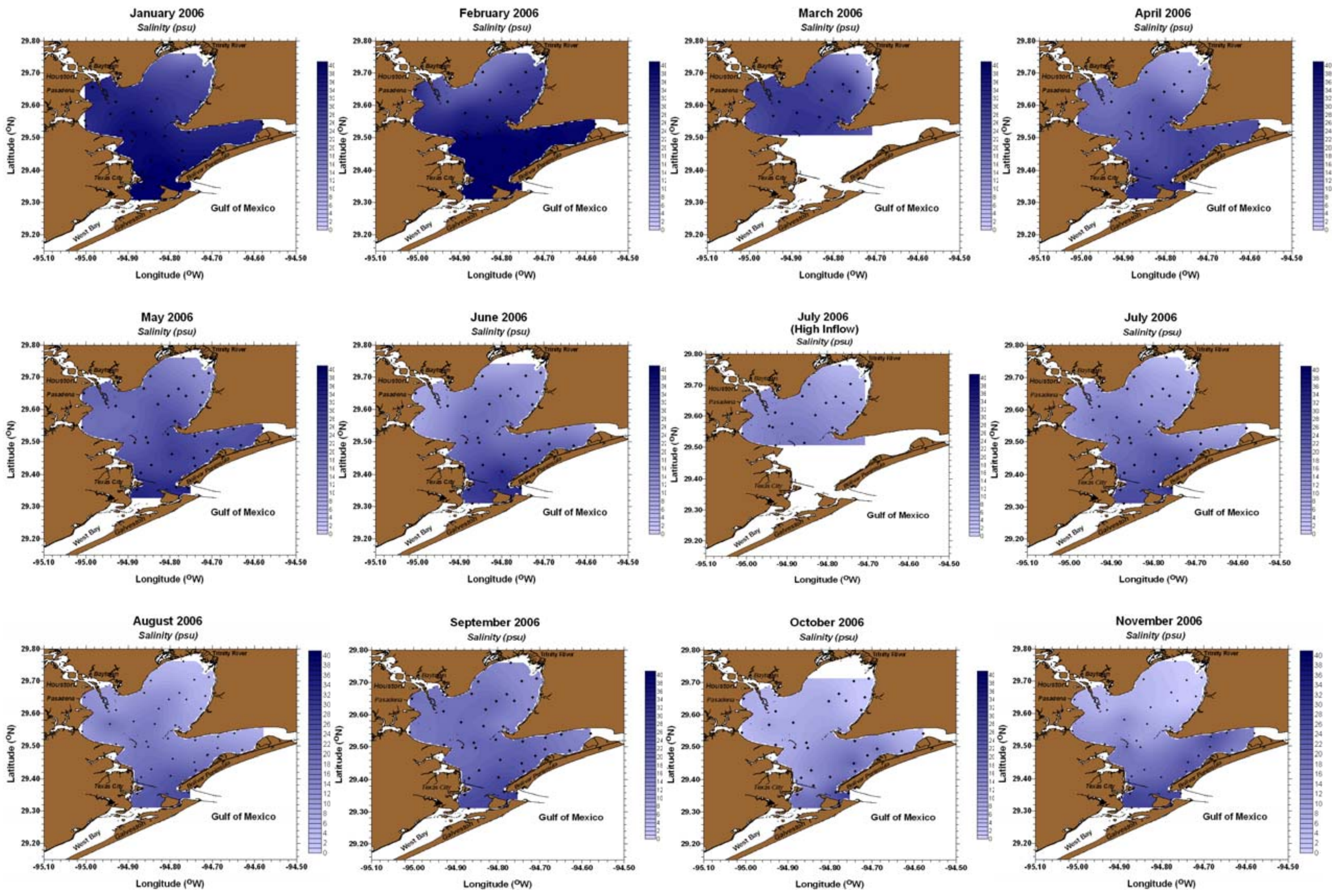
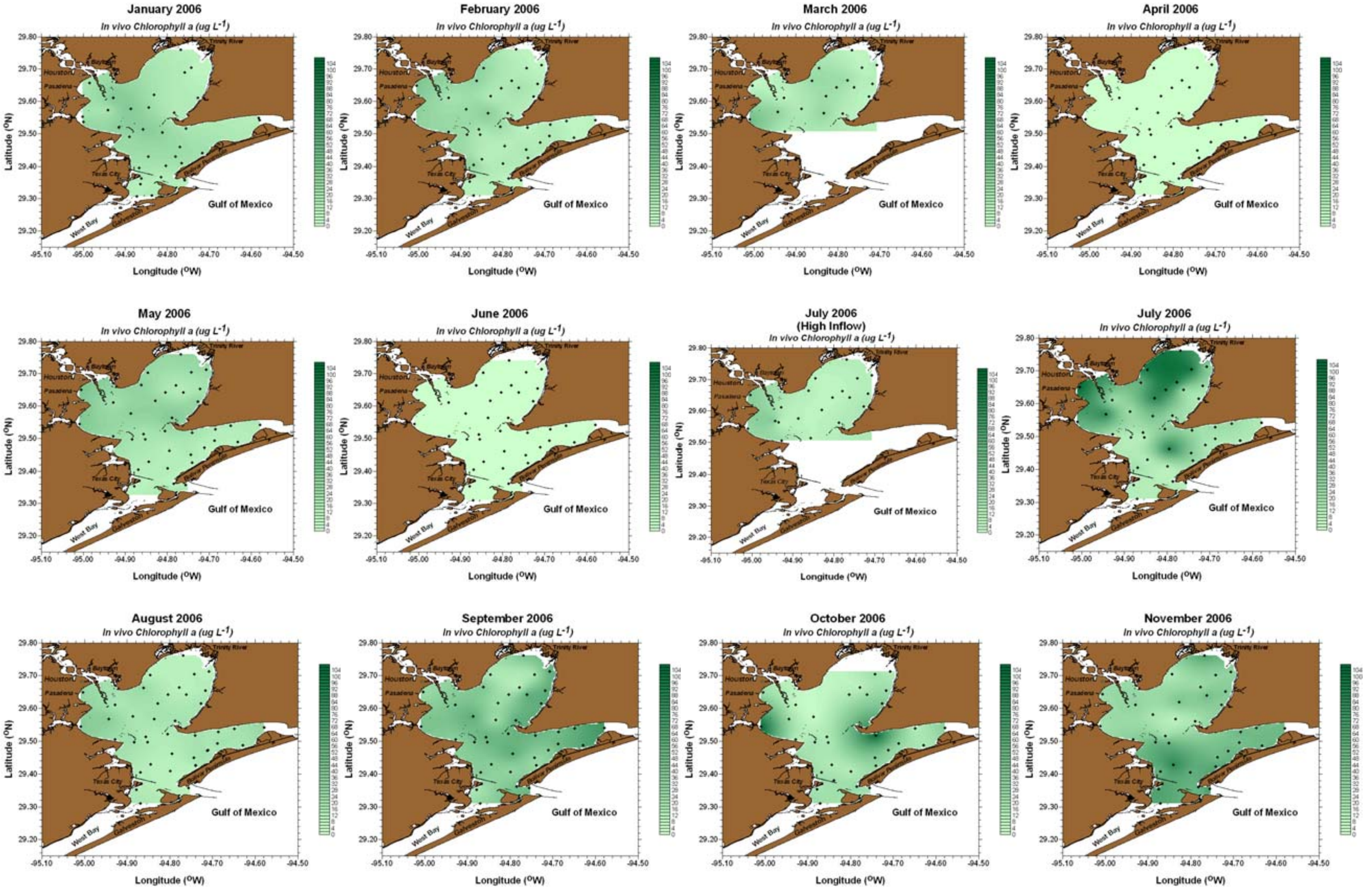

January 2006
February 2006
March 2006
April 2006
May 2006
June 2006
July 2006 (High Inflow)
July 2006
August 2006
September 2006
October 2006
November 2006

Fig. 6: Monthly spatial distribution of salinity in Galveston Bay.


January 2006

February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

August 2006

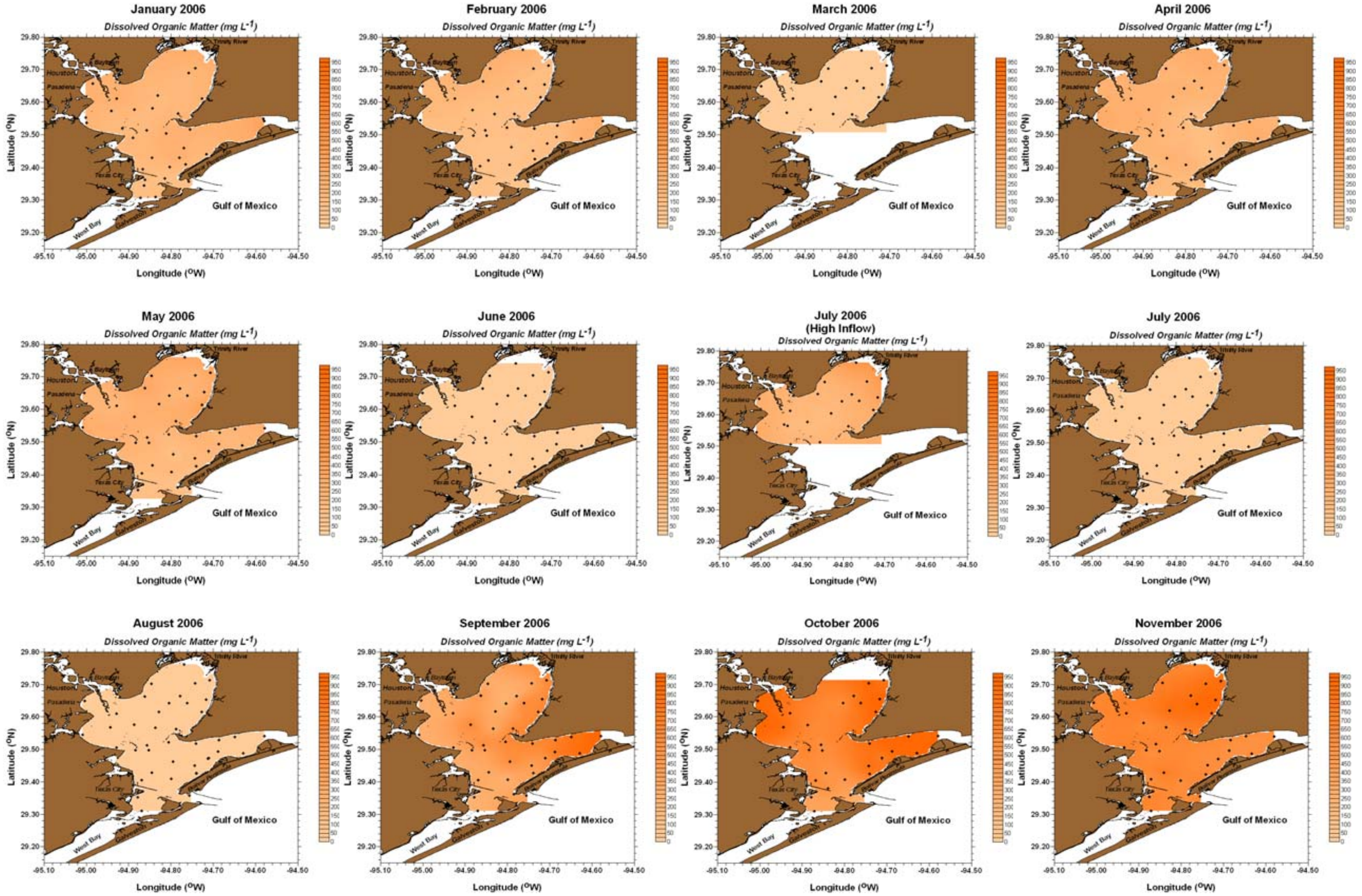
September 2006

October 2006

November 2006

In vivo Chlorophyll *a* (ug L^{-1})

Fig. 7: Monthly spatial distribution of chl *a* in Galveston Bay.


January 2006

February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

August 2006

September 2006

October 2006

November 2006

Fig. 8: Monthly spatial distribution of DOM in Galveston Bay.

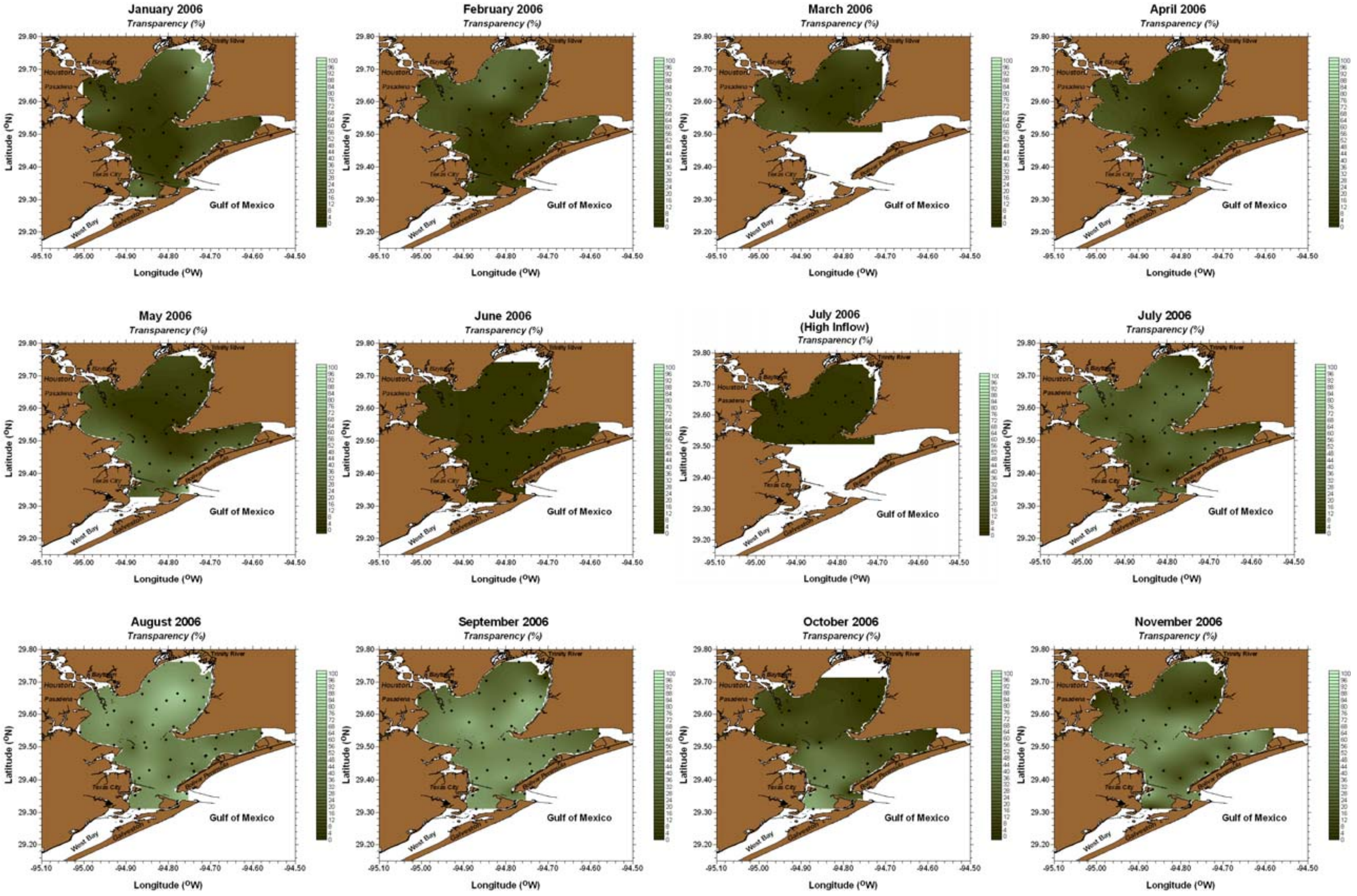


Fig. 9: Monthly spatial distribution of transparency in Galveston Bay.

3.3 Phytoplankton Community – PhytoPAM Data

3.3.1 Temporal Trends

The mean Fm for the phytoplankton community during 2006 was 1,991 rel. units, with a 5.5- fold range of 934-5,259 rel. units over the year (Table 2). The wet months had a lower mean (1,890 rel. units) and a smaller range (1,055-4,839 rel. units) than the dry months (2,076 rel. units, 934-5,259 rel. units, respectively). *Rel*ETR values for the year had a 24-fold range from 14.8-362 µmol electrons m^{-2} s^{-1} with a mean value of 132 µmol electrons m^{-2} s^{-1} (Table 2). *Rel*ETR values during the wet months ranged from 14.8-362 µmol electrons m^{-2} s^{-1}, with a mean of 127 µmol electrons m^{-2} s^{-1}. During the dry months the *rel*ETR ranged from 45.5-333 µmol electrons m^{-2} s^{-1}, with a mean value of 136 µmol electrons m^{-2} s^{-1}. Although *rel*ETR was variable between stations and between months, on average, there was no significant difference between wet and dry months. The mean alpha value during the year was 0.18 µmol electrons µmol $photons^{-1}$ m^{-2} s^{-1}, with a 7.5-fold range from 0.03-0.23 µmol electrons µmol $photons^{-1}$ m^{-2} s^{-1} (Table 2). The mean was significantly different between dry months (mean = 0.18 µmol electrons µmol $photons^{-1}$ m^{-2} s^{-1}) and wet months (mean = 0.17 µmol electrons µmol $photons^{-1}$ m^{-2} s^{-1}), but the range was greater in the wet months (0.03-0.23 µmol electrons µmol $photons^{-1}$ m^{-2} s^{-1}) than in the dry months (0.12-0.23 µmol electrons µmol $photons^{-1}$ m^{-2} s^{-1}). The annual yield covered a 17-fold range of 0.05-0.85 rel. units (Table 2). While the mean did not vary (0.42 rel. units), the range for the wet months (0.05-0.85 rel. units) was greater than that measured for the dry months (0.23-0.80 rel. units).

Table 2: PhytoPAM data for the phytoplankton community during 2006. Wet indicates the period of high inflow from Oct – Apr. Dry indicates the period of low inflow from May – Sep. Jul (H) is the sampling survey conducted after a large rain event during mid-July.

		Year	Wet	Dry	Feb	Mar	Apr	May	Jun	Jul (H)	Jul	Aug	Sep	Oct	Nov
Fm (rel. units)	Mean	1991	1890	2076	2226	1850	2007	2409	2135	1820	1998	1988	2109	1619	1746
	Min	934	1055	934	1447	1297	1166	1600	1628	934	1375	1365	1319	1055	1308
	Max	5259	4869	5259	3145	2769	4869	5259	2873	2470	2506	2673	3007	2497	2383
	Median	1991	1853	2068	2217	1853	1946	2340	2096	1863	2040	1991	2101	1524	1717
ETR (µmol electrons m^{-2} s^{-1})	Mean	132.16	127.00	136.15	141.73	137.40	136.57	134.40	141.17	144.06	146.62	129.32	125.26	96.36	127.21
	Min	14.80	14.80	45.50	50.70	85.80	89.70	68.40	58.10	63.80	76.10	45.50	65.10	14.80	63.30
	Max	362.40	362.40	332.70	362.40	178.80	236.60	294.30	282.70	332.70	220.60	244.40	213.00	176.70	242.40
	Median	128.80	120.95	134.00	155.00	146.60	124.50	121.90	130.55	123.85	146.60	138.00	131.05	96.35	122.85
Alpha (µmol electrons µmol photons^{-1} m^{-2} s^{-1})	Mean	0.179	0.172	0.184	0.198	0.172	0.188	0.185	0.185	0.176	0.187	0.190	0.180	0.135	0.165
	Min	0.030	0.030	0.117	0.144	0.141	0.133	0.152	0.117	0.128	0.121	0.119	0.133	0.030	0.105
	Max	0.233	0.232	0.233	0.231	0.196	0.232	0.218	0.222	0.218	0.223	0.233	0.216	0.221	0.209
	Median	0.185	0.180	0.187	0.199	0.173	0.189	0.184	0.189	0.186	0.189	0.197	0.187	0.140	0.173
Yield (rel. units)	Mean	0.433	0.421	0.442	0.498	0.450	0.510	0.510	0.494	0.406	0.415	0.415	0.393	0.295	0.357
	Min	0.050	0.050	0.230	0.300	0.380	0.330	0.050	0.290	0.230	0.280	0.260	0.270	0.050	0.210
	Max	0.850	0.850	0.800	0.610	0.540	0.850	0.800	0.680	0.570	0.510	0.520	0.500	0.480	0.470
	Median	0.430	0.420	0.440	0.520	0.445	0.510	0.490	0.500	0.410	0.420	0.430	0.405	0.300	0.370

A MANOVA was performed to investigate temporal differences in the phytoplankton characteristics measured by the PhytoPAM. The dependent variables were Fm, *rel*ETR, alpha, and yield. The independent variable was wet or dry month. There was a significant difference between wet and dry months on the combined dependent variables (Pillai's trace: $p \sim 0.000$). When the results were considered separately using a Bonferroni adjusted alpha level of 0.0125, a statistically significant difference was seen between wet and dry months for biomass (Fm; $p \sim 0.000$), photosynthetic efficiency (alpha; $p \sim 0.000$), and photosynthetic potential (yield; $p = 0.002$). There was not a significant difference in *rel*ETR ($p = 0.083$).

The transect stations (in a line from the Trinity River to the Gulf of Mexico) shown in Fig. 4A were also used to map PhytoPAM variables across Galveston Bay. Biomass (Fm) did not show a trend with freshwater inflow events (Fig. 10A). Maximum photosynthetic rate (*rel*ETR), photosynthetic efficiency (alpha), and photosynthetic potential (yield) values were fairly consistent throughout the year, with no real change across Galveston Bay based on freshwater inflows (Fig. 10B, 10C, 10D).

The PhytoPAM channels can also be used to distinguish between 3 basic groups of phytoplankton as described above (section *2.3.2*): green algae (chlorophytes and prasinophytes), cyanobacteria, and diatoms & dinoflagellates. Green algae were rarely observed in Galveston Bay and therefore were not included in further analyses. Dominating were the cyanobacteria and diatoms/dinoflagellates, the latter of which were grouped (Fig. 10E). Diatoms/dinoflagellates were present in higher concentrations during the winter while cyanobacteria were present in higher concentrations during the summer. Both groups were present in high concentrations from mid-April through May.

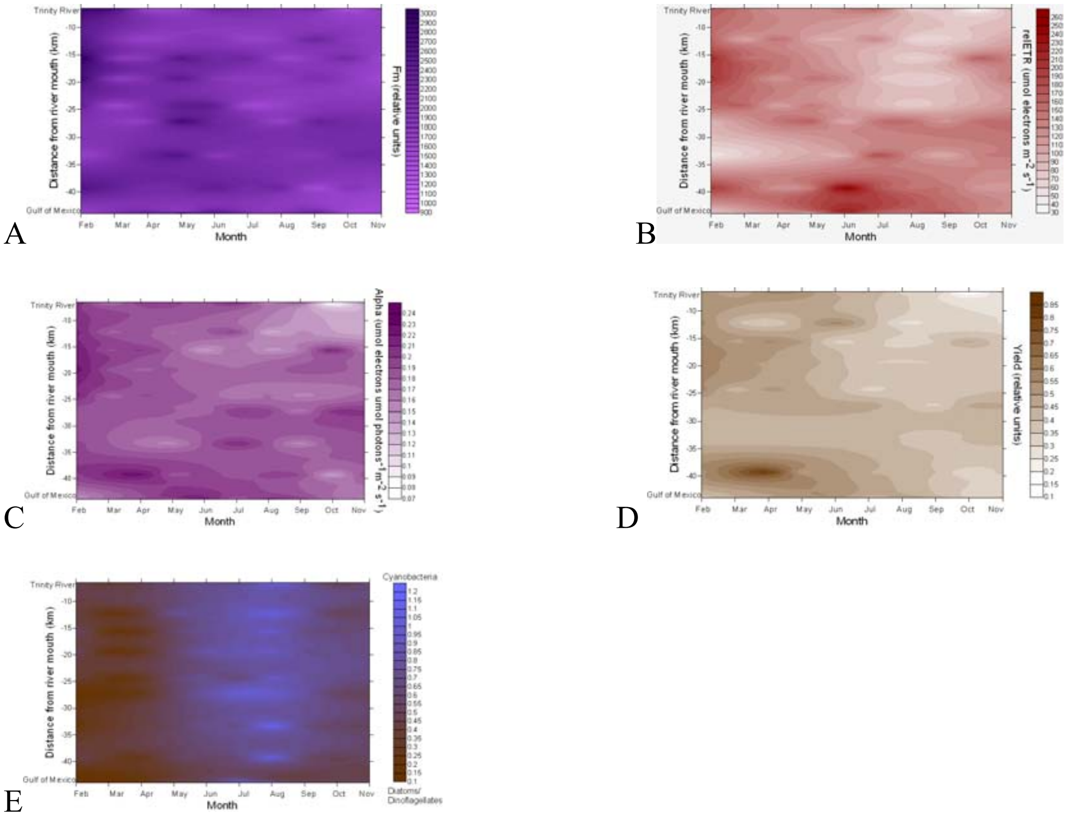
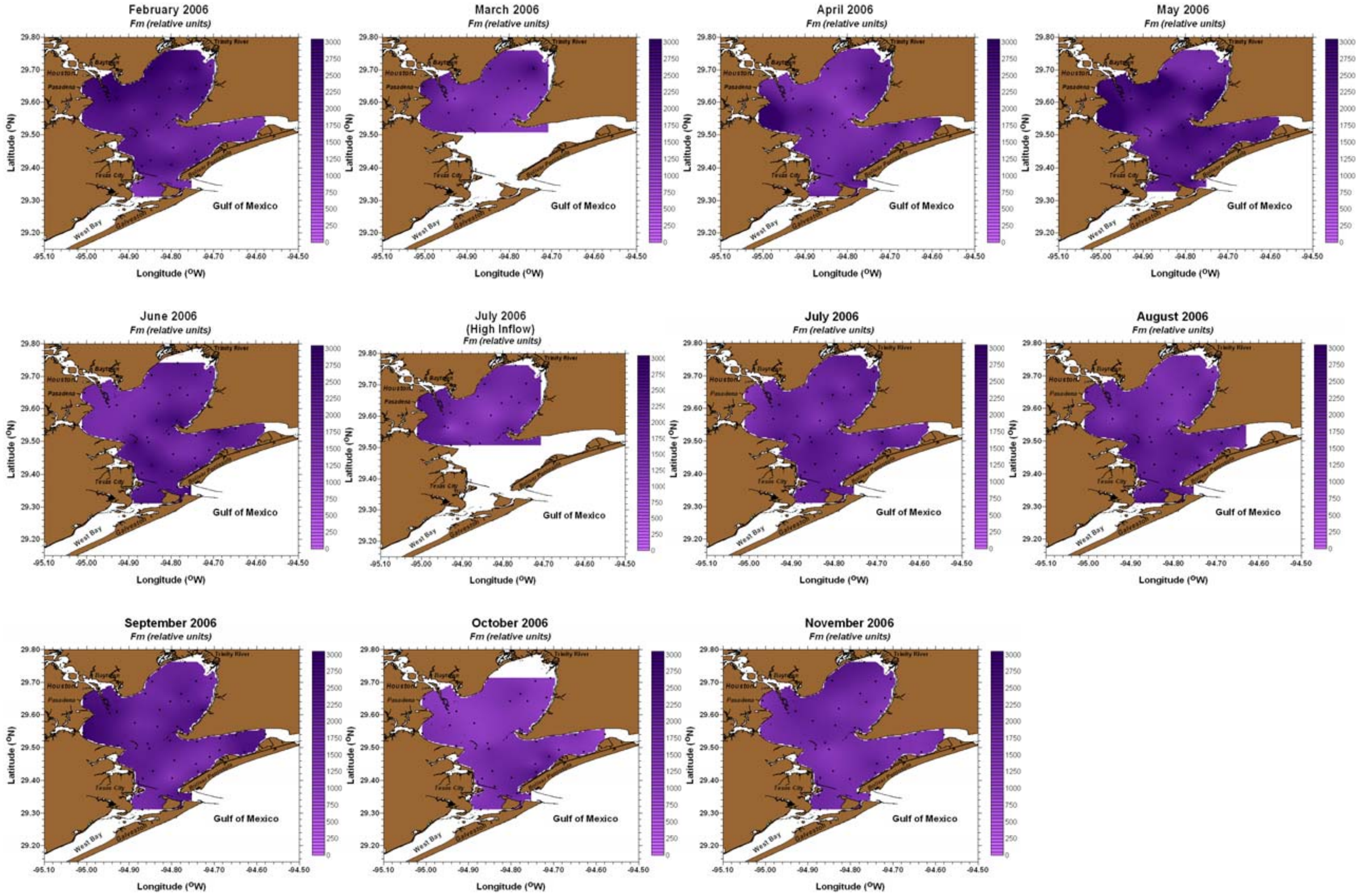


Fig. 10: PhytoPAM data for phytoplankton community from a transect running from the mouth of the Trinity River to the Gulf of Mexico. Distance from the Trinity River is shown along the primary y-axis. Month is shown on the x-axis. The parameter being mapped is shown along the secondary y-axis. A: Fm, B: *rel*ETR, C: alpha, D: yield, E: distribution of cyanobacteria and diatoms/dinoflagellates.

3.3.2 Spatial Trends

Phytoplankton biomass (Fm; Fig. 11) was found to be fairly uniform throughout the year. *Rel*ETR was also fairly uniform, but occasionally there were areas with 1.5-fold higher photosynthetic rates (Fig. 12). Photosynthetic efficiency (alpha) was slightly higher in the southern bay, but was otherwise quite uniform throughout the bay (Fig. 13). Yield values were also fairly uniform with occasional patches of 0.5-fold higher photosynthetic potential observed (Fig. 14) in parts of the bay.

A MANOVA was performed to investigate spatial differences in the phytoplankton characteristics measured by the PhytoPAM. The dependent variables


February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

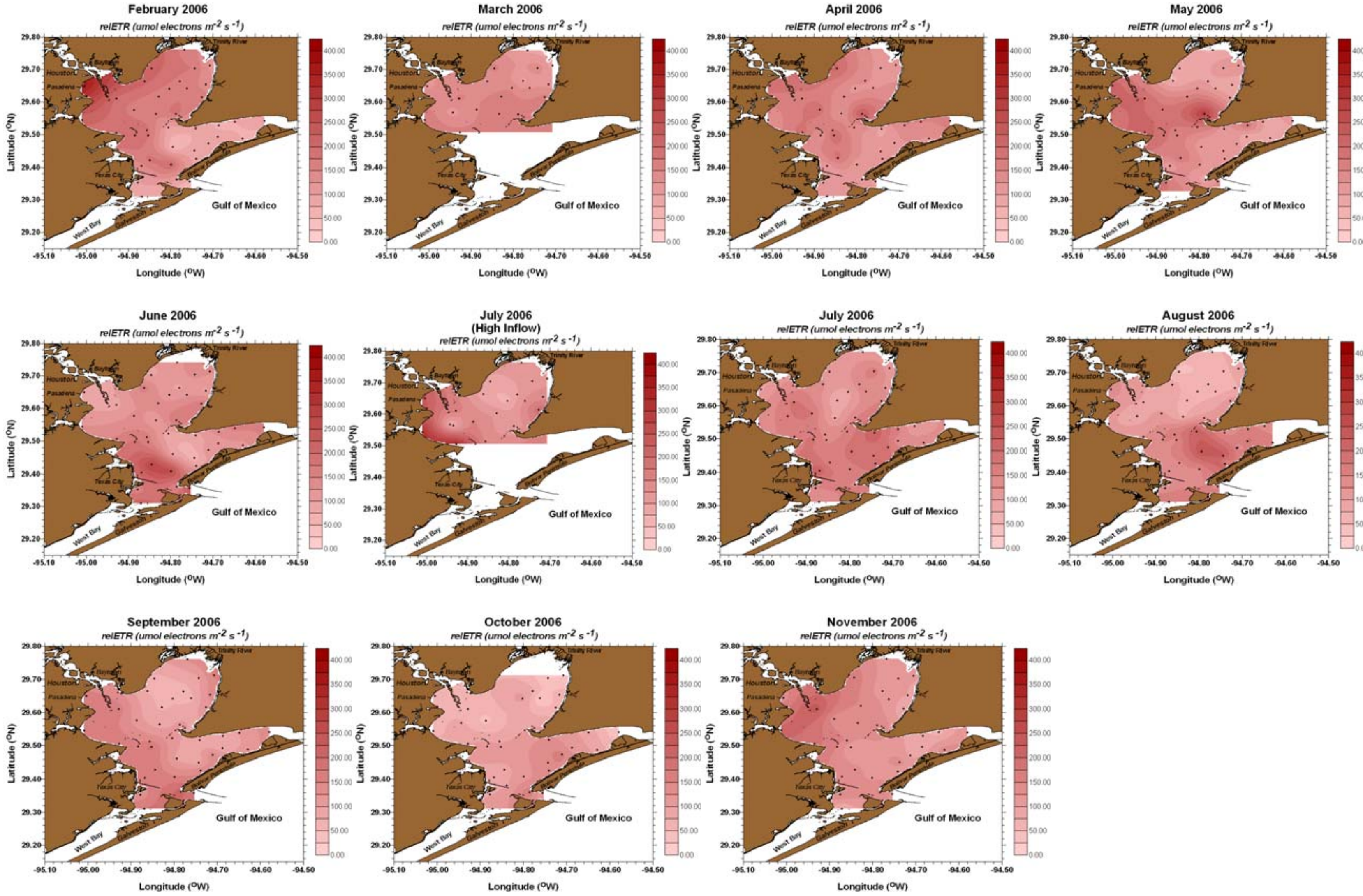
August 2006

September 2006

October 2006

November 2006

Fig. 11: Monthly spatial distribution of biomass (Fm) in Galveston Bay.



February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

August 2006

September 2006

October 2006

November 2006

Fig. 12: Monthly spatial distribution of *rel*ETR in Galveston Bay.

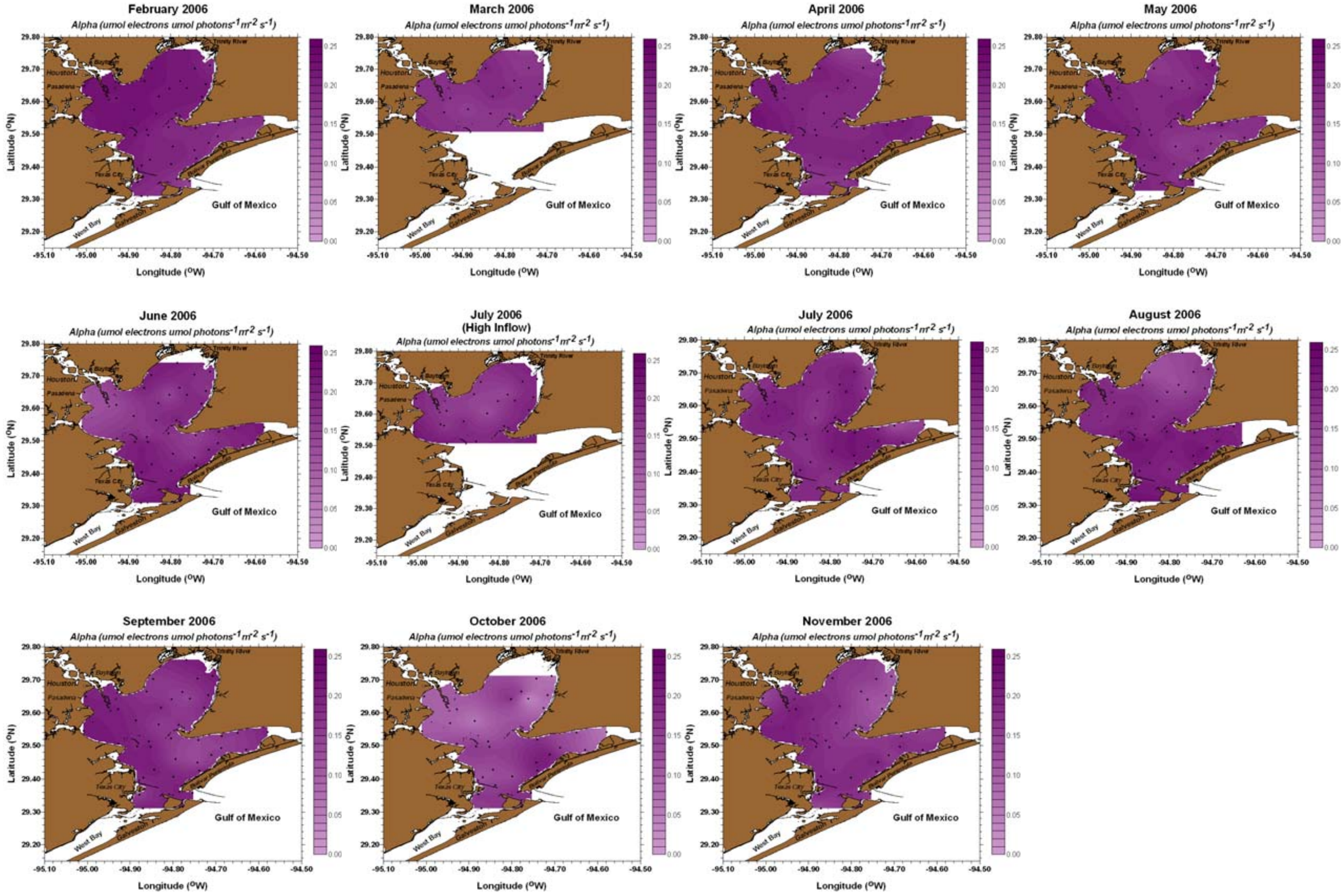
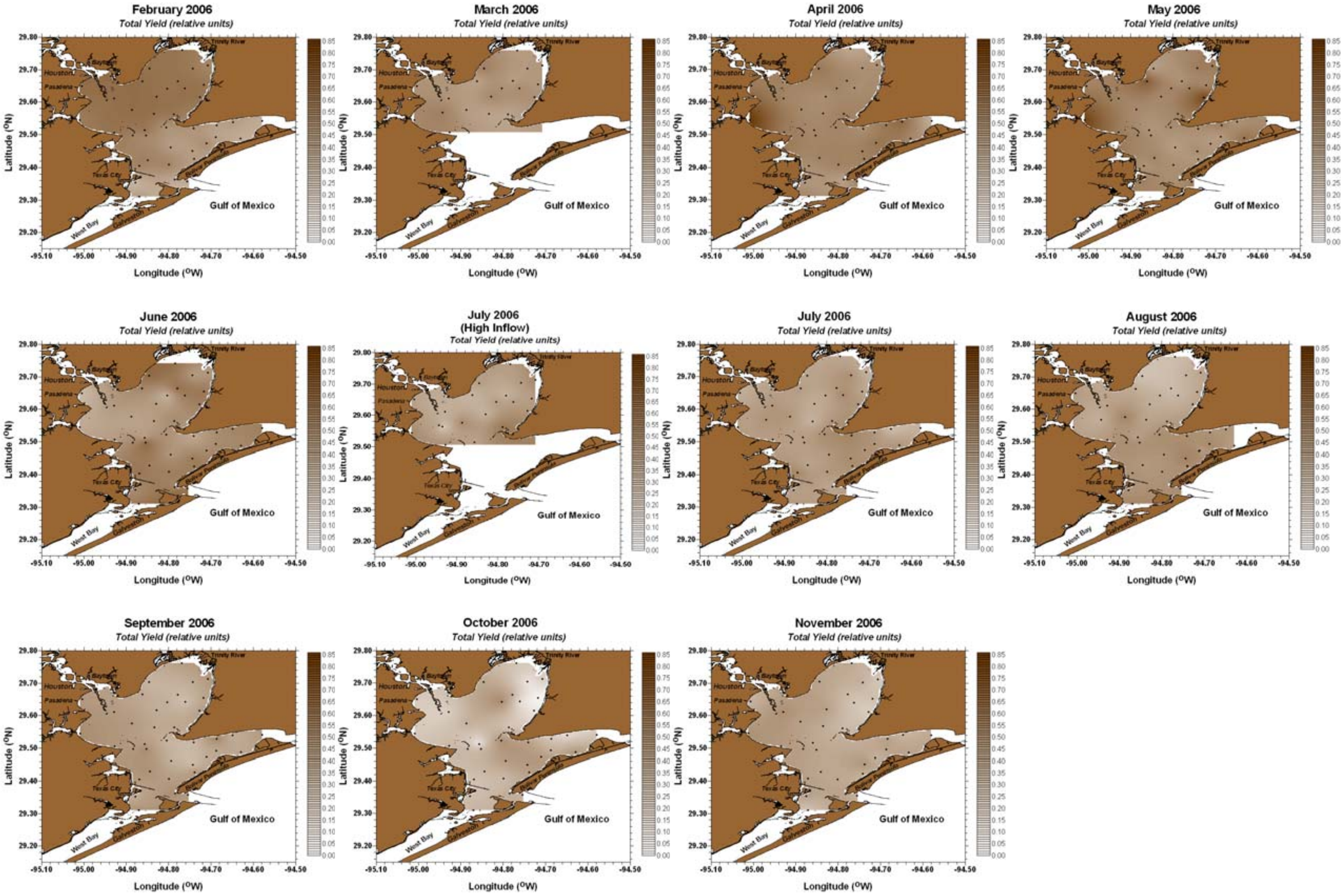


Fig. 13: Monthly spatial distribution of alpha in Galveston Bay.


February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

August 2006

September 2006

October 2006

November 2006

Fig. 14: Monthly spatial distribution of yield in Galveston Bay.

were Fm, *rel*ETR, alpha, and yield. The independent variable was north or south portion of the bay. There was a significant difference between north and south on the combined dependent variables (Pillai's trace: p = 0.003). When the results were considered separately using a Bonferroni adjusted alpha level of 0.0125, a statistically significant difference was seen between the north and south portions of the bay for alpha (p = 0.003). There was not a significant difference between the north and south for Fm (p = 0.704), *rel*ETR (p = 0.158), and yield (p = 0.151), consistent with the lack of distinct patterns in the spatial maps.

3.3.3 Phytoplankton Community Composition

The PhytoPAM was used to determine the physiological status of the entire phytoplankton community, but also that of various groups (cyanobacteria and diatoms/dinoflagellates) within the community. Spatial distributions of taxon-specific biomass (Fm) values were similar between the groups (Fig. 15, 18), as were spatial distributions of *rel*ETR (Fig. 16, 19) and yield (Fig. 17, 20). Independent samples t-tests were used to compare the PhytoPAM parameters between wet and dry months (ex. Fm of cyanobacteria in wet vs. dry months). The biomass (Fm) of cyanobacteria was significantly higher during the dry months than the wet months (p ~ 0.000), while the opposite was observed for the diatoms/dinoflagellates (Figs. 15, 18). The biomass of diatoms/dinoflagellates was significantly higher during the wet months than the dry months (p ~ 0.000). The yield measured for diatoms/dinoflagellates was significantly higher during the dry months (p ~ 0.000) and the *rel*ETR of the cyanobacteria was significantly higher during the wet months (p = 0.003). There was not a statistically significant difference in yield of cyanobacteria ($p = 0.486$) or *rel*ETR of diatoms/ dinoflagellates ($p = 0.130$) between wet and dry months.

An independent sample t-test was also used to compare the biomass (Fm) of cyanobacteria and diatoms/dinoflagellates during both wet and dry months (ex. Fm of cyanobacteria for wet months vs. Fm of diatoms/dinoflagellates for wet months). There was a significant difference in biomass ($p \sim 0.000$) during the wet months for cyanobacteria (mean = 221 rel. units) and diatoms/dinoflagellates (mean = 372 rel. units). There was also a significant difference ($p \sim 0.000$) during the dry months between cyanobacteria (mean = 213 rel. units) and diatoms/dinoflagellates (mean = 316 rel. units). An independent sample t-test conducted to compare the yields of the two groups showed a significant difference ($p \sim 0.000$) in means during the wet months (cyanobacteria = 0.469 rel. units; diatoms/ dinoflagellates = 0.412 rel. units) but not during the dry months ($p = 0.705$). An independent samples t-test to compare the *rel*ETR values indicated a significant difference ($p \sim 0.000$) between cyanobacteria (mean = 177 µmol electrons m^{-2} s^{-1}) and diatoms/dinoflagellates (mean = 136 µmol electrons m^{-2} s^{-1}) during the wet months. There was also a significant difference ($p = 0.002$) between the *rel*ETR means during the dry months (cyanobacteria = 160 µmol electrons m^{-2} s^{-1}; diatoms/ dinoflagellates = 144 µmol electrons m^{-2} s^{-1}). The only parameter that was not statistically different between the groups was photosynthetic potential (yield) during the dry months.

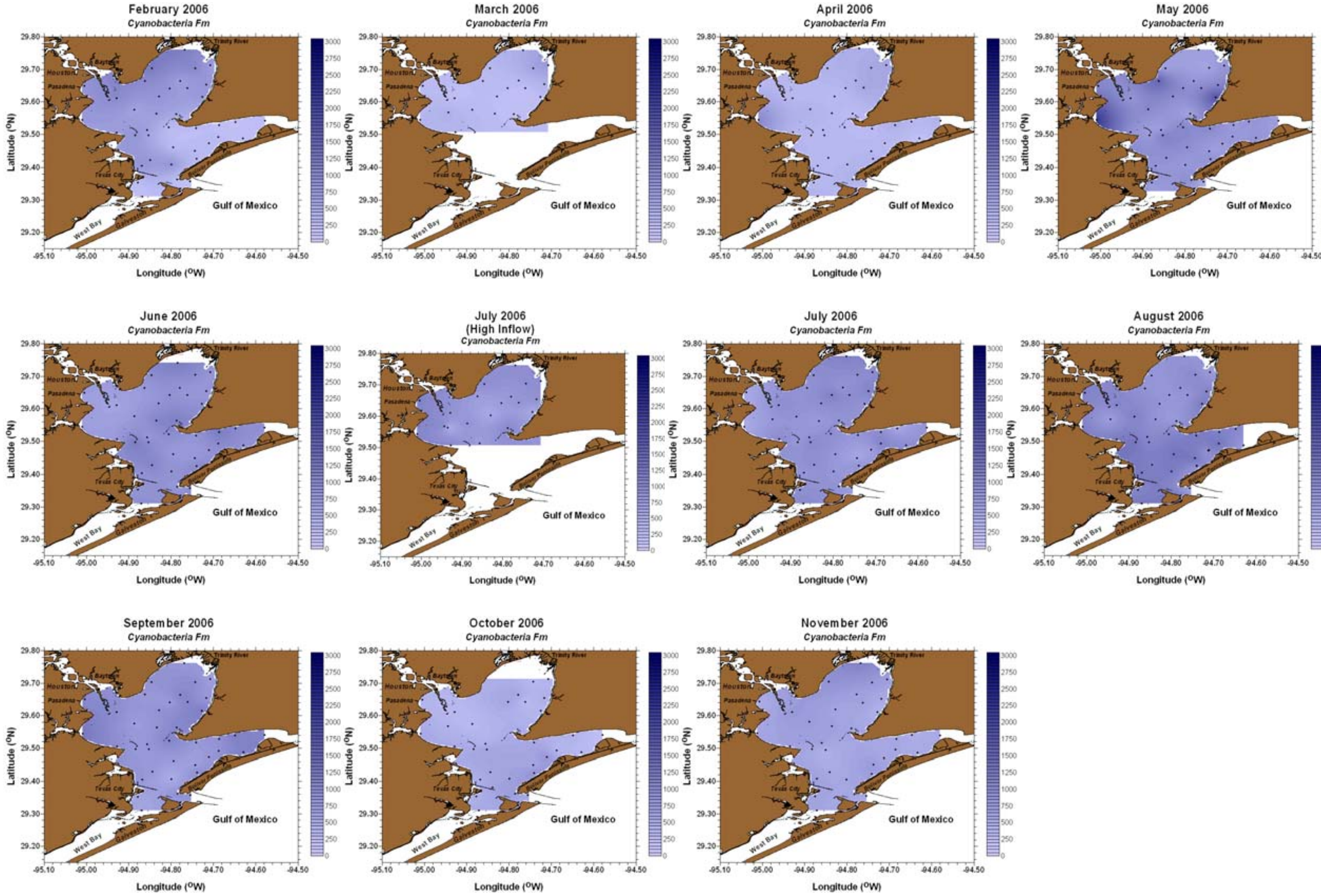
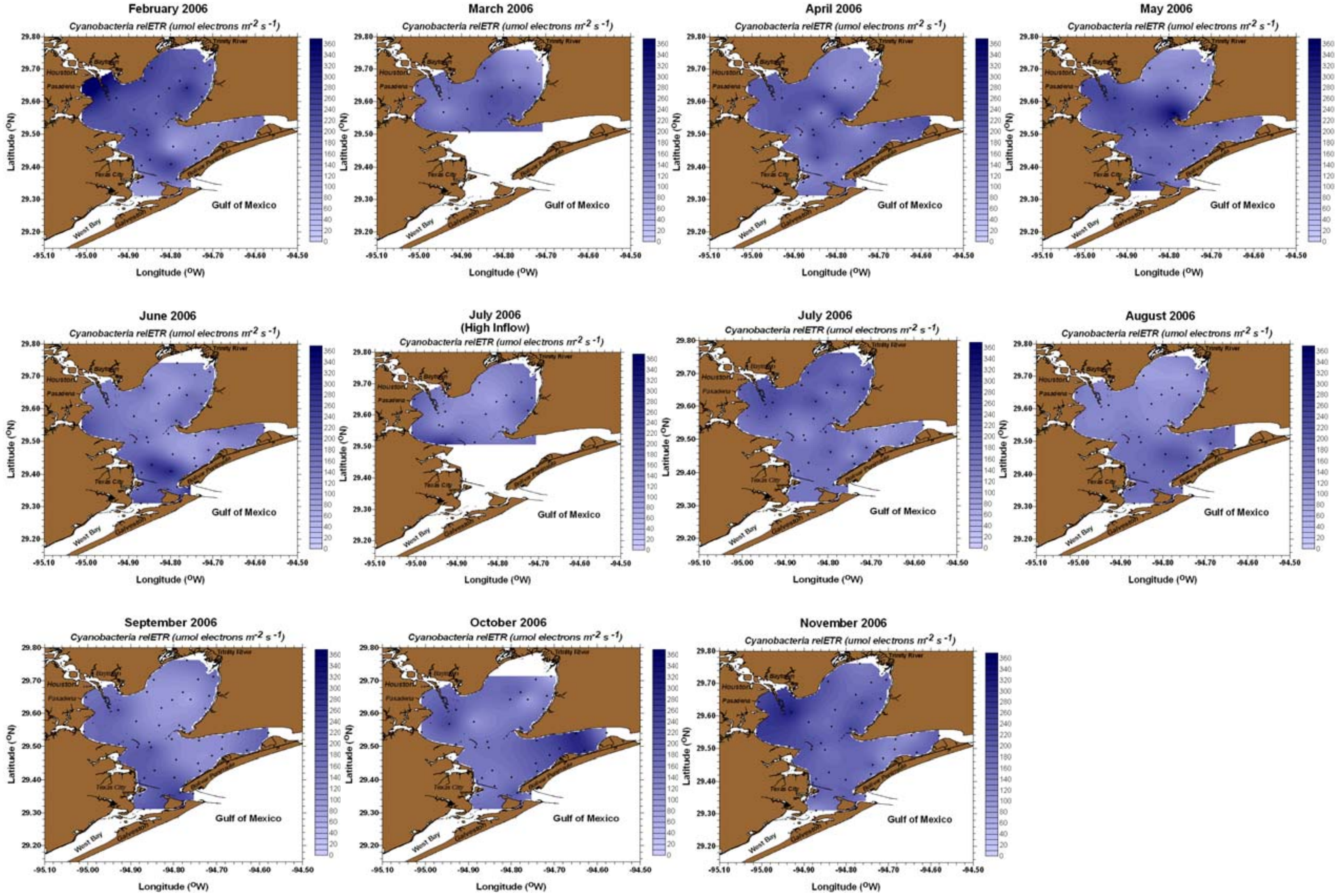


Fig. 15: Monthly spatial distribution of biomass (Fm) of cyanobacteria in Galveston Bay.


February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

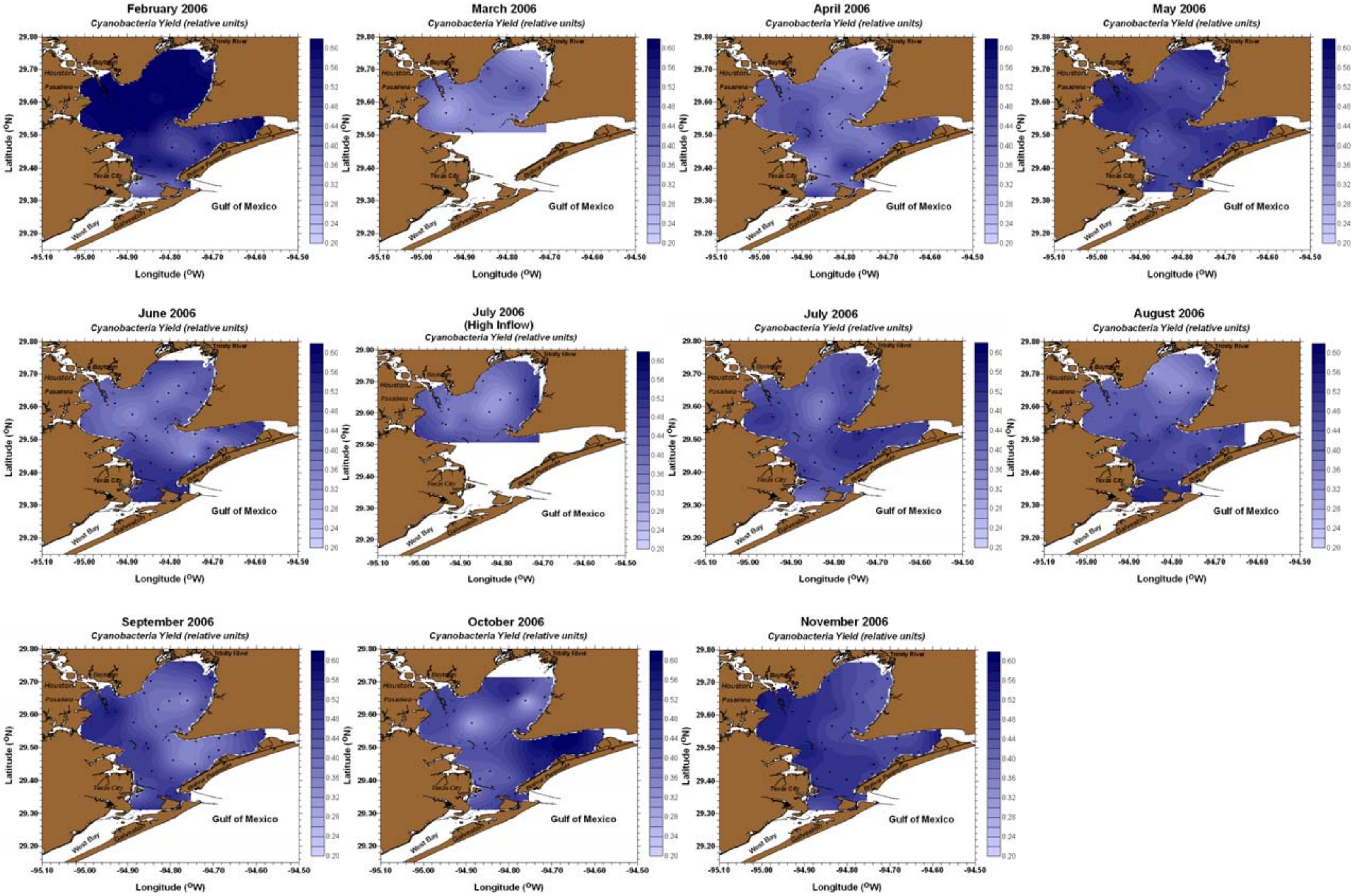
August 2006

September 2006

October 2006

November 2006

Fig. 16: Monthly spatial distribution of *rel*ETR of cyanobacteria in Galveston Bay.


February 2006

March 2006

April 2006

May 2006

June 2006

July 2006 (High Inflow)

July 2006

August 2006

September 2006

October 2006

November 2006

Fig. 17: Monthly spatial distribution of the yield of cyanobacteria in Galveston Bay.

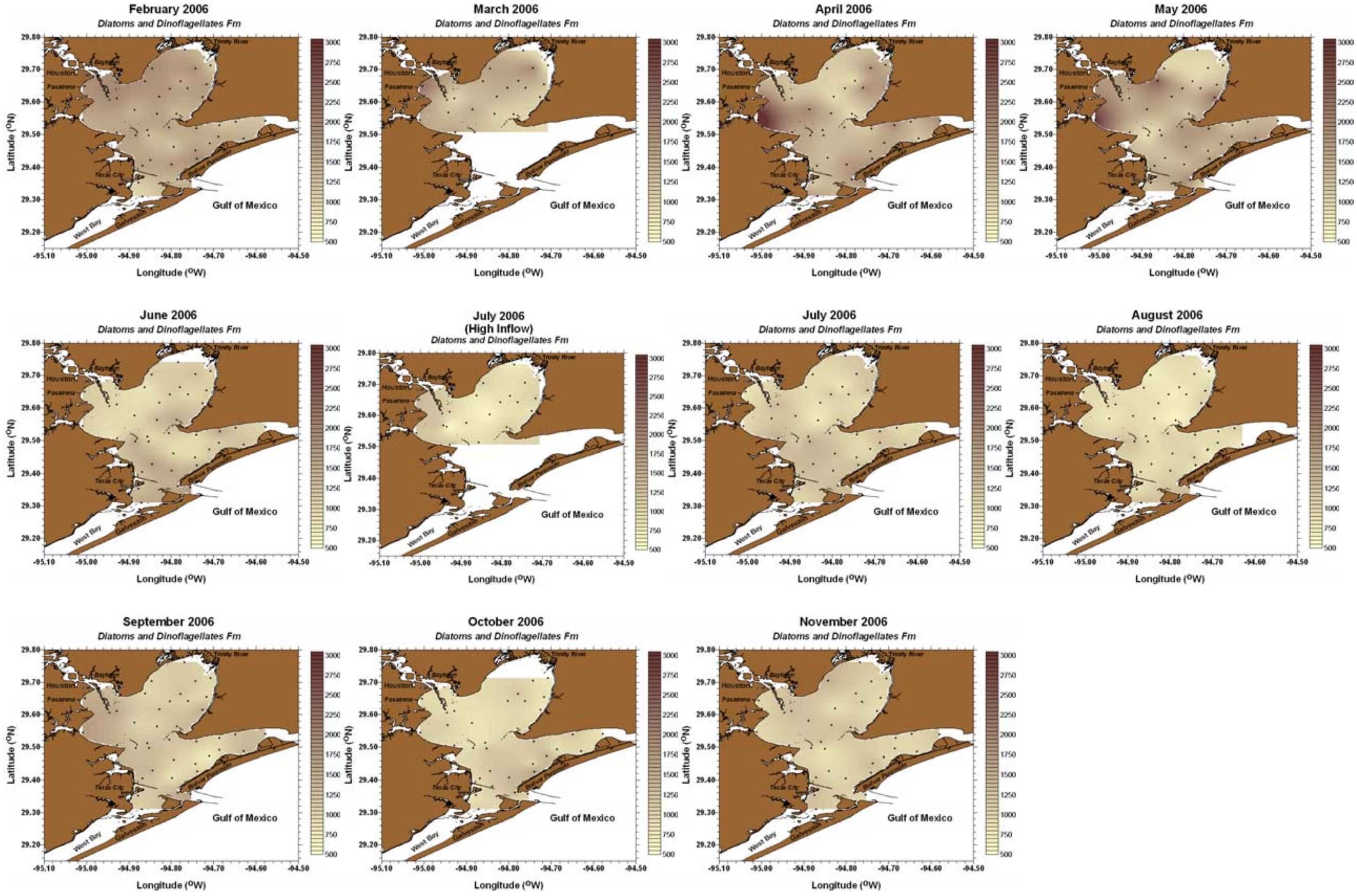

February 2006
March 2006
April 2006
May 2006
June 2006
July 2006 (High Inflow)
July 2006
August 2006
September 2006
October 2006
November 2006

Fig. 18: Monthly spatial distribution of biomass (Fm) of diatoms and dinoflagellates in Galveston Bay.

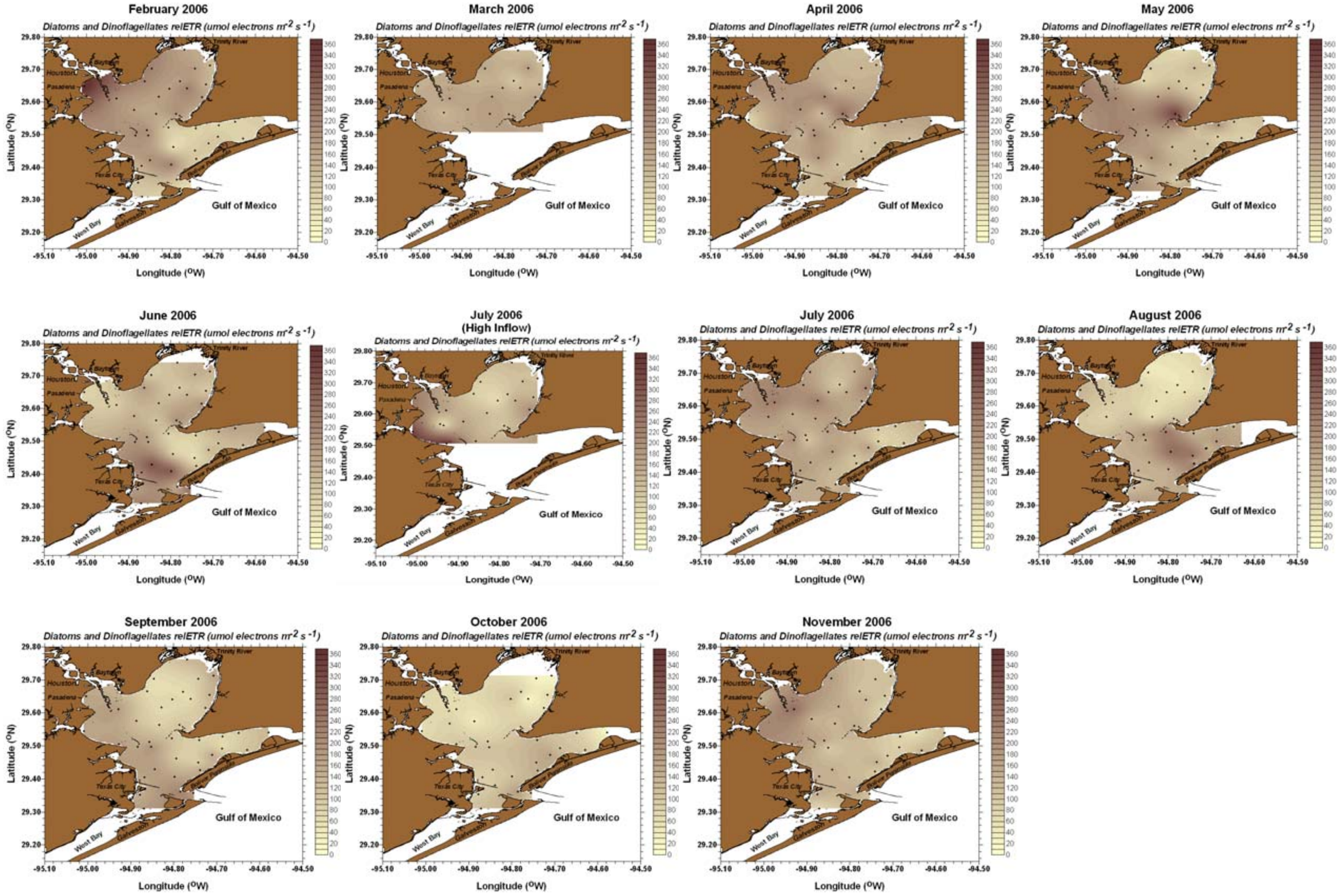


Fig 19: Monthly spatial distribution of *rel*ETR of diatoms and dinoflagellates in Galveston Bay.

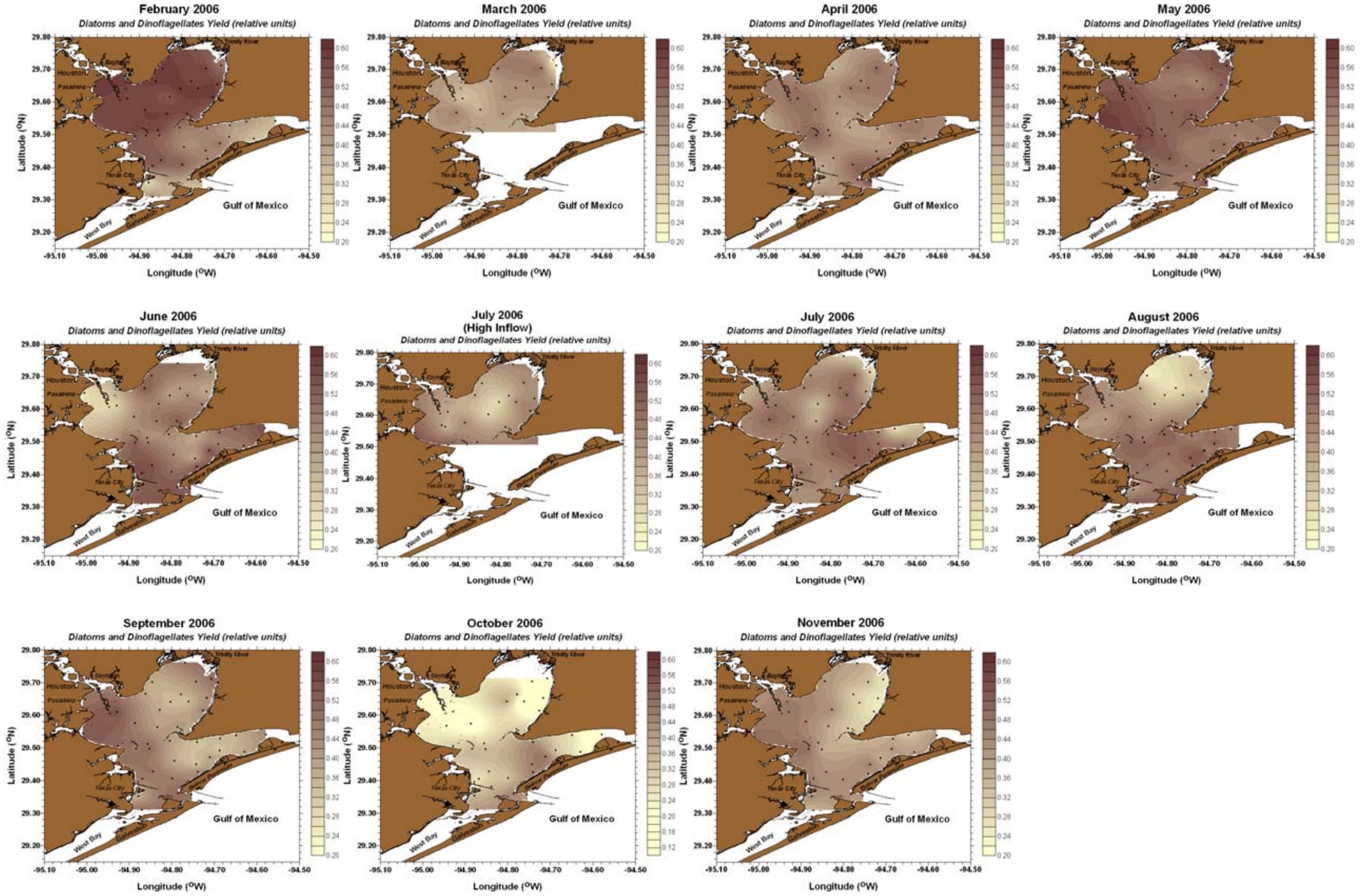


Fig 20: Monthly spatial distribution of the yield of diatoms and dinoflagellates in Galveston Bay.

3.4 Resource Limitation Assays

RLAs were performed at 8 sites throughout the bay during the late spring/summer months of 2006 to determine if addition of nutrients stimulated phytoplankton growth. An increase in chl *a* concentrations in treatments relative to the controls was used to indicate previous nutrient limitation of the phytoplankton community. Chl *a* concentrations in all treatments containing N (All, N, NP, NSi; Fig. 21) increased at all stations compared to treatments not containing N (Control, P, Si, PSi), indicating N was the principle limiting nutrient in Galveston Bay.

Offatt's Bayou (off West Bay) showed an increase in treatments containing N starting at 20 hours after nutrient additions and continued to increase until about 68 hours in the RLA, after which chl *a* concentrations started to decrease (Fig. 21A). Christmas Bay (southwest of West Bay) treatments increased chl *a* concentrations throughout the duration of the RLA in all treatments with N additions (Fig. 21B); there was little or no change in other treatments. The Texas City Dike station (northeast of West Bay; Fig. 21C) showed increased in chl *a* levels in treatments containing N up to 46 hours; chl *a* concentrations then decreased to the same levels as the treatments not containing N by 204 hours indicating a crash or dying phytoplankton community. At these three stations the phytoplankton responded rapidly (within 20-40 hrs.) to nutrient addition. By contrast, chl *a* concentrations in treatments containing N at the Smith Point (southern Trinity Bay; Fig. 21D) and Eckert's Bayou (West Bay; Fig. 21E) stations did not start to increase until after approximately 40 hours into the RLA, with levels continuing to rise until the end of the RLA. N treatments in Trinity Bay (Fig. 21F) did not show increases in chl *a* concentrations until approximately 80 hours into the RLA. In the Houston Ship Channel samples (northeast portion of the bay), chl *a* concentrations started higher and remained higher than those at the other stations (Fig. 21G). Chl *a* concentrations started to decrease after approximately 30 hours, but around 48 hours they increased for the treatments containing N and continued to decrease for all other treatments. At Rollover Pass (eastern part of East Bay), RLA treatments showed an immediate increase of chl *a* concentrations for all treatments containing N; after approximately 100 hours these treatments had decreased to levels similar to the treatments not containing N (Fig. 21H).

All of the treatments with N added were significant at Christmas Bay (+NPSi: $p = 0.003$; +N: $p \sim 0.000$; +NP: $p = 0.011$; +NSi: $p \sim 0.000$). At Smith Point, there were significant differences between the control group and +N ($p = 0.011$), and +NP ($p = 0.024$). This was also the case at Eckert's Bayou (+N: $p = 0.011$; +NP: $p = 0.024$). Rollover Pass had significant differences for +NP ($p = 0.022$) and +NSi ($p = 0.010$). None of the treatments at Offatt's Bayou, Trinity Bay, Texas City Dike or the Houston Ship Channel were significantly different than the control, suggesting possible light limitation rather than nutrient limitation in these parts of Galveston Bay (F, C, G, respectively, in Fig. 21I).

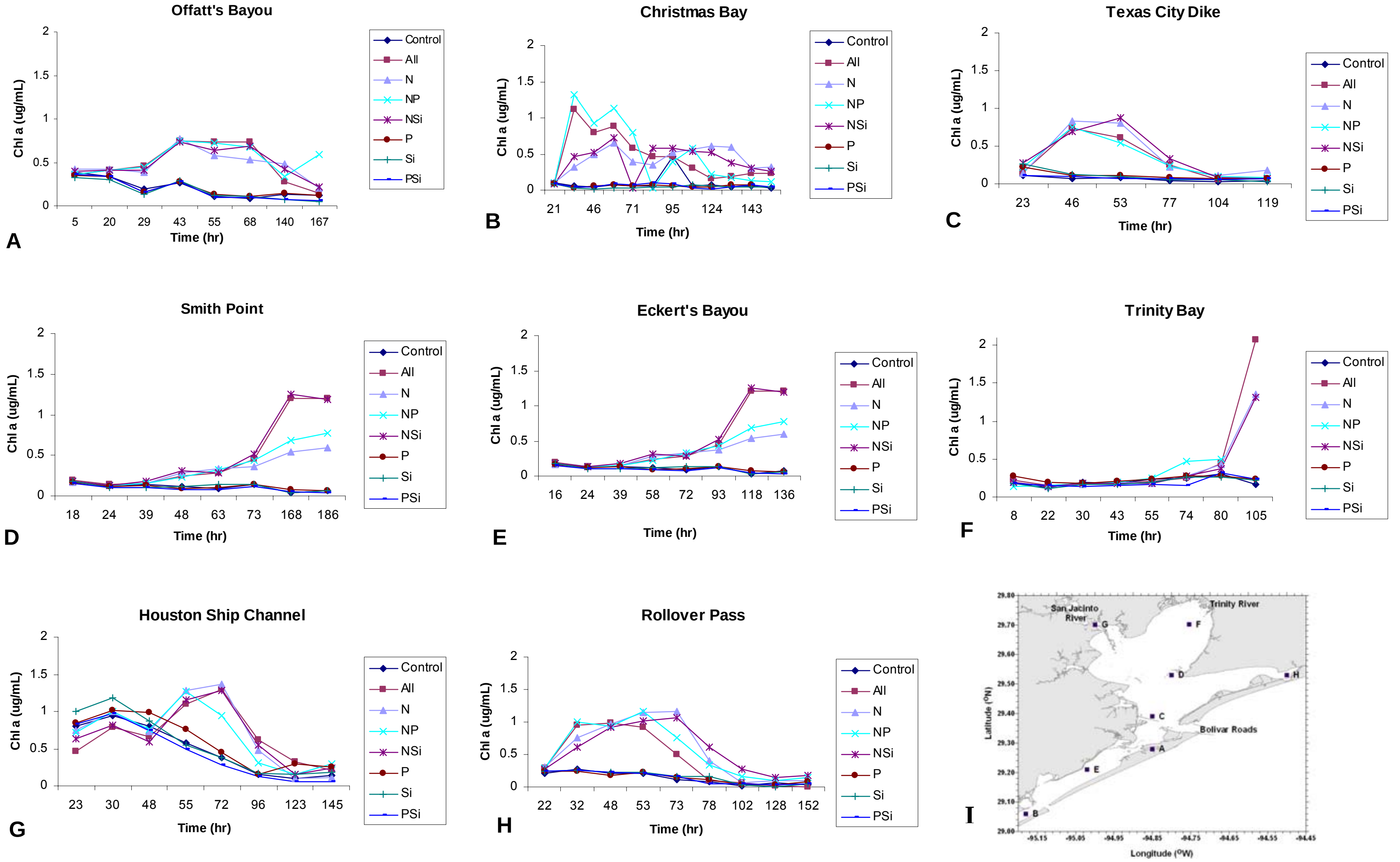


Fig. 21: Responses of chl *a* to nutrient additions during RLAs at 8 different sites in Galveston Bay.

4. DISCUSSION

4.1 Freshwater Inflows

Freshwater inflows affect the dynamics of phytoplankton in Galveston Bay. Inflows moderate the dilution of seawater to brackish water and supply nutrients to the system (Longley 1994). Previous studies have shown the importance of freshwater inflows, particularly in the form of pulsed inflow events, to increased productivity within an estuarine system (Montagna and Kalke 1992; Ward et al. 2002; Roelke et al. 2004; Pinckney 2006). In order to maintain a healthy ecosystem, minimum freshwater inputs need to be maintained. In addition to consideration of the magnitude, there is the issue of frequency (pulsed versus continuous). State and federal agencies would like to determine the most appropriate regime so that they may better manage the watershed and its associated resources for future generations.

Freshwater inflow into Texas estuaries typically occurs in a pulsed fashion, with seven large (>7,000 $\text{ft.}^3\ \text{sec}^{-1}$) events occurring during 2006 in Galveston Bay. The annual mean daily freshwater discharge for 2006 was 2,629 $\text{ft.}^3\ \text{sec}^{-1}$, which was much lower than the average annual daily mean of 7,856 $\text{ft.}^3\ \text{sec}^{-1}$ (1925-2006; Fig. 22). The highest mean daily freshwater discharge into Galveston Bay (17,610 $\text{ft.}^3\ \text{sec}^{-1}$) was recorded in 1992, while the lowest, a mere 1,264 $\text{ft.}^3\ \text{sec}^{-1}$, was recorded in 1956. Rainfall and temperature data collected by NOAA in the Galveston area showed that 2006 had higher than average rainfall and temperature, and the 9th wettest July on record since 1871. 2006 was also the warmest year on record, with 2005 being the second warmest (NOAA 2008). The absence of these rain events in the freshwater discharge data (Fig. 3) indicated that the rainfall occurred south of the river gauge.

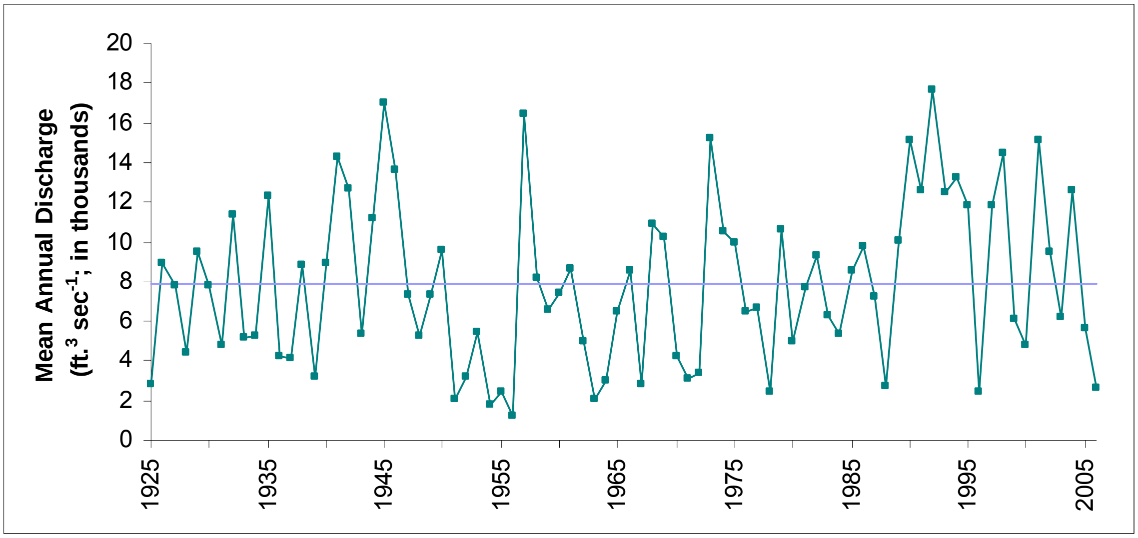


Fig. 22: Mean annual discharge via the Trinity River into Galveston Bay from 1925-2006. Data were collected from USGS gauge 08066500 in Liberty, TX. The straight line shows the mean annual discharge during the period of record.

River flow into Galveston Bay was highest during spring and fall (February to April; October to December), and lowest during the summer (May to September; Fig. 3). This seasonal trend is similar to that typically observed in other estuaries in the Gulf of Mexico. Escambia Bay, Florida had highest flows occurring during spring (February to April) and lowest flows during summer and fall (June to November, Murrell et al. 2007). The mean inflow for 2006 was much lower than the typical annual mean, which may be why chl *a* concentrations during the study period were relatively low compared to those measured in previous years (Lester and Gonzalez 2002). This may also explain why no significant algal blooms were observed during this period. River flow affects biomass by controlling the salinity gradient of the estuary, physically flushing the phytoplankton, and supplying nutrients. Periods of high inflow can enhance bloom conditions, while reduced inflows can reduce or washout a bloom event (Reaugh et al. 2007). It is likely that blooms will form in Galveston Bay in years with higher mean inflows.

4.2 Water Quality

The only water quality parameter measured by the Dataflow in Galveston Bay that was significantly different between the wet and dry months was temperature. This was most likely a seasonal effect, but may have been moderated by freshwater inflows. While other parameters varied in response to inflow events, statistically significant responses were not found when comparing these parameters between wet and dry months. The simplest explanation may be that the magnitude of the inflow was not sufficient to reach the southern portion of Galveston Bay. The lack of perturbation to this system by freshwater inflows during 2006 is evident in the spatial maps (Fig. 5-9), particularly those for salinity and transparency. While these water quality parameters did vary seasonally, the changes observed were relatively homogenous across Galveston Bay. Ongoing mapping studies in Galveston Bay will provide information on the magnitude of freshwater required to significantly impact water quality parameters between wet and dry months.

Salinity was the only water quality parameter that displayed a statistically significant difference when the north and south portions of Galveston Bay were compared. Salinities closest to the mouth of the Trinity River tended to be lower than those measured in the southern portion of the bay. DOM and transparency are typically affected by the particulate matter that enters the bay via freshwater inflows (Boyer et al. 2006). However, DOM values, also often associated with increasing chl *a* concentrations, and turbidity did not show a trend with freshwater inflows. Boyer et al.

(2006) implicated the bioavailability of DOM as a contributing factor in regulating the onset, persistence, and composition of phytoplankton blooms, suggesting that increases in freshwater discharge could lead to phytoplankton blooms.

4.3 Phytoplankton Biomass

Phytoplankton biomass in Chesapeake Bay was greater during wet years than dry or average flow years (Reaugh et al. 2007). Chl *a* concentrations did not show a definite trend in 2006 with freshwater discharges into Galveston Bay, and overall they were lower than typically measured in this system (Lester and Gonzalez 2002). The findings of Reaugh et al. (2007) suggest that the phytoplankton biomass in Galveston Bay during 2006 may be less than during a wet year. Future studies may show a correlation between freshwater inflows and chl *a* concentrations if done during years in which freshwater inflows are significantly greater than those experienced during 2006. This correlation is anticipated given that freshwater inflows bring nutrient and sediment loads into estuarine systems (Longley 1994). Interestingly, an overall declining trend in monthly chl *a* concentrations has been observed in Galveston Bay since the 1950s, which has been attributed to the reduction in pollutant loading as a result of the Clean Water Act (Lester and Gonzalez 2002). Hence, future studies must be careful to separate trends in chl *a* concentrations that may be a function of freshwater inflow relative to those associated with the improved water quality of Galveston Bay.

Malone et al. (1988) found that by examining chl *a* concentrations relative to freshwater inflow that had occurred a month prior, a significant correlation between freshwater inflows and chl *a* levels was measured in the mesohaline portion of Chesapeake Bay; and seasonal and interannual variation in phytoplankton biomass occurred in response to variations in freshwater inflows and associated variations in nitrate flux. A similar situation may be occurring in Galveston Bay; that is, a lag of up to one month may be required before a significant change in phytoplankton biomass is observed in response to freshwater input. Examination of the data collected in 2006 reveals that only parameters (Dataflow and PhytoPAM) measured in the northern portion of the bay responded, if at all, to freshwater inflows and there was no lag observed. This may reflect the low discharge rates in 2006 rather than a lack of response by the phytoplankton community. Alternatively, the amplitude of the response may not have been measureable given the sampling regime used. Future studies will be required to examine if a similar lag may be observed in Galveston Bay.

While the above discussion refers to the response of systems to chl *a* concentrations for the phytoplankton community and freshwater inflow, an examination considering individual phytoplankton groups revealed changes in phytoplankton biomass in Galveston Bay in 2006 which were associated with seasonal cycles of phytoplankton community succession. The PhytoPAM measured chl *a* biomass (Fm) associated with cyanobacteria and diatoms/dinoflagellates. Concentrations of both groups were found to be high during the spring (especially May), while cyanobacteria concentrations were higher in the dry months (summer) and diatoms and dinoflagellates concentrations were higher in the wet months (winter). Roelke et al. (2004) found the same trend in Lake Somerville, a shallow, well-mixed reservoir in eastern TX. Cyanobacteria were more prevalent during dry periods, resulting in low secondary productivity. Phytoplankton biomass in Suisun Bay, California also varied inversely with river discharge. The small winter populations were dominated by microflagellates and freshwater diatoms, while the summer blooms were dominated by neritic diatoms (Cloern et al. 1983).

4.4 Nutrient Limitation

Nitrogen is typically considered the limiting nutrient in estuaries, particularly during the summer months. However, previous studies have found phosphorus and possibly silica to be limiting in spring (Fisher et al. 1992; Harding 1994; Chan and Hamilton 2001). Nutrient distributions in Escambia Bay, Florida suggested phosphorus limitation during normal flow and nitrogen limitation during low flow periods (Murrell et al. 2007). Juhl and Murrell (2008) found that phosphorus limitation during April 2001 in Pensacola Bay, Florida coincided with a period of high river flow that produced the lowest salinities during their study period. Previous studies in the bay had found phosphorus limitation in several sites further up the estuary in Pensacola Bay. Consistent with these studies, the current study conducted in Galveston Bay found N limitation at all 8 stations during late spring/summer. These findings were consistent with earlier studies by Örnólfsdóttir et al. (2004) and Pinckney (2006), who also found that N is the limiting nutrient in Galveston Bay. Conducting seasonal RLAs in Galveston Bay should give an indication as to whether or not the limiting nutrient changes during the year in response to changing flows. In addition, the findings from the RLA conducted in this study are consistent with what might be predicted during low freshwater inflow periods (Murrell et al. 2007). That the phytoplankton community at the station closest to the Trinity River (Fig. 21G) took so long to increase in biomass in response to nutrient additions, and that all treatments responded similarly, indicated that the phytoplankton community in this part of Galveston Bay was light-limited. This will be discussed further below (see section *4.5*).

Two strategies have been proposed for phytoplankton response to nutrient pulsing: the growth response (rapid uptake of nutrients, little internal storage in nutrient pools, and rapid cell division) and the storage response (moderate uptake rates, accumulation of nutrients in internal pools, and a delayed (up to 24 h) growth response, Pinckney et al. 1999). The growth response is advantageous when the pulsing occurs at a frequency higher than the cell division rate and the storage response is advantageous when nutrient pulsing occurs at a rate less than the cell division rate. The growth response was seen at the Christmas Bay, Texas City Dike, and Rollover Pass stations, while the storage response was seen at the Smith Point, Trinity Bay, and Eckert's Bayou stations. Phytoplankton communities closest to the freshwater inflows apparently take advantage by maintaining a baseline growth rate and storing nutrients for periods of low to no flows. In addition, phytoplankton utilizing the storage response will enhance secondary productivity by transferring more nutrients up the food chain. Those at stations furthest from the nutrient source, in the southern most sections of Galveston Bay, instead respond quickly to pulses in nutrients, taking advantage of this supply which may infrequently deliver nutrients due to their distance from the source. Although Eckert's Bayou is located in the southern portion of the bay, it is not showing a similar response. This may be due to the fact that the other stations are all located near tidal exchange areas with the Gulf of Mexico.

Nutrients present in the spring inflows to Chesapeake Bay were taken up by phytoplankton and generated the large biomass that supported high secondary production.

The breakdown of this biomass has been linked to deleterious processes with severe aesthetic and economic consequences (Harding 1994). This same phenomenon may be occurring in Galveston Bay where cyanobacteria and diatoms/dinoflagellates are present in elevated (i.e., above typical) concentrations during late spring. The corresponding bacterial respiration and decay as the phytoplankton community dies off may ultimately contribute to decreased levels of dissolved oxygen in the water column. Texas, especially Galveston Bay, has historically recorded a high number of fish kill events, with the majority occurring during the summer months, particularly August (Thronson and Quigg 2008). The lack of major fish kill events reported in Galveston Bay during 2006 may have been due to the absence of a large spring bloom.

4.5 Light Limitation

Harding (1994) found that phytoplankton growth in the upper, oligohaline portions of Chesapeake Bay may be light limited due to an increase in turbidity from freshwater inflows. During the flood in 2001 in Escambia Bay, Florida, productivity decreased due to turbid waters and rapid flushing times. Phytoplankton productivity increased strongly over the next several months before returning to pre-flood conditions (Murrell et al. 2007). Decreases in transparency caused by increased inflows may cause the phytoplankton community to become light limited. Contrarily, increases in transparency leading to increased light penetration can result in increases in chl *a* even if there is a concurrent reduction in nutrient concentrations (Chan and Hamilton 2001). In addition, if the community is nutrient limited then nutrients introduced via freshwater inflows can cause a succession from less edible, slower growing species to more edible, faster growing species, stimulating secondary productivity (Buyukates and Roelke

2005a). Pinckney (2006) found that water clarity in Galveston Bay was typically lower during periods of high freshwater inflow, possibly leading to benthic microalgal photosynthesis being light-limited. However, the shallow water column is generally well-mixed, indicating the phytoplankton community would not typically be light-limited. The only exception may be for phytoplankton in the Trinity River Basin (see *4.4* above).

4.6 Photosynthetic Efficiency

Earlier studies (Örnólfsdóttir et al. 2004; Pinckney 2006; Reaugh et al. 2007) have measured total chlorophyll as a proxy for phytoplankton biomass, light penetration and/or nutrient concentrations. By assessing phytoplankton physiology with the PhytoPAM, the response of the phytoplankton community to these perturbations in Galveston Bay was assessed for the first time. Yields were generally >0.4 rel. units from February through August, but <0.4 rel. units from September to November (Fig. 14). This indicated that the phytoplankton community was nutrient or light stressed, or a combination of the two during the fall. These fluctuations in phytoplankton activity do not appear to be correlated simply to freshwater inflow given that the variables were measured in both wet and dry months, and in the north and south sections. Nonetheless, they provide insights into why we observe succession of different phytoplankton taxa, and perhaps why blooms typically are observed in the spring months, despite evidence for N limitation.

Closer examination reveals that cyanobacteria and diatoms/dinoflagellates yields were highest in February (0.56 and 0.49 rel. units) and May (0.49 and 0.50 rel. units, respectively). The *rel*ETR values, an estimate of the net primary production rate, mirrored those for photosynthetic efficiency (yield). This indicated that higher photosynthetic efficiency results in higher net primary productivity. This also corresponded with their greatest biomass (Fig. 15, 18) and large amounts of freshwater in Galveston Bay as a consequence of multiple large inflows (Fig. 3). Hence, the timing of spring blooms is also associated with the greatest productivity of these groups. While this may be presumed, this is the first series of large scale spatial and temporal measurements which supports this established paradigm, and additionally, provides a physiological basis for the phenomenon.

March was the only month when a yield value <0.4 (0.37 rel. units) was measured for the cyanobacteria while diatoms/dinoflagellates measured low during October (0.31 rel. units) and November (0.39 rel. units). Given these months were all "wet" indicated freshwater inflows, and thus nutrient inputs, were not limiting. Further studies will be required to determine what other factor may be reducing phytoplankton productivity. While samples were collected to measure nutrient concentrations each month, the data are not yet available to assist in providing insights into the key factors regulating primary production.

4.7 Phytoplankton Blooms

Phytoplankton blooms were not observed during 2006, but may develop during normal or high inflow years. Freshwater chlorophytes are dominant and form blooms only when the salinity is less than 6 psu (Chan and Hamilton 2001). It was uncommon for the salinity in Galveston Bay to be that low during 2006; therefore chlorophytes were rarely seen in the bay. Dinoflagellates have the narrowest range of growth rates, from 0.3 to 0.7 doublings day^{-1}. They are found in salinities from about 10 to 34 psu. Diatoms have the widest range of maximum growth rates, from 0.4 to 4 doublings day^{-1}. They therefore typically occur over the widest range of flow rates. Diatom blooms can occur in salinities from 4 to 28 psu, with a decline at salinities of 7 to 12 psu; and receive an advantage during high flow periods because the turbulence allows for resuspension of sinking cells (Chan and Hamilton 2001). This supports data from the current study as the biomass of diatoms in Galveston Bay was significantly higher during the wet months. Previous studies in Galveston Bay have shown an increase in diatom biomass following nitrate additions, indicating that diatoms would be favored by N pulsing events, while long periods of low loading could promote growth of smaller phytoplankton such as cyanobacteria (Örnólfsdóttir et al. 2004; Pinckney 2006). Dominance of cyanobacteria (occurring during low inflow periods) often results in diminished grazing rates, allowing accumulation of phytoplankton biomass and decreased light penetration, which typically favors cyanobacteria over other phytoplankton. Pulsed inflow events, which favor diatoms/dinoflagellates, typically result in increased zooplankton productivity which keeps the phytoplankton biomass cropped and maintains deeper light penetration (Roelke et al. 2004). This indicates that in order to maintain a healthy food web in Galveston Bay, pulsed inflow events must occur. However, the optimum magnitude and frequency of these events has yet to be determined.

4.8 Responses of Higher Trophic Levels

Flow is a key determinant of phytoplankton succession and may be critical to eutrophication in estuaries with reduced inflows due to anthropogenic activities (Chan and Hamilton 2001). A river diversion project in the Nueces Delta, Texas, showed that temporary pulsed inflows corresponded to dramatic increases in net ecosystem productivity, including improved abundance and diversity of intertidal vegetation and benthic communities. Under these pulsed inflow conditions, phytoplankton biovolume was lower and phytoplankton species diversity was higher, stimulating energy transfer up the food web (Buyukates and Roelke 2005a). Neritic diatoms in San Francisco Bay, California, which includes Suisun Bay, are an important dietary component of the mysid shrimp *Neomysis*, which is in turn consumed by the larvae of striped bass (*Morone saxatilis*) and other fish in the estuary (Cloern et al. 1983). A decline of the neritic diatom population in Suisun Bay may have resulted in the near-complete collapse of the *Neomysis* population during 1977. This was also the year of the lowest recorded abundance of juvenile striped bass in northern San Francisco Bay. This indicates that river inflows may influence the entire pelagic food web of northern San Francisco Bay (Cloern et al. 1983). This scenario may also occur in Galveston Bay, but has not yet been assessed.

5. CONCLUSIONS

The objective of this study was to provide a more comprehensive understanding of the relationships between the nature of inflow events and estuarine ecosystem health in Galveston Bay. Data from this study support the hypothesis that variations in freshwater inflows affect primary productivity and phytoplankton community structure in Galveston Bay. Temperature, biomass (Fm), photosynthetic efficiency (alpha) and photosynthetic potential (yield) values were significantly different between wet and dry months, and salinity and photosynthetic efficiency were significantly different between the north and south portions of the bay. The mode of freshwater inflow events (continuous vs. pulsed) can have a significant impact on the phytoplankton community. Continuous inflow events favor cyanobacteria dominance, resulting in low secondary productivity, while pulsed inflow events result in enhanced secondary productivity by favoring diatoms and dinoflagellates (Roelke et al. 2004). What still needs to be determined, however, is the frequency and magnitude of freshwater inflows required to maintain a healthy estuarine system. This study shows the effect of a low inflow year on the phytoplankton community, but inter-annual studies need to be performed to determine the impact of average and above-normal freshwater inflow years.

Nutrient loads are also an important factor in determining the response of the estuarine system to freshwater inflow events. Major N (in the form of nitrate) events are directly related to Trinity River discharge (Pinckney 2006). Short-term nutrient pulses may favor diatoms and long periods of low loading would favor smaller, less desirable phytoplankton (Huisman and Weissing 1995). An automatic sampler has been placed on the Trinity River to determine daily nutrient loads into the system. Data collected from this sampler will be essential for determining which nutrients are being introduced, in what levels, and, in conjunction with the continuation of this study, how the ecosystem is responding to this influx.

One of the challenges that resource managers face is the ability to accurately predict how changes in land use practices influence estuarine ecosystems (Murrell et al. 2007); yet these predictions are essential for making informed decisions before land use changes occur. As freshwater demands for inland users increase (possibly an additional 9.25×10^9 m^3 by year 2050), there is an increasing need to incorporate results from research into the management decisions so that the least harm is done to the environment while still allowing maximum beneficial use of state waters (Powell et al. 2002). Inter-annual studies are an essential component to understanding the impacts of higher inflow years on the Galveston Bay Estuary, and determining which impacts need to be incorporated into water management decisions to maintain a healthy ecosystem.

REFERENCES

Arhonditsis, G. B., C. A. Stow, H. W. Paerl, L. M. Valdes-Weaver, L. J. Steinberg and K. H. Reckhow. 2007. Delineation of the role of nutrient dynamics and hydrologic forcing on phytoplankton patterns along a freshwater-marine continuum. *Ecological Modeling* 208:230-246.

Boyer, J. N., S. K. Daily, P. J. Gibson, M. T. Rogers and D. Mir-Gonzalez. 2006. The role of dissolved organic matter bioavailability in promoting phytoplankton blooms in Florida Bay. *Hydrobiologia* 569:71-85.

Buyukates, Y. and D. Roelke. 2005a. Influence of pulsed inflows and nutrient loading on zooplankton and phytoplankton community structure and biomass in microcosm experiments using estuarine assemblages. *Hydrobiologia* 548:233-249.

Buyukates, Y. and D. Roelke. 2005b. *Management tools for aquatic systems: The role of periodic hydraulic disturbances on planktonic communities*. Texas Water Resources Institute.

Buyukates, Y. and D. L. Roelke. 2005c. Investigating system characteristics of a Southeast Texas wetland: Nutrient and plankton dynamics of a tidal creek in lower Nueces Delta. *Journal of Applied Sciences* 5:820-828.

Chan, T. U. and D. P. Hamilton. 2001. Effect of freshwater flow on the succession and biomass of phytoplankton in a seasonal estuary. *Marine and Freshwater Research* 52:869-884.

Cloern, J. E., A. E. Alpine, B. E. Cole, R. L. J. Wong, J. F. Arthur and M. D. Ball. 1983. River discharge controls phytoplankton dynamics in the Northern San-Francisco Bay estuary. *Estuarine Coastal and Shelf Science* 16:415-429.

Dunton, K. H., B. Hardegree and T. E. Whitledge. 2001. Response of estuarine marsh vegetation to interannual variations in precipitation. *Estuaries* 24:851-861.

Engle, V. D., J. C. Kurtz, L. M. Smith, C. Chancy and P. Bourgeois. 2007. A classification of U.S. estuaries based on physical and hydrologic attributes. *Environmental Monitoring and Assessment* 129:397-412.

Fisher, T. R., A. B. Gustafson, K. Sellner, R. Lacouture, L. W. Haas, R. L. Wetzel, R. Magnien, D. Everitt, B. Michaels and R. Karrh. 1999. Spatial and temporal variation of resource limitation in Chesapeake Bay. *Marine Biology* 133:763-778.

Fisher, T. R., E. R. Peele, J. W. Ammerman and L. W. Harding. 1992. Nutrient limitation of phytoplankton in Chesapeake Bay. *Marine Ecology-Progress Series* 82:51-63.

GBEP. 2001. The Comprehensive and management plan for the Galveston Bay Ecosystem. http://gbic.tamug.edu/GBPlan/GBPlan.html. Last accessed 28 Nov 2007.

Harding, L. W. 1994. Long-term trends in the distribution of phytoplankton in Chesapeake Bay - Roles of light, nutrients and streamflow. *Marine Ecology Progress Series* 104:267-291.

Heilman, J. L., D. R. Cobos, F. A. Heinsch, C. S. Campbell and K. J. McInnes. 1999. Tower-based conditional sampling for measuring ecosystem-scale carbon dioxide exchange in coastal wetlands. *Estuaries* 22:584-591.

Huisman, J. and F. Weissing. 1995. Competition for nutrients and light in a mixed water column: A theoretical approach. *American Naturalist* 146:536-564.

Jakob, T., U. Schreiber, V. Kirchesch, U. Langner and C. Wilhelm. 2005. Estimation of chlorophyll content and daily primary production of the major algal groups by means of multiwavelength-excitation PAM chlorophyll fluorometry: Performance and methodological limits. *Photosynthesis Research* 83:343-361.

Juhl, A. R. and M. C. Murrell. 2008. Nutrient limitation of phytoplankton growth and physiology in a subtropical estuary (Pensacola Bay, Florida). *Bulletin of Marine Science* 82:59-82.

Lester, J. and L. Gonzalez. 2002. The state of the bay: A characterization of the Galveston Bay Ecosystem. The Galveston Bay Estuary Program.

Lohrenz, S. E., M. J. Dagg and T. E. Whitledge. 1990. Enhanced primary production at the plume/oceanic interface of the Mississippi River. *Continental Shelf Research* 10:639-664.

Longley, W. L. (ed.). 1994. Freshwater inflows to Texas bays and estuaries: Ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department. 386 p.

Madden, C. J. and J. W. Day, Jr. 1992. An instrument system for high-speed mapping of chlorophyll *a* and physico-chemical variables in surface waters. *Estuaries* 15:421-427.

Malone, T. C., L. H. Crocker, S. E. Pike and B. W. Wendler. 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. *Marine Ecology Progress Series* 48:235-249.

Montagna, P. A. and R. D. Kalke. 1992. The effect of freshwater inflow on meiofaunal and macrofanal populations in the Guadalupe and Nueces Estuaries, Texas. *Estuaries* 15:307-326.

Moulton, D. W., L. D. McKinney and D. L. Buzan. 2004. Texas Coastal Ecosystems: Past, present and future. Texas Parks and Wildlife Department.

Murrell, M. C., J. D. Hagy, E. M. Lores and R. M. Greene. 2007. Phytoplankton production and nutrient distributions in a subtropical estuary: Importance of freshwater flow. *Estuaries and Coasts* 30:390-402.

NOAA. 1989. Galveston Bay: Issues, resources, status, and management. Department of Commerce.

NOAA. 2008. Southeast Texas climate data. http://www.srh.noaa.gov/hgx/climate.htm. Last accessed 18 June 2008.

Örnólfsdóttir, E. B., S. E. Lumsden and J. L. Pinckney. 2004. Nutrient pulsing as a regulator of phytoplankton abundance and community composition in Galveston Bay, Texas. *Journal of Experimental Marine Biology and Ecology* 303:197-220.

Pallant, J. 2007. SPSS survival manual. New York: Open University Press.

PHA. 2006. The Port of Houston Authority. Houston, TX. http://www.portofhouston.com. Last accessed 12 November 2007.

Pinckney, J. L. 2006. System-scale nutrient fluctuations in Galveston Bay, Texas (USA). p. 141-164. In J. C. Kromkamp, Jody F.C. de Brouwer, G. F. Blanchard, R. M. Forster and V. Créach, ed. *Functioning of microphytobenthos in estuaries*. Amsterdam, the Netherlands: Royal Netherlands Academy of Arts and Sciences.

Pinckney, J. L., H. W. Paerl and M. B. Harrington. 1999. Responses of the phytoplankton community growth rate to nutrient pulses in variable estuarine environments. *Journal of Phycology* 35:1455-1463.

Powell, G. L., J. Matsumoto and D. A. Brock. 2002. Methods for determining minimum freshwater inflow needs of Texas Bays and estuaries. *Estuaries* 25:1262-1274.

Quigg, A. and J. Beardall. 2003. Protein turnover in relation to maintenance metabolism at low photon flux in two marine microalgae. *Plant Cell and Environment* 26:693-703.

Raven, J. A. and P. G. Falkowski. 1997. *Aquatic photosynthesis*. Malden, MA: Blackwell Publishing.

Rawlence, D. J. 1988. *Selenastrum capricornutum* Printz algal assay: Bottle test for determination of limiting nutrient status. In *Experimental phycology: A laboratory manual*, eds. C. S. Lobban, D. J. Chapman and B. P. Kremer, 56-77. New York: Cambridge University Press.

Reaugh, M. L., M. R. Roman and D. K. Stoecker. 2007. Changes in plankton community structure and function in response to variable freshwater flow in two tributaries of the Chesapeake Bay. *Estuaries and Coasts* 30:403-417.

Riera, P., P. A. Montagna, R. D. Kalke and P. Richard. 2000. Utilization of estuarine organic matter during growth and migration by juvenile brown shrimp Penaeus aztecus in a South Texas estuary. *Marine Ecology Progress Series* 199:205-216.

Roelke, D., Y. Buyukates, M. Williams and J. Jean. 2004. Interannual variability in the seasonal plankton succession of a shallow, warm-water lake. *Hydrobiologia* 513:205-218.

Thronson, A. and A. Quigg. 2008. Fifty-Five Years of Fish Kills in Coastal Texas. *Estuaries and Coasts* 31:802-813.

TWDB. 2001. Water for Texas: Summary of regional water plans. Texas Water Development Board.

TWDB. 2007. Highlights of the 2007 state water plan. Texas Water Development Board.

Ward, G. H., M. J. Irlbeck and P. A. Montagna. 2002. Experimental river diversion for marsh enhancement. *Estuaries* 25:1416-1425.

White, A. J. and C. Critchley. 1999. Rapid light curves: A new fluorescence method to assess the state of the photosynthetic apparatus. *Photosynthesis Research* 59:63-72.

VITA

Amanda Mae Thronson received her Bachelor of Science degree in Marine Biology from Texas A&M University at Galveston in 2004. She received her Master of Science degree from Texas A&M University in Zoology in December 2008.

Ms. Thronson may be reached at Texas A&M University at Galveston, Phytoplankton Dynamics Laboratory, 5007 Ave U, Galveston, TX 77551. Her email is: amandathronson@hotmail.com.